

Article

Assessing the Hydromorphological Quality of the Middle and Lower Sabato River (Southern Italy): A Preliminary Step to River Restoration and Flood Risk Analysis

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Abstract

The assessment of the hydromorphological state of a river is fundamental for both correctly evaluating its ecological conditions and planning its restoration. Despite this, there is a critical gap in studies on this topic in Southern Italy, although they are recommended by several EU Framework Directives. This research provides a contribution to filling this gap by assessing the hydromorphological quality of the Middle and Lower Sabato River (Southern Italy), by using the method officially adopted by the Italian Institute for Environmental Protection and Research (ISPRA), named IDRAIM. The method presents the advantage of considering the specific Italian context in terms of channel adjustments and anthropogenic impacts. However, it also considers pre-existing geomorphological approaches developed in other countries that make the method applicable at least in the entire Mediterranean area. To apply the method, in this study, we used data obtained by GIS analysis, remotely sensed data, and field-surveyed data. The study has highlighted that, in the Middle and Lower Sabato R., eight river reaches out-of-fifteen have displayed a “moderate or sufficient” morphological quality, five reaches a “good” morphological quality, while the remaining two reaches have been characterized by a “poor” morphological quality. Functional alterations have seemed to prevail over artificiality and intensity of short-term channel adjustments in conditioning hydromorphological quality. These results will be a key starting point for already planned studies dealing with both the restoration of the Sabato R. and flood hazard and risk assessment.

Keywords: river artificiality; river functionality; channel adjustments; IDRAIM; fluvial geomorphology; GIS-analysis; river ecology; Campania region; Mediterranean area



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1. Introduction

River ecosystems are strongly affected by anthropogenic impacts, which represent a major driver of ecological degradation. Alterations of river morphology result from both catchment-scale pressures, such as land-use changes, and direct interventions on the channel, including channelization, bank protections, damming, in-channel sediment extraction, and removal of riparian vegetation [1–3]. These pressures induce channel adjustments which may manifest as bed incision or aggradation, channel narrowing or widening, and changes in channel pattern [4–7]. In many Italian rivers, studies have shown

that since the 1950s, these adjustments have been particularly intense, with multi-meter bed incision, marked channel narrowing, and shifts from multi-thread to single-thread channel patterns [8–11]. Such morphological changes alter the functioning of the fluvial corridor by reducing lateral connectivity of water and sediment fluxes and enhancing channel–floodplain disconnection, thereby negatively affecting key morphological, hydrogeological, and ecological functions of river systems [12–14]. For this reason, maintaining fluvial geomorphic processes under conditions of dynamic equilibrium has been widely recognized as a key factor for sustaining habitat diversity and the functioning of aquatic and riparian ecosystems [15–17]. From the 1970s onwards, this understanding has promoted the development of more sustainable river management approaches and river restoration actions aimed at improving fluvial system functionality [18,19].

The relevance of river morphology for ecological conditions has been formally acknowledged by the European Water Framework Directive (WFD; 2000/60/EC) [20,21], which includes hydromorphological elements among the components used to assess river ecological status [22]. In response to WFD, several geomorphology-based hydromorphological assessment methods have been developed, including the River Styles Framework [23], the Hydrogeomorphological Index (IHG) [24,25], the SYRAH method [26], and the approaches proposed by Wyzga et al. [27,28]. These methods are aimed at improving the representation of physical processes across appropriate spatial and temporal scales. However, such approaches have been generally developed for specific geographical and management contexts and may present limitations when directly applied to Italian river systems. The latter, in fact, are characterized by high geomorphological diversity and complex anthropogenic pressures. In this framework, the adoption of a standardized and nationally consistent framework is particularly relevant.

Accordingly, the IDRAIM methodology [29–32], developed for hydromorphological assessment and river management in Italy and officially adopted at the national level by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) under the supervision of the Italian Ministry of the Environment and Energy Security (MASE), represents a suitable framework for hydromorphological assessment. The method allows a systematic application in the Italian context and provides a process-based, spatially explicit evaluation of river morphology. IDRAIM also remains fully consistent with the requirements of the WFD. Indeed, by considering processes such as channel incision, narrowing, and changes in channel–floodplain connectivity, the IDRAIM approach supports the analysis of river behavior not only in ecological terms, but also in relation to flood dynamics [30]. Therefore, hydromorphological assessment complements, rather than replaces, conventional flood risk analyses based on hydraulic modeling and flood mapping [33]. This approach is consistent with recent European restoration policies, including the EU Nature Restoration Law [34], which emphasizes the need to restore hydromorphological processes and fluvial connectivity, and identifies priorities among river reaches for restoration.

Within the IDRAIM framework, the Morphological Quality Index (MQI) represents the reference tool for assessing current river morphological conditions through indicators of geomorphic functionality, artificiality, and channel adjustments [29,30,32]. Although the methodology has been applied in some European contexts [27,35–37], in Southern Italy, the papers by Licciardello et al. [38] and Magliulo et al. [39] currently represent the only two examples of application of the IDRAIM methodology aimed at assessing the morphological quality of rivers. Thus, taking into account both the large number of rivers located in Southern Italy and the recommendations by the WFD, systematic, reach-scale and spatially explicit MQI assessments in Southern Italy are unquestionably limited and new case-studies are needed.

The aim of the present study is to assess the hydromorphological state of the Sabato River, an anthropized river system in Southern Italy, through the calculation of the MQI by using the IDRAIM method. The spatial distribution of MQI is analyzed along the river through the evaluation of geomorphic functionality, artificiality, and channel adjustment indicators.

The study aims to provide a spatially explicit assessment of river hydromorphological quality and support the identification of river reaches where restoration actions are most needed, in line with the requirements of the WFD [21], the EU Floods Directive [40], and the EU Nature Restoration Law [34] thereby contributing to strengthening the assessment of MQI in Southern Italy and supporting the development of a more consistent basis for future comparative analyses across river systems in the region.

2. Materials and Methods

2.1. Study Area

The Sabato R. basin is located in Southern Italy, within the Campanian sector of the Southern Apennines fold-and-thrust belt, which developed as a result of compressional tectonics mainly active during the Tertiary (Figure 1). The basin has an area of 401.5 km² and extends between 40°46' N and 41°08' N latitude and between 14°45' E and 14°59' E longitude. The Sabato R. flows for approximately 61 km from Mount Accellica, where elevations reach 1801 m a.s.l., to the basin outlet at 112 m a.s.l. The mean annual discharge is about 4.2 m³/s. The climate of the study area is sub-continental, characterized by temperate–humid winters and dry summers. Mean annual temperatures range between 14 °C and 17 °C, while annual precipitation varies from 956 mm to 1340 mm, with maximum rainfall occurring in November and December and minimum values in June, July, and August.

