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# Contribution of the Sediment Flow Connectivity Index (SfCI) in Landscape Archaeology Investigations: Test Case of a New Interdisciplinary Approach

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**Abstract:** The integration of geomorphological analysis in archaeological investigations is essential to describe physical geography and land morphology in order to understand the relationship between the environment and human activities. Recently, the sediment flow connectivity index (SfCI) has been demonstrated to be a powerful geomorphic indicator for defining the most sensitive areas to geomorphological modifications in a catchment. This work presents the experimental application of the SfCI for a landscape archaeological analysis in order to assess the contribution of the index to potentially recognize, monitor, and interpret the historical evidence in the evaluation of landscape evolution. The investigation was performed in the basin of Lama Camaggi in the Apulia region (southern Italy), characterized by precious archaeological evidence found on the surface during field surveys in the years 2001–2002 and 2012–2013. The results show (1) the correlation between high-sediment-connectivity areas and areas with high densities of archaeological sites, and (2) the capacity of the SfCI to identify surface processes that may potentially affect the readability of the archaeological records to support data interpretation. These results confirm the advantage of applying an interdisciplinary approach in archaeology and opens innovative research scenarios.

**Keywords:** sediment connectivity; heritage vulnerability; geomorphology; landscape archaeology

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## 1. Introduction

An interdisciplinary approach based on the comparative assessment of different information sources (geology, geomorphology, geophysics, archaeology, history, topography, cartography, toponymy, literature, epigraphy, etc.) is essential to reconstruct paleolandscapes. Indeed, the availability of various data is useful in all phases of archaeological studies, from the preliminary analysis of sites to planning field surveys, from the detection of archaeological evidence to the interpretation of discovery contexts, and from the monitoring to the preservation of cultural heritage [1–6]. In this wide framework of archaeological investigations, the analysis of the evolution of the landforms (i.e., geomorphology) plays a very important role to better understand: (a) the relationship between environment and human activities over time, (b) the unfolding of historical events, (c) the interrelation of surface-occurring phenomena and the surficial distribution of archaeological data, and (d) the natural and anthropogenic processes that affect heritage assets [7–11]. As demonstrated in the literature, all these fields of research, in which the contribution of geomorphology is indispensable, are closely interconnected: the preservation of cultural heritage requires the examination of past events and the reconstruction of the interaction of nature and human actions involved in the archaeological evidence [7,10–16]. Over the years, researchers have highlighted the importance of jointly investigating natural and cultural heritage in order to sustain it through its promotion and protection [17–21]. It is therefore evident that an important tool for achieving the sustainability goals defined by the United Nations (Sustainability Development Goals—SDG 8 and 11, [22]) is the analysis of the forms and processes occurring on the Earth's surface applied to archaeological investigations. In particular, the morphological dynamics of the surface and its modification over time have always influenced human choices, and, moreover, conditioned the possibility of site discovery and the readability of surface archaeological traces [23–26]. Furthermore, erosion, transport, and deposition processes that shape landforms continue to modify the physical environment to which the archaeological heritage is closely connected, conditioning its cultural value and preservation. In fact, archaeological heritage, either standing above soil or still buried, is affected by surface mobility. This should therefore be quantitatively analyzed to better define the dynamics of discovered remains, together with their conservation and interpretation [27–29]. Therefore, it becomes necessary to describe and consider these processes in the analysis of archaeological surface evidence in order to exploit the advantages of geomorphometry so to monitor their evolution and understand their significance and relevance.

During the past years, geomorphologists focused on sediment connectivity that described sediment paths within a catchment by investigating the contiguity of landscape components and their interaction in geomorphic, hydrological, and ecological systems [30–35]. Various aspects have been explored, and new approaches and methods have been developed, providing helpful tools (indices and models) to evaluate and estimate sediment mobilization and transport from sources to sinks, and the consequent connection with the hydrographic network [36–39]. From the earliest studies, the increasingly widespread use of geomorphic indicators to assess the processes of the supply, transfer, and storage of sediment on the surface demonstrates the applicability of sediment connectivity in different disciplinary fields: river monitoring and management [40–42], geodiversity and biodiversity [43,44], and climatology and pedology [45–47]. However, the contribution of sediment connectivity assessment in the analysis of the processes involving surface archaeological evidence has not yet been investigated.

This work presents the experimental application of the sediment flow connectivity index (SfCI) in landscape archaeology analysis. The SfCI is a powerful geomorphological indicator for defining the most sensitive areas to geomorphological modifications in a catchment; it has been previously tested to correlate the effects of various events that occur in a catchment, conditioned by water and sediment displacement [48–50]. The investigations were performed in the Lama Camaggi basin, in the Apulia region (southern Italy), which is characterized by a large presence of archaeological evidence, found on the surface during field surveys in the years 2001–2022 and 2012–2013. The present work analyses the relationship between sediment connectivity and the occurrence of surface archaeological data by assessing whether the SfCI can provide useful information to reconstruct and preserve paleolandscapes. Then, the experimentation aims to assess the role of phenomena, such as surface water outflow, downslope wash, or sediment burial, in the evaluation of the reliability of archaeological records. The main objective is to explore the potential of the SfCI to monitor and interpret surface archaeological evidence. The relevance to define the potential contribution of the SfCI in landscape archaeology investigations lies in a promising opening of new research scenarios in geoarchaeology.

## 2. Study Area

The rather small basin of Lama Camaggi (210 km$^2$), located in the north–central area of the Apulia region (southern Italy), extends from the border between the high and low part of the carbonate Murge plateau, whose evolution is controlled by climate and sea-level changes [51–54], to the Adriatic coast (Figure 1). Lama Camaggi is a characteristic fluvio-karst valley in the Apulian landscape that is intersected by caves and depressions (such as collapse dolines) and a surface runoff and drainage network of valleys, locally named Lame and Gravine, incised in Plio–Pleistocene calcarenites and Mesozoic limestones. The lithological aspect, the change of the base (sea) level, and the low gradient of the topography conditioned the generation and the morphological features of these valleys that are characterized by subvertical walls and flat bottoms filled with colluvial and alluvial deposits [10,54,55]. These valleys represent the main hydrographic network of the region. The main characteristics of the Lama Camaggi catchment are: (1) the ephemeral hydrological regime of the streams; (2) the overall low-slope angles alternating with the presence of the Murge hills, such as Monte Santa Barbara (262 m msl) and Monte Faraone (232 m msl); (3) the low spatial variability in precipitation, soil units, and land use. Furthermore, during extreme-rainfall events, flood phenomena occurred along Lama Camaggi near the towns of Andria and Barletta, where some sections of the channel have been buried and diverted.

