Landscape Metrics Integrated in Hydraulic Modeling for River Restoration Planning

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Landscape metrics integrated in hydraulic modeling for river restoration planning

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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.
Response to Reviewers:	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.

16 January 2020

Paolo Tamagnone

Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy

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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

Authors

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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, ecologist 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 anabranched 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.

1.1 The aim of the research

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

2. Study area

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

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

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

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

3. Materials and Methods

This section describes the multidisciplinary method proposed in this work, between hydraulics and landscape ecology, which benefits from the combined use of software with different features. It can be divided into three main steps (see Fig. 2): (1) the construction of a land cover map using the overlapping of different maps and satellite images into the GIS module of SMS-11.1-Surface-water Modeling System [35]; (2) the implementation of the two-dimensional hydraulic model and hydrodynamic simulations using SMS in the pre and post-processing phases and BASEMENT 2.6-Basic Simulation Environment [36] for the processing step; (3) the manipulation of categorical maps in ArcMap 10.3.1 and calculation of landscape metrics with FRAGSTATS. The current released version (FRAGSTATS v4.2) is an efficient tool able to compute a great number of landscape metrics from a wide variety of image formats [15].

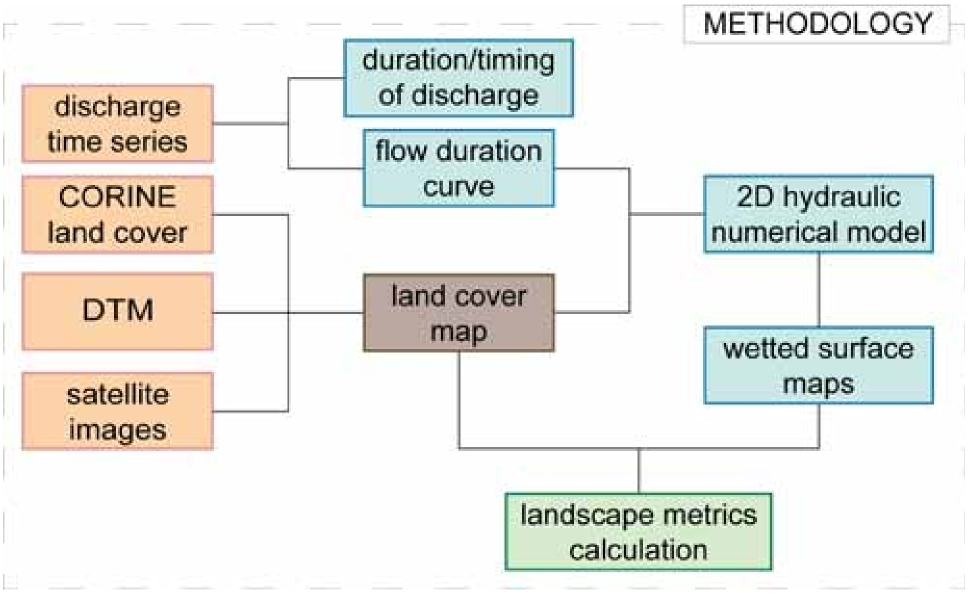


Fig. 2 Schematization of the methodology: input (orange boxes), GIS elaboration (brown box), hydrological/hydraulic calculation (light blue boxes) and ecological assessment (green box)

3.1 Land cover assessment

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

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	

Then each class was matched with a Manning's Roughness Coefficient which represents the hydraulic resistance offered by each surface to the water flow. The identification of the appropriate roughness coefficient derived from a back-analysis carried out during the calibration of the hydraulic model [37]. The high-resolution data permitted also to consider the shapes and geographical positions of structures within the domain such as bridge piers, levees, and road embankments. All these data were necessary to build the hydraulic model and accomplish hydrodynamic simulations.

3.2 Hydraulic simulations

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

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

$$U_t + \nabla \cdot (F, G) + S = 0, \tag{1}$$

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

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

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

where h is the water depth (m), u and v are the cartesian components of the flow velocity vector (m/s), g is gravity acceleration (m/s^2), ν is the total viscosity (m^2/s), S_f is the friction slope (-) and S_b is the bed slope (-).

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

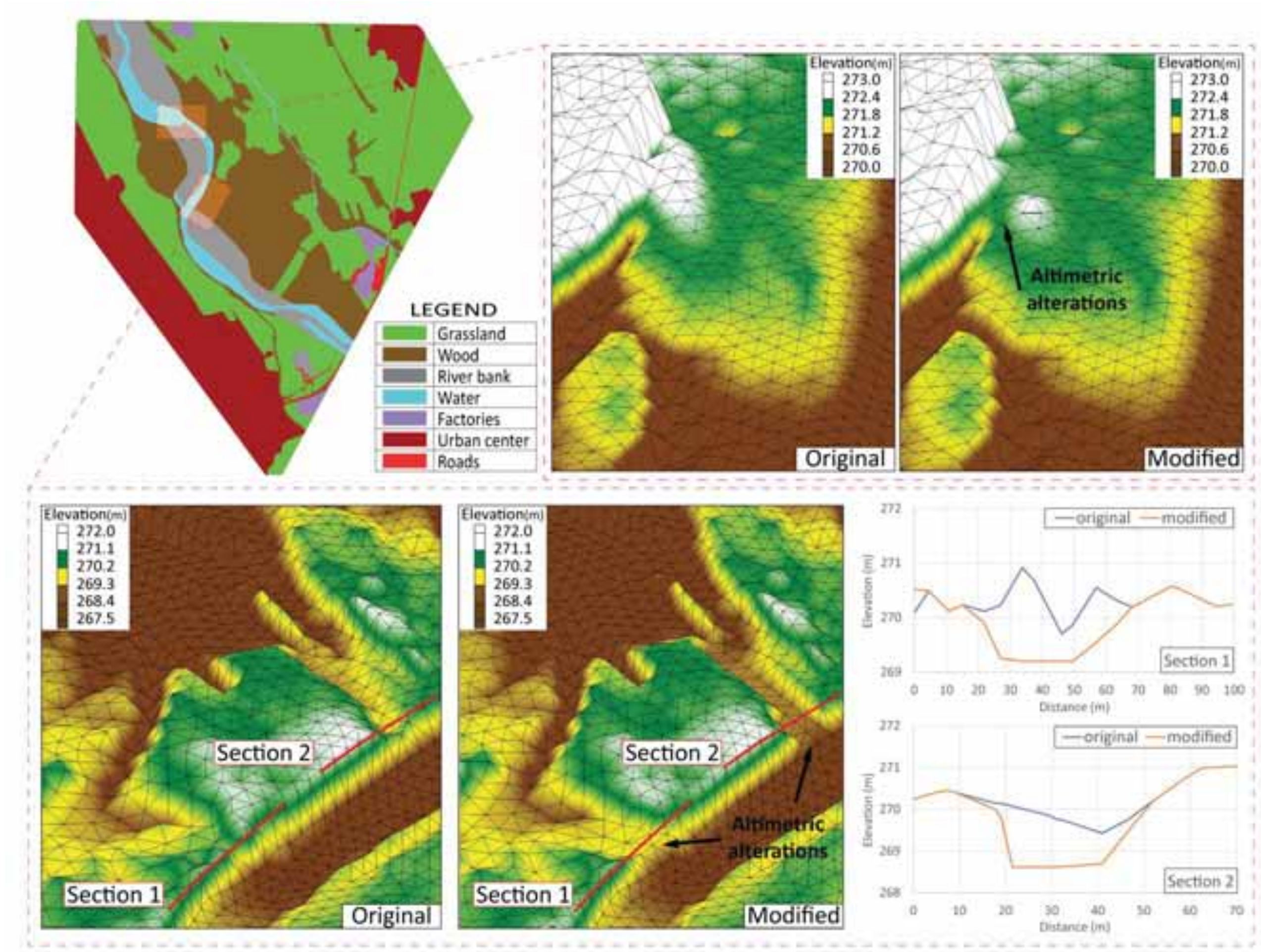


Fig. 3 Land cover map and morphological alterations. Top: enlargement on the original and modified mesh of the first altered site. Bottom: enlargement on the original and modified mesh of the second altered site, and two graphs that display the modified profile of the river bank.

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:

1. ED: Edge Density equals the sum of the lengths of all edge segments in the landscape, divided by the total landscape area;
2. AREA_AM: Area-weighted Mean patch Area equals the sum, across all patches in the landscape, of the patch area, multiplied by the proportional abundance of the patch;
3. AREA_SD: Standard Deviation in patch Area equals the square root of the sum of the squared deviations of each patch size from the mean patch size computed for all patches in the landscape, divided by the total number of patches;
4. AREA_CV: Coefficient of Variation in patch Area equals the standard deviation divided by the mean, multiplied by 100 to convert to a percentage;

II. Shape metrics:

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

III. Aggregation metrics:

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

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

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)	$\mathrm{AREA\_AM} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$	Where a_{ij} is the area of patch i of the patch type j
Standard Deviation in patch Area (AREA_SD)	$\mathrm{AREA\_SD} = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij-}\left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}{N}\right)\right]^{2}}{N}}$	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)	$\mathrm{AREA\_CV} = \left[\mathrm{AREA\_SD} \Big/ \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}{N}\right](100)$	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)	$\mathrm{AREA\_AM} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(0.25 \cdot p_{ij} \Big/ \sqrt{a_{ij}}\right)\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$	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

