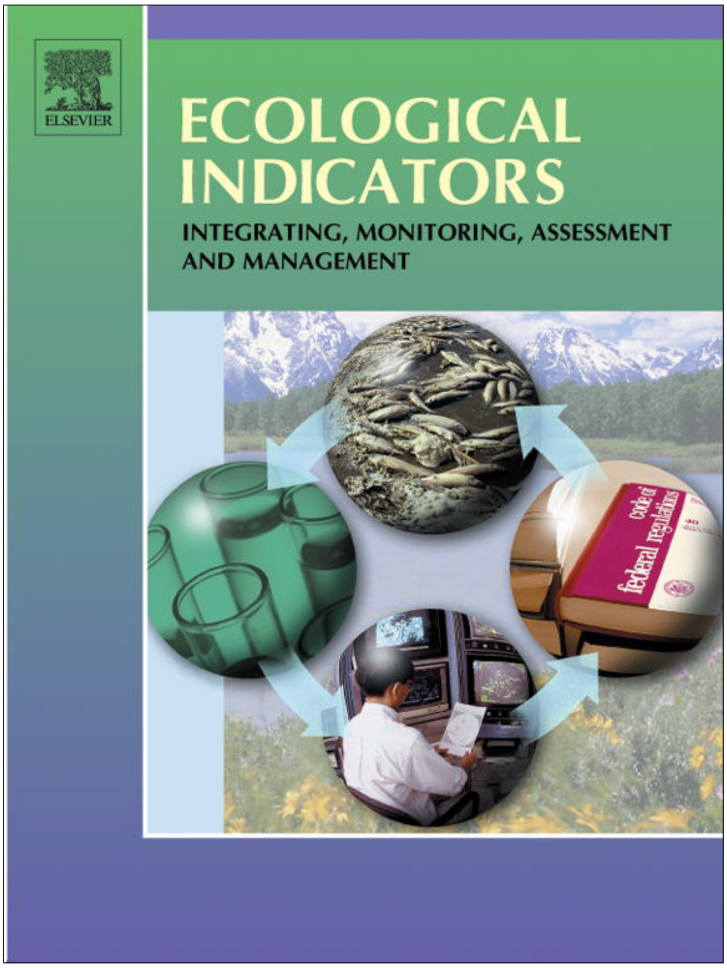
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Pan-European distribution modelling of stream riparian zones based on multi-source Earth Observation data

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ABSTRACT

Freshwater ecosystems are among the most degraded and threatened globally. A need for systematic assessment of riverine habitats is thus well-documented. Riparian zones are especially important due to the large array of ecosystem and social services they can provide, while also recently gaining a major role in the new European biodiversity policy. In this context, the necessity to gather spatial information on extent, distribution and characteristics of the riparian zones is clear. This paper presents the development of a novel model to derive geographical distribution and basic characteristics of stream riparian zones in Europe, including both river-floodplain systems and the riparian networks of minor and ephemeral streams. A series of relevant descriptive attributes (water boundary, vegetation presence, land-cover, upland boundary and local geomorphology) is initially selected from the existing literature to describe the presence of riparian zones. Spatially explicit estimates of these attributes are obtained using available Earth Observation data and pan-European thematic datasets. Finally, the information layers are combined through an aggregation system that assigns a degree of belonging to the riparian zone class using two fuzzy membership functions to evaluate water influence and presence of natural vegetation, respectively. Riparian zones with no hydrological connection are also incorporated in by the model based on functional considerations. The distribution of stream riparian zones was derived and mapped for the whole of Europe at fine resolution. Modelled riparian zones extend for approximately 91,000 km^2, considering the entire range of low to high membership to the riparian class. A characterization of land-cover types was derived based on Corine Land Cover 2000 data, showing that European riparian zones are strongly dominated by forest habitats. Accuracy assessment was performed using independent ecological datasets and visual validation, indicating that producer accuracy is equal to $84.5 \pm 1.3\%$ and user accuracy to $72.6 \pm 5.8\%$ at 95% confidence level. The proposed model and output can represent valuable information for large-scale research activities of riparian environments and to support national and supra-national conservation programmes.

1. Introduction

In light of current widespread degradation and threats to freshwater ecosystems, the need for systematic assessment of riverine habitats is well-documented (MEA, 2005; Dudgeon et al., 2006; Malmqvist and Rundle, 2002). At European level this is endorsed by a series of key legislative acts; most importantly the Water Framework Directive (2000/60/EC), which introduced the legal obligation for Member States to assess the ecological conditions of river and adjacent land habitats as a basis for effective management policies. Riverine habitats are gaining an increasingly significant role within the new European biodiversity policy and conservation targets for 2020, which are largely based on the implementation of the new European *Green Infrastructure* (Sundseth and Silwester, 2009). This multi-faceted concept, developed in the mid 1990s in the US, can be defined as a strategically planned and managed network of natural lands, working landscapes and other open spaces that conserve biodiversity, ecosystem values and functions and provide associated benefits to human population (Benedict and McMahon, 2006).

To support research and monitoring activities related to the abovementioned policy framework, the need for information on extent, distribution and characteristics of the riparian zones (from the Latin *ripa*, bank) is clear. 'Riparian zones' refer to transitional areas occurring between land and freshwater ecosystems,

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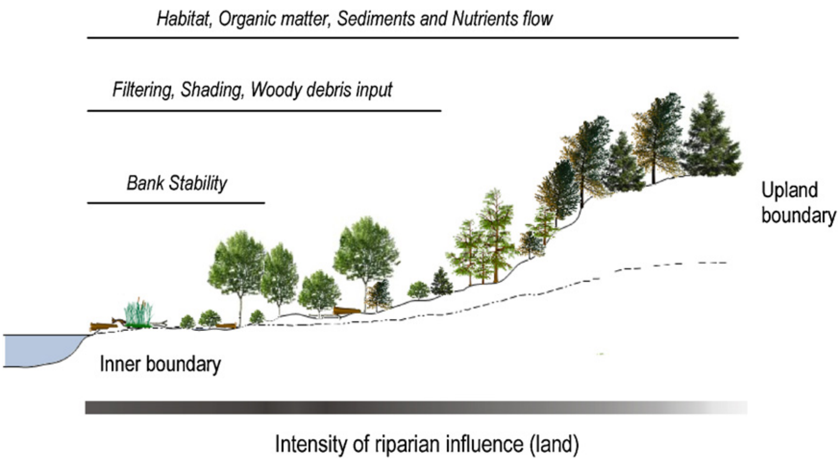

Fig. 1. Schematic representation of a riparian zone including its zone of influence (land), main functions and processes. Adapted from NRC (2002).

characterized by distinctive hydrology, soil and biotic conditions strongly influenced by the stream water (Naiman et al., 2005; Verry et al., 2004). These are not limited to areas associated with floodplain indicators, but they also include portions of upland away from the bank that have some water-land interaction (Gregory et al., 1991); typically, near-slope zones ecologically connected to the watercourse by surface and subsurface hydrology (NRC, 2002). Fig. 1 provides a schematic representation of a riparian zone and main characteristic functions.

Despite the variety of concepts and definitions present in the literature, there is strong agreement with regard to the importance of the riparian systems due to the natural and social services they provide. Riparian zones can encompass valuable natural habitats and are often characterized by high productivity and biodiversity (Whitaker et al., 2000; Knopf and Samson, 1994). They provide reduction of non-point-nutrient and pollution sources via plant uptake, physical filtering and chemical transformation (e.g. denitrification), together with trapping sediment-bound pollutants and waters coming from upstream (Daniels and Gilliam, 1996; Peterjohn and Correll, 1984). Riparian corridors play a major role in maintaining landscape connectivity, functioning as 'dispersal corridors' within fragmented landscapes (Gillies and Cassidy Saint Clair, 2008; Machtans et al., 1996). From a hydrological risk perspective, riparian environments supply river bank stabilization and provide resistance to runoff during flood events (Bennett and Simon, 2004).

The majority of research related to riparian zones has focused on permanent and seasonal watercourses, while few studies have focused on small headwaters and ephemeral tributaries (Goebel et al., 2003). Nevertheless, recent research based on surveys of amphibians and plant communities has claimed that these latter watercourse types can also have discernible riparian zones (Hagan et al., 2006; Perkins and Hunter, 2006). We therefore considered relevant to include in this study not only 'river-floodplain' systems (Bayley, 1995), but also the riparian networks of minor and ephemeral watercourses.

To the authors' knowledge, no continental-scale modelling and mapping of riparian zones has previously been performed; most literature describes local-scale analyses, with a few studies extending to a regional or watershed scale. Sutula et al. (2006) developed a method based on remote-sensing data to map potential riparian zones in Southern California watersheds. Their approach was based on purely geomorphological criteria applied to 10 m and 30 m DEMs, together with superimposed NDVI satellite data to report vegetation distribution. Ivits et al. (2009) considered as riparian zones the regions within a 1 km buffer zone from the river network of Andalusia (Spain), and analysed the permanent vegetation present in relation to EU agri-environmental measures. Much literature focuses on smaller scales (e.g. river basins) and on recent techniques, such as LiDAR, to acquire characteristics of riparian vegetation and topography (Johansen et al., 2010; Goetz, 2006).

The generation of a model to derive riparian zones distribution for the whole of Europe being a primary target of the present work, the proposed approach relies mostly on satellite imagery and continental GIS datasets. A large-scale assessment of this kind faces a series of challenges: (i) establishing a trade-off between processing effort/data availability and spatial resolution due to the vast study area and the generally small size of riparian zones, (ii) the high heterogeneity of these environments (e.g. spectral variance, biota, geomorphological setup), (iii) the need to introduce theoretical criteria in order to include functional considerations (NRC, 2002).

Specific objectives of this research are the development of a model to derive the continental distribution of European stream riparian zones, to report broad spatial patterns, and discuss their basic characteristics.

