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Riparian zones: where green and blue networks meet

Pan-European zonation modelling based on remote sensing and GIS

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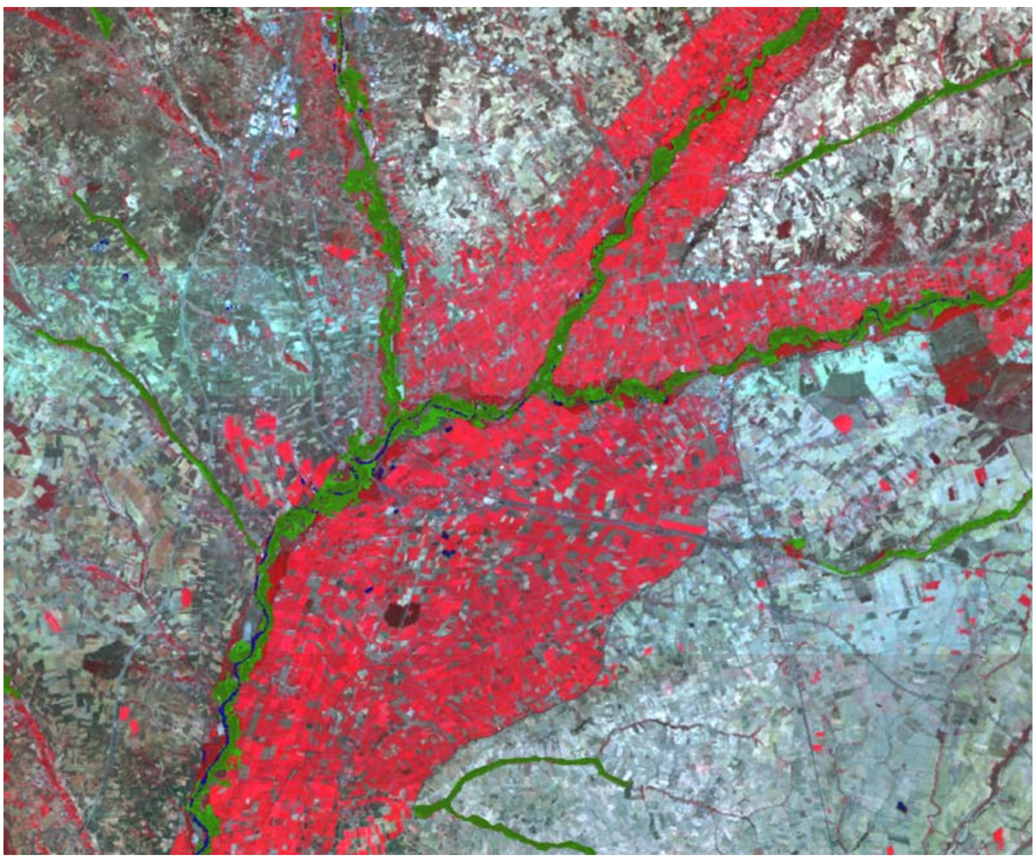

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Summary

Freshwater ecosystems are among the more degraded and threatened at global scale (Millennium Ecosystem Assessment, 2005). At European level a big legislative effort is put in place in order to address biodiversity conservation policies and management of river basins and riverine habitats (e.g. Water Framework Directive or Habitat Directive, etc). Recently, the European Commission through the Directorate Environment (DG ENV) is addressing effort in supporting initiatives that investigate and implement applications based on the Green Infrastructure concept in Europe: "the system/network of open space, consisting of natural and man-made structures, that provide directly or indirectly multiple benefits to society and support and improve ecological functions" (DG ENV, 2009).The Green Infrastructure aims at strengthening ecosystems resilience, it addresses their capacity to provide ecosystem services and conserve biodiversity, while contributing to climate change mitigation and reduction of natural disaster risks.

Among the key structures that contribute to build the Green Infrastructure we find those ecological systems contiguous to water streams, characterized by unique functions and characteristics: the *riparian zones.* These can be defined as transitional areas occurring along land and freshwater ecosystems, characterized by distinctive soil, hydrology and biotic conditions strongly influenced by the stream water (Naiman et al., 2005; Verry et al., 2000). Due to the key ecological role of these environments, their fragility and the ecosystem services they provide to society, it is motivated the need for an extensive assessment of riparian coverage in Europe. Knowing their distribution can provide the basis for a comprehensive characterization and ecological analysis on a continental scale, to identify key riparian zone patches to maintain landscape connectivity, to monitor change trends and to assess targeted ecosystem services that riparian zones can provide.

This work proposes a new riparian zonation model for continental Europe. Specific objectives of the study are developing a cost-effective methodology to identify riparian zones using satellite remote sensing and GIS, report their distribution patterns and basic characteristics, and identify data limitations at the European level for further model improvement. The proposed riparian zonation model is based on a multi-layer approach: the model takes into account a series of descriptive attributes and assigns a degree of belonging to the riparian zone class based on fuzzy membership scores (Zimmermann et al., 1984). In order to take into account the wide structural heterogeneity and complexity of these environments, a set of environmental attributes to describe riparian zones was identified based on scientific literature. The selected descriptors are: contiguity to river streams, ecological integrity as derived by habitat type, presence of vegetation, influence of water from geomorphological indices and a minimum buffer distance to preserve functional riparian zones. Model output has a spatial resolution of 25 m, which represented an optimal trade-off between a computationally and cost efficient approach together with the availability of continental remote sensing-based data. Datasets refer to the year 2000 and are projected to the European Terrestrial Reference System 1989 and Lambert Azimuthal Equal Area projection (ETRS-LAEA), following the INSPIRE standards (Annoni, 2005).

The modelled riparian zone class extends for about 90,415 km^2, approximately the 2% of the European continental area under study. Statistics of land cover were extracted from the CLC2000 dataset, indicating that European riparian zones are strongly dominated by natural forested habitats (around 69%). This study provides the first quantitative indication and distribution of forested habitats in Europe which also have an ecological significance as riparian zones. About 13.3% of riparian zones are associated with transitional woodland shrub, 6.0% with grasslands, 4.2% moors and heathland, 3.6% with sclerophyllous vegetation, and 3.4% with non-vegetated CLC2000 habitats.

Three different strategies were followed to discuss uncertainties and limitations related to the model: 1) report accuracy measures associated to input datasets; 2) discuss sources of errors in the model through visual analysis of medium/high resolution satellite imagery; 3) derive quantitative accuracy measures at regional and European level using Visual Validation Points (VISVAL) and other independent ecological datasets. A quantitative accuracy measure calculated using 3067 ecological survey points (RHS and QBR) produced an overall value of 84.6%, although being highly variable at regional level. The main sources of error identified derive by river path misplacements (especially in plain and coastal areas), and by the generalization process used to build the CLC2000 dataset. The study finally stresses the importance of developing a European 2D river network dataset at high resolution for future investigation of riparian zones and freshwater ecosystems.

1. Introduction

Due to a series of factors, like growing water demands, agricultural expansion and climate change effects, freshwater ecosystems are considered among the more degraded and threatened at global scale (Millennium Ecosystem Assessment, 2005). As a consequence, there is a growing need for river habitats assessment, in order to correctly address biodiversity conservation policies and management of river basins. At European level the Water Framework Directive (2000/60/EC) introduced the legal obligation for Member States to assess river and riverine habitats ecological conditions, as a basis to support effective water management policies. Council Regulation (EC) 73/2009 establishing common rules for direct support schemes for farmers under the Common Agricultural Policy (CAP) introduces as a Statutory Management Requirement the definition of buffer strips to protect water courses by no later than 2012. The Habitat Directive (Council Directive 92/43/EEC), whose main aim is biodiversity conservation through protection and monitoring of natural habitats and species, also addressed the importance of habitat mapping, together with the assessment of their change dynamics (Ledoux et al., 2000).

Recently, the European Commission through the Directorate Environment (DG ENV) is addressing effort in supporting initiatives that investigate and implement applications based on the Green Infrastructure concept in Europe (DG ENV, 2009). This concept, developed in the mid 1990s in the US, is not based on a single strict definition but encompasses a variety of comparable notions (Benedict and McMahon, 2006). The Green Infrastructure can be defined as "*the system/network of open space, consisting of natural and man-made structures, that provide directly or indirectly multiple benefits to society and support and improve ecological functions*", or a "*strategic or/and management approach to improve and sustain the multifunctional system of natural and man-made green structures, that provides benefits to society and maintain ecological functions"* (DG ENV, 2009). The Green Infrastructure aims at strengthening ecosystems resilience, it addresses their capacity to provide ecosystem services and conserve biodiversity, while contributing to climate change mitigation and reduction of natural disaster risks. Among the key structures that contribute to build the Green Infrastructure we find those ecological systems contiguous to water streams, characterized by unique functions and characteristics: the *riparian zones*, natural interfaces between water 'blue network' and land 'green network' (Honk, 2007).

This study proposes a pilot zonation model of riparian zones for continental Europe. These environments were selected for their exceptional importance in providing societal and ecosystem services, and to respond to institutional needs to characterize such key structural elements of the natural environment. The results of the zonation model will provide the information basis for a series of ecological assessments planned by the European Commission Joint Research Centre (EC-JRC) through the Rural Water and Ecosystem Unit's research activities.

Specific objectives of this study include:

- Develop a cost-effective methodology to identify riparian zones of Europe using remote sensing and GIS techniques;
- Report their distribution patterns and provide a basic characterization based on land cover types;
- Identify data limitations at the European level for further model improvement.

Background

From the latin '*ripa'*, shore or bank, riparian zones are among the more important ecological systems from a natural, societal and ecosystem services point of view (Naiman and Décamps, 1997). The large body of scientific literature that investigated various aspects of such transitional environments presents a wide permutation of published terms, making difficult to rely on a well established and univocal terminology. Different disciplines can adopt the same term to describe diverse objects of study, or at the contrary use different terms to define the same concept. Among the more widely used terms we found: riparian areas, riparian buffers, riparian management areas, riparian ecosystems, streamside protection zones. Especially for regulatory purposes, these environments are often called riparian zones (NRC, 2002).

A comparative analysis of designations and concepts it is not within the purpose of this study, however a series of representative definitions found in literature reviews is reported in *Table 1* (e.g. Verry et al., 2004; Collins et al., 2006). Two important remarks can be done: 1) the term 'riparian' encompasses a wide array of heterogeneous definitions, and 2) being riparian zones environments characterized by *gradients* in environmental conditions, ecological processes, vegetation and animal species, it is not straightforward to assign them discrete boundaries (Naiman and Décamps, 1990).

In the present study for riparian zones we mean in general terms transitional areas occurring along land and freshwater ecosystems, characterized by unique soil, hydrology and biotic conditions strongly influenced by the stream water (Naiman et al., 2005; Verry et al., 2000). Characteristic features are gradients in biophysical conditions and environmental processes, together with a generally high biological diversity, density and productivity (NRC, 2002; Naiman and Dècamps, 1990). This does not refer only to those areas associated with floodplain and wetland indicators, but it also includes those portions of upland away from the shore that have a direct water-land interaction (Gregory *et al.*, 1991). Typically, near-slope zones which are ecologically connected with the lower water stream areas by surface and subsurface hydrology (NRC, 2002), also sometimes defined as riparian influence areas (Ilhard et al., 2000). A schematic representation of a riparian zone is shown in *Figure 1.*

Riparian zones can be found in a wide variety of ecological, climatic, geomorphic and hydrologic conditions. Johnson et al.(1984) grouped riparian zones examining the presence of water flow in the channel and the connection of stream flow to groundwater. The three riparian types the Authors identified are:

- *Hydroriparian*, usually associated with perennial streams, hydric soils (formed under conditions of saturation or flooding long enough during growing season to develop anaerobic conditions in its upper part) or substrates rarely dry. Vegetation is composed by obligate or preferential riparian species[1].
- *Mesoriparian*, related to intermittent streams, associated with non-hydric soils and substrates seasonally dry. Vegetation is characterized by preferential and facultative riparian but also obligate and non-riparian.
- *Xeroriparian,* associated with ephemeral streams, and non-hydric soils which are dry most of the year. They have average annual soil moisture higher than upland areas, but only after rainfall events. Plant species are mostly facultative riparian and non-riparian.

Most of the scientific work on riparian zones focuses on permanent and seasonal streams, while little was done on small headwater streams or ephemeral tributaries (Goebel et al., 2003). Nevertheless, recent research based on surveys of amphibians and plant communities demonstrated that also small headwater and ephemeral streams can have a discernible riparian zone (Hagan et al., 2006; Perkins and Hunter, 2006). It is thus important when assessing riparian environments to consider also minor and ephemeral streams.

1 See Johnson et al. (1984) for a detailed description of the Authors riparian vegetation scheme.

Table 1. Selected definitions and concepts of 'riparian' in scientific and State Agencies literature.

Source (Year)	*Concept*
Hunter (1990)	Riparian as a scale-dependent concept: at the smallest scale is represented by the distinct plants and animals communities at the immediate water's edge; at a upper scale they include areas subject to periodical flooding, while at the largest scale they also include the forested environments significantly influenced by the water stream.
Naiman et al. (1993)	A riparian corridor comprehends the portion of terrestrial landscape from the high water mark towards the upland where elevated water tables/floodings may influence vegetation and soil influence to retain water
USDA FS (1994)	Riparian areas include the aquatic ecosystem, wetlands and the riparian ecosystem. The latter is characterized by distinctive soil conditions and vegetation that requires unbound water
Ilhardt et al.(2000)	Riparian areas are 3D ecotones that include terrestrial and aquatic ecosystems, extending to groundwater, above canopy, across the floodplain, up to near-slopes, laterally into terrestrial ecosystems and along the watercourse at variable width
US EPA (1993)	Riparian areas are vegetated ecosystems along a water body through which energy, materials and water pass. They are characterized by a high water table and are subject to periodic flooding and influence from the adjacent water body. These systems encompass wetlands, uplands, or some combinations of the two landforms. They do not possess all the characteristics to be classified as wetlands.
US FandWS (2004)	Riparian areas are plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent lotic and lentic water bodies. Riparian areas have one or both the following characteristics: vegetation species distinctive from adjacent areas, and species similar to adjacent areas but showing more vigorous growth forms. Riparian areas are transitional between upland and wetland.
US NRC (2002)	Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine–marine shorelines.
Lowrance et al. (1985)	Riparian areas as a complex assemblage of plants and other organisms in an environment adjacent to water. Without definite boundaries, it may include stream banks, floodplain, and wetlands …forming a transitional zone between upland and aquatic habitat. Mainly linear in shape and extent, they are characterized by laterally flowing water that rises and falls at least once within a growing season.

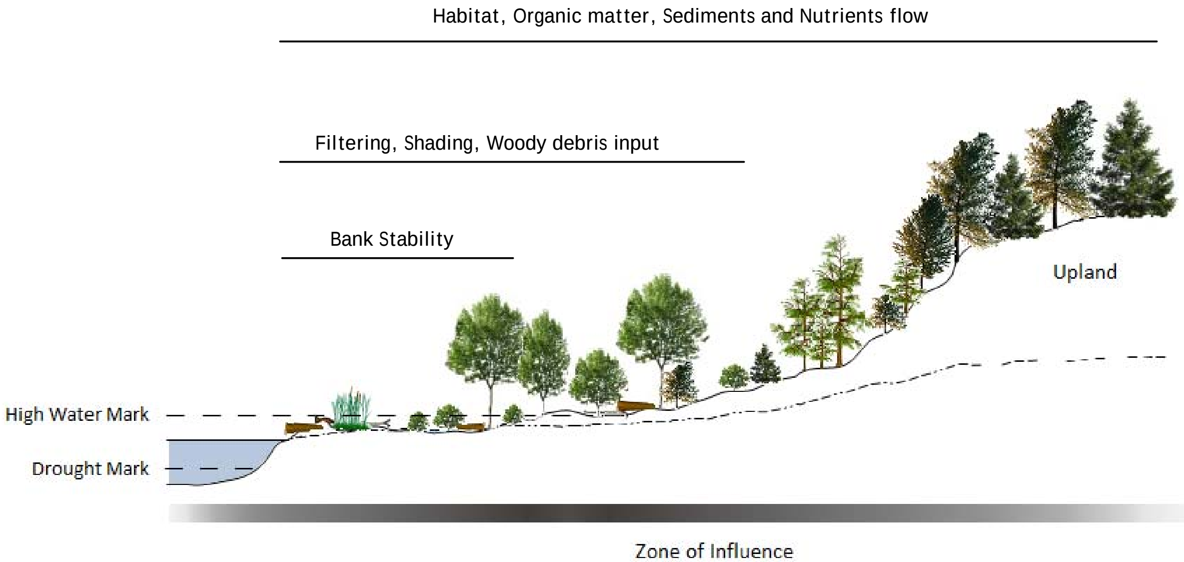


Figure 1. Schematic representation of a riparian zone and its zone of influence (land and water). Main functions and processes are also reported (adapted from NRC, 2000).

Despite the different concepts and definitions present in the literature, a strong agreement is found with respect to the importance of these environments for the large series of natural and societal services they provide. Some main aspects can be shortly summarized as follows:

- *Habitats*. Riparian areas can host highly valuable natural habitats, characterized by elevated productivity and rich biodiversity (Whitaker et al., 2000. Bedford, 1999), also acting as refuges sites, e.g. for regional flora during dry periods (Naiman and Dècamps, 1997).
- *Connectivity*: they provide key components to maintain biological connections for plants and animals (dispersal corridors) in fragmented landscapes (Gillies and Cassidy Saint Clair, 2008; Degraaf and Yamasaki, 2000; Machtans et al., 1996);
- *Filtering*. Riparian areas perform a reduction of nonpoint nutrient and pollution sources towards the streams by plant uptake, physical filtering and chemical transformation (e.g. denitrification), together with trapping sediment-bound pollutants and waters coming from streams (Daniels and Gillian, 1996; Haycock and Pinay, 1993; Peterjohn and Correll, 1984);
- *Stabilize river banks* via vegetation roots, provide friction and resistance to runoff during floods (Bennett and Simon, 2004).

Due to the key ecological role of these environments and their fragility, it is motivated the need for an extensive assessment of riparian coverage in Europe; knowing their distribution can provide the basis for a comprehensive characterization and ecological analysis on a continental scale. The term *riparian zone* will be adopted through all this work to define the object of study and the class identified by the model proposed.

Being the study area of continental extension the model approach is based on satellite remote sensing and GIS datasets with full European coverage. A continental scale assessment of this kind faces a series of complex challenges:

- Establishment of a trade off between continental scale and the characteristic small extension of riparian environments (processing effort / data availability *versus* spatial resolution).
- The high heterogeneity characterizing these environments, both in terms of spectral variance, life forms and geo-morphological setup.
- The necessity of additional theoretical criteria for delineation when the riparian boundaries are not directly identifiable from the data available.

To our knowledge no continental-scale analysis based on remote sensing data of riparian zones has been previously performed, while large extent analyses focused at the 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. The authors approach is based on purely geomorphic criteria applied to 10 m and 30 m DEMs, together with superimposing NDVI data from Landsat and very high resolution images to detect vegetation distribution. Ivits et al. (2009) consider as riparian zones the regions within a 1 km buffer from the river network of the Andalusia region (Spain) and analyzed the permanent vegetation present in relation with EU agri-environmental measures using phenological indices from AVHRR data. An assessment of land cover within riparian buffer zones and their link to stream health was performed by Goetz et al. (2003) using IKONOS very high resolution imagery for a range of watersheds in Maryland (USA). At the contrary, a large body of literature focuses on smaller areas (e.g. river basins), and on recent techniques, like LiDAR, to acquire parameters on vegetation and topography (see Goetz, 2006 for a short review).

2. Materials and Methods

2.1 Information layers and model development

In order to take into account the wide structural heterogeneity and complexity of these environments, a set of environmental attributes to describe riparian zones was selected based on the scientific literature. The proposed riparian zonation model is based on a multi-layer approach: the model takes into account a series of descriptive attributes and assigns a degree of belonging to the *riparian zone* class based on membership scores (Zimmermann et al., 1984). Being riparian zones boundaries implicitly fuzzy, a mathematical approach using fuzzy sets (Zadeh, 1965) was considered particularly adequate. The key selected attributes are hereafter discussed:

1- It is implicit the contiguity or proximity of the riparian environments to a water stream. In the present analysis we will focus uniquely on freshwater lotic streams, while excluding lake banks and estuarine-marine shorelines, characterized by different disturbance regimes and ecological processes. The identification of a two-dimensional river network provides an indication of the water-land interface, or in other words a potential inner boundary of the riparian zone (see *Figure 1)*.

2- The upland boundary of a riparian zone is a complex and fuzzy edge whose delineation depends on a large series of factors, depending also on the focus of the analysis and the modelling criteria adopted (Ilhardt et al., 2000). In this study we considered both floodplains and geomorphological information, together with an estimated minimum functional buffer necessary to accomplish basic ecological riparian functions (NRC, 2000). The latter is derived from theoretical and experimental studies found in the literature.

3- To ensure the functioning of biotic/abiotic processes and their natural structuring, riparian environments should preserve a certain degree of ecological integrity (Woodley et al., 1993). Hence, we considered only vegetated natural and semi-natural land cover where riparian zones can potentially develop. Areas characterized by any productive activity (e.g. agricultural areas, pasture, agro-forestry, etc), artificial environments (e.g. urban areas), together with natural environments where riparian areas cannot exist (e.g. bare rocks, glaciers) are not considered.

4- In almost the totality of the literature on the riparian zones it is given emphasis to the presence of vegetation, as a result of its key role in performing a wide series of ecological processes. A strong importance is especially given to *forest* vegetation, due to its functional role in providing key microhabitats to several riparian species (Darveau et al., 2001; Prenda and Granado-Lorencio, 1996), woody debris (Milner and Gloyne-Phillips, 2005; Harmon et al., 1986) and a number of different ecosystem services (Sweeney et al., 2004).

5- Geomorphology has a strong control in the movement of surface and subsurface water (Thorndycraft et al., 2008; Sutula et al., 2006). The riparian zone extension is connected to complex geomorphological boundaries that allow water to move to a lateral extent and influence the terrestrial habitats. Flat areas face minimum energy resistance, while steep slopes represent strong energy constrains. These conditions can be approximated (being water movement a function also of others parameters, e.g. soil permeability) using proxy cost functions which can define regions where water has a higher potential capacity to move laterally.