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

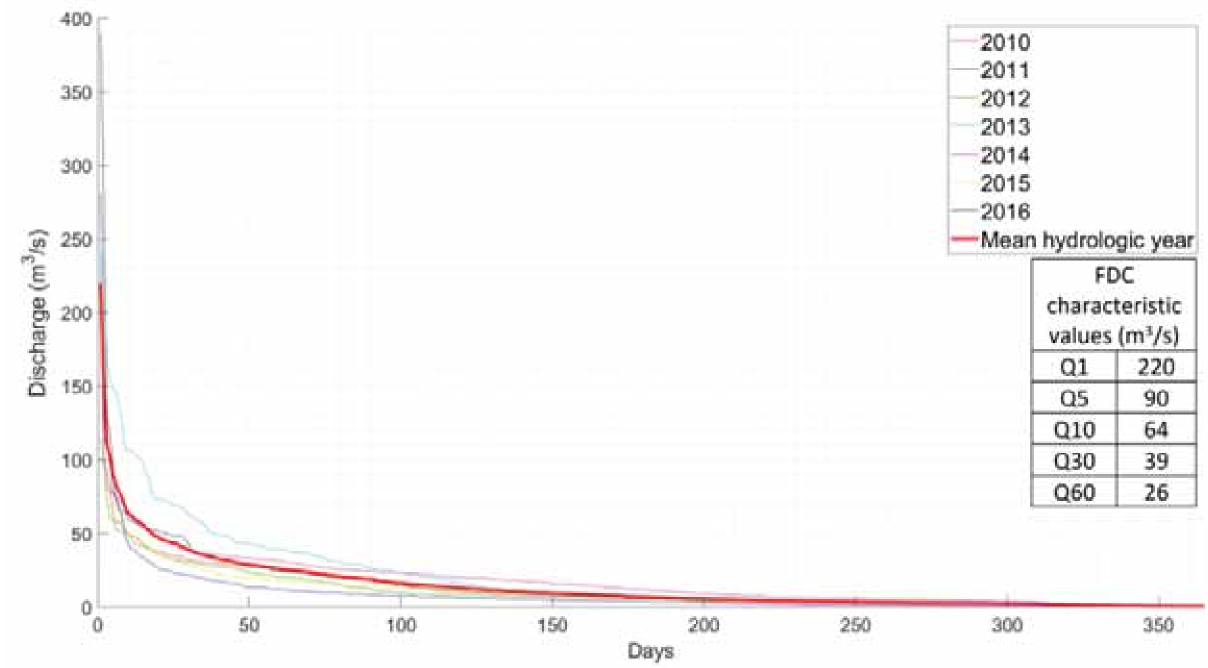
$$\Delta = metrics_{modified\ scenario} - metrics_{original\ scenario}. \tag{3}$$

4. Results

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

4.1 Hydraulic outputs

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



FDC characteristic values (m³/s)	
Q1	220
Q5	90
Q10	64
Q30	39
Q60	26

Fig. 4 Flow duration curve and its characteristic values

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

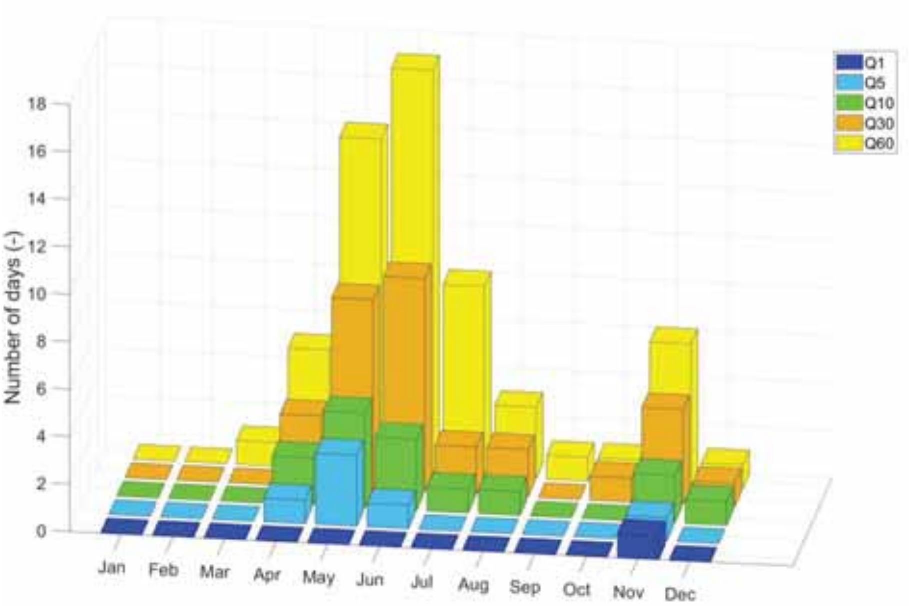


Fig. 5 Timing and duration of each analyzed discharge (mean number of days per month in which that amount of discharge flows into the river).

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 among 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).

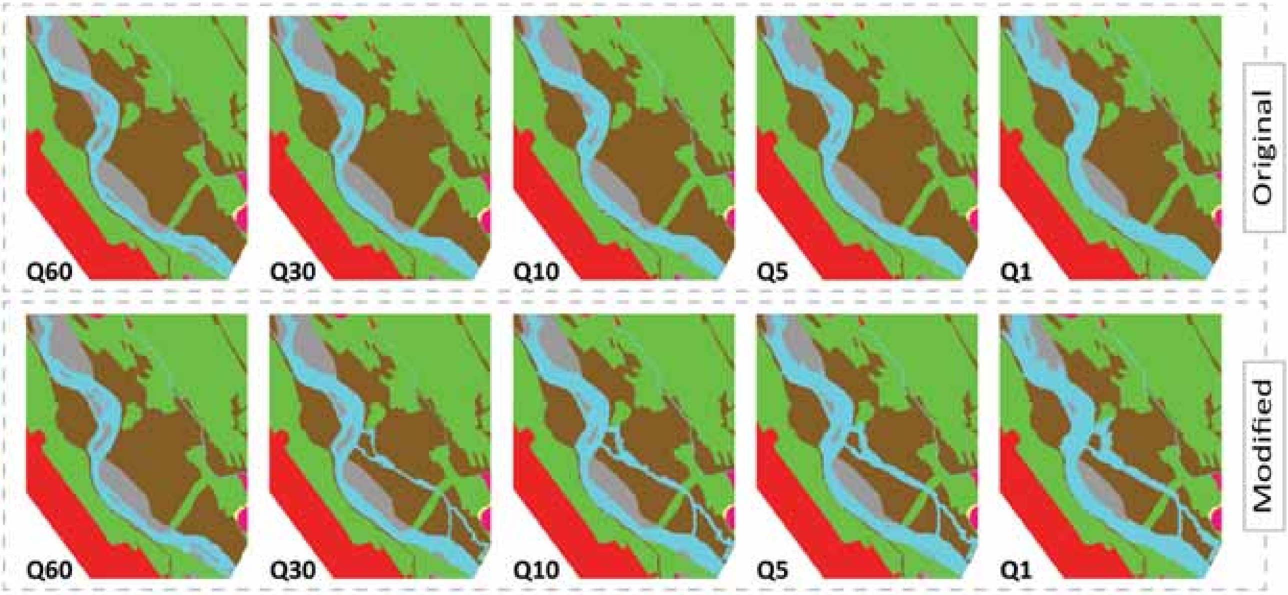


Fig. 6 Hydraulic outcomes for both scenarios with increasing discharge from left to right. The reactivation of the remnant streambeds leads to an increase of the wetted surface of 1.8%, 18.9%, 21.8%, 22.1% and 23.3% respectively for the scenario with Q60, Q30, Q10, Q5 and Q1.

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

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

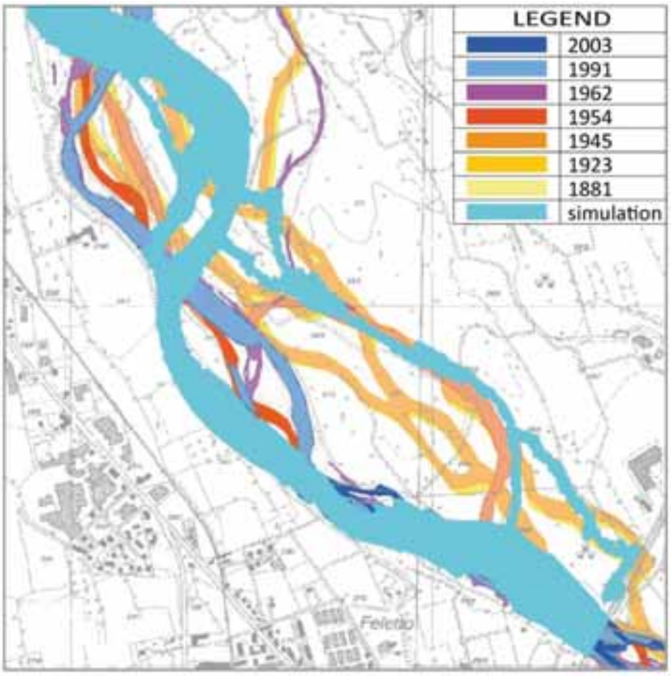


Fig. 7 Superimposition of the modified wetted surface map over the planimetric variations in the Orco river map (realized by Research Institute for the Hydrogeological Protection–Turin section)

4.2 Ecological outputs

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

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
Δ	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
Δ							
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