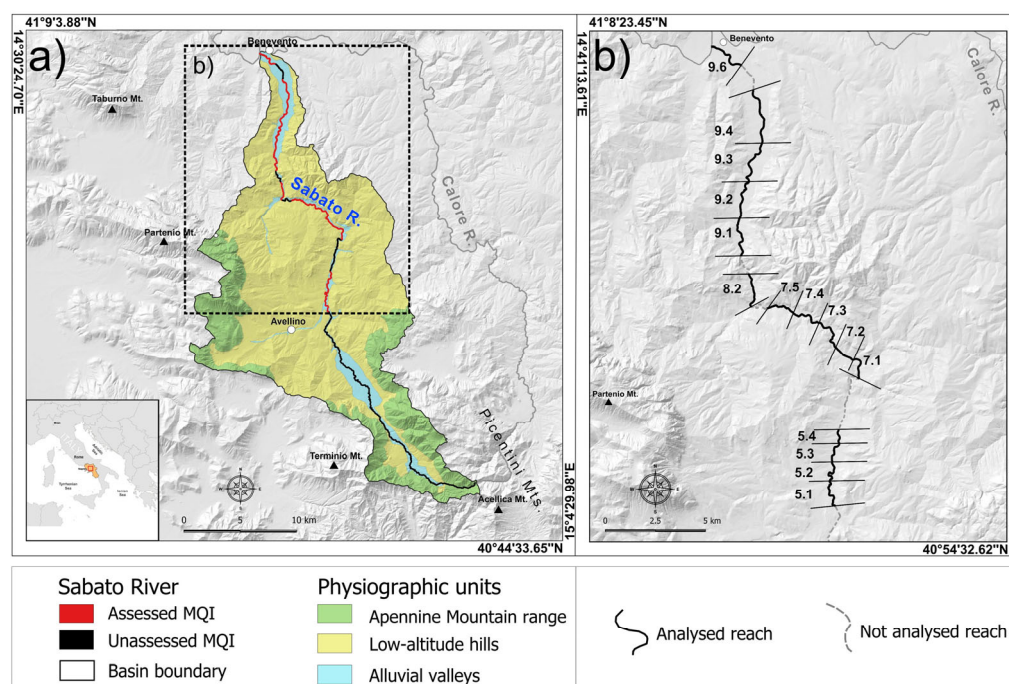


Figure 1. (a) Location map of the Sabato River basin. Physiographic units are reported, together with river segments analyzed for the Morphological Quality Index (MQI) assessment. The inset dashed box indicates the area enlarged in (b). (b) Detailed view of the reaches analyzed along the main channel of the Sabato R. Numbers indicate the reach codes.

The geological substratum of the basin mainly consists of Upper Cretaceous limestone deposits, which predominantly crop out in the upper and western parts of the basin.

These units are tectonically overlaid by Miocene- and Pliocene-aged terrigenous deposits (Tufo–Altavilla Units; [41]). This pre-Quaternary, tectonically deformed substratum is unconformably overlaid by Quaternary deposits of volcanic and alluvial origin, which infill the main morphostructural depressions crossed by the river. The Sabato R. basin can be subdivided into three main physiographic units [42]: (a) the Apennine mountain sector, shaped in Mesozoic carbonate rocks and characterized by steep slopes, locally incised by tributary streams; (b) low- to medium-altitude hilly areas, predominantly shaped into Miocene–Pliocene aged terrigenous deposits and characterized by gently rolling morphologies, locally affected by water erosion and mass movements; and (c) alluvial valleys, shaped into Quaternary-aged sediments and largely of morphostructural origin, characterized by thick successions of alluvial and slope deposits and by the presence of terraced landsurfaces (Figure 1).

Land-use within the Sabato R. basin has undergone marked changes over the last decades [42]. Between 1960 and 2012, forested areas increased from ~14% to ~40% of the basin area, while agricultural land decreased from ~74% to ~38%; most of these changes occurred between 1960 and 1990. Artificial surfaces also expanded, from ~2% to ~10% of the basin. Human pressures on the river system have included sediment extraction and channel engineering works. The in-channel sediment extraction activity started in the late 1950s and officially ended in the late 1980s, likely replaced, in the following decades, by extraction from the surrounding alluvial plain. Channel modifications are further documented by an increase in weirs density from 1.9 to 3.2 weirs*km⁻¹ between 1998 and 2014; a rise in bridge density from 0.42 bridges*km⁻¹ in 1870 to 1.53 bridges*km⁻¹ in 2004; and a sharp growth in bank protection works, whose total length increased from <1 km in 1955 to ~29 km in 2014, particularly within urbanized valley reaches [42].

2.2. Data Source and Methodology

The study has involved: (i) the characterization of the fluvial system, (ii) the assessment of its past morphological evolution, and (iii) the evaluation of the current conditions of the Sabato R.

The overall methodological workflow has consisted of a sequence of steps, mainly carried out in GIS environment: (i) acquisition, georeferencing, and integration of multi-source spatial datasets (topographic maps, Google Earth satellite imagery, and DTM); (ii) manual digitization of geomorphological and anthropogenic features, which have been used as basis for the following analyses; (iii) extraction and/or calculation of morphometric and geomorphological parameters in GIS environment (e.g., confinement indices, sinuosity); (iv) segmentation of the river into homogeneous reaches according to confinement conditions, channel morphology, and hydrological discontinuities; and (v) classification of river reaches in terms of artificiality, functionality, channel adjustments and morphological quality according to the procedures described in detail by Rinaldi et al. [30–32]. All spatial analyses and parameter calculations have been carried out in a GIS environment, ensuring consistency, traceability, and reproducibility of the results.

Acquisition, processing, and analysis of all the spatial data have been performed by using QGIS software (v. 3.42; OSGeo, Beaverton, OR, USA). As a preliminary step, all environmental features that have been necessary for the Morphological Quality Index (MQI) calculation have been manually digitized following the methodological framework proposed by Rinaldi et al. [29,30,32].

The mapped elements have included: (i) the active channel of Sabato R.; (ii) the channel centerline, defined as the line connecting points equidistant from the riverbanks; (iii) the valley axis, used to calculate channel sinuosity; (iv) the fluvial bars, whose spatial distribution is necessary to assess the channel pattern; and (v) anthropogenic structures,

including bridges, weirs, sediment extraction sites, and retaining structures. Digitization has been carried out, using the following datasets as background layers: (i) satellite images from Google Earth (2023); (ii) a 10 m Digital Terrain Model (DTM) derived from the TINITALY dataset (INGV); and (iii) 1:25,000-scale topographic maps produced in 1955 by the Italian Military Geographical Institute (IGMI), provided in *.ecw format.

In upstream and narrowest reaches of the Sabato R., the identification of fluvial bars and, in some cases, of the active channel has not been reliable due to limited channel width, reduced bar development, and dense overhanging riparian vegetation. Under these conditions, channel pattern and the corresponding MQI cannot be consistently derived; therefore, these reaches have been excluded from the analysis. The potential use of higher-resolution datasets (e.g., LiDAR data and UAV imagery) to solve these problems has been evaluated. However, LiDAR data available from the Italian Ministry for the Environment Geoportal [43] refer to surveys carried out in 2008 and do not provide complete spatial coverage of the studied river. Furthermore, they are not representative of current channel conditions, given the occurrence of recent, mainly flood-induced morphological adjustments (e.g., channel pattern, morphology; [42]). Similarly, UAV imagery is not available for the entire study area within a consistent spatial and temporal framework. Accordingly, we have preferred to carry out an analysis based on spatially continuous and temporally consistent datasets, actually representative of the most recent conditions available, in order to ensure comparability among all investigated reaches.

