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Jessica Pic, Étienne Cossart, Mathieu Fressard, Nadia Carluer. Drainage network analysis to comprehend structural sediment (dis)connectivity in wine-growing Beaujolais (France). Geocarto International, 2024, 37 (27), pp.16323-16341. 10.1080/10106049.2022.2108907 . hal-03767504

HAL Id: hal-03767504
https://hal.science/hal-03767504

Submitted on 5 Oct 2022

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Geocarto International

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tgei20

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To cite this article: Jessica Pic, Étienne Cossart, Mathieu Fressard & Nadia Carluer (2022): Drainage network analysis to comprehend structural sediment (dis)connectivity in wine-growing Beaujolais (France), Geocarto International, DOI: 10.1080/10106049.2022.2108907

To link to this article: https://doi.org/10.1080/10106049.2022.2108907

Accepted author version posted online: 01 Aug 2022.

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Drainage network analysis to comprehend structural sediment (dis)connectivity in wine-growing Beaujolais (France)

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Abstract

Drainage infrastructure is an important element of the agricultural landscape, influencing hydro-sedimentary transfers from plots to rivers. The objective of this paper is to demonstrate how the description of the main characteristics of drainage networks allows a better understanding of sediment (dis)connectivity. This study focuses on an 8 km^2 catchment in the Beaujolais vineyards (France) that is characterised by a complex drainage network. We applied methods using field surveys, a geographical information system, and graph theory to map and analyse how such man-made infrastructures may act as barriers, buffers, or shortcuts. The catchment shows dense and complex drainage networks characterised by sediment trapping strategies in the upper slopes, and flow concentration and export in the lower slopes. The results exemplify winegrowers' strategies to disconnect sediments sources from the river to preserve soil resources.

Keywords: Drainage network; Landscape structure; Soil erosion; Structural connectivity

Introduction

The protagonist Charles Duchemin in the French movie The Wing or the Thigh (1976) assures us that "Le vin, c'est la terre" ("The wine, is the soil."). This rather short statement agrees with the current definition of terroir (Leturcq, 2020; Vaudour, 2002), in which the quality of a wine is largely inferred from the quality of the soil. Paradoxically, vineyards are particularly prone to soil losses due to water erosion (e.g. Bagagiolo et al., 2018; Brenot, 2007; Fressard & Cossart, 2019; García-Ruiz et al., 2015; Perović et al., 2018; Videla et al., 2020). Soil management is an everyday concern for winegrowers who need to care for the soil and adapt their cultivation practices to cope with local physical situations, with the aim of maintaining the quality of their terroir and its associated productivity. Consequently, over many centuries, French winegrowers have developed a deep empirical knowledge of the hydro-sedimentary processes within the landscape (Garcia et al., 2018). Nowadays, the management of runoff water and associated sediments involves a complex network of linear drainage structures and sediment traps (Fressard & Cossart, 2019).

It has been amply demonstrated that anthropogenic landscape structure influences the spatial pattern of hydro-sedimentary transfers from plots to rivers (Gascuel-Odoux et al., 2011; Levavasseur, 2012; Nario et al., 2009; Reulier et al., 2019). While the roles of land-use on soil erosion and sediment routing are well studied, the role of linear drainage infrastructure on the hydro-sedimentary dynamics at catchment scale remains complex and difficult to understand (Carluer & De Marsily, 2004; Cossart, Fressard, et al., 2020; Dotterweich, 2013; Viaud et al., 2004). Each item of the linear infrastructure leads to interception, rerouting, and acceleration/deceleration of water and sediment flow according to its individual characteristics (Bereswill et al., 2012, 2014; Bocher, 2005; Lefrancq et al., 2014; Montgomery, 1994; Rouzies et al., 2019). While characterisation of the hydrological

function of a single linear landscape structure is possible (Ouvry et al., 2012; Reulier, 2015), deciphering the role of entire networks – seen as a complex system – remains challenging (Cossart et al., 2018). The transfer of runoff water and associated sediments from plots to the river depends on the flow paths between the production zones and the output. While both inputs and outputs can be assessed with an efficient field survey, the role of a routing network tends to remain only partly documented.

In this context, connectivity gives us a conceptual framework to understand the transfers of matter, energy, and organisms between landscape compartments (Fryirs, 2013; Jain & Tandon, 2010; Pringle, 2001; Wainwright et al., 2011). Connectivity usually combines two aspects: (1) functional connectivity and (2) structural connectivity. Functional connectivity, also called process-based connectivity (Bracken et al., 2015), focuses on interactions of hydro-sedimentary processes between themselves and with landscape units, resulting in nonlinearities in hillslope and catchment responses to rainfall. Structural connectivity focuses on the landscape elements themselves, and the way and to what extent they determine a place to be connected to another (Heckmann et al., 2018; Wainwright et al., 2011). While structural connectivity governs the spatial gradient of sediment pattern routing and blockages, functional connectivity provides the grounds for understanding the form-process linkages (Fryirs et al., 2007; Poeppl et al., 2020). Although, several metrics of structural connectivity now exist (e.g., Borselli et al., 2008; Cavalli et al., 2013; Fressard & Cossart, 2019), it remains difficult to determine to what extent landscape structures hamper sediment and water transfer.

This paper contributes to this latter scientific debate by considering (dis)connectivity under an erosion management context. We focus on analysing structural connectivity to better understand sediment routing patterns and blockage in highly structured landscapes such as vineyards.

For this work, we employed spatial analysis methods to describe the complex networks of linear infrastructure in agricultural lands. We studied the North Beaujolais vineyard, where a dense drainage network has been implemented by winegrowers to address the soil erosion issue. This paper aims to describe the spatial organisation of drainage networks built to control sediment export by winegrowers and to evaluate their effectiveness in bringing about sediment dis-connectivity. We developed an approach based on a detailed field inventory and application of graph theory at the catchment scale to highlight relevant structural characteristics of the drainage infrastructure and its potential effects on sediment routing. We first describe the study area, the organisation pattern of the Beaujolais drainage infrastructure, and the methodology based on spatial analysis. We then question the landscape organisation and discuss the impact of little-visible but very widespread landscape components on hydro-sedimentary fluxes in a small catchment of the Beaujolais vineyard.

Study area

The Beaujolais region is located in the lower part of the Saône catchment, in the northern part of the Rhône department (France). It covers a 50-km-long zone from the northern Lyon conurbation to the south of Mâcon. The Beaujolais region, located along the eastern hillslopes of the Massif Central, is well known for its vineyards. The altitude ranges from 450–500 m to approximately 170 m within the alluvial plain of the Saône River. The mean annual precipitation is approximately 850 mm, with precipitation being regularly distributed throughout the year. The area receives approximately 1900 hours of solar radiation per year, and temperatures exceeding 30°C are typical during the summer (Météo-France, 2019).

