

Landscape Metrics Integrated in Hydraulic Modeling for River Restoration Planning

*Original*

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# Environmental Modeling & Assessment

## Landscape metrics integrated in hydraulic modeling for river restoration planning

--Manuscript Draft--

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<b>Abstract:</b>	<p>Engineers have shaped the environment across the centuries in order to improve the quality and safety of human life. The unrestrained invasion of nature led to significant environmental problems, for this reason nowadays engineering projects should be based on ecological concepts to protect our environment. This paper presents an integrated methodology that involves GIS tools, hydraulic numerical models and landscape metrics to investigate ecological consequences caused by river restoration activities. The combined use of these different tools represents a bridge to connect the field of engineering with ecological techniques. The proposed method was tested to predict and assess the influence of a river restoration plan on a reach of the Orco river located in the north-west of Italy. Morphological alterations were simulated to reconnect remnant meanders and provide water to the floodplain, enhancing the ecological value of riparian ecosystems. The application of the hydraulic model permitted to evaluate the distribution of water inside the study area before and after the restoration plan. Thereafter, spatial configuration and temporal dynamics of the landscape structures were quantified using landscape metrics. The increase of patch density (PD) by 9% and edge density (ED) up to 10% highlights that restoration activities lead to a new configuration characterized by a higher level of fragmentation and heterogeneity. The characteristics of versatility, repeatability and the possibility to predict the outcomes of a specific plan make the proposed method a useful tool that could help decision-makers to manage the territory while safeguarding natural ecosystems.</p>
<b>Response to Reviewers:</b>	<p>The present letter reports feedback given by the advisory editor and the replies of the authors.</p> <p>The advisory editor's comments are written in black and the author's replies are written in blue.</p> <p>I would like to thank the advisory editor for further precious feedback. The revised version of the draft follows and replies all comments.</p> <p>Advisory Editor's Comments:</p>

Dear authors,

Thank you for submitting the revised version of your manuscript. You have processed all comments of the reviewer and me. I particularly like the sections you added to the discussion about the expected impact of the changes on animal. Good job.

I now consider your manuscript ready for publication, on the condition that you perform the following seven format/layout changes:

1. All variables in all equations need to be defined and (shortly) described below the equation. Please do this for the variables in equation 1.

The description of variables has been added. To avoid a repetition, the last section "Notation has been removed.

2. In our journal, each displayed mathematical expression needs to be treated as part of an English sentence and end in a comma if the sentence continues (e.g., as in (1)), or in a period if the sentence stops (e.g., as in (2)).

The authors may wish to use the following manuscript as an example of good and consistent formatting of mathematical expressions:

The Strategic Impact of Adaptation in a Transboundary Pollution Dynamic Game B Vardar, G Zaccour *Environmental Modeling & Assessment* 23 (6), 653-669.  
Punctuation has been added.

3. The legends of the meshes and graphs in Figure 3 are too small; please enlarge them.

The image has been improved.

4. Line 224: Please change "the previous image" to "Fig. 6", as images might be placed in a different part of the article in the typesetted version.

The sentence has been modified.

5. In my opinion, the current Fig. 6 fits better between Fig. 4 and Fig. 5, as Fig. 6 displays the current flow regimes, and Fig. 5 the impacts of this regime on the channel activation for the two scenarios.

The Fig. 6 has been moved before the actual Fig 5, inverting the order of images.

6. Please provide the full names of the landscape metrics in the caption of Table 3, such that the table is understandable in isolation.

Full names of metrics have been added.

7. Line 286: Please only use the word significant if you actually performed a significance test.

The word "significant" has been substituted.

16 January 2020

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To

Environmental Modeling & Assessment

Dear editors,

I am writing this letter in support to the submission of the last version of my research paper.

The present paper represents the revised version of the manuscript ENMO-D-19-00190R1.

During the submission process, I have also uploaded a file reporting a detailed point-by-point reply to the advisory editor's comments (Decision letter- author's replies).

Sincerely,

Paolo Tamagnone

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## Title

Landscape metrics integrated in hydraulic modeling for river restoration planning

## Abstract

Engineers have shaped the environment across the centuries in order to improve the quality and safety of human life. The unrestrained invasion of nature led to significant environmental problems, for this reason nowadays engineering projects should be based on ecological concepts to protect our environment. This paper presents an integrated methodology that involves GIS tools, hydraulic numerical models and landscape metrics to investigate ecological consequences caused by river restoration activities. The combined use of these different tools represents a bridge to connect the field of engineering with ecological techniques. The proposed method was tested to predict and assess the influence of a river restoration plan on a reach of the Orco river located in the north-west of Italy. Morphological alterations were simulated to reconnect remnant meanders and provide water to the floodplain, enhancing the ecological value of riparian ecosystems. The application of the hydraulic model permitted to evaluate the distribution of water inside the study area before and after the restoration plan. Thereafter, spatial configuration and temporal dynamics of the landscape structures were quantified using landscape metrics. The increase of patch density (PD) by 9% and edge density (ED) up to 10% highlights that restoration activities lead to a new configuration characterized by a higher level of fragmentation and heterogeneity. The characteristics of versatility, repeatability and the possibility to predict the outcomes of a specific plan make the proposed method a useful tool that could help decision-makers to manage the territory while safeguarding natural ecosystems.

## Keywords

landscape metrics; hydraulic numerical modeling; river restoration; riverine environment; landscape management

# 1. Introduction

Nowadays there is a deeper sensibility toward natural spaces after many years of uncontrolled use of the territory. Anthropogenic disturbances have altered landscape structure and its ecological processes [1]. In this framework, ecologists and engineers have strived to conserve, defend and restore the “green” part of our planet.

Focusing on riverine environments, different disciplines were born in past decades trying to connect the world of hydraulics with ecological concepts such as the eco-hydraulics [2–4] and hydro-ecology [5]. Much effort has been devoted to the research of effective actions with the purpose to restore disturbed ecosystems and natural landscapes [6]. To successfully accomplish restoration techniques, it is important to understand the correlation between ecological features, physical factors (such as hydraulic behavior of rivers) and landscape patterns [7–9]. The analysis of the relationship between human disturbances and landscape structure is the key to accomplish a suitable landscape planning and management [10]. The management of the landscape structure must begin from the full comprehension of all its features because the landscape should be analyzed as a whole using a holistic approach [11,12].

A consolidated technique for the quantification of the main characteristics of a landscape such as structure, function and change is the use of ecological indicators called landscape metrics [13,14]. A large number of metrics have been developed in the past few decades able to assess landscape structure based on categorical maps [7]. Today, the combination of GIS applications and mathematical codes such as FRAGSTATS [15] are widely used in the field of ecological applications. Numerous studies have shown how landscape metrics can provide a large amount of information on landscape composition and configuration [16]. In many cases, landscape metrics are also used to assess how the landscape changes over time under human pressure or to evaluate the effectiveness of conservative plans in protected zones [17–19]. Other studies focused on fluvial landscape configuration and dynamics [20–22].

In the framework of the eco-hydraulics a number of studies have used hydraulic modelling to analyze specific ecological aspects such as the determination of the ecological flow (called also instream flow) [23–25] or the evaluation of habitats suitability [26,27]. Meanwhile, a few studies have investigated the potential advantages of the synergic application of landscape metrics and hydraulic modeling in suitable environments planning [1]. Entwistle et al. [4] used a 2D hydraulic model and FRAGSTATS to evaluate the ecological value of unbranched channels. Van Nieuwenhuyse et al. [28] has utilized landscape metrics to evaluate the degree of hydrological connectivity among artificial catchments. Rare is the application of both methodology to assess the spatial structure of a hydraulic environment [29] and the lack of spatial analysis from hydraulic assessments was previously highlighted by Newson and Newson [30].

The present paper aims to extend the field of spatial analysis application in riverine environments, introducing a methodology that integrates hydraulic modelling and landscape metrics. The proposed method allows predicting the effects of restoration plans on riverine landscapes quantifying ecological features such as connectivity and heterogeneity. Therefore, it could be a useful tool to provide important information guiding decision-makers in territorial planning.

The paper is organized into three main parts:

1. a brief contextualization describing the study area in which the work was carried out;
2. the software used are listed and the adopted methodology is described;
3. the outcomes of the study are presented and discussed, and conclusions are drawn.

46 1.1 The aim of the research

47 The objective of this work is to introduce an integrated method which has four purposes: (1)  
48 linking hydraulic knowledge with ecological analysis, mainly using hydraulic models and landscape  
49 metrics; (2) predicting spatial pattern changes and ecological impacts resulting from a river  
50 restoration plan; (3) assessing the spatial configuration and temporal dynamics of different  
51 landscape structures; (4) giving a useful tool to guide local administrations and landscape planners  
52 to choose the most non-invasive plans for territory management.

53 2. Study area

54 The research is focused on the first lowland part of the Orco river's catchment, located in  
55 Piedmont in the north-west of Italy. This part covers approximately 22% of the whole river basin  
56 and it is characterized by a hilly and flat landscape. In this area, the Orco river flows 40 Km to  
57 downstream until his confluence in the Po river and its riverbed shows a sinuous trend with an  
58 alternation of braided and meandering channels. The river reach between the villages of Rivarolo  
59 Canavese and Lusigliè (TO, Italy) was selected for the implementation of the hydraulic model [31].  
60 The study area of 600 hectares was used to carry out hydraulic and ecological analyses [32] (see Fig.  
61 1).



62  
63 Fig. 1 Geographical location of the study area (source of the aerial image: Google Earth®, 2018)

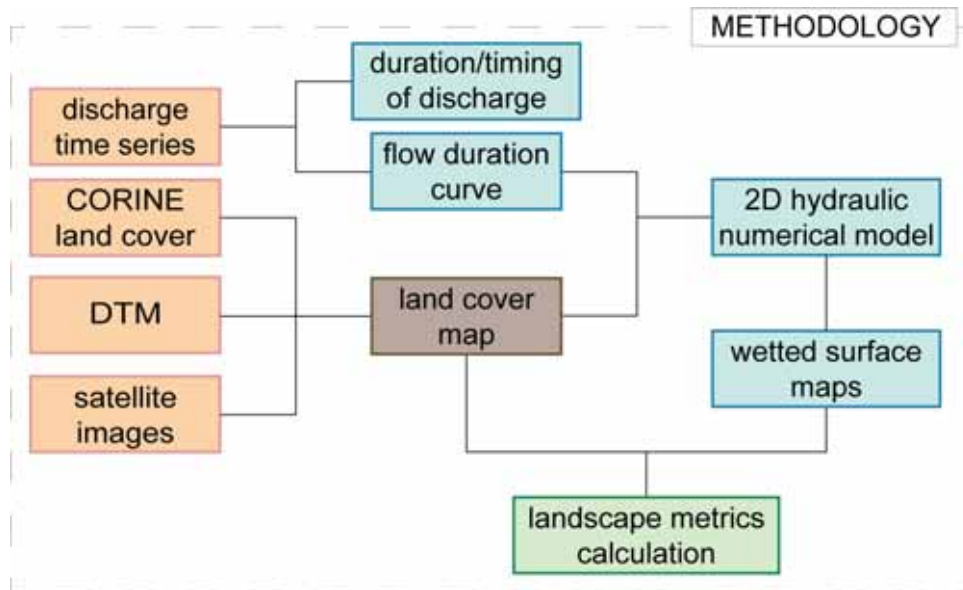
64 From the geomorphological point of view, the chosen reach is slightly carved and its riparian  
65 areas are characterized by the presence of secondary forms and relict water paths on the left and  
66 steep banks on the right. Indeed, the widespread presence of banks in erosion states the planimetric  
67 instability of the river. During flooding events, the river tends to restore the pre-existing braided  
68 shape. This phenomenon affects variations of the main flow direction, leading to a wide range of  
69 historical mobility of the riverbed [33].

70 The land cover presents a patchwork structure, typical of the fluvial plains. Agricultural lands  
71 dominate the study area, almost 50% is covered by meadow and cultivated fields. Woods cover one-  
72 fifth of the surveyed area and its forest vegetation is mainly composed by *Robinia pseudoacacia*  
73 [34].

74 3. Materials and Methods

75 This section describes the multidisciplinary method proposed in this work, between hydraulics  
76 and landscape ecology, which benefits from the combined use of software with different features.  
77 It can be divided into three main steps (see Fig. 2): (1) the construction of a land cover map using  
78 the overlapping of different maps and satellite images into the GIS module of SMS-11.1-Surface-

79 water Modeling System [35]; (2) the implementation of the two-dimensional hydraulic model and  
 80 hydrodynamic simulations using SMS in the pre and post-processing phases and BASEMENT 2.6-  
 81 Basic Simulation Environment [36] for the processing step; (3) the manipulation of categorical maps  
 82 in ArcMap 10.3.1 and calculation of landscape metrics with FRAGSTATS. The current released  
 83 version (FRAGSTATS v4.2) is an efficient tool able to compute a great number of landscape metrics  
 84 from a wide variety of image formats [15].



85  
 86 Fig. 2 Schematization of the methodology: input (orange boxes), GIS elaboration (brown box), hydrological/hydraulic  
 87 calculation (light blue boxes) and ecological assessment (green box)

### 88 3.1 Land cover assessment

89 The first main action necessary for all following analyses was the detection of the spatial  
 90 configuration of the study area. The land cover map was obtained by the combination of spatial  
 91 information from CORINE Land Cover 2000, Digital Terrain Model DTM with a high resolution (on  
 92 average 1 point each square meter) realized by Ministry for the Environment and the Protection of  
 93 the Territory and the Sea during the extraordinary Plan of Environmental Remote Sensing with  
 94 LiDAR scan and upgraded satellite images. The resulting land cover map was divided into seven  
 95 categories: grassland, wood, river bank, water, factories, urban center and roads (see Fig. 3). The  
 96 distribution of each land cover class in the study area is shown in Table 1.

97 Table 1 Area, percentage cover and Manning's Roughness Coefficient of each land cover class in the study area

Land cover class	Area [ha]	Percentage cover [%]	Manning's Roughness Coefficient
Grassland	276.2	46.0	0.07
Wood	124.5	20.7	0.08
River bank	33.1	5.5	0.045
Water	41.3	6.9	0.045
Factories	8.9	1.5	0.15
Urban center	112.2	18.7	0.15
Roads	4.0	0.7	0.03
Total	600	100	

98 Then each class was matched with a Manning's Roughness Coefficient which represents the  
 99 hydraulic resistance offered by each surface to the water flow. The identification of the appropriate  
 100 roughness coefficient derived from a back-analysis carried out during the calibration of the hydraulic  
 101 model [37]. The high-resolution data permitted also to consider the shapes and geographical

102 positions of structures within the domain such as bridge piers, levees, and road embankments. All  
 103 these data were necessary to build the hydraulic model and accomplish hydrodynamic simulations.

### 104 3.2 Hydraulic simulations

105 The two-dimensional hydraulic model was implemented to simulate the behavior of the river  
 106 reach and to estimate the amount of wetted area with specific discharges. Throughout a preliminary  
 107 hydrologic analysis, we calculated the flow duration curve (FDC) and its characteristic values (Qxx)  
 108 were extracted. In this paper, the value of Qxx will refer to the amount of discharge that should be  
 109 present on average at least xx days per year in the analyzed river reach. The FDC was calculated  
 110 from the elaboration of flow data collected from 2010 to 2016 by a gage station near to the  
 111 upstream boundary of the hydraulic model domain. Each Qxx value was used as an inner boundary  
 112 condition for hydrodynamic simulations. Moreover, the duration and timing of each discharge were  
 113 investigated.