2. Materials and methods

The methodology followed is structured in three major sequential steps: (i) the selection in the literature of relevant common descriptors to characterize stream riparian zones; (ii) the production of thematic geospatial datasets as required information layers to represent the riparian descriptors; (iii) the implementation of a riparian detection model based on a fuzzy membership approach. All the methodological steps are described in detail in the following sections.

2.1. Selection of morphological and environmental descriptors

Riparian zones are characterized by large structural heterogeneity and complexity both within and across biogeographical regions (Naiman et al., 2005). In order to take into account such diversity, a set of common relevant environmental descriptors of stream riparian zones was selected based on available literature:

(1) Inner boundary: Proximity to a watercourse is intrinsically necessary for the development of a riparian zone. In the present study we focus on freshwater lotic systems, while excluding lentic systems, characterized by different ecological processes and disturbance regimes (Resh et al., 1988). A spatial delineation of the stream riverbank indicates the water-land

Table 1
European continental datasets used to build the model information layers.

Information layer	Source	Reference
River network	Catchment Characterisation and Modelling (CCM ver. 2.1)	Vogt et al. (2007)
	Corine Land Cover 2000, Water courses class	Bossard et al. (2000)
	European Hydraulic Geometries	Pistocchi and Pennington (2006)
Fifty-year frequency floodplains	LISFLOOD	Van Der Knijff et al. (2010) and Feyen et al. (2007)
DEM, path distance	ASTER GDEM	Hayakawa et al. (2008)
Vegetation	SRC-based classification of Image 2000 dataset	Baraldi et al. (2006) and Nunes de Lima (2005)
	EC JRC Forest Mask 2000	Pekkarinen et al. (2009)
Land-cover land use	Corine Land Cover 2000	Bossard et al. (2000)
Water mask	SRC-based classification of Image 2000 dataset	Baraldi et al. (2006) and Nunes de Lima (2005)
	Spectral Classification of Image 2006 dataset	Kempeneers et al. (2011)

interface, thereby defining the inner riparian zone boundary (Fig. 1).

(2) Upland boundary: The upland boundary is a complex and fuzzy edge, whose delineation depends on a number of factors, on the focus of the analysis and on the modelling criteria adopted (Ilhardt et al., 2000). Here we considered for boundary delineation both floodplain and geomorphological information, together with an estimated minimum functional buffer-zone required to maintain basic ecological riparian functions.
(3) Land-use/land-cover: To ensure a proper functioning of their functional processes and provision of stream ecosystem services (*sensu* Daily et al., 1997) riparian environments should preserve a certain degree of ecological integrity (Woodley et al., 1993). In the design of the model we considered only natural and semi-natural land-cover, excluding those areas characterized by artificial production (e.g. agricultural areas) or other man-made environments.
(4) Vegetation presence: Vegetation has a fundamental role in a wide series of ecological processes within the riparian zone (Naiman and Decamps, 1997). Key importance is given to forest vegetation, which controls woody debris input (Milner and Gloyne-Phillips, 2005), provides micro-habitats for several riparian species (Darveau et al., 2001; Prenda and Granado-Lorencio, 1996), as well as supplying a plethora of ecosystem services (Sweeney et al., 2004).
(5) Local geomorphology: Geomorphology strongly determines the movement of surface and subsurface water (Thorndycraft et al., 2008; Sutula et al., 2006); consequently, the extent of the riparian zone is linked to local geomorphology, which strongly controls lateral water movement and its subsequent influence on the terrestrial habitat.

2.2. Generation of the information layers

Based on the abovementioned elements, the proposed approach models the presence of riparian zones using spatially distributed datasets derived from remote-sensing imagery and validated information databases (Table 1). A spatial resolution of 25 m was set as an optimal trade-off between efficiency of the computational approach and data availability. The study area encompassed the 27 Member States of the European Union (EU27), excluding European Atlantic islands and overseas territories. Due to availability, the data reference year is 2000. All cartographic outputs are in the European Terrestrial Reference System 1989 and Lambert Azimuthal Equal Area projection (ETRS-LAEA).

2.2.1. River network and inner riparian boundaries

Despite the fact that rivers are non-equilibrium systems, the inner riparian zone boundary can reasonably be assumed to be a fixed spatial delineation of the watercourse banks. A high resolution dataset providing both watercourse path and width information for the whole of Europe is not available, thus a 2-D hydrographic network was generated by integrating information from three available continental datasets: the Catchment Characterization and Modelling (CCM) river network (Vogt et al., 2007), the Corine Land Cover 2000 (CLC2000) seamless vector data (EEA, 2006), and the European Hydraulic Geometries (EHG) database (Pistocchi and Pennington, 2006). CCM data were gathered by Vogt et al. (2007) using a 3″ DEM from the Shuttle Radar Topography Mission (Hayakawa et al., 2008) and processed at a grid-cell resolution of 100 m. The data provide a complete linear river network for Europe, but lack river width information. In order to include width, the spatial extent of large rivers was obtained from the CLC2000 data, selecting the 'water courses' class (code 511). The CLC2000 watercourse boundaries are accurate, although, having a minimum width of 100 m (Nunes de Lima, 2005), the majority of European streams are not included. Consequently, for smaller watercourses the European Hydraulic Geometries database was used, which provides European river width information at a 1 km resolution. EGH river width information was accordingly applied to smaller streams, not present in the CLC2000 dataset, in order to obtain a full continental two-dimensional river network dataset.

2.2.2. Upland boundary: maximum potential riparian extent

The delineation of a riparian upland boundary is a complex task, due to the fuzzy nature of the ecological gradients characterising the riparian zones. While fixed buffers along water streams have been widely used in the scientific literature on riparian zones and in management plans, it is clear that they are insufficient to represent the complexity of riparian environments delineation (e.g. Müller, 1997). This work aims at identifying transitional areas occurring along land and river ecosystems where abiotic and biotic conditions are significantly influenced by stream water. Ilhardt et al. (2000) indicated the 50-year frequency floodplain as an optimal hydrological descriptor for riparian ecotones, because the elevation correspondent to these floodplains generally reaches the first terrace and initial upward-sloping surfaces. In our model this information was provided with adequate spatial detail and continental coverage by LISFLOOD data (Van Der Knijff et al., 2010; Feyen et al., 2007), a complex hydrological rainfall-runoff-routing model that simulates catchment hydrological processes. The LISFLOOD-modelled 50-year frequency European floodplain areas at a 100 m spatial resolution (FZ_{50}) were used as a basis for defining the upland boundary of riparian zones in river-floodplain systems.

For stream-riparian systems, where floodplain formation conditions are not present, a geomorphological approach was followed. Recent approaches make use of DEMs and ancillary information to identify geomorphological breaks representing riparian zone boundaries (Collins et al., 2006). Sutula et al. (2006) implemented a cost-effective method of identifying riparian potential maximum

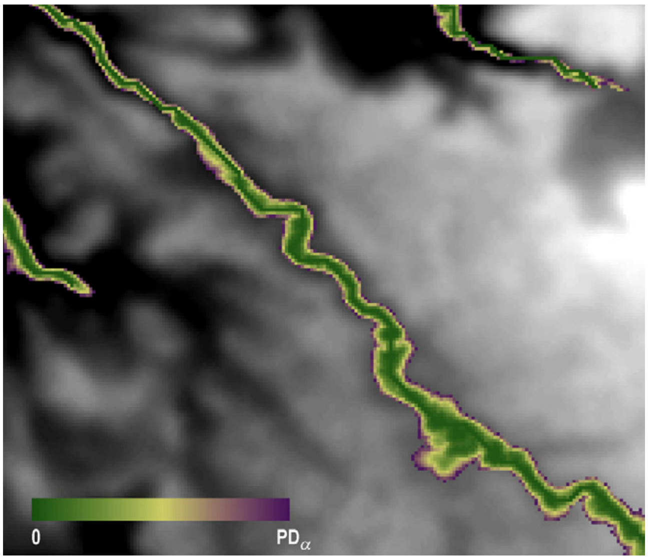

Fig. 2. Example of calibrated Path Distance calculated from a river stream, overlapped on a digital elevation model (ASTER GDEM); brighter grey tones represent higher altitude.

lateral extent, based on DEM-derived indices. Among the geomorphological indices used, the Path Distance (PD) was considered. This function represents the topographic cost of water to move horizontally and vertically from a specified feature (Sutula et al., 2006); in our study it represents the accumulated cost of water moving laterally from the river. Path Distance calculation requires a source layer (the two-dimensional river network) and a cost layer, which represents the surface constraint to overcome in order to move to the next position. We assumed terrain slope to be the most important factor representing the cost layer for water: flat areas offer minimum resistance, while steep slopes represent strong energy constraints.

By calibrating the Path Distance layer against reference riparian zone widths, an optimal index value that represents the maximum riparian geomorphic extent can be identified (see Sutula et al., 2006). To achieve sufficient topographic detail, a pan-European DEM mosaic was created using ASTER Global DEM scenes at 1″ (Hayakawa et al., 2008) and re-sampled to 25 m. Although some locations are contaminated by artefacts such as clouds or stripe features (Reuter et al., 2009), ASTER GDEM data provide, for the majority of European terrain, unprecedented richness of topographic detail. The calibration process used a reference floodplain dataset from LISFLOOD FZ_{50} data, representing an upland limit of water influence. Several river reaches, totalling 12,533 ha, were selected as calibration targets to calculate a PD threshold which would best coincide with the corresponding FZ_{50} floodplain extent by maximizing the match between the two layers. The minimum average error defined the optimal corresponding PD value, namely PD_α. An advantage of this method, with respect to the commonly used fixed width buffer, is its sensitivity to geomorphology: steep valleys will produce a narrow PD-derived geomorphological riparian extent, while relatively flat areas will produce a wider zone (Fig. 2). Calibrated Path Distance and FZ_{50} floodplains are then merged, defining the riparian upland boundaries taking into account the hydrological connection with adjacent streams.