This study focuses on the Morcille catchment (8 km^2) located in the northern part of the Beaujolais vineyard (Fig. 1). This catchment has been studied for diffuse pesticide pollution by the French National Research Institute for Agriculture, Food and Environment (INRAE) for more than 30 years (Gouy et al., 2021). The catchment is characterised by an altered hercynian crystalline basement of

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mainly porphyric biotite granite (Frésard, 2010; Party, 1996; Pomerol, 1984; Wahl, 2017) with three types of soils having been identified: (1) sandy soils developed on altered granite on the upper slopes, (2) shallow clay-based soil on the right bank of the river, and (3) sandy soils on lower slopes and thalwegs. The catchment includes slopes averaging around 7° but reaching almost 35° in the steepest parts. The mean elevation is approximately 390m, ranging from 207 to 806 m above sea level.

The vineyard covers 59% of the catchment surface (Fig. 1), while grasslands represent another 18%, being present in the lower part of the hillsides in a varying strip around the river and the catchment head. Forested areas occupy similar areas and represent 14% of the catchment area. Abandoned vine plots are generally located on the steepest plots, and represent 2.5% of the catchment area. The abandonment is interpreted to be a consequence of the decline of agriculture in the region from the 1990s because of the economic crisis that struck the Beaujolais vineyard (Cossart et al., 2020; Pic et al., 2020).

The study area is located in the "AOC Cru-du-Beaujolais" wine appellation territory, which includes 10 local vintages. These are considered the best quality wines of the Beaujolais vineyard, and are located on the best terroir (steep slope, southern/south-eastern aspects, metamorphic/volcanic rocks) compared with the appellations located in the southern part of the vineyard. Concerns on maintaining the wine quality and its renown are directly linked to concerns over maintenance of the terroir, which implies the use of infrastructure to prevent soil erosion.

Soil erosion is at a high rate in the Beaujolais vineyard because of the steep and bare soil, as classically observed in other vineyards (Bagagiolo et al., 2018; Brenot, 2007; Cerdan et al., 2006). Wine-growing in Beaujolais is traditionally conducted under 'goblet' management with low vine stocks and dense plantations on bare soils (approximately 10 000 vine stocks per hectare). To cope with the soil erosion issue, winegrowers have developed a deep empirical knowledge of hydro-sedimentary processes, the geometry of hydro-sedimentary paths, and the effects of landscape structure on sediment supply. Linear structures (e.g., ditches, counter-slope paths) are individually implemented to reroute runoff and associated sediment flows and prevent soil erosion. Moreover, an increasing number of vine plots tend to be partially grassed to limit soil erosion, in accord with the current wine appellation specifications (Légifrance, 2011). However, although drainage networks are a main component of the landscape with a direct influence on flows, there is no database of the spatial distribution of such features in the Beaujolais region, and analysis of their spatial patterns remains lacking.

Materials and methods

The influence of the drainage networks on the organisation of hydro-sedimentary flows is a main issue. The small size of individual structures (often less than 1 m wide) and their occurrence in large numbers create a complex structure that is difficult to describe and map. The lack of knowledge regarding such structures hampers consideration of their potential impacts on sediment connectivity. Hence, we developed a methodology to map and highlight the spatial patterns of the drainage structures (Fig. 2).

Typology and functions of the drainage network structures

We built a drainage network infrastructure typology (Fig. 2) according to descriptions in the literature (Bocher, 2005; Fressard & Cossart, 2019; Levavasseur et al., 2016; Reulier, 2015; Tortrat, 2005; Viel, 2012) and a previous work on the Morcille catchment (Escot, 2005). Four types of linear landscape structures interact differently with flowing water and sediments in Beaujolais: (1) roads, (2) ditches, (3) soil bunds, and (4) hedges (Fig. 3).

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- Roads and tracks play a crucial role in flow channelling in the sense that they can intercept, reroute, gather and/or accelerate flowing processes (Bereswill et al., 2012, 2014; Lefrancq et al., 2014; Montgomery, 1994; Rouzies et al., 2019). Three parameters have an influence on the flow accumulation and transport capacities of road and track networks: (1) the floor type, (2) the cross-profile, and (3) the orientation (slope and aspect) (Bocher, 2005). In the current study, we focus on floor type to distinguish three types of roads and tracks: (1) main roads, (2) dirt tracks, and (3) grassed tracks (Fig. 3A–C). Main roads (Fig.3A) consist of tarmacked roads mainly assigned for use by motorised vehicles. The two types of tracks (Fig. 3B & C) are dedicated for agricultural or pedestrian uses. The floor type of these two track types varies, but they can be classified into two categories: dirt or grassed. They are mostly located within the vineyard and divide it into small plots. These plots are generally surrounded with buffer strips that look like grassed tracks. The main difference is that they are meant for runoff water infiltration and sediment deposition, and are located across slope lengths at plot extremities, in addition to other types of drainage network structures or nearby streams.
- A ditch is a linear structure encased in the topography and made to reroute hydro-sedimentary fluxes downstream from hillslope by means of gravity. Three types of ditches were identified in the Beaujolais' landscape (Fig. 3D–F). (1) Gutters (Fig. 3E) are concrete lined ditches collecting flows from vine plots to evacuate them as fast as possible (concentration and acceleration of flows). They are generally located along the slope. (2) Pipes are underground ditches (Fig. 3F) located along the slope and vary in size from 25 cm to 1 m in diameter, according to the surface area that they drain and the amount of flow they collect. Runoff water and sediments enter the underground network through pipe inlets. (3) Grassed ditches (Fig. 3D) are mostly located along main roads or dirt tracks and are generally transverse to the slope gradient. This type of infrastructure tends to channel and slow down hydro-sedimentary flows. They can also be located along the slope within plots, in which case they contribute to accelerating the flows.
- Soil bunds (Fig. 3G & H) are embankments built from soil along the contour. They are generally less than 50 cm high and collect hydro-sedimentary flows from plots and route them to ditches. They can be located within plots (Fig. 3H) in densities that vary according to the plot steepness or bordering tracks (Fig. 3G). They contribute to slowing down hydro-sedimentary flows and limit soil erosion when located within plots. When they are located along dirt and grassed tracks, their function is equivalent to gutters and grassed ditches, respectively.
- Hedges are relatively few in the Beaujolais's landscape, and those that are present are mostly located along rivers as riparian forests, or along grassed ditches. They generally do not completely intercept hydro-sedimentary flows and only act as a partial barrier because of vegetation discontinuity and the absence of soil bunds at their base. As a consequence, they are not considered to be a component of the drainage network.

In addition to linear structures, sediment traps were inventoried within the Morcille catchment (Fig. 3I & J). These structures are aimed at removing transported sediments from running water, with the sediments being collected by winegrowers to generally build or reinforce soil bunds. Sediments sink to the bottom under the influence of gravity and water is carried away from the traps through ditches. In this sense, they lead to a disconnection of sediments, but not always water, from the river. The size of sediment traps varies considerably, from one to several tons of m^3, and their construction varies from concrete settling tanks with several internal walls to simple holes dug in the ground.