114 The 2D numerical model is based on the numerical resolution of the Shallow Water Equations.  
 115 These equations calculate the flow field assuming a hydrostatic distribution of the pressures along  
 116 the depth and neglecting the vertical component of the flow [38]. The conservative form of the  
 117 equation system can be written as:

$$118 \quad U_t + \nabla \cdot (F, G) + S = 0, \quad (1)$$

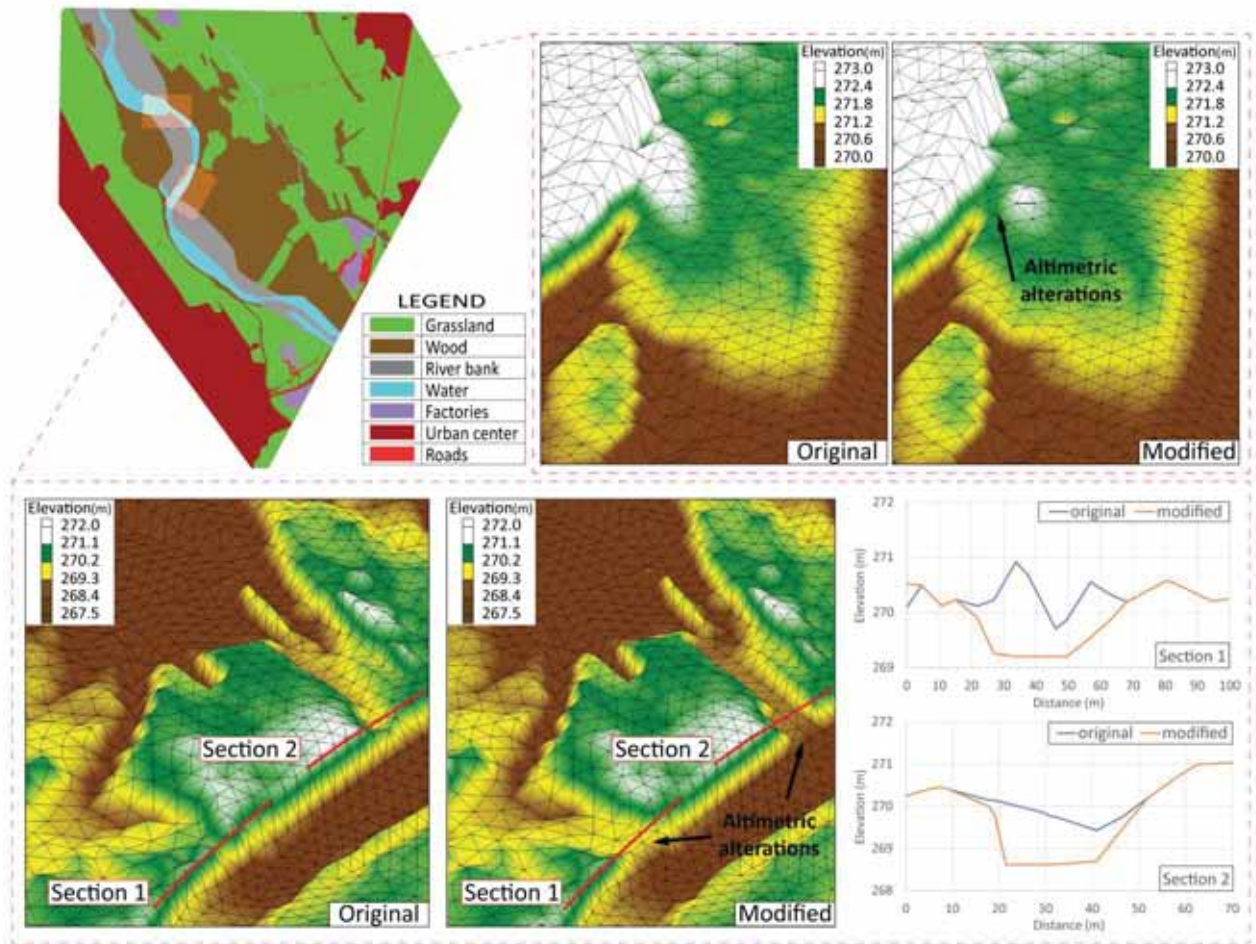
119 where  $U_t$  is the derivation with respect to time ( $t$ ) of the conserved variables vector,  $F$  and  $G$  are  
 120 the vectors of fluxes and  $S$  is the vector of source terms, in the  $x$  and  $y$  directions, given by:

$$121 \quad U = \begin{pmatrix} h \\ uh \\ vh \end{pmatrix}, \quad F = \begin{pmatrix} uh \\ u^2h + \frac{1}{2}gh^2 - vh \frac{\partial u}{\partial x} \\ uvh - vh \frac{\partial u}{\partial y} \end{pmatrix},$$

$$122 \quad G = \begin{pmatrix} vh \\ uvh - vh \frac{\partial v}{\partial x} \\ v^2h + \frac{1}{2}gh^2 - vh \frac{\partial v}{\partial y} \end{pmatrix}, \quad S = \begin{pmatrix} 0 \\ gh(S_{fx} - S_{Bx}) \\ gh(S_{fy} - S_{By}) \end{pmatrix}. \quad (2)$$

123 where  $h$  is the water depth (m),  $u$  and  $v$  are the cartesian components of the flow velocity vector  
 124 (m/s),  $g$  is gravity acceleration (m/s<sup>2</sup>),  $\nu$  is the total viscosity (m<sup>2</sup>/s),  $S_f$  is the friction slope (-) and  $S_b$   
 125 is the bed slope (-).

126 The land cover map obtained in the previous step was matched with the altimetric data of the  
 127 DTM to create a computational grid (mesh). This grid represents the mathematical representation  
 128 of the river topography and the basic geometry of the two-dimensional hydraulic model. Two  
 129 different sets of simulations were carried out: in the first, the river behavior on the actual  
 130 topography was simulated, this will be called "original" scenario. In the second, the wetted area on  
 131 a modified computational mesh simulating the river restoration plan was calculated, this will be  
 132 called "modified" scenario. In order to obtain the "modified" scenario, a series of altimetric  
 133 alterations were applied to modify the original mesh. These alterations were circumscribed along  
 134 100 m of natural riverbanks digging natural levees for reconnecting remnant meanders with the  
 135 main channel. These levees were created by the intensive sediment transport of floods over time.  
 136 The alterations of the mesh are displayed in Fig. 3.



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Fig. 3 Land cover map and morphological alterations. Top: enlargement on the original and modified mesh of the first altered site. Bottom: enlargement on the original and modified mesh of the second altered site, and two graphs that display the modified profile of the river bank.

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### 3.3 Calculation of landscape metrics

As output of the hydraulic simulation stage, vector layers were produced from each simulation reporting the total amount of wetted area and its distribution into the study area. They have been edited through GIS tools to create raster files used as FRAGSTATS inputs. The high accuracy of the hydraulic model outcomes permitted to keep a high-resolution during the rasterization of the vector maps. The grain size of 1 m was set up during the rasterization process [39].

Landscape composition and configuration have been evaluated using FRAGSTATS for both cases, “original” and “modified” scenarios. The analyses were carried out with the standard patch neighbor 8-cell rule option. FRAGSTATS calculates a number of landscape indices but sometimes several of them are redundant, especially when two equivalent landscapes are compared. Thus, in order to choose the most representative indices, metrics that did not show a remarkable variation between the “original” and “modified” landscape ( $\Delta < 0.1$ ) have been discarded. Furthermore, a smaller set of seven metrics have been selected according to the most used landscape indices in literature. For a comprehensive characterization of the landscape, we selected metrics belonging to three different metrics categories called Area-Edge, Shape and Aggregation. Each category reveals specific information such as: (I) Area-Edge analyzes the degree of fragmentation, (II) Shape measures the geometry complexity and (III) Aggregation quantifies the landscape configuration, namely the level of patch dispersion [7]. The classification and description of each metrics are listed as follows:

I. Area-Edge metrics:

- 160 1. ED: Edge Density equals the sum of the lengths of all edge segments in the landscape, divided  
 161 by the total landscape area;  
 162 2. AREA\_AM: Area-weighted Mean patch Area equals the sum, across all patches in the  
 163 landscape, of the patch area, multiplied by the proportional abundance of the patch;  
 164 3. AREA\_SD: Standard Deviation in patch Area equals the square root of the sum of the squared  
 165 deviations of each patch size from the mean patch size computed for all patches in the  
 166 landscape, divided by the total number of patches;  
 167 4. AREA\_CV: Coefficient of Variation in patch Area equals the standard deviation divided by the  
 168 mean, multiplied by 100 to convert to a percentage;  
 169 II. Shape metrics:  
 170 5. SHAPE\_AM: Area-weighted Mean Shape index equals the sum, across all patches in the  
 171 landscape, of the patch perimeter divided by the square root of patch area standardized to  
 172 a square, multiplied by the proportional abundance of the patch;  
 173 III. Aggregation metrics:  
 174 6. PD: Patch Density equals the number of patches in the landscape divided by total landscape  
 175 area;  
 176 7. ENN\_MN: Mean Euclidean Nearest Neighbor distance equals the sum, across all patches in  
 177 the landscape, of the distance to the nearest neighboring patch of the same type, based on  
 178 shortest edge-to-edge distance, divided by the total number of patches.  
 179 The equations and the corresponding terms of these metrics are shown in Table 2.

180 Table 2 List of landscape metrics used in the study [15]

Metrics	Equations	Terms
Edge Density (ED)	$ED = E/A$	Where E is the total length of the edge in landscape and A is total landscape area
Area-weighted Mean patch Area (AREA_AM)	$AREA\_AM = \sum_{i=1}^m \sum_{j=1}^n \left[ a_{ij} \left( \frac{a_{ij}}{\sum_{i=1}^m \sum_{j=1}^n a_{ij}} \right) \right]$	Where $a_{ij}$ is the area of patch i of the patch type j
Standard Deviation in patch Area (AREA_SD)	$AREA\_SD = \sqrt{\frac{\sum_{i=1}^m \sum_{j=1}^n \left[ a_{ij} - \left( \frac{\sum_{i=1}^m \sum_{j=1}^n a_{ij}}{N} \right) \right]^2}{N}}$	Where $a_{ij}$ is the area of patch i of the patch type j and N is the total number of patches in the landscape
Coefficient of Variation in patch Area (AREA_CV)	$AREA\_CV = \left[ \frac{AREA\_SD}{\frac{\sum_{i=1}^m \sum_{j=1}^n a_{ij}}{N}} \right] (100)$	Where $a_{ij}$ is the area of patch i of the patch type j and N is the total number of patches in the landscape
Area-weighted Mean Shape index (SHAPE_AM)	$SHAPE\_AM = \sum_{i=1}^m \sum_{j=1}^n \left[ \left( 0.25 \cdot p_{ij} / \sqrt{a_{ij}} \right) \left( \frac{a_{ij}}{\sum_{i=1}^m \sum_{j=1}^n a_{ij}} \right) \right]$	Where $p_{ij}$ is the perimeter of the patch i of the patch type j and $a_{ij}$ is the area of patch i
Patch Density (PD)	$PD = N/A$	Where N is the total number of patches in the landscape and A is the total landscape area
Mean Euclidean Nearest Neighbor distance (ENN_MN)	$ENN\_MN = \frac{\sum_{i=1}^m \sum_{j=1}^n h_{ij}}{N}$	Where $h_{ij}$ is the distance from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center and N is the

181

182 The set of seven ecological metrics was calculated for both “original” and “modified” scenarios  
183 and for each Qxx. The difference between the two analyzed cases will be indicated with the  
184 parameter  $\Delta$ , calculated as follows:

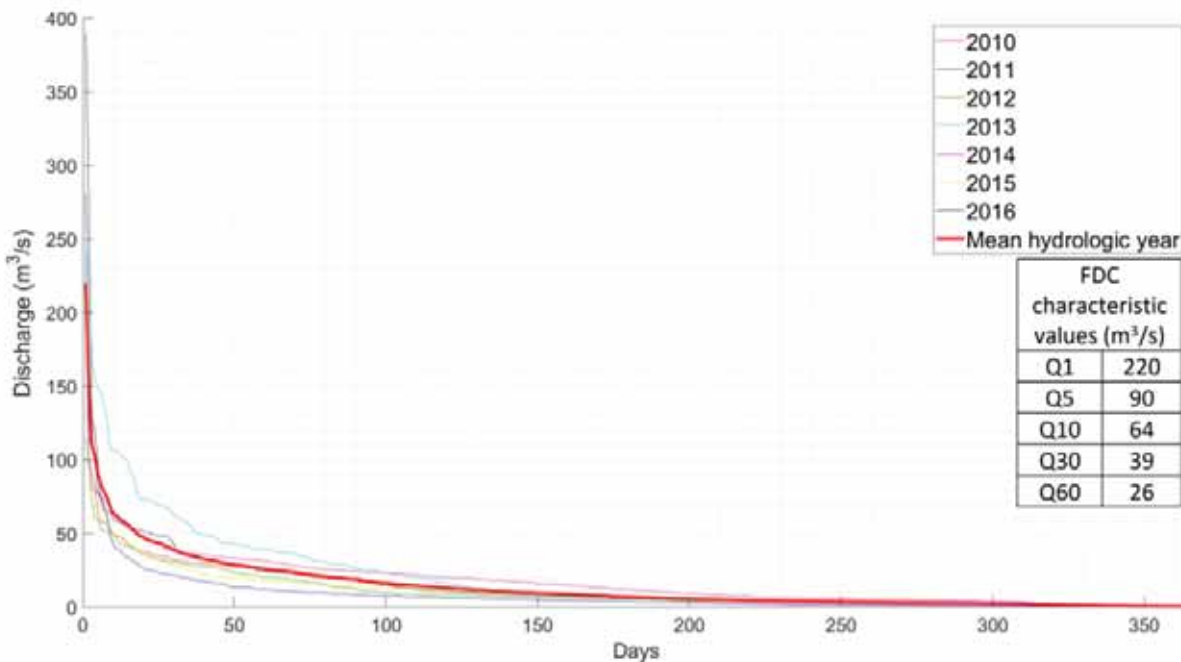
185 
$$\Delta = metrics_{modified\ scenario} - metrics_{original\ scenario} \quad (3)$$

186 **4. Results**

187 Results obtained in this study have both hydraulic and ecological nature. Hydraulic outputs  
188 represent the input for the ecological analysis. For this reason, results will be described in two  
189 different subsections.

190 **4.1 Hydraulic outputs**

191 The examined FDC represents the relationship between the amount of discharge and its  
192 persistence during a mean hydrologic year [40]. The FDC and its characteristic values are shown in  
193 Fig. 4.

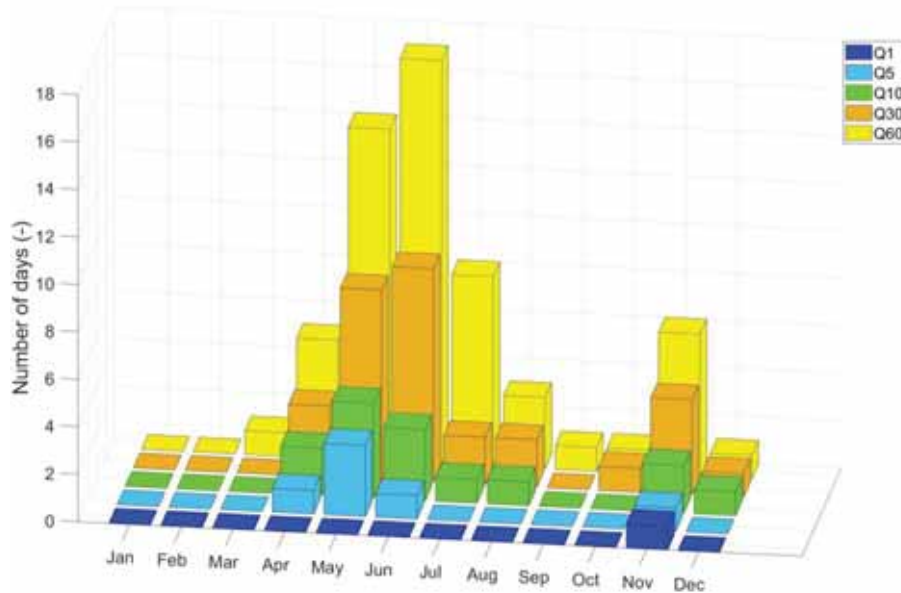


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195 Fig. 4 Flow duration curve and its characteristic values

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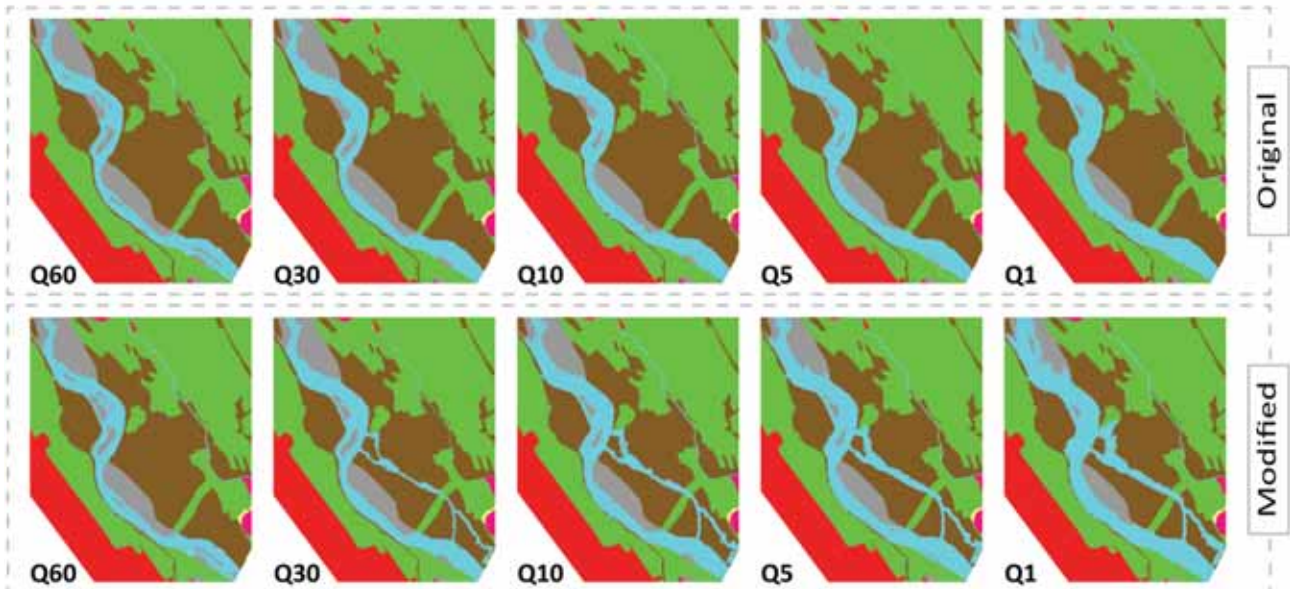
The duration and timing of the different discharges are displayed in Fig. 5.



197  
198 Fig. 5 Timing and duration of each analyzed discharge (mean number of days per month in which that amount of  
199 discharge flows into the river).