In the case of very steep slopes, active hydrological connection may be lacking. Nevertheless, ecological flows can still be high, due to the biotic and abiotic exchanges between the terrestrial and freshwater systems. In accordance with the literature (e.g. NRC, 2002, p. 43), in areas with absent or negligible hydrological connection, functional criteria should be used to delineate riparian

Table 2
Average minimum buffer widths around watercourses necessary to maintain selected riparian functions.

Riparian function	Average values of minimum width (m)
Sediment entrapment	12
Chemical filtration/transformation	12
Large woody debris input to channel	40
Leaf litter input to channel	0.5
Flood control	16
Aquatic life support	19
Bank stabilization	14
Riparian wildlife support	41

Adapted from review data of Collins et al. (2006).

zones. Collins et al. (2006) summarized from the literature the average estimated minimum and preferred buffer widths to account for a series of key riparian functions. An estimated buffer width of approximately 40 m from the stream would provide the necessary land extension to minimally allow the functioning of eight key riparian functions considered (Table 2). Therefore, this functional buffer zone is computed around the river network delineation, defining the 'functional riparian zones'. This layer is finally merged (union) with the Floodplains and calibrated Path Distance layer. The combined data define the *maximum potential riparian extent* (MPRE), considering both hydrological and functional connections. Outside this region the model assumes no riparian zone is present.

2.2.3. Vegetation detection

Vegetation is fundamental in characterizing riparian zones functioning, and is the primary regulator of a number of ecological processes and ecosystem services (Gillies and Cassidy Saint Clair, 2008; Lowrance et al., 1997). To gather the continental distribution of vegetated areas at a 25 m resolution we exploited two independent thematic datasets providing complementary semantic information.

A first dataset was automatically generated from Landsat satellite imagery using the SRC, Spectral Rule-based decision-tree Classifier (Baraldi et al., 2006). SRC, which requires neither user-defined parameters nor training data samples to run, is implemented as a static decision-tree classifier capable of mimicking a reference dictionary of spectral signatures taken from the remote sensing literature and data observations. Due to its operational properties, SRC is extremely suitable for vegetation/non-vegetation (V/NV) binary classifications (Baraldi et al., 2006). The preliminary classification generated by the SRC consists of spectral categories (spectral-based semi-concepts, e.g., strong/average/weak vegetation, etc.), which are semantic conjecture based solely on the per-pixel spectral properties. This means the SRC preliminary classification map is not designed to provide categorical information of vegetation types in ecological terms (e.g. grasslands or forest), but it does provide the distribution of every vegetated area present.

An SRC-based classification performed by EC-JRC of satellite data for Europe was exploited. Firstly, a full European coverage of Landsat-7 ETM+ scenes was acquired from the JRC Image 2000 dataset (Nunes de Lima, 2005) and the NASA Global Orthorectified Landsat Dataset (Tucker et al., 2004). Secondly, all Landsat scenes were radiometrically calibrated and mosaicked. Finally, scenes were automatically classified by the SRC into 20 kernel spectral categories belonging to six super-categories, namely, (i) Cloud, (ii) Snow or Ice, (iii) Water or Shadow, (iv) Vegetation (v) Bare soil or Built-up and (vi) Outliers. Vegetation comprised 12 different vegetation spectral categories.

The second reference dataset consisted of the JRC Forest Cover Map 2000 (Pekkarinen et al., 2009), also derived by Landsat ETM+ imagery acquired in 1999–2000, with pan-European coverage and

Table 3
Natural and semi-natural CLC2000 classes selected in the model.

Level 1	Level 2	Level 3	CLC2000 code
Forest and semi-natural areas	Forests	Broad-leaved forest	311
		Coniferous forest	312
		Mixed forest	313
	Scrub and/or herbaceous vegetation associations	Natural grasslands	321
		Moors and heathland	322
		Sclerophyllous vegetation	323
		Transitional woodland-shrub	324
	Open space with little or no vegetation	Sands, Beaches, Dunes	331
Water bodies	Inland waters	Watercourses	511

a spatial resolution of 25 m. The dataset provides the continental distribution of forest vegetation (presence/absence), but does not deliver semantic information on non-forested vegetated land-cover classes.

2.2.4. Land-cover land-use

In our approach the presence of natural/semi-natural land-cover was a necessary condition in order to assign an area to the riparian zone class. This condition was driven by the need to include regions that could minimally perform the main riparian ecological functions. Man-made surfaces, production/agricultural areas, and natural areas where riparian zones are unlikely to develop (e.g. rocky surfaces, glaciers, etc.) were not considered. The only continental dataset with the required land-cover land-use information for Europe, with an adequate spatial resolution for the purpose of this analysis, is the Corine Land Cover 2000 map (CLC2000, Bossard et al., 2000). CLC2000 is derived from on-screen interpretation of Landsat imagery; the original image data have a resolution of 20 m and were processed with a minimum mapping unit (mmu) of 25 ha by merging small land-cover patches with the dominant surrounding classes.

A series of natural/semi-natural CLC2000 land-cover classes were selected, targeting habitats where stream riparian environments could potentially occur (Table 3). Land-cover typically observed at the interface with riparian environments, such as river sands/sediments were also considered. The land-cover class 'sparsely vegetated areas' was excluded due to both its low overall accuracy, 53.6% (EEA, 2006) and because, often associated with arid and rocky environments, led in pilot studies to riparian zone overestimation. Inland and maritime wetland classes were also excluded: wetlands have ecological and hydrological regimes different from those of the riparian zones, such as marked low-oxygen conditions, derived from seasonal/permanent soil saturation, less intensive disturbance regimes, and characteristic vegetation communities (Keddy, 2010).

2.3. Geospatial detection of riparian zones using a fuzzy approach

The model was developed to detect and map riparian zones by evaluating the presence of natural/semi-natural land-cover, vegetation occurrence and the influence of water within the maximum potential riparian extent region (MPRE), through two main processing blocks. In the first step artificial land-cover, together with natural classes where riparian zones are unlikely to be present, are masked out. In other words, only the land-cover classes shown in Table 3 were considered.

In the second step the assignment to riparian zone class is established based on a fuzzy approach (Zimmermann, 2001). The use of fuzzy sets is an organized method developed to deal with uncertainties and ambiguities (Zadeh, 1965). Fuzzy set theory allows a gradual belonging of elements to sets, in contrast with dichotomous memberships: an element can belong to a fuzzy set with different grades of membership defined by a membership function. In mathematical terms, any element x_i part of a set X belongs to subset A according to a membership function $\mu_A: X \to [0, 1]$, where $\mu_A(x)$ is interpreted as the degree of membership in fuzzy set A for $x_i \in X$. The element is fully included in A if $\mu_A(x) = 1$, while it is not included if $\mu_A(x) = 0$.

In the model, two membership functions were introduced to assign a value quantifying the degree of belonging to the 'natural vegetation' (μ_V) and the 'water influence' (μ_W) sets, respectively.

In order to derive the membership function defining the degree of belonging μ_V to the fuzzy set V 'natural vegetation', information deriving from the SRC-classified vegetation and the JRC Forest Cover Map 2000 is combined. The twelve SRC vegetation classes are spectral categories, rather than land-cover classes, and consequently do not differentiate between natural and cultivated/urban vegetation. Furthermore, the masking process, which operates by selecting natural and semi-natural CLC2000 classes, is not sufficient to derive the 'natural vegetation' pixels, due to the generalization process applied to achieve a mmu of 25 ha. In other words, 25 m pixels of non-natural vegetated land-cover (e.g. crops or urban vegetation) can be present within patches of natural/semi-natural CLC2000 land-cover due to the spatial generalization adopted to reach the minimum mapping unit. To deal with this issue, a fuzzy membership classifier based on shares is applied to the SRC vegetation categories. Each of the twelve categories is assigned a $\mu_{V\_SRC}(x)$ value equal to the proportion of the category that spatially falls within the group of natural and semi-natural CLC2000 classes. This means that all pixels p belonging to the same SRC vegetation category are assigned the same membership function value. For example, if a vegetation category is found 10% of the time within classes in Table 3, these pixels are given the value $\mu_{V\_SRC}(p) = 0.1$ (equivalent to a low membership to the 'natural vegetation' set). Table 4 summarizes the values of membership function μ_{V_SRC} for all SRC vegetation categories.

Table 4
Membership values for the class 'natural vegetation' assigned to vegetation spectral categories and forest.