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

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

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

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

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

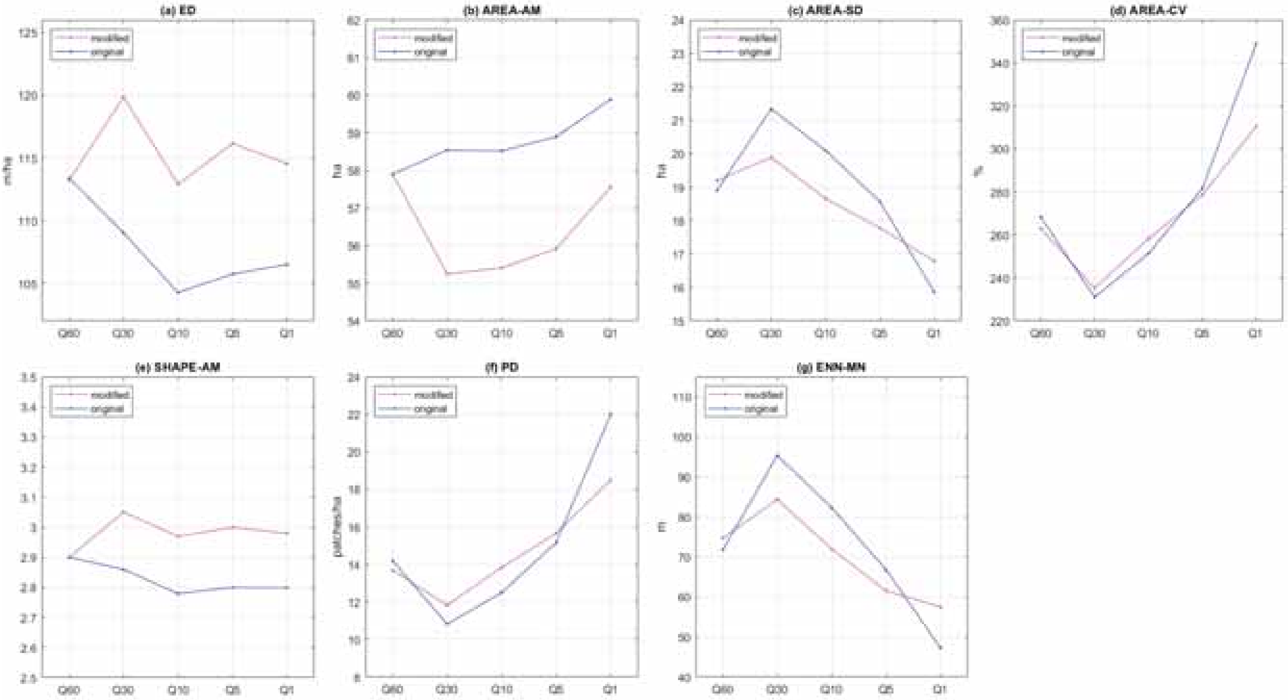


Fig. 8 Landscape metrics representing the dynamics of landscape structure in terms of fragmentation (a: Edge Density, b: Area-weighted Mean patch Area, c: Standard Deviation in patch Area, d: Coefficient of Variation in patch Area), complexity (e: Area-weighted Mean Shape index) and configuration (f: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

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

5. Discussion

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

In the studied case a river restoration action was carried out reactivating natural watercourses among the floodplain and its impact on the landscape structure was analyzed. Results obtained in the previous section are metrics used to give a quantification of four fundamental ecological attributes such as fragmentation, isolation, complexity, and heterogeneity. The chosen discharges have permitted to analyze the spatial configuration and dynamics of these components since the hydraulic conditions that reactivate the watercourses are non-stationary. When flow rate in the river is less than Q30, no water flows in the floodplain and the lower level of fragmentation means a higher level of connectivity among the patches with the same class type. For some species such as mammals, this landscape is more hospitable because larger areas offer stable conditions required to host a flourishing population. While, when discharge is greater than the threshold Q30, flow reactivates watercourses watering riparian ecosystems and increasing the degree of fragmentation especially for the wood class. The landscape with a mosaic of varied ecosystems is more attractive for the multi-habitat species [39]. Thus, the higher level of fragmentation does not involve habitat losses or impoverishment of biodiversity but on the contrary, the modified morphology proves to be more suitable for a greater variety of ecosystems [46,47].

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

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

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

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

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

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

6. Conclusion

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

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

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

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

Future work should test this methodology on a wider range of river restoration plans. The results of this study should encourage all actors to use multidisciplinary approaches in order to design and 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, ecologist 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 anabranched 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.

1.1 The aim of the research

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

2. Study area

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

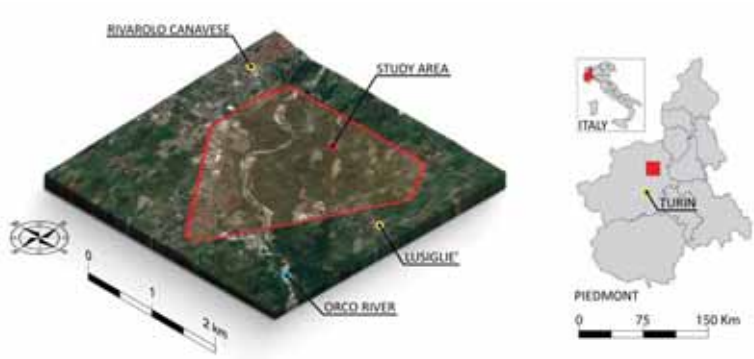

Fig. 1 Geographical location of the study area (source of the aerial image: Google Earth®, 2018)

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

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

3. Materials and Methods

This section describes the multidisciplinary method proposed in this work, between hydraulics and landscape ecology, which benefits from the combined use of software with different features. It can be divided into three main steps (see Fig. 2): (1) the construction of a land cover map using the overlapping of different maps and satellite images into the GIS module of SMS-11.1-Surface-water Modeling System [35]; (2) the implementation of the two-dimensional hydraulic model and hydrodynamic simulations using SMS in the pre and post-processing phases and BASEMENT 2.6-Basic Simulation Environment [36] for the processing step; (3) the manipulation of categorical maps in ArcMap 10.3.1 and calculation of landscape metrics with FRAGSTATS. The current released version (FRAGSTATS v4.2) is an efficient tool able to compute a great number of landscape metrics from a wide variety of image formats [15].

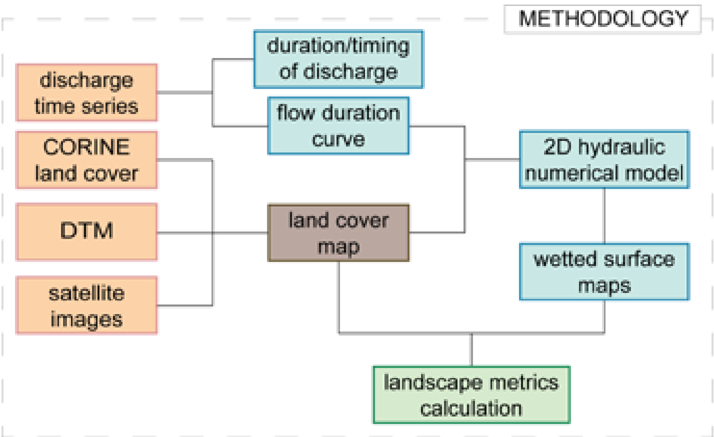

Fig. 2 Schematization of the methodology: input (orange boxes), GIS elaboration (brown box), hydrological/hydraulic calculation (light blue boxes) and ecological assessment (green box)

3.1 Land cover assessment

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

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	

Then each class was matched with a Manning's Roughness Coefficient which represents the hydraulic resistance offered by each surface to the water flow. The identification of the appropriate roughness coefficient derived from a back-analysis carried out during the calibration of the hydraulic model [37]. The high-resolution data permitted also to consider the shapes and geographical positions of structures within the domain such as bridge piers, levees, and road embankments. All these data were necessary to build the hydraulic model and accomplish hydrodynamic simulations.

3.2 Hydraulic simulations

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

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

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

~~(1)~~

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

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

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

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

where h is the water depth (m), u and v are the cartesian components of the flow velocity vector (m/s), g is gravity acceleration (m/s^2), ν is the total viscosity (m^2/s), S_f is the friction slope (-) and S_b is the bed slope (-).