200 Using these discharges as upstream boundary condition in hydrodynamic simulations, the  
201 numerical model produces different wetted area maps for both “original” and “modified”  
202 configurations. Hydraulic simulations on the “original” mesh depict all the same scenarios in which  
203 the total among of water flow only into the main channel (Fig. 6). Whereas, simulations on the  
204 “modified” geometry show a different behavior of the river as the flow increases:

- 205 · if the discharge is less than Q30, the water flows into the main channel and exclusively the  
206 little channel in the first modified site is reactivated (Fig. 6, Q60);
- 207 · if the discharge is greater than or equal to Q30, the discharge overtops the river bank and  
208 starts to flow not only in the original streambed but also through the floodplain bringing  
209 water to the riparian ecosystem (Fig. 6, Q30-Q1).

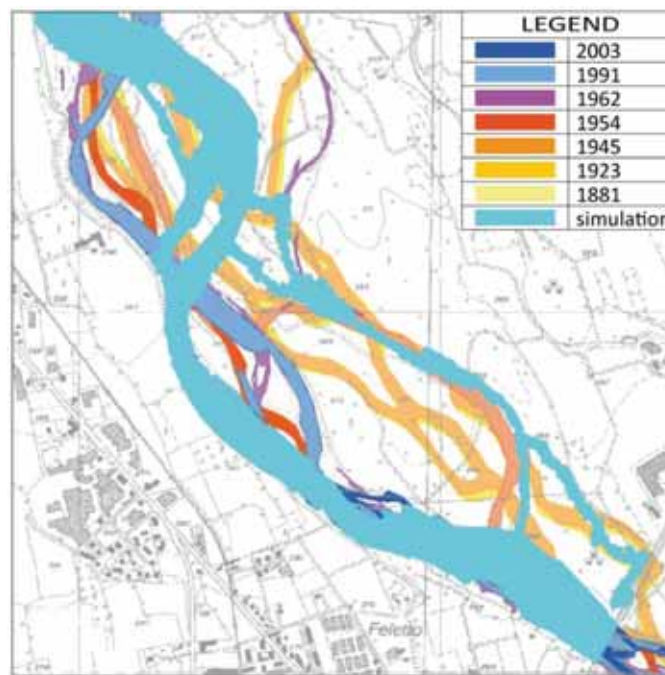


210  
211 Fig. 6 Hydraulic outcomes for both scenarios with increasing discharge from left to right. The reactivation of the  
212 remnant streambeds leads to an increase of the wetted surface of 1.8%, 18.9%, 21.8%, 22.1% and 23.3% respectively  
213 for the scenario with Q60, Q30, Q10, Q5 and Q1.

214 The reactivation of the remnant meanders is strictly connected with the hydrology of the Orco  
215 river, which is yearly characterized by two distinct periods of high flow (Fig. 5). The first, in which

216 the discharge grows according to spring rainfalls together with the snow melting in the headwater;  
 217 the second, characterized by the occurrence of yearly flood events caused by intense autumn  
 218 rainstorms. This flow pattern leads to the reactivation of the channels for 24 days from April to  
 219 August, and for 6 days from October to December. June and November show the maximum duration  
 220 of discharge greater than Q30.

221 The river restoration action is completely respectful of the original ecosystem since the  
 222 subtracted water flows in the floodplain and then gets back to the river 1 Km downstream. This new  
 223 configuration is also in accordance with the planimetric divagation range (streamway) of the river.  
 224 Superimposing the wetted surface map of the “modified” scenario over the planimetric variations  
 225 map of the Orco river, it is clear how the flow retraces the paths of old abandoned riverbeds (Fig.  
 226 7). Reconnecting remnant meanders or rebuilding secondary channels are restoration actions  
 227 widely adopted to enhance the ecological value of the riverine ecosystems and recreate the  
 228 continuum with the floodplain [6,41–44].



229  
 230 Fig. 7 Superimposition of the modified wetted surface map over the planimetric variations in the Orco river map  
 231 (realized by Research Institute for the Hydrogeological Protection–Turin section)

## 232 4.2 Ecological outputs

233 In order to assess the effects of the restoration plan on the landscape structure and its riverine  
 234 ecosystem, a series of comparisons were carried out. Firstly, the comparison at the class and  
 235 landscape level of metrics obtained from both scenarios with Q30 aims to highlight changes in the  
 236 spatial configuration due to reactivated channels. All outcomes are summarized in Table 3.

237 Table 3 The group of seven metrics (ED – Edge Density, AREA\_AM – Area-weighted Mean patch Area, AREA\_SD –  
 238 Standard Deviation in patch Area, AREA\_CV – Coefficient of Variation in patch Area, PD – Patch Density, SHAPE\_AM –  
 239 Area-weighted Mean Shape index and ENN\_MN – Mean Euclidean Nearest Neighbor distance) calculated with Q30 for  
 240 both scenarios and their comparison. Factories, urban center and roads classes have been neglected since they have  
 241 not been altered by the restoration plan.

Metrics	Landscape level						
	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Original scenario	109.0	58.5	21.3	231.1	10.8	2.9	95.3
Modified scenario	119.9	55.2	19.9	235.3	11.8	3.0	84.4
$\Delta$	10.8	-3.3	-1.4	4.2	1.0	0.2	-10.9

Class level							
Original scenario							
Land cover class	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Grassland	73.2	66.2	29.1	168.3	2.7	2.8	11.7
Wood	60.3	44.8	17.4	209.7	2.5	3.2	29.2
River bank	18.0	9.6	4.6	138.0	1.7	2.0	53.4
Water	30.8	37.5	18.1	131.2	0.5	4.7	164.0
Modified scenario							
Land cover class	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Grassland	73.5	65.9	28.4	174.9	2.8	2.8	12.3
Wood	70.2	25.6	11.0	177.8	3.2	3.2	26.6
River bank	17.8	9.7	4.5	150.3	1.8	2.0	44.2
Water	42.4	45.2	21.7	132.8	0.5	6.8	81.6
$\Delta$							
Grassland	0.3	-0.2	-0.7	6.6	0.2	0.0	0.6
Wood	9.9	-19.1	-6.4	-31.9	0.7	0.1	-2.6
River bank	-0.2	0.1	-0.1	12.4	0.2	0.0	-9.2
Water	11.6	7.8	3.7	1.6	0.0	2.1	-82.4

242 Focusing at the landscape level, the modified landscape shows a slight increase in fragmentation  
243 degree. Consistent with observations of Sowińska-Świerkosz and Soszyński [39], alterations caused  
244 by the reactivated channels among the floodplain lead to a separation into a larger number of  
245 smaller patches increasing the fragmentation degree. This information is justified by the growth of  
246 ED and AREA\_CV values and in the AREA\_AM and AREA\_SD decreasing. As reported by McGarigal  
247 and Marks [7], the variation of AREA\_CV and AREA\_SD means that on the modified study area  
248 patches become smaller and their distribution size is farther from the average size than in the  
249 original area.

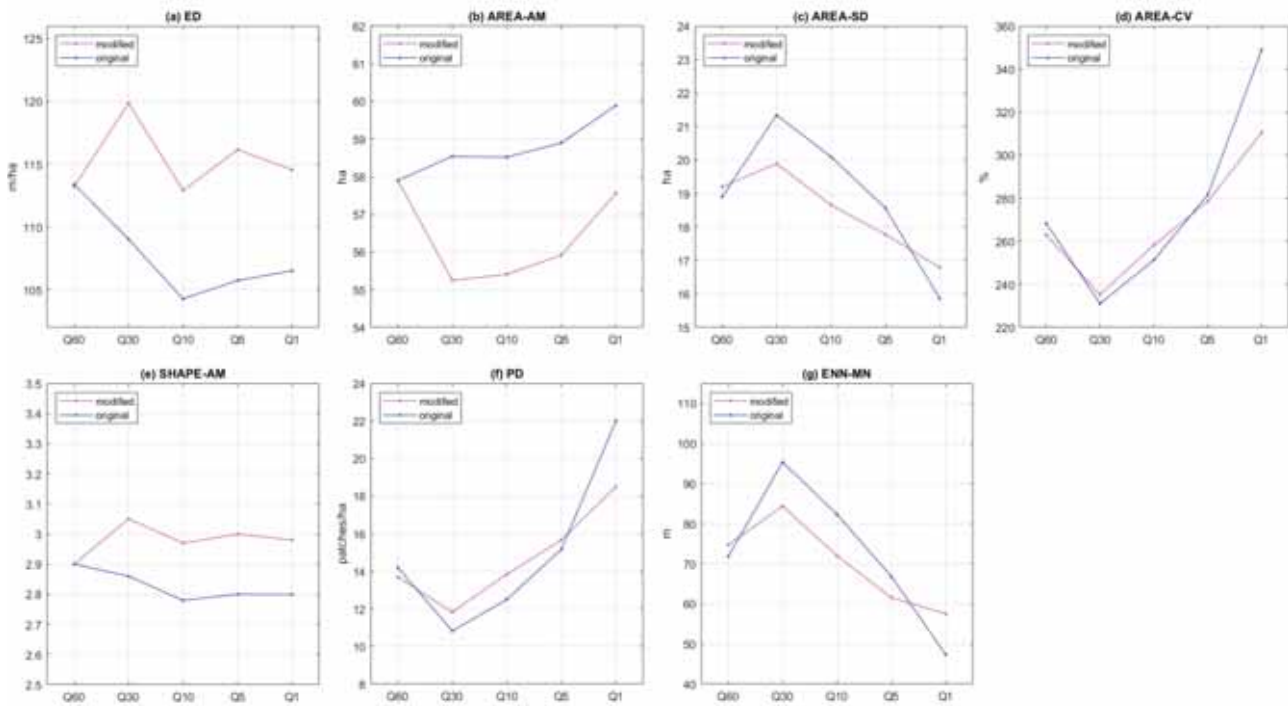
250 In the context of habitat fragmentation, the grade of patch isolation is calculated with the  
251 Euclidean Nearest Neighbor distance (ENN) metric [15,45]. The modified area presents a smaller  
252 value of ENN\_MN, with a decrease of 11.5%. This means that even if the patches are more  
253 fragmented, they are less isolated.

254 Another important ecological factor is the landscape complexity. The modified landscape shows  
255 a slight increase in the degree of complexity in the planar shape given by the raised value of  
256 SHAPE\_AM. This metrics illustrates how much the patch shape is different from the standard square  
257 shape. Generally, natural shapes are not regular, therefore the restored configuration appears to  
258 be more akin to a natural environment. The last analyzed ecological metrics was PD. The slight  
259 increase of 9% in PD value in the modified landscape, in correlation with ED, means that the  
260 modified landscape has a higher level of heterogeneity. Previous studies have confirmed the  
261 effectiveness of PD and ED as indicators of the spatial heterogeneity degree in landscapes [32].

262 Landscape attributes at class level were also analyzed in order to understand in-depth the results  
263 of this stage. The most modified land cover classes were wood and water because the reactivated  
264 watercourses run across the floodplain covered by wood (Fig. 6). As reported in Table 3, there is a  
265 substantial difference in nearest neighbor distance for water patches, from 164 to 81. While the  
266 variation of AREA\_AM and AREA\_CV in wood class caused by the subdivision in more smaller  
267 patches shows a remarkable decrease of 40%.

268 In the second stage, since in a natural river the amount of flow varies during the year, the  
269 evaluation of dynamics of the landscape structure was carried out tracking the wetted area

270 distribution for the different discharges. Landscape metrics calculated at the landscape level are  
271 summarized in Fig. 8.



272  
273 Fig. 8 Landscape metrics representing the dynamics of landscape structure in terms of fragmentation (a: Edge  
274 Density, b: Area-weighted Mean patch Area, c: Standard Deviation in patch Area), complexity (e: Area-weighted Mean Shape index) and configuration (f: Patch Density, g: Mean Euclidean Nearest  
275 Neighbor Distance) as the flow increases.  
276

277 For the Q60 both scenarios are very similar, whereas a considerable variation can be noticed for  
278 the other discharges. ED value in the modified scenario rises and falls at each increment due to the  
279 intermittent ramification of water paths creating isolated wood and river bank patches. SHAPE\_AM  
280 is almost unvaried meaning that neither restoration activity nor increasing discharge do not strongly  
281 affect the complexity level of the landscape. However, all metrics show the same trend in both  
282 scenarios stating how the restoration action have not changed the response of the riverine  
283 landscape to discharge variation. Only for the maximum discharge Q1, the number of patches  
284 classified as river bank increase in the original scenarios and decrease in the modified scenario  
285 leading to a reversion of the value of the metric (Fig. 8c, d, f, g).

## 286 5. Discussion

287 The methodology presented in this study is a procedure able to assess the impacts of changes in the  
288 spatial structure of riverine landscapes. Different scenarios may be developed according to different  
289 strategies to achieve specific objectives [10]. Moreover, it is possible to analyze different landscapes  
290 to identify needs and lacks in an attempt to apply specific restoration actions aimed at improving  
291 ecological conditions [39]. Using a numerical-based approach, a wide range of scenarios can be  
292 compared, and the most suitable plan may be chosen by authorities improving the management of  
293 the territory.

294 In the studied case a river restoration action was carried out reactivating natural watercourses  
295 among the floodplain and its impact on the landscape structure was analyzed. Results obtained in  
296 the previous section are metrics used to give a quantification of four fundamental ecological  
297 attributes such as fragmentation, isolation, complexity, and heterogeneity. The chosen discharges  
298 have permitted to analyze the spatial configuration and dynamics of these components since the  
299 hydraulic conditions that reactivate the watercourses are non-stationary. When flow rate in the

300 river is less than Q30, no water flows in the floodplain and the lower level of fragmentation means  
301 a higher level of connectivity among the patches with the same class type. For some species such as  
302 mammals, this landscape is more hospitable because larger areas offer stable conditions required  
303 to host a flourishing population. While, when discharge is greater than the threshold Q30, flow  
304 reactivates watercourses watering riparian ecosystems and increasing the degree of fragmentation  
305 especially for the wood class. The landscape with a mosaic of varied ecosystems is more attractive  
306 for the multi-habitat species [39]. Thus, the higher level of fragmentation does not involve habitat  
307 losses or impoverishment of biodiversity but on the contrary, the modified morphology proves to  
308 be more suitable for a greater variety of ecosystems [46,47].

309 The edge density is directly correlated to the grade of spatial heterogeneity and fragmentation  
310 [7]. The increasing of this metrics means that when water flows into the floodplain a higher amount  
311 of edges affects the landscape. The increased level of fragmentation and the reduction in patch size  
312 could influence the behavior of some animal species, particularly these periodic changes can  
313 support, alternately, the growth of species that prefer edge habitats or interior kinds [48]. When  
314 discharge periodically increases, the variation of connections between patches with no-water  
315 classification may influence the migration of terrestrial species which require connectedness. For  
316 instance, the early reactivation of the remnant streambeds coincides with the hedgehog breeding  
317 season (species living in the study area, [49]). Thus, the lack of connectivity within the riparian forest  
318 could affect the mobility of these animals hindering them reproduction. On the contrary, in the  
319 same period, the presence of new wetlands provides an attractive habitat for pond breeding  
320 amphibians [50].

321 However, cyclical dry and wet periods raise the production of nutrient matter improving the  
322 environmental quality of aquatic biota. The autumnal reactivation will move organic matter that  
323 covers the ground, such as leaf litter, enhancing the abundance of detritivorous macroinvertebrates,  
324 in particular, shredders such as Ephemeroptera and Plecoptera [51,52]. These organisms will break  
325 the coarse particulate organic material up into a finer size feeding the collectors leaving in the river  
326 downstream. Since the riparian area is covered by trees, the presence of coarse wood in the  
327 reactivated channels provides a favorable habitat for organisms such as biofilm algae which will  
328 represent a new source of food for invertebrates such as snails and beetles [53].

329 The slight increase in shape complexity shows that the applied geomorphological modifications  
330 do not produce great variations in landscape structure in both landscape and class level. This  
331 demonstrates how the tested river restoration plan is non-invasive towards the patch geometry.  
332 Anthropogenic activities in river restoration planning should be as eco-friendly as possible in order  
333 to enhance the ecological value of the landscape without leaving human evidence. The monitoring  
334 of the complexity degree can be an efficient indicator to assess the interference of human activities  
335 in the landscape.

336 The variation of ENN\_MN is concentrated mainly in water patches until Q5 and involves markedly  
337 river bank class with Q1. It represents a reduction in patch isolation, meaning that the altered  
338 landscape configuration has a smaller interpatch distance. Indeed, when water flows through the  
339 floodplain, the distribution of wetted surfaces is more homogeneous into the study area. Regarding  
340 the wood class, several studies have claimed that patch isolation influences the life of bird  
341 communities and the insularity due to fragmented habitats has a negative impact on bird species  
342 [54]. In the proposed restoration plan the difference in isolation degree is favorable in most cases.  
343 Only the grassland class presents a negligible increase of almost 5%. The modified configuration  
344 conduces to a more heterogeneous landscape able to host a proliferation of vast varieties of animal  
345 populations, both aquatic and terrestrial species. The level of heterogeneity will change over the

346 year, according to the hydrology of the river, varying ecological processes among landscape pattern  
347 [55].