Drainage network inventory and mapping

To inventory the drainage network structures, a protocol was defined to combine a geographical information system, interpretation of areal images, and field surveys (Fig. 2). The main road network was extracted from the French national topographic database (BDTOPO, IGN, 2017) and completed

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with analysis of areal ortho-images (1:2000, IGN, 2017) to map the agricultural paths neighbouring agricultural plots.

Systematic field surveys were conducted to (1) verify the hydrological role of mapped structures, (2) map the structures that were not visible on the aerial photographs (e.g. soil bunds, diches) and the effective connections between the different elements, and (3) to locate sediment traps and identify their types and dimensions. Sometimes drainage structures were connected to infrastructure located outside the catchment, and sometimes structures from outside the catchment were connected to the Morcille network. We inventoried all the structures upstream and connected to the infrastructure located within the studied catchment. The spatial database was built using the open source QGIS environment.

The drainage infrastructure cannot be clearly represented at the catchment scale because of the high number of linear structures. To map the spatial scheme of the drainage infrastructure we built density maps based on 25- and 50-m resolution grids with the drainage infrastructure length aggregated within each cell. These thresholds were manually selected after a calibration procedure to estimate the best compromise between map resolution and readability of the spatial patterns of mapped elements at the catchment scale. To compare the effect of the landscape on local drainage network density, we divided the catchment landscape into three units: (1) the catchment's head with upper-slope grasslands and forest, (2) the hillslopes that mostly encompass the vineyard, and (3) the floodplain that includes grassland and riparian forests along the river.

Building and analysing a drainage network infrastructure graph

A graph representation was built from the drainage infrastructure database, along with a specific methodology to analyse it (Fig. 2). The graph building and spatial analysis was conducted using QGIS software with its Python application programming interface and Jupyter-lab (Python 3.9).

The drainage network is represented as a graph, where the drainage structures are vertices and their connections are nodes. The graph is divided into connected subgraphs where each subgraph of the network is independent and made up of (1) inlets, (2) an outlet, and (3) a sequence between them (Fig. 4).

(1) The inlets of a sub-network are the upstream nodes of every subgraph.

(2) The outlet of a sub-network is the opposite of the inlet: the most downstream node of the subgraph. It is the zone where running water and associated sediments leave the drainage network to reach another type of landscape component. It can either be:

- directly connected, if it directly reaches the river;

- completely disconnected, if the sub-network drains outside the watershed;

- a sediment sink, if the sub-network does not reach the river directly, but instead connects to another type of landscape component. Sediment sinks consists of a transition zone before the river where water can potentially infiltrate and sediment can be deposited. We identified eight types of sediment sinks: hedges, sediment traps, and six represented by diverse land-uses: grassland, abandoned plot, forest, vineyard, urban area, and dump/construction site. Water and sediments that reach these zones are considered to be partially (in respect to volume and time) disconnected.

(3) A drainage sequence is defined as the succession of linear structures travelled from a tree inlet to its corresponding outlet. Within a subgraph, there is a unique simple path between every pair of

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vertices. A subgraph has a unique outlet but can have several inlets. Subgraphs can consist of either chains or trees with several connected branches (Fig. 4). The last section of the sequence is recorded as many times as the number of subgraph inlets. Several steps were processed to build the drainage graph (Fig. 2). Every linear structure in the spatial database was checked as to whether it was split but connected to other structures at junctions and oriented according to slope direction (Fig. 5). Subgraph inlets and outlets were extracted and all subgraph sequences were recorded from every inlet to the corresponding outlet.

Results

Drainage network density

Within the Morcille catchment, the total length of linear drainage infrastructure reaches 297 km. Roads and tracks account for more than 70% (almost 210 km) of the total length of the drainage infrastructure, ditches for 20% (58 km), and soil bunds for 10% (Table 1). Soil bunds are found within only 10% of vine plots, and their density within these plots is very variable. Grassed-type structures (i.e., grassed tracks and grassed ditches) represent almost 60% of the total length of drainage infrastructure (175 km). The catchment includes 24 sediment traps, located in various contexts, but more frequently in the steepest parts of the catchment.

The overall drainage infrastructure density at the catchment scale was 360 $m.ha^{-1}$ (36 $km.km^{-2}$). If only ditches were considered, the density reached around 70 $m.ha^{-1}$ (7 $km.km^{-2}$). Both density maps (Fig. 6) used to assess the local variability in the drainage network density indicate very high density at the catchment scale.

A higher density, averaging 424 $m.ha^{-1}$ (Fig. 6A), was observed on the hillslopes where the vineyard is mainly located. The densities of linear drainage infrastructure in the valley bottom and catchment head (which mainly consist of grasslands and forests) were much lower, averaging 257 $m.ha^{-1}$ and 79 $m.ha^{-1}$, respectively. The higher density observed in the valley bottom can be explained by the vineyard located upslope, from which linear infrastructure provides water and sediment.

The 25-m resolution grid (Fig. 6A) highlights the highest drainage infrastructure density along the main roads, which can reach up to 2679 $m.ha^{-1}$. The zones along the sides of main roads are particularly dense because the combination of the main roads, grassed ditches (sometimes on both sides of the road), and grassed strips creates a set of parallel linear structures. The 50-m resolution grid (Fig. 6B) exhibits denser zones that mostly correspond to soil bunds within vineyard plots and are generally located on the steepest parts of the catchment.

Connectivity patterns to the hydrologic network

Among the 448 sub-networks of the Morcille drainage network, 30% of the drainage infrastructure is directly connected to the river (Table 2. Fig. 6A & B). Conversely, flows travelling within 13% of the drainage infrastructure length are exported to another catchment. Sub-networks that end in sediment sinks (57% of the drainage infrastructure) are unevenly distributed within the catchment according to its characteristics (Table 2, Fig. 6D & E). The hillslope is divided into two parts. Urban areas and sediment traps correspond to most of the sub-network outlets on the upper parts of the hillslopes. In these cases, flows are trapped in the upper parts of the hillslopes. In contrast, most of the outlets on the lower parts are grasslands and riparian forests, where the flows reach the valley bottom and might have travelled a long distance on the hillslope (Fig. 7C & D). The average length of upstream drainage structures to sub-network outlets is very variable (Table 2), but the average length of sub-networks directly connected to the river is 1746 m, whereas the second longest type of

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sub-network outlet to settling tanks only averages 751 m. Plots located in the upper parts of the catchment can be directly connected to the river via the drainage network (Fig. 7E).