All datasets have been georeferenced in the Universal Transverse Mercator (hereinafter, UTM) coordinate system based on the World Geodetic System 1984, datum WGS84, Zone 33N (EPSG:32633).

The positional errors associated with georeferencing have been calculated according to the method proposed by Slama et al. [44] and Taylor [45] and have been equal to 15 m for 1:25,000 scale maps from 1955. The channel width measurement errors have been assessed according to the methodology proposed by Mount et al. [46]. The methodology sums two independent errors. The first is associated with bank-line digitization and depends on both map scale and pixel dimensions. To calculate this error, pixel resolution has been multiplied by the mean of the maximum number between repeat left and right bank-line delineations, and estimated to range from 4 to 25 m. For the second error, related to distortions of orthophotos and topographic maps, the root mean square errors (RMSE) provided by the GIS software ranged from 1 to 5 m for orthophotos and 10 to 15 m for topographic maps. The values of the errors that we have calculated are in excellent accordance with those calculated in other studies dealing with channel adjustments in Southern Italy [47,48].

The analyzed Sabato R. centerline has been derived from the active channel polygon through a semi-automated GIS-based procedure involving Voronoi polygons. The active channel polygon has first been converted into lines and then into points distributed at regular intervals along both the riverbanks. Using the “v.voronoi.skeleton” function within the GRASS environment, Voronoi polygons have been generated. The internal edges of these polygons, which represent lines equidistant from the banks, have been extracted to obtain the channel centerline for each active channel considered.

Finally, all the digitized features, both natural and anthropogenic (i.e., active channels, riverbanks, fluvial bars, bridges, weirs, sediment extraction sites, and artificial levees) have been checked during field surveys.

2.2.1. Characterization of Fluvial System

Physiographic Units, River Segments (RS), and Confinement Conditions Definition

With specific reference to lithological, physiographic, and geomorphological features, three main physiographic units (Figure 1) have been identified at the basin scale: Apennine

Mountain Range (AMR), low-altitude hills (LAH), and alluvial valleys (AV). The boundary between AMR and LAH coincides with the 600 m a.s.l. contour line [29] and has been derived from the 10 m resolution Digital Terrain Model (DTM), while the boundary between the LAH and AV units corresponds to the upper lithological limit of Quaternary alluvial deposits. The latter has been digitized from geological sheets at 1:100,000 scale produced by the Servizio Geologico d'Italia (Sheets n. 173 "Benevento" [49], n. 174 "Ariano Irpino" [50], n. 185 "Salerno" [51], and n. 186 "S. Angelo dei Lombardi" [52]), which have been previously scanned, imported into the QGIS environment and georeferenced in the UTM-WGS84 coordinate system. The intersections between the physiographic unit boundaries and the Sabato R. centerline have been used to delineate an initial set of river segments (hereinafter, RS; Figure 2), as required by the IDRAIM protocol [32]. This preliminary segmentation has been subsequently refined by incorporating information on channel confinement, channel pattern and hydrological discontinuities.

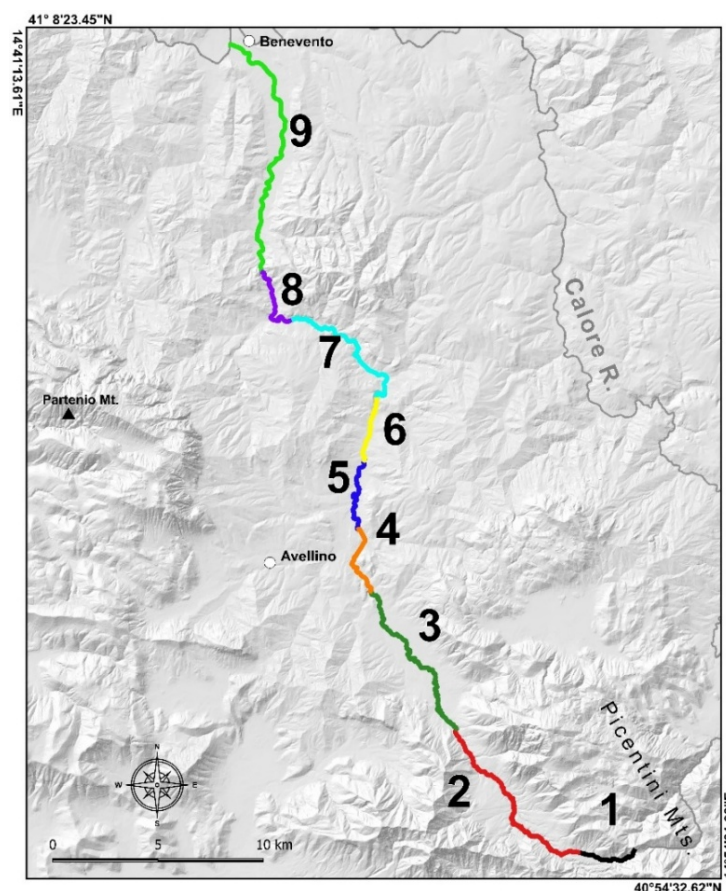


Figure 2. River segments (RS) of the Sabato River and associated ID numbers.

To this end, confinement conditions have been quantified through the calculation of the Confinement Degree (CD), which expresses lateral confinement, and the Confinement Index (CI), which expresses longitudinal confinement [29–32].

Lateral confinement has been assessed by analyzing the lateral relationships between the active channel and adjacent geomorphic units. Previously digitized riverbanks have been overlaid to geological maps and 10 m DTM to distinguish riverbanks laterally constrained by valley slopes, landslide bodies, alluvial fans or Pleistocene terraces from unconstrained riverbanks, i.e., bordered by Holocene alluvial plain. For each RS, the total length of the riverbanks and the length of laterally constrained riverbanks have been calculated in a GIS environment. The Confinement Degree (CD) has then been computed as the ratio between the length of constrained riverbanks and the total riverbank length and expressed as

a percentage. According to IDRAIM thresholds, in terms of CD, river segments have been classified as confined (more than 90% of the riverbanks are constrained), partly confined (10–90%), or unconfined (less than 10% of the riverbanks are constrained). The CD values have allowed a first subdivision of each RS into shorter River Reaches (hereinafter, RRs).

Longitudinal confinement of each RR has been assessed through the Confinement Index (CI), which has required a digitation of the Sabato R. alluvial plain. The alluvial plain was first delineated by mapping the outcropping area of the Holocene alluvial deposits on the geological maps and subsequently refined using the Digital Terrain Model. For each RR, channel and alluvial plain areas have been automatically calculated. Both the active channel and alluvial plain centerlines have been automatically extracted by using the procedure described in Section 2.2. By dividing both the active channel area and the alluvial plain area by the lengths of the respective centerlines, both the alluvial plain mean width and the active channel mean width have been calculated [11]. Then, the CI has been calculated as the ratio between the mean width of the alluvial plain and the mean width of the active channel. According to CI values, the river longitudinal confinement has been classified as high ($1 < CI < 1.5$), medium ($1.5 < CI \leq k$), or low ($CI > k$); given the single-thread channel pattern of the Sabato R., k was set equal to 5 [29,30,32]. Finally, the overall confinement conditions of each RR have been defined by jointly considering CD and CI values, following the classification scheme reported in Table 1.