SRC Vegetation spectral category	Acronym	$\mu_{V\text{-SRC}}(p)$
Strong vegetation	SV	0.52
Average vegetation	AV	0.60
Scarce vegetation	WV	0.30
Vegetation under shadow	SHV	0.67
Strong shrub rangeland	SSR	0.55
Average shrub rangeland	ASR	0.42
Strong herbaceous rangeland	SHR	0.99
Average herbaceous rangeland	AHR	0.56
Weak rangeland	WR	0.16
Wetland or dark rangeland	WEDR	0.28
Rangeland in shadowed areas or wetland	SHRWE	0.56
Bogs	PB	0.35

JRC Forest Mask 2000	Acronym	$\mu_{V\text{-FOR}}(p)$
Forest presence	FOR	1

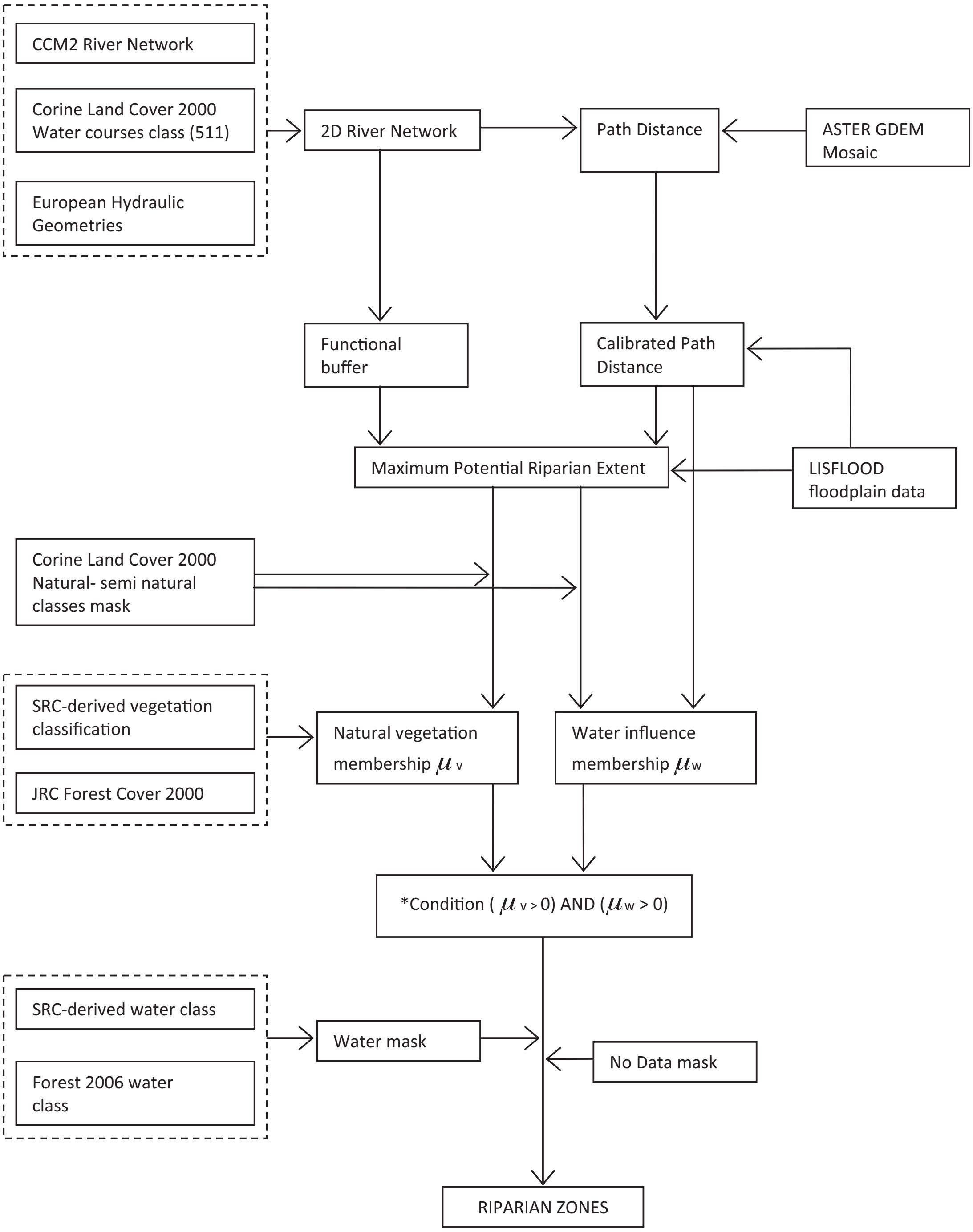

Fig. 3. Descriptive flow chart of the sequential processing steps in the riparian zonation model. Condition (*) is not applied in functional buffers with PD > PD_{α}.

An additional crisp membership $\mu_{V\_FOR} \in \{0, 1\}$ is added, based on the JRC Forest Cover Map 2000. This function assumes only two values: 1 for forest presence and 0 for forest absence. The crisp assignment of μ_{V_FOR} is based on the assumption that mapped forests fully belong to the natural vegetation set; this is justified by the fact that the absolute majority (92%) of European forest is classified as semi-natural or natural (MCPFE, 2007) and that, as a component of riparian systems, plantation forest can still potentially provide a large number of ecological functions and ecosystem services. Consequently, it is reasonable to assume that when a pixel is classified as forest by the JRC Forest Cover Map 2000 dataset this class label supersedes the SRC spectral category information. The two membership functions $\mu_{V\text{-}SRC}$ and μ_{V_FOR} are then combined using a fuzzy_OR (max) operator to derive the final function $\mu_V(p)$ of membership to the natural vegetation set:

$$\begin{aligned}\mu_V(p) \in [0, 1] &= \text{fuzzy\_OR}\{\mu_{V\_SRC}(p), \quad \mu_{V\_FOR}(p)\} \\ &= \max\{\mu_{V\_SRC}(p), \quad \mu_{V\_FOR}(p)\}\end{aligned} \tag{1}$$

The aggregation applies a maximum t-conorm between a graded layer and a binary layer.

The second membership function building the riparian index evaluates water influence, by definition key to the formation of riparian zones. Water influence can be reasonably considered as inversely proportional to the accumulated cost of lateral water

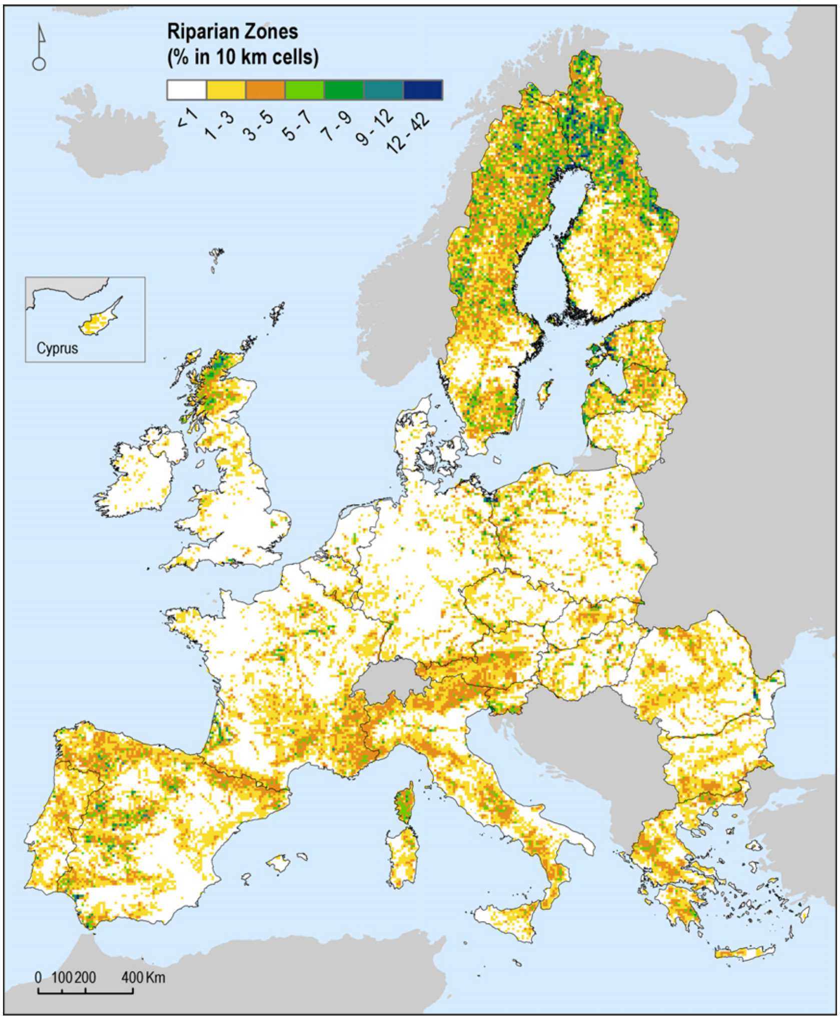

Fig. 4. Pan-European distribution of riparian zones, including both river-floodplain and stream-riparian systems (percentage in 10-km cells). Lamberth Azimuthal Equal Area (LAEA) Projection.

movement. The Path Distance layer was assumed adequate to assess water influence in riparian zones, representing a proxy for the topographic cost of water to move from the stream outwards (Sutula et al., 2006). We introduced a membership function μ_W to assign a degree of belonging to the 'water influence' set *W*, built on a simple linear inverse-relationship with Path Distance: minimum accumulated cost values of near-stream water movement, where PD is low, represent maximum water influence (μ_W close to 1). PD_α represents the furthest point of water influence (calibrated Path Distance) and delineated, together with the LISFLOOD floodplains, the maximum potential riparian extent. The membership function μ_W is defined as:

$$\mu_W(p) = \begin{cases} 1 - \left[\dfrac{p}{PD_\alpha + 1}\right], & 0 \le p \le PD_\alpha \\ 0, & \text{elsewhere} \end{cases} \quad (2)$$

In certain large river deltas, LISFLOOD floodplains have considerable dimension, extending in some cases far beyond the calibrated PD layer. In order not to exclude such floodplains, the function $\mu_W(p)$ is here (locally) defined differently. If $PD \ge PD_\alpha$ within floodplains then $\mu_W(p)$ is set equal to a minimum value necessary to avoid masking, and equal to $1/(PD_\alpha + 1)$. This is applied until $PD = 2PD_\alpha$, empirically determined after visual analysis of large floodplains located too far away from the river course to be properly considered riparian zones (maximum distance set to 2 km).

Both vegetation presence and water influence are in our study necessary conditions for the existence of a riparian zone. Therefore, a riparian zone must satisfy the condition: ($\mu_V > 0$) AND ($\mu_W > 0$). Locations where this condition is not satisfied are assigned a 0 value in the model (not riparian). Every riparian zone can be described by both membership functions in a single bivariate index I_{RZ}, which describes the overall belonging to the Riparian Zone class:

$$I_{RZ} = (\mu_V, \mu_W) \quad (3)$$

Functional riparian zones, by model definition, do not have an active hydrological connection. These regions were processed under the unique conditions of being vegetated and within the described 40 m functional buffer. Final processing involved the overlapping of a 25 m water mask, derived from classified satellite imagery (Table 1), in order to define more accurately the stream water presence (Clerici et al., 2011).