The criteria discussed above are assessed based on remote sensing-derived information, and represent the inputs for a scoring system based on a fuzzy approach (Zadeh, 1965). The theoretical framework provided by the fuzzy set theory is particularly indicated to deal with entities which are not well defined in dichotomic classifications, typically riparian zones and their boundaries. The choice of the methodology was partially driven by data availability, by constraints deriving from the continental extension, together with the necessity to detect relatively small features. The spatial resolution of 25 m represents an optimal trade-off between a computationally and cost efficient approach together with the availability of continental remote sensing-based datasets. The extension considered is the territory of EU27, excluding European Atlantic islands, Malta and overseas territories. Remote sensing datasets refer to the year 2000 and are projected to the European Terrestrial Reference System 1989 and Lambert Azimuthal Equal Area projection (ETRS-LAEA), following the INSPIRE standards (Annoni, 2005).

2.2 Water streams and water boundary delineation

Despite rivers are non-equilibrium systems, the internal riparian zone boundary can be reasonably assumed to be defined by a fixed spatial delineation of the water stream bank. The streams considered in this study cover three main types (Prichard et al., 1993): *perennial* (continuous flow throughout the year), *seasonal* (stream flowing only at certain times of the year) and *ephemeral* (flowing in response to precipitation and with a channel always above the water table). We hereafter considered water flowing in natural channels, while excluding artificial canals.

At present there is not a high resolution continental dataset that hold rivers paths and river width information for the whole of Europe. EU Member States produce regularly river datasets with national specifications, different scales and heterogeneous methods; an effort to combine coherently all of them is considered to be an inefficient strategy for a cost effective continental-scale analysis. Nevertheless, the implementation of the EU Water Framework Directive (2000/60/EC) made explicit the needs for comprehensive digital data of river networks and drainage basins for Europe. As a result, the CCM dataset (Catchment Characterization and Modelling) was developed by the European Commission Joint Research Centre (EC-JRC), as a comprehensive pan-European database of river networks and catchments (Vogt et al., 2003; 2007a). The dataset was derived using a 3 arc-second DEM from the Shuttle Radar Topography Mission –SRTM- (Farr et al., 2007), processed with a grid-cell resolution of 100 m to follow the INSPIRE specifications for European grids (Annoni, 2005). Areas uncovered by SRTM (North of 60 degrees) where replaced with national DEMs and resampled at the same resolution (Sweden, Finland). The CCM river network was derived using algorithms based on mathematical morphology (Soille, 2003) and adaptive drainage enforcement to improve river positioning in flat areas (Soille *et al.*, 2003). Network validation was performed against Landsat TM data and national datasets. The version used in this study is the CCM 2.1 (July 2008).

One of the major strengths of the CCM dataset is to be fully coherent throughout its entire coverage and with the underlying layers (e.g. SRTM DEM). On the other hand, gaining information on streams width is a necessary step to define a potential boundary of the riparian zones, thus a strong limitation of the CCM dataset for the purposes of this research is its 1-D linear structure. To counteract this limitation, information from other geographical datasets was integrated into the CCM data. Firstly, large river streams from the Corine Land Cover 2000 (CLC 2000) seamless vector data (EEA, 2010) were coherently integrated into the dataset using GIS modelling. Overlapping features were eliminated, and water courses polygons (CLC Class 511) merged to the CCM river network. Although they provide considerably accurate boundaries of large water streams, the majority of the European rivers are not included in CLC2000, which has a 10 ha minimal mapping unit (mmu). In order to associate a river width to water stream, the European Hydraulic Geometries database (Pistocchi and Pennington, 2006) was employed. In this dataset, runoff estimates were used to produce a 1 km-resolution European map of annual discharge based on flow accumulation computed for the GTOPO30 DEM. A regression equation was fitted to predict river width as a function of river discharge using a power law equation (see Haan et al., 1994):

$$W = \alpha Q^{\beta}$$

Q = river discharge; W = river width; α and β the regression coefficients.

The Authors finally derived the regression coefficients using sets of rivers widths and flow rates in Europe, and provided error estimates. Using the EHG database an average width was associated to every segment of the river network built originally in the CCM dataset. The mean was calculated by extracting W values (one per squared km in the original dataset) correspondent to every vertex of the river vector and averaged per CCM segment of stream. This operation although based on a simplification, provided with a consistent set of river width values for the whole European continent. The vector structure of the final polygonal river network is the backbone for delineation of regions where to run the riparian zonation model. *Figure 2* shows the major steps performed to process the water layer.

A pure ‘spectral approach’ classification of satellite data would not allow to achieve a complete coverage of river widths with pertinent values, since a raster layer of this type would not provide values for seasonal, small and ephemeral streams (limited or no water signal), and secondly would be date/season dependent. Nevertheless, when the water signal is detectable it is possible to use this information with a high spatial and spectral accuracy. Hence, an additional water layer with continental coverage was also produced by merging two 25 m raster European water mosaics based on spectral classification of Landsat ETM+ (Baraldi et al., 2006) and SPOT/ LISS data (Kempeneers et al., 2010). The layer provides a finer mask for detectable lotic streams, together with other inland water bodies (lakes, ponds, etc.).

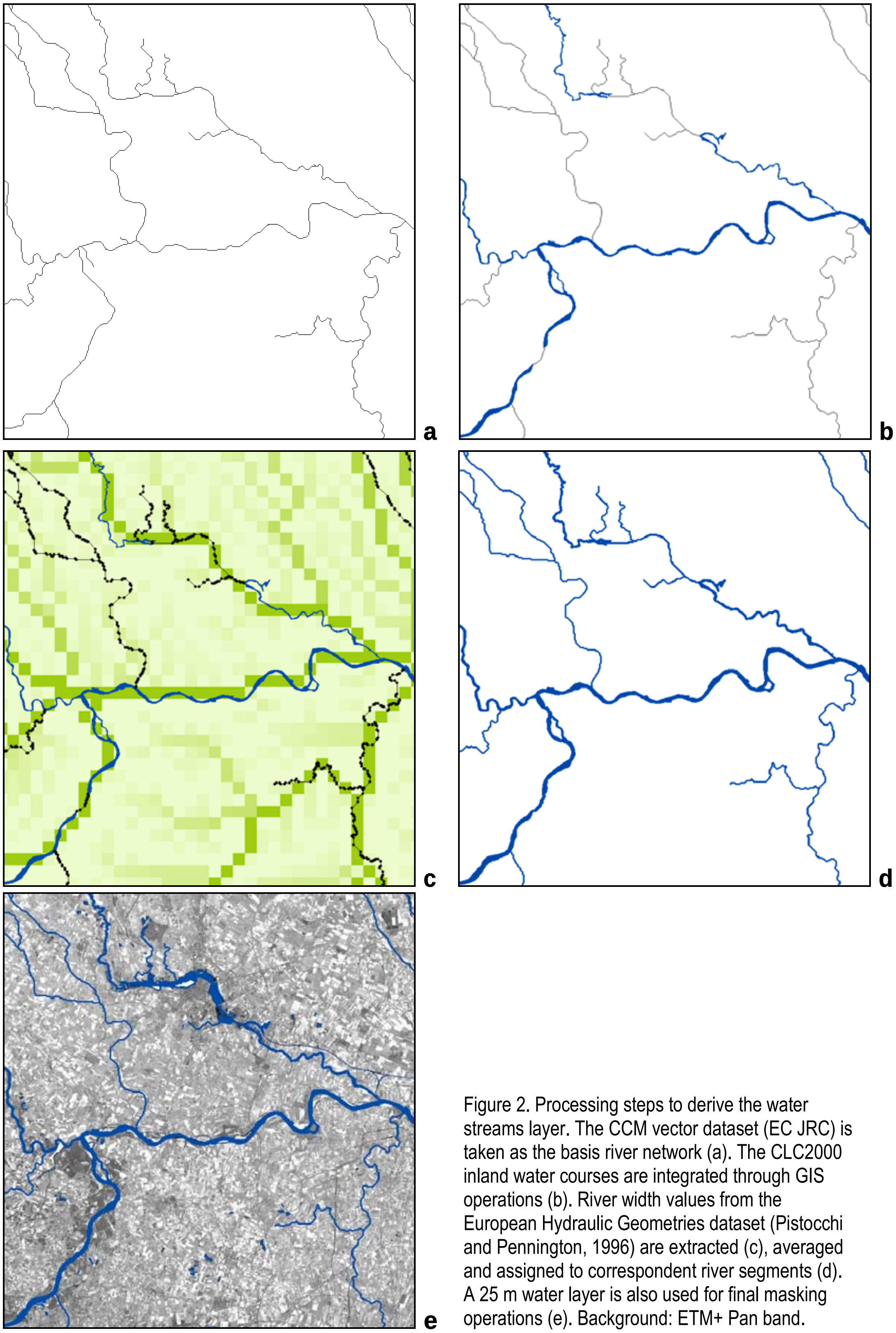


Figure 2. Processing steps to derive the water streams layer. The CCM vector dataset (EC JRC) is taken as the basis river network (a). The CLC2000 inland water courses are integrated through GIS operations (b). River width values from the European Hydraulic Geometries dataset (Pistocchi and Pennington, 1996) are extracted (c), averaged and assigned to correspondent river segments (d). A 25 m water layer is also used for final masking operations (e). Background: ETM+ Pan band.

2.3 Upland boundary delineation

Defining the outer boundary of a riparian zone is a complex task and characterized by a high degree of uncertainty due to its intrinsic fuzzy nature. From the adopted riparian zone definition we wanted to target transitional areas occurring along land and freshwater ecosystems, where abiotic and biotic conditions are significantly influenced by the stream water. While fixed buffers along water streams have been widely used in the scientific literature and in management plans, they are recognized to be an insufficient criterion to represent the complexity of riparian environments and their extension (e.g. Palik et al., 2000; Müller, 1997). Ilhardt et al. (2000) indicated the 50-years frequency floodplain as an optimal hydrological descriptor for riparian ecotones. This is because the elevation correspondent to this floodplain frequency is generally intersecting the first terrace and up-sloping surfaces. Although being far from a highly accurate measurement of the outer fuzzy boundary of the riparian zone, it provides a slightly consistent measure of where the limit of water influence can be placed.

To achieve this information with adequate spatial detail and pan-European coverage we relied on LISFLOOD-derived data (Van Der Knijff et al., 2010; De Roo et al., 2000). LISFOOD is a complex hydrological rainfall-runoff-routing model developed by EC-JRC that simulates catchment hydrological processes. The model was developed for operational flood forecasting at the European scale, and is able to take into account spatial variations in land use, soil properties and precipitation. Apart from deriving information from a large series of European datasets, some model parameters were estimated by calibrating against historical records of river discharge in 231 catchments and sub-catchments. An in depth description of the model processes, European-wide setup and calibration exercise can be found in Van Der Knijff et al. (2010) and Feyen et al. (2007). Modelled flooded areas for large catchments of continental Europe[2] with 50-years frequency at 100 m spatial resolution (FZ_{50}) were used as a basis to define a potential upland riparian boundary for riparian zones in large rivers.

For the purpose of this research two limitations arise from the use of this dataset: the inclusion of large flooded plains occasionally present near river delta regions (e.g. Po delta, Italy), and the lack of information available for small catchments, *i.e.* for the majority of small permanent/seasonal water streams and ephemeral streams. To counteract these two limitations a geomorphological approach was followed. Recent approaches made use of Digital Elevation Models and ancillary information to identify geomorphological breaks representing riparian zone boundaries (Sutula et al., 2006; Collins et al., 2006). Sutula *et al.* (2006) implemented a cost-effective method to identify riparian geomorphic extent based on DEM-derived indices. The methodology was applied in 5 watersheds in Southern California using a 10 m and a 30 m DEM to produce maps of maximum potential lateral extent of riparian areas. Among the geomorphic indices used, the Path Distance Index was considered by the Authors. The index (herafter PD) represents a topographic cost to move horizontally (laterally) or vertically from a specified *source* layer (the river stream):

$$PD = D * VF * (f_a * HF_a + f_b * HF_b)/2)$$

where D is the surface distance, VF and HF are respectively Vertical and Horizontal Factors and f is a friction coefficient. For sake of simplicity, considering an isotropic medium, the Path Distance index can be expressed as:

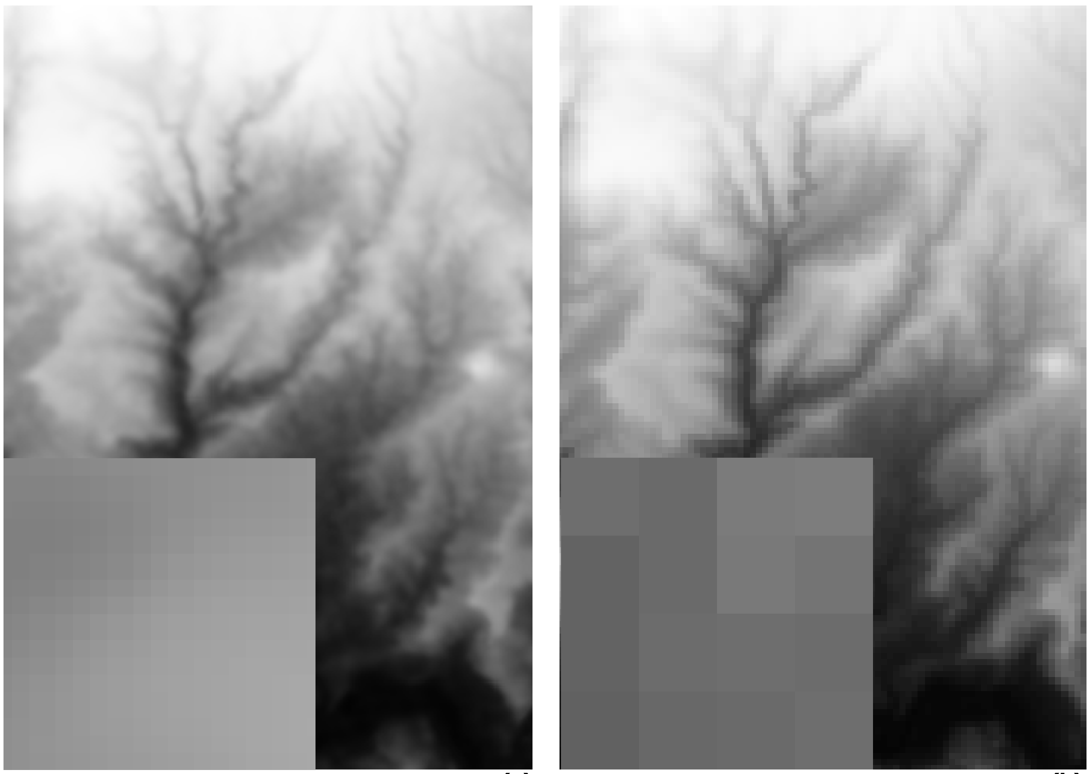
$$PD = D * F_{Sl}$$

with F_{Sl} a overall friction parameter corresponding to the derived slope layer of the DEM.

By calibrating the Path Distance against reference riparian zone widths, it is possible to identify an 'optimal' value of the index to represent potential riparian geomorphic extents (Sutula et al., 2006). In the present

[2] Not available for Cyprus

investigation the initial calibration tests performed using PD indices calculated using SRTM DEM data at 100 m resolution (Farr et al., 2007) revealed inadequate spatial detail for small streams. To achieve sufficiently adequate topographic detail, a pan-European DEM mosaic was created using ASTER Global DEM scenes (Hayakawa et al., 2008) at 1 arc-second. Although known to be in some locations contaminated by artefacts as clouds or stripe features (Reuter et al., 2009), ASTER GDEM data provide for the big majority of the European territory an unprecedented richness of topographic detail (see *Figure 3*). More than 1200 ASTER GDEM scenes were mosaicked and resampled to 25 m following INSPIRE specifications (Annoni, 2005). Some pitfalls present in northern regions of Sweden and Finland were processed as missing data in the model.



(a) **(b)**

Figure 3 Example of ASTER GDEM data at 25 m resolution (a) and SRTM data at 100 m resolution (b), with zoom insets.

The Path Distance function needs in input a *source* layer (the 'baseline' level to start index calculation), which is represented by the rasterized river network (see *Section 2.2*). The friction parameter F_{Sl} in the PD formulation corresponds to the slope as calculated from the ASTER-derived DEM. Using a calibrated Path Distance approach is possible to derive a potential riparian zone extension for all the territory covered by both river network and DEM. The calibration process made use of a set of reference riparian zones from the LISFLOOD 50-years frequency floodplains data (FZ_{50}). Several river reaches located in the transition upstream areas were selected as calibration targets to calculate a PD threshold which would best coincide with the correspondent FZ_{50} extension by maximizing the coincident area between the two layers. About 4178 ha of riverine area were processed for calibration. Following an approach similar to the one developed by Sutula et al. (2006), an initial PD threshold was chosen and varied recursively towards higher and lower levels using threshold steps of 25 units. The minimum average error defined the optimal correspondent PD value, namely PD_{α}, which resulted equal to a value of 350. The advantage of this method with respect to the commonly used fixed width buffers is its sensitivity to geomorphology. As an example, narrower valley portions due to closer and steeper slopes produce a consequent narrowing of the calibrated Path Distance area (arrows in *Figure 4*).

The PD_α threshold was applied to pan-European extension to derive a calibrated Path Distance layer (CPD). The CPD generally coincides well with the FZ_{50} dataset, except in few extended flooded plains present near river delta regions. In these regions an additional masking was applied to cut-off areas distant from water streams, using a threshold of 2 PD_α and considering in any case a maximum distance of 2 km from the river. This asymptotic threshold was derived after on-screen measurement of maximum riparian zone widths in major European delta plains.

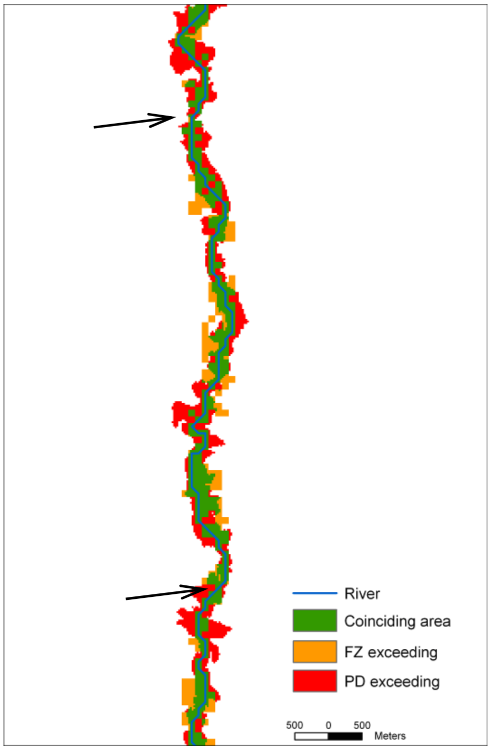


Figure 4. Calibrated Path Distance (CPD) was derived by calculating in a set of thresholded PD layers the maximum overlap surface and minimum exceeding surface with FZ50 flood zones (FZ). Arrows indicate narrowing of the CPD due to steeper slopes.

Calibrated Path Distance and FZ_{50} floodplains are finally merged (union operation). This final layer (hereafter FPD) defines in the model an estimation of the maximum potential riparian extent by assessing *a hydrological connection with adjacent streams*. Although the layer is based on the use of a relatively simple proxy variable, it is more informative than a Euclidean distance buffer to define potential riparian zone extension, being the former sensitive to topographic variations (reflected into costs of water to move laterally).

In the case of steep surfaces, *e.g.* in high mountain valleys or any extended steep slope, such active hydrological connection may be lacking (*Figure 5*). However, the ecological flows can still remain high due to the biotic and abiotic exchanges of energy and matter between terrestrial and freshwater ecosystems. Upland riparian zones represent ecological corridors and key habitats for a number of riparian species; they provide woody and non-woody inputs to the river, together with controlling micro-climate conditions (Naiman and Dècamps, 1997). Consistently with the concept of riparian environments adopted in this study, and in accordance with relevant literature (*e.g.* NRC, 2000), in areas with very narrow hydrological connection due to steep topography, *functional criteria should be used to distinguish riparian zones*. This is typically the case of small mountain valleys with narrow valley floor and headwater streams.

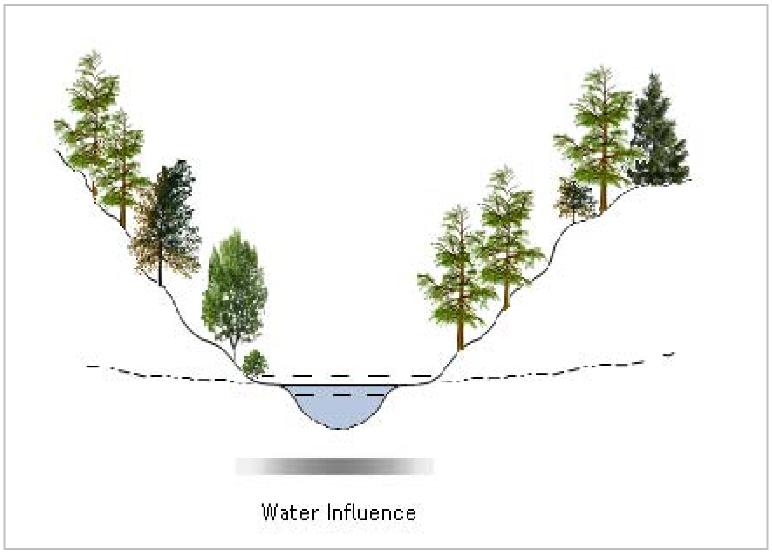


Figure 5. Schematic representation of riparian zones showing a general lack of active hydrological connection.

A method commonly used to take into account functionality is considering a fixed width buffer region from the stream necessary to preserve key riparian ecological functions. Verry et al. (2004) proposed a 30 m buffer to account for basic ecological functions around riparian ecotone delineation. Sutula et al. (2006) after vast literature analysis summarized estimated minimum and preferred buffer widths to account for a series of key riparian functions. As a result, an estimated buffer of 41 meters from stream would comprehend the minimum necessary upland extension to allow a proper functioning of all the eight functions considered (Table below).

Table 2. Average minimum buffer width around water stream necessary to maintain basic riparian functions (Adapted from Collins et al., 2006).