Drainage networks in Beaujolais: a complex but structured sequence pattern

The study of the sub-network sequences from inlets to outlets emphasises the diversity of drainage networks in the Morcille catchment (Table 3). A total of 2637 sequences were recorded, with 449 individual patterns, illustrating the complexity of the drainage structures along the slopes (Fig. 8). More than 50% of the recorded sequences were observed more than one time. While the diversity of sequences was high for all types of sub-network outlets, half of the total number of sequences directly connected to the river and sediment sinks were represented by only a limited number of sequences (Fig. 8). The mean sequence length was 350 m and included three segments. The sequences directly connected to the river were on average 488 m long. The ones connected to the river and to sediment traps had a more complex structure than the others, with a mean of four successive segments per sequence.

The Morcille drainage network is very fragmented and is characterised by simple structures. More than 40% of sediment sink sequences consisted of the simplest types with one or two segments (Fig. 8). Only one sequence included more than four segments. Sequences connected to the river were a little more complex. Thirty-two percent of sequences were of the simplest type, with an average of less than four segments, although seven sequences included more than four segments, and one even included eight successive segments.

Several main patterns were observed in the most frequent sequences (Fig. 8). First, at the sub-network scale, grassed tracks and grassed ditches were often repeated several times within sequences, acting in alternation between high-rugosity routing and low-rugosity routing. Such a pattern creates a hindrance to hydro-sedimentary transfers. Grassed ditches are generally the last travelled segment. In this position, they collect a large number of flows from several sub-network branches upstream, whose flows cannot infiltrate the ground nor their sediment deposit. Thus, they reinforce the hydro-sedimentary connectivity.

Discussion

Drainage network patterns

Our results allow us to draw a general landscape pattern induced by drainage networks in the northern Beaujolais vineyard (Fig. 9). Denser drainage networks are observed within the vineyard, especially on the upper slopes, the steepest zones, and along main roads. Within sequences, differences are observed between parts located on the upper and lower slopes. Soil bunds, roads, and tracks are mainly located on the upper slopes, and such transverse structures tend to reduce hydro-sedimentary connectivity. In contrast, ditches, the most channelling type of drainage structure, are generally the last structures of the drainage sequences, especially sequences directly connected to the river.

This landscape structure seems to reduce the sediment connectivity on the upper parts of the hillslopes through barrier effects or increases in the length travelled by eroded sediments. On the lower parts of the hillslopes, the connectivity seems to be increased to favour sediment collection within sediment sinks, and especially sediment traps.

We observed a high diversity in the drainage network connections and their upstream sequences and sub-networks, but with different functionality according to their type. An important role is attributed to networks directly connected to the river that might directly transfer sediments from plots. Indeed,

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the sub-networks connected to the river were the longest, and had the highest number of branches and the most complex sequences within the studied catchment. It is only a matter of time (and some rain) before the sediments trapped in these long networks reach the river.

Sediment traps, although little represented in the catchment (24 traps connected to 6% of the drainage network), seem to be located in strategic locations (lower slopes, connected to long and channelling sub-networks) to collect sediment. Other types of sediment sinks involve simpler and shorter spatial patterns (sequences, sub-network lengths, and branches), and tend to completely or partially disconnect some plots from the river.

High-density drainage networks in Beaujolais

The drainage network density observed in our case study in Beaujolais was very high (360 $m.ha^{-1}$). It is about the same order of magnitude as that measured for the Peyne vineyard (Languedoc, France) (40 km^2), which included 96 $m.ha^{-1}$ of ditches, and the Roujan sub-catchment (0.91 km^2) with 120 $m.ha^{-1}$ of ditches (Lagacherie et al., 2010; Levavasseur et al., 2016). Other areas for which the hydro-sedimentary flows have been characterised showed much lower drainage densities than the Beaujolais vineyard landscape. For instance, the densities of drainage network structures ranged from 11 to 41 $m.ha^{-1}$ for hedgerow catchments in Normandy (Gascuel-Odoux et al., 2011; Reulier, 2015), and 45 $m.ha^{-1}$ (roads and ditches included) for the agricultural Paines Creek catchment in California (Buchanan et al., 2013). The high-density values found in our study show the care taken with the soil resource and the reorganisation of the drainage network, with the drainage density being higher within the vineyard itself, at an average of 377 $m.ha^{-1}$. The pattern of the infrastructure type and size along the slope highlights a good understanding of the processes by the winegrowers.

Drainage sub-network – outlet relationships

Our example reveals that the winegrowers have good knowledge of spatial organisation, defining functional units for the hydro-sedimentary processes. Although it remains poorly visible, the dense drainage network confirms that land maintenance strategies cannot be understood at the plot scale alone, but have to take into account a broader scale (Bagagiolo et al., 2018; Biddoccu et al., 2014; Follain et al., 2012). In the case of Beaujolais, the role of drainage infrastructure is to avoid runoff transfers from one vine plot to another, and thus concentrate flows within the vineyard. In this sense, they collect flows from vine plots and reroute them to other landscape elements: other types of land use (forest, grassland), hedges, or the river, according to the landscape management goal. Sediment traps can be located along drains to remove suspended particles from water and thus limit transfers to rivers.

The drainage networks connected directly to the river (25% of the total number of outlets) typically exhibited long and complex upstream networks. They drained a large number of plots and the sediments were stored within the network. Fifty-six percent of the total number of sediment sinks were located in a 100-m buffer zone along the Morcille river (floodplain). This questions the potential sediment transfers from these neighbouring sediment sinks to the river. These sinks could be seen as temporary stores from where sediments can be mobilized during flood events and contribute to flow concentration. Sediment storage in the upper slope sinks is more perennial. Likewise, 20% of sub-networks exported flows outside the watershed. This implies a difference between topographic and effective catchment due to the effect of drainage systems.

Drainage networks connected directly to rivers with insufficient sediment settling processes remain a large issue in many agricultural landscapes. New management strategies to limit direct connection of sediments to rivers still need to be defined. These strategies might be more effective with a thorough understanding of the structure of drainage sub-networks, that is to say their length, number of

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branches, spatial organisation, roughness, location of sediment sinks, and use of sediment traps. The methods we developed should be relevant for considering these aspects. In the case of the Beaujolais vineyard, rethinking the drainage network and reducing connectivity might come about in parallel with the current landscape transition, which is characterised by a decrease in the surface area of the vineyard (Cossart et al., 2020; Pic et al., 2020), the evolution of winegrowing practices, and increases in hedges.

Main contributions of the methods and future improvements

Our approach shows the importance of integrating drainage networks into spatial analysis and modelling. This task is still difficult to address with classical modelling tools based on raster images and the use of digital elevation models whose resolution is often not adapted to the size of individual linear elements. In such situations, graphs have a major role to play in modelling this type of environment (Fressard & Cossart, 2019; Rouzies et al., 2019).