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

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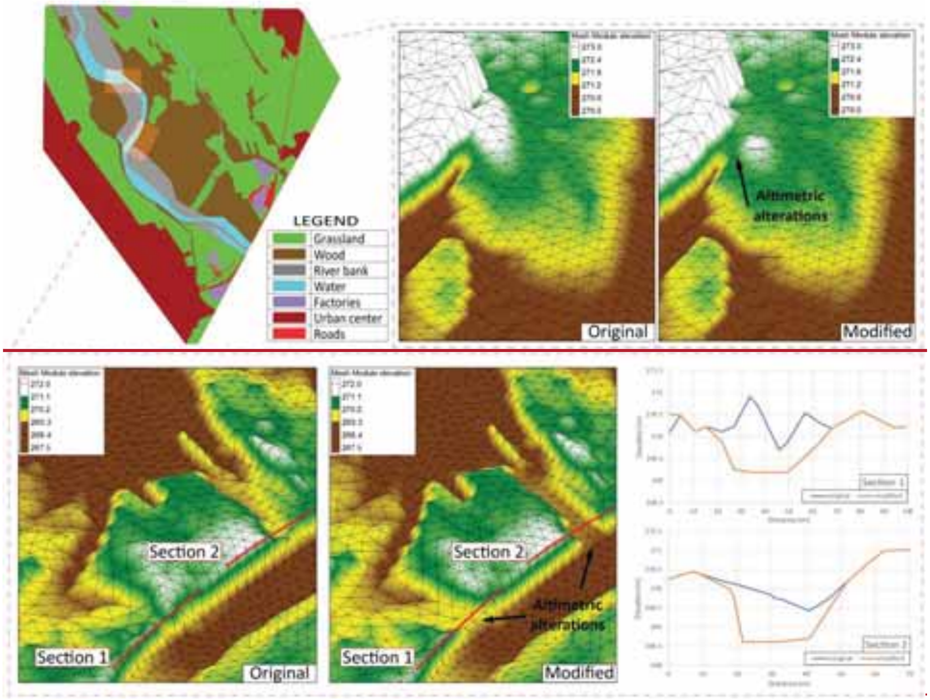
topography was simulated, this will be called “original” scenario. In the second, the wetted area on a modified computational mesh simulating the river restoration plan was calculated, this will be called “modified” scenario. In order to obtain the “modified” scenario, a series of altimetric alterations were applied to modify the original mesh. These alterations were circumscribed along 100 m of natural riverbanks digging natural levees for reconnecting remnant meanders with the main channel. These levees were created by the intensive sediment transport of floods over time. The alterations of the mesh are displayed in Fig. 3.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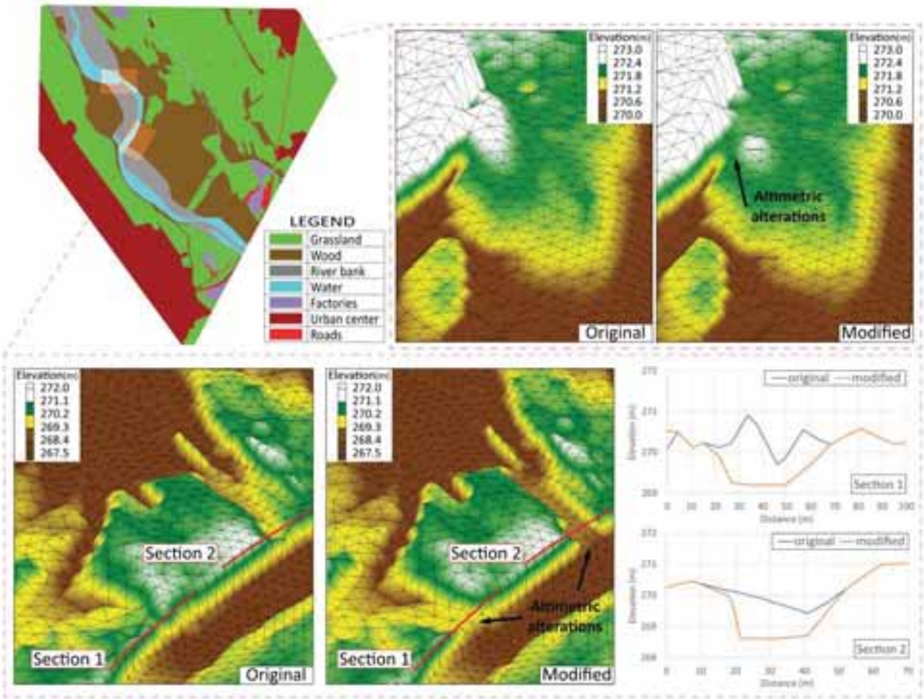
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Fig. 3 Land cover map and morphological alterations. Top: enlargement on the original and modified mesh of the first altered site. Bottom: enlargement on the original and modified mesh of the second altered site, and two graphs that display the modified profile of the river bank.

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 ~~significant~~ 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:

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I. Area-Edge metrics:
   1. ED: Edge Density equals the sum of the lengths of all edge segments in the landscape, divided by the total landscape area;
   2. AREA_AM: Area-weighted Mean patch Area equals the sum, across all patches in the landscape, of the patch area, multiplied by the proportional abundance of the patch;
   3. AREA_SD: Standard Deviation in patch Area equals the square root of the sum of the squared deviations of each patch size from the mean patch size computed for all patches in the landscape, divided by the total number of patches;
   4. AREA_CV: Coefficient of Variation in patch Area equals the standard deviation divided by the mean, multiplied by 100 to convert to a percentage;

II. Shape metrics:
   5. SHAPE_AM: Area-weighted Mean Shape index equals the sum, across all patches in the landscape, of the patch perimeter divided by the square root of patch area standardized to a square, multiplied by the proportional abundance of the patch;

III. Aggregation metrics:
   6. PD: Patch Density equals the number of patches in the landscape divided by total landscape area;
   7. ENN_MN: Mean Euclidean Nearest Neighbor distance equals the sum, across all patches in the landscape, of the distance to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance, divided by the total number of patches.

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

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)	$\mathrm{AREA\_AM} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$	Where a_{ij} is the area of patch i of the patch type j
Standard Deviation in patch Area (AREA_SD)	$\mathrm{AREA\_SD} = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij-}\left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}{N}\right)\right]^{2}}{N}}$	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)	$\mathrm{AREA\_CV} = \left[\mathrm{AREA\_SD}\Big/\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}{N}\right](100)$	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)	$\mathrm{AREA\_AM} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left({}^{0.25\cdot p_{ij}}\Big/_{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$	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

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

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

4. Results

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

4.1 Hydraulic outputs

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

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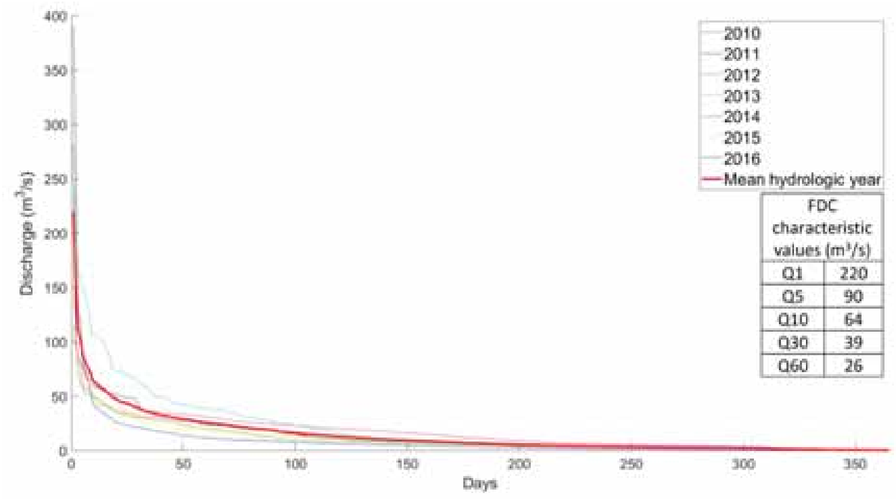

FDC characteristic values (m³/s)	
Q1	220
Q5	90
Q10	64
Q30	39
Q60	26

Fig. 4 Flow duration curve and its characteristic values

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

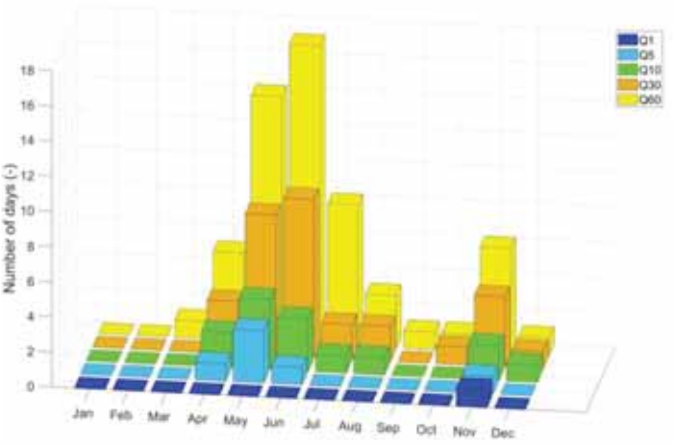

Fig. 5 Timing and duration of each analyzed discharge (mean number of days per month in which that amount of discharge flows into the river).

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 among 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).

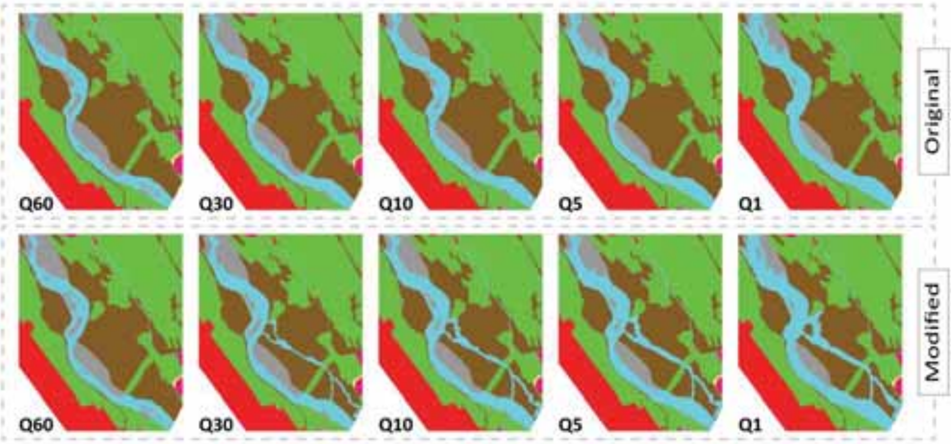

Fig. 6 Hydraulic outcomes for both scenarios with increasing discharge from left to right. The reactivation of the remnant streambeds leads to an increase of the wetted surface of 1.8%, 18.9%, 21.8%, 22.1% and 23.3% respectively for the scenario with Q60, Q30, Q10, Q5 and Q1.