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

In the present study a theoretical value of 30-40 meters is thus considered adequate. From a raster data structure point of view this would correspond, with respect to the resolution used in this work, to 1 - 2 pixels (25 – 50 m). In both cases the functional buffer is generally contained in the Floodplains and calibrated Path Distance (FPD) layer extension, except around mountainous headwater streams or narrow steep valleys. As a consequence, a value of 1 pixel (25 m buffer) was considered more adequate for ephemeral/small stream size.

A 25 m functional buffer built around the river network is finally merged with the Floodplains and calibrated Path Distance layer (FPD). This combined layer defines the *maximum potential riparian zones extent*. Outside these boundaries the model assumes no riparian zones are present (*Figure 6*).

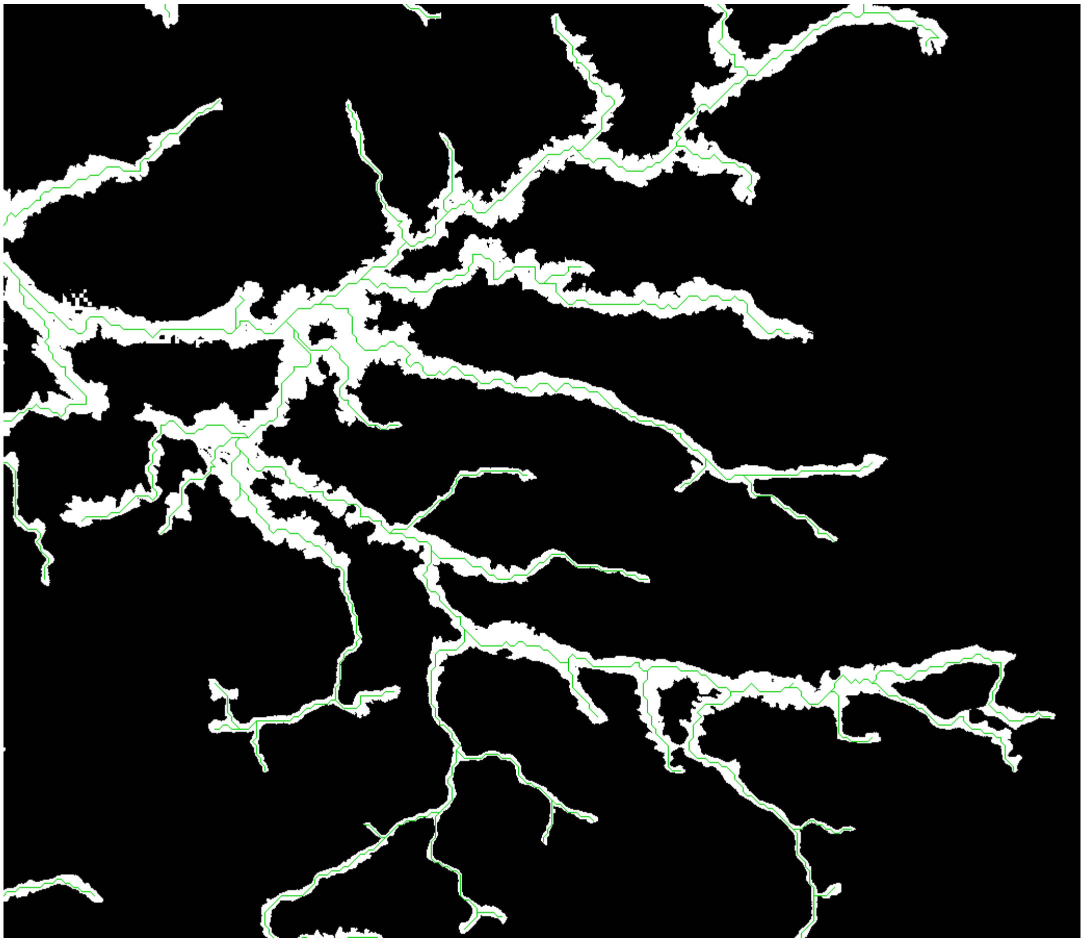


Figure 6. Example of maximum potential riparian zones extent layer (white). River network is showed in green. Headwater streams in mountainous areas (lower part of the image) show a narrower extent (steep valleys).

2.4 *Vegetation detection*

Vegetation is a fundamental element characterizing riparian zones functioning; a number of ecological processes are regulated by the riparian plant communities, providing key ecosystem services (Sweeney et al., 2004). Among others, riparian vegetation has a fundamental role in: 1) conservation of animal and plant biodiversity, by providing ecologically valuable habitats, together with natural structures that maintain landscape connectivity; 2) buffering non point source pollutants and nutrients; and 3) in stabilizing riverbanks (NRC, 2002; Lowrance et al., 1997,1985; Gillies and Cassidy Saint Clair, 2008). These riparian functions are controlled and maintained by vegetation under all its multiple life forms (herbaceous, shrubs and trees).

At present, no European databases with continental coverage provide a 'natural vegetation layer' at 25 m resolution. To counteract this lack of data a strategy based on two independent datasets was implemented: 1) the use of a Spectral Rule-based Classifier -SRC- (Baraldi et al., 2006) to derive a layer of vegetated locations from Landsat ETM+ imagery, and 2) the exploitation of a well consolidated database of European forest distribution, the JRC *Forest Cover Map 2000* (Pekkarinen et al., 2009). The use of a synergic strategy based on two different datasets was justified by the advantages and limitations each of data layer possess with respect to the objectives of this study:

- The SRC-derived dataset provides a distribution of any vegetated locations (forest, grassland, green crop fields, etc.) at 25 m at the acquisition time of the Landsat imagery. The SRC method has been widely validated and is known to be accurate (Baraldi et al., 2006; 2010a,b), but it is not designed to provide comprehensive information on ‘vegetation types’ in ecological terms.

- On the other hand, the JRC *Forest Cover Map 2000*, also at 25 m resolution, provides an accurate characterization of distribution patterns of a key ecological element of the riparian zones (Forests), but it relates only to this single category of vegetation.

The two databases together represented an adequate trade off in order to bring validated information at continental scale for a key life form in riparian environments (trees), and at the same time consider all the vegetation presence and its distribution. A detailed description of the datasets is following.

Spectral Rule-based Classified Vegetation

Baraldi et al. (2006) recently developed a new spectral knowledge-based system of fuzzy decision rules designed to map calibrated satellite images. The system is based on kernel spectral rules which are used to mimic known spectral signatures (from the remote sensing literature) of land cover targets. In this way spectral categories can be detected without the need of supervised training samples (null user supervision). The symbolic meaning of the kernel spectral categories is higher than those of clusters or segments (null), but lower than that of land cover classes. As an example, a group of pixels classified in the kernel spectral category 'strong vegetation' can potentially correspond to a number of land cover- land use classes, e.g.: green urban areas, irrigated arable land, pastures, etc. The SRC system is in fact a first stage classifier suitable to drive in a second step stratified application-specific classifications, segmentation, or clustering of remote sensing imagery. Nevertheless, the SRC system is extremely suitable for vegetation-non vegetation binary (V/NV) classifications. Accuracy estimation based on qualitative and quantitative assessment of test sites using 1-m orthophotos in a V/NV classification of Landsat ETM+ imagery, produced an overall accuracy of 98.2% and a Kappa coefficient of 0.94 (Baraldi et al., 2006). The method, tested at regional and local level (Baraldi et al, 2010a,b), resulted accurate and robust against the presence of shadow areas and large within-class spectral variations.

A SRC-based classification was performed by the EC-JRC Land Management and Natural Hazards Unit using algorithms and kernel spectral rules based on Baraldi et al.(2006) approach. A full European coverage of Landsat ETM+ scenes calibrated and transformed into planetary reflectance (albedo) were automatically processed. ETM+ imagery was acquired from NASA's Global Orthorectified Landsat Dataset (Tucker et al., 2004) available at the Global Land Cover Facility (www.glcf.umd.edu), and from the JRC Image2000 dataset (Nunes de Lima, 2005). The architecture of the SRC-based system as implemented considered a set of 20 kernel spectral classes that covered all the families of spectral signatures. The vegetation spectral family can be grouped into 12 vegetation spectral categories (*Table 3*). The name of these categories represents an indication of the vegetation signal strength/properties, but by no means they represent an univocal land-cover class. A general view of the mosaic with the vegetation layer derived by merging the twelve spectral classes mapped is shown in *Figure 7*.

Table 3.Vegetation spectral categories in the SRC-based vegetation/non-vegetation classification performed.

ID	Spectral category name	Acronym
1	Strong vegetation	SV
2	Average vegetation	AV
3	Scarce vegetation	WV
4	Vegetation under shadow	SHV
5	Strong shrub rangeland	SSR
6	Average shrub rangeland	ASR
7	Strong herbaceous rangeland	SHR
8	Average herbaceous rangeland	AHR
9	Weak rangeland	WR
10	Wetland or dark rangeland	WEDR
11	Rangeland in shadowed areas or wetland	SHRWE
12	Bogs	PB

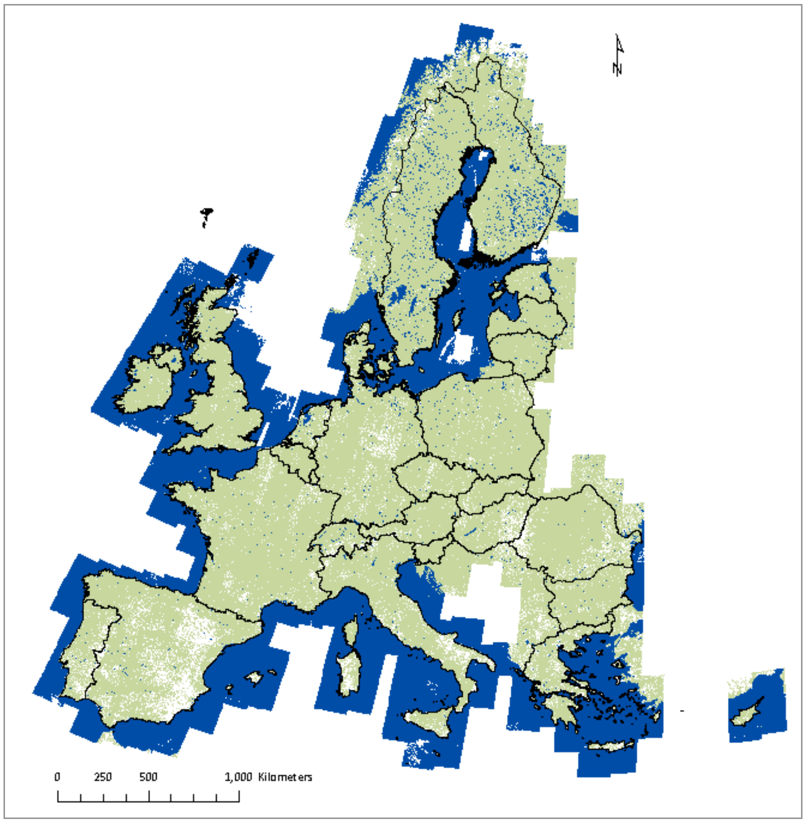


Figure 7. Vegetation layer derived using the SRC classifier (light green) and water spectral class (blue).

Forest vegetation

The presence of a tree vegetation community grants unique ecological functions to riparian habitats. The removal of treed riparian buffer can produce a large decline of natural woody debris input to small stream systems and lakes (France et al.,1996; Bilby and Bisson, 1992). Occurrence and extension of forest contiguous to the river channel is found to be positively correlated with biodiversity level and biotic integrity of the freshwater environment. The amount of forest in a 30 m river buffer, as derived from Landsat-based land cover maps, was found to be positively correlated with species richness of macro-invertebrate assemblages in watersheds of Southeastern U.S. (Sawyer et al., 2004). Analyzing headwater streams of the US mid-Atlantic region, Snyder et al. (2003) found that the riparian forest cover within a 120 m buffer from the water channel was the second most important predictor of the Index of Biotic Integrity (IBI) of streams. Clearing riparian habitats of tree vegetation can produce drastic changes in bird species assemblages, such as transitions from a rich species domination of small-bodied insectivores and nectarivores, to a few large-bodied generalists (Martin et al., 2006). Sweeney et al. (2004), analyzing 16 streams in North America, showed how deforestation of riparian environments can produce loss of a large series of ecosystem services.

Mapping of forest vegetation elements is critical for riparian zones characterization. One of the most valuable datasets of forest distribution with European coverage is the *Forest Cover Map 2000* (hereafter FC2000), developed by the EC JRC (Pekkarinen et al., 2009). The dataset has a spatial resolution of 25 m, and it is derived by Landsat ETM+ imagery acquired in 1999-2000 (for classification algorithms and processing chain see Pekkarinen et al., 2009). The forest class includes broad-leaved and coniferous forests, together with their mixed formations. These include the categories listed in *Table 4*, excluding forest nurseries and regeneration (with canopy closure less than 30%) , woodlands with trees lower than 5 m height (except in sub-arctic regions), burnt areas and clearcuts. Due to spectral signature similarities, some classes like wooded parks, dense olive groves, fruit tree plantations, agro-forestry areas and transitional woodlands can be difficult to separate, and in some cases they are classified as forest. The dataset was validated using three different data sources: 1) Field plot data from the Land/Use cover Area frame statistical survey (LUCAS2001); 2) Visual interpretation of very high resolution imagery (VISVAL); 3) Country-level Forest Resource Statistics Assessment 2005 (FRA2005). Accuracy information is discussed in *Section 3.2*. The Forest Cover Map 2000 dataset is shown in *Figure 8.*

Table 4. Categories included in the forest class in the Forest Cover Map 2000 (from the JRC LMU Forest Action Website, http://forest.jrc.ec.europa.eu/forest-mapping/forest-cover-map/2000. Updated 19th january 2010)

Categories
Broad-leaved - broad-leaved forest with more than 30% crown cover - plantations of e.g. eucalyptus, poplars - evergreen broad-leaved woodlands composed of sclerophyllous trees (mainly *Quercus ilex, Quercus Suber, Quercus Rotondifolia*) - arborescent mattoral with sclerophyllous species - olive-carob forests dominated by *Oleaeuropaea sylvestris, Ceratonia siliqua* - palm groves woodlands, tamarix woodlands, holly woodlands - broad-leaved wooded dunes - sub-arctic broad-leaved forests not reaching the 5 m height - transitional woodland areas when the canopy closure of trees cover more than 50% of the area and if their average breast height diameter is at least 10 cm.
Coniferous: - coniferous forest with more than 30% crown cover - non-evergreen coniferous trees woodland composed of *Larix* species - arborescent mattoral with dominating *Juniperus oxycedrus/phoenica* - Christmas trees plantations - coniferous wooded dunes - sub-arctic coniferous forest, not reaching the 5 m height.
Mixed: - mixed forest, the share of coniferous or broad-leaved does not exceed 25% in the canopy closure - mixed wooded dunes.

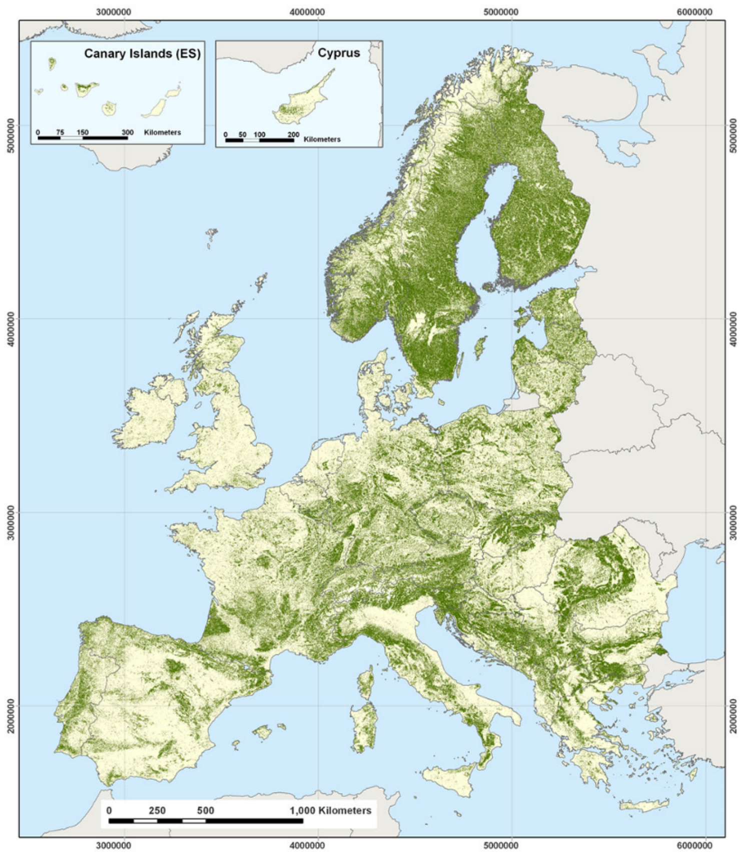


Figure 8. The Forest Cover Map 2000 (from the JRC LMU Forest Action website, http://forest.jrc.ec.europa.eu/forest-mapping/forest-cover-map/2000 (Updated 19th January 2010).

2.5 Land Use-Land Cover

In the current study we aimed to consider only those riparian zones in natural or semi-natural habitats. Firstly because correct ecosystems development and ecological functioning of their biotic/abiotic processes occur in areas with a certain degree of *ecological integrity* (Woodley et al., 1993). On a second instance, natural areas are also the more important reservoirs of biodiversity. For these reasons artificial surfaces or areas with productive activities have been excluded from the model (e.g. agriculture or areas under pasture pressure). Additionally, natural areas where riparian zones are unlikely to develop were also excluded from the assessment (e.g. rocky surfaces, glaciers).

This type of information is achievable for large regions from maps of land cover- land use derived by remote sensing data (Franklin and Wulder, 2002). In Europe, the only continental map with a sufficiently adequate spatial resolution for the purpose of this analysis was developed within the European CORINE Programme (Coordination of Information on the Environment). The *Corine Land Cover 2000* map (CLC2000) has a pan European coverage and it has been developed based on Landsat ETM+ imagery. The minimum mapping unit adopted is 25 ha (mmu) and all land cover patches smaller than the mmu were merged with the dominant surrounding classes (Bossard et al., 2000). A CLC2000 raster map at 25 m was obtained from the rasterization of CLC2000 vector data, downloaded from the European Environmental Agency website (*www.eea.europa.eu*). A series of natural and semi-natural land cover classes were selected targeting habitats where riparian environments, with reference to lotic systems, can potentially occur (see *Table 5*). Land cover typically observed at the interface with riparian environments, like sands/sediments and water courses were considered. Corine Class 333 ('Sparsely vegetated areas') was excluded due to its very low accuracy in the original dataset (53.6%), and because often associated with arid and rocky environments, which could have led to an overestimation of riparian zones. Inland marshes and peat bogs were also purposely excluded having wetlands ecological and hydrological characteristics different from riparian zones, like composition of plant communities, disturbance regimes, soil saturation (NRC, 2000). *Figure 9* represents the distribution in Europe of the layer derived by merging the cover classes in *Table 5,* excluding inland waters.

Table 5. Corine Land Cover 2000 classes selected in the riparian zonation model.

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

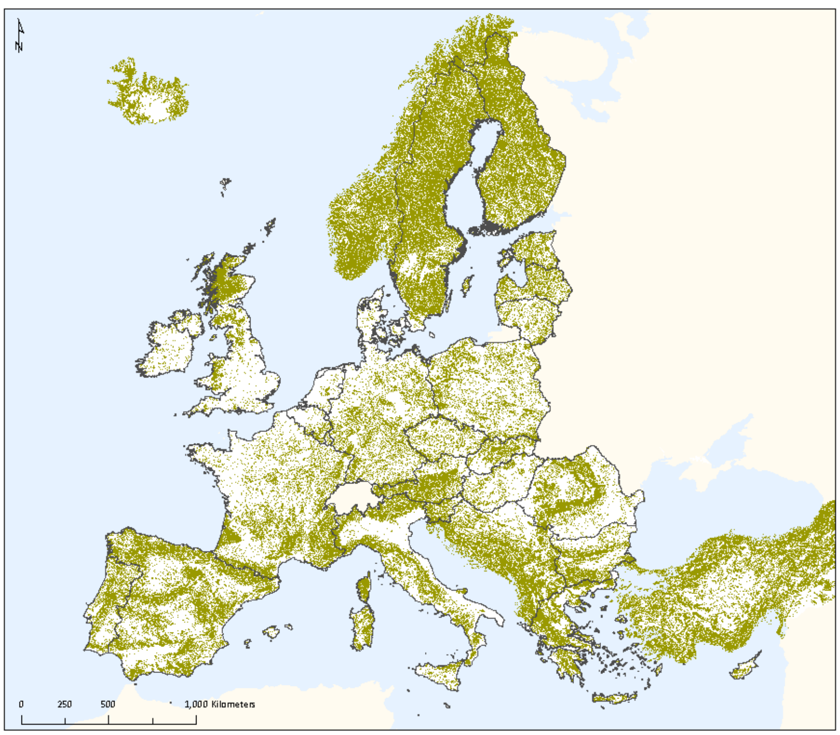


Figure 9. Distribution of the CLC2000 selected classes (green). Study area administrative boundaries in grey.

Photo 1. Location of riparian banks lacking a 'natural or semi natural' condition (lower part of the image) are not considered by the model (Photo: Southwings - for Choctawhatchee Riverkeeper, Inc.).

2.6 Riparian Zones and fuzzy membership approach

The zonation model considers the maximum potential riparian extent (*Section 2.3)* as the area where to evaluate three basic attributes of riparian zones: presence of a natural/semi natural land cover, natural vegetation occurrence and influence of water. In the first step the locations characterized by CLC2000 land cover classes not listed in *Table 5* (selected natural/semi natural) are assigned a 0 value (i.e. no riparian zone), thus being excluded from further assessment for the reasons discussed in the previous Section. The zonation algorithm masks non natural areas together with the regions where riparian areas are unlikely to be present (e.g. Glaciers and perpetual snow, etc).

The model establishes the assignment to the Riparian Zone class based on a fuzzy approach (Zimmermann, 2001). The use of fuzzy sets is an organized method introduced to deal with uncertainties and ambiguities (Zadeh, 1965). The fuzzy set theory allows a gradual belonging of elements to sets, in contrast with dichotomic (binary) memberships. An element can belong to a fuzzy set with different grades of membership, defined by a *membership function*. In other words, any element x_i part of a set X belongs to subset A according to a membership function μ_A: A → [0, 1], where μ_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 μ_A (x) =1, and is not included in A if μ_A (x) = 0.