Table 1. Definition of the RS confinement classes [29,30,32].

Confinement Class	Description
Confined	All cases with $CD > 90\%$; or
	$10\% < CD < 90\%$ and $CI \leq 1.5$
Partly Confined	$10\% < CD < 90\%$ and $CI > 1.5$; or
	$CD < 10\%$ and $CI \leq k$
Unconfined	$CD < 10\%$ and $CI > k$

Channel Morphology Assessment

Channel morphology has been defined through the combined analysis of channel sinuosity and planform morphological pattern. Channel sinuosity has been quantified by calculating the sinuosity index (SI; [4]) for each previously defined RR. The channel centerline has been first split according to the RR boundaries and the lengths have been automatically calculated within the GIS environment. The valley axis has been defined as the straight line connecting the upstream and downstream endpoints of each RR, and its length has also been automatically calculated. The sinuosity index (SI) has been computed for each RR as the ratio between the channel centerline length and the corresponding valley-axis length (Table 2).

Table 2. Classes of channel morphology and associated threshold values of sinuosity index [29,30,32].

Typology	Sinuosity Index
Straight (ST)	$1 \leq SI < 1.05$
Sinuuous (S)	$1.05 \leq SI < 1.5$
Meandering (M)	≥ 1.5
Sinuuous with alternate bars (SAB)	< 1.5
Wandering (W)	< 1.5
Braided (B)	Any (normally low)

To complete the characterization of the channel morphology, the spatial distribution of fluvial bars within the active channel has also been considered. Fluvial bars have been digitized from 2023 orthophotos and used to classify the channel pattern according to Rinaldi [8]. Finally, channel sinuosity and planform morphological pattern have been jointly considered to assign a channel morphology class to each RR, according to the classification proposed by Rinaldi et al. [36]. Based on channel morphology, the RR that have been previously defined have undergone further internal subdivisions.

As already stated above (see Section 2.2), in some cases it has not been possible to correctly assess channel patterns. In particular, on the upper and narrower segments of the Sabato R., fluvial bars, as well as the entire active channel, have not been reliably identifiable because of one or more of the following: (i) very narrow channel; (ii) limited bar development; and (iii) presence of dense overhanging riparian vegetation. As a result, channel morphology and the related MQI have not been evaluated for these river sectors (Figure 1). Consequently, they have been excluded from the analysis, as well as the confined Sabato R. reaches.

Final Definition of the River Reaches (RRs)

In this step, the river has been finally subdivided into reaches. This subdivision has been based on the previously defined RS and on the combined analysis of confinement conditions and channel morphology. Where necessary, the draft segmentation was refined by further subdividing the river according to: (i) the presence of major hydrological discontinuities, such as confluences with main tributaries; (ii) excessive reach length (>5 km); (iii) presence of sediment extraction sites; and (iv) additional changes in channel morphology [30–32]. The resulting river reaches have represented the final spatial units used for all subsequent analyses.

2.2.2. Recent Morphological Evolution Assessment

In this phase, the previously collected data have been analyzed within a morpho-evolutionary framework in order to assess the current morphological conditions of the river in relation to its short-term evolution. The analysis has focused on three main types of channel adjustments: (i) channel pattern, (ii) channel width, and (iii) riverbed level [29–32].

Assessment of Channel Pattern Adjustments

Adjustments in channel pattern have been evaluated by comparing the morphology of each RR in 1955 and 2023 within the GIS environment. This comparison has allowed the identification of changes in channel morphological configuration over the analyzed time span.

Following the classification proposed by Rinaldi et al. [30], three possible cases of morphological adjustment have been considered: (i) unchanged morphological configuration; (ii) limited or moderate variation in morphological configuration, involving transitions between contiguous channel types; and (iii) intense variation in morphological configuration, involving transitions between non-contiguous channel types. Contiguous channel types refer to similar morphological configurations (e.g., a transition from meandering to sinuous), whereas non-contiguous types indicate changes between markedly different morphologies (e.g., from multi-thread to single-thread channels).

Based on this scheme, changes in channel pattern have been classified according to whether the channel has maintained its original morphology or shifted to a different morphological configuration during the period 1955–2023 (Table 3).

Table 3. Definition of contiguous and non-contiguous morphologies in the variations in morphological configuration. Morphologies: ST = straight, S = sinuous, M = meandering, SAB = sinuous with alternating bars, W = wandering; $\longleftrightarrow$ = passage in both directions. Class: B = transition to contiguous morphology; C = transition to non-contiguous morphology (From: Rinaldi et al. [30,32]).

Morphologies	Class
ST $\longleftrightarrow$ S	B
ST $\longleftrightarrow$ M	C
ST $\longleftrightarrow$ SAB	B
ST $\longleftrightarrow$ W	C
S $\longleftrightarrow$ M	B
S $\longleftrightarrow$ SAB	B
S $\longleftrightarrow$ W	C
M $\longleftrightarrow$ SAB	B
M $\longleftrightarrow$ W	C
SAB $\longleftrightarrow$ W	B

Assessment of Channel Width Adjustments

Adjustments in channel width have been assessed by comparing the mean active channel width of each RR in 1955 and 2023. To ensure consistency between the two dates, the channel configuration from 1955 has been subdivided according to the same RRs identified for the channel from 2023. For each RR from 1955, the channel area has been calculated within the GIS environment. The channel centerline from 1955 has then been split using the same RR boundaries, and the centerline length of each RR has been automatically calculated.

For each RR, the channel mean width in 1955 ($RRCMW_{1955}$) has been calculated as the ratio between channel area and centerline length [11]:

$$RRCMW_{1955} = \frac{\text{channel area}_{1955}}{\text{centreline length}_{1955}} \quad (1)$$

Mean channel width values from 1955 were then compared with those obtained from 2023 ($RRCMW_{2023}$), previously calculated for the assessment of longitudinal confinement conditions. Channel mean width variation between 1955 and 2023 ($\Delta CMW_{1955-2023}$) has been calculated as:

$$\Delta CMW_{1955-2023} = RRCMW_{2023} - RRCMW_{1955} \quad (2)$$

The observed variation has also been expressed as a percentage of the 1955 mean width:

$$\Delta CMW_{1955-2023}(\%) = \frac{\Delta CMW_{1955-2023}}{RRCMW_{1955}} * 100 \quad (3)$$

According to Rinaldi et al. [29], channel width adjustments have been classified into three classes: (i) unchanged channel or limited variation ($\Delta CMW_{1955-2023} \leq 15\%$ of $RRCMW_{1955}$); (ii) moderate narrowing or widening ($15\% < \Delta CMW_{1955-2023} < 35\%$); and (iii) intense narrowing or widening ($\Delta CMW_{1955-2023} > 35\%$) [30].

2.2.3. Assessment of the Morphological Quality Index (MQI)

The current hydromorphological conditions of the Sabato R. have been evaluated by calculating the Morphological Quality Index (MQI), following the IDRAIM methodology [29].

The MQI assessment has been based on the analysis of three main components that describe river hydromorphology: (i) geomorphic functionality, related to the presence and

activity of fluvial landforms and processes; (ii) artificiality, which accounts for the presence, frequency, and spatial continuity of human-made structures and activities affecting the river; and (iii) channel changes.