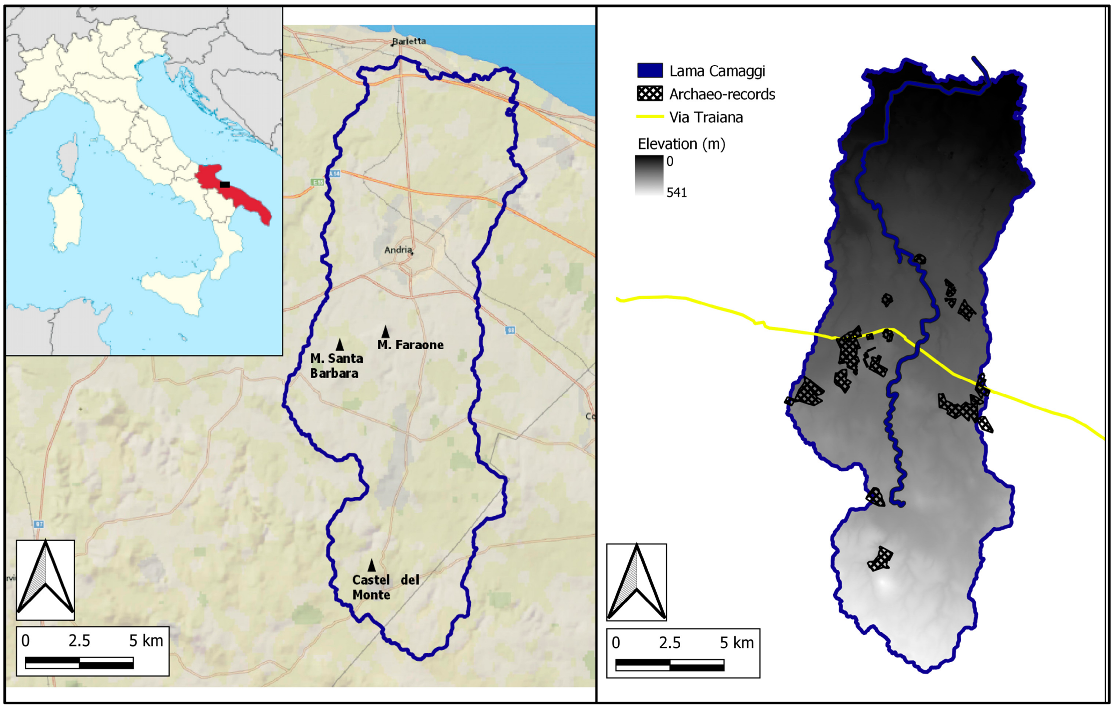


**Figure 1.** Lama Camaggi basin in the north–central of the Apulia region (location area at the top left), with topographic, geomorphological, and archaeological features. Base map: ESRI National Geographic (on the left) model and Digital Elevation model (on the right).

The morphology of the area of the Lama Camaggi catchment has influenced the anthropic dynamics since the earliest times. In fact, the analysis of the archaeological traces here found (see Section 3.2 and Figure 1) demonstrate that topography affected the historical evolution of the ancient settlements, as well as the anthropic displacement in the territory from the Prehistoric to the Medieval age [56]. Furthermore, the ancient track of the Via Traiana Roman road was identified in an area that crosses the catchment in the east–west direction [57–59]. These geomorphological aspects, coupled with the archaeological evidence, make the basin of Lama Camaggi a suitable test area to investigate the applicability of the SfCI in archaeology.

## 3. Materials and Methods

### *3.1. Geomorphological Analysis*

#### 3.1.1. SfCI Computation

As presented in [48], the SfCI is based on a mapping approach that includes functional aspects in the structural component of sediment connectivity. Structural connectivity indicates the physical contiguity of morphological units in a hydrographic catchment, while functional connectivity indicates the interaction between morphological units through geomorphic processes [31,47,60]. In particular, in the SfCI, the connectivity is defined as the connection by sediment transport, considering the mobilization (erosion) of sediment and its transfer along the channel to the outlet in the lateral and longitudinal directions; then, assessing sediment linkages through material transport. The index is founded on two main assumptions: (i) if there is no sediment mobilization, there is no connection; (ii) the greater the sediment mobilization in a cell, the greater the possibility that mobilized sediment reaches other cells [36,48]. This combination of structural and functional components is supported by the definition of a soil stability index (recognized as a functional property of sediment connectivity, [61]) and by the use of a flow-routing algorithm (considered as a proxy for runoff processes) to estimate water- and sediment-contributing areas, thus defining sediment paths according to the steepest descent direction. Clearly, the latter is a simplified method to describe the complex dynamics of sediment transport that partly limits the analysis; nevertheless, it is justified by the initial assumptions (i-ii) and by the common application of similar contributing-area approaches in sediment connectivity assessment ([61,62] and reference therein).

The computation of the SfCI consists of three main steps: (1) the computation of a sediment mobility map, (2) the derivation of the SfCI map through flow routing, and (3) the (optional) production of a simplified SfCI map for applicative purposes (see Figure 1 in [48]). The sediment mobility map estimates the potential detachment and mobilization of sediment, while the sediment-flow-accumulation algorithm estimates the potential sediment fluxes through slope-driven flow accumulation.

The sediment mobility map (*SM*) derives from the product of two factors, $SM_1$ (potential sediment detachment, controlled by rainfall, soil stability, and land use) and $SM_2$ (potential movement towards surrounding cells, controlled by topographic and morphological aspect of the surface). *SM* is defined as:

$$SM = SM_1 \cdot SM_2 \tag{1}$$

with

$$SM_1 = \frac{R}{SI} L \tag{2}$$

$$SM_2 = \frac{S}{Ru} \tag{3}$$

where *R* is a rainfall index, *SI* is a soil stability index, *L* is a land-use index, *S* is a slope index, and *Ru* is a surface ruggedness index (which describes the topographic variability as the mean difference of height between a central pixel and its surrounding cells; see [48]). Each of these indices is dimensionless and determined by ranking the values of all the corresponding variables through a qualitative approach based on the a priori interpretation of erosion surface processes [35,48]. In this simplified approach, 1 is assigned to the maximum value, 0.05 (in order to avoid null values) is assigned to the minimum value, and the range from 0.05 to 1 is assigned to intermediate values in relatively uniform intervals [48,49].

The sediment flow connectivity map is obtained by propagating the *SM* values (initial seed values) through a classical flow-accumulation algorithm *F* [63,64], which allows us to simulate a "sediment contributing area" for each cell according to a steepest slope principle. In this way, after iterations, the cells with the highest flow-accumulated values are sediment-active cells (i.e., cells that contribute to sediment flux), and the cells with the lower flow-accumulated values are sediment-inactive cells (i.e., the cells that are not on a sediment pathway). The SfCI is given by:

$$\text{SfCI} = \log_{10} F(SM) \tag{4}$$

The applicative SfCI (a_SfCI) map is derived by applying a mean filter through a rectangular window to the SfCI map in order to aggregate similar connectivity data over map areas (and not single paths). This smoother map is classified in three connectivity classes (high, medium, and low) defined through a natural break index (Jenks). This sediment connectivity representation helps highlighting hotspots (corresponding to high-sediment-connectivity areas) in the catchment, i.e., areas most sensitive to geomorphological modification. Therefore, the a_SfCI constitutes the main tool to directly apply the sediment connectivity index to fluvial, alluvial, and (here) archaeological contexts [48,49].