The descriptive approach for the network that we developed in this paper allowed us to highlight the spatial pattern of the winegrowers' strategies for mitigating runoff on hillslopes. Additionally, the approach allowed us to identify areas where improvements to the strategy could be suggested (e.g., direct connection to the river network, sediment sinks located in mobilizable areas such as floodplain).

On the basis of the created database and graph analysis, several improvements to the approaches can be suggested. (1) Include the slope, length, and roughness of the network to provide a more functional assessment of it (e.g., to produce sediment transfer efficiency indicators). (2) Include the hillslopes' drained surfaces using plots or topographic graphs. (3) Include soil erosion equations or sediment connectivity indices to integrate sediment transport capacity and source area potential.

Considering the functional aspects of hydro-sedimentary transfers through transported flow quantities and drained surfaces would be a way to confirm how much the landscape hampers connectivity. This assessment of (dis)connected areas is not easy because it is strongly dependent on the characteristics of the rainfall-runoff events (López-Vicente et al., 2021). Hence, the role of the drainage network in transferring sediments to the river is highly variable.

Conclusions

We developed a descriptive analysis of the spatial pattern of the drainage network in a vineyard-dominated catchment (Beaujolais, France). In this small agricultural catchment, runoff is controlled by linear infrastructure that aims at disconnecting vine plots from each other on the hillslopes. This infrastructure routes sediments to sediment sinks (traps or other settling areas such as forests or grasslands) impeding their transfer to rivers. The very high density of networks (360 $m.ha^{-1}$ on average in the catchment, and 377 $m.ha^{-1}$ on average within the vineyard) shows the local importance of such management strategies to prevent soil erosion and its consequences. Analysis of the spatial pattern of the networks' sequences showed the efforts of the winegrowers to manage sediment connectivity at the catchment scale (lower connectivity on the upper slopes to avoid runoff concentration, and higher connectivity on the lower slopes through runoff channelling). Several outlet types or locations (i.e., directly connected to the river or in the floodplain) raise question of the aims behind the observed infrastructure. Hence, this type of approach can be recommended to assess the general (catchment scale) coherence of such drainage infrastructure. From a methodological point of view, the detailed field inventory combined with a graph theory-based analysis offered a practical framework that allowed detailed analysis of the network in an automated procedure that went beyond more traditional analyses based on DEM and runoff simulation. Hydro-sedimentary transfers at the catchment scale greatly depend on the spatial patterns of land uses. We exhibited the

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role of hidden elements such as drainage networks and associated sediment traps. In the future, we might investigate a more process-based approach.

Acknowledgements

This research was funded by the PULSE project of AERMC/ZABR consortium and a PhD grant from the Université Jean Moulin Lyon 3. A sincere thank you goes to Jules Grillot and Rémi Mourgues for their much-needed help with Python and to Théophile Yeme for field surveys.

Declaration of interest statement

The authors report that they have no competing interests to declare.

Data availability statement

The data that support the findings of this study are available from the corresponding author, J.P., upon reasonable request.

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Table 1. Summary of the drainage infrastructure lengths in the Morcille catchment

Drainage infrastructure type	Infrastructure length (km)	
Main roads	63.72	209.81
Dirt tracks	8.64	
Grassed tracks	137.45	
Grassed ditches	37.05	58.21
Gutters	6.83	
Pipes	14.33	
Soil bunds	28.89	28.89
	296.9	

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Table 2. Summary of the outlet characteristics

	Number of outlets	Proportion of outlets	Drainage network length (m)	Proportion of drainage network length	Mean length of trees (m)
Urban area	18	4.0%	4 678	1.6%	260
Dump and construction site	2	0.4%	431	0.2%	216
Edge	31	6.9%	20 218	7.1%	652
Abandoned plot	15	3.3%	7 486	2.6%	499
Forest	64	14.3%	33 378	11.6%	522
Vineyard	48	10.7%	16 395	5.7%	342
Grassland	110	24.6%	64 894	22.6%	590
River	48	10.7%	83 813	29.2%	1 746
Settling tank	24	5.4%	17 272	6.0%	751
Outside the watershed	88	19.6%	38 021	13.3%	432
	448	100%	286 586	100%	641

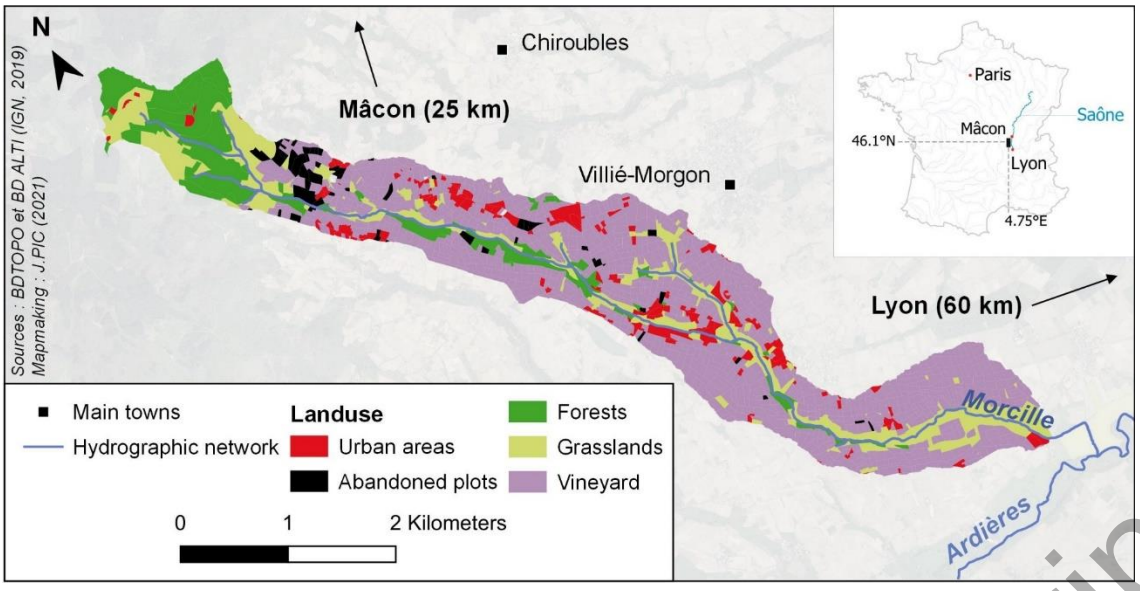
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Table 3. Summary of the sequence characteristics

Outlet types	Number of sequences	Number of different sequences	Percentage of different sequences occurring more than once	Mean number of elements per sequence	Mean length of sequences (m)
Urban area	46	9	78%	1.7	163
Dump and construction site	4	2	100%	1	107
Edge	171	50	50%	2.6	292
Abandoned plot	90	31	55%	2.6	170
Forest	337	105	52%	2.7	196
Vineyard	179	34	59%	2.1	256
Grassland	618	142	56%	2.8	223
River	725	184	54%	3.7	488
Settling tank	159	77	51%	4.2	525
Outside the watershed	308	79	56%	2.8	543
	2 637	449	54%	3.0	350