A flow chart representing the sequential processing steps of the riparian zonation model is added (Fig. 3).

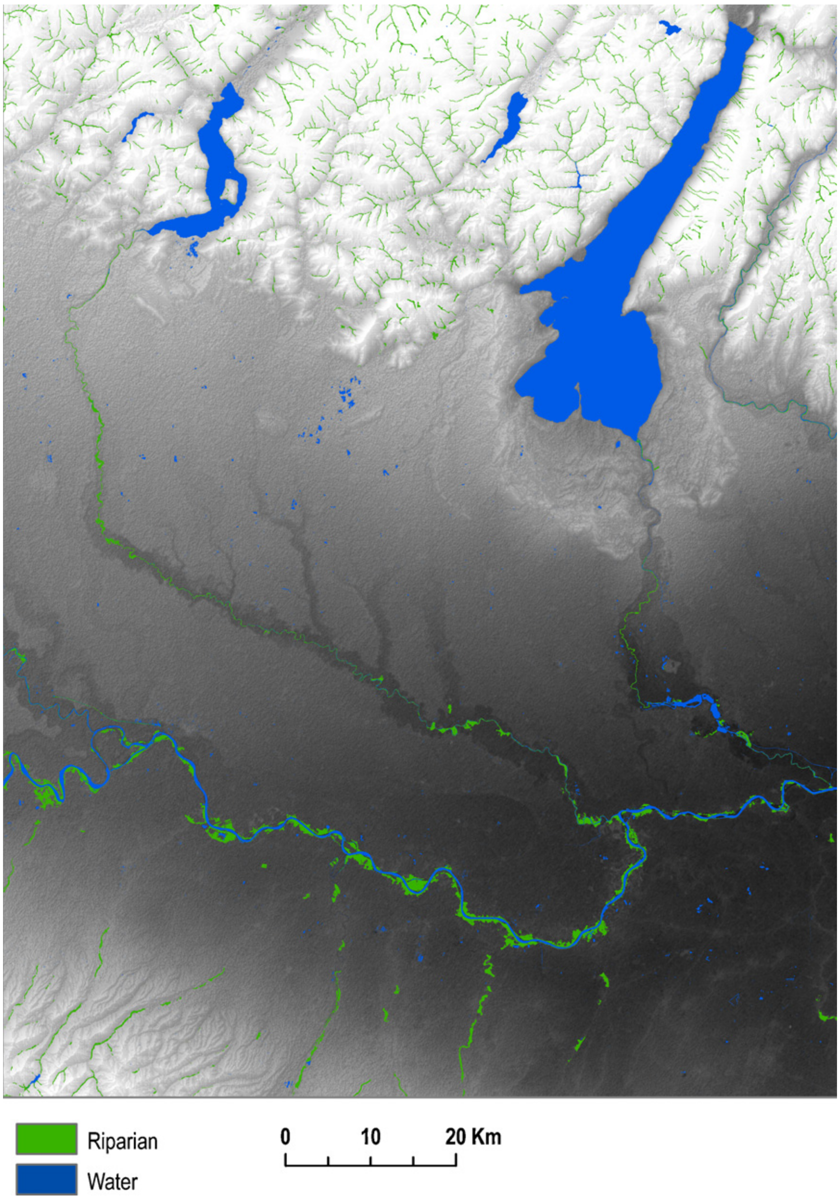

Fig. 5. Modelled riparian zones (25 m resolution) in a mountainous region of central Italian Alps (upper part) and in the Po river valley (lower part). Background image is SRTM elevation data (height proportional to grey brightness).

3. Results and discussion

3.1. Overview of distribution and characteristics

The model output provides a distribution map[1] and basic characterization of the entire continental riparian network. A representation of the model output is illustrated in Fig. 4; riparian zone distribution is indicated using 10-km cells to improve visual observation of its continental extension. Riparian zone distribution strongly depends on the river network density. The hydrographic system, based mainly on CCM data, is particularly dense in mountainous areas where, due to the particular topography, the number of small and ephemeral streams is high (Vogt et al., 2007). The Alpine and Pyrenees regions, characterized by extended naturally vegetated habitats, show a large proportion of narrow riparian zones (Fig. 5, upper). In these regions, and in other mountainous environments, the highest amount of functional riparian zone also occurs, due to the common presence of steep slopes associated to mountain watercourses. Large clusters of riparian zones are also present in Sweden and Finland as a result of a particularly dense water network within widespread natural landscapes. In the main European plains, which are characterized by predominantly agricultural land and built-up environment, riparian zone density is lower, due to the scarcity of natural environment and significantly lower density of watercourses. At the same time, flat topography and large rivers allow the formation of wide riparian zones (Fig. 5), generally characterized by high μ_W values, which indicates a strong hydrological connection and often the presence of river-floodplain systems.

The riparian zone class extends for 91,144 km^2, approximately 2% of the study area. Locations with high I_{RZ} riparian membership values (i.e. $\mu_V > 0.5$ and $\mu_W > 0.5$) represent approximately 47% of all riparian zones. These areas have high water influence and vegetation most probably natural; in other words, these are regions

[1] A website for public download of the riparian zones dataset is under planning.

Table 5
Riparian zones (RZ) country-level statistics.

	RZ country share over total RZ (%)	RZ proportion over country extension (%)	RZ in floodplains over total RZ (%)
Bulgaria	2.1	1.7	8.0
Belgium	0.4	1.3	9.9
Czech Republic	1.1	1.3	9.6
Cyprus	0.1	1.4	N/A
Denmark	0.2	0.4	2.5
Germany	4.1	1.1	10.6
Estonia	2.0	4.0	10.2
Greece	3.1	2.2	5.0
Spain	11.5	2.1	9.7
France	10.4	1.7	10.4
Ireland	0.5	0.6	9.4
Italy	7.2	2.2	7.6
Latvia	2.4	3.3	12.2
Lithuania	1.1	1.5	9.1
Luxembourg	<0.05	1.6	14.4
Hungary	1.7	1.6	35.9
Malta	<0.01	<0.1	0
Netherlands	0.3	0.7	11.4
Austria	2.4	2.6	7.0
Poland	4.7	1.4	10.6
Portugal	1.9	2.0	7.0
Romania	3.9	1.5	15.5
Slovenia	0.6	2.8	8.5
Slovakia	0.8	1.5	8.4
Finland	15.6	4.2	11.4
Sweden[a]	18.6	3.8	4.9
United Kingdom	3.3	1.2	3.3

[a] A no data region is present in the Swedish territory.

which can be considered more likely as riparian zones. Locations with low riparian membership ($\mu_V < 0.5$ and $\mu_W < 0.5$), i.e. with high associated uncertainty, represent only 6.3% of the riparian zone. Riparian zones within 50-year floodplains provide an indication of river-floodplain riparian systems extent, and represent almost 9.3% of total riparian zone area (8454 km^2). Functional riparian zones cover 1669 km^2, only 1.8% of total riparian zone area. The most northerly European countries (Sweden, Finland, Estonia) host the highest relative proportions of riparian zone with regard to their extent (3.8–4.2%), while Malta, Denmark and Ireland are characterized by the lowest proportions (0.1–0.6%). These values concur with the amount of respective natural/semi-natural habitat and with the density of their watercourse networks. Table 5 reports the EU27 country-level statistics.

To obtain a basic characterization of the riparian zone class, land-cover statistics were extracted from the CLC2000 dataset. Results indicate that European stream riparian environments are dominated by forest habitats (approximately 69%). This value decreases to ca. 54% if we refer to the JRC Forest Map 2000, which has a higher spatial resolution and does not use generalization processes. The importance of forest habitats for ecosystem services and biodiversity conservation is well documented (e.g. Fahey, 2001; Simberloff, 1999); the present study provides a first quantitative indication of the amount and broad distribution of forest habitats in Europe that also have an ecological significance as riparian zones. Approximately 13.3% of riparian zones are associated with transitional woodland shrub and, to a minor extent, to other land cover types (Fig. 6). A measure of the ecological value of riparian zone habitats and of their degree of protection can be derived exploiting two major European datasets of land protection schemes: the Common Database on Designated Areas (CDDA) and the Natura2000 network. The former, maintained by the European Topic Centre on Biological Diversity, considers *designated areas* for protection comparable to the IUCN protected areas categories (EIONET, 2011). The second database includes the EU-wide system of protected natural areas established under the Habitat Directive (92/43/EEC) comprising both Special Protection Areas for birds (SPAs) designated under the Birds Directive (2009/147/EC) and Special Areas of Conservation for habitats and non-bird species (SACs). Approximately 33.2% of the riparian zone class is located in either one of the two networks of protected areas, indicating that a significant proportion of riparian zone is characterized by habitats of high ecological value, currently under a protection scheme.