#### 3.1.2. SfCI Data Processing

All maps derived for the SfCI computation (i.e., rainfall, soil stability, land-use, slope, and ruggedness indices maps) have here a spatial resolution of 8 m that corresponds to the resolution of the regional DEM used in the extraction of surface characteristics. The regional DEM of the Apulian territory was realized by combining the photogrammetry and technical regional cartography with a vertical accuracy of 1 m; the dataset, which is composed by tiles in ASCII format, can be downloaded from the UTM33N-WGS84 projection system from the regional WebGIS site (http://www.sit.puglia.it; accessed on 12 September 2023).

Rainfall data correspond to the mean annual precipitation (MAP) recorded by rain-gauge stations (located in Apulia, Campania and Basilicata regions) in the period 1921–2020, freely available from Puglia, Dipartimento di Protezione Civile Regione Puglia (https://protezionecivile.puglia.it; accessed on 12 September 2023). Data were converted to isohyet maps by applying inverse distance-weighted interpolation (Shepard, 1968) [65]. In particular, the range of the MAP values over the Lama Camaggi basin, corresponding to 517–598 (mm/y), was extracted from the isohyet map and rescaled into index values from 0.05 to 1 (see Table 1 and Figure 2a).

**Table 1.** Mean annual precipitation (MAP) in the Lama Camaggi basin classified in rainfall index values. The maximum values correspond to 1, the minimum values correspond to 0.05, and intermediate values correspond to uniform ranges (see text for details).

| MAP<br>(mm per Year) | Rainfall Index Value |
|---|---|
| 517–522 | 0.05 |
| 523–541 | 0.25 |
| 542–560 | 0.50 |
| 561–579 | 0.75 |
| 580–598 | 1 |

Soil stability data were obtained from the classification of soil properties, such as thickness and permeability, considered for the evaluation of the layer saturation and drainage-runoff capacity of the soil surface, respectively (Cevasco et al., 2014 [66]; Zingaro et al., 2019 [48]; Zingaro et al., 2020 [49]). Soil units and relative properties come from a regional soil map (1:100.000 scale) and from the ACLA (Agro-ecological characterization of Apulia) dataset (https://pugliacon.regione.puglia.it; accessed on 12 September 2023). First, the classes of permeability (from 1 to 6) and the values of the thickness of the soil units were examined and classified (high, medium, and low permeability and thickness; see Table 2); then, a matrix of combined properties was developed (Table 3) and the definition of three classes of the soil stability index, with corresponding values from 0.05 to 1, was derived (Table 4 and Figure 2b). In addition, the field observation of the soil units described in the database was applied.

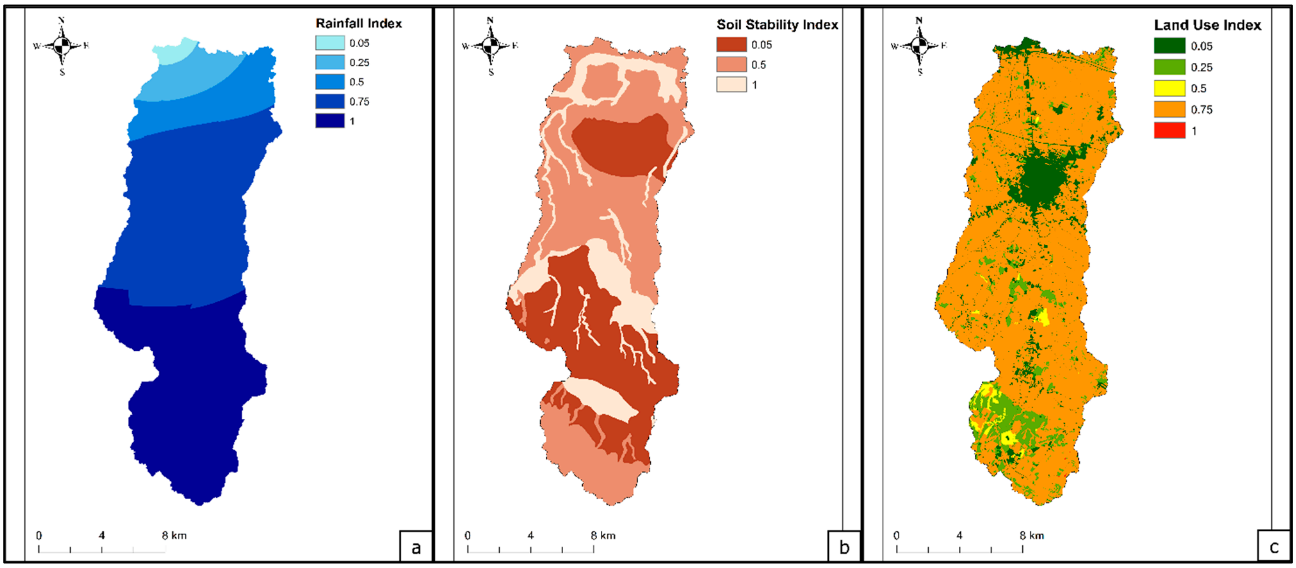


**Figure 2.** SfCI input data in the Lama Camaggi basin. (**a**) Rainfall data: isohyets in the value classes (mean annual precipitation). (**b**) Soil stability data: soil properties conditions in assigned value classes. (**c**) Land-use data in associated value classes.

**Table 2.** Classification of soil properties (permeability and thickness) useful to determine the soil stability conditions. Categories of the properties are derived from the relative classes and values (see text for details). LP = low permeability; MP = medium permeability; HP = high permeability; LT = low thickness; MT = medium thickness; HT = high thickness.

| Soil Properties | Soil Properties Classes |
|---|---|
| **Permeability Classes** | |
| **1** | HP |
| **2** | HP |
| **3** | MP |
| **4** | MP |
| **5** | LP |
| **6** | LP |
| **Thickness Classes** | |
| **<100 cm** | LT |
| **100–199 cm** | MT |
| **>199 cm** | HT |

**Table 3.** Soil stability classes defined by the matrix of soil properties conditions (see text for details and previous caption for the soil properties abbreviations). HS = high soil stability; MS = medium soil stability; LS = low soil stability.

| | HT | MT | LT |
|---|---|---|---|
| HP | HS | MS | MS |
| MP | HS | MS | LS |
| LP | MS | MS | LS |

**Table 4.** Soil stability classes with corresponding soil stability index values (see text for details and previous caption for abbreviations).

| Soil Stability Classes | Soil Index Value |
|---|---|
| LS | 0.05 |
| MS | 0.5 |
| HS | 1 |

Land-use data were derived from the regional soil-use map (updated to 2011), available on the WebGis site (http://www.sit.puglia.it; accessed on 12 September 2023). The classification of the land-use index was defined by assigning high values to classes that can favor sediment detachment (e.g., poorly vegetated, croplands) and low values to classes that can obstruct sediment detachment (grasslands, pastures, shrubs). The classification is reported in Table 5 and Figure 2c.