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

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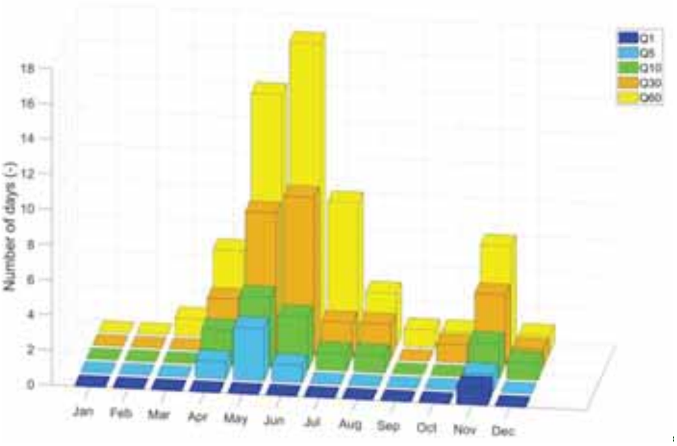

~~**Fig. 6** Timing and duration of each analyzed discharge (mean number of days per month in which that amount of discharge flows into the river).~~

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

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

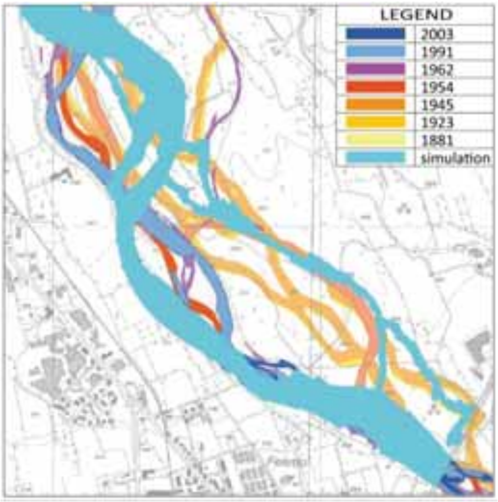

Fig. 7 Superimposition of the modified wetted surface map over the planimetric variations in the Orco river map (realized by Research Institute for the Hydrogeological Protection–Turin section)

4.2 Ecological outputs

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

Table 3 The group of seven ~~M~~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.

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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
Δ	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
			Δ				
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

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

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

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

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

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

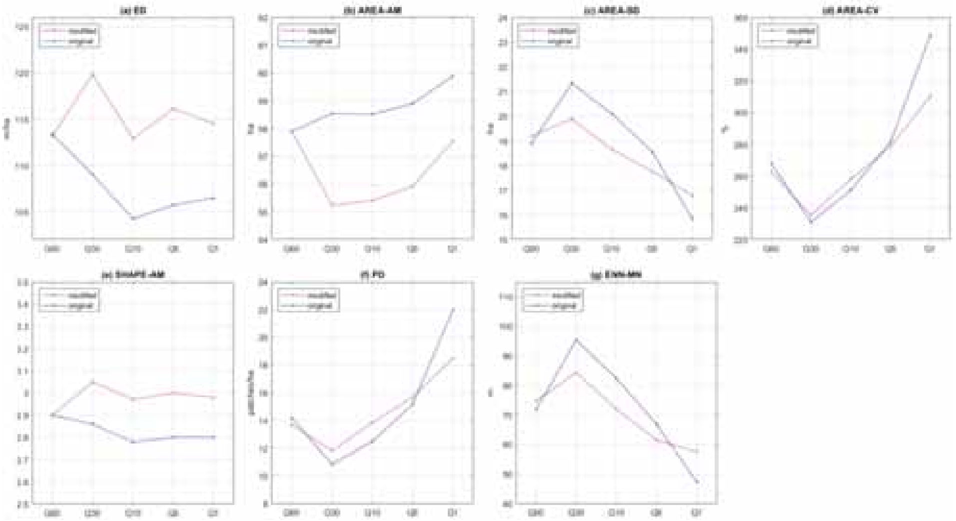

Fig. 8 Landscape metrics representing the dynamics of landscape structure in terms of fragmentation (a: Edge Density, b: Area-weighted Mean patch Area, c: Standard Deviation in patch Area, d: Coefficient of Variation in patch Area), complexity (e: Area-weighted Mean Shape index) and configuration (f: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

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

5. Discussion

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

In the studied case a river restoration action was carried out reactivating natural watercourses among the floodplain and its impact on the landscape structure was analyzed. Results obtained in the previous section are metrics used to give a quantification of four fundamental ecological attributes such as fragmentation, isolation, complexity, and heterogeneity. The chosen discharges have permitted to analyze the spatial configuration and dynamics of these components since the hydraulic conditions that reactivate the watercourses are non-stationary. When flow rate in the river is less than Q30, no water flows in the floodplain and the lower level of fragmentation means a higher level of connectivity among the patches with the same class type. For some species such as mammals, this landscape is more hospitable because larger areas offer stable conditions required to host a flourishing population. While, when discharge is greater than the threshold Q30, flow reactivates watercourses watering riparian ecosystems and increasing the degree of fragmentation especially for the wood class. The landscape with a mosaic of varied ecosystems is more attractive for the multi-habitat species [39]. Thus, the higher level of fragmentation does not involve habitat losses or impoverishment of biodiversity but on the contrary, the modified morphology proves to be more suitable for a greater variety of ecosystems [46,47].

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

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

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

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

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

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

6. Conclusion

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

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

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

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

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

~~Notations~~

- ~~$\boldsymbol{U}$: vector of conserved variables [–]~~
- ~~$\boldsymbol{F}, \boldsymbol{G}$: flux vectors [–]~~

- ~~$\boldsymbol{S}$: vector of source terms $[-]$~~
- ~~h: water depth $[m]$~~
- ~~u, v: cartesian components of the flow velocity vector $[m/s]$~~
- ~~g: gravity acceleration $[m/s^2]$~~
- ~~ν: total viscosity $[m^2/s]$~~
- ~~S_f: friction slope $[-]$~~
- ~~S_b: bed slope $[-]$~~
- ~~t: time $[s]$~~
- ~~$\boldsymbol{U}_t$: derivation with respect to variable t of the $\boldsymbol{U}$ vector~~
- ~~∇: Nabla operator~~
- ~~$\frac{\partial}{\partial x}$: partial differential operator for derivation with respect to variable x~~
- ~~$\frac{\partial}{\partial y}$: partial differential operator for derivation with respect to variable y~~

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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.

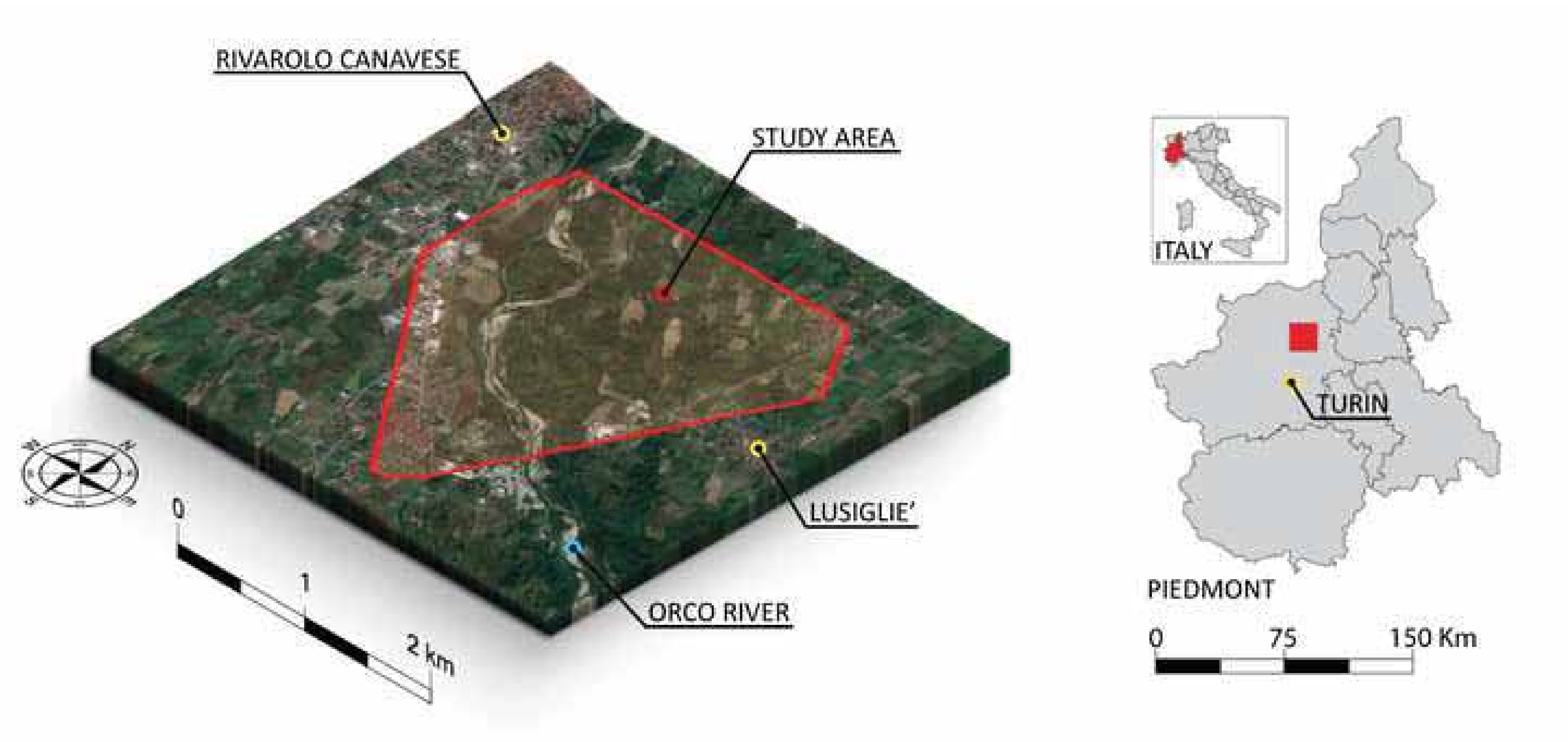
6. Please provide the full names of the landscape metrics in the caption of Table 3, such that the table is understandable in isolation.
Full names of metrics have been added.