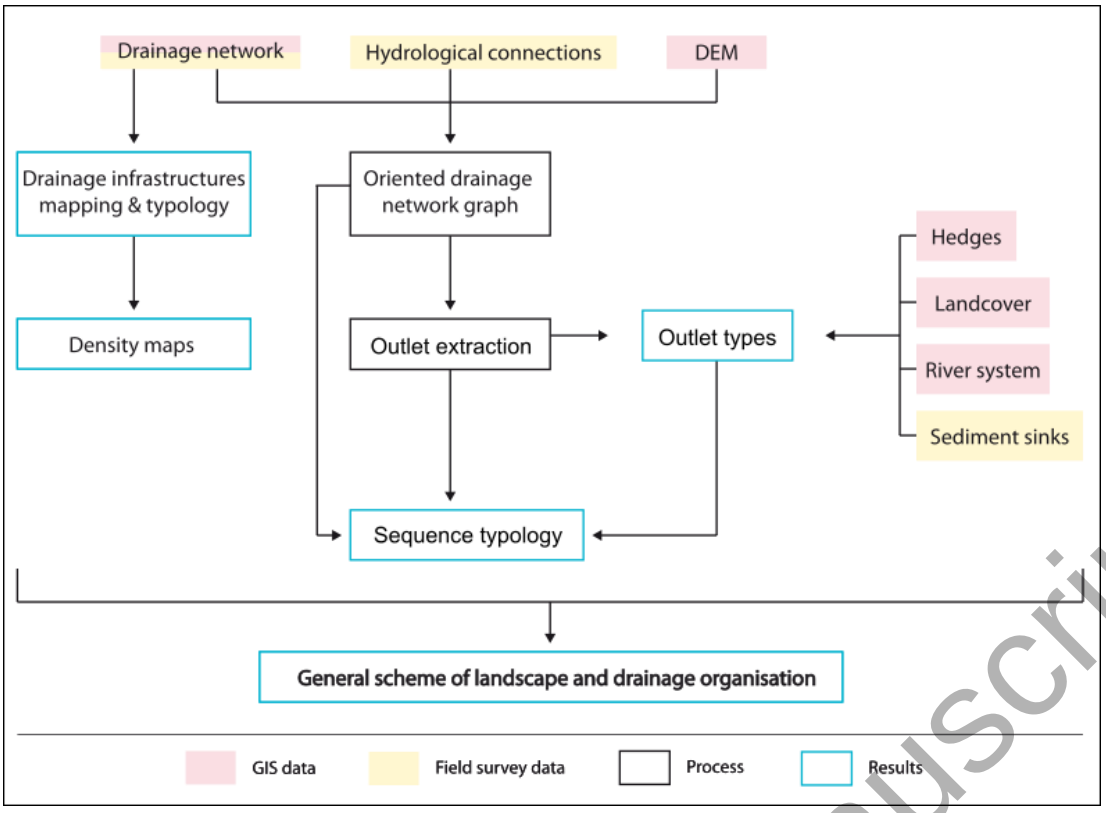
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Figure 1. Morcille catchment location and land use



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Figure 2. General diagram of the methodology



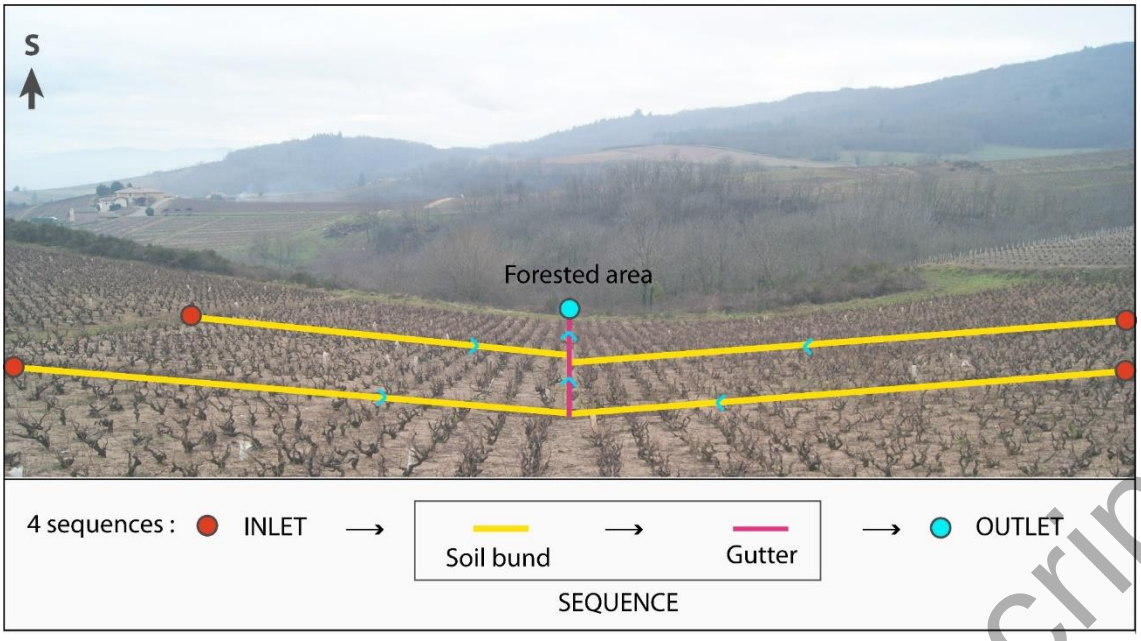
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Figure 3. Typology of the linear infrastructure and sediment traps. A – Main road. B – Dirt track. C – Grassed track. D – Grassed ditch. E – Gutter. F – Pipe inlet. G – Soil bund boarding a dirt track. H – Mid-plot soil bund. I & J – Two kinds of sediment traps.



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Figure 4. Sketch of a simple sub-network (inlet, outlet, and corresponding sequences) on the Morcille catchment



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Figure 5. Examples of landscape influence on flows. A – Grassed track–soil bund combination leading to flow rerouting. B – Grassed track–soil bund combination and sediment deposit. C – Flowing water running from an inside-plot soil bund to a ditch. D – Flowing water running from a main road to a grassed ditch. Source: J. PIC & T. YEME, 2020–2021.