**Table 5.** Land-use classes and index values assigned considering the related sediment mobility (see text for details).

| Land-Use Classes | Land-Use Index Value |
|---|---|
| Urban areas | 0.05 |
| Grassland/pastures/shrubs | 0.25 |
| Woods | 0.50 |
| Croplands | 0.75 |
| Beaches/Poorly vegetated | 1 |

Slope and ruggedness indices maps were obtained by computing slope and ruggedness from the regional DEM (see Section 3.1.1) and classifying the corresponding ranges of values. In particular, the TRI (terrain ruggedness index, Wilson et al., 2007) [67] was computed by using a tool implemented in the "gdaldem" module of the GDAL/OGR Geospatial Data Abstraction software library, version 3.7.2 (Open Source Geospatial Foundation, https://gdal.org; accessed on 12 September 2023). The ranges of the slope and ruggedness were rescaled into values from 0.05 to 1 (see Tables 6 and 7 and Figure 3).

**Table 6.** Slope ranges rescaled in slope index values from 0.05 and 1 (see text for details).

| Slope (Degree) | Slope Index Value |
|---|---|
| 0.00–0.99 | 0.05 |
| 1.00–15.99 | 0.25 |
| 16.00–30.99 | 0.50 |
| 31.00–45.99 | 0.75 |
| 46.00–60.74 | 1 |

**Table 7.** Terrain ruggedness index ranges rescaled in TRI values from 0.05 to 1 (see text for details).

| TRI (m) | TRI Value |
|---|---|
| 0.00–0.25 | 0.05 |
| 0.26–3.00 | 0.25 |
| 3.01–6.00 | 0.50 |
| 6.01–9.00 | 0.75 |
| 9.01–12.65 | 1 |

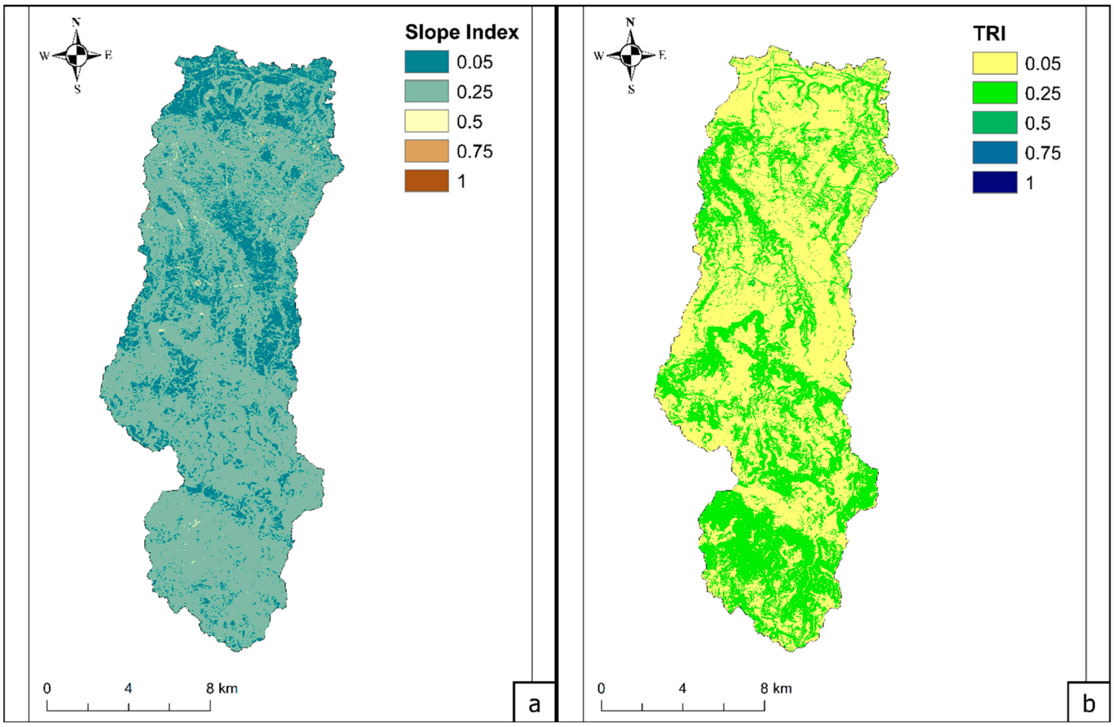


**Figure 3.** SfCI data in the Lama Camaggi basin. (**a**) Slope index map; (**b**) Terrain ruggedness index map.

All the steps of the mapping procedure were carried out using ArcMap®, version 10.8 (ESRI, www.esri.com; accessed on 12 September 2023) and QGIS®, version 3.16.1 (Open Source Geospatial Foundation Project, http://qgis.org; accessed on 12 September 2023) software.

### 3.2. Archaeological Analysis

Historical analysis and field surveys have been performed in the Lama Camaggi basin in recent years as part of various scientific research and urban-planning investigations. In particular, archaeological evidence found during the activities performed in the years 2001–2002 and 2012–2013 in the territory of Andria (involving part of the Lama Camaggi basin) are considered here [56,68]. Following a preliminary landscape study, the archaeologists of the University of Bari (https://www.uniba.it; accessed on 12 September 2023) and the Superintendence of Archaeology, Fine Arts and Landscape (https://sabapba.cultura.gov.it/; accessed on 12 September 2023) carried out systematic surface surveys in the areas of greatest geomorphological and historical interest, according to the current guidelines of landscape archaeology investigations [14,69–71]. As described in the related literature [56,68], tools, such as cartographic support (map of the Italian Military Geographic Institute, digital terrain model—DTM, orthophotos, hydrogeomorphological, and cadastral maps), global positioning system (GPS) devices, and site and topographical unit cards, were used in the field; digital database and GIS platforms were used in the processing phase. The evidence (areas of archaeological material, ancient structures) identified on the surface, henceforth called archaeo-records (Figure 1), were recognized as traces of the anthropogenic presence in the territory from Prehistory to the Modern Age, made easier by the morphological characteristics of the natural landscape. In fact, through the historical interpretation of this evidence, the archaeologists described the anthropic choice to occupy this area, above all in the Prehistoric and Protohistoric ages, as strongly determined by the availability of shelter and defense in hills and caves (represented by the karst and tectonic morphologies of the Murge hills), and the proximity of primary sources (such as water, wild fruits and plants, game, wood). Thus, deep valleys

(Lama Camaggi and other smaller valleys in the catchment) could represent advantageous territories and could be exploited as reference lines for moving around the territory from the high part of the Murge plateau to the Adriatic coast [10,72]. A greater human organization of spaces could then be ascribed to the Archaic–Classical and Roman ages, documented by the traces of settlements (such as the sites of Monte Santa Barbara, Tavernola, and Quadrone) and roads. Moreover, historical analysis shows that the Via Traiana and other minor roads continue to follow the orientation of the natural forms (see Figures 2 and 3 in [56]). Archaeological remains (pottery artifacts, ruins, cisterns, masserias) demonstrate that the territory was highly populated in the Medieval and Modern ages.