Two membership functions are introduced to assign a score regarding the belonging to the natural vegetation presence (μ_v) and water influence (μ_w) sets. SRC-classified vegetation data and the Forest Cover map 2000 are assessed as a unique layer using a membership function which defines the degree of belonging μ_V to the fuzzy set V 'natural vegetation'. Being the SRC-classified vegetation data the representation of every vegetated location, they can introduce as well areas which are vegetated and not natural (e.g. green cultivated fields). The masking process operated by using natural and semi natural classes of CLC2000 is not fully sufficient, as a result of the lower resolution (100 m) of this dataset, and the *generalization* process to achieve a mmu of 25 ha (Mackaness et al., 2007). For example, in the CLC2000 data when simplifying areas of agricultural land cover, single or small pixel clusters can be included within other classes (e.g. a natural land cover class). As a consequence, these would be equally treated than the other unmasked vegetated locations during the evaluation process (*Figure 10*). Such a class assignment process is also valid in the contrary direction: natural classes can be included in clusters of agricultural land class.

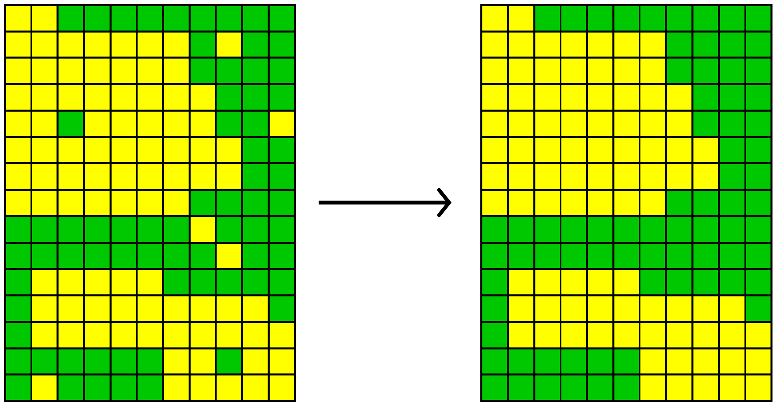


Figure 10. The generalization processes in the CLC2000 data (from left to right) can add pixels of agricultural areas (yellow) to a natural/semi natural class (green).

To partially counteract this issue, a membership system based on shares is applied to all vegetation spectral classes (*Table 6*). The value assigned to each SRC spectral category class is calculated from the proportion each of these classes fall within natural/semi-natural land cover classes of the CLC2000 dataset (%); this means that from a share value they are assigned a membership degree μ_V of belonging to set V (natural vegetation). As an example, if a hypothetical vegetation spectral class A is 10% of the times within CLC2000 natural and semi natural classes, it is given a membership value to set V equal to $\mu_V = 0.1$ (low belonging to natural vegetation class). When both a SRC and a forest attribute are present (overlap in the same pixel), priority is given to forest. The value $\mu_V = 1$ is assigned to the forest class, to maximize in the scoring system the importance of riparian forested habitats in providing ecological functions and ecosystem services. Moreover, this allows to identify where forested riparian zones are located. *Table 6* summarizes values assigned to the membership function, with $\mu_V: \mathbb{N} \rightarrow [0, 1]$.

Table 6. Values $\mu_V(x)$ assigned to SRC-derived vegetation spectral categories and to the Forest 2000 map data.

SRC Spectral category name	Acronym	Class ID value (x)	$\mu_V(x)$
Strong vegetation	SV	1	0.52
Average vegetation	AV	2	0.60
Scarce vegetation	WV	3	0.30
Vegetation under shadow	SHV	4	0.67
Strong shrub rangeland	SSR	5	0.55
Average shrub rangeland	ASR	6	0.42
Strong herbaceous rangeland	SHR	7	0.99
Average herbaceous rangeland	AHR	8	0.56
Weak rangeland	WR	9	0.16
Wetland or dark rangeland	WEDR	10	0.28
Rangeland in shadowed areas or wetland	SHRWE	11	0.56
Bogs	PB	12	0.35
Forest 2000 map data	**Acronym**		$\mu_V(x)$
Forest	FOR	-	1

The third attribute taken into account by the model is water influence, by definition *key* in the formation of riparian zones. In probabilistic terms we can reasonably assume water influence decreases with increasing Euclidean distance from the stream. However, this is very site dependent, as steep slopes or plains can show a very different behavior at the same distance from water. More reasonably, water influence can be assumed to be inversely proportional to the water cost of lateral movement. The Path distance layer is thus considered more adequate to evaluate water influence in riparian zones, being a proxy representing the topographic cost of water to move from the stream outwards. The zonation model introduces a membership function (μ_w) to assign a degree of belonging to the 'water influence' set *W*. The function is built on a simple linear inverse relation between water influence and Path Distance. Minimum accumulated cost values of water movement (near to stream, where PD is low) represents maximum water influence (near $\mu_w = 1$). As discussed, the value PD_α represents the upper limit where water is considered having influence and which delineates, together with the LISFLOOD data, the maximum potential riparian extent. Membership function μ_w is thus defined as:

$$\mu_w(x) = \begin{cases} 1 - [x/(PD_\alpha + 1)], & 0 \le x \le PD_\alpha \\ 0, & \text{elsewhere} \end{cases} \qquad [1]$$

Especially in large river deltas LISFLOOD floodplain data have considerable dimension, extending in some cases far over the calibrated Path Distance layer. In order to consider floodplain regions characterized by values of $PD \ge PD_\alpha$, , the function μ_w is here defined differently. If $PD \ge PD_\alpha$ then μ_w is set equal to a minimum value necessary to avoid masking. This is applied till levels of $PD = 2PD_\alpha$, empirically determined to limitate the extension of large floodplain areas located too far from the water stream to be considered appropriate riparian regions.

Membership function μ_w is here defined as:

$$\mu_w(x) = \begin{cases} 1 - [x/(PD_\alpha + 1)], & 0 \le x \le PD_\alpha \\ 1/(PD_\alpha + 1), & PD_\alpha < x \le 2PD_\alpha \\ 0, & \text{elsewhere} \end{cases} \qquad [2]$$

Figure 11 represents graphically the functions defined in [1] and [2].

Presence of natural vegetation and influence of water are considered both necessary conditions for the existence of a riparian zone. The following rule is thus applied in the model to consider a location *i* to be a riparian zone:

$$(\mu_v > 0) \text{ AND } (\mu_w > 0) \qquad [3]$$

Areas where this condition is not respected are assigned by the model a 0 value (no riparian zone). Under this condition 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:

$$I_{RZ} = (\mu_v\ ,\ \mu_w) \qquad [4]$$

Functional buffer areas which do not have an active hydrological connection (*Figure 5*), i.e. in the model with $PD > PD_\alpha$ and not floodplains, are not processed under the condition [3]. They represent 'functional riparian zones' defined uniquely by their close proximity to the river network (25 m), independently by their vegetation state or water influence, and thus flagged differently.

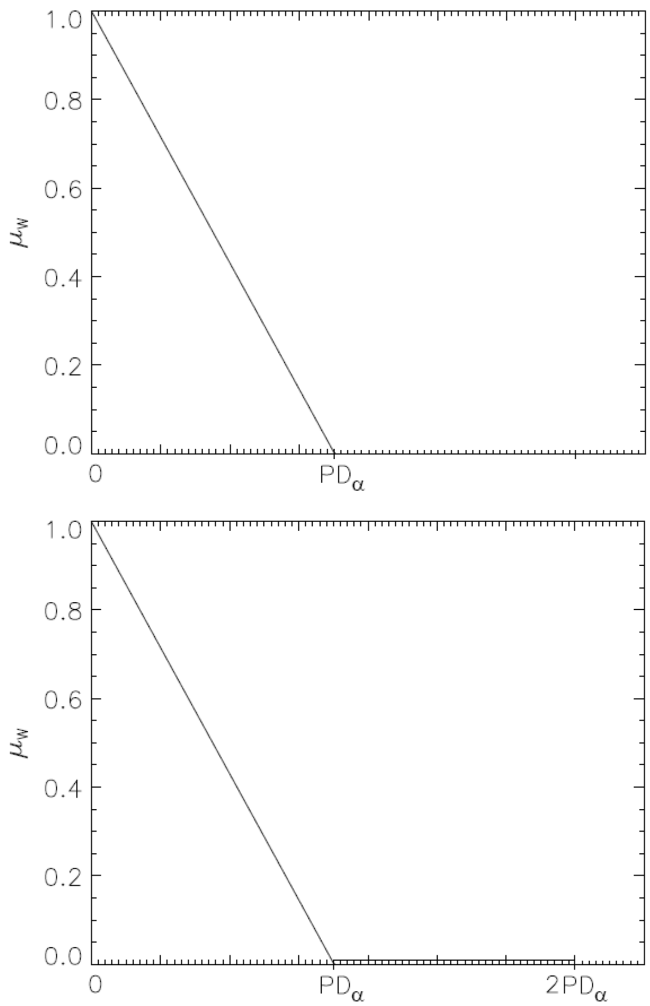


Figure 11. Membership functions μ_w for water influence. Upper figure represents function [1]. Lower figure represents function [2], defined where floodplain areas have PD > PD_α.

Riparian zone pixels are further partitioned in four clusters based on the bivariate index $I_{RZ,}$ and defined by a Cartesian plane (*Figure 15*) with origin O_{xy}: (μ_v = 0.5 , μ_w= 0.5). To each class a value is assigned from 1 to 4. Final raster values of the dataset are reported in the following table (Model version March 2011).

Table 7. Raster values of Riparian zones output

Class		Raster value
Riparian Zone	$\mu_v > 0.5,\ \mu_w > 0.5$	1
	$\mu_v > 0.5,\ \mu_w < 0.5$	2
	$\mu_v < 0.5,\ \mu_w > 0.5$	3
	$\mu_v < 0.5,\ \mu_w < 0.5$	4
Functional Riparian Zone		5
Water		250
No data		255
Other		0

A descriptive flow chart regarding the entire processing chain for the riparian zonation model is illustrated hereafter (*Figure 12*). A characterization of the riparian zones class as derived by the model was performed by extracting statistics from the CLC2000 and Forest Map 2000 datasets. Uncertainty and reliability measures are produced and discussed starting from accuracy of input layers, visual validation points and independent datasets.

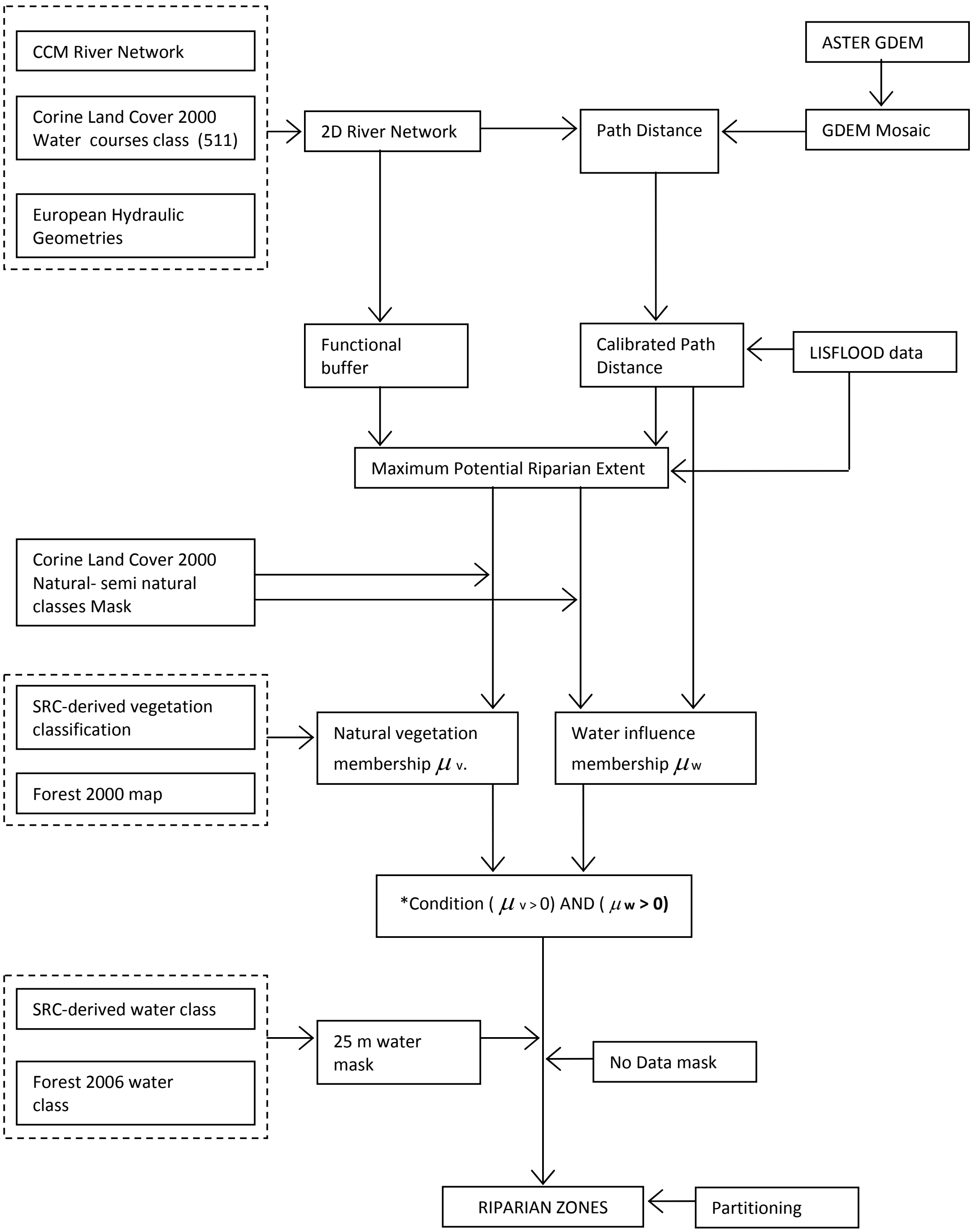


Figure 12. Descriptive processing chain of the riparian zonation model. Condition(*) is not applied to functional buffers with $PD > PD_{\alpha}$.

3. Results and discussion

3.1 Output and basic characterization

An overall output of the Riparian zonation model with European extent is shown in *Figure 13*, and a lower scale image in *Figure 14*. Distribution patterns are summarized in terms of share (%) in 1 km cells to improve visual observation at continental extension. As expected riparian zones distribution reveals a strong dependence from the river network density. The network, based on CCM data, is particularly dense in mountainous areas, where due to the marked topography the number of water streams (especially ephemeral streams) is very high (see Vogt et al., 2003; 2007a,b). As a consequence, the Alpine and Pyrenees regions, characterized by extended natural vegetated habitats, show high proportion of riparian zones. A similar pattern is also visible in Sweden and Finland, as a result of a particularly dense water network and large presence of natural land cover classes. In the main European plains, where the landscape is characterized by extended agricultural land, riparian zones presence is generally low due to the large masking of non natural land cover. At the same time, the flat topography and presence of large rivers allow the formation of wider riparian zone regions, which are generally correctly detected by the model.

Overall the riparian zone class covers about 90,415 km^2, approximately the 2% of the European continental area under study. Points with higher values of μ_v and μ_w, in the upper right quadrant (I) in *Figure 15*, represent approximately 45% of the total. This quadrant represents locations nearer to river streams and with classes of vegetation more probably natural, in other words regions which are more likely riparian zones. Points with low memberships to the riparian zone class (IV) represent only 6.6% of the total (*Table 8*), i.e. locations with lower probability of being riparian zones are present in considerable minor proportion in the output dataset. Riparian zones with higher μ_v (quadrants I, II) have the highest share (together 84.8 %), which means that most riparian zones exhibit a strong degree of natural vegetation.

Functional riparian zones are represented by 1,668 km^2, about 1.8% of all riparian classes (1 to 5, in *Table 5*).

To get a basic characterization of the riparian zone class, statistics of land cover were extracted from the CLC2000 dataset (*Table* 8). Results of the model indicate that European riparian zones are strongly dominated by natural forested habitats (around 69%). The importance of forest habitats for ecosystem services and biodiversity conservation is a well established ecological topic (e.g. Fahey, 2001; Simberloff, 1999); this study provides for the first time a quantitative indication and location of forested habitats in Europe which also have an ecological significance as riparian zones.

About 13.3% of riparian zones is associated with transitional woodland shrub, 6.0% with grasslands, 4.2% moors and heathland, 3.6% with sclerophyllous vegetation, 0.7% by beaches, dunes and sands and 2.7% water courses. Riparian zones associated with CLC2000 water courses class are due to proximity effects with the water stream, with the coarser spatial resolution of the CLC2000 dataset and with the generalization processes operated to derive the land cover dataset.

In Annex 1 are shown some examples of the riparian zones output at 25 m resolution in four different geographical regions In Europe.

Figure 13. Pan European map of percentage of riparian areas in 1 km cells. Zoom A is shown in *Figure 14*.

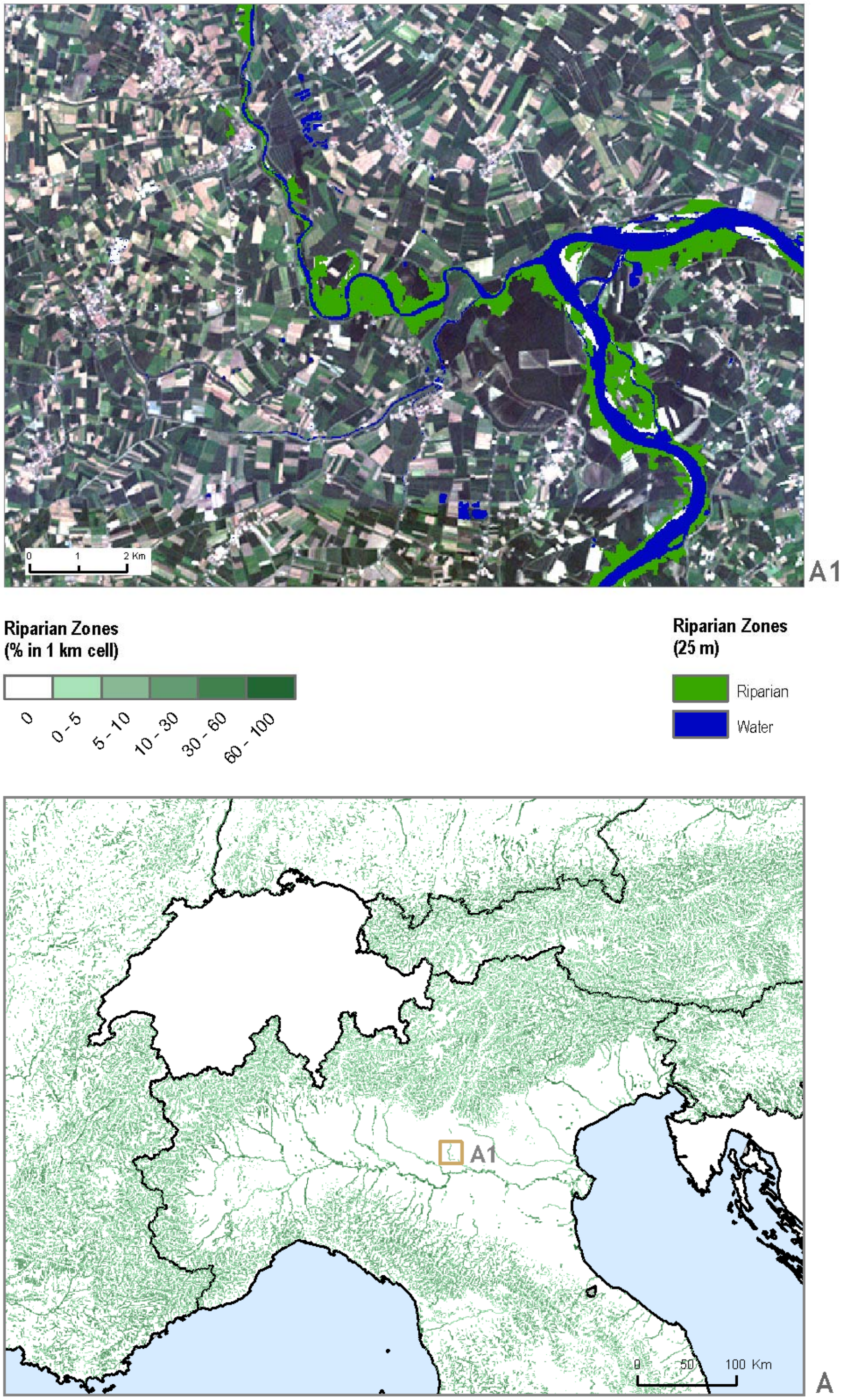


Figure 14. Percentage of modelled riparian zones in 1 km cells for North of Italy and surroundings (A). Upper image (A1) shows a zoom with riparian zones at 25 m (green).

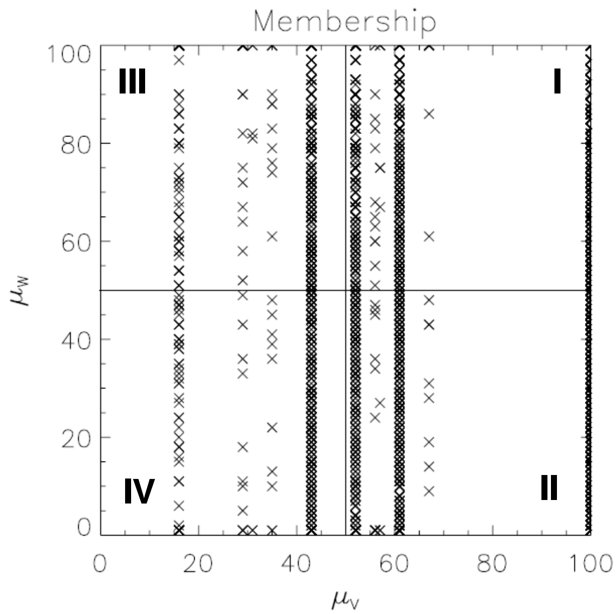


Figure 15. Scatterplot of riparian zone membership values for a random representative sample (Europe).