348 All the above-mentioned considerations derive from the interpretation of the analyzed metrics  
349 and their values. The quantification of these metrics is strongly conditioned by the parameters  
350 selected by the operator. Especially during the rasterization of the vector files, the choice of the cell  
351 size could alter the outcome leading to an erroneous division or union of patches. This problem is  
352 emphasized for landscape metrics based on the size and number of patches [7]. Many studies have  
353 shown how grain size affects the outcomes of landscape metrics applications [56–58]. For this  
354 reason, we chose a very fine grain size, 1 m, in order to generate a raster file representative of the  
355 reality.

356 Moreover, as stated by Plexida et al. [32], some landscape metrics are influenced by the size of  
357 the analyzed domain such as area-edge and shape metrics. The use of a restricted area size could  
358 lead to analyze a landscape characterized by a single class, impeding the assessment of ecological  
359 attributes of the study area. In addition, whether the restoration plan aims to recover plants and  
360 animals, the presented methodology should be applied considering a scale compatible with the  
361 species' perception of the environment [59]. For instance, an agricultural field could represent an  
362 entire habitat for an insect but, simultaneously, only a single patch for a bird.

## 363 6. Conclusion

364 Nowadays an increased sensibility towards environment joins experts, authorities, and researchers  
365 in the search for the best solutions for sustainable management of the territory. Multidisciplinary  
366 approaches are needed to understand the interactions between natural processes and human  
367 activities.

368 In this paper, a method was proposed that integrates hydraulic and landscape ecological  
369 knowledge with the purpose of creating a tool able to simulate a river restoration plan and quantify  
370 its impact on the landscape structure and its ecosystems. This methodology can predict the  
371 achievement of the objectives in landscape planning and evaluate whether the proposed design is  
372 suitable and valid in a cost-benefit analysis perspective. The entire procedure is based on  
373 geographical information and numerical data. Therefore, it represents a significant advantage  
374 because required data can be extrapolated from thematic maps or numerical simulation, reducing  
375 the necessity of costly on-site surveys.

376 The feature of reusability of the hydraulic models makes it possible to simulate and compare  
377 different landscape scenarios to assess the best solution. This method may be helpful for local  
378 administrations to better understand the configuration of their territory and to choose the most  
379 suitable plan to restore altered areas. In order to limit overengineering in restoration plans, all  
380 actors should keep in mind the capabilities of the ecosystems to self-design and avoid the over-  
381 engineering.

382 However, the proposed methodology highlighted two main limitations. Firstly, the choice of the  
383 study area extent must be compatible with the available computational power, being it directly  
384 related to the accuracy of the hydraulic numerical model. The second issue, the choice and  
385 interpretation of landscape metrics are conditioned by the features of the analyzed area.

386 Future work should test this methodology on a wider range of river restoration plans. The results  
387 of this study should encourage all actors to use multidisciplinary approaches in order to design and  
388 manage the territory in accordance with the conservation and protection of natural ecosystems.

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## Title

Landscape metrics integrated in hydraulic modeling for river restoration planning

## Abstract

Engineers have shaped the environment across the centuries in order to improve the quality and safety of human life. The unrestrained invasion of nature led to significant environmental problems, for this reason nowadays engineering projects should be based on ecological concepts to protect our environment. This paper presents an integrated methodology that involves GIS tools, hydraulic numerical models and landscape metrics to investigate ecological consequences caused by river restoration activities. The combined use of these different tools represents a bridge to connect the field of engineering with ecological techniques. The proposed method was tested to predict and assess the influence of a river restoration plan on a reach of the Orco river located in the north-west of Italy. Morphological alterations were simulated to reconnect remnant meanders and provide water to the floodplain, enhancing the ecological value of riparian ecosystems. The application of the hydraulic model permitted to evaluate the distribution of water inside the study area before and after the restoration plan. Thereafter, spatial configuration and temporal dynamics of the landscape structures were quantified using landscape metrics. The increase of patch density (PD) by 9% and edge density (ED) up to 10% highlights that restoration activities lead to a new configuration characterized by a higher level of fragmentation and heterogeneity. The characteristics of versatility, repeatability and the possibility to predict the outcomes of a specific plan make the proposed method a useful tool that could help decision-makers to manage the territory while safeguarding natural ecosystems.

## Keywords

landscape metrics; hydraulic numerical modeling; river restoration; riverine environment; landscape management

## 1. Introduction

Nowadays there is a deeper sensibility toward natural spaces after many years of uncontrolled use of the territory. Anthropogenic disturbances have altered landscape structure and its ecological processes [1]. In this framework, ecologists and engineers have strived to conserve, defend and restore the “green” part of our planet.

Focusing on riverine environments, different disciplines were born in past decades trying to connect the world of hydraulics with ecological concepts such as the eco-hydraulics [2–4] and hydroecology [5]. Much effort has been devoted to the research of effective actions with the purpose to restore disturbed ecosystems and natural landscapes [6]. To successfully accomplish restoration techniques, it is important to understand the correlation between ecological features, physical factors (such as hydraulic behavior of rivers) and landscape patterns [7–9]. The analysis of the relationship between human disturbances and landscape structure is the key to accomplish a suitable landscape planning and management [10]. The management of the landscape structure must begin from the full comprehension of all its features because the landscape should be analyzed as a whole using a holistic approach [11,12].

A consolidated technique for the quantification of the main characteristics of a landscape such as structure, function and change is the use of ecological indicators called landscape metrics [13,14]. A large number of metrics have been developed in the past few decades able to assess landscape structure based on categorical maps [7]. Today, the combination of GIS applications and mathematical codes such as FRAGSTATS [15] are widely used in the field of ecological applications. Numerous studies have shown how landscape metrics can provide a large amount of information on landscape composition and configuration [16]. In many cases, landscape metrics are also used to assess how the landscape changes over time under human pressure or to evaluate the effectiveness of conservative plans in protected zones [17–19]. Other studies focused on fluvial landscape configuration and dynamics [20–22].

In the framework of the eco-hydraulics a number of studies have used hydraulic modelling to analyze specific ecological aspects such as the determination of the ecological flow (called also instream flow) [23–25] or the evaluation of habitats suitability [26,27]. Meanwhile, a few studies have investigated the potential advantages of the synergic application of landscape metrics and hydraulic modeling in suitable environments planning [1]. Entwistle et al. [4] used a 2D hydraulic model and FRAGSTATS to evaluate the ecological value of anabranching channels. Van Nieuwenhuysen et al. [28] has utilized landscape metrics to evaluate the degree of hydrological connectivity among artificial catchments. Rare is the application of both methodology to assess the spatial structure of a hydraulic environment [29] and the lack of spatial analysis from hydraulic assessments was previously highlighted by Newson and Newson [30].

The present paper aims to extend the field of spatial analysis application in riverine environments, introducing a methodology that integrates hydraulic modelling and landscape metrics. The proposed method allows predicting the effects of restoration plans on riverine landscapes quantifying ecological features such as connectivity and heterogeneity. Therefore, it could be a useful tool to provide important information guiding decision-makers in territorial planning.

The paper is organized into three main parts:

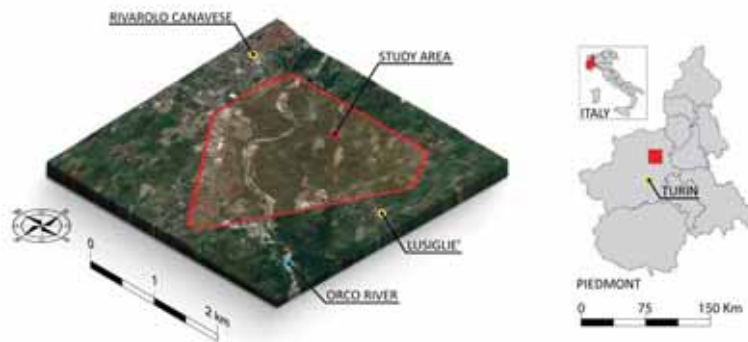
1. a brief contextualization describing the study area in which the work was carried out;
2. the software used are listed and the adopted methodology is described;
3. the outcomes of the study are presented and discussed, and conclusions are drawn.

46 1.1 The aim of the research

47 The objective of this work is to introduce an integrated method which has four purposes: (1)  
48 linking hydraulic knowledge with ecological analysis, mainly using hydraulic models and landscape  
49 metrics; (2) predicting spatial pattern changes and ecological impacts resulting from a river  
50 restoration plan; (3) assessing the spatial configuration and temporal dynamics of different  
51 landscape structures; (4) giving a useful tool to guide local administrations and landscape planners  
52 to choose the most non-invasive plans for territory management.

53 2. Study area

54 The research is focused on the first lowland part of the Orco river's catchment, located in  
55 Piedmont in the north-west of Italy. This part covers approximately 22% of the whole river basin  
56 and it is characterized by a hilly and flat landscape. In this area, the Orco river flows 40 Km to  
57 downstream until his confluence in the Po river and its riverbed shows a sinuous trend with an  
58 alternation of braided and meandering channels. The river reach between the villages of Rivarolo  
59 Canavese and Lusigliè (TO, Italy) was selected for the implementation of the hydraulic model [31].  
60 The study area of 600 hectares was used to carry out hydraulic and ecological analyses [32] (see Fig.  
61 1).



62 Fig. 1 Geographical location of the study area (source of the aerial image: Google Earth®, 2018)

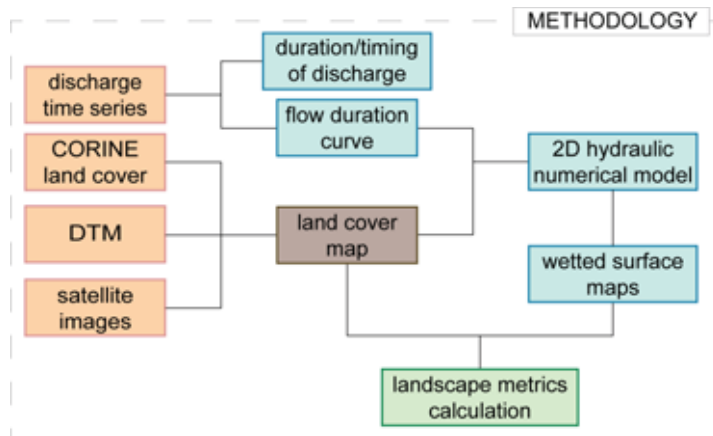
64 From the geomorphological point of view, the chosen reach is slightly carved and its riparian  
65 areas are characterized by the presence of secondary forms and relict water paths on the left and  
66 steep banks on the right. Indeed, the widespread presence of banks in erosion states the planimetric  
67 instability of the river. During significant-flooding events, the river tends to restore the pre-existing  
68 braided shape. This phenomenon affects variations of the main flow direction, leading to a wide  
69 range of historical mobility of the riverbed [33].

70 The land cover presents a patchwork structure, typical of the fluvial plains. Agricultural lands  
71 dominate the study area, almost 50% is covered by meadow and cultivated fields. Woods cover one-  
72 fifth of the surveyed area and its forest vegetation is mainly composed by *Robinia pseudoacacia*  
73 [34].

74 3. Materials and Methods

75 This section describes the multidisciplinary method proposed in this work, between hydraulics  
76 and landscape ecology, which benefits from the combined use of software with different features.  
77 It can be divided into three main steps (see Fig. 2): (1) the construction of a land cover map using  
78 the overlapping of different maps and satellite images into the GIS module of SMS-11.1-Surface-

79 water Modeling System [35]; (2) the implementation of the two-dimensional hydraulic model and  
 80 hydrodynamic simulations using SMS in the pre and post-processing phases and BASEMENT 2.6-  
 81 Basic Simulation Environment [36] for the processing step; (3) the manipulation of categorical maps  
 82 in ArcMap 10.3.1 and calculation of landscape metrics with FRAGSTATS. The current released  
 83 version (FRAGSTATS v4.2) is an efficient tool able to compute a great number of landscape metrics  
 84 from a wide variety of image formats [15].



85 Fig. 2 Schematization of the methodology: input (orange boxes), GIS elaboration (brown box), hydrological/hydraulic  
 86 calculation (light blue boxes) and ecological assessment (green box)  
 87

88 **3.1 Land cover assessment**

89 The first main action necessary for all following analyses was the detection of the spatial  
 90 configuration of the study area. The land cover map was obtained by the combination of spatial  
 91 information from CORINE Land Cover 2000, Digital Terrain Model DTM with a high resolution (on  
 92 average 1 point each square meter) realized by Ministry for the Environment and the Protection of  
 93 the Territory and the Sea during the extraordinary Plan of Environmental Remote Sensing with  
 94 LiDAR scan and upgraded satellite images. The resulting land cover map was divided into seven  
 95 categories: grassland, wood, river bank, water, factories, urban center and roads (see Fig. 3). The  
 96 distribution of each land cover class in the study area is shown in Table 1.

97 Table 1 Area, percentage cover and Manning's Roughness Coefficient of each land cover class in the study area

Land cover class	Area [ha]	Percentage cover [%]	Manning's Roughness Coefficient
Grassland	276.2	46.0	0.07
Wood	124.5	20.7	0.08
River bank	33.1	5.5	0.045
Water	41.3	6.9	0.045
Factories	8.9	1.5	0.15
Urban center	112.2	18.7	0.15
Roads	4.0	0.7	0.03
Total	600	100	

98 Then each class was matched with a Manning's Roughness Coefficient which represents the  
 99 hydraulic resistance offered by each surface to the water flow. The identification of the appropriate  
 100 roughness coefficient derived from a back-analysis carried out during the calibration of the hydraulic  
 101 model [37]. The high-resolution data permitted also to consider the shapes and geographical

102 positions of structures within the domain such as bridge piers, levees, and road embankments. All  
 103 these data were necessary to build the hydraulic model and accomplish hydrodynamic simulations.

### 104 3.2 Hydraulic simulations

105 The two-dimensional hydraulic model was implemented to simulate the behavior of the river  
 106 reach and to estimate the amount of wetted area with specific discharges. Throughout a preliminary  
 107 hydrologic analysis, we calculated the flow duration curve (FDC) and its characteristic values (Qxx)  
 108 were extracted. In this paper, the value of Qxx will refer to the amount of discharge that should be  
 109 present on average at least xx days per year in the analyzed river reach. The FDC was calculated  
 110 from the elaboration of flow data collected from 2010 to 2016 by a gage station near to the  
 111 upstream boundary of the hydraulic model domain. Each Qxx value was used as an inner boundary  
 112 condition for hydrodynamic simulations. Moreover, the duration and timing of each discharge were  
 113 investigated.

114 The 2D numerical model is based on the numerical resolution of the Shallow Water Equations.  
 115 These equations calculate the flow field assuming a hydrostatic distribution of the pressures along  
 116 the depth and neglecting the vertical component of the flow [38]. The conservative form of the  
 117 equation system can be written as:

$$118 U_t + \nabla \cdot (F, G) + S = 0, \quad (1)$$

119 where  $U_t$  is the derivation with respect to time ( $t$ ) of the conserved variables vector,  $F$  and  $G$  are  
 120 the vectors of fluxes and  $S$  is the vector of source terms, in the  $x$  and  $y$  directions, given by: where

$$123 U = \begin{pmatrix} h \\ uh \\ vh \end{pmatrix}, \quad F = \begin{pmatrix} uh \\ u^2h + \frac{1}{2}gh^2 - vh \frac{\partial u}{\partial x} \\ uvh - vh \frac{\partial u}{\partial y} \end{pmatrix},$$

$$124 G = \begin{pmatrix} vh \\ uvh - vh \frac{\partial v}{\partial x} \\ v^2h + \frac{1}{2}gh^2 - vh \frac{\partial v}{\partial y} \end{pmatrix},$$

$$125 S = \begin{pmatrix} 0 \\ gh(S_{fx} - S_{Bx}) \\ gh(S_{fy} - S_{By}) \end{pmatrix}. \quad (2)$$

126 where  $h$  is the water depth (m),  $u$  and  $v$  are the cartesian components of the flow velocity vector  
 127 (m/s),  $g$  is gravity acceleration (m/s<sup>2</sup>),  $\nu$  is the total viscosity (m<sup>2</sup>/s),  $S_f$  is the friction slope (-) and  $S_b$   
 128 is the bed slope (-).