3.2. Accuracy and reliability

No independent dataset of riparian zones for the whole of Europe is, to our knowledge, currently available. An in situ verification campaign was not considered feasible because of cost and time considerations, involving an extensive field survey in locations representative of the whole range of conditions found within the EU27 territory. Consequently, three different strategies were followed in order to identify uncertainties and derive model reliability

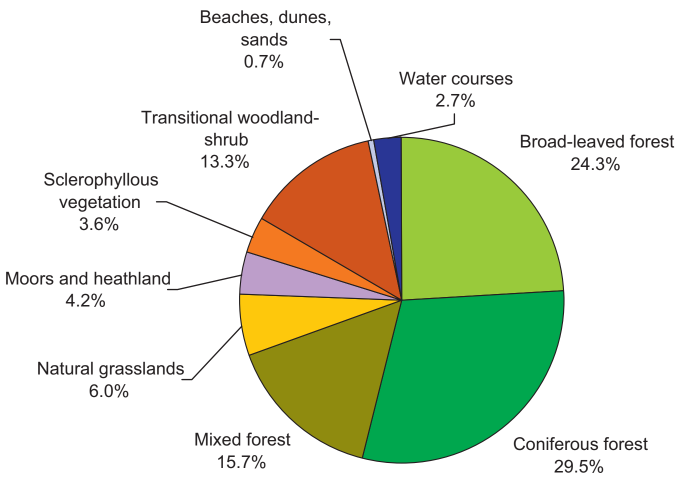

Fig. 6. Distribution (%) of land-cover type within the riparian zone class, based on CLC2000 data.

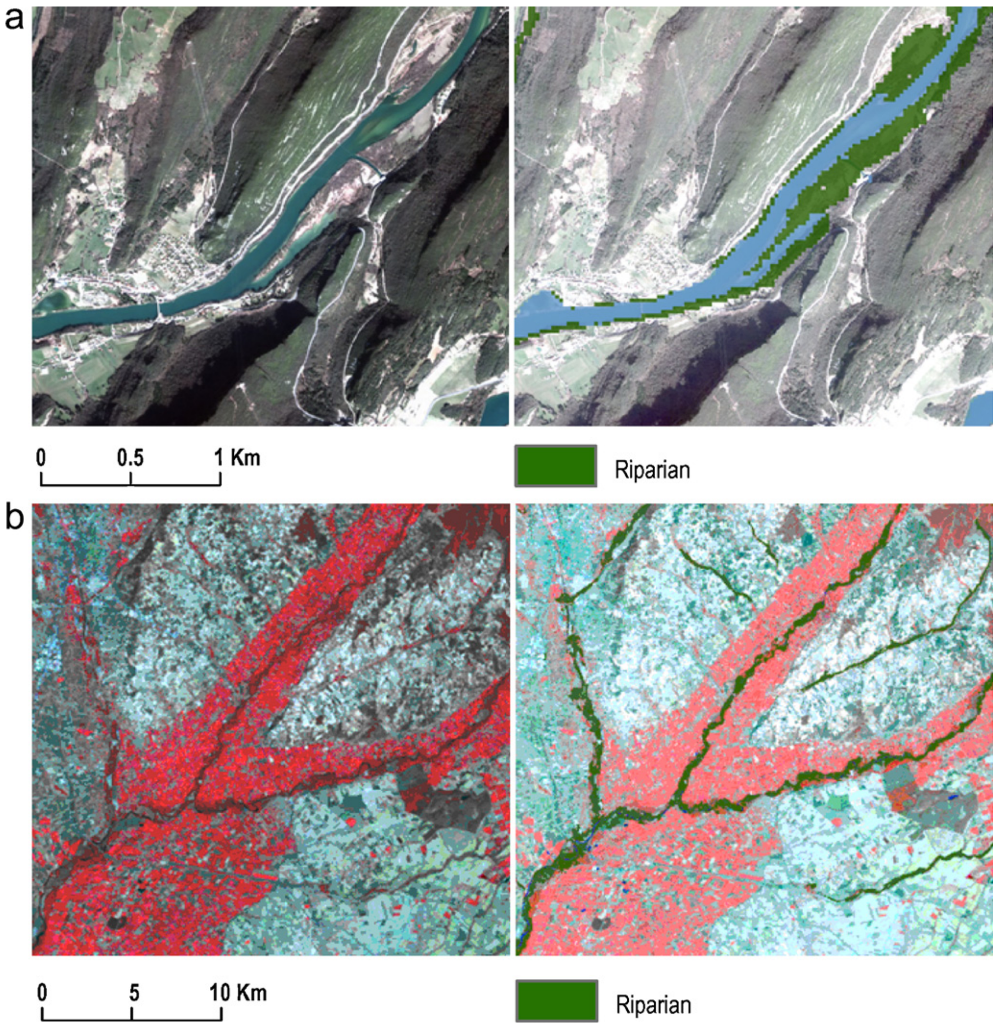

Fig. 7. Examples of modelled riparian zones at 25-m resolution (dark green) overlapped onto high and medium resolution imagery: (a) Rhône-Alpes, France (Quickbird image) and (b) Castilla y Leòn, Spain (Landsat image).

indications: (i) discuss published accuracy measures associated with input datasets; (ii) examine sources of error in model output through visual analysis of satellite imagery; and (iii) provide quantitative accuracy measures using independent datasets and Visual Validation Points (VISVAL).

3.2.1. *Input datasets confidence and accuracy*

The locations of the majority of European watercourses were derived using the CCM dataset. Within this dataset all watercourse segments have a confidence reliability attribute, which is labelled as 'high' for 87% of all watercourses (Vogt et al., 2007). ASTER GDEM data, on which the Path Distance index calculation was based, have vertical errors of approximately 20 m at 95% confidence on a global basis (AGVT, 2009). The DEM was found to contain, in certain locations, anomalies and artefacts; the major ones stemming from the presence of residual clouds in the ASTER scenes used to generate the DEM. At European level, regions with artefacts were predominantly found north of 60° latitude in central Sweden and western Finland. An extended thematic accuracy evaluation was performed for the CLC2000 dataset based on European Land Use/Cover Area Frame Statistical Survey (LUCAS). Reliability of the CLC2000 classes selected in this study, calculated as a percentage of matches with ground truth points, is reported to be on average 86.1% (EEA, 2006), decreasing to 82.1% when considering only the vegetated classes. An indication of the SRC vegetation/non-vegetation high classification accuracy is provided by Baraldi et al. (2006) using Landsat imagery, showing a value of $98.2 \pm 0\%$. An accuracy assessment of the JRC Forest map 2000 was performed by Pekkarinen et al. (2009) using LUCAS data and high resolution images from GoogleEarth® (visual validation). The first showed an overall accuracy (OA) of 83.7%, while accuracy derived using visual validation points produced an OA of 88.4%. For EHG and LISFLOOD data no systematic accuracy measures were derived; however, the literature reported good qualitative agreement with other independent datasets (Pistocchi and Pennington, 2006; Feyen et al., 2007).

3.2.2. *Visual assessment using satellite imagery*

A set of eighteen medium (Landsat) and high resolution scenes from a variety of satellite imagery (Quickbird, RapidEye, SPOT5) were acquired to perform a qualitative visual assessment. Riparian zones were overlaid onto the imagery, together with the input datasets in order to (i) obtain reliability indications and (ii) identify at which level of the model errors were generated. Overall, the riparian distribution patterns are generally well represented, with the addition of notable spatial details being able to delineate narrow riparian corridors (Fig. 7a) and small river islands. Masking using CLC2000 causes in some cases errors of omission, due to its generalization process and because of masked heterogeneous

Table 6
Producer accuracy of the riparian zone class based on independent ecological datasets and LUCAS2009 data.

Data type	Source provider	Location	Points (n)	Matched points (n)	Sample producer accuracy
RHS (Raven et al., 1998)	ISA, Technical University Lisboa;	Portugal	110	96	87.3%
	Various institutions, data collected in the context of the MARCE Project; University of Cantabria;	Spain	374	319	85.3%
	Environment Agency of England and Wales, Scottish Environment Protection Agency, Centre for Ecology and Hydrology.	UK, Europe	2551	2152	84.4%
QBR (Munne et al., 2003)	Freshwater Ecology and Management Research group, University of Barcelona	Catalunya (NE Spain)	32	29	90.6%
Total					84.6%
LUCAS2009 Flood Forests (Eurostat, 2009)	Eurostat, European Commission	Europe	111	90	81.1%
Overall Producer Accuracy			3178	2686	84.5%

agricultural classes containing natural habitat patches. The scale of the CCM river network (built on a 100 m DEM), can be a source of misplacement for river paths, especially where landscape topography is not accentuated.

3.2.3. Accuracy measures using independent datasets

Quantitative measures of accuracy for riparian zone absence/presence were derived using three different data sources: regional ecological surveys of riparian zones, LUCAS2009 data (Eurostat, 2009), and visual validation points (VISVAL) analysed in GoogleEarth®. Regional surveys of riparian habitat quality provide precise location and characteristics of riparian zones. The ecological datasets used are based on two survey types: (i) the River Habitat Survey (RHS), a method to characterize and assess in broad terms the physical character of freshwater streams and rivers (Raven et al., 1998), and (ii) the Quality of Riparian Forest (QBR) survey, a combined index to derive measures of riparian habitat quality (Munne et al., 2003). These two methodologies address different issues and indicators, but they commonly share riparian zones as assessment targets. Data sources are listed in Table 6. The LUCAS2009 survey (Eurostat, 2009), carried out in 2008–2009 and initially developed to deliver European crop estimates for the European Commission, included over 230,000 survey-points. Data are usually gridded in a 2 km × 2 km grid and, for each survey-point,