Table 8. Statistics of Corine 2000 land cover classes and relative extension for the four riparian zones clusters.

	km2					%				
CLC2000 class	I	II	III	IV	All	I	II	III	IV	All
Broad-leaved forest	10,769.5	9,357.2	1,041.4	793.9	21,961.9	26.2	26.2	13.5	13.3	24.3
Coniferous forest	12,814.7	12,428.1	748.9	683.1	26,674.8	31.2	34.9	9.7	11.5	29.5
Mixed forest	6,856.4	6,549.2	433.8	377.8	14,217.2	16.7	18.4	5.6	6.3	15.7
Natural grasslands	1,960.0	1,453.5	1,122.2	906.5	5,442.2	4.8	4.1	14.5	15.2	6.0
Moors and heathland	1,110.7	903.5	955.3	831.8	3,801.4	2.7	2.5	12.3	14.0	4.2
Sclerophyllous vegetation	861.6	657.4	952.0	747.7	3,218.7	2.1	1.8	12.3	12.6	3.6
Transitional woodland-shrub	4,795.8	4,114.9	1,668.9	1,457.3	12,036.9	11.7	11.5	21.6	24.5	13.3
Beaches, dunes, sands	164.7	95.0	258.6	136.8	655.1	0.4	0.3	3.3	2.3	0.7
Water courses	1,737.0	93.4	554.3	22.2	2,406.9	4.2	0.3	7.2	0.4	2.7
Sum	41,070.3	35,652.2	7,735.4	5,957.2	90,415.2					
%	45.42	39.43	8.56	6.59	100					

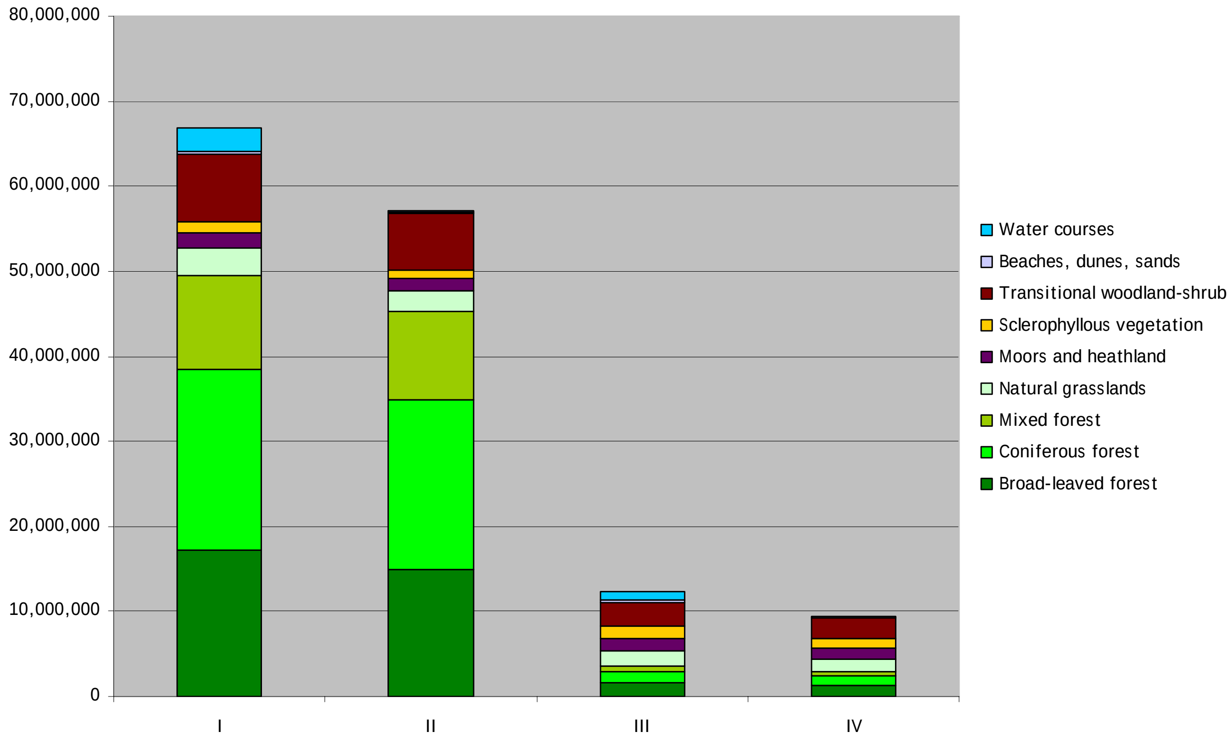


Figure 16. Corine land cover classes correspondent to the four Riparian zones clusters (pixels number).

3.2 Uncertainty and Limitations

Modelling always requires the employment of basic assumptions and simplifications. These need to be explicitly recognized and discussed, together with indications of the uncertainty present in the datasets used as input and in the outputs produced. No independent datasets of riparian zones covering the whole of Europe and directly comparable with the proposed zonation index are to our knowledge currently available, considering also the fuzzy structure and the elements of originality present in the model.

As a consequence, three different strategies were followed to discuss uncertainties and limitations related to the model:

- Report accuracy measures associated to the datasets used as input layers in the model;
- Discuss sources of errors in model output through visual analysis of medium and high resolution satellite imagery;
- Provide quantitative accuracy measures at regional and European level using Visual Validation Points (VISVAL) and other independent ecological datasets.

Datasets confidence and accuracy

European river streams were derived using the CCM dataset, which is built on 3 arc second SRTM data, and processed with a grid-cell resolution of 100 m (Vogt et al., 2003). Due to the dataset scale, mismatches of different magnitude implicitly exist between real and CCM river paths, as visually observed using high and very high resolution imagery, especially the case of plain areas (*Figure 17*).

In the CCM data all river segments own a confidence attribute, which can have three different values (Vogt et al., 2007b):

- 1, if derived uniquely from the DEM within an area of sufficient relief. As DEM accuracy is here generally high, a high confidence is attributed to the result.
- 2, if derived uniquely from the DEM, within areas of low relief and without using a reference river for correction (Soille et al., 2003). Low confidence is attributed to the result, although often river paths are correct (visual inspection).
- 3, if segments are derived from the DEM within areas of low relief and by using a reference river. In this case to the result is attributed a high confidence (path modified by the reference layer).

The percentages of confidence attributes for river segments in EU27 are reported in *Table 9* (Vogt et al., 2007b). Overall, high confidence river segments represent the 85.2% of the total. The presence of a geomorphological layer (Calibrated Path Distance) in the zonation model partially counteracts stream misplacements, which are more problematic when using buffering operations based on Euclidean distance (see buffer in *Figure 17*).

The EHG dataset (Pistocchi and Pennington, 2006) was used to derive an estimation of width for rivers for which no other source of continental data was available. River width error estimation was performed by Pistocchi and Pennington (2006), which reported EHG river widths values showed a good agreement with literature, providing an adequate estimation of this parameter at continental scale (1 km).

Table 9. Percentage of river segments from the three classes of confidence in the CCM dataset (after Vogt et al., 2007b).

Country	Percentage of all River Pixels (EU-27)	Derived from DEM only high confidence (%)	Derived from DEM only lower confidence (%)	Derived from DEM and Reference Layer high confidence (%)
AT	3.36	91.8	4.4	3.9
BE	0.58	64.1	15.3	20.6
BG	3.09	83.4	4.7	11.9
CY	0.21	80.2	10.6	9.3
CZ	1.95	84.3	6.2	9.4
DE	7.54	65.3	15.7	18.9
DK	0.46	48.8	35.2	16.1
EE	0.72	21.5	32.6	45.9
ES	13.95	88.9	5.9	5.2
FI	4.97	54.9	44.0	1.1
FR	13.80	81.6	9.1	9.3
GR	4.78	89.9	6.2	3.9
HU	1.56	39.9	13.3	46.8
IE	1.37	59.8	17.4	22.8
IT	10.51	81.2	3.2	15.6
LT	1.17	38.5	22.7	38.8
LU	0.07	90.2	2.6	7.2
LV	1.20	26.1	26.9	47.0
MT	0.00	99.6	0.4	0.0
NL	0.24	11.0	35.3	53.7
PL	5.64	49.6	35.6	14.9
PT	2.33	91.8	1.8	6.4
RO	5.79	77.6	13.7	8.8
SE	7.50	79.2	19.8	1.0
SI	0.77	82.2	3.4	14.4
SK	1.53	79.8	4.9	15.3
UK	4.92	77.2	9.8	13.0
Average (EU 27):		**68.1**	**14.8**	**17.1**

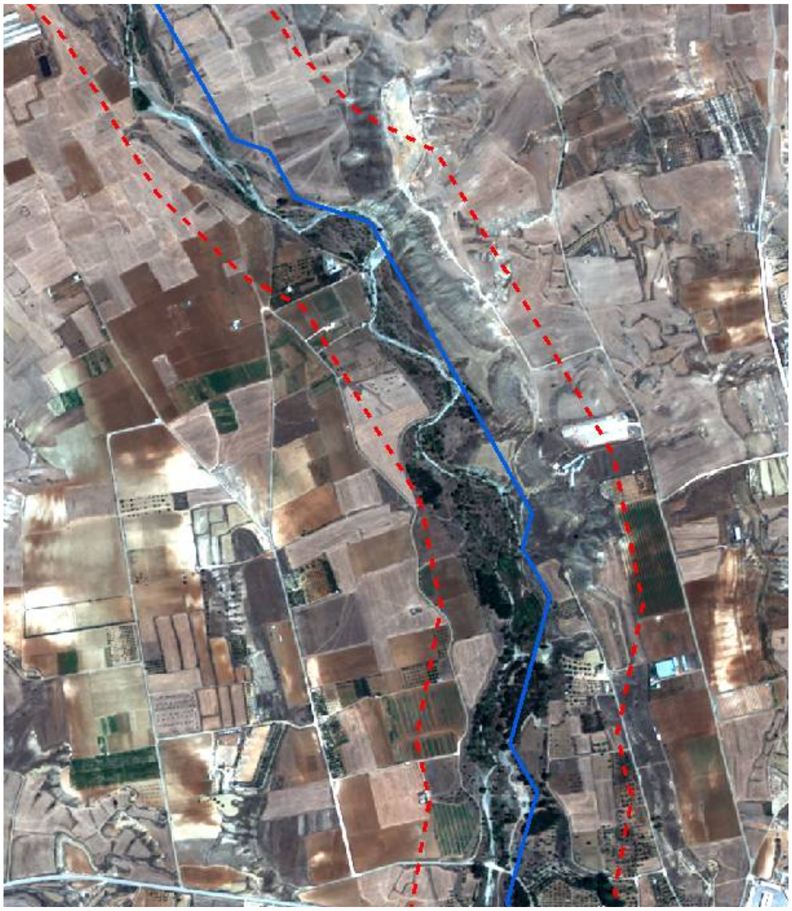


Figure 17. Mismatches between actual river path (Quickbird imagery) and CCM river, in blue. A 250 m buffer is overlaid (dotted, red)

For LISFLOOD data a systematic accuracy assessment was not implemented (L.Feyen, personal communication). However, due to 1) the use of simulated climate data, 2) flood return levels estimated using extreme value analysis based on 30 years time series and 3) approximations in calculation of river water levels and river cross sections, it derives that flood inundation extent is inherently uncertain.

ASTER GDEM data, on which was based the Path Distance index calculation, have vertical errors of approximately 20 m at 95% confidence on a global basis (ASTER GDEM VALIDATION TEAM, 2009). ASTER GDEM data was found to contain in some locations anomalies and artefacts. The more important source of anomalies observed in this study is known to be the presence of residual clouds in the ASTER scenes used to generate the DEM. At European level, regions with artefacts were found north of 60° of Latitude in central Sweden (*Figure 18*) and west Finland. An appropriate masking of areas clearly identifiable as artefacts/no data was performed. Despite the presence of this and other source of errors, NASA (US National Aeronautics and Space Administration) and METI (Japan's Ministry of Economy, Trade and Industry) decided to release ASTER GDEM data because they believe '*its potential benefits outlaw its flaws*' (ASTER GDEM VALIDATION TEAM, 2009).

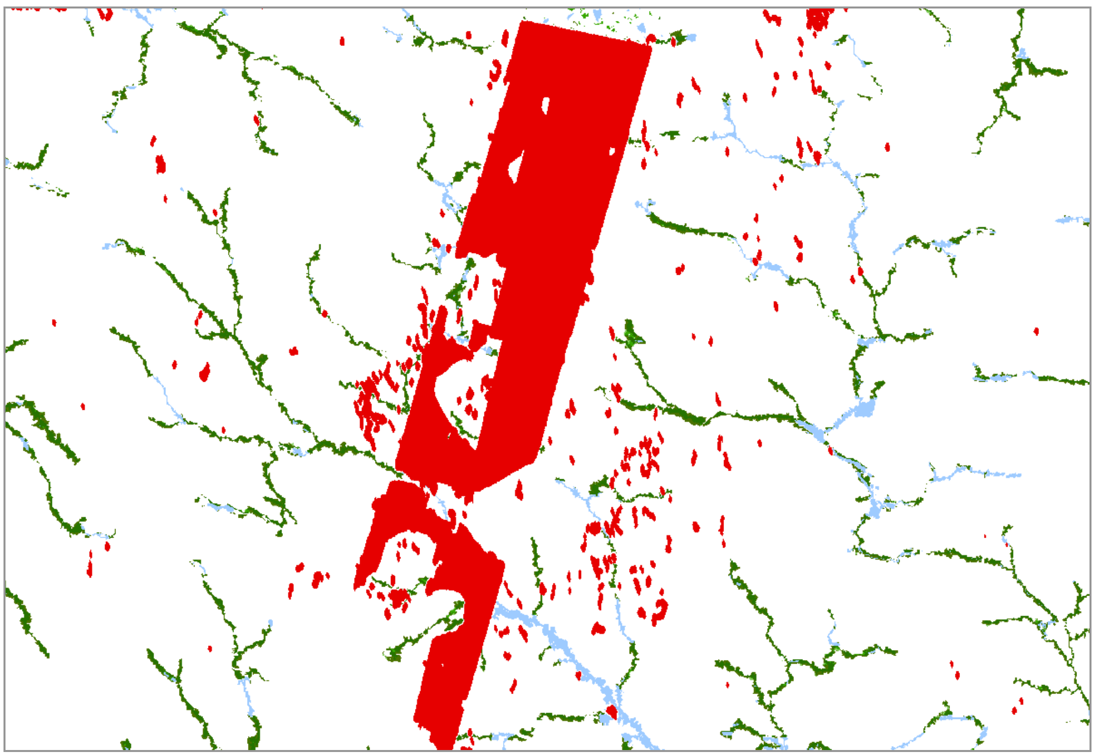


Figure 18. 'Pits' present in the ASTER GDEM data in central Sweden (red), and treated as No Data in the model. Riparian zones output pictured in green.

The Corine Land Cover 2000 dataset (Bossard et al., 2000) was the basis to achieve information on the extension of large river and distribution of natural/semi-natural land cover classes. An extended thematic accuracy evaluation was performed by the European Environment Agency and EU Member States partners (see EEA, 2006) based on LUCAS data (European Land Use/Cover Area Frame Statistical Survey; Eurostat, 2005). The main purpose of the LUCAS project is to provide harmonized information on agri-environment, by collecting detailed land use/land cover data. LUCAS data represented the only European–wide independent dataset collected with high accuracy in a nearly coincident time window. A total number of 8231 points were analyzed over 18 countries using two methods:

1- Reinterpretation of Image2000 data based on LUCAs codes and photographs;

2- Unsupervised comparison of CLC2000 codes and LUCAS codes.

Overall the reinterpretation method (1) reported the total reliability of CLC2000 to be 87.0±0.8%. Method 2 indicated a percentage of total agreement (PTA) of 74.8±0.6%. Reliability of single CLC2000 classes selected in this study (method 2) is reported in *Table 10*. Rivers (class 511) and Sands/beaches/Dunes (class 331) showed a higher reliability but they were assessed with a very low number of points. Overall, the reliability regarding the CLC2000 classes selected for this study equal 86.1%, while for vegetated classes average value is 82.1%.

Table 10. Reliability of CLC2000 classes selected in this study (data from EEA, 2006).

CLC CODE	CLC LABEL 3	# Points controlled	% Points correct
311	Broad-leaved forest	602	87.5
312	Coniferous forest	1239	90.6
313	Mixed forest	490	89.4
321	Natural grasslands	200	75.8
322	Moors and heathland	126	71.7
323	Sclerophyllous vegetation	202	76.8
324	Transitional woodland-shrub	466	82.8
331	Sands, Beaches, Dunes	5	100.0
511	Water courses	17	100.0
Reliability			
Average CLC classes reliability			86.1%
Average vegetated CLC classes reliability			82.1%

A pan-European vegetation layer derived from Landsat ETM+ data based on a Spectral Rule-based Classification approach (Baraldi et al., 2006) was included in the model. The authors evaluated the accuracy of the classifier in a vegetation/non vegetation classification using imagery from the same sensor. Overall accuracy was 98.2% (K=0.94) thus proving the high performance of the SRC in V/NV binary classifications using ETM+ data.

Information from the JRC Forest map 2000 (Pekkarinen et al., 2009) was also incorporated in the model to provide accurate continental information on forested land. The dataset accuracy assessment was performed by the authors using 1) visual validation (high resolution images in GoogleEarth) and 2) LUCAS data (Eurostat, 2005). The former method showed an overall accuracy (OA) of 88.4%, while the latter produced an OA of 83.7% (up to 90.8% for *homogeneous points* which fell into a 3x3 block of forest/non forest). Statistics at the country level (available for EU15) are shown in *Table 11*.

Table 11. Overall Classification accuracy statistics (OA,) of the forest/non-forest map based on all, and homogeneous forested LUCAS2001 points with 95%-confidence intervals (from Pekkarinen et al., 2009).

	All points		Homogeneous points	
Country	Number	OA (%)	Number	OA (%)
AT	2523	84.0	1816	93.8
BE	989	89.3	784	96.8
DE	10966	90.4	8800	96.5
DK	1365	89.6	1114	95.2
ES	12496	81.4	9907	87.8
FI	10368	76.6	7084	84.8
FR	16898	87.2	13145	94.3
GR	4038	81.8	3275	87.5
IE	2158	91.1	1964	94.0
IT	9252	81.3	7208	88.1
LU	80	92.5	58	98.3
NL	1154	93.6	1038	96.6
PT	2730	73.5	1773	83.0
SE	13789	78.2	9501	86.5
UK	7483	91.7	6450	95.9
Total	96289	83.7	73917	90.8

Visual analysis of medium and high resolution imagery

General qualitative considerations on model accuracy can also integrate quantitative accuracy assessments. A large set of very high resolution imagery (Quickbird, Ikonos, RapidEye, SPOT hi-res) and Landsat ETM data was downloaded from the JRC Community Image Data Portal –CID- (http://cidportal.jrc.ec.europa.eu). Overlap with the Riparian Zone model output allows discussing strengths and weaknesses of the data used and model structure. Three representative examples are shortly discussed.

Figure 19 shows a RapidEye image (FCC RGB 321) at 1 meter resolution of the Southern Portugal-Spain border. Modelled riparian zones have been overlaid in the same location (lower image). Higher IRZ values are represented by darker green tonalities, and modelled water in blue. The vector river network (*Section 2.2*) is also overlaid in red. Visual observation is regionally in accordance with output results. Simplified CCM river paths together with the 'cut-off' effect of Calibrated Path Distance (calculated starting from the river network) produced few false negatives, indicated by arrow A. This is mainly due to the scale of the CCM dataset, based on the SRTM DEM at 100 meters resolution (river path visible in the figure in red). At the same time, such misplacements are counteracted by the CPD layer (location 'B'); a Euclidean buffer from the river network, being not sensitive to topography, would have potentially produced false positives. These are also sometimes produced by the model when the river path is deviated and with gentle topography (C). Very small streams are often not present in the CCM dataset, thus small riparian areas are not detected (D). Although the area is dry, the SRC-based vegetation classification performed well in identifying sparsely vegetated locations. Larger riparian banks of the Guadiana River are cultivated, and masked by the Corine2000 data (E).

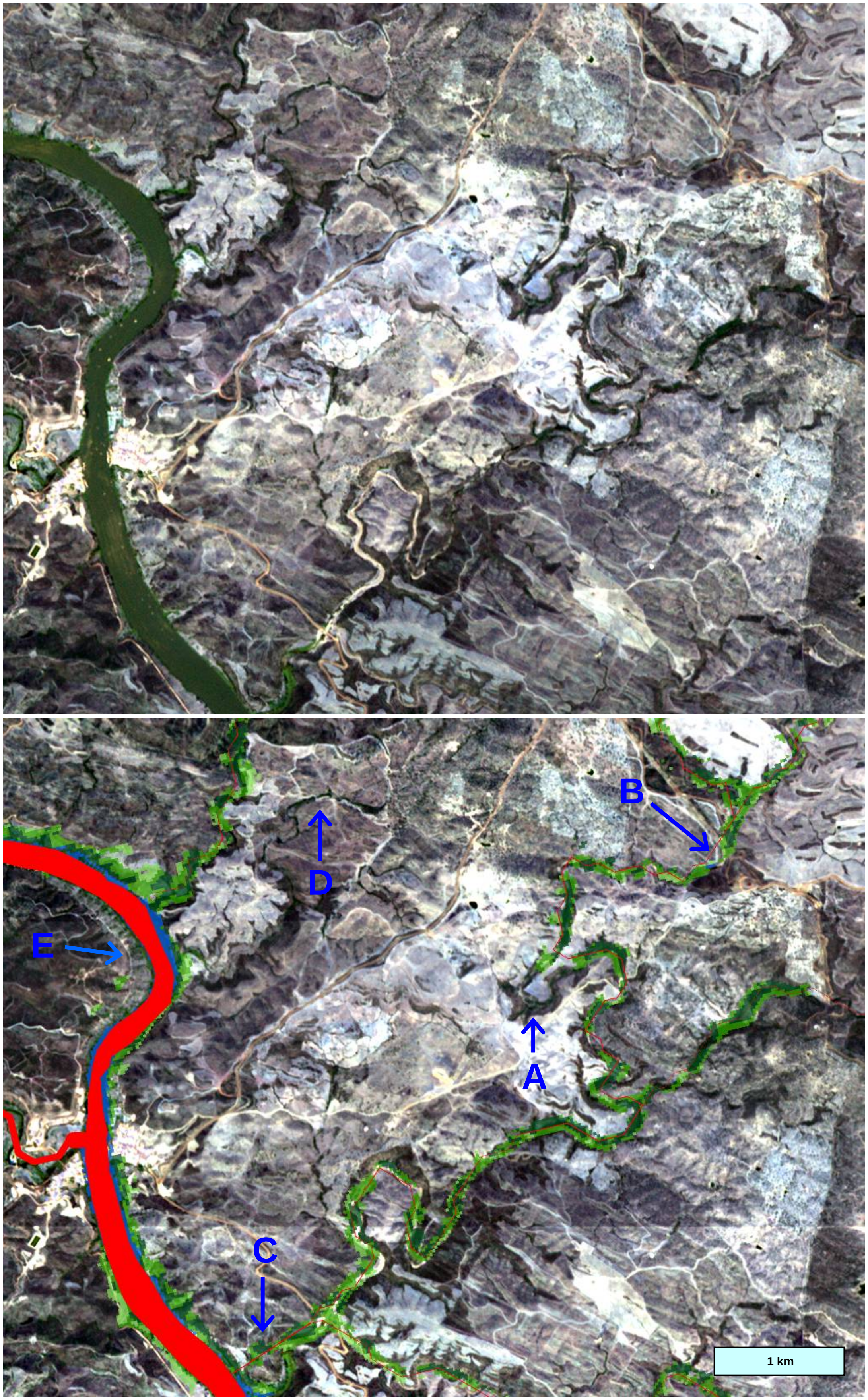


Figure 19. Riparian zones overlaid on a 1 m RapidEye image (lower image). Darker green tonalities represent higher I_{RZ} values. For points discussion (A...E) refer to text.