130 The land cover map obtained in the previous step was matched with the altimetric data of the  
 131 DTM to create a computational grid (mesh). This grid represents the mathematical representation  
 132 of the river topography and the basic geometry of the two-dimensional hydraulic model. Two  
 133 different sets of simulations were carried out: in the first, the river behavior on the actual

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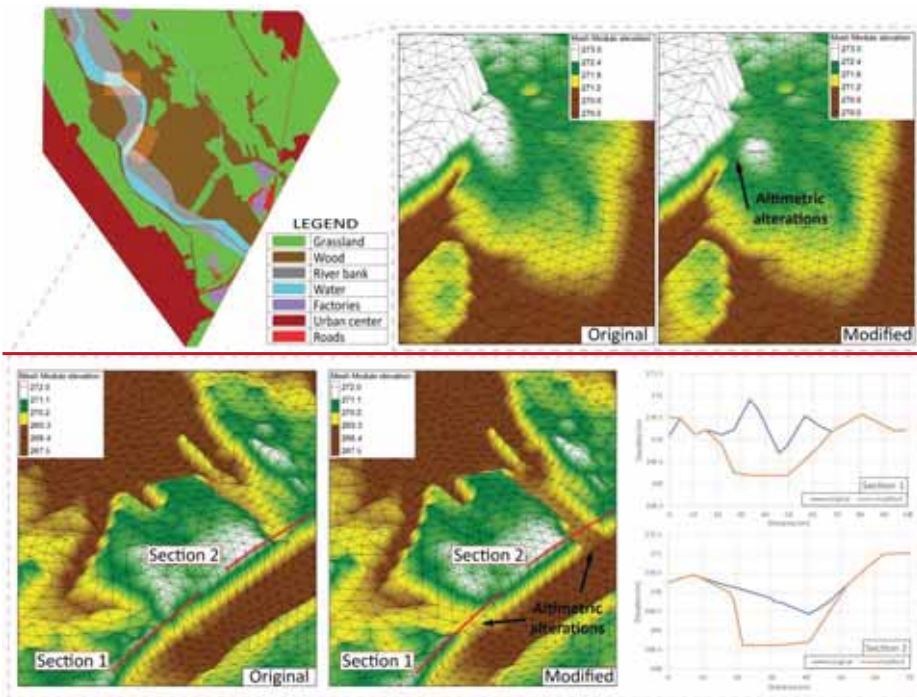
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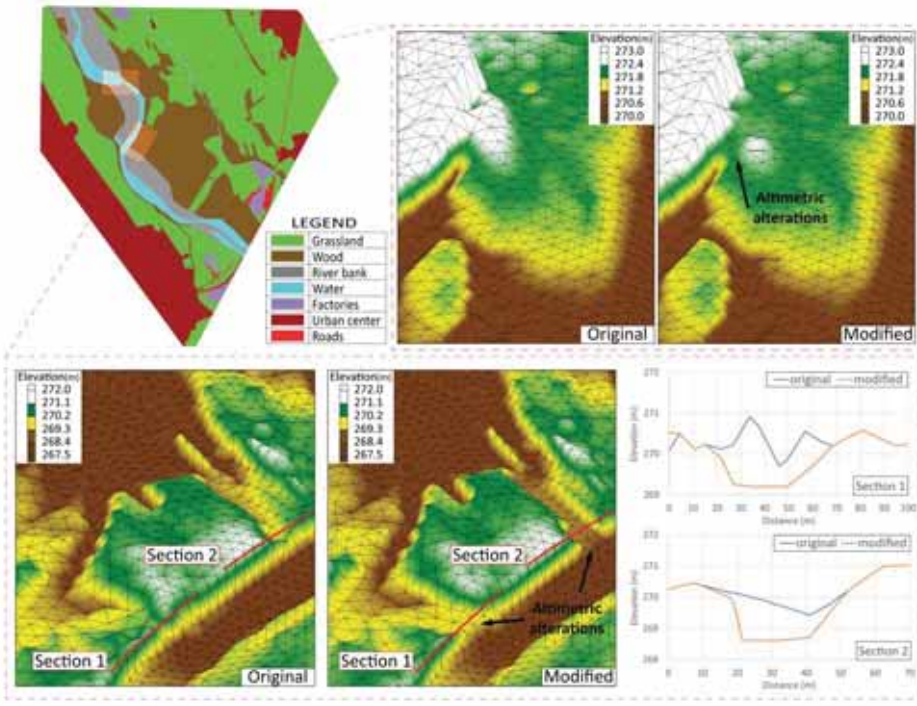
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134 topography was simulated, this will be called “original” scenario. In the second, the wetted area on  
135 a modified computational mesh simulating the river restoration plan was calculated, this will be  
136 called “modified” scenario. In order to obtain the “modified” scenario, a series of altimetric  
137 alterations were applied to modify the original mesh. These alterations were circumscribed along  
138 100 m of natural riverbanks digging natural levees for reconnecting remnant meanders with the  
139 main channel. These levees were created by the intensive sediment transport of floods over time.  
140 The alterations of the mesh are displayed in Fig. 3.

141



142



143 Fig. 3 Land cover map and morphological alterations. Top: enlargement on the original and modified mesh of the first  
144 altered site. Bottom: enlargement on the original and modified mesh of the second altered site, and two graphs that  
145 display the modified profile of the river bank.

### 146 3.3 Calculation of landscape metrics

147 As output of the hydraulic simulation stage, vector layers were produced from each simulation  
148 reporting the total amount of wetted area and its distribution into the study area. They have been  
149 edited through GIS tools to create raster files used as FRAGSTATS inputs. The high accuracy of the  
150 hydraulic model outcomes permitted to keep a high-resolution during the rasterization of the vector  
151 maps. The grain size of 1 m was set up during the rasterization process [39].

152 Landscape composition and configuration have been evaluated using FRAGSTATS for both cases,  
153 “original” and “modified” scenarios. The analyses were carried out with the standard patch neighbor  
154 8-cell rule option. FRAGSTATS calculates a number of landscape indices but sometimes several of  
155 them are redundant, especially when two equivalent landscapes are compared. Thus, in order to  
156 choose the most representative indices, metrics that did not show a ~~significant, remarkable~~ variation  
157 between the “original” and “modified” landscape ( $\Delta < 0.1$ ) have been discarded. Furthermore, a  
158 smaller set of seven metrics have been selected according to the most used landscape indices in  
159 literature. For a comprehensive characterization of the landscape, we selected metrics belonging to  
160 three different metrics categories called Area-Edge, Shape and Aggregation. Each category reveals  
161 specific information such as: (I) Area-Edge analyzes the degree of fragmentation, (II) Shape  
162 measures the geometry complexity and (III) Aggregation quantifies the landscape configuration,  
163 namely the level of patch dispersion [7]. The classification and description of each metrics are listed  
164 as follows:

#### 165 I. Area-Edge metrics:

- 166 1. ED: Edge Density equals the sum of the lengths of all edge segments in the landscape, divided  
167 by the total landscape area;
- 168 2. AREA\_AM: Area-weighted Mean patch Area equals the sum, across all patches in the  
169 landscape, of the patch area, multiplied by the proportional abundance of the patch;
- 170 3. AREA\_SD: Standard Deviation in patch Area equals the square root of the sum of the squared  
171 deviations of each patch size from the mean patch size computed for all patches in the  
172 landscape, divided by the total number of patches;
- 173 4. AREA\_CV: Coefficient of Variation in patch Area equals the standard deviation divided by the  
174 mean, multiplied by 100 to convert to a percentage;

#### 175 II. Shape metrics:

- 176 5. SHAPE\_AM: Area-weighted Mean Shape index equals the sum, across all patches in the  
177 landscape, of the patch perimeter divided by the square root of patch area standardized to  
178 a square, multiplied by the proportional abundance of the patch;

#### 179 III. Aggregation metrics:

- 180 6. PD: Patch Density equals the number of patches in the landscape divided by total landscape  
181 area;
- 182 7. ENN\_MN: Mean Euclidean Nearest Neighbor distance equals the sum, across all patches in  
183 the landscape, of the distance to the nearest neighboring patch of the same type, based on  
184 shortest edge-to-edge distance, divided by the total number of patches.

185 The equations and the corresponding terms of these metrics are shown in Table 2.

186 Table 2 List of landscape metrics used in the study [15]

Metrics	Equations	Terms
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Edge Density (ED)	$ED = E/A$	Where E is the total length of the edge in landscape and A is total landscape area
Area-weighted Mean patch Area (AREA_AM)	$AREA\_AM = \sum_{i=1}^m \sum_{j=1}^n \left[ a_{ij} \left( \frac{a_{ij}}{\sum_{i=1}^m \sum_{j=1}^n a_{ij}} \right) \right]$	Where $a_{ij}$ is the area of patch i of the patch type j
Standard Deviation in patch Area (AREA_SD)	$AREA\_SD = \sqrt{\frac{\sum_{i=1}^m \sum_{j=1}^n \left[ a_{ij} - \left( \frac{\sum_{i=1}^m \sum_{j=1}^n a_{ij}}{N} \right) \right]^2}{N}}$	Where $a_{ij}$ is the area of patch i of the patch type j and N is the total number of patches in the landscape
Coefficient of Variation in patch Area (AREA_CV)	$AREA\_CV = \left[ \frac{AREA\_SD}{\sum_{i=1}^m \sum_{j=1}^n a_{ij}} \right] (100)$	Where $a_{ij}$ is the area of patch i of the patch type j and N is the total number of patches in the landscape
Area-weighted Mean Shape index (SHAPE_AM)	$AREA\_AM = \sum_{i=1}^m \sum_{j=1}^n \left[ \left( 0.25 \cdot p_{ij} / \sqrt{a_{ij}} \right) \left( \frac{a_{ij}}{\sum_{i=1}^m \sum_{j=1}^n a_{ij}} \right) \right]$	Where $p_{ij}$ is the perimeter of the patch i of the patch type j and $a_{ij}$ is the area of patch i
Patch Density (PD)	$PD = N/A$	Where N is the total number of patches in the landscape and A is the total landscape area
Mean Euclidean Nearest Neighbor distance (ENN_MN)	$ENN\_MN = \frac{\sum_{i=1}^m \sum_{j=1}^n h_{ij}}{N}$	Where $h_{ij}$ is the distance from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center and N is the total number of patches in the landscape

187  
188 The set of seven ecological metrics was calculated for both “original” and “modified” scenarios  
189 and for each Qxx. The difference between the two analyzed cases will be indicated with the  
190 parameter  $\Delta A$ , calculated as follows:

191  $\Delta = metrics_{modified\ scenario} - metrics_{original\ scenario}$  (3)

## 192 4. Results

193 Results obtained in this study have both hydraulic and ecological nature. Hydraulic outputs  
194 represent the input for the ecological analysis. For this reason, results will be described in two  
195 different subsections.

### 196 4.1 Hydraulic outputs

197 The examined FDC represents the relationship between the amount of discharge and its  
198 persistence during a mean hydrologic year [40]. The FDC and its characteristic values are shown in  
199 Fig. 4.

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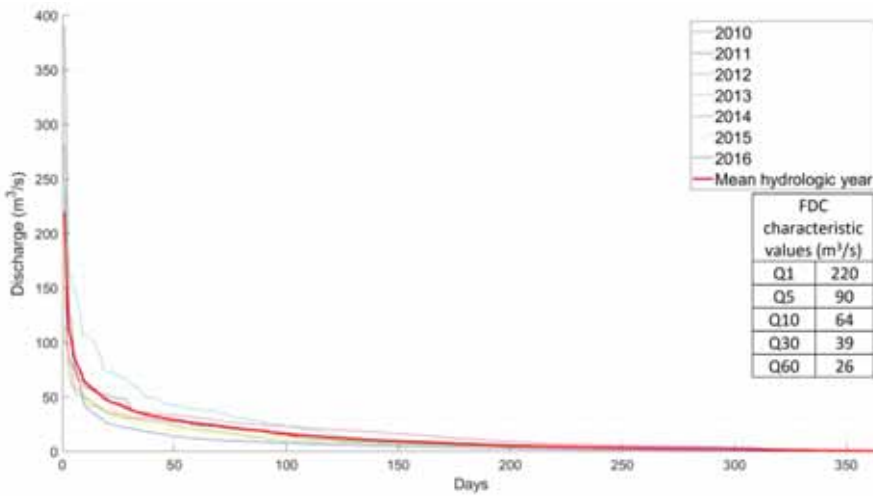


Fig. 4 Flow duration curve and its characteristic values

The duration and timing of the different discharges are displayed in Fig. 5.

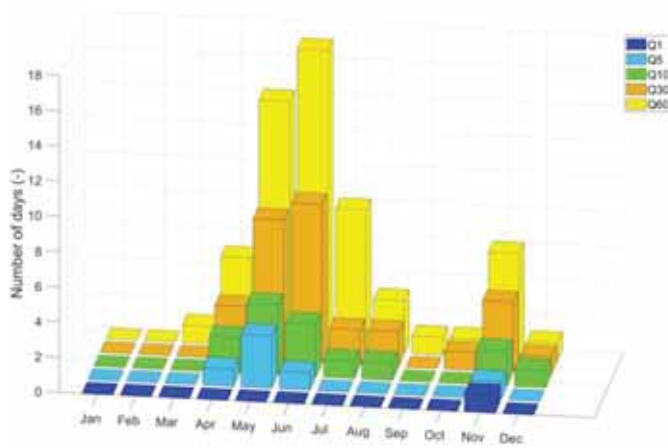
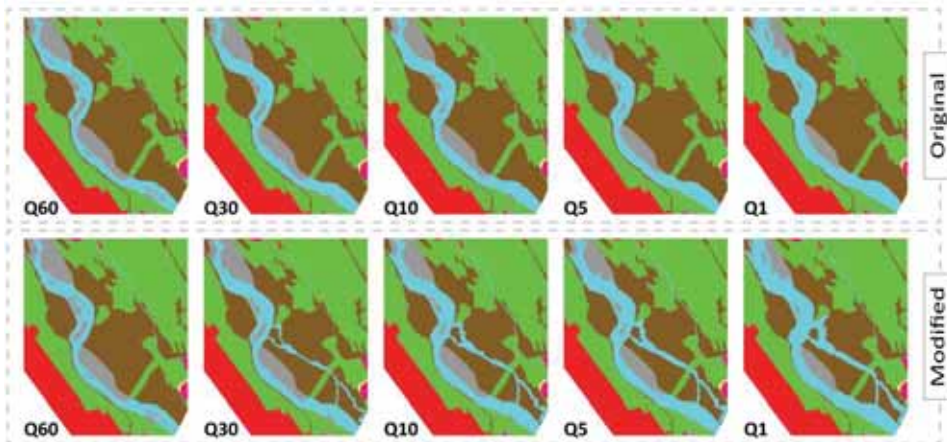


Fig. 5 Timing and duration of each analyzed discharge (mean number of days per month in which that amount of discharge flows into the river).

Using these discharges as upstream boundary condition in hydrodynamic simulations, the numerical model produces different wetted area maps for both “original” and “modified” configurations. Hydraulic simulations on the “original” mesh depict all the same scenarios in which the total amount of water flow only into the main channel (Fig. 6). Whereas, simulations on the “modified” geometry show a different behavior of the river as the flow increases:

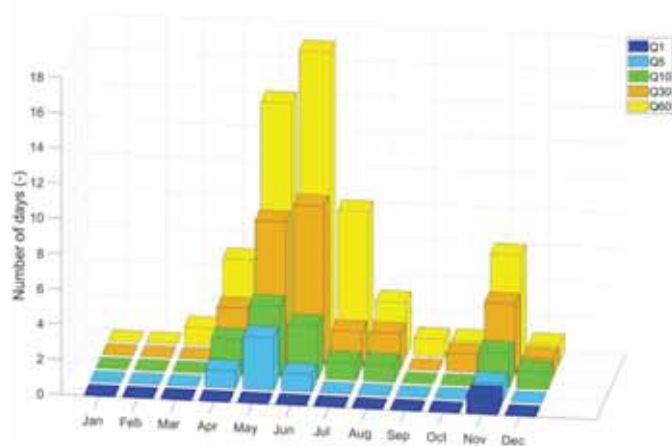
- if the discharge is less than Q30, the water flows into the main channel and exclusively the little channel in the first modified site is reactivated (Fig. 6, Q60);
- if the discharge is greater than or equal to Q30, the discharge overtops the river bank and starts to flow not only in the original streambed but also through the floodplain bringing water to the riparian ecosystem (Fig. 6, Q30-Q1).



216  
217 Fig. 6 Hydraulic outcomes for both scenarios with increasing discharge from left to right. The reactivation of the  
218 remnant streambeds leads to an increase of the wetted surface of 1.8%, 18.9%, 21.8%, 22.1% and 23.3% respectively  
219 for the scenario with Q60, Q30, Q10, Q5 and Q1.

220 The reactivation of the remnant meanders ~~The duration and timing of the different discharges~~  
221 ~~are displayed in Fig. 6.~~

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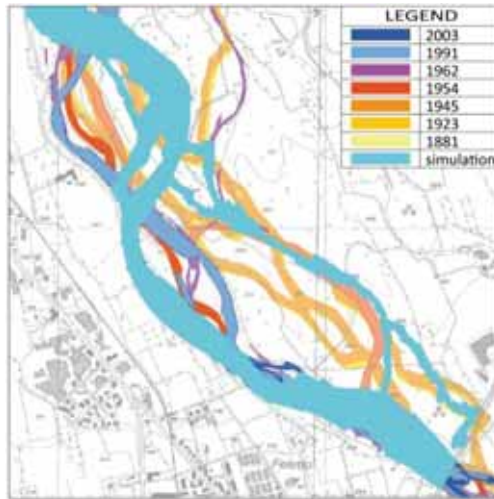


222  
223 ~~Fig. 6 Timing and duration of each analyzed discharge (mean number of days per month in which that amount of~~  
224 ~~discharge flows into the river).~~

225 As shown by the previous image, is strictly connected with the hydrology of the Orco river, which  
226 is yearly characterized by two distinct periods of high flow (Fig. 5). The first, in which the discharge  
227 grows according to spring rainfalls together with the snow melting in the headwater; the second,  
228 characterized by the occurrence of yearly flood events caused by intense autumn rainstorms. This  
229 flow pattern leads to the reactivation of the remnant meanderschannels for 24 days from April to  
230 August, and for 6 days from October to December. June and November show the maximum duration  
231 of discharge greater than Q30.

232 The river restoration action is completely respectful of the original ecosystem since the  
233 subtracted water flows in the floodplain and then gets back to the river 1 Km downstream. This new  
234 configuration is also in accordance with the planimetric divagation range (streamway) of the river.