This archaeological analysis, which is based on past works, was applied here with reference to two main aspects: (1) acquiring the location of archaeo-records in the Lama Camaggi basin and (2) understanding the cultural significance of this evidence closely related to the landscape context.

### *3.3. SfCI and Archaeo-Records Comparison*

In order to compare sediment connectivity values with the archaeological occurrence, a visual analysis was applied. In particular, the a_SfCI map and archaeo-records were overlapped to identify a potential spatial correspondence of high-sediment-connectivity areas with archaeo-records areas. Moreover, a further focus on surface-occurring phenomena was attempted by using the SfCI map in order to observe the sediment paths in areas affected by the presence of the archaeological evidence.

## 4. Results

### *4.1. SM, SfCI, and a_SfCI Maps*

Figure 4 shows the SM, SfCI, and a_SfCI maps derived from Equations (1)–(4). In the SM map (Figure 4a), most of the Lama Camaggi basin is characterized by low sediment mobility (blue cells), with higher values of mobility (orange–red cells) predominantly distributed in two parts of the catchment. This sediment mobility pattern is mostly conditioned by the lower stability of soils in these areas of the basin rather than by the rainfall rate, land use, and topography. In fact, the presence of thinner and less permeable soils (see Section 3.1.2 and Figure 2b) appears to be the most important contributor to increased sediment mobility, given the low spatial variability of other mobility factors (see Figures 2 and 3).

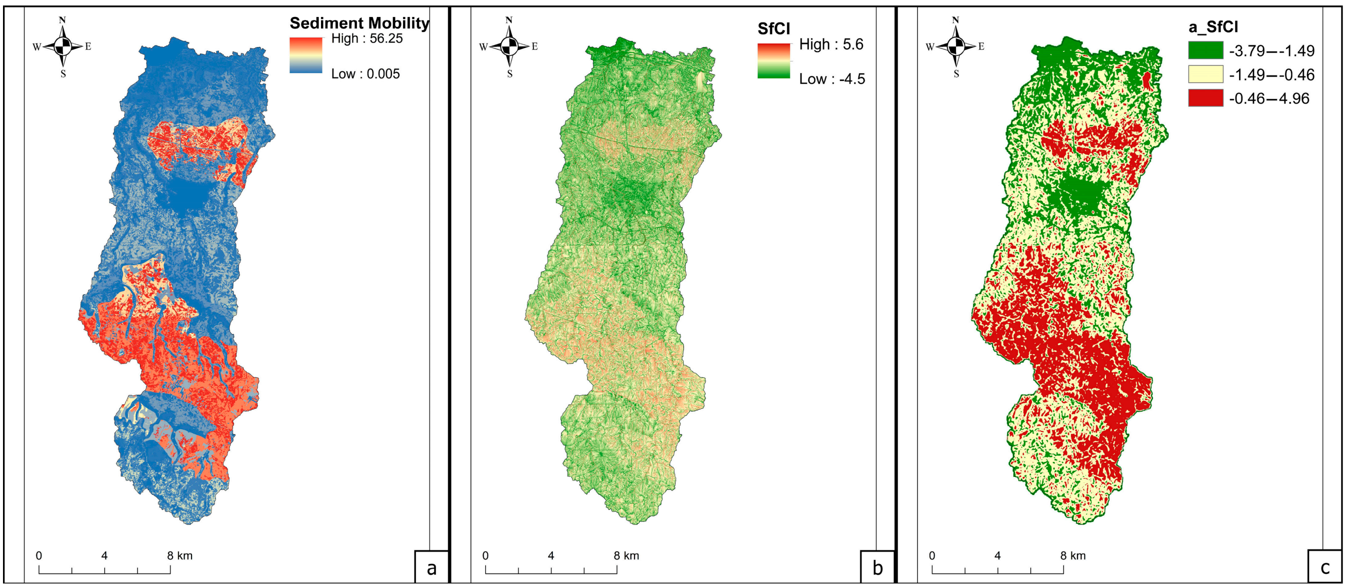


**Figure 4.** SfCI maps of the Lama Camaggi basin. (**a**) Sediment mobility (SM) map (derived from Equations (1)–(3)), (**b**) sediment flow connectivity index (SfCI) map, and (**c**) a_SfCI map.

The SfCI map (Figure 4b) shows values of the index ranging between −4.5 (very low) and 5.6 (very high). Sediment paths are identified by high SfCI values (red cells) in greater sediment mobility areas, showing that sediment flow tends to concentrate only in those parts of the basin where sediment supply in the drainage network occurs from local sediment sources (higher areas). Disconnected areas (green cells) are present in almost the entire basin, with a greater extent in the northern part.

In the a_SfCI map (Figure 4c), areas with low, medium, and high sediment connectivity are more visible (green, yellow, and red, respectively). The spatial distribution of sediment connectivity shown by the map makes the presence of hotspot areas (red) in the Lama Camaggi basin even more identifiable in two main regions of the catchment.

*4.2. SfCI Comparison with Archaeological Occurrence*

Figure 5 shows the visual comparison between the sediment connectivity areas and archaeological occurrence areas through the overlap of the a_SfCI map and archaeo-records. As visible in the figure, most areas with archaeological evidence are located in one of the two main hotspot regions, thus showing a higher tendency of areas most active in geomorphological dynamics (i.e., affected by high sediment connectivity) to host areas characterized by the presence of archaeological data on the surface (detailed box).