Figure 20 shows a Quickbird image (2.5 m meter resolution) of mountainous areas in Southeast France, together with a detailed zoom. Riparian zones are also overlaid (green) together with the 25 m water mask (blue). Also in this case general pattern is in accordance with visual observation. Arrows in A indicate terminations of riparian zones corridors as a result of the presence of agricultural land cover, thus due to masking of non-natural habitats. Spatial detail level is adequate, as shown for example by the detection of a very narrow stripe of vegetated sediments within the Rhone river (B). Masking of inland marshes is also evident by the absence of riparian zones in location C (Corine2000 data). In the zoomed image is possible to observe how the steep topography is reflected in the calibrated Path Distance index, which allows the detection of narrow (1-2 pixels) riparian zones on the slopes (location D). When good accuracy level is present in the Corine Land cover dataset is possible to detect precise masking of cultivated fields and agro-forestry areas contiguous to the river (arrows in E and F).

Landsat ETM+ imagery was also largely used for visual analysis of model outputs. *Figure 21* represents riparian zones overlaid on one ETM+ image of northern Spain (Leòn). The modelled result is reflecting well the general picture of riparian zones, however the effect of the Corine masking is in some places very evident, due to the generalization process used in this land cover dataset. Location indicated by arrow A shows a potential riparian zone which is not detected by the model due to the land cover attribute assigned to this area (permanent irrigated land). This false negative type of error can be relatively frequent when the landscape is vastly dominated by non natural land cover classes, and when local Corine data accuracy is lower. Location B indicates an area where possibly the seasonal drier condition (image was taken in mid summer) could have influence on the absence of vegetation detection (role of seasonality). Smaller riparian zones not detected are due to the density of the modeled river network. In areas with more gentle topography the CCM river dataset often appears considerably less dense and small rivers are often not represented. Locations indicated by arrows in D and C show potential riparian zones which are not detected due to the absence of a river mapped in the CCM dataset.

After visual analysis of riparian zones and high/medium resolution satellite imagery, some general considerations can be expressed on the types and sources of model errors. The Corine masking operations (*Section 2.5*) represent often the main source of false negatives in riparian zones detection. This is due to two main reasons: 1) the generalization process used to reach the 25 ha minimal mapping units. As a consequence, the local accuracy of the land-cover dataset has a direct influence on riparian zones extension. 2) Heterogeneous agricultural areas (CLC2000 classes labelled 243 and 244) have by definition patches of natural habitats, which cannot be discriminated and isolated from the agricultural matrix.

Small riparian corridors are occasionally not detected because small streams, especially in flat areas, are absent in the hydrographic network used. Dry conditions can also have an influence on vegetation detection, thus the choice of the right season in satellite image acquisition for classification possibly plays an important role in riparian zonation of the European dryland regions.

In flat regions the maximum potential riparian extent layer is observed to occasionally determine an overestimation of riparian zones, especially in concomitance with coastal areas because of the presence of very short ephemeral CCM river segments discharging to sea. Calibrated Path Distance index and the CCM dataset show generally higher accuracy in regions with a marked topography. Consequently, false positives appear to be more present in plain areas or where landscape topography is not accentuated.

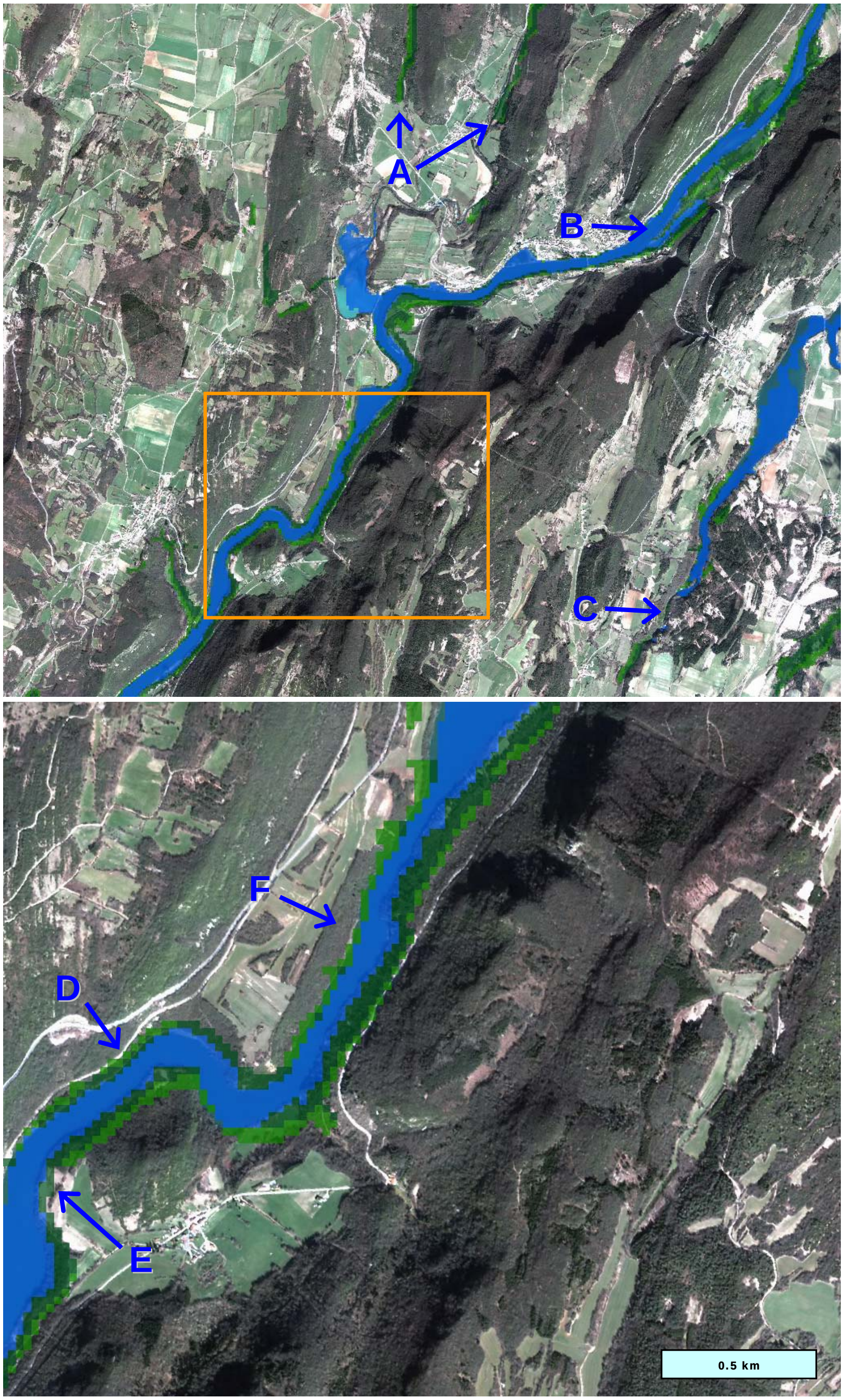


Figure 20. Riparian zones overlaid on a 2.5 m Quickbird image and detail (orange box). Darker green tonalities represent higher I_{RZ} values. For points discussion refer to text.

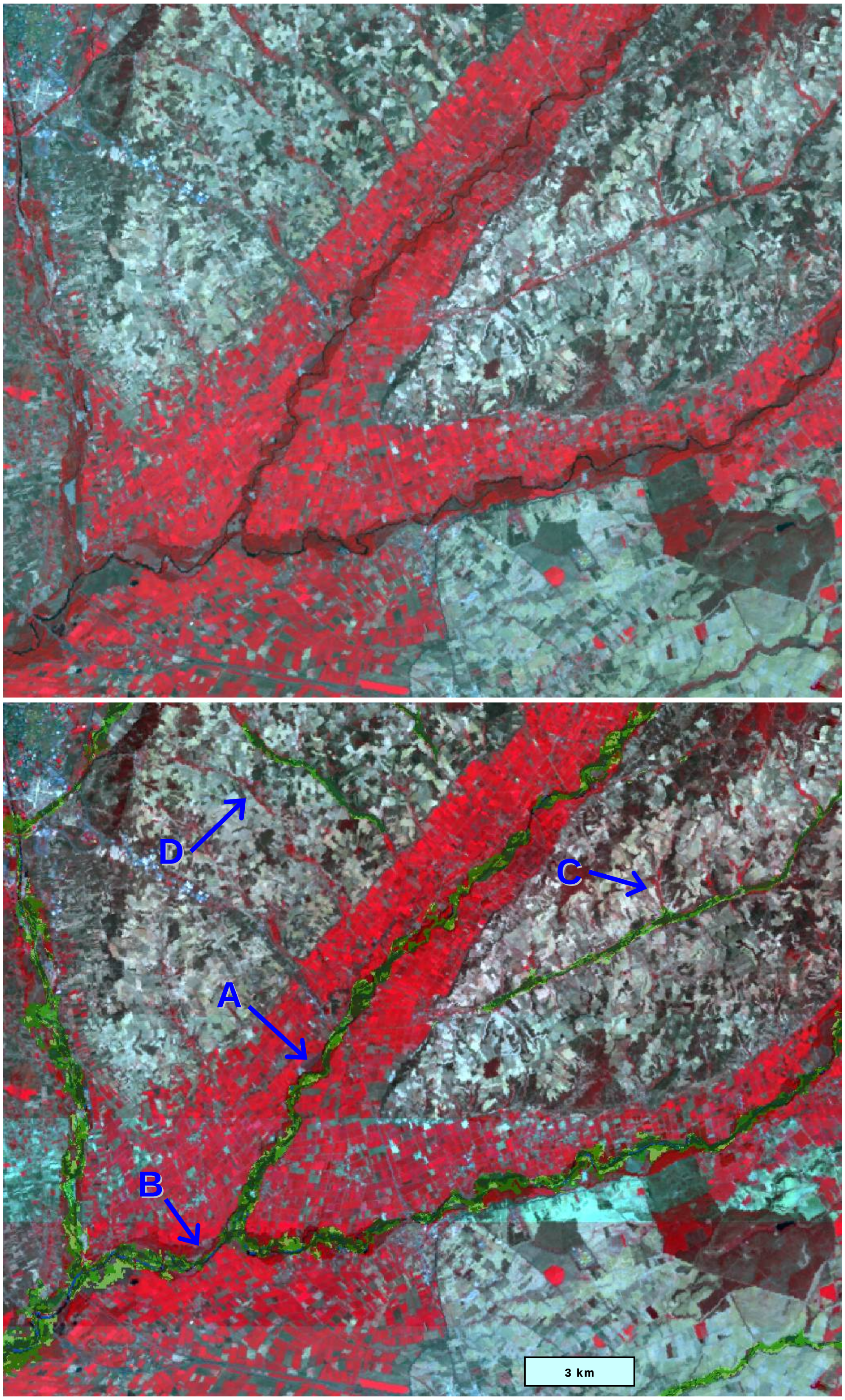


Figure 21. Riparian zones overlaid on a 30 m Landsat ETM+ image. Darker green tonalities represent higher I_{RZ} values. For points discussion refer to text.

Accuracy measures using VISVAL and independent datasets

The riparian zones model proposed is based on a fuzzy approach and it has pan-European coverage. This makes a continental accuracy assessment particularly complex, for both data availability and extension. However, quantitative reliability measures on absence/presence of riparian zone at regional and European level can be derived, by using Visual Validation points (VISVAL) and other independent datasets. Three strategies were followed:

1- Visual validation points based on very high resolution images from GoogleEarth® (2011);
2- Regional accuracy based on local ecological surveys of riparian zones.
3- Accuracy using LUCAS2009 pan-European dataset.

The first approach covered the whole study area with a low density set of random sampling points. Two hundred points were randomly extracted from the continental Riparian Zones class output, with the constraints of minimum 20 km distance each other. Points were transformed in circular polygons with a 25 m diameter and imported in GoogleEarth® using KML format (*Figure 22*). An indication of model reliability was derived through supervised (visual) analysis of false positives.

Overall 72.4% of the points were assessed as correct, while 27.6% as wrong (false positives/misplaced). This quantitative value should be taken with caution, being the visual assessment partially biased by the difficulty to recognize ephemeral/small stream paths from satellite imagery when water is not a limiting factor (less discernible from background), or in presence of plain areas. For some sample points very high resolution images where not available or the visual evaluation was uncertain, hence these points were excluded from the analyses. In the 59% of the cases river network misplacement was the source of error, 35% land-cover misclassifications (CLC2000), and 6% due to other causes. Also, in this case it was observed that flat areas are generally more affected by false positives than areas with pronounced topography.

Another indication of accuracy for absence/presence of riparian zones can be derived by ecological field studies. Regional surveys of river habitats quality can provide locations and characteristics of riparian zones. In order to be used as comparable datasets for deriving reliability or accuracy measures, attention should be posed to the way these data are collected and what they represent. The datasets used are based on four different sources:

1- River Habitat Survey (RHS) data provided by Instituto Superior de Agronomia, Technical Univ. of Lisboa (Prof. M.T.Ferreira, F.Aguiar);
2- UK RHS data collected by the Environment Agency of England and Wales, the Scottish Environment Protection Agency and the Centre for Ecology and Hydrology, and non-UK data derived from a benchmarking exercise (Raven et al., 2010). Data provided by the Centre for Ecology and Hydrology (M.J. Dunbar and P. Scarlett);
3- RHS data from various institutions collected in the context of the MARCE Project (J.Barquín, Univ.Cantabria, Spain);
4- Quality of Riparian Forest data, namely QBR index (Munne et al., 2003), provided by the Freshwater Ecology and Management Research group, coordinated by Prof N.Prat (Univ.of Barcelona, Spain).

The first three datasets are composed of data collected for a number of European streams using the River Habitat Survey methodology (RHS), a method to characterize and assess in broad terms, the physical character of freshwater streams and rivers (see Raven et al., 1988). The last dataset is based on QBR ('Qualitat del Bosc de Ribera') surveys in NE Spain (Catalunya), a combined index to derive measures of riparian quality (Munne et al., 2003). The two methodologies address different issues and indicators, but they commonly share riparian environments as target for assessment. For detailed information regarding the field sampling procedures refer to the cited literature.

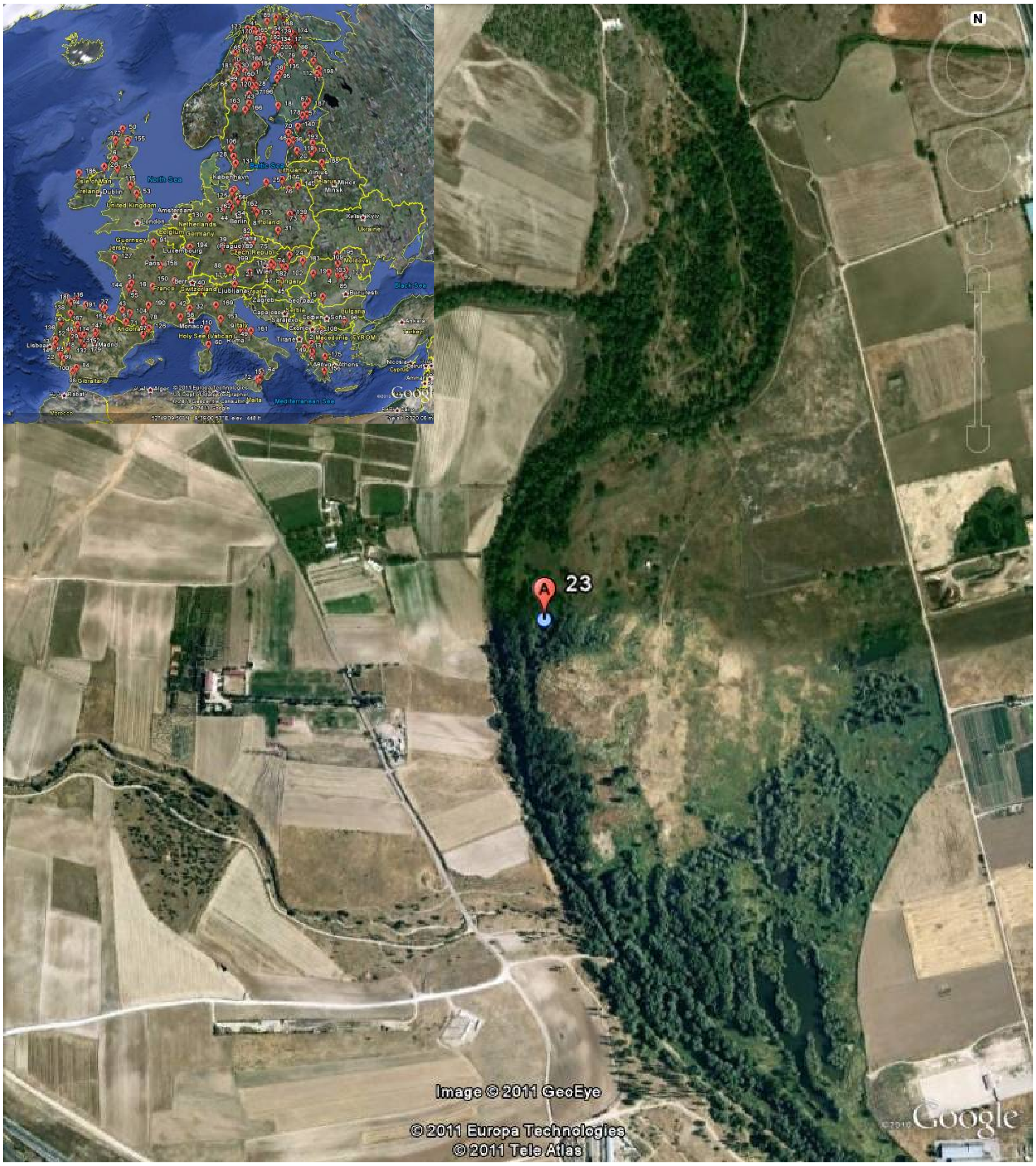


Figure 22. Randomly extracted points from the Riparian zone class imported in GoogleEarth® for visual validation.

A subset of points was extracted from the RHS and QBR databases under the condition of being related to the rivers used in this study (inclusion in a 250 m buffer of the river network used). Also, only field points in natural or semi-natural environments were considered (based on CLC2000). A bias would be otherwise introduced because the original field survey points include also riparian environments in highly disturbed areas ('non natural'), which are masked by the model. The distribution of the field points from the four ecological datasets is represented in *Figure 24*. The RHS survey makes use of 500 m sampling transects and assess both river banks, while the QBR sampling area can be approximated by a region with a length of 100 m, and variable width (25 meters for headwaters and at least 100 meters for lower courses). A common geometry representative of the riparian zone surveys should be established, being each GPS point coordinate provided just one representative location for the whole survey transect. A circular buffer with 50 m radius is finally applied to the RHS and QBR points. A match is considered when there is overlap between a pixel of the riparian zone output and the buffered field point (*Figure 23*). Summary and results of the accuracy assessment of absence/presence of riparian zone are reported in *Table 12*. Overall accuracy results equal to 84.6%, using 3067 RHS and QBR points. The satisfactory accuracy values calculated are also due to the location of the survey points, generally positioned very near to the river stream, where the riparian zone detection is less uncertain.

Table 12. Summary of accuracy values using RHS and QBR field data.

Survey Type, Source	Location	# Points	Buffer (m)	Matched points	Accuracy
RHS, UTL	Portugal	110	50	96	87.3%
RHS, MARCE	Spain	374	50	319	85.3%
RHS, EA CEH	UK, Europe	2551	50	2152	84.4%
QBR, UB	Catalunya (NE Spain)	32	50	29	90.6%
Total		3067		2596	84.6%

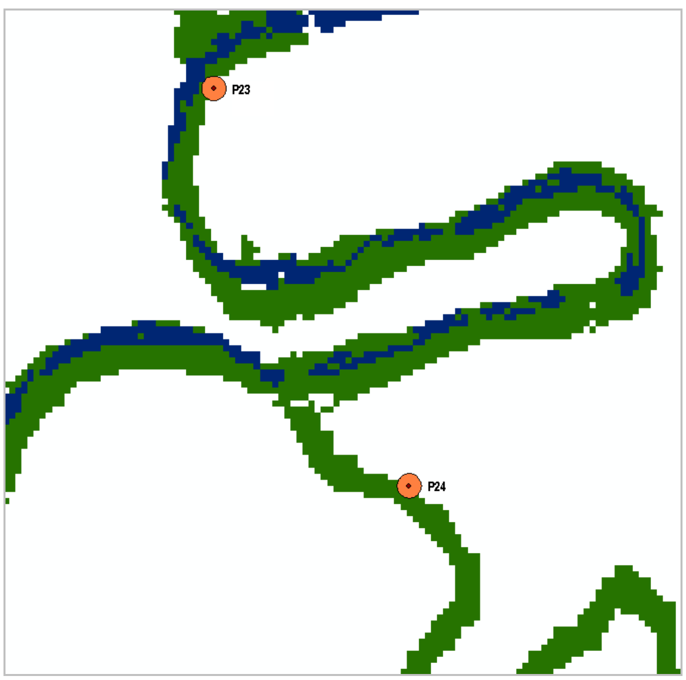


Figure 23. Example of positive match between field survey points (50 m buffer) and model output (riparian zones, in green); modelled water is depicted in blue.