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

Fig1


RIVAROLO CANAVESE
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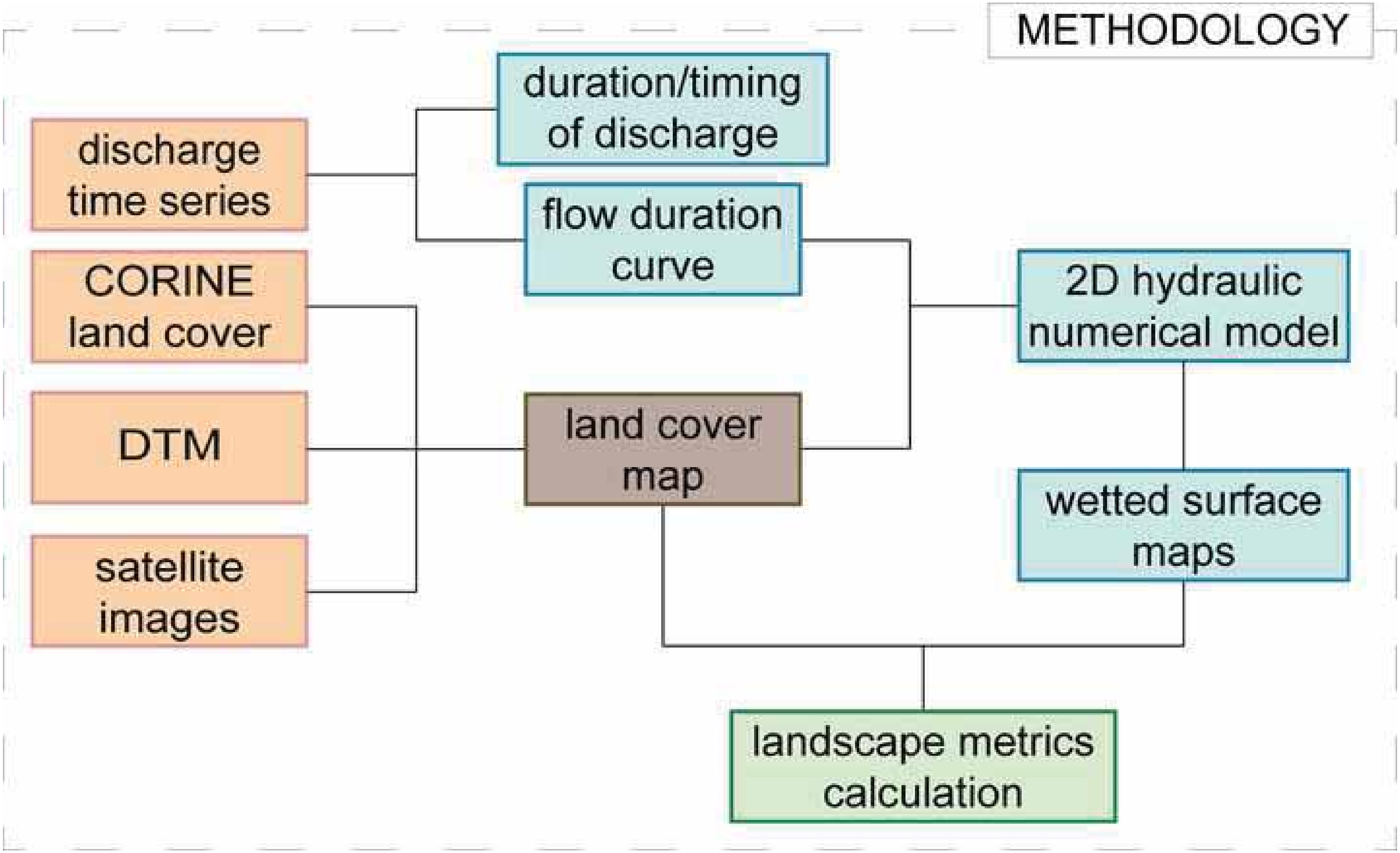

METHODOLOGY
discharge time series
CORINE land cover
DTM
satellite images
duration/timing of discharge
flow duration curve
land cover map
2D hydraulic numerical model
wetted surface maps
landscape metrics calculation