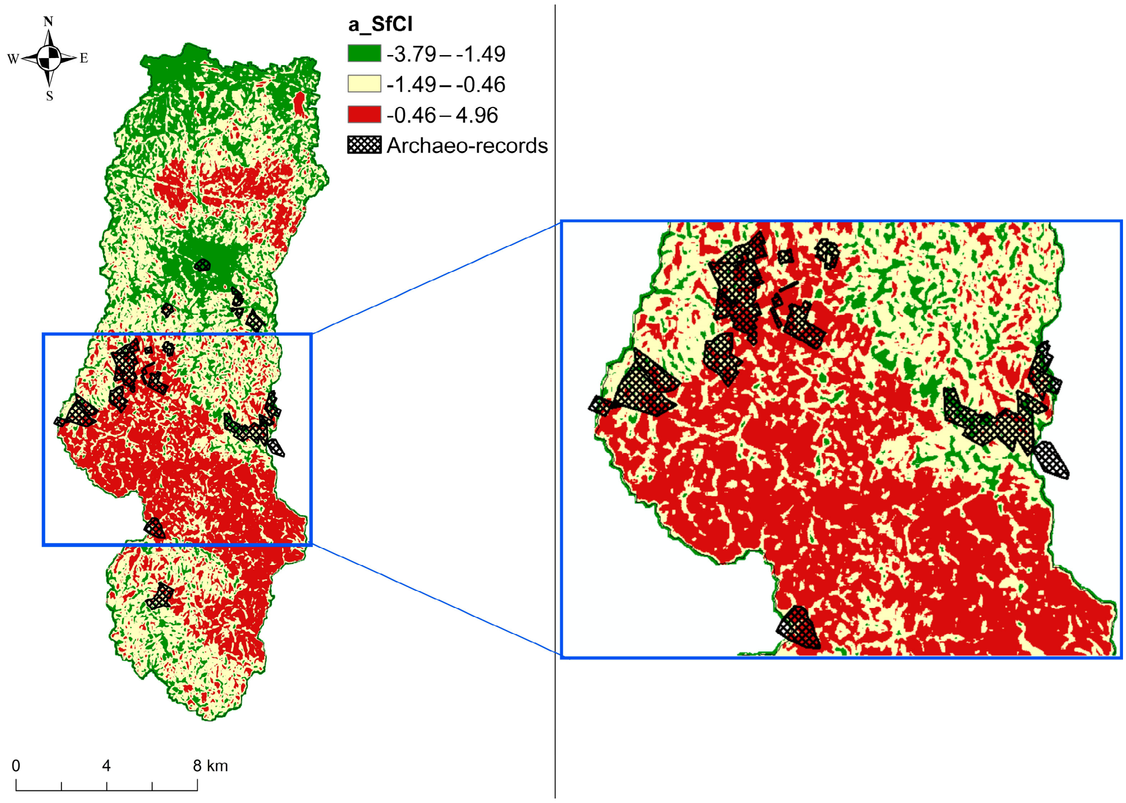


**Figure 5.** Visual comparison of the a_SfCI map with archaeo-records.

Figures 6 and 7 focus the analysis in the most significant area for the presence of archaeological evidence (the site of Monte Santa Barbara, see Section 3.2 and Figure 7a) by observing the location of the archaeo-records within the sediment paths (SfCI map, Figure 6b). The comparison shows that there are archaeological areas (highlighted in light blue in Figure 6 and visible in photos in Figure 7b–d) receiving a high contribution of water and sediment due to their location on sediment flows (marked by red arrows in Figure 6a,b).

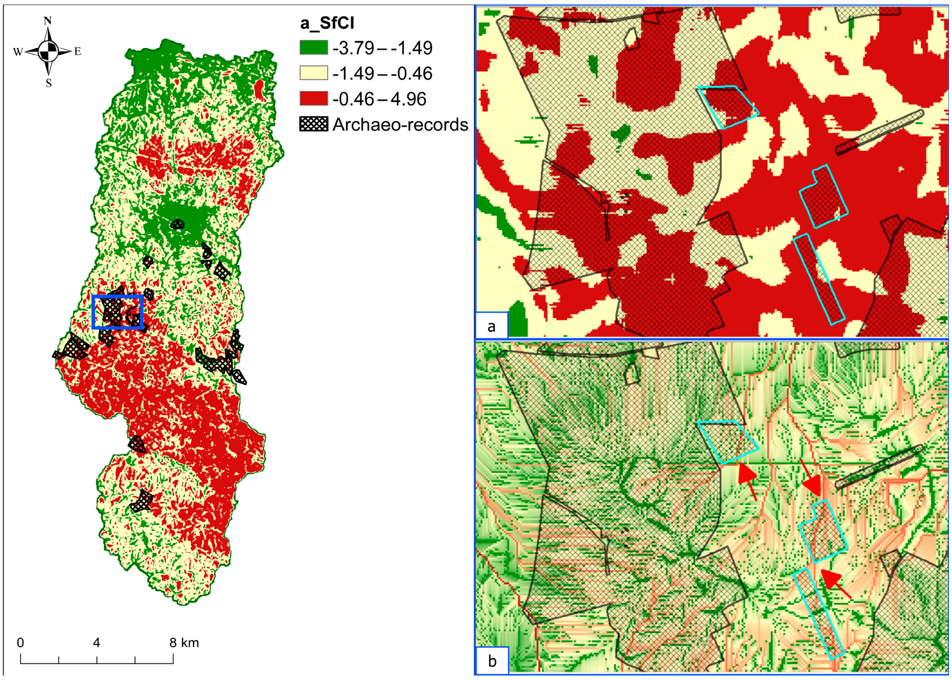


**Figure 6.** Focused visual comparison in the Monte Santa Barbara area. Right: detailed a_SfCI (**a**) and SfCI (**b**) maps corresponding to the blue box on the left. Archaeo-records highlighted in light blue are located in hotspot areas (**a**), and on sediment paths marked by red arrows (**b**).