A further accuracy measure was derived using Land Use/Cover Area frame Survey data (LUCAS2009). The LUCAS Project was initially developed (2001) to deliver European crop estimates for the EC. LUCAS2009 survey was carried out in the years 2008 and 2009, and it includes now over 230,000 survey points. Survey points are usually gridded in a 2 x 2 km raster. For each point Land cover, Land use and other information is recorded. For validation purposes of the riparian zones model, the *Floodplain Forests* class (C*x*C, namely C1C, C2C or C3C depending on forest type) was extracted, being recorded at 363 sites in 23 Countries (EU27 excluding Malta, Cyprus, Bulgaria and Romania). The class is defined as: "*Alluvial and riparian woodlands and galleries close to main European river channels. These are species-rich often multi-layered communities characterised by different assemblages of forest dominant trees. Forest composition and structure largely* *depends on the frequency of flooding. […] Included are those forest communities typically associated with alluvial or riparian woodlands that may constitute locally important forest types...*" (Eurostat, 2009).

Similarly to the procedure used for RHS and QBR data, Floodplain forests points were selected if falling inside the 250 m buffer around the river network used by the model and within CLC2000 natural or semi-natural classes. After this operation, 111 points were available (*Figure 24*). Also in this case a buffer of 50 m was applied to each field point to account for the survey extension. Point buffers were then overlaid to the modelled riparian zones. Accuracy using LUCAS2009 data resulted equal to 81.1 %.

Table 13. Accuracy value using LUCAS2009 field data.

Survey Data	Location	# Points	Buffer (m)	Matched points	%Accuracy
LUCAS2009	Europe	111	50	90	81.1%

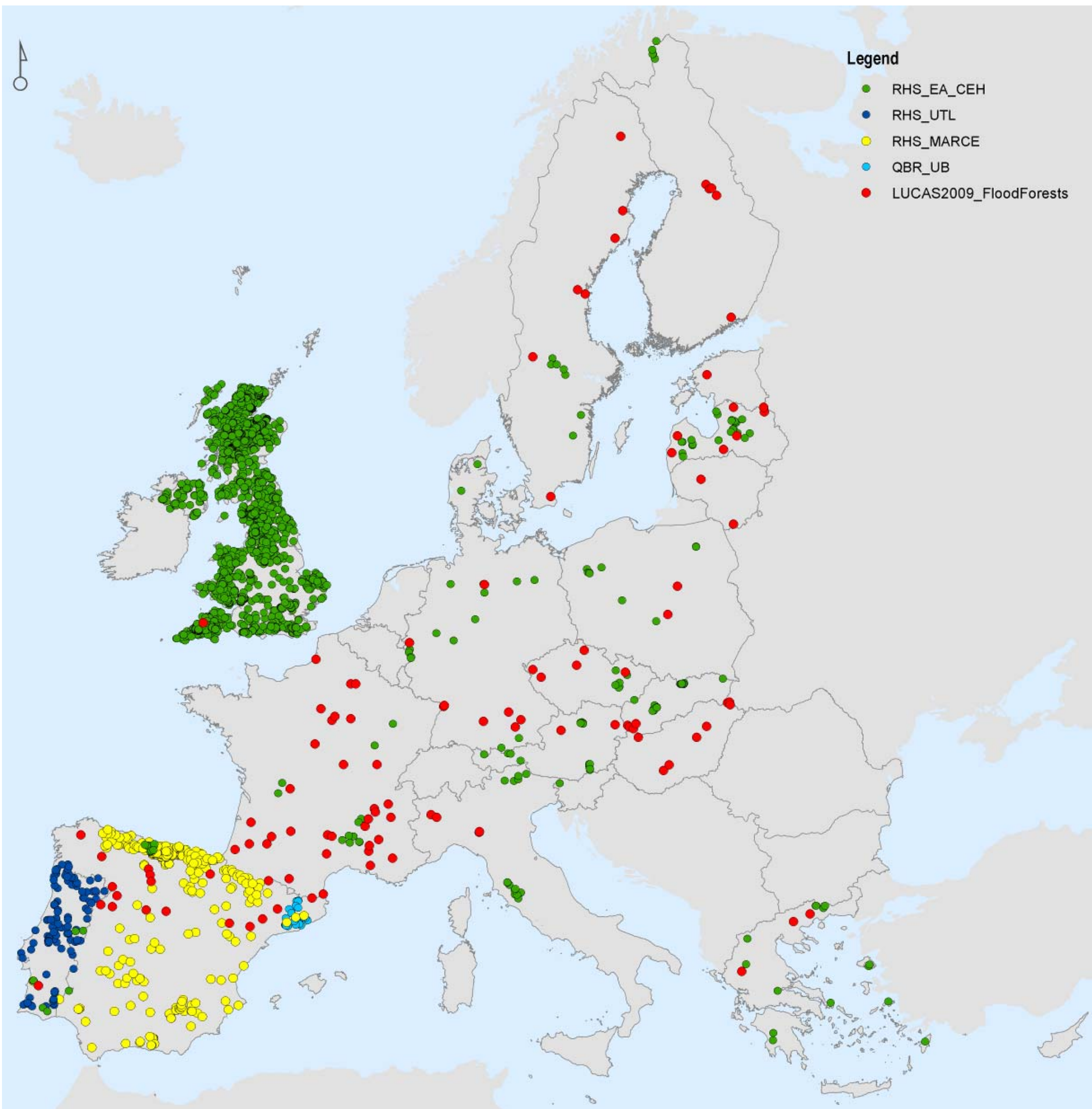


Figure 24. Distribution of RHS,QBR and LUCAS2009 points used in the accuracy assessment.

Potential developments and improvements

The present modelling approach was developed also in relation to the information and datasets fully available at European continental level. Even if counteracted in many cases by the use of the Calibrated Path Distance, the scale of the CCM river network (built on a 100 m DEM), implicitly produced misplacements in river path estimation, not being designed originally for precise river delineation. It is straightforward that the availability of a higher resolution river network dataset with 2D information (e.g. river width) would have considerably lowered this main source of errors. For future modelling and monitoring of riparian environments and freshwater ecosystems, we stress the importance of producing such a river dataset at European level.

In the model we assume that agricultural classes cannot host fully functional riparian zones due to the ecological alterations produced by productive activities. This assumption, necessary to mask vegetated non natural classes (e.g. cropfields) is not always valid. In some cases pastures or heterogeneous agricultural areas can potentially be characterized by patches of natural habitats or small regions with high ecological integrity. A further development of the model could also take into account a degree of *naturalness* (Machado, 2004) of land-cover classes, to generate a more complex riparian zone aggregated index.

In addition, we believe that the use of local calibration values for the Path Distance index can potentially improve model reliability, in order to reflect regional and local landscape variations and rivers morphology.

4 Conclusions

A new riparian zonation model based on satellite remote sensing data is proposed. The model makes use of spectral, land-use and topographic information to derive riparian zones at 25 m resolution for continental Europe based on a fuzzy approach. The zonation model is not designed as a high-precision mapping tool for local scale analysis, but to provide the first picture of riparian zone distribution patterns for Europe at continental scale. This information will provide the basis to further characterize these environments, which are key components of the European Green Infrastructure. Presence and distribution of riparian zone clusters would provide the necessary information to assess a series of landscape indicators (e.g. connectivity, etc) at European scale and to derive the location of key riparian patches to support biodiversity conservation programs.

Based on model results, about 2% of continental Europe is detected as riparian. High density of riparian zones is found in mountainous areas, where the dense hydrographic network and extended natural habitats create the conditions for riparian abundance. In plain areas the presence of agricultural areas is the main cause of riparian zone low density and high fragmentation. A first characterization, based on CLC2000 data, shows that a large part of European riparian zones (around 70%) is associated to forested habitat, while to a minor extent to other vegetation life forms. This result is important as it provides location and a quantitative indication of forested habitats in Europe which also have an ecological significance as riparian zones.

The three strategies used to achieve reliability indications and accuracy of the model (input data accuracy, qualitative observation using VHR imagery, and independent ecological datasets) produced satisfactory results. Accuracy calculated using 3067 ecological survey points produced an overall value of 84.6%, although being highly variable at regional level. The main sources of error are produced by river path misplacements (especially in plain and coastal areas), and by the generalization process used to build the CLC2000 dataset. Lower accuracy levels of input datasets in northern European countries, have increased riparian detection inaccuracy in the same regions.

This study allowed the identification of some main gaps and weaknesses present in European spatial datasets of continental extent, hindering the achievement of higher accuracy values in riparian zones modelling. We stress the importance of developing in the near future a European 2D river network dataset at high resolution for the investigation of riparian zones and freshwater ecosystems.

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References

Annoni, A. (Ed.), 2005. European Reference Grids. EUR 21494 EN, European Commission, Joint Research Centre.

ASTER GDEM VALIDATION TEAM, 2009. *ASTER global DEM validation Summary 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

Baldock D, Beaufoy G, Bennett G, Clark J., 1993. Nature conservation and new directions in the EC Common Agricultural Policy. IEEP, London, UK.

Baraldi, A., Durieux, L., Simonetti, D., Conchedda, G., Holecz, F., Blonda, P. , 2010a. Automatic Spectral-Rule-Based Preliminary Classification of Radiometrically Calibrated SPOT-4/-5/IRS, AVHRR/MSG, AATSR, IKONOS/QuickBird/OrbView/GeoEye, and DMC/SPOT-1/-2 Imagery; Part I: System Design and Implementation. *IEEE Transactions on Geoscience and Remote Sensing*, 48, 1299-1325.

Baraldi, A., Durieux, L., Simonetti, D., Conchedda, G., Holecz, F., Blonda, P., 2010b. Automatic Spectral Rule-Based Preliminary Classification of Radiometrically Calibrated SPOT-4/-5/IRS, AVHRR/MSG, AATSR, IKONOS/QuickBird/OrbView/GeoEye, and DMC/SPOT-1/-2 Imagery; Part II: Classification Accuracy Assessment. *IEEE Transactions on Geoscience and Remote Sensing*, 48, 1326-1354.

Baraldi, A., Puzzolo, V., Blonda, P., Bruzzone, L., and Tarantino, C., 2006. Automatic Spectral Rule-Based Preliminary Mapping of Calibrated Landsat TM and ETM+ Images. *IEEE Transactions on Geoscience and Remote Sensing, 44*, 2563-2586.

Bedford, B.C. 1999. Patterns in nutrient availability and plant diversity of temperate North American wetlands. *Ecology* 80: 2151-2162.

Benedict, M.A., McMahon, E.T., 2006. Green Infrastructure: Linking landscapes and Communities, Washington, Island Press.

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

Bilby, R.E., Bisson, P.A., 1992. Allochthonous versus autochthonous organic matter contributions to the trophic support of fish populations in clear-cut and old growth forested streams. *Canadian Journal of Fisheries and Aquatic Sciences* 49, 540–551.

Bossard M., Feranec, J., Otahel, J., 2000. Technical report no. 40. CORINE land cover technical guide. Addendum 2000. European Environment Agency.

Collins, J.N., Sutula, M., Stein,E., Odaya, M., Zhang, E., Larned, K., 2006. Comparison of methods to map California riparian areas. 2006. Technical Report 502 prepared for the California Riparian Habitat Joint Venture. Contribution No. 522. San Francisco Estuary Institute. San Francisco, CA.

Dall, D., Elliott, C. and Peters, D., 1998. *A system for mapping riparian areas in the western United States*. USDI Fish and Wildlife Service, National Wetlands Inventory, Lakewood, CO, 15 pp.

Daniels, R.B., Gilliam, J.W., 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal, 60 (1), pp. 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 Ecology and Management.* Volume 143, Issues 1-3, Pages 95-104, ISSN 0378-1127.

De Roo, A. P. J., Wesseling, C.G., Van Deurzen, W.P.A., 2000. Physically based river basin modelling within a GIS: The LISFLOOD model. *Hydrological Processes*, 14, 1981 – 1992.

Degraaf, R.M. , Yamasaki, M. 2000. Bird and Mammal Habitat in Riparian Areas. Chpt.8. In *Riparian management in forests of the continental eastern United States*. Edited by E.S. Verry, J.W. Hornbeck, and A. Dolloff.Lewis Publishers, Boca Raton, Florida. pp. 139-156.

DG ENV -Directorate General Environment of the European Commission, 2009. Towards Green Infrastructure for Europe, Proceedings of EC workshop 25-26 March 2009, Brussels, Belgium. Edited by Sundseth, K. and Silwester, A. Downloadable at: http://green-infrastructure-europe.org/

EEA -European Environment Agency-, 2010. Corine Land Cover 2000 seamless vector data (Publish date: 27 May 2010).URL: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-seamless-vector-database-2

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. ISBN 92-9167-844-9. URL: http://www.eea.europa.eu/publications/technical_report_2006_7

Eurostat, 2005. LUCAS 2005 (Land use/Cover Area Frame Survey) Technical Reference Document C-3: Nomenclature. Statistical Office of the European Communities, Luxembourg.

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. Forest Ecology, in: Levin, S.A., ed. *Encyclopedia of Biodiversity*, Elsevier, NY, 2001. Pages 41-51, ISBN 978-0-12-226865-6, DOI: 10.1016/B0-12-226865-2/00127-9.

Farr, T. G., et al., 2007. The Shuttle Radar Topography Mission, *Review of Geophysics*, VOL.45, RG2004, 33, pp. doi:10.1029/2005RG000183.

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. *Journal of Hydrology* 332(1):276–289

Forman, R. T. T., 1995. *Land Mosaics: The Ecology of Landscapes and Regions*. Cambridge University Press, Cambridge. 632 pages.

France, R., Culbert, H., Peters, R., 1996. Decreased carbon and nutrient input to boreal lakes from particulate organic matter following riparian clear-cutting. *Environmental Management* 20, 579–583.

Franklin, S., Wulder, M., 2002. Remote sensing methods in medium spatial resolution satellite data land cover classification of large areas. *Progress in Physical Geography*. 26:2 p. 173-205.

Gilles, C.S., Cassady St. Clair, C.2008. Riparian corridors enhance movement of a forest specialist bird in fragmented tropical forest . *PNAS* 2008 105 (50) 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., Wright, R.K., Smith, A.J., Zinecker, E., Schaub, E., 2003. IKONOS imagery for resource management: Tree cover, impervious surfaces, and riparian buffer analyses in the mid-Atlantic region. *Remote Sensing of Environment*, 88 (1-2), pp. 195-208.

GoogleEarth, 2011. Web. Accessed 15 Feb 2011, <http://earth.google.com/>.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective on riparian zones focus on links between land and water. *Bioscience* 41:540-551.

Haan, C.T., Barfield, B.J., Hayes, J.C., 1994. *Design Hydrology and Sedimentology for Small Catchments*, Academic Press, San Diego, CA. 588 pp.

Hagan, J.M., Pealer, S., Whitman, A.A. 2006. Do small headwater streams have a riparian zone defined by plant communities? *Canadian Journal of Forest Research* 36: 2131–2140.

Harmon, M.E., Franklin F.J., Swanson P., Sollins S.V., Gregory J.D., Lattin N.H., Anderson S.P., Cline N.G., Aumen et al. 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* 15, 133-302.

Haycock, N.E., Pinay, G., 1993. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during the winter. *Journal of Environmental Quality*, 22 (2), pp. 273-278.

Hill, M.O., Roy, D.B., Thompson, K., 2002. Hemeroby, urbanity and ruderality: bioindicators of disturbance and human impact. *Journal of Applied Ecology* 39 (5): 708-720. Wiley. doi:10.1046/j.1365-2664.2002.00746.x

Hong, S.K., 2007. Linking Man and Nature Landscape Systems, Landscaping blue-green network, in Hong, S.K., Nakagoshi, N., Fu, B., Morimoto, Y. (Eds.), *Landscape Ecological Applications in Man-Influenced Areas*. 2007. Pag. 505-523. Springer Netherlands. Doi: 10.1007/1-4020-5488-2_30.

Hunter, M.L. Jr., 1990. *Wildlife, forests, and forestry: Principles of managing forests for biological diversity*. Prentice-Hall, Englewood Cliffs, NJ. 370pp.

Ilhardt, B.L., Verry, E.S., and B.J. Palik, 2000. Defining Riparian Areas. In Verry, E.S., Hornbeck, J.W., and C.A. Dolloff (editors) *Riparian Management in Forests of the Continental Eastern United States*, Lewis Publishers, Baca Raton, Chapter 2, p 34.

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. *Ecological Indicators*, 9 (3),pp.422-431.

Jacobs, T.C., Gilliam, J.W., 1985. Riparian losses of nitrate from agricultural drainage waters. *Journal of Environmental Quality*, 14 (4), pp. 472-478.

Johnson,R. R.,Carothers, S.W., Simpson,J.M., 1984. A riparian classification system. In: R. E. Warner and K. M. Hendrix (eds.), *California riparian systems*. Univ. of California Press. Berkeley, CA. pp. 375-382.

Hayakawa, Y. S., Oguchi, T., and Lin, Z., 2008. Comparison of new and existing global digital elevation models: ASTER G-DEM and SRTM-3. *Geophysical Research Letters*, *35*(17), 1-5.

Kempeneers, P., Sedano, F., Seebach, L., San Miguel Ayanz, J., 2010. A high resolution PAN-European forest type map based on multispectral and multi-temporal remote sensing data. Proceedings of ForestSat2010 Conference: Operational Tools in Forestry using Remote Sensing Techniques. 7-10 Semptember 2010, Lugo y Santiago de Compostela, Spain.

Ledoux, L., Crooks, S., Jordan, A., Turner,K., 2000. Implementing EU biodiversity policy UK experiences, *Land Use Policy*, 17(4): 257–268. Springer.

Lowrance, R., L.S. Altier, J.D. Newbold, R.R. Schnabel, P.M. Groffman,and J.M. Denver, 1997. Water Quality Functions of Riparian Forest Buffer Systems in the Chesapeake Bay Watershed. *Environmental Management*, 21:687-712.

Lowrance, R. R., R. Leonard, and J. Sheridan. 1985. Managing riparian ecosystems to control nonpoint pollution. *J. Soil Water Conserv*. 40:87–91.

Machado, A., 2004. An index of naturalness. *Journal for Nature Conservation*, Volume 12, Issue 2, 22 October 2004, Pages 95-110.

Machtans,C.S., Villard,M.A., Hannon,S.J. 1996. Use of riparian buffer strips as movement corridors by forest birds. *Conservation Biology*, 10 (5), pp. 1366-1379.

Magette, W.L., Brinsfield, R.B., Palmer RE, Wood., J.D., 1989. Nutrient and sediment removal by vegetated filter strips. *Transactions of the American Society of Agricultural Engineers* 32: 663–667.

Mackaness, W.A., Ruas, A., Sarjakoski, L.T. (Eds), 2007. *Generalisation of Geographic Information. Cartographic Modelling and Applications*. Elsevier.

Martin, T. G., S. McIntyre, C. P. Catterall and H. P. Possingham, 2006. Is Landscape Context Important for Riparian Conservation? Birds in Grassy Woodland. *Biological Conservation* 127:201-214.

Millennium Ecosystem Assessment, 2005. *Ecosystems and HumanWell-being: Synthesis.* Island Press, Washington.

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 Research and Applications* 21: 403–420. DOI: 10.1002/rra.815.

Müller,E., 1997. Mapping riparian vegetation along rivers: old concepts and new methods, *Aquatic Botany* 58, p. 437.

Munne, A., Prat, N., Sola, C., Bonada, N., Rieradevall, M. 2003. A simple field meted for assessing the ecological quality of riparian habitats in rivers and streams: QBR index. *Aquatic conservation: Marine and Freshwater Ecosystems*, 13:147-163.

Naiman, R.J., *and* Décamps, H., 1990. *The ecology and Management of Aquatic-Terrestrial Ecotones.* Man and Biosphere. Series - volume 4. UNESCO Paris :; Park Ridge, N.J., USA : Parthenon Pub. Group, 1990. xvi, 316 p. : ill. ; 24 cm.; ISBN: 0929858255 (Parthenon).

Naiman, R.J., H. Dé camps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212.

Naiman, R.J., and H. Decamps. 1997. The ecology of interfaces - riparian zones. Annual Review of Ecology and Systematics 28:621-658.

Naiman, R., Decamps, H., McClain,M., 2005. *Riparia - Ecology, Conservation, and Management of Streamside Communities*. Academic Press, 448 pp. ISBN 9780126633153.

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; xii + 428 pp., ISBN 0 309 08295 1, Washington, DC, USA: National Academy Press.

Nunes de Lima,M.V., 2005. IMAGE2000 and CLC2000: Products and Methods. European Commission, Joint Research Centre, 2005, vol.EUR 21757 EN.

Paracchini M.L., J.-E.Petersen, Y.Hoogeveen, C.Bamps, I.Burfield, C.van Swaay, 2008. High Nature Value Farmland in Europe - An estimate of the distribution patterns on the basis of land cover and biodiversity data, Report EUR 23480 EN. 87 p.

Palik, B.J., Tang, S.M., Chavez , Q., 2004. Estimating riparian area extent and land use in the Midwest. Gen.Tech.Rep. NC-248. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 28 p.

Pekkarinen, A., Reithmaier, L. and Strobl, P. 2009. Pan-European forest/non-forest mapping with Landsat ETM+ and CORINE Land Cover 2000 data. ISPRS Journal of Photogrammetry and Remote Sensing 64: 171-183.

Perkins, D.W., Hunter, M.L., Jr. 2006. Use of amphibians to define riparian zones of headwater streams. Canadian Journal of Forest Research. 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 (5), pp. 1466-1475.

Pistocchi, A., Pennington, D., 2006. European hydraulic geometries for continental scale environmental modelling . *Journal of Hydrology* 329, 553– 567.