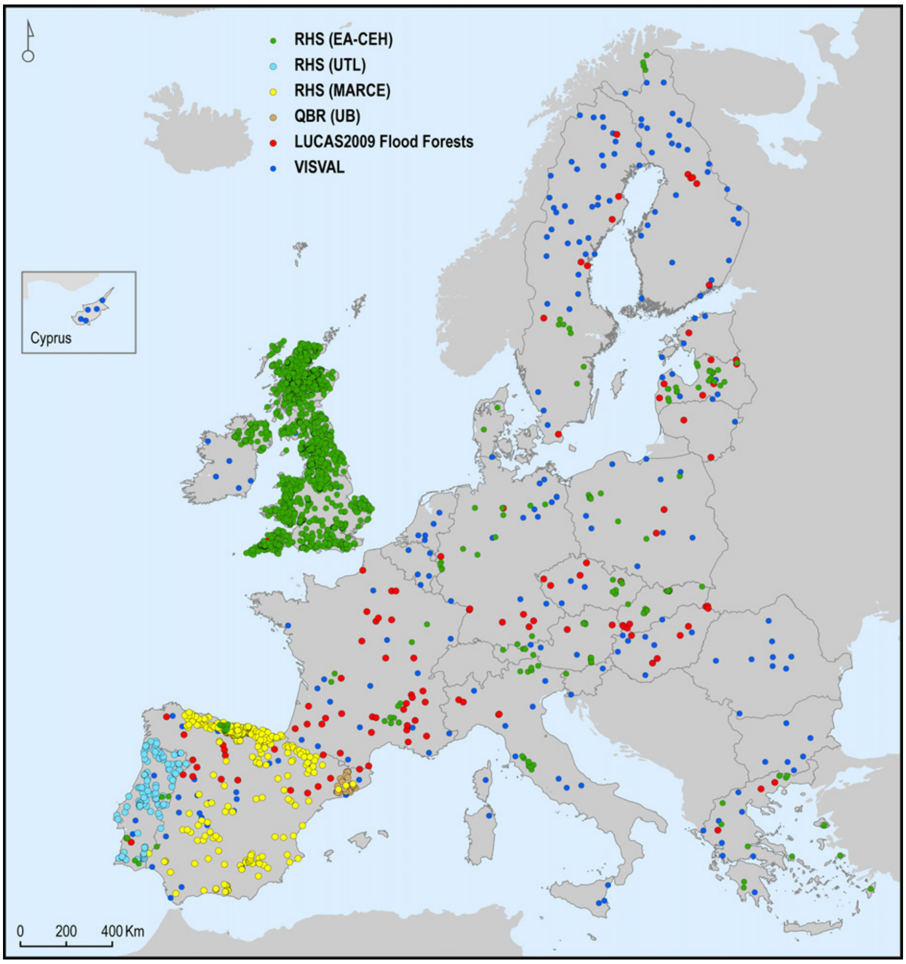

Fig. 8. Distribution of the ecological survey (RHS, QBR), LUCAS2009 data, and visually validated points (VISVAL) used in the accuracy assessment. Lamberth Azimuthal Equal Area (LAEA) Projection.

land-cover, land-use and other relevant information is recorded. For validation purposes, the *Floodplain Forests* class was selected, defined as 'alluvial and riparian woodlands and galleries close to main European river channels' (Eurostat, 2009).

All GPS points of the abovementioned survey data were assigned a 50 m buffer, a common simplified geometry necessary to represent the extension of each survey plot. The validation set was selected with the condition of being related to the river network and the land-cover classes considered in the model (Table 3).

A unique measure of overall accuracy, built for example from a common confusion matrix, would not be fully meaningful (Boschetti et al., 2004), as the riparian zone is a relatively rare class (ca. 2% of the study area). Instead, the producer's accuracy was calculated, by considering positive matches between survey points and riparian zone class. The producer accuracy value, explaining omission errors, was $p_{PA} = 84.5 \pm 1.3\%$ at 95% confidence level considering all survey points (Table 6).

The VISVAL points (230) were randomly extracted from the riparian class and imported into GoogleEarth®. A user accuracy value was also derived through on-screen supervised assessment of high resolution images, giving $p_{UA} = 72.6 \pm 5.8\%$. This estimation of the omission errors can be considered a conservative estimate, as in unclear visual interpretation a 'no match' was always considered. Fig. 8 shows the spatial distribution of all validation points.

4. Conclusions

Information on the spatial distribution of riparian zones is crucial for the assessment of ecological functions of riverine environments (Ward et al., 2002), especially in the context of biodiversity conservation and the evaluation of ecosystem services. A novel model to derive the distribution of stream riparian zones is proposed, considering both stream-riparian ecosystems, related to small size and ephemeral streams, and river-floodplain ecosystems of large flood-prone systems. We illustrated that a small set of relevant riparian attributes provided sufficient information to predict riparian zones presence at the landscape scale. At the same time current available Earth Observation data allowed spatially explicit estimates of the selected attributes, and to map riparian zones distribution at pan-European level.

To our best knowledge, this work represents the first attempt to model and map riparian zones at fine resolution and continental scale. The proposed thematic mapping system is designed to provide regional pictures of riparian zone networks and their basic characteristics at 25 m resolution using a fuzzy approach. An advantage of the proposed fuzzy index over crisp representations is the customization of high-level products, allowing final users to retrieve their own specific subset of riparian zones based on the choice of minimum membership values. Furthermore, performing regional calibration of model parameters and depending on EO data availability, the model is potentially applicable to other continents and eco-regions of the world.

In terms of mapping accuracy, the proposed riparian zone modelling system for large-scale applications is considered satisfactory, following, e.g. Thomlinson's (1999) minimum 70% per-class accuracy, although this should depend on the end-user's application and specific needs. Further developments of the proposed fuzzy classifier are currently being planned in order to include a more accurate northern European DEM and decrease classification errors in coastal zones. In particular, the development of a pan-European high-resolution watercourses dataset containing width information is expected to be highly beneficial to large-scale modelling of riparian zones and freshwater ecosystems.

In conclusion, the generated high-level fuzzy dataset and its further development can represent a step ahead in support of large-scale research activities for riparian environments. Knowing the 'backbone' of the European riparian network is in fact highly valuable for comprehensive continental-scale land-use modelling and environmental assessments (e.g. Lavalle et al., 2011). Important applications are potentially related to the prioritization of riparian corridors to maintain or improve landscape connectivity, or the assessment of riparian ecosystem services at pan-European scale, e.g. the estimation of continental riparian-buffering and chemical transformation capacity. The model is expected to provide valuable information to support the new European biodiversity strategy, with special reference to the implementation of the European *Green Infrastructure*.

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References

AGVT – ASTER GDEM Validation Team, 2009. ASTER Global DEM Validation Summary Report. Report Prepared by METI/ERSDAC, NASA/LPDAAC and USGS/EROS. In Collaboration with NGA and Other Collaborators. Available at: http://www.ersdac.or.jp/GDEM/E/image/ASTERGDEM_ValidationSummaryReport_Ver1.pdf (accessed September 2011).

Baraldi, A., Puzzolo, V., Blonda, P., Bruzzone, L., Tarantino, C., 2006. Automatic spectral rule-based preliminary mapping of calibrated Landsat^{TM} and ETM+ Images. IEEE Geosci. Remote Sens. 44, 2563–2586.

Bayley, P.B., 1995. Understanding large river-floodplain ecosystems. Bioscience 45, 153–158.

Benedict, M.A., McMahon, E.T., 2006. Green Infrastructure: Linking Landscapes and Communities. Island Press, Washington, DC, 299 pp.

Bennett, J., Simon, A., 2004. Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington, DC.

Boschetti, L., Flasse, S.P., Brivio, P.A., 2004. Analysis of the conflict between omission and commission in low spatial resolution dichotomic thematic products: the Pareto boundary. Remote Sens. Environ. 91, 280–292.

Bossard, M., Feranec, J., Otahel, J., 2000. CORINE Land Cover Technical Guide – Addendum 2000. Technical Report No. 40. European Environment Agency.

Clerici, N., Weissteiner, C.J., Paracchini, M.L., Strobl, P., 2011. Riparian Zones: Where Green and Blue Networks Meet – Pan-European Zonation Modelling Based on Remote Sensing and GIS. JRC Scientific and Technical Report, JRC EUR 24774 EN 2011. Office for Official Publication of the European Communities, Luxembourg, 60 pp.

Collins, J.N., Sutula, M., Stein, E., Odaya, M., Zhang, E., Larned, K., 2006. Comparison of Methods to Map California Riparian Areas. Technical Report 502. Prepared for the California Riparian Habitat Joint Venture. Contribution No. 522. San Francisco Estuary Institute, San Francisco, CA.

Daily, G.C. (Ed.), 1997. Nature's Services: Societal Dependence on Natural Systems. Island Press, Washington, DC.

Daniels, R.B., Gilliam, J.W., 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Sci. Soc. Am. J. 60, 246–251.

Darveau, M., Labbe, P., Beauchesne, P., Belanger, L., Huot, J., 2001. The use of riparian forest strips by small mammals in a boreal balsam fir forest. Forest Ecol. Manag. 143, 95–104.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z., Knowler, D., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A., 2006. Freshwater biodiversity: importance, status, and conservation challenges. Biol. Rev. 81, 163–182.

EEA – European Environment Agency, 2006. The Thematic Accuracy of Corine Land Cover 2000 Assessment Using LUCAS (Land Use/Cover Area Frame Statistical Survey). 85 pp., available at: http://www.eea.europa.eu/publications/technical_report_2006_7 (accessed September 2011).

EIONET – European Environment Information and Observation Network, 2011. Data Dictionary: Dataset Specification for Common Database on Designated Areas (CDDA), Version December 2011. European Topic Centre on Biological Diversity. Available at: http://dd.eionet.europa.eu/GetPrintout?format=PDF&obj_type=DST&obj_id=2981&out_type=GDLN.

Eurostat, 2009. LUCAS 2009 (Land Use/Cover Area Frame Survey). Technical Reference Document C-3. Land Use and Land Cover: Nomenclature. Statistical Office of the European Communities, Luxembourg. Version of 16/03/2009.