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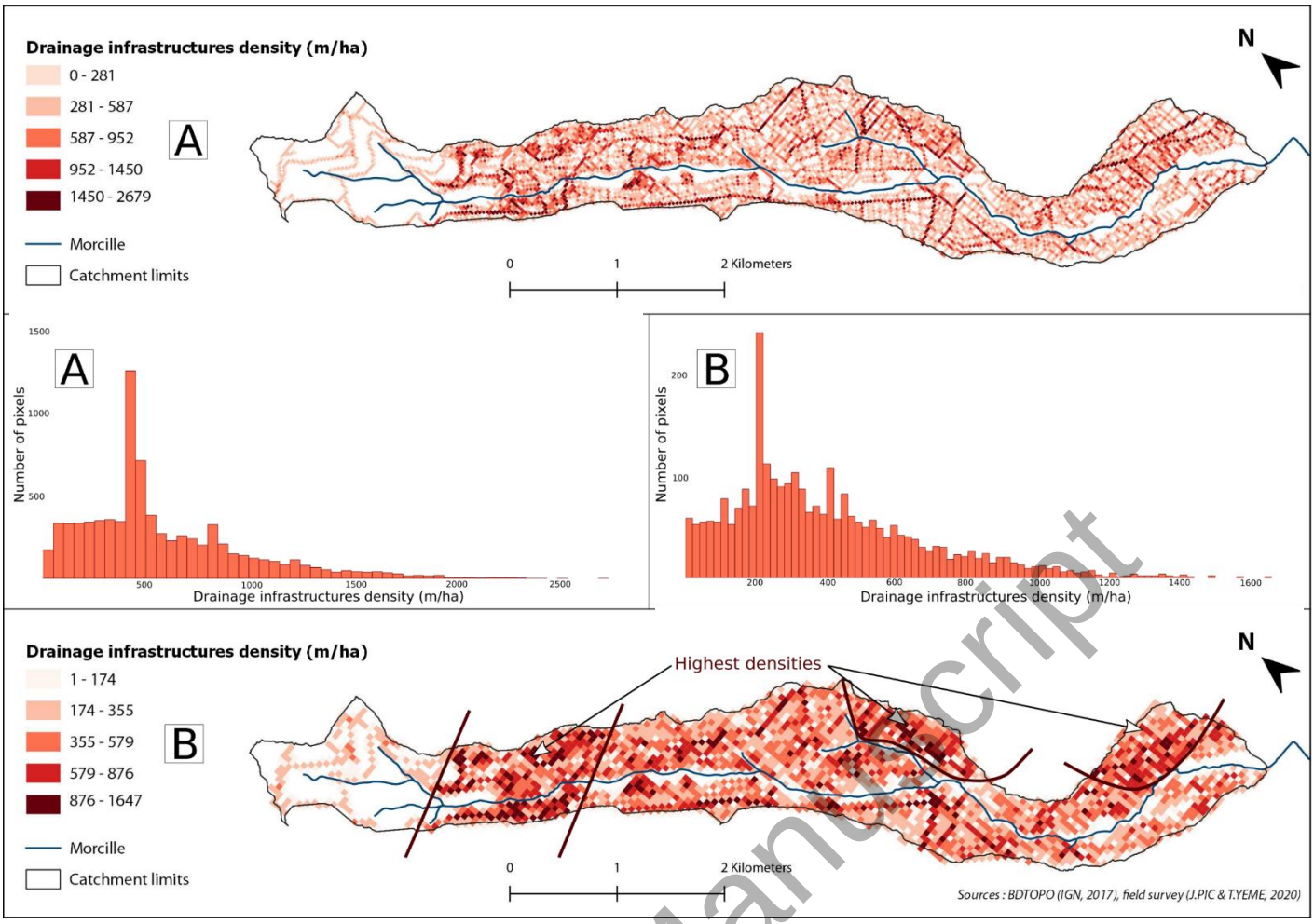
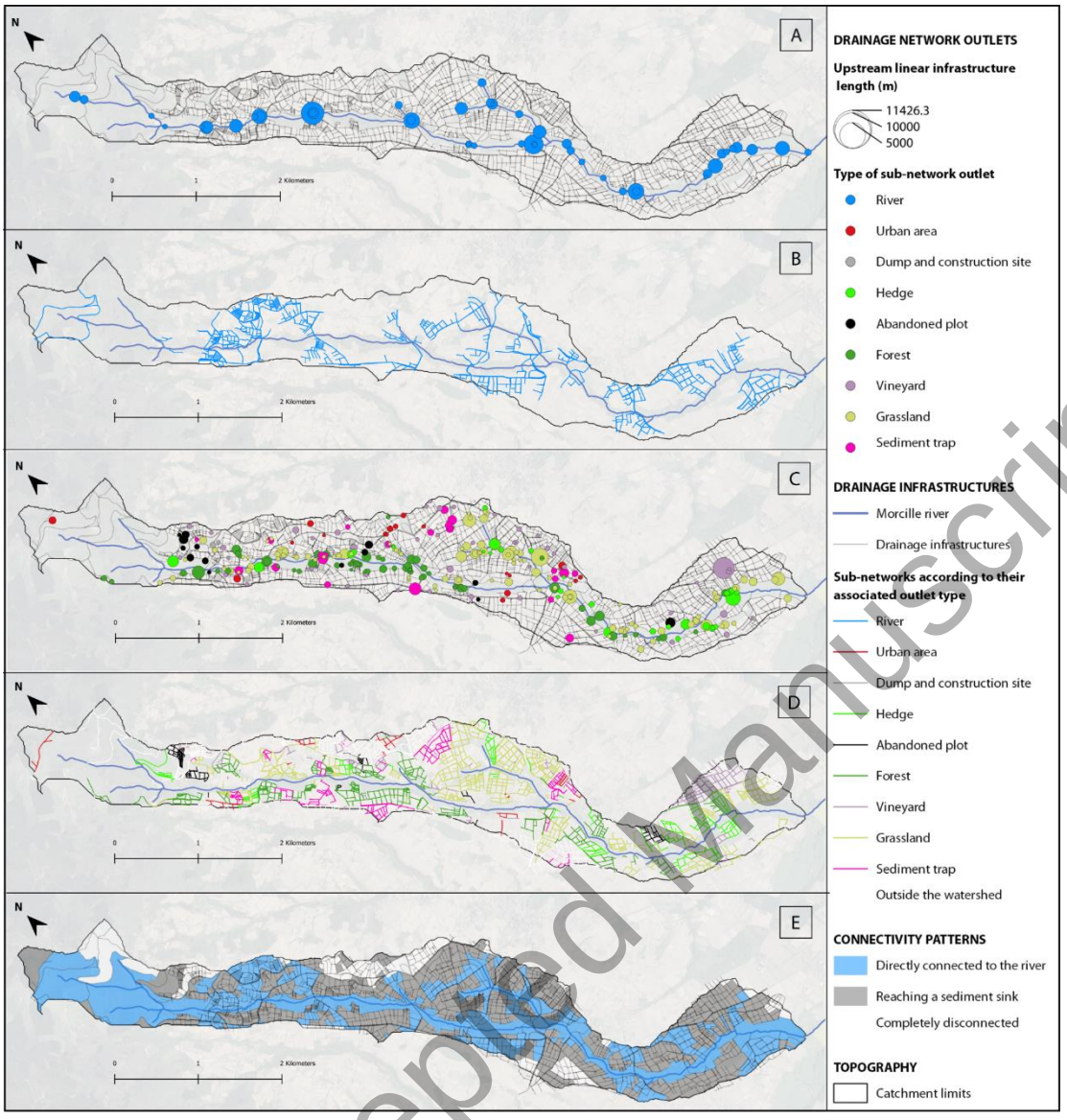


Figure 6. Drainage infrastructure density map and associated probability distributions. A - Drainage network density for a 25-m grid. B - Drainage network density for a 50-m grid.