Prenda, J., Granado-Lorencio, C. The relative influence of riparian habitat structure and fish availability on otter *Lutra lutra* L. sprainting activity in a small Mediterranean catchment, *Biological Conservation*, Volume 76, Issue 1, 1996, Pages 9-15, ISSN 0006-3207.

Prichard, D., H. Barrett, J. Cagney, R. Clark, J. Fogg, K. Gebhart, P.L. Hansen, B. Mitchell, and D. Tippy. 1993. *Riparian area management: Process for assessing proper functioning condition*. TR 1737-9 (Revised 1998). U.S. Department of the Interior , Bureau of Land Management—Service Center BLM/SC/ST-93/003+1737+REV95+REV98, CO. 51 pp.

Raven, P. J., Holmes, N. T., Vaughan, I. P., Dawson, F. H., Scarlett, P., 2010. Benchmarking habitat quality: observations using River Habitat Survey on near-natural streams and rivers in northern and western Europe. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 20: S13–S30. doi: 10.1002/aqc.1103.

Raven P.J., Holmes N.T.H., Dawson F.H., Everard M., 1998. Quality assessment using River Habitat Survey data. *Aquatic Conservation - Marine and Freshwater Ecosystems,* 8: 477-499.

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. *International Geoscience and Remote Sensing Symposium* (IGARSS), 5, art.: 5417688, pp. V240-V243.

Sawyer, J.A., Stewart, P.M. , Mullen, M.M., Simon, T.P., Bennett, H.H., 2004. Influence of Habitat, Water Quality, and Land use on Macro-Invertebrate and Fish Assemblages of a Southeastern Coastal Plain Watershed, USA. *Aquatic Ecosystem Health and Management* 7(1):85-99.

Sedell, J.R., Reeves, G.H., Hauser, F.R., Stanford, J.A., Hawkins, C.P., 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. *Environmental Management* 14, 711–724.

Simberloff,D., 1999. The role of science in the preservation of forest biodiversity, *Forest Ecology and Management*, Volume 115, Issues 2-3, 22 March 1999, Pages 101-111.

Snyder, C.D., J.A. Young, and R. Villella. 2003. Influences of upland and riparian land use patterns on stream biotic integrity. Landscape Ecology 18:647–64.

Soille, P., 2003. Morphological Image analysis. Principles and applications. 2nd Edition, Springer, NY, pp.391.

Soille, P., Vogt J.V., Colombo , R., 2003. Carving and Adaptive Drainage Enforcement of Grid Digital Elevation Models. Water Resources Research, 39(12):1366-1378.

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.

Thorndycraft, V.R., Benito, G., Gregory,K.J., 2008. Fluvial geomorphology: A perspective on current status and methods, *Geomorphology*, Volume 98: 1-2, The Geomorphological and Palaeohydrological Response of Fluvial Systems to Climatic, Human and Tectonic Controls, 1 June 2008, Pages 2-12, ISSN 0169-555X, DOI: 10.1016/j.geomorph.2007.02.023.

Tucker, C.J., Grant, D.M., Dykstra, J.D., 2004. NASA's global orthorectified Landsat data set. *Photogrammetric Engineering and Remote Sensing* 70 (3), 313-322.

USDA FS (US Department of Agriculture Forest Service), 1994. Watershed Protection and Management, Forest Service Manual Chapter 2520, WO Amendment 2500, 94-3, 26 pp.

US EPA. 1993. Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. EPA Report No. 840-B-92-002.

US FandWS (US Fish and Wildlife Service), 2004. National Standards and Quality Components For Wetlands, Deepwater and Related Habitat Mapping. U.S. Fish and Wildlife Service, Division of Habitat and Resource Conservation, Branch of Habitat Assessment, Arlington, VA. 18 pp.
Verry, E.S., Hornbeck, J.W., Dolloff, C.A., eds. 2000. *Riparian management in forests of the continental eastern United States*. Lewis Publishers, CRC Press, Boca Raton, FL. 432 pp.

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. *International Journal of Geographical Information Science*, 24:2, 189 - 212.

Verry, E.S., Dolloff, C.A., Manning, M.E., 2004. Riparian ecotone: A functional definition and delineation for resource assessment. *Water, Air, and Soil Pollution: Focus*, 4 (1), pp. 67-94.

Vogt, J.V., P. Soille, A.L. de Jager, E. Rimaviciute, W. Mehl .2007a. A pan-European River and Catchment Database , EUR Report, , 124, ISBN 22920 EN, , JRC Report, Luxembourg.

Vogt, J.V., P. Soille, A.L. de Jager, E. Rimaviciute, W. Mehl, P. Haastrup, M.L. Paracchini, 2007b. Developing a pan-European Data Base of Drainage Networks and Catchment Boundaries from a 100 Metre DEM. *Proceedings 10th AGILE International Conference on Geographic Information Science*, 8-11 May 2007, Aalborg, Denmark, 10p.

Vogt, J.V., R. Colombo, M.L. Paracchini, A.L. de Jager, P. Soille, 2003. *CCM River and Catchment Database*, Version 1.0 , EUR Report, , 1-32, ISBN 20756. EN,JRC Report, Luxembourg.

Whitaker, D.M., Carroll, A.L., and Montevecchi, W.A. 2000. Elevated numbers of flying insects and insectivorous birds in riparian buffer strips. *Canadian Journal of Zoology* 78: 740-747.

Woodley, S., Kay, J., Francis, G. , Eds. 1993. Ecological Integrity and the Management of Ecosystems. Boca Raton, FL: St. Lucie Press.

Zadeh, L.A. , 1965. Fuzzy sets. Information and Control 8 (3): 338–353. doi:10.1016/S0019-9958(65)90241-X. ISSN 0019-9958.

Zimmermann, H., 2001. Fuzzy set theory and its applications. Boston: Kluwer Academic Publishers. ISBN 0-7923-7435-5.

Zimmermann, H.J., Zadeh, L.A., Gaines, A.R. (editors). 1984. *Fuzzy Sets and Decision Analysis*. North Holland, New York.

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Annex 1

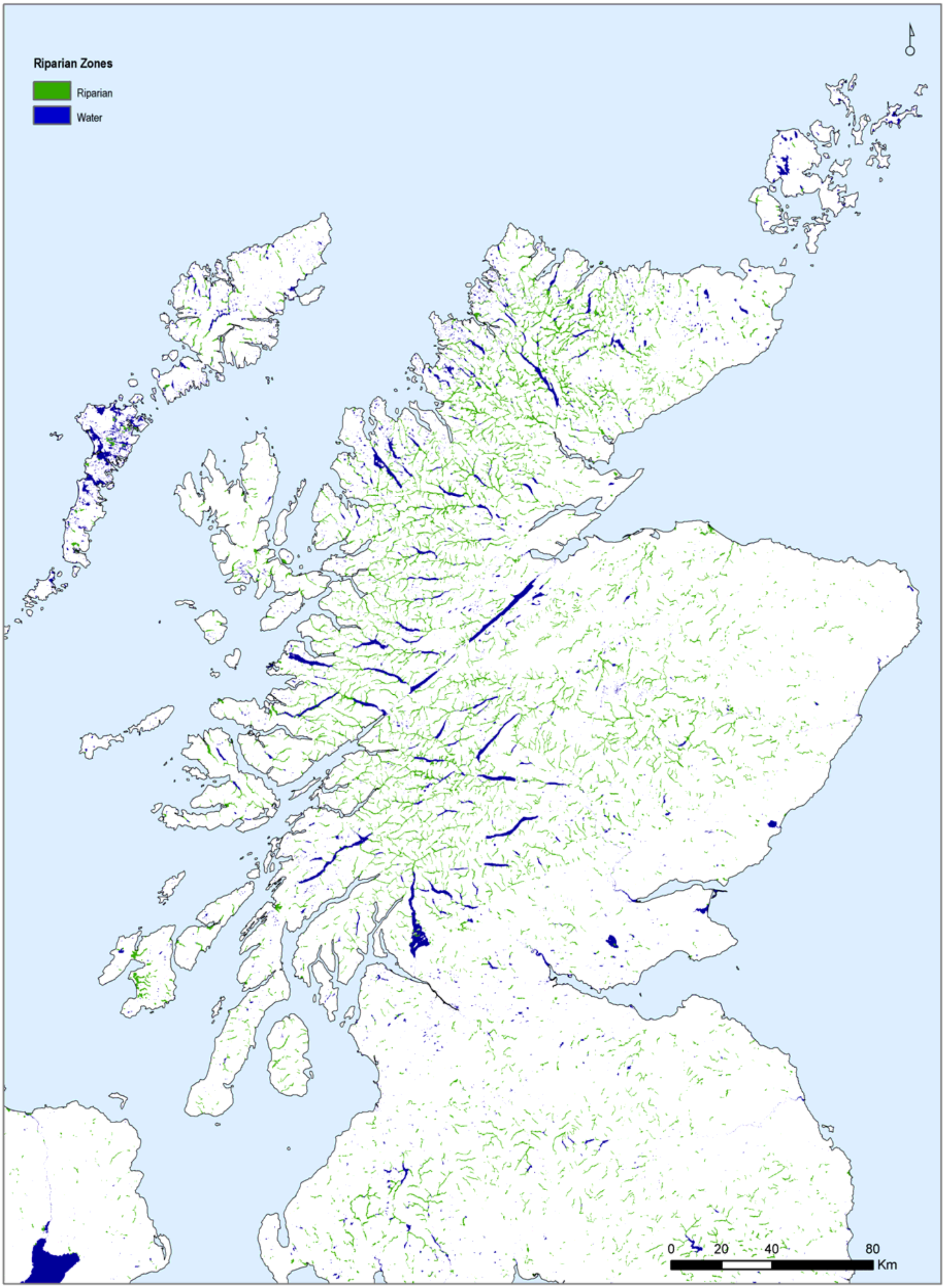

Figure A1. Riparian zones model output in Scotland (25 m spatial resolution).

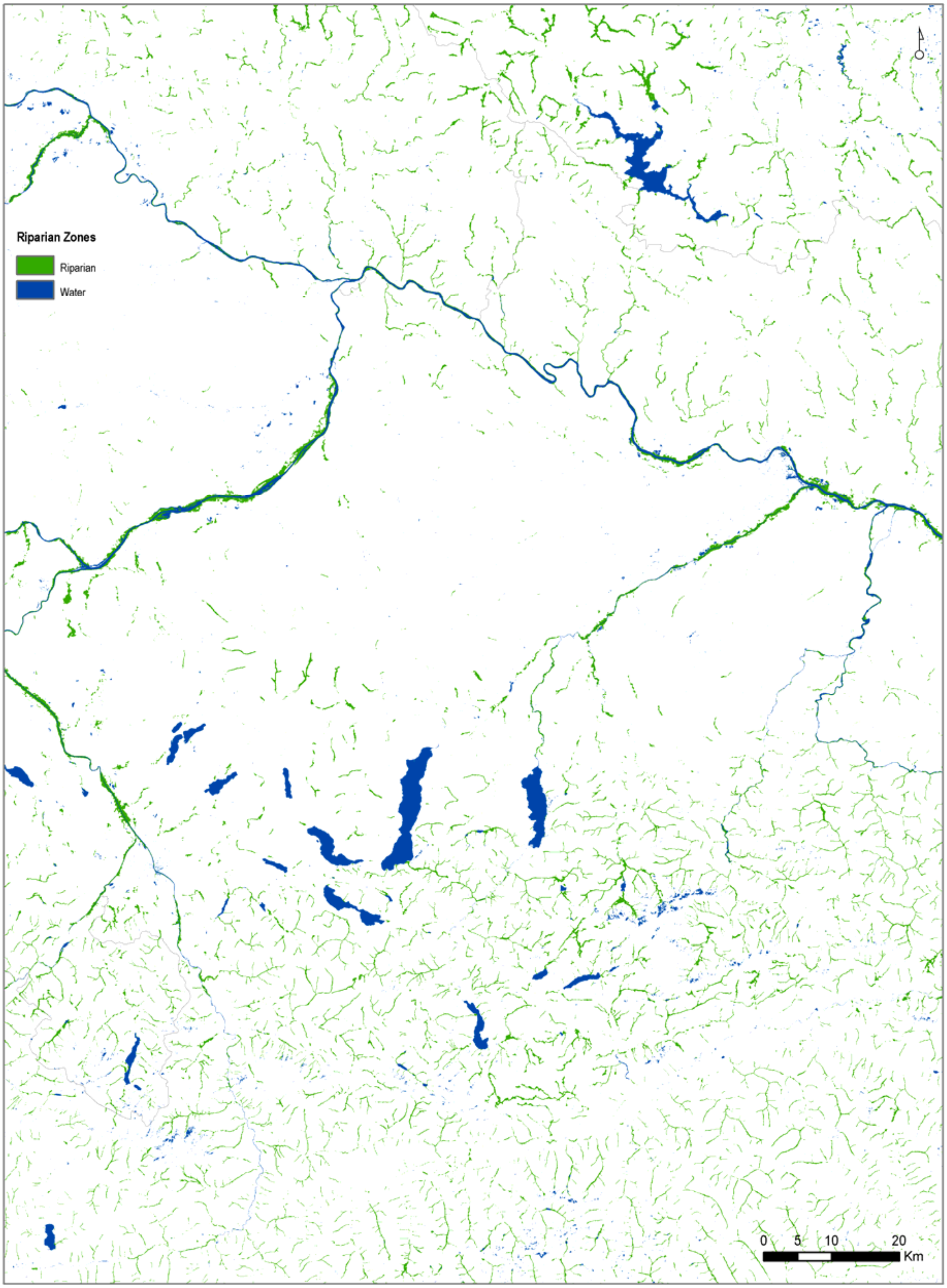

Figure A2. Riparian zones model output near Linz (Austria), Danube river (25 m spatial resolution).

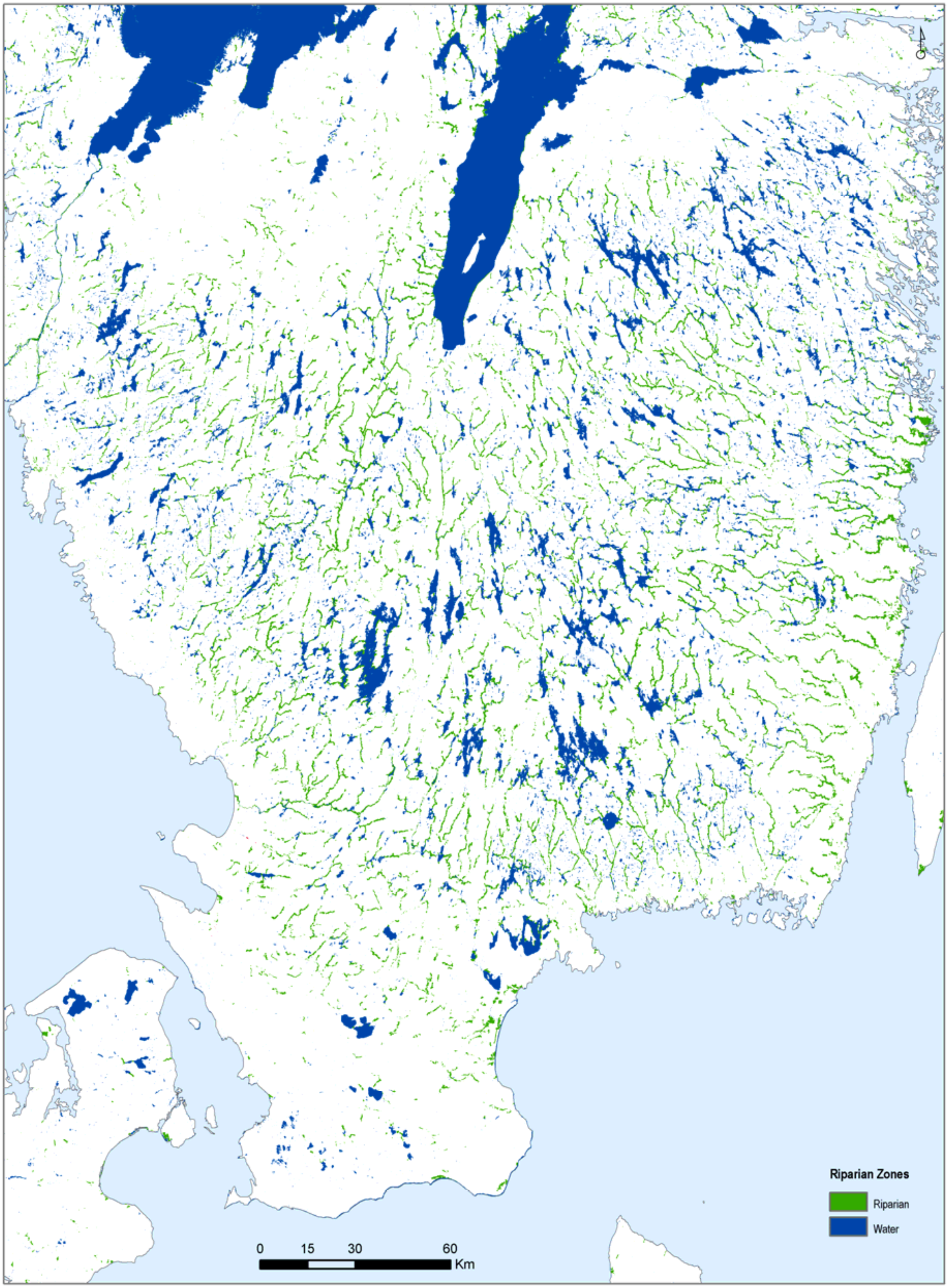

Figure A3. Riparian zones model output in Southern Sweden (25 m spatial resolution).

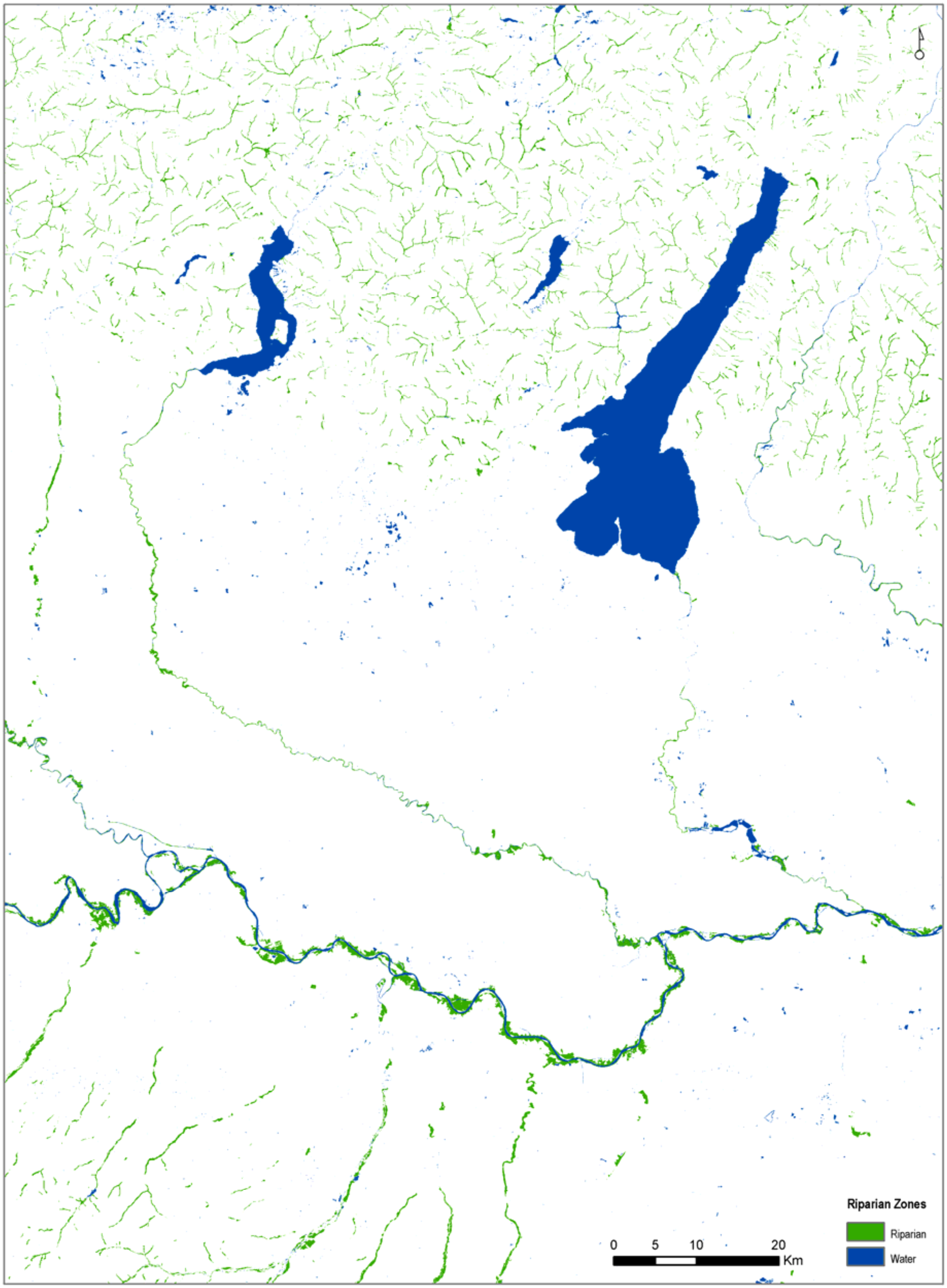

Figure A4. Riparian zones model output in Northern Italy (25 m spatial resolution).

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Abstract
This Technical Report presents a new riparian zonation model for Europe based on satellite remote sensing and GIS techniques. Riparian zones are key ecological systems that provide a wide array of ecosystem services to society and the natural environment, as well as being fundamental structural elements of the European Green Infrastructure. The zonation model is based on a multi-layer approach, which takes into account a series of descriptive attributes and assigns a degree of belonging to the riparian zone class based on fuzzy membership scores. Model output has a 25 m spatial resolution and follows INSPIRE standards. A short characterization of model output is also proposed, together with a detailed assessment of accuracy. Information about riparian zone distribution will provide the basis for comprehensive characterization and ecological analysis at European scale, such as the identification of key riparian zones maintaining landscape connectivity, the evaluation of targeted riparian ecosystem services and monitoring of change at continental scale.

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