Fig 3

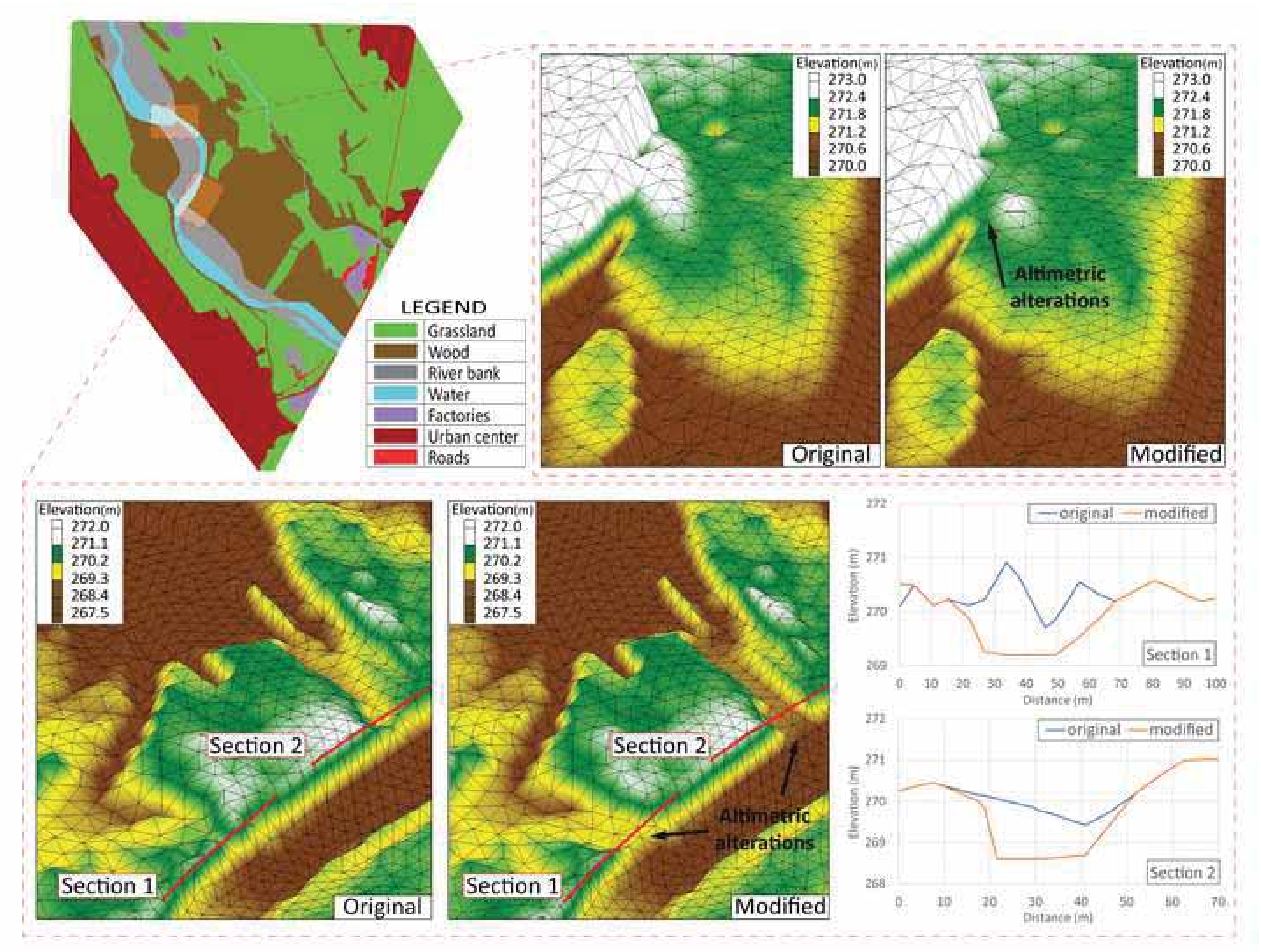
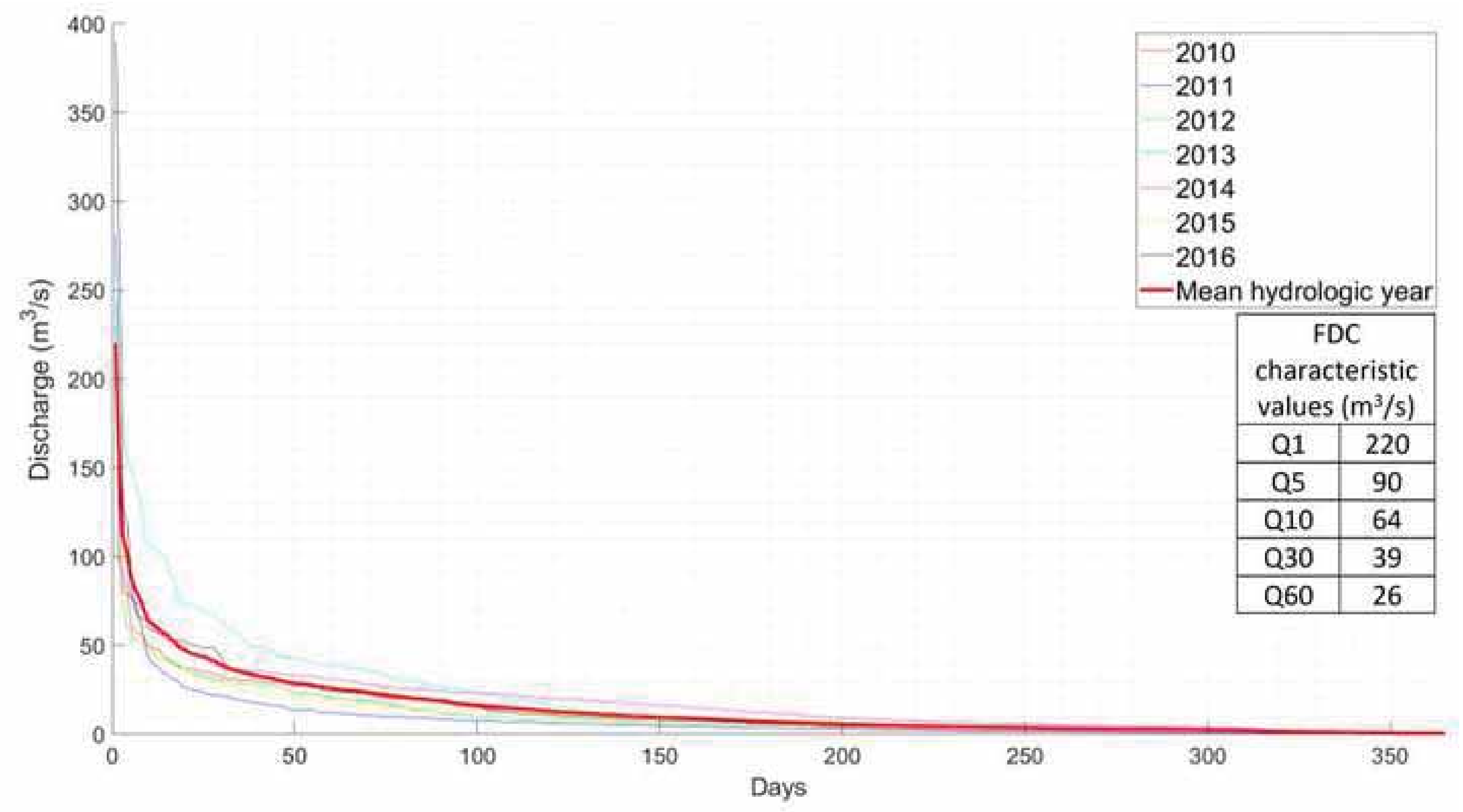
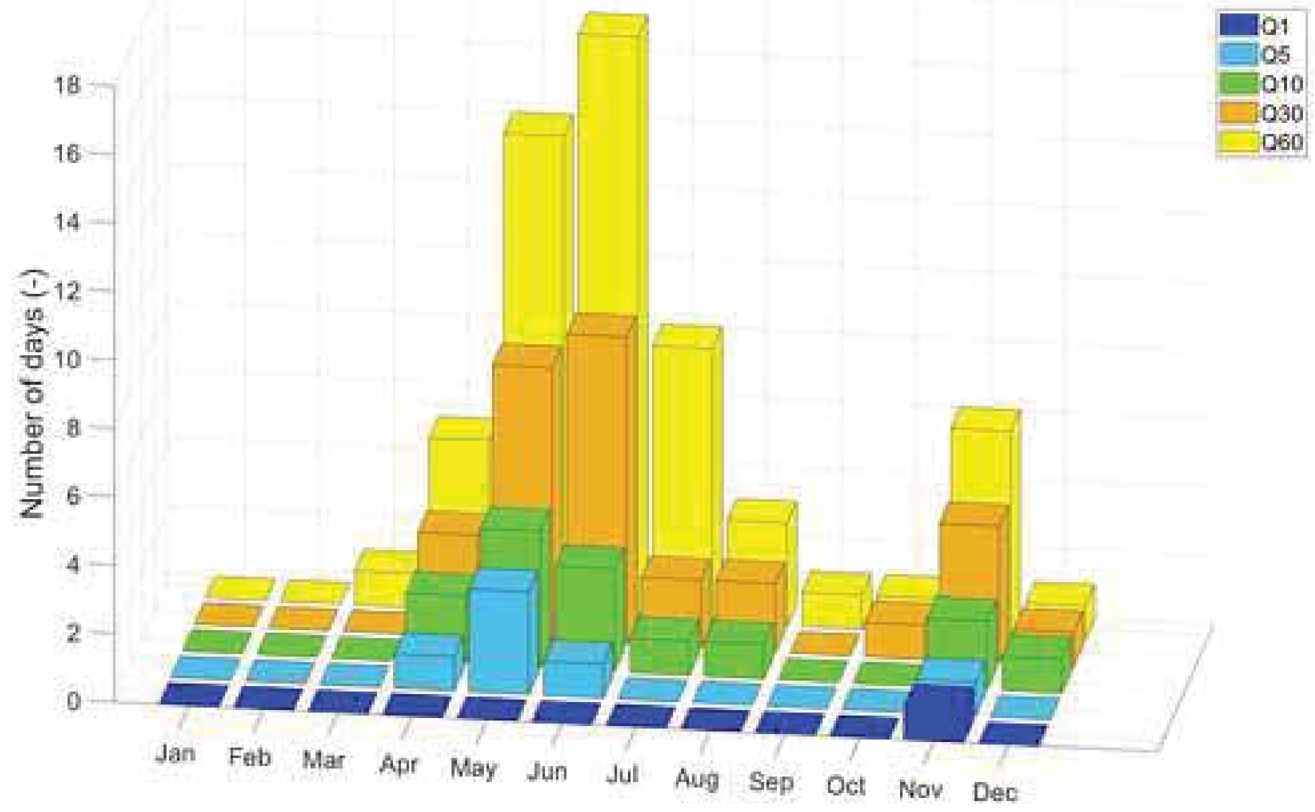

LEGEND
🟩 Grassland
Wood
River bank
Water
Factories
Urban center
🟥 Roads
Elevation(m)
273.0
272.4
271.8
271.2
270.6
270.0
Original
Elevation(m)
273.0
272.4
271.8
271.2
270.6
270.0
Altimetric alterations
Modified
Elevation(m)
272.0
271.1
270.2
269.3
268.4
267.5
Section 2
Section 1
Original
Elevation(m)
272.0
271.1
270.2
269.3
268.4
267.5
Section 2
Section 1
Altimetric alterations
Modified
original
modified
Elevation (m)
272
271
270
269
Section 1
0 10 20 30 40 50 60 70 80 90 100
Distance (m)
original
modified
Elevation (m)
272
271
270
269
268
Section 2
0 10 20 30 40 50 60 70
Distance (m)