235 Superimposing the wetted surface map of the “modified” scenario over the planimetric variations  
 236 map of the Orco river, it is clear how the flow retraces the paths of old abandoned riverbeds (Fig.  
 237 7). Reconnecting remnant meanders or rebuilding secondary channels are restoration actions  
 238 widely adopted to enhance the ecological value of the riverine ecosystems and recreate the  
 239 continuum with the floodplain [6,41–44].



240  
 241 Fig. 7 Superimposition of the modified wetted surface map over the planimetric variations in the Orco river map  
 242 (realized by Research Institute for the Hydrogeological Protection–Turin section)

243 **4.2 Ecological outputs**

244 In order to assess the effects of the restoration plan on the landscape structure and its riverine  
 245 ecosystem, a series of comparisons were carried out. Firstly, the comparison at the class and  
 246 landscape level of metrics obtained from both scenarios with Q30 aims to highlight changes in the  
 247 spatial configuration due to reactivated channels. All outcomes are summarized in Table 3.

248 Table 3 The group of seven metrics (ED – Edge Density, AREA\_AM – Area-weighted Mean patch Area, AREA\_SD –  
 249 Standard Deviation in patch Area, AREA\_CV – Coefficient of Variation in patch Area, PD – Patch Density, SHAPE\_AM –  
 250 Area-weighted Mean Shape index and ENN\_MN – Mean Euclidean Nearest Neighbor distance) calculated with Q30 for  
 251 both scenarios and their comparison. Factories, urban center and roads classes have been neglected since they have  
 252 not been altered by the restoration plan.

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Landscape level							
Metrics	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Original scenario	109.0	58.5	21.3	231.1	10.8	2.9	95.3
Modified scenario	119.9	55.2	19.9	235.3	11.8	3.0	84.4
$\Delta$	10.8	-3.3	-1.4	4.2	1.0	0.2	-10.9

Class level							
Original scenario							
Land cover class	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Grassland	73.2	66.2	29.1	168.3	2.7	2.8	11.7
Wood	60.3	44.8	17.4	209.7	2.5	3.2	29.2
River bank	18.0	9.6	4.6	138.0	1.7	2.0	53.4
Water	30.8	37.5	18.1	131.2	0.5	4.7	164.0

Modified scenario							
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Land cover class	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Grassland	73.5	65.9	28.4	174.9	2.8	2.8	12.3
Wood	70.2	25.6	11.0	177.8	3.2	3.2	26.6
River bank	17.8	9.7	4.5	150.3	1.8	2.0	44.2
Water	42.4	45.2	21.7	132.8	0.5	6.8	81.6
$\Delta$							
Grassland	0.3	-0.2	-0.7	6.6	0.2	0.0	0.6
Wood	9.9	-19.1	-6.4	-31.9	0.7	0.1	-2.6
River bank	-0.2	0.1	-0.1	12.4	0.2	0.0	-9.2
Water	11.6	7.8	3.7	1.6	0.0	2.1	-82.4

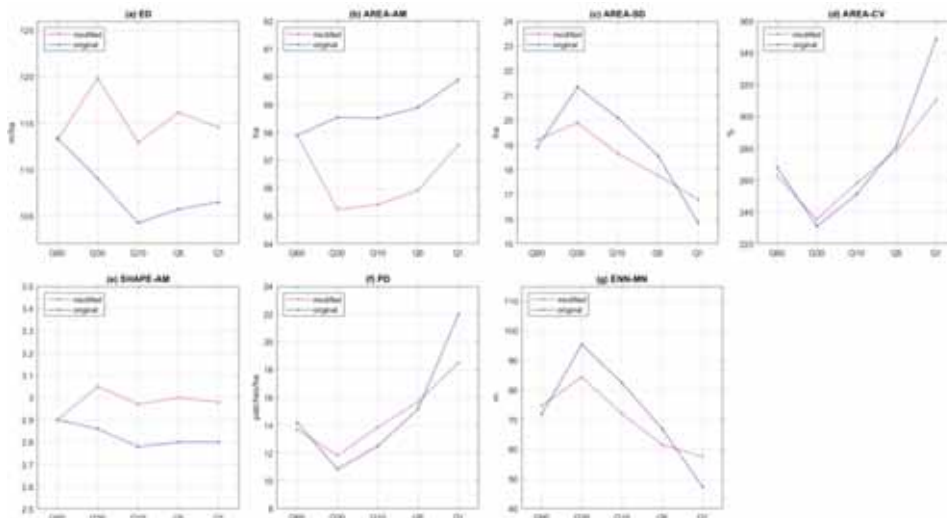
253 Focusing at the landscape level, the modified landscape shows a slight increase in fragmentation  
254 degree. Consistent with observations of Sowińska-Świerkosz and Soszyński [39], alterations caused  
255 by the reactivated channels among the floodplain lead to a separation into a larger number of  
256 smaller patches increasing the fragmentation degree. This information is justified by the growth of  
257 ED and AREA\_CV values and in the AREA\_AM and AREA\_SD decreasing. As reported by McGarigal  
258 and Marks [7], the variation of AREA\_CV and AREA\_SD means that on the modified study area  
259 patches become smaller and their distribution size is farther from the average size than in the  
260 original area.

261 In the context of habitat fragmentation, the grade of patch isolation is calculated with the  
262 Euclidean Nearest Neighbor distance (ENN) metric [15,45]. The modified area presents a smaller  
263 value of ENN\_MN, with a decrease of 11.5%. This means that even if the patches are more  
264 fragmented, they are less isolated.

265 Another important ecological factor is the landscape complexity. The modified landscape shows  
266 a slight increase in the degree of complexity in the planar shape given by the raised value of  
267 SHAPE\_AM. This metrics illustrates how much the patch shape is different from the standard square  
268 shape. Generally, natural shapes are not regular, therefore the restored configuration appears to  
269 be more akin to a natural environment. The last analyzed ecological metrics was PD. The slight  
270 increase of 9% in PD value in the modified landscape, in correlation with ED, means that the  
271 modified landscape has a higher level of heterogeneity. Previous studies have confirmed the  
272 effectiveness of PD and ED as indicators of the spatial heterogeneity degree in landscapes [32].

273 Landscape attributes at class level were also analyzed in order to understand in-depth the results  
274 of this stage. The most modified land cover classes were wood and water because the reactivated  
275 watercourses run across the floodplain covered by wood (Fig. 6). As reported in Table 3, there is a  
276 **significant substantial** difference in nearest neighbor distance for water patches, from 164 to 81.  
277 While the variation of AREA\_AM and AREA\_CV in wood class caused by the subdivision in more  
278 smaller patches shows a remarkable decrease of 40%.

279 In the second stage, since in a natural river the amount of flow varies during the year, the  
280 evaluation of dynamics of the landscape structure was carried out tracking the wetted area  
281 distribution for the different discharges. Landscape metrics calculated at the landscape level are  
282 summarized in Fig. 8.



283  
 284 Fig. 8 Landscape metrics representing the dynamics of landscape structure in terms of fragmentation (a: Edge  
 285 Density, b: Area-weighted Mean patch Area, c: Standard Deviation in patch Area, d: Coefficient of Variation in patch  
 286 Area), complexity (e: Area-weighted Mean Shape index) and configuration (f: Patch Density, g: Mean Euclidean Nearest  
 287 Neighbor Distance) as the flow increases.

288 For the Q60 both scenarios are very similar, whereas a significant considerable variation can be  
 289 noticed for the other discharges. ED value in the modified scenario rises and falls at each increment  
 290 due to the intermittent ramification of water paths creating isolated wood and river bank patches.  
 291 SHAPE\_AM is almost unvaried meaning that neither restoration activity nor increasing discharge do  
 292 not strongly affect the complexity level of the landscape. However, all metrics show the same trend  
 293 in both scenarios stating how the restoration action have not changed the response of the riverine  
 294 landscape to discharge variation. Only for the maximum discharge Q1, the number of patches  
 295 classified as river bank increase in the original scenarios and decrease in the modified scenario  
 296 leading to a reversion of the value of the metric (Fig. 8c, d, f, g).

## 297 5. Discussion

298 The methodology presented in this study is a procedure able to assess the impacts of changes in the  
 299 spatial structure of riverine landscapes. Different scenarios may be developed according to different  
 300 strategies to achieve specific objectives [10]. Moreover, it is possible to analyze different landscapes  
 301 to identify needs and lacks in an attempt to apply specific restoration actions aimed at improving  
 302 ecological conditions [39]. Using a numerical-based approach, a wide range of scenarios can be  
 303 compared, and the most suitable plan may be chosen by authorities improving the management of  
 304 the territory.

305 In the studied case a river restoration action was carried out reactivating natural watercourses  
 306 among the floodplain and its impact on the landscape structure was analyzed. Results obtained in  
 307 the previous section are metrics used to give a quantification of four fundamental ecological  
 308 attributes such as fragmentation, isolation, complexity, and heterogeneity. The chosen discharges  
 309 have permitted to analyze the spatial configuration and dynamics of these components since the  
 310 hydraulic conditions that reactivate the watercourses are non-stationary. When flow rate in the  
 311 river is less than Q30, no water flows in the floodplain and the lower level of fragmentation means  
 312 a higher level of connectivity among the patches with the same class type. For some species such as

313 mammals, this landscape is more hospitable because larger areas offer stable conditions required  
314 to host a flourishing population. While, when discharge is greater than the threshold Q30, flow  
315 reactivates watercourses watering riparian ecosystems and increasing the degree of fragmentation  
316 especially for the wood class. The landscape with a mosaic of varied ecosystems is more attractive  
317 for the multi-habitat species [39]. Thus, the higher level of fragmentation does not involve habitat  
318 losses or impoverishment of biodiversity but on the contrary, the modified morphology proves to  
319 be more suitable for a greater variety of ecosystems [46,47].

320 The edge density is directly correlated to the grade of spatial heterogeneity and fragmentation  
321 [7]. The increasing of this metrics means that when water flows into the floodplain a higher amount  
322 of edges affects the landscape. The increased level of fragmentation and the reduction in patch size  
323 could influence the behavior of some animal species, particularly these periodic changes can  
324 support, alternately, the growth of species that prefer edge habitats or interior kinds [48]. When  
325 discharge periodically increases, the variation of connections between patches with no-water  
326 classification may influence the migration of terrestrial species which require connectedness. For  
327 instance, the early reactivation of the remnant streambeds coincides with the hedgehog breeding  
328 season (species living in the study area, [49]). Thus, the lack of connectivity within the riparian forest  
329 could affect the mobility of these animals hindering them reproduction. On the contrary, in the  
330 same period, the presence of new wetlands provides an attractive habitat for pond breeding  
331 amphibians [50].

332 However, cyclical dry and wet periods raise the production of nutrient matter improving the  
333 environmental quality of aquatic biota. The autumnal reactivation will move organic matter that  
334 covers the ground, such as leaf litter, enhancing the abundance of detritivorous macroinvertebrates,  
335 in particular, shredders such as Ephemeroptera and Plecoptera [51,52]. These organisms will break  
336 the coarse particulate organic material up into a finer size feeding the collectors leaving in the river  
337 downstream. Since the riparian area is covered by trees, the presence of coarse wood in the  
338 reactivated channels provides a favorable habitat for organisms such as biofilm algae which will  
339 represent a new source of food for invertebrates such as snails and beetles [53].

340 The slight increase in shape complexity shows that the applied geomorphological modifications  
341 do not produce great variations in landscape structure in both landscape and class level. This  
342 demonstrates how the tested river restoration plan is non-invasive towards the patch geometry.  
343 Anthropogenic activities in river restoration planning should be as eco-friendly as possible in order  
344 to enhance the ecological value of the landscape without leaving human evidence. The monitoring  
345 of the complexity degree can be an efficient indicator to assess the interference of human activities  
346 in the landscape.

347 The variation of ENN\_MN is concentrated mainly in water patches until Q5 and involves markedly  
348 river bank class with Q1. It represents a reduction in patch isolation, meaning that the altered  
349 landscape configuration has a smaller interpatch distance. Indeed, when water flows through the  
350 floodplain, the distribution of wetted surfaces is more homogeneous into the study area. Regarding  
351 the wood class, several studies have claimed that patch isolation influences the life of bird  
352 communities and the insularity due to fragmented habitats has a negative impact on bird species  
353 [54]. In the proposed restoration plan the difference in isolation degree is favorable in most cases.  
354 Only the grassland class presents a negligible increase of almost 5%. The modified configuration  
355 conduces to a more heterogeneous landscape able to host a proliferation of vast varieties of animal  
356 populations, both aquatic and terrestrial species. The level of heterogeneity will change over the  
357 year, according to the hydrology of the river, varying ecological processes among landscape pattern  
358 [55].

359 All the above-mentioned considerations derive from the interpretation of the analyzed metrics  
360 and their values. The quantification of these metrics is strongly conditioned by the parameters  
361 selected by the operator. Especially during the rasterization of the vector files, the choice of the cell  
362 size could alter the outcome leading to an erroneous division or union of patches. This problem is  
363 emphasized for landscape metrics based on the size and number of patches [7]. Many studies have  
364 shown how grain size affects the outcomes of landscape metrics applications [56–58]. For this  
365 reason, we chose a very fine grain size, 1 m, in order to generate a raster file representative of the  
366 reality.

367 Moreover, as stated by Plexida et al. [32], some landscape metrics are influenced by the size of  
368 the analyzed domain such as area-edge and shape metrics. The use of a restricted area size could  
369 lead to analyze a landscape characterized by a single class, impeding the assessment of ecological  
370 attributes of the study area. In addition, whether the restoration plan aims to recover plants and  
371 animals, the presented methodology should be applied considering a scale compatible with the  
372 species' perception of the environment [59]. For instance, an agricultural field could represent an  
373 entire habitat for an insect but, simultaneously, only a single patch for a bird.

## 374 6. Conclusion

375 Nowadays an increased sensibility towards environment joins experts, authorities, and researchers  
376 in the search for the best solutions for sustainable management of the territory. Multidisciplinary  
377 approaches are needed to understand the interactions between natural processes and human  
378 activities.

379 In this paper, a method was proposed that integrates hydraulic and landscape ecological  
380 knowledge with the purpose of creating a tool able to simulate a river restoration plan and quantify  
381 its impact on the landscape structure and its ecosystems. This methodology can predict the  
382 achievement of the objectives in landscape planning and evaluate whether the proposed design is  
383 suitable and valid in a cost-benefit analysis perspective. The entire procedure is based on  
384 geographical information and numerical data. Therefore, it represents a significant advantage  
385 because required data can be extrapolated from thematic maps or numerical simulation, reducing  
386 the necessity of costly on-site surveys.

387 The feature of reusability of the hydraulic models makes it possible to simulate and compare  
388 different landscape scenarios to assess the best solution. This method may be helpful for local  
389 administrations to better understand the configuration of their territory and to choose the most  
390 suitable plan to restore altered areas. In order to limit overengineering in restoration plans, all  
391 actors should keep in mind the capabilities of the ecosystems to self-design and avoid the over-  
392 engineering.

393 However, the proposed methodology highlighted two main limitations. Firstly, the choice of the  
394 study area extent must be compatible with the available computational power, being it directly  
395 related to the accuracy of the hydraulic numerical model. The second issue, the choice and  
396 interpretation of landscape metrics are conditioned by the features of the analyzed area.

397 Future work should test this methodology on a wider range of river restoration plans. The results  
398 of this study should encourage all actors to use multidisciplinary approaches in order to design and  
399 manage the territory in accordance with the conservation and protection of natural ecosystems.

## 400 Notations

401  $\rightarrow U$ : vector of conserved variables [–]

402  $\rightarrow F, G$ : flux vectors [–]

- 403  $\mathbf{S}$ : vector of source terms [—]  
 404  $h$ : water depth [m]  
 405  $u, v$ : cartesian components of the flow velocity vector [m/s]  
 406  $g$ : gravity acceleration [m/s<sup>2</sup>]  
 407  $\nu$ : total viscosity [m<sup>2</sup>/s]  
 408  $S_f$ : friction slope [—]  
 409  $S_b$ : bed slope [—]  
 410  $t$ : time [s]  
 411  $\frac{\partial}{\partial t}$ : derivation with respect to variable  $t$  of the  $\mathbf{U}$  vector  
 412  $\nabla$ : Nabla operator  
 413  $\frac{\partial}{\partial x}$ : partial differential operator for derivation with respect to variable  $x$   
 414  $\frac{\partial}{\partial y}$ : partial differential operator for derivation with respect to variable  $y$

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- 554

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The present letter reports feedback given by the advisory editor and the replies of the authors. The advisory editor's comments are written in black and the author's replies are written in blue.

I would like to thank the advisory editor for further precious feedback. The revised version of the draft follows and replies all comments.

Advisory Editor's Comments:

Dear authors,

Thank you for submitting the revised version of your manuscript. You have processed all comments of the reviewer and me. I particularly like the sections you added to the discussion about the expected impact of the changes on animal. Good job.

I now consider your manuscript ready for publication, on the condition that you perform the following seven format/layout changes:

1. All variables in all equations need to be defined and (shortly) described below the equation. Please do this for the variables in equation 1.

The description of variables has been added. To avoid a repetition, the last section "Notation has been removed.

2. In our journal, each displayed mathematical expression needs to be treated as part of an English sentence and end in a comma if the sentence continues (e.g., as in (1)), or in a period if the sentence stops (e.g., as in (2)).

The authors may wish to use the following manuscript as an example of good and consistent formatting of mathematical expressions:

The Strategic Impact of Adaptation in a Transboundary Pollution Dynamic Game B Vardar, G Zaccour  
Environmental Modeling & Assessment 23 (6), 653-669.