These components have been analyzed by combining information obtained from GIS-based analyses of topographic maps and remotely sensed data with direct observations collected during field surveys. For each RR, indicator scores have been assigned in accordance with the criteria established in the official IDRAIM Evaluation Forms issued by ISPRA and reported in Table 4. Indicators F3 and F6 are not listed in Table 4, as, according to the IDRAIM method, they have not been considered in this study. In fact, such indicators should be taken into account only for confined reaches, which have been excluded from our analysis for the reasons explained in the Channel Morphology Assessment Section.

Table 4. Scores related to the indicators of functionality, artificiality, and channel adjustments in unconfined and partly confined river reaches considered in this study. (A) absence of alterations, (B) medium alteration, (C) high alteration.

Indicators	Scores		
	A	B	C
Functionality			
F1—longitudinal continuity in sediment and wood flux	0	3	5
F2—presence of a modern floodplain	0	3	5
F4—processes of bank retreat	0	2	3
F5—presence of a potentially erodible corridor	0	2	3
F7—forms and processes typical of the channel pattern	0	3	5
F8—presence of typical fluvial forms in the alluvial plain	0	2	3
F9—variability of the cross-section	0	3	5
F10—structure of the channel bed	0	2	5 or 6
F11—presence of in-channel large wood	0		3
F12—width of functional vegetation	0	2	3
F13—linear extension of functional vegetation	0	3	5
Artificiality			
A1—upstream alteration of flows	0	3	6
A2—upstream alteration of sediment discharges	0	3 or 6	9 or 12
A3—alteration of flows in the reach	0	3	6
A4—alteration of sediment discharge in the reach	0	4	6
A5—crossing structures	0	2	3
A6—bank protections	0	3	6
A7—artificial levees	0	3	6
A8—artificial changes in river course	0	2	3
A9—other bed stabilization structures	0	3	6 or 8
A10—sediment removal	0	3	6
A11—wood removal	0	2	5
A12—vegetation management	0	2	5
Channel adjustments			
CA1—adjustments in channel pattern	0	3	6
CA2—adjustments in channel width	0	3	6
CA3—bed-level adjustments	0	4	8 or 12

The scores have been then combined to calculate the Morphological Alteration Index (MAI) for each RR, defined as the ratio between the total score obtained (S_{tot}) and the

maximum possible score ($S_{\max}$) for the corresponding stream typology, which represents the reference (unaltered) condition:

$$MAI = \frac{S_{\text{tot}}}{S_{\max}} \quad (4)$$

MAI values range from 0, indicating a completely altered river reach, to 1, indicating an unaltered river reach [29,30,32].

For each RR, the Morphological Quality Index (MQI) has been subsequently calculated as:

$$MQI = 1 - MAI \quad (5)$$

Based on MQI values, each RR has been assigned to a morphological quality class according to the classification scheme proposed by Rinaldi et al. [29,30,32]. The corresponding quality classes are reported in Table 5.

Table 5. Morphological quality classes.

MQI	Class of Morphological Quality
$0 \leq MQI < 0.3$	Very poor or bad
$0.3 \leq MQI < 0.5$	Poor or scarce
$0.5 \leq MQI < 0.7$	Moderate or sufficient
$0.7 \leq MQI < 0.85$	Good
$0.85 \leq MQI \leq 1$	Very good or high

Finally, the overall morphological condition of the Sabato R. has been synthesized by calculating the Mean Morphological Quality Index (MMQI), defined as the length-weighted average of MQI values across all river reaches:

$$MMQI = \frac{\sum MQI_{RR-i} * L_{RR-i}}{\sum L_{RR-i}} \quad (6)$$

where MQI_{RR-i} is the Morphological Quality Index of the i -th RR and L_{RR-i} is the length of the same RR.

3. Results

3.1. Physiographic Units and River Segments (RS) Definition

Following the approach proposed by Rinaldi et al. [30,31], the Sabato R. basin has been subdivided into three physiographic units: the Apennine Mountain Range (AMR), the Low-Altitude Hills (LAH), and the Alluvial Valleys (AV). Their location is shown in Figure 1, while their areal extent is reported in Table 6. The LAH unit represents the dominant physiographic unit, accounting for ~70% of the total basin area. It mainly occupies the inner central and, subordinately, northern portion of the basin and is primarily shaped into terrigenous deposits. The AMR, located along the western and southern boundaries of the basin, consists predominantly of carbonate lithologies and accounts for 22.3% of the Sabato R. basin total area. The AV unit covers the remaining 8% of the basin and is associated with the main valley floors shaped into recent alluvial deposits.

Table 6. Main features of the Sabato R. basin physiographic units.

Physiographic Unit	Area (km ²)	% of the Basin Area
Apennine Mountain Range	89.7	22.3
Low-altitude hills	279.7	70.0
Alluvial valleys	32.2	7.7

The intersections between the physiographic unit boundaries and the Sabato R. channel centerline have been used to split the river into nine distinct river segments (RSs; Figure 2).

Table 7 shows that the RS9 is the longest one, as it accounts for ~23% of the total Sabato R. length, while RS1 is the shortest, as it accounts for 5.1% of the total river length. Due to the reasons described in the Channel Morphology Assessment Section, RSs n. 1, 2, 3, 4 and 6 have been excluded from the analysis.

Table 7. Length and percentage of the detected RS along the Sabato River.

RS	Length (km)	% of the Total Sabato R. Length
1	3.1	5.1
2	10.4	17.2
3	10	16.5
4	3.8	6.3
5	4.4	7.2
6	3.1	5.1
7	8.3	13.6
8	3.8	6.2
9	13.8	22.8

3.2. Confinement and Channel Morphology Assessment

Table 8 reports the Confinement Degree (CD), Confinement Index (CI), and the resulting Confinement Class (CC) of the 15 analyzed reaches of the Sabato R. Among them, eight RRs are classified as “partly confined”, showing CD values between 10% and 90% and CI values greater than 1.5. The remaining seven RRs are classified as “unconfined”. These RRs are characterized by CI values greater than 5 and by CD values lower than 10%, in accordance with the criteria proposed by Rinaldi et al. [29,30,32] for single-thread rivers (as the Sabato R. is). Reaches 8.1 and 8.3 have resulted in being “confined” and have been subsequently excluded from the following analysis.

Table 8. Main parameters of the 15 analyzed Sabato R. reaches. RR = river reach; CD = Confinement Degree; CI = Confinement Index; CC = Confinement Class; SI = sinuosity index; UC = unconfined; PC = partly confined; S = sinuous. RRs that present the same CC and SI-based morphological pattern (e.g., RRs 7.1 and 7.2) have been separated based on channel morphology (Figure 3) and/or hydrological discontinuities and/or presence of anthropogenic structures.