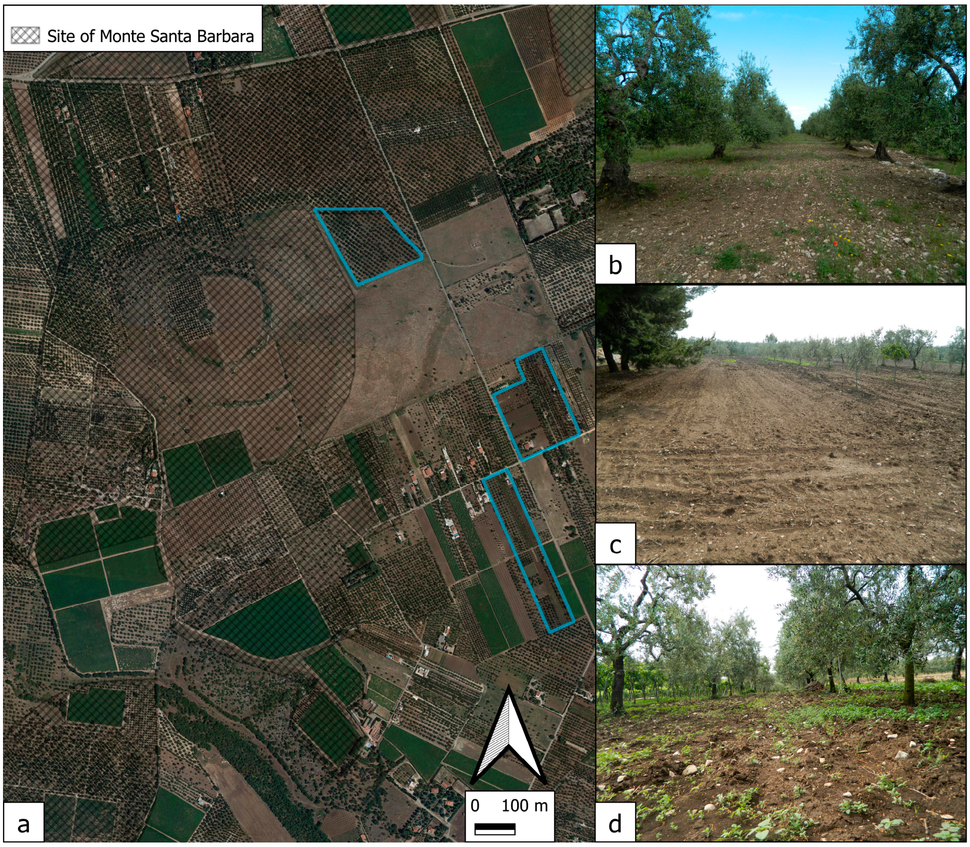


**Figure 7.** Most significant archeological area. (**a**) Image of the site of Monte Santa Barbara (from Google Earth satellite images). (**b**–**d**) Photos of the fields corresponding to archeo-records highlighted in light blue, in north to south order.

## 5. Discussion

The geomorphological processes modify the environment where human actions take place, thus affecting evolution, the finding conditions, and the preservation of the ancient sites [9,25]. The application of geomorphological indicators that define the most sensitive areas to modifications can contribute to assessing the effects of surface phenomena on landscape archaeology investigations, thus helping to understand the cultural value of surface evidence. The processes of sediment erosion, transport, and deposition can, respectively, expose, move, and bury the archaeological material, thus influencing the context of discovery, the opportunity of detection, and the state of analysis and interpretation, in addition to the possibility of preservation [9,12,28,29]. An archaeological record uncovered on the surface by soil erosion could be transported and then deposited and discovered, just as it could be covered and buried again. Similarly, eroded material could be dispersed and never again found. Again, the transported sediment could be deposited to layers of storage covering potential archaeological deposits. These and other situations define the role of surface natural phenomena, here represented by sediment connectivity and described by the SfCI in the postdepositional dynamics of the archaeological record.

The computation of the SfCI index in the Lama Camaggi basin, which can be considered an archaeological-prone area for the significant presence of evidence (see Section 3.2), allows for the evaluation of the potential contribution of sediment connectivity to the archaeological landscape analysis. The results first define hotspot areas, where greater sediment mobilization and transport increase exposure to morphological changes (Figure 4); then, they suggest that the areas with the greatest archaeological occurrence mostly fall in hotspot areas (Figures 5 and 6). This agreement establishes a connection between geomorphological-modification-prone areas and archaeological-prone areas, potentially making the SfCI a useful tool for evaluating the vulnerability of the evidence to the surface processes. In fact, the greater displacement of sediment (due to intense linkage with the sources and the paths of sediment flow) in hotspot areas results in greater preservation precariousness of the archaeological records on the surface, and thus the potential loss of information. It might be argued that sediment and archaeological material move on the surface according to the same geomorphological dynamics, assuming that the transport process is similar to that controlling water flow (simplified in the SfCI calculus as a basic propagation in the steepest descent direction; [48]). Moreover, [49] demonstrated the applicability of the SfCI in flood susceptibility, proving the connection between morphological and hydraulic conditions, partly described by the index and flood dynamics. It is thus plausible that the effects of surface-occurring phenomena (processes of supply, transfer and the storage of sediment, and extreme events) could affect both areas of archaeological material and ancient structures. If this is true, archaeo-records found in sediment-hotspot areas of the Lama Camaggi basin could be considered heritage emergencies to be monitored (1) to reduce the risk of damaging and biasing and (2) to interpret their historical value. The latter aspect can be deduced from the results of the comparative analysis shown in Figure 6. In fact, the finding of archaeological material in areas where sediment flow occurs cannot but be conditioned by surface processes. This could mean that the evidence documented on the surface may not be indicative of an archaeological deposit in the area of discovery, but may have been transported from another site along sediment paths according to a process of surface water outflow or downslope wash, above all in higher regions. For example, archaeo-records near Monte Santa Barbara (Figure 8) could be related to the same namesake site by interpreting the materials as sliding down the valley along the slope of the hillside (potential sediment source) by sediment flow (schematically reconstructed in Figure 8b). This data analysis is supported by the consistency of materials found in the archaeo-records and on the site of Monte Santa Barbara (Figure 8c).

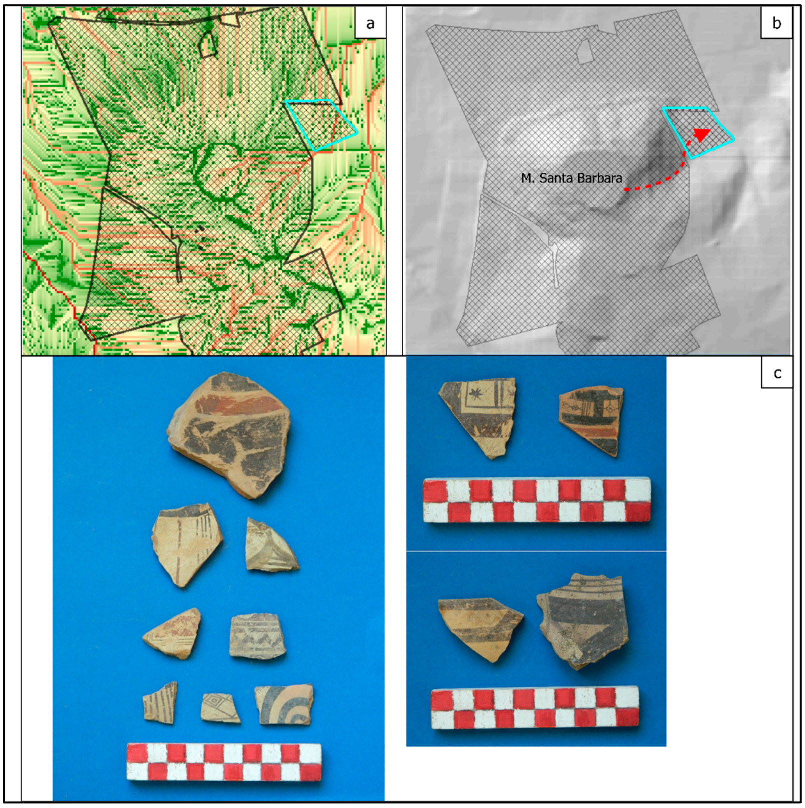


**Figure 8.** Interpretation of the relation between sediment connectivity and archaeo-records (highlighted in light blue) near the Monte Santa Barbara site. (**a**) Detailed SfCI map; (**b**) Hillshade DEM of the area with schematic reconstruction of potential downslope wash path (red arrow); (**c**) Archaeological material (sherds of geometric pottery–subgeometric II style–with bichromatic decoration: checkerboard patterns, wavy lines, zigzags, lozenges, squares, circles) from the Monte Santa Barbara site (on the left) and archaeo-records (on the right) documented on the surface during surveys in 2012–2013 (details of archaeological survey results can be found in [56]).