Punctuation has been added.

3. The legends of the meshes and graphs in Figure 3 are too small; please enlarge them.

The image has been improved.

4. Line 224: Please change "the previous image" to "Fig. 6", as images might be placed in a different part of the article in the typesetted version.

The sentence has been modified.

5. In my opinion, the current Fig. 6 fits better between Fig. 4 and Fig. 5, as Fig. 6 displays the current flow regimes, and Fig. 5 the impacts of this regime on the channel activation for the two scenarios.

The Fig. 6 has been moved before the actual Fig 5, inverting the order of images.

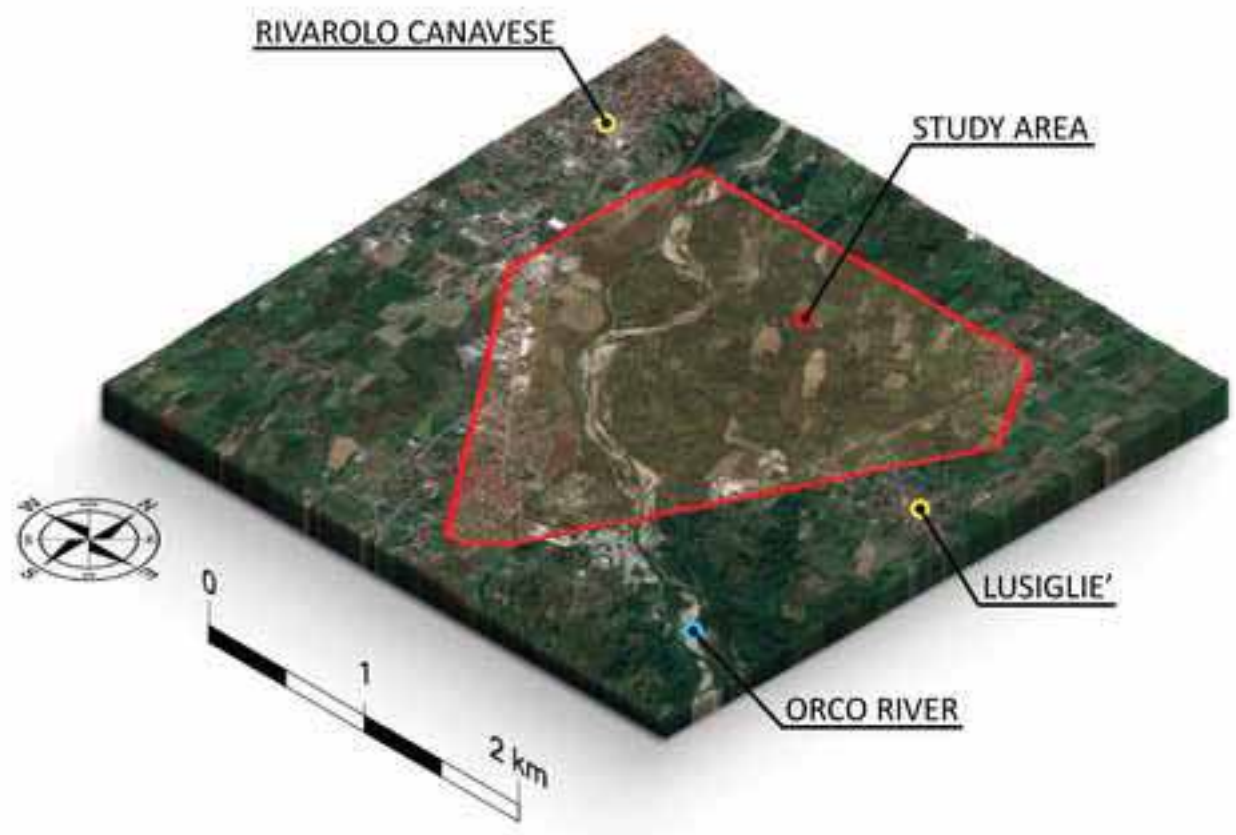
6. Please provide the full names of the landscape metrics in the caption of Table 3, such that the table is understandable in isolation.

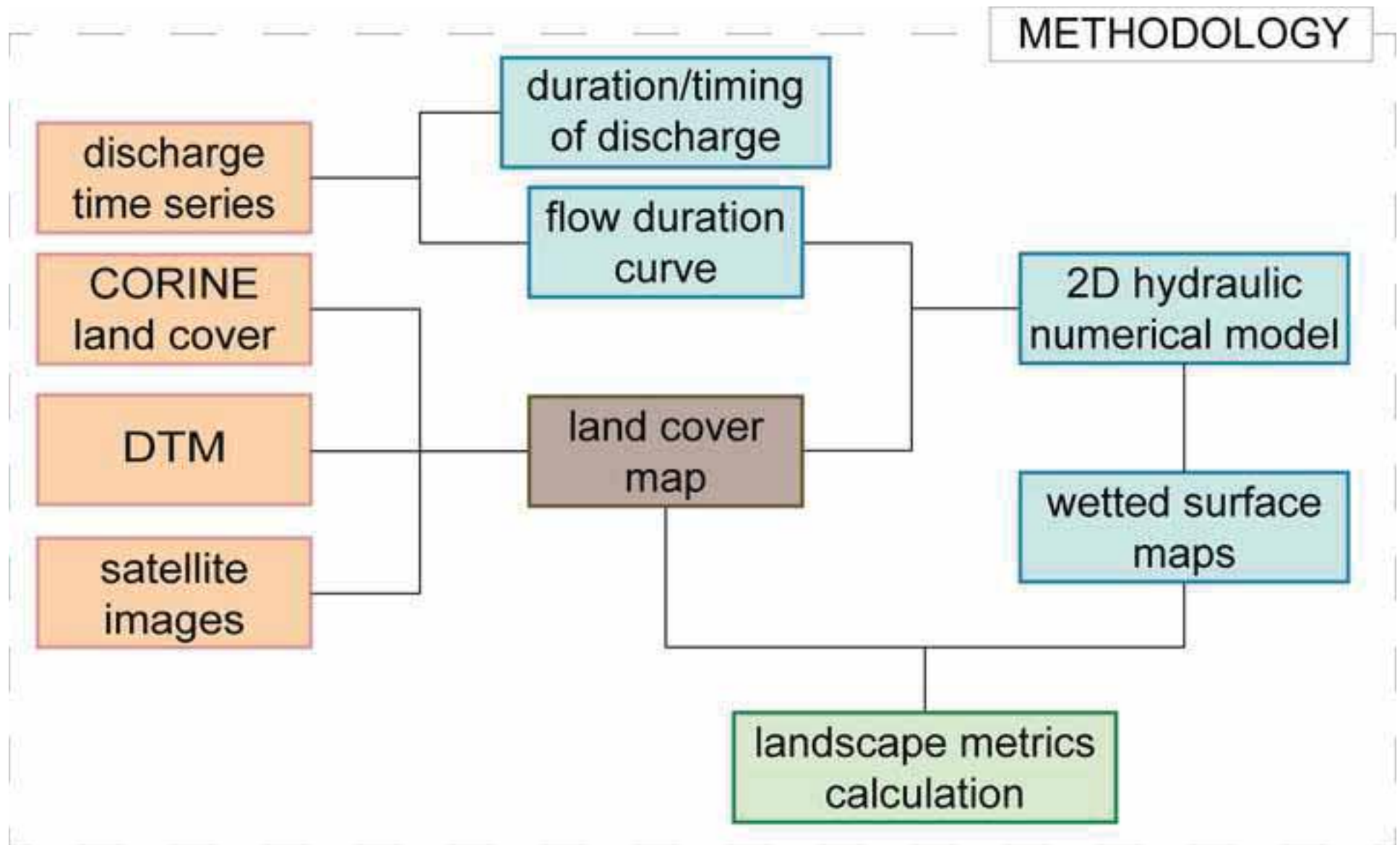
Full names of metrics have been added.

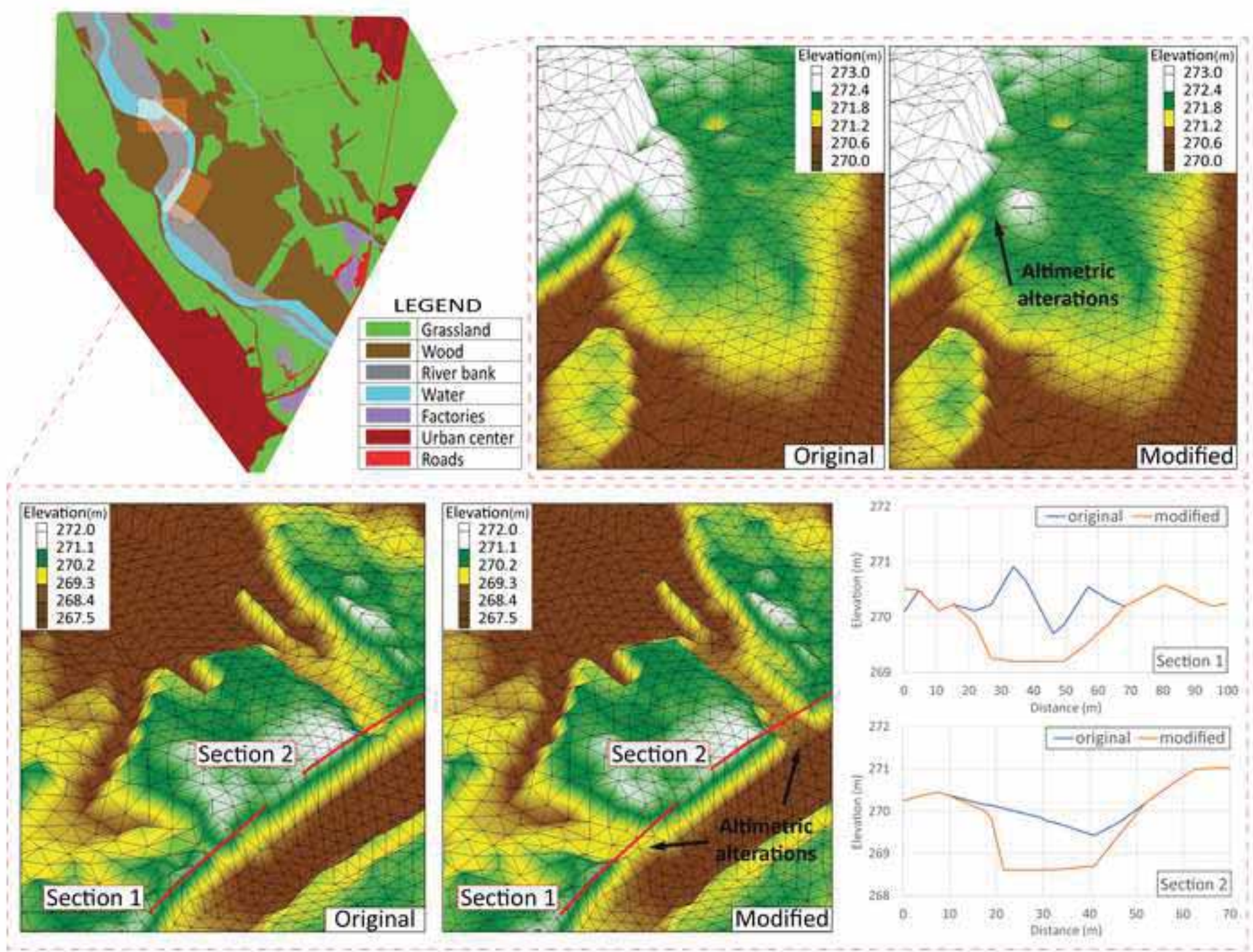
7. Line 286: Please only use the word significant if you actually performed a significance test.

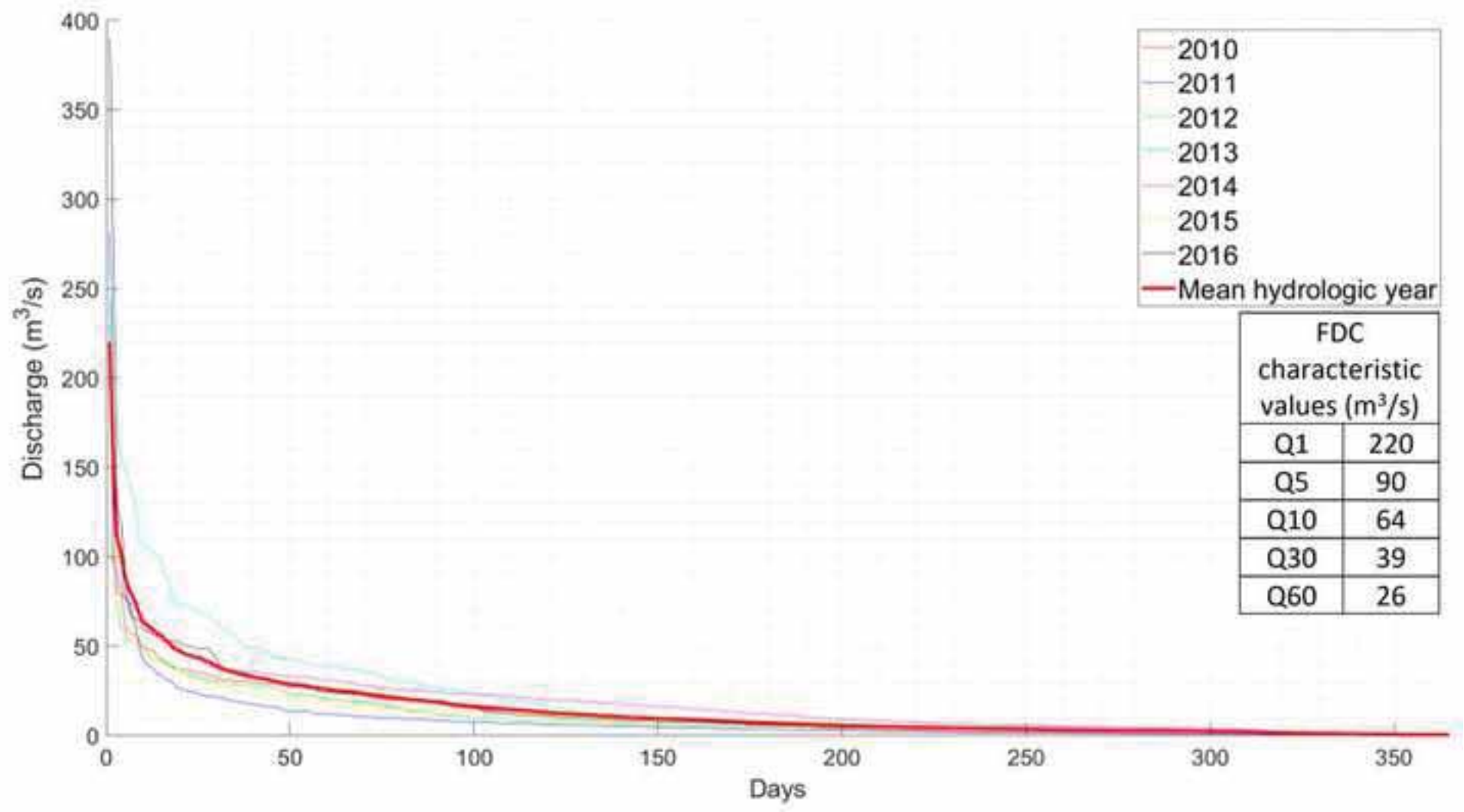
The word "significant" has been substituted.