RR	CD (%)	CI	CC	SI	SI-Based Morphological Pattern
5.1	8.5	23.9	UC	1.28	S
5.2	15.0	8.1	PC	1.44	S
5.3	-	26.0	UC	1.10	S
5.4	49.9	13.1	PC	1.21	S
7.1	-	20.2	UC	1.36	S
7.2	4.1	15.5	UC	1.10	S
7.3	50.0	6.0	PC	1.41	S
7.4	27.7	9.8	PC	1.23	S
7.5	32.9	6.5	PC	1.17	S
8.2	46.6	4.7	PC	1.12	S
9.1	27.4	7.1	PC	1.19	S
9.2	-	16.6	UC	1.10	S
9.3	-	22.2	UC	1.28	S
9.4	-	37.9	UC	1.12	S
9.6	46.5	17.5	PC	1.20	S

Along the Sabato R., all the analyzed RRs have shown sinuosity index (SI) values ranging between 1.1 and 1.4, indicating a sinuous pattern along the analyzed river course (Table 8). The classification of channel morphology, obtained by integrating the SI-based planform pattern with the spatial distribution of fluvial bars within the active channel (Table 9; Figure 3), has shown that the sinuous channel morphology is the most widespread, characterizing 13 out-of-15 RRs. The remaining two RRs have displayed different channel morphologies; in particular, RR 7.5 is characterized by a wandering channel morphology, whereas RR 9.6 (Figure 3) is sinuous with alternate bars.

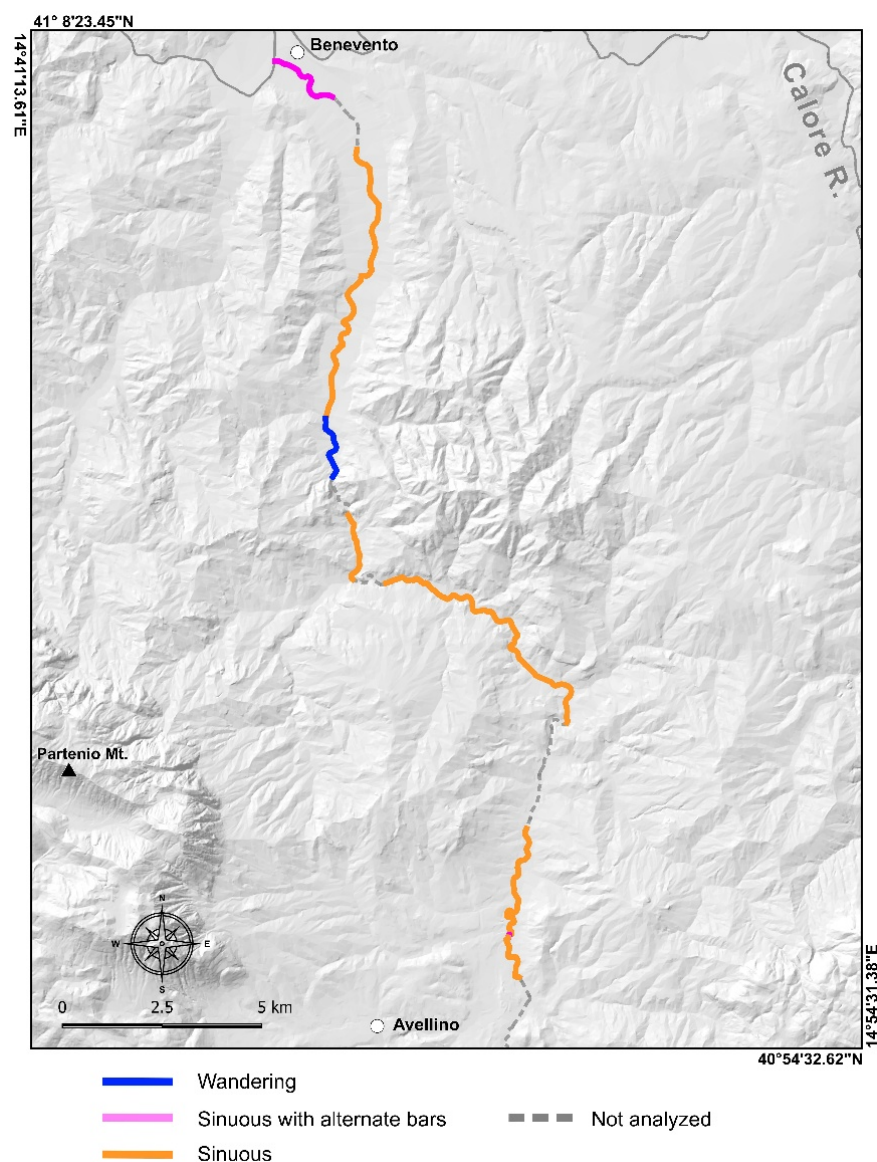


Figure 3. Spatial distribution of the channel patterns along the Sabato R. The classification of the RRs channel morphology derives from the SI-based morphological pattern shown in Table 8, integrated with observations about the spatial distribution of the fluvial bars.

Table 9. Comparison between RRs channel morphologies from 1955 and 2023. Sab = sinuous with alternated bars; W = wandering; S = sinuous; L = limited; U = unchanged; and I = intense.

RR	Morphology 1955	Morphology 2023	Morphological Variation
5.1	S	S	U
5.2	S	S	U
5.3	S	S	U
5.4	S	S	U

Table 9. Cont.

RR	Morphology 1955	Morphology 2023	Morphological Variation
7.1	S	S	U
7.2	S	S	U
7.3	S	S	U
7.4	S	S	U
7.5	Sab	W	L
8.2	S	S	U
9.1	S	S	U
9.2	Sab	S	L
9.3	Sab	S	L
9.4	Sab	S	L
9.6	S	Sab	L

3.3. Short-Term Channel Changes

Channel adjustments affecting the Sabato R. over the period 1955–2023 have included changes in channel width, channel morphology, and channel depth.

Active channel mean width variations between 1955 and 2023 are reported in Table 10 and Figure 4. Thirteen out-of-15 analyzed RRs have shown a decrease in mean channel width (i.e., narrowing) over the study period. Only RRs 7.1 and 7.2 have exhibited a “limited” or “moderate” increase (i.e., widening), equal to +2.1 m and +4.6 m, respectively.

Table 10. Active channel mean width variations and associated classification experienced by the Sabato RRs between 1955 and 2023. RR = River Reach; $\Delta\text{CMW}_{1955-2023}$ = variation in channel mean width between 1955 and 2023.

RR	$\Delta\text{CMW}_{1955-2023}$ (m)	$\Delta\text{CMW}_{1955-2023}$ (%)	Classification
5.1	−25.9	−77.2	Intense narrowing
5.2	−18.2	−51.7	Intense narrowing
5.3	−19.9	−55.2	Intense narrowing
5.4	−12.9	−38.3	Intense narrowing
7.1	2.1	10.5	Limited widening
7.2	4.6	28.2	Moderate widening
7.3	−2.8	−11.7	Limited narrowing
7.4	−10.7	−36.3	Intense narrowing
7.5	−11.8	−29.2	Moderate narrowing
8.2	−9.0	−32.6	Moderate narrowing
9.1	−15.6	−37.8	Intense narrowing
9.2	−77.4	−73.5	Intense narrowing
9.3	−48.6	−66.7	Intense narrowing
9.4	−79.6	−77.8	Intense narrowing
9.6	−10.1	−22.1	Moderate narrowing

Changes in channel morphology between 1955 and 2023 are summarized in Table 9.