In relation to the reconstruction of surface dynamics, the SfCI might provide information even when archaeological evidence is not in the hotspot areas. In fact, if it is known that low-sediment-connectivity areas are representative of poor occurrence or the lack of supply and mobilization of sediment (as explained in Section 4.1), archaeo-records, such as those located in the Quadrone site (Figure 9), might be surface traces of potential archaeological deposits. In this perspective, the SfCI could be useful in preliminary excavation investigations and in preventive archaeology evaluation to support the detection of remains [73,74]. However, it should be considered that, in flat areas (as with the Quadrone site), sediment tends to accumulate in layers. Therefore, the presence of a potential archaeological deposit would not be detectable by traces on the surface, being covered by burying colluvial and alluvial sediment. It follows that the historical interpretation of the archaeological material on the surface could be greatly affected by these considerations, which would change the meaning of the surface data. As this study shows, the experimental application of the SfCI in the Lama Camaggi basin demonstrates the contribution of sediment connectivity to the interrelation of surface processes influencing the readability of archaeological data through an interdisciplinary approach. The possibility of using a geomorphological indicator in landscape investigations can improve detection, monitoring, and analysis activities, opening new research scenarios in geoarchaeology. Moreover, the applicability of geomorphometry in mitigating the impact of damage to archaeological evidence fits very well with the new trends in the research community, aimed at providing a structured framework of innovative methodologies for risk assessment and the management of cultural heritage [20,75]. Indeed, the present test case contributes to developing a new interdisciplinary approach, useful for enhancing the research effort towards sustainability. In particular, this experimentation can be considered a step forward to the achievement of SDG 11 [22], which aims to protect and safeguard the world's natural and cultural heritage.

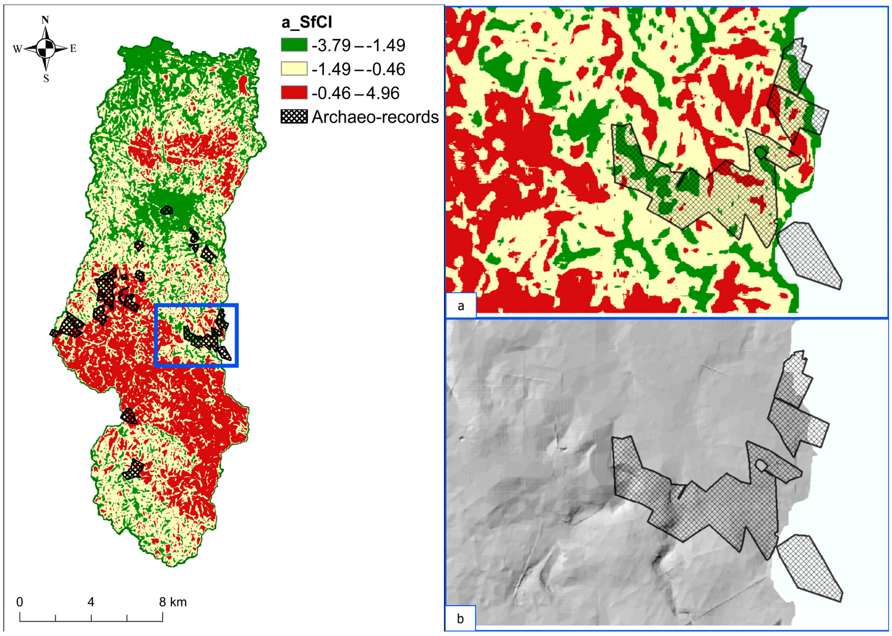


**Figure 9.** Focused visual comparison in the Quadrone area. Right: detail of the a_SfCI (**a**) and hillshade DEM (**b**) maps, corresponding to blue box on the left.

## 6. Conclusions

The applicability of the sediment flow connectivity index (SfCI) was tested in the Lama Camaggi basin, a high-density archaeological area, in order to explore the potential contribution of sediment connectivity to landscape archaeology investigations. A visual comparative assessment of the SfCI maps and archaeo-records found during field surveys in the years 2001–2022 and 2012–2013 was applied. The main results show (1) the correlation between areas affected by high sediment connectivity and areas characterized by the occurrence of surface archaeological data, and (2) the potential of the SfCI to support the interpretation of data by identifying the interrelation of surface processes.

The results suggest that the computation of the SfCI might be useful to assess the readability and the conservation of archaeological evidence. Therefore, this work has the advantage to be a novelty in the current research scenario for applying a new approach based on the integration of data and methods.

On the other hand, the experimental study has limitations that can be summarized as follows:

1. The simplified approach of our index may overlook: (i) the complex dynamics of sediment transport (represented by the use of a flow-accumulation algorithm, and justified by the assumptions on which the index itself is based); (ii) the different characteristics of the various factors involved in the calculation (represented by the intermediate dimensionless indices, i.e., rainfall, soil stability, land use, slope, and ruggedness, defined by normalization procedure);
2. Some characteristics of the Lama Camaggi basin (such as the poor spatial variability of precipitation, overall low slopes) could affect the results; which, however, were shown to be such that they did not invalidate the test. It should be specified that our study area, while not constituting an exemplar case study, represents a good test case because of the significant presence of surface archaeological evidence and the presence of fluvio-karst valleys that correspond to the main surface hydrographic network;

3. The spatial resolution of maps (8 m) partially limits the sediment connectivity analysis and the subsequent assessment, especially when considered in relation to the spatial extent of the archaeological evidence.

Considering these limitations, the index can be claimed as a first guide to identify sites to be investigated by excavations. Indeed, subsequent geoarchaeological investigations at the site scale could provide information on the presence of archaeological records (along and/or downstream of sediment paths and/or buried by sediment layers, etc.) so as to possibly validate retrospectively the SfCI contribution to landscape archaeology analyses. Indeed, the most important outcome of the present work is to provide the scientific community with the opportunity to apply the geomorphological indicator of sediment connectivity in evaluating the vulnerability and the historical significance of archaeological evidence. This awareness can be used in the future to further develop this interdisciplinary approach, contributing to one of the sustainability goals.

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