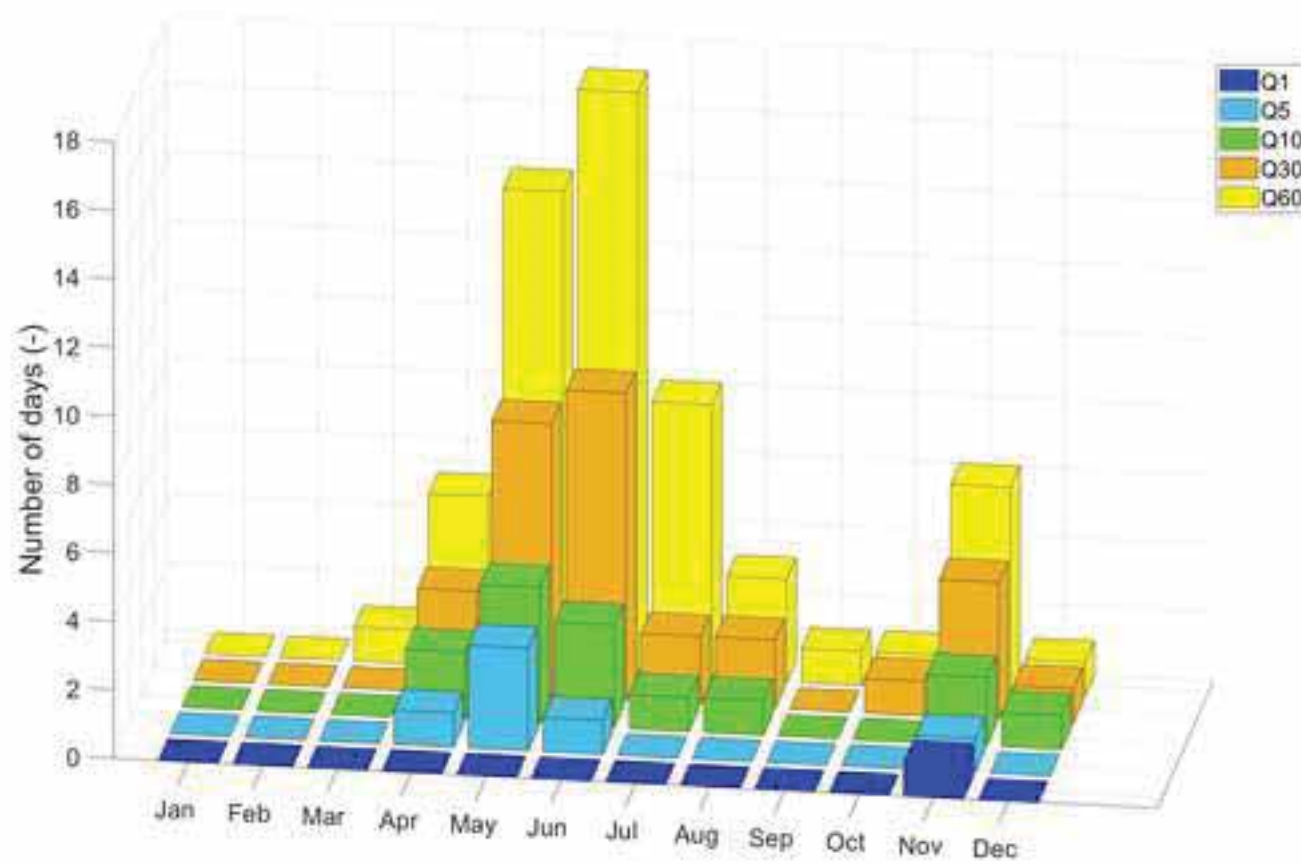
Best regards,  
The AE

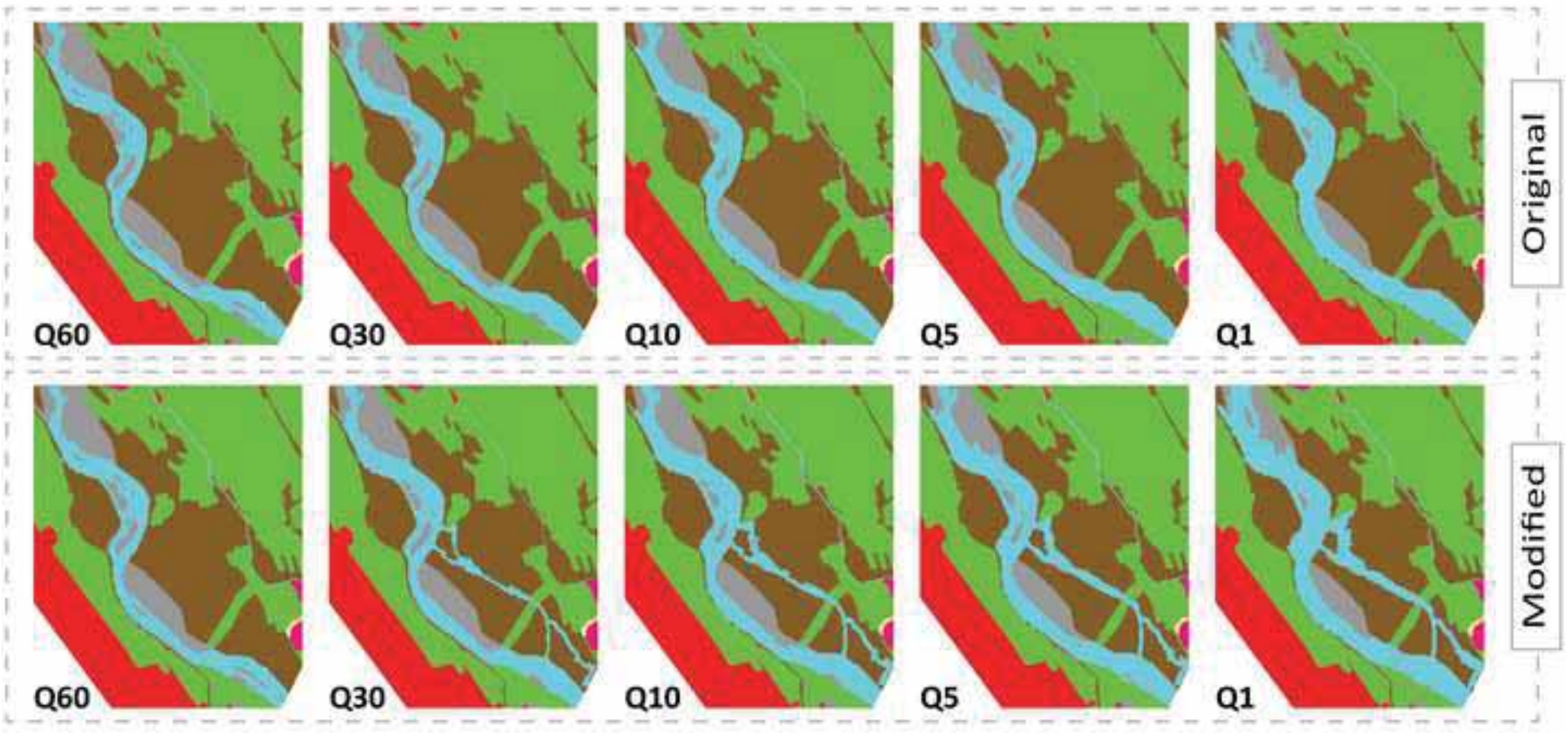


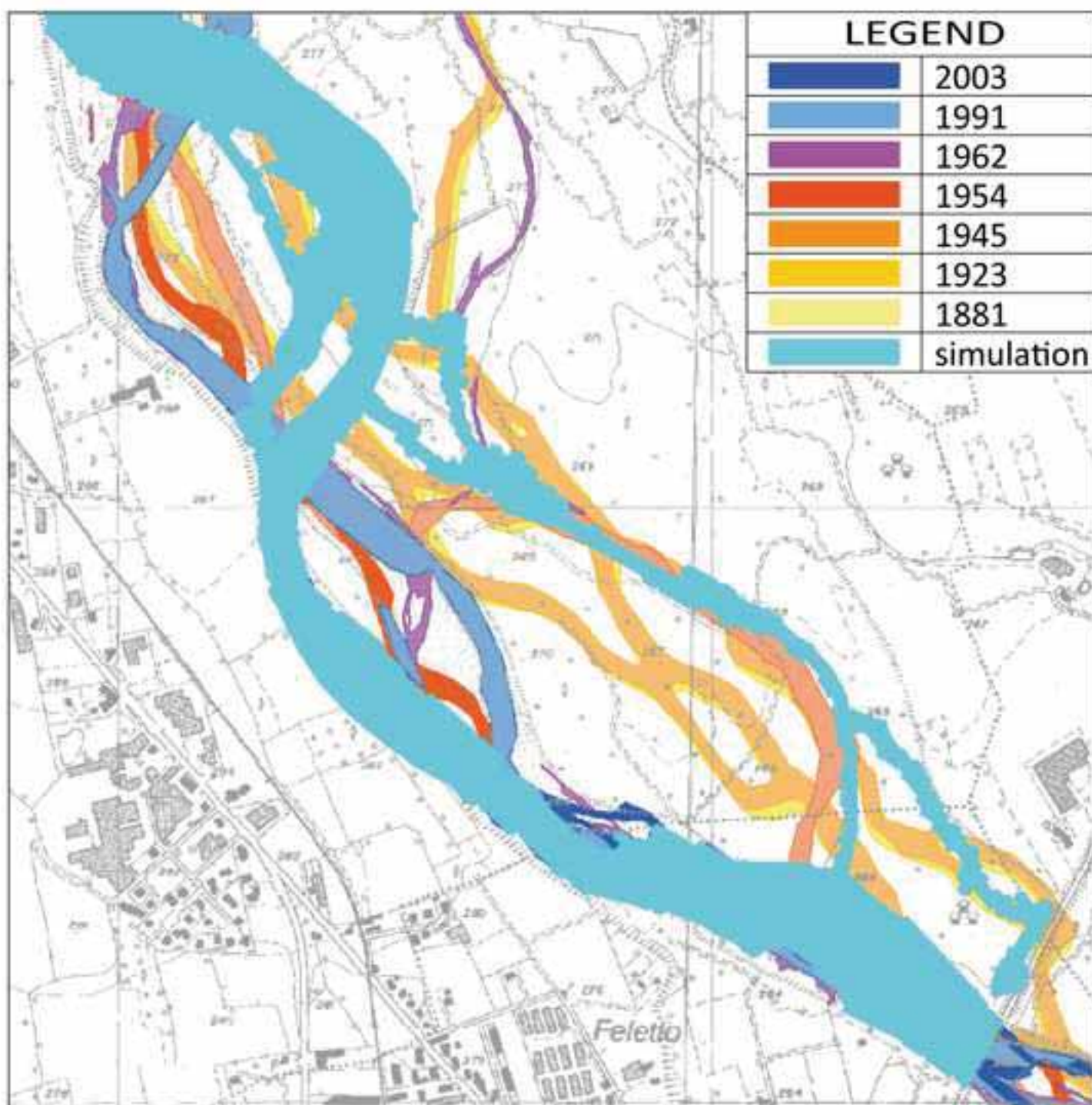


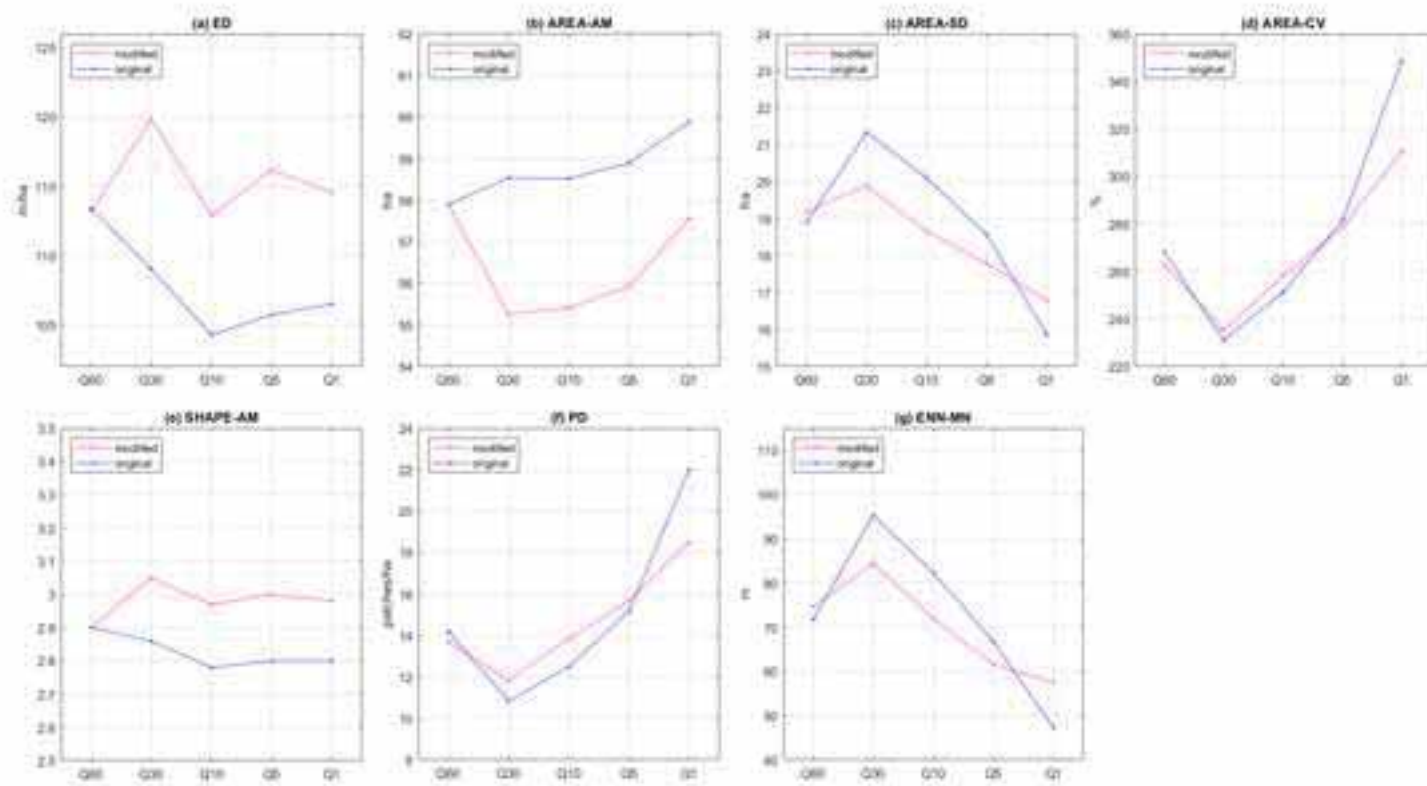












*Table 1 Areas, percentage cover and Manning's Roughness Coefficient of each land cover class in the study area*

Land cover class	Area [ha]	Percentage cover [%]	Manning's Roughness Coefficient
Grassland	276.2	46.0	0.07
Wood	124.5	20.7	0.08
River bank	33.1	5.5	0.045
Water	41.3	6.9	0.045
Factories	8.9	1.5	0.15
Urban center	112.2	18.7	0.15
Roads	4.0	0.7	0.03
Total	600	100	

*Table 2 List of landscape metrics used in the study [15]*

Metrics	Equations	Terms
Edge Density (ED)	$ED = E/A$	Where E is the total length of the edge in landscape and A is total landscape area
Area-weighted Mean patch Area (AREA_AM)	$AREA\_AM = \sum_{i=1}^m \sum_{j=1}^n \left[ a_{ij} \left( \frac{a_{ij}}{\sum_{i=1}^m \sum_{j=1}^n a_{ij}} \right) \right]$	Where $a_{ij}$ is the area of patch i of the patch type j
Standard Deviation in patch Area (AREA_SD)	$AREA\_SD = \sqrt{\frac{\sum_{i=1}^m \sum_{j=1}^n \left[ a_{ij} - \left( \frac{\sum_{i=1}^m \sum_{j=1}^n a_{ij}}{N} \right) \right]^2}{N}}$	Where $a_{ij}$ is the area of patch i of the patch type j and N is the total number of patches in the landscape
Coefficient of Variation in patch Area (AREA_CV)	$AREA\_CV = \left[ \frac{AREA\_SD}{\frac{\sum_{i=1}^m \sum_{j=1}^n a_{ij}}{N}} \right] (100)$	Where $a_{ij}$ is the area of patch i of the patch type j and N is the total number of patches in the landscape
Area-weighted Mean Shape index (SHAPE_AM)	$AREA\_AM = \sum_{i=1}^m \sum_{j=1}^n \left[ \left( 0.25 \cdot p_{ij} / \sqrt{a_{ij}} \right) \left( \frac{a_{ij}}{\sum_{i=1}^m \sum_{j=1}^n a_{ij}} \right) \right]$	Where $p_{ij}$ is the perimeter of the patch i of the patch type j and $a_{ij}$ is the area of patch i
Patch Density (PD)	$PD = N/A$	Where N is the total number of patches in the landscape and A is the total landscape area
Mean Euclidean Nearest Neighbor distance (ENN_MN)	$ENN\_MN = \frac{\sum_{i=1}^m \sum_{j=1}^n h_{ij}}{N}$	Where $h_{ij}$ is the distance from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center and N is the total number of patches in the landscape

**Table 3** The group of seven metrics (*ED* – Edge Density, *AREA\_AM* – Area-weighted Mean patch Area, *AREA\_SD* – Standard Deviation in patch Area, *AREA\_CV* – Coefficient of Variation in patch Area, *PD* – Patch Density, *SHAPE\_AM* – Area-weighted Mean Shape index and *ENN\_MN* – Mean Euclidean Nearest Neighbor distance) calculated with Q30 for both scenarios and their comparison. Factories, urban center and roads classes have been neglected since they have not been altered by the restoration plan.

Landscape level							
Metrics	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Original scenario	109.0	58.5	21.3	231.1	10.8	2.9	95.3
Modified scenario	119.9	55.2	19.9	235.3	11.8	3.0	84.4
$\Delta$	10.8	-3.3	-1.4	4.2	1.0	0.2	-10.9
Class level							
Original scenario							
Land cover class	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Grassland	73.2	66.2	29.1	168.3	2.7	2.8	11.7
Wood	60.3	44.8	17.4	209.7	2.5	3.2	29.2
River bank	18.0	9.6	4.6	138.0	1.7	2.0	53.4
Water	30.8	37.5	18.1	131.2	0.5	4.7	164.0
Modified scenario							
Land cover class	ED	AREA_AM	AREA_SD	AREA_CV	PD	SHAPE_AM	ENN_MN
Grassland	73.5	65.9	28.4	174.9	2.8	2.8	12.3
Wood	70.2	25.6	11.0	177.8	3.2	3.2	26.6
River bank	17.8	9.7	4.5	150.3	1.8	2.0	44.2
Water	42.4	45.2	21.7	132.8	0.5	6.8	81.6
$\Delta$							
Grassland	0.3	-0.2	-0.7	6.6	0.2	0.0	0.6
Wood	9.9	-19.1	-6.4	-31.9	0.7	0.1	-2.6
River bank	-0.2	0.1	-0.1	12.4	0.2	0.0	-9.2
Water	11.6	7.8	3.7	1.6	0.0	2.1	-82.4