Fahey, T.J., 2001. In: Levin, S.A. (Ed.), Forest Ecology, Encyclopedia of Biodiversity. Elsevier, NY, pp. 41–51.
Feyen, L., Vrugt, J.A., Nualláin, B.Ó., van der Knijff, J., De Roo, A., 2007. Parameter optimisation and uncertainty assessment for large-scale streamflow simulation with the LISFLOOD model. J. Hydrol. 332, 276–289.
Gillies, C.S., Cassidy St. Clair, C., 2008. Riparian corridors enhance movement of a forest specialist bird in fragmented tropical forest. Proc. Natl. Acad. Sci. U.S.A. 105, 19774–19779.
Goebel, P.C., Hix, D.M., Dygert, C.E., Holmes, K.L., 2003. Ground-Flora Communities of Headwater Riparian Areas in an Oldgrowth Central Hardwood Forest. USDA For. Serv. Gen. Tech. Rep. NC-234, pp. 136–145.
Goetz, S.J., 2006. Remote sensing of riparian buffers: past progress and future prospects. J. Am. Water Resour. Assoc. 42, 133–143.
Gregory, S.V., Swanson, F.J., McKee, W.A., Cummins, K.W., 1991. An ecosystem perspective on riparian zones focus on links between land and water. Bioscience 41, 540–551.
Hagan, J.M., Pealer, S., Whitman, A.A., 2006. Do small headwater streams have a riparian zone defined by plant communities? Can. J. Forest Res. 36, 2131–2140.
Hayakawa, Y.S., Oguchi, T., Lin, Z., 2008. Comparison of new and existing global digital elevation models: ASTER G-DEM and SRTM-3. Geophys. Res. Lett. 35, 1–5.
Ilhardt, B.L., Verry, E.S., Palik, B.J., 2000. In: Verry, E.S., Hornbeck, J.W., Dolloff, C.A. (Eds.), Defining Riparian Areas. Riparian Management in Forests of the Continental Eastern United States. Lewis Publishers, Boca Raton.
Ivits, E., Cherlet, M., Mehl, W., Sommer, S., 2009. Estimating the ecological status and change of riparian zones in Andalusia assessed by multi-temporal AVHHR datasets. Ecol. Indic. 9, 422–431.
Johansen, K., Arroyo, L.A., Armston, J., Phinn, S., Witte, C., 2010. Mapping riparian condition indicators in a sub-tropical savanna environment from discrete return LiDAR data using object-based image analysis. Ecol. Indic. 10, 796–880.
Keddy, P.A., 2010. Wetland Ecology: Principles and Conservation, 2nd edition. Cambridge University Press, Cambridge.
Kempeneers, P., Sedano, F., Seebach, L., Strobl, P., San-Miguel-Ayanz, J., 2011. Data fusion of different spatial resolution remote sensing images applied to forest-type mapping. IEEE Trans. Geosci. Remote Sens. 99, 1–10.
Knopf, F.L., Samson, F.B., 1994. Scale perspectives on avian diversity in western riparian ecosystems. Conserv. Biol. 8, 669–676.
Lavalle, C., Baranzelli, C., Mubareka, S., Rocha Gomes, C., Hiederer, R., Batista, E., Silva, F., Estreguil, C., 2011. Implementation of the CAP Policy Options with the Land Use Modelling Platform – A First Indicator-Based Analysis – EUR 24909 EN. Publications Office of the European Union, Luxembourg.
Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., 1997. Water quality functions of riparian forest buffer systems in the Chesapeake Bay watershed. Environ. Manage. 21, 687–712.
Machtans, C.S., Villard, M.A., Hannon, S.J., 1996. Use of riparian buffer strips as movement corridors by forest birds. Conserv. Biol. 10, 1366–1379.
Malmqvist, B., Rundle, S., 2002. Threats to running water ecosystems of the world. Environ. Conserv. 29, 134–153.
MCPFE – Ministerial Conference on the Protection of Forests in Europe, 2007. State of Europe's Forests. The MCPFE Report on Sustainable Forest Management in Europe. MCPFE Liaison Unit Warsaw, UNECE and FAO, Warsaw. ISBN-10: 83-922396-8-7.
MEA – Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis Report. Island Press, Washington, DC.
Milner, A.M., Gloyne-Phillips, I.T., 2005. The role of riparian vegetation and woody debris in the development of macroinvertebrate assemblages in streams. River Res. Appl. 21, 403–420.
Müller, E., 1997. Mapping riparian vegetation along rivers: old concepts and new methods. Aquat. Bot. 58, 411–437.
Munne, A., Prat, N., Sola, C., Bonada, N., Rieradevall, M., 2003. A simple field method for assessing the ecological quality of riparian habitats in rivers and streams: QBR index. Aquat. Conserv. 13, 147–163.
Naiman, R.J., Decamps, H., 1997. The ecology of interfaces – riparian zones. Annu. Rev. Ecol. Syst. 28, 621–658.
Naiman, R., Decamps, H., McClain, M., 2005. Riparia – Ecology, Conservation, and Management of Streamside Communities. Academic Press, 448 pp.
National Research Council – NRC, 2002. Riparian Areas. Functions and Strategies for Management. Committee on Riparian Zone Functioning and Strategies for Management, Water Science and Technology Board, National Research Council, National Academy Press, Washington, DC, xii + 428 pp., ISBN: 0-309-08295-1.
Nunes de Lima, M.V., 2005. IMAGE2000 and CLC2000: Products and Methods. European Commission, Joint Research Centre, EUR 21757 EN.
Pekkarinen, A., Reithmaier, L., Strobl, P., 2009. Pan-European forest/non-forest mapping with Landsat ETM+ and CORINE Land Cover 2000 data. ISPRS J. Photogramm. 64, 171–183.
Perkins, D.W., Hunter Jr., M.L., 2006. Use of amphibians to define riparian zones of headwater streams. Can. J. Forest Res. 36, 2124–2130.
Peterjohn, W.T., Correll, D.L., 1984. Nutrient dynamics in an agricultural watershed: observations on the role of riparian forest. Ecology 65, 1466–1475.
Pistocchi, A., Pennington, D., 2006. European hydraulic geometries for continental scale environmental modelling. J. Hydrol. 329, 553–567.
Prenda, J., Granado-Lorencio, C., 1996. The relative influence of riparian habitat structure and fish availability on otter *Lutra lutra* L. sprainting activity in a small Mediterranean catchment. Biol. Conserv. 76, 9–15.
Raven, P.J., Holmes, N.T.H., Dawson, F.H., Everard, M., 1998. Quality assessment using River Habitat Survey data. Aquat. Conserv. 8, 477–499.
Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.R., Sheldon, A.L., Wallace, J.B., Wissmar, R.C., 1988. The role of disturbance in stream ecology. J. N. Am. Benthol. Soc. 7, 433–455.
Reuter, H.I., Nelson, A., Strobl, P., Mehl, W., Jarvis, A., 2009. A first assessment of aster GDEM tiles for absolute accuracy, relative accuracy and terrain parameters. In: International Geoscience and Remote Sensing Symposium (IGARSS), 5, art.: 5417688, pp. V240–V243.
Simberloff, D., 1999. The role of science in the preservation of forest biodiversity. Forest Ecol. Manag. 115, 101–111.
Sundseth, K., Silwester, A., 2009. Towards green infrastructure for Europe. In: Sundseth, K., Silwester, A. (Eds.), Proceedings of EC Workshop. 25–26 March 2009, DG ENV – Directorate General Environment of the European Commission, Brussels, Belgium, Available at: http://green-infrastructure-europe.org/ (accessed December 2011).
Sutula, M., Stein, E.D., Inlander, E., 2006. Evaluation of a Method to cost-Effectively Map Riparian Areas in Southern California Coastal Watersheds. Technical Report 480. Southern California Coastal Water Research Project, Westminster, CA.
Sweeney, B.W., Bott, T.L., Jackson, J.K., Kaplan, L.A., Newbold, J.D., Standley, L.J., Hession, W.C., Horwitz, R.J., 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proc. Natl. Acad. Sci. U.S.A. 101, 14132–14137.
Thomlinson, J.R., Bolstad, P.V., Cohen, W.B., 1999. Coordinating methodologies for scaling land-cover classifications from site-specific to global: steps toward validating global map products. Remote Sens. Environ. 70, 16–28.
Thorndycraft, V.R., Benito, G., Gregory, K.J., 2008. Fluvial geomorphology: a perspective on current status and methods. Geomorphology 98, 2–12.
Tucker, C.J., Grant, D.M., Dykstra, J.D., 2004. NASA's global orthorectified Landsat data set. Photogramm. Eng. Remote Sens. 70, 313–322.
Van Der Knijff, J.M., Younis, J., De Roo, A.P.J., 2010. LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. Int. J. Geogr. Inf. Sci. 24, 189–212.
Verry, E.S., Dolloff, C.A., Manning, M.E., 2004. Riparian ecotone: a functional definition and delineation for resource assessment. Water Air Soil Pollut. 4, 67–94.
Vogt, J.V., Soille, P., de Jager, A.L., Rimaviciute, E., Mehl, W., Foisneau, S., Bodis, K., Dusart, J., Paracchini, M.L., Haastrup, P., Bamps, C., 2007. A Pan-European River and Catchment Database, Report EUR 22920 EN, Luxembourg. 120 pp.
Ward, J.V., Tockner, K., Arscott, D.B., Claret, C., 2002. Riverine landscape diversity. Freshw. Biol. 47, 517–539.
Whitaker, D.M., Carroll, A.L., Montevecchi, W.A., 2000. Elevated numbers of flying insects and insectivorous birds in riparian buffer strips. Can. J. Zool. 78, 740–747.
Woodley, S., Kay, J., Francis, G., 1993. Ecological Integrity and the Management of Ecosystems. St. Lucie Press, Boca Raton, FL.
Zadeh, L.A., 1965. Fuzzy sets. Inform. Control 8, 338–353, http://dx.doi.org/10.1016/S0019-9958(65)90241-X.
Zimmermann, H., 2001. Fuzzy Set Theory and Its Applications. Kluwer Academic Publishers, Boston.