Channel narrowing has ranged from “moderate” (i.e., $15\% < \Delta\text{CMW}_{1955-2023} < 35\%$) to “intense” (i.e., $\Delta\text{CMW}_{1955-2023} > 35\%$). In particular, nine RRs (5.1, 5.2, 5.3, 5.4, 7.4, 9.1, 9.2, 9.3 and 9.4; Figure 4) have undergone an “intense” narrowing (*sensu*, Rinaldi et al., [29]). The highest reductions in CMW have exceeded 60% in RRs 5.1 (77.2%), 9.2 (73.5%), 9.3 (66.7%) and 9.4 (77.8%). Three RRs (7.5, 8.2, and 9.6) have shown variations in CMW between 15% and 35%, i.e., a “moderate” narrowing. In particular, CMW decreased by −29.2% in RR 7.5 (Figure 4c,d), −32.6% in RR 8.2 and −22.1% in 9.6. Finally, only RR 7.3 has experienced a “limited” narrowing (i.e., equal to or lower than 15%). The CMW of this RR has decreased by −11.7%. The $\Delta\text{CMW}_{1955-2023}$ of the investigated reaches of the Sabato R. has accounted for 55%, as CMW has decreased from 51 m in 1955 to 23 m in 2023.

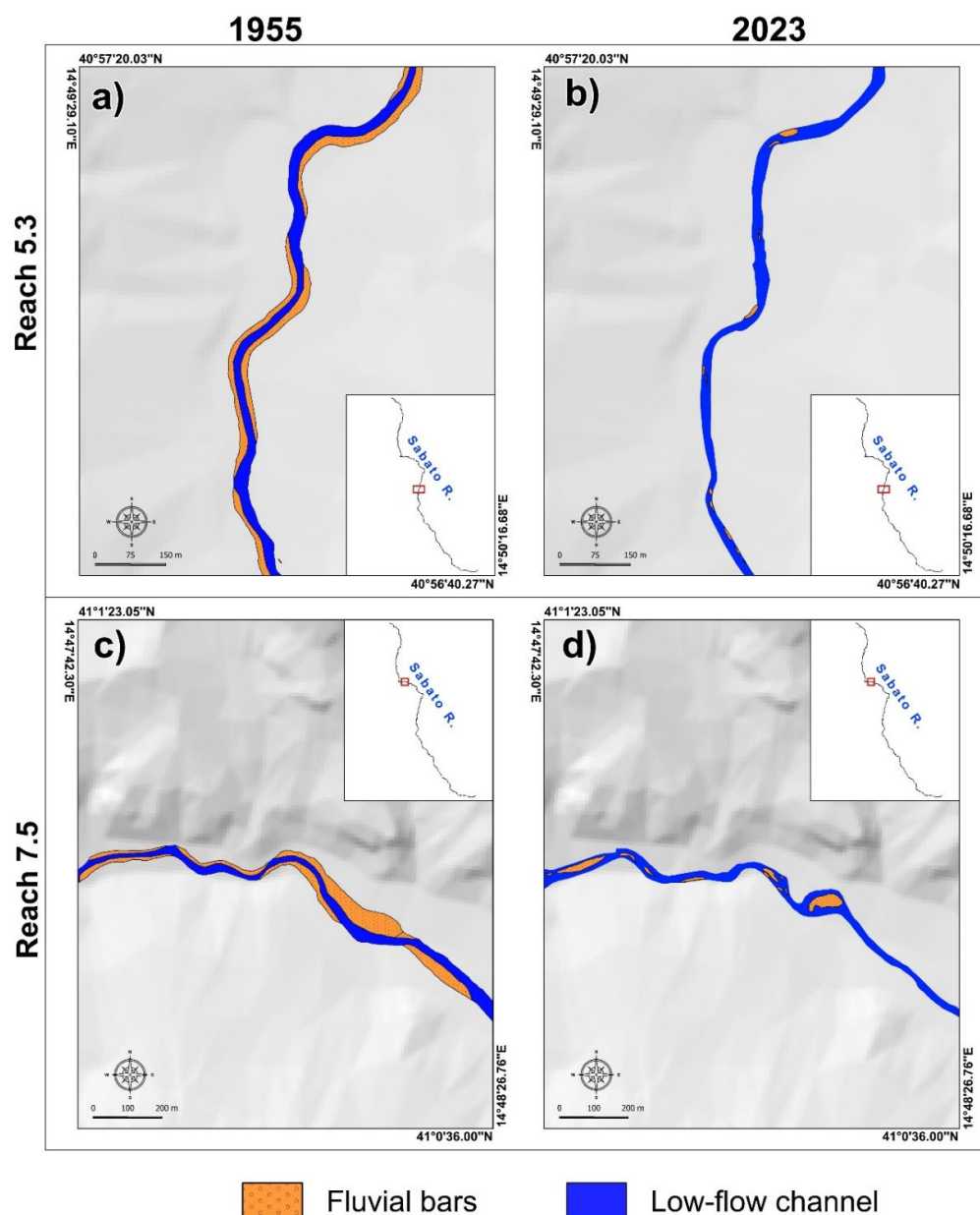


Figure 4. Geomorphological sketches illustrating channel morphology variations (*sensu* Rinaldi et al. [30,32]) observed in Reach 5.3 (a,b) and Reach 7.5 (c,d). Reach 5.3 exhibits intense channel narrowing between 1955 (a) and 2023 (b), without substantial changes in morphological configuration. In contrast, Reach 7.5 shows moderate channel narrowing associated with a transition in channel pattern from sinuous with alternated bars to wandering over the same period.

In 1955, all the river reaches (RRs) were sinuous (S), except for three RR (i.e., 9.2, 9.3 and 9.4) that displayed a sinuous with alternate bars (Sab) morphology. In 2023, sinuous channel patterns have remained strikingly dominant along the analyzed river. In fact, only RR 7.5 and 9.6 have shown a different morphology, i.e., wandering and sinuous with alternate bars, respectively (Table 9)

A comparison between channel patterns from 1955 and 2023 has shown that ten RRs out-of-15 (5.1, 5.2, 5.3, 5.4, 7.1, 7.2, 7.3, 7.4, 8.2 and 9.1) have not experienced morphological changes between 1955 and 2023. The remaining five RRs (7.5, 9.2, 9.3, 9.4 and 9.6) have undergone a “limited” change in channel morphology, i.e., a transition between adjacent channel patterns, namely sinuous and sinuous with alternate bars. Among these five RRs, only RR 7.5 has displayed a transition between sinuous with alternated bars and wandering morphologies.

Channel-bed elevation changes for the Sabato R. have been assessed in terms of the overall altitude variations associated with one or more incision phases, in accordance with the available literature. In particular, Martucci et al. [42] have reported a net riverbed lowering of ~50 cm from the 1950s onwards, more pronounced between the mid-1980s and the mid-1990s, and locally interrupted by phases of aggradation. Available literature [47] also indicates that river incision exceeding 3 m over comparable time spans is rare at the regional scale in rivers of Southern Italy. These literature data support the interpretation of a limited (i.e., ranging from 0.5 to 3 m) riverbed lowering in the Sabato R.

Field evidence consistent with channel incision, including hydraulic structures undermined and actively eroding banks, has been observed at several sites across the study area (Figure 5), supporting the interpretation of channel-bed lowering as a widespread process.