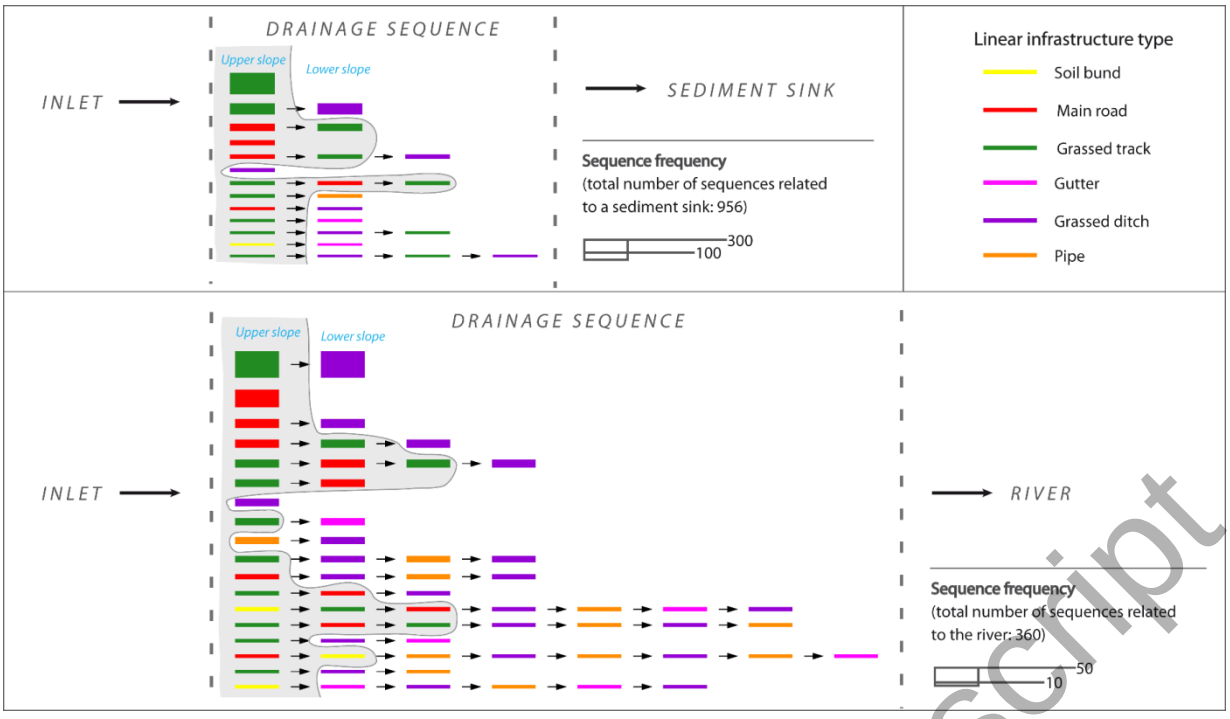
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Figure 7. Types of connections resulting from the drainage infrastructure, Morcille catchment (2020). A – River outlet locations. B – Drainage infrastructure leading directly to the river. C – Sediment sink locations and associated upstream sub-network lengths. D – Classification of drainage infrastructures according to their associated sediment sink. E – Distribution of connection types.



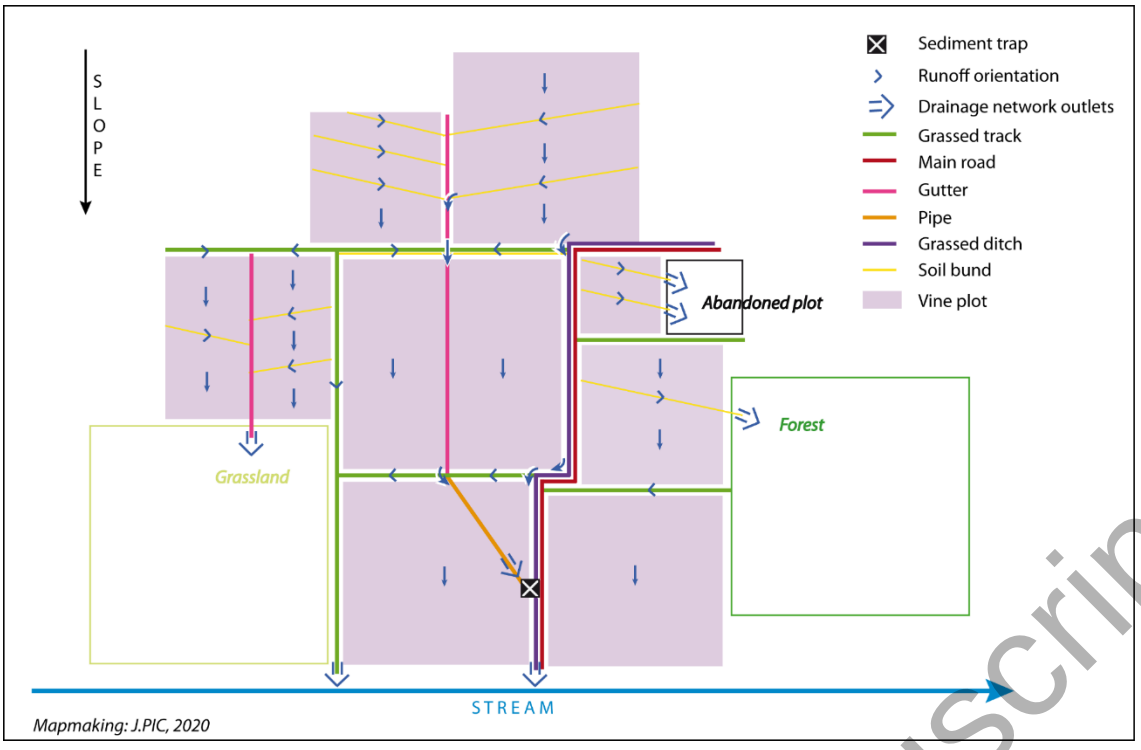
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Figure 8. Most frequent sequences connected to (1) sediment sinks and to (2) the river



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Figure 9. Sketch of the influence of linear infrastructure on runoff and associated sediment pathways



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