Fig4



FDC characteristic values (m³/s)	
Q1	220
Q5	90
Q10	64
Q30	39
Q60	26

Fig 5


Q1
Q5
Q10
Q30
Q60
Number of days (-)
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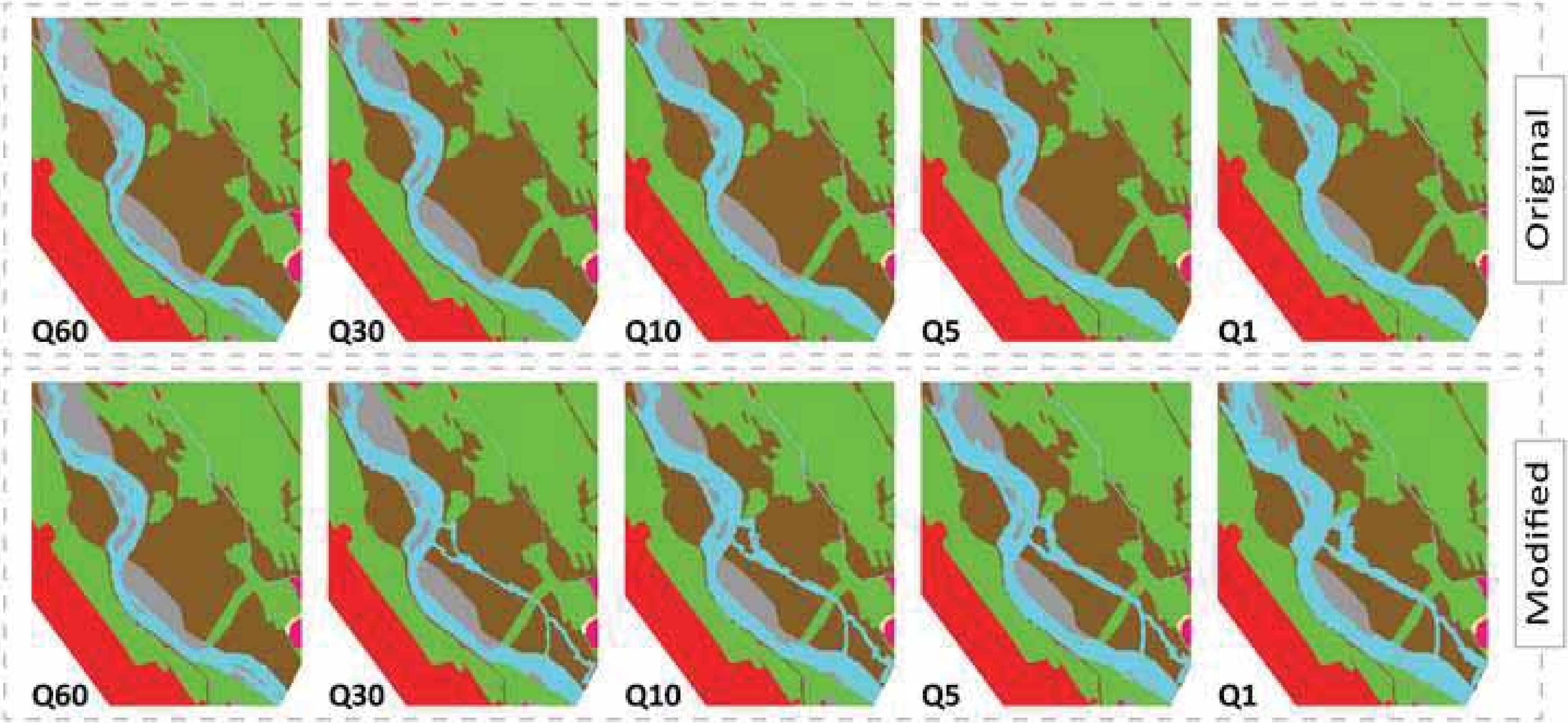
Original
Modified
Q60
Q30
Q10
Q5
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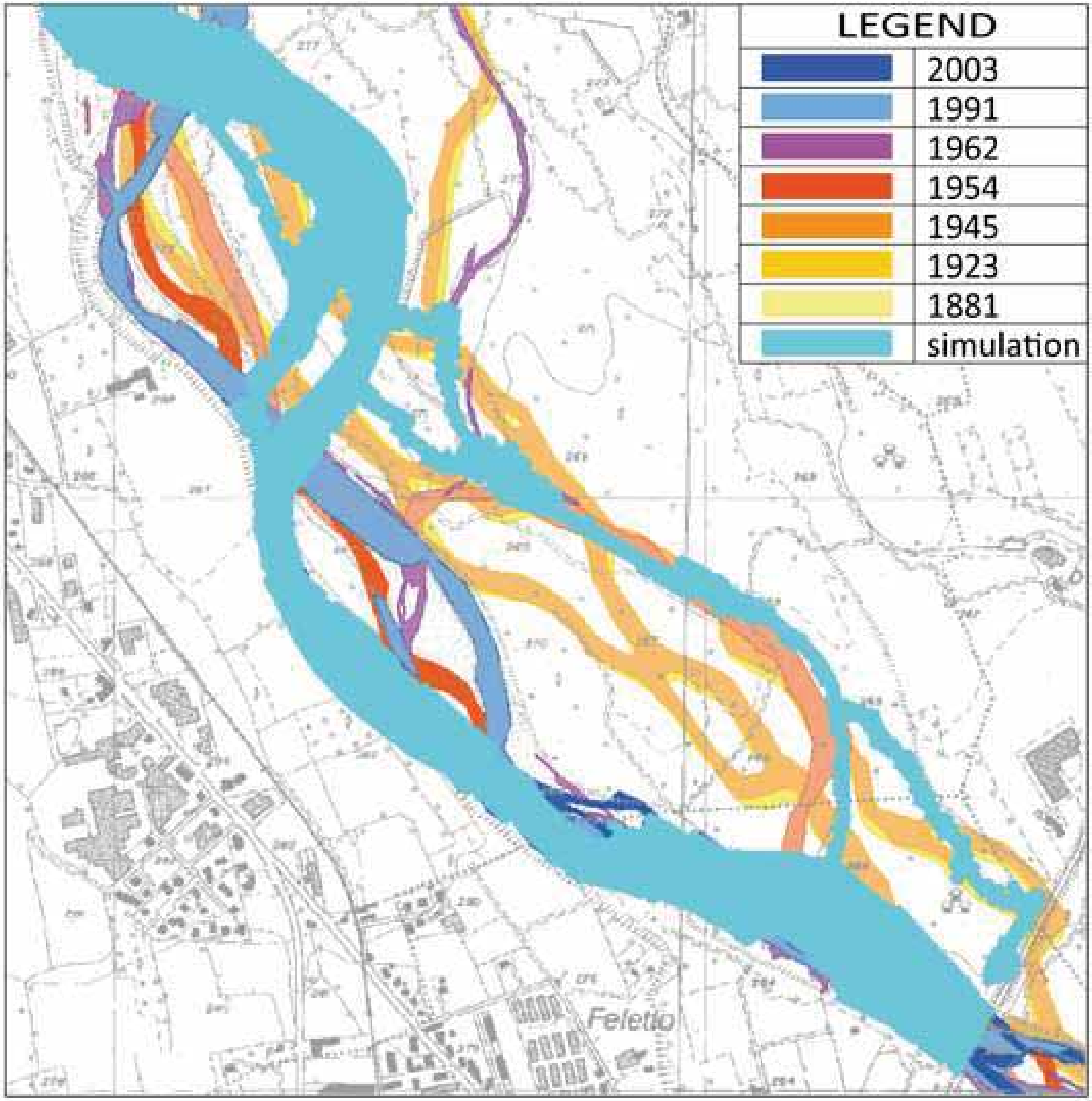
Q60
Q30
Q10
Q5
Q1

Fig7


LEGEND
2003
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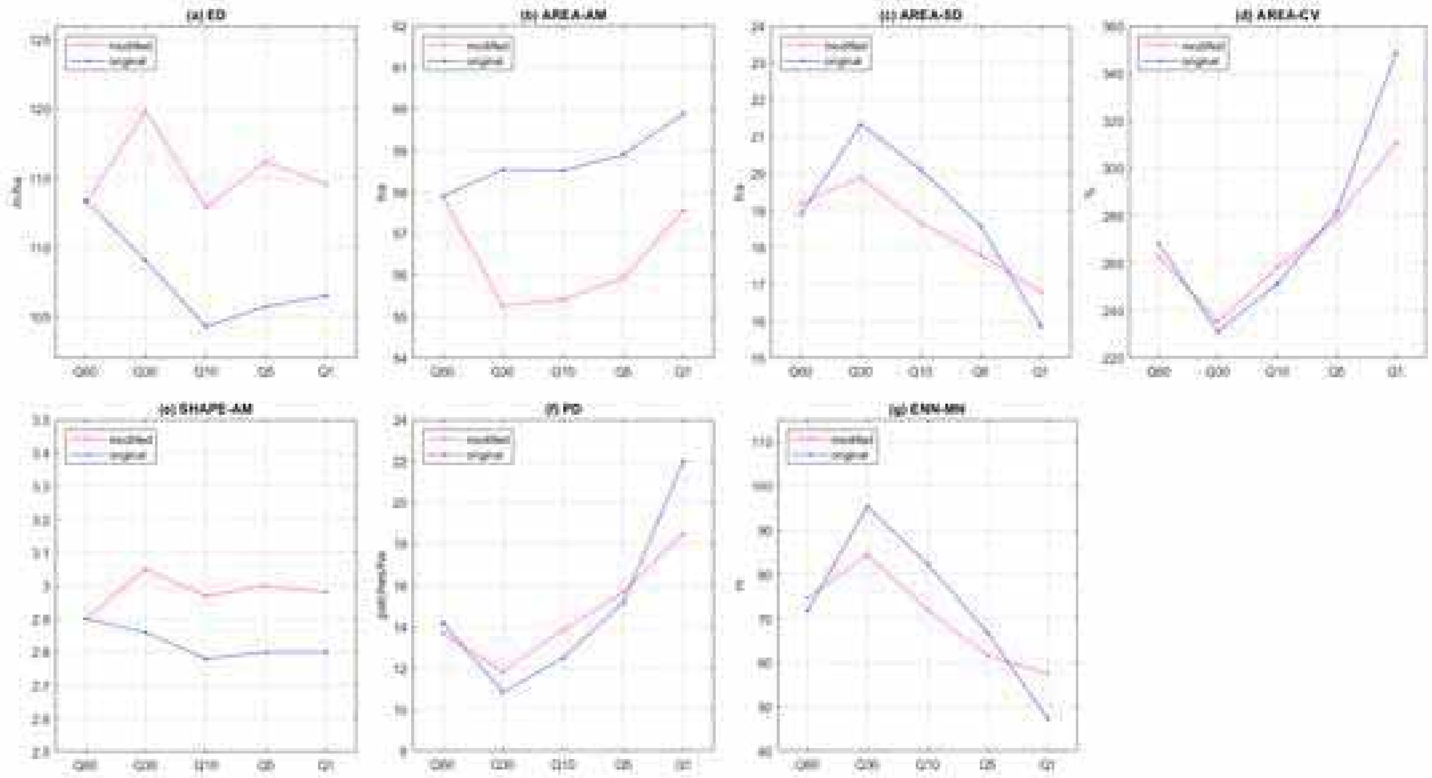
1962
1954
1945
1923
1881
simulation
Feletto

Fig8


(a) ED
(b) AREA-AM
(c) AREA-SD
(d) AREA-CV
(e) SHAPE-AM
(f) PD
(g) ENN-MN
modified
original
m/ha
ha
ha
%
patches/ha
m
125
120
115
110
105
62
61
60
59
58
57
56
55
54
24
23
22
21
20
19
18
17
16
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360
340
320
300
280
260
240
220
3.5
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3.1
3
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2.7
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2.5
24
22
20
18
16
14
12
10
8
110
100
90
80
70
60
50
40
Q60
Q30
Q10
Q5
Q1

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)	$\mathrm{AREA\_AM} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$	Where a_{ij} is the area of patch i of the patch type j
Standard Deviation in patch Area (AREA_SD)	$\mathrm{AREA\_SD} = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij-}\left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}{N}\right)\right]^{2}}{N}}$	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)	$\mathrm{AREA\_CV} = \left[{}^{\mathrm{AREA\_SD}}\Big/_{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}{N}}\right](100)$	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)	$\mathrm{AREA\_AM} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left({}^{0.25\cdot p_{ij}}\Big/_{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$	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
Δ	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

Δ

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