Figure 5. Field images illustrating indirect evidence of riverbed lowering due to channel incision: (a) ~1 m-high fluvial erosional scarp; (b) fluvial erosional scarp and weir deformed by undermining processes connected to riverbed degradation.

3.4. Morphological Quality Index (MQI) Assessment

As reported in Section 2.2.3, the MQI has been calculated by evaluating indicators of functionality (FI), Artificiality (AI) and channel adjustment (CAI) for each river reach (RR), following the IDRAIM methodological framework defined by Rinaldi et al. [29,30,32].

Functionality scores (Table 11) express the cumulative value of the functionality indicators considered for each RR and represent the degree of functional alteration with respect to the reference river conditions. The higher the scores, the deeper the functionality alterations. According to the IDRAIM method, indicator F8 has not been evaluated (Table 11), as it should be taken into account only for meandering rivers flowing through broad alluvial plains, which is not the case for the Sabato R. The obtained FI values ranged between 10 and 30. The highest FI value has been recorded in RR 9.6 (FI = 30), while the lowest has been in RR 9.4 (FI = 10). By dividing the range of values of FI into discrete and equidimensional classes, we have found that most of the RRs (i.e., 6 out of 15) have shown a moderate-high functionality (i.e., $21 \leq FI \leq 27$; Table 11). Differently, three RRs have shown a low functionality ($7 \leq FI \leq 13$), three RRs a moderate-low functionality ($14 \leq FI \leq 20$) and three RRs a high functionality ($28 \leq FI \leq 34$). No RRs have displayed a null or very low functionality ($0 \leq FI \leq 6$) and a very high functionality ($FI \geq 35$). The distribution of FI values among the analyzed RRs is spatially variable along the analyzed Sabato R. and is shown in Figure 6.

Table 11. Scores assigned to the functionality indicators. F1 = longitudinal continuity in sediment and wood flux; F2 = presence of a modern floodplain; F4 = processes of bank retreat; F5 = presence of a potentially erodible corridor; F7 = forms and processes typical of the channel pattern; F8 = presence of typical fluvial forms in the alluvial plain; F9 = variability of the cross-section; F10 = structure of the channel bed; F11 = presence of in-channel large wood; F12 = width of functional vegetation; F13 = linear extension of functional vegetation; FI = sum of the considered functionality indicator; $\text{Max}(\text{SF}_{\text{tot}})$ = sum of the highest possible scores of all the functionality indicators (i.e., F1 to F13); $\text{SF}_{\text{max}} = \text{Max}(\text{SF}_{\text{tot}})$ minus the sum of highest possible scores of the not considered indicators (i.e., F8 for the whole river; F2 for RR 7.5; F10 for RR 5.1); N.E. = not evaluated.

RR	F1	F2	F4	F5	F7	F8	F9	F10	F11	F12	F13	FI	Max (SF _{tot})	SF _{max}
5.1	0	3	2	2	3	N.E.	0	N.E.	3	2	3	18	46	37
5.2	3	3	0	2	5	N.E.	3	2	3	2	3	26	46	43
5.3	0	5	2	2	5	N.E.	3	0	3	3	5	28	46	43
5.4	0	5	3	3	5	N.E.	0	0	3	3	5	27	46	43
7.1	3	3	2	0	5	N.E.	5	0	3	2	3	26	46	43
7.2	0	3	2	0	0	N.E.	3	2	3	0	0	13	46	43
7.3	0	3	2	0	0	N.E.	3	2	3	0	0	13	46	43
7.4	0	5	2	3	3	N.E.	3	2	3	2	3	26	46	43
7.5	3	N.E.	0	3	5	N.E.	5	2	3	2	0	23	46	38
8.2	3	3	2	2	0	N.E.	3	2	3	2	3	23	46	43
9.1	3	3	2	2	5	N.E.	3	2	3	2	3	28	46	43
9.2	0	3	0	2	0	N.E.	3	2	3	2	3	18	46	43
9.3	0	3	0	0	0	N.E.	3	5	3	2	3	19	46	43
9.4	0	3	2	0	0	N.E.	0	2	3	0	0	10	46	43
9.6	3	5	2	2	5	N.E.	3	2	3	2	3	30	46	43

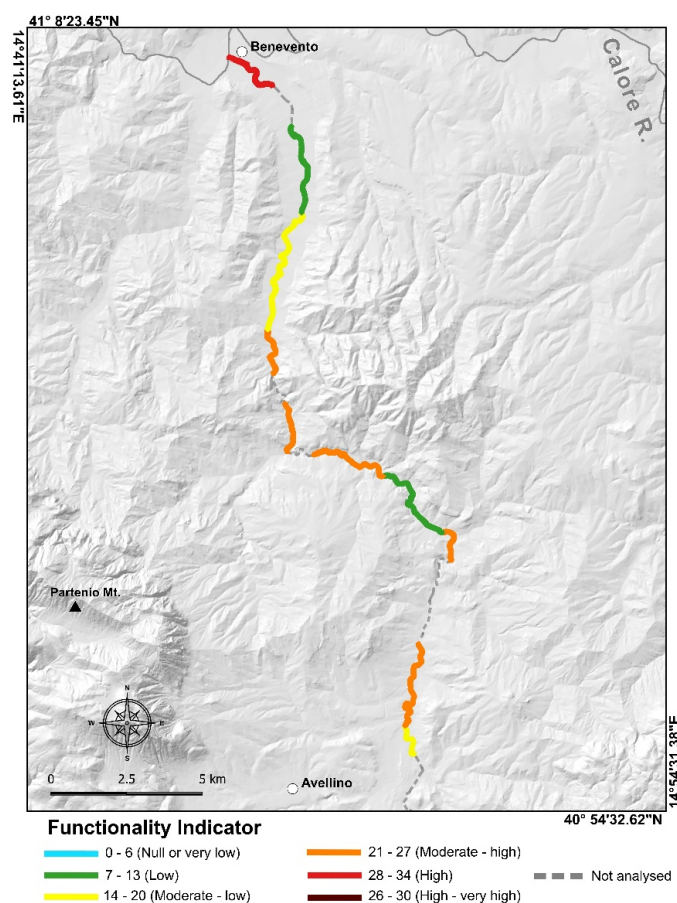


Figure 6. Spatial distribution of the functionality indicator (FI). The higher the FI value, the higher the functionality disturbance.

Artificiality indicators, reported in Table 12, assess the presence and frequency of artificial elements or interventions along the river channel within each RR. The spatial distribution of weirs, crossing structures and artificial levees along the Sabato R. is reported in Figure 7A–C, respectively. Artificiality values have varied among the analyzed Sabato R. reaches, ranging from a minimum of 7 to a maximum of 32 (Table 12). The highest AI value is recorded in RR 5.4 (AI = 32), while the lowest in RRs 9.2 (AI = 7) and RR 9.4 (AI = 8). By dividing the range of AIs into discrete and equidimensional classes, we have observed that 4 RRs out of 15 have been characterized by a null or very low artificiality ($0 \leq AI \leq 12$), 7 RRs by a low artificiality ($13 \leq AI \leq 25$) and 4 RRs by a moderate-low artificiality ($26 \leq AI \leq 38$). No reaches have displayed a moderate-high ($39 \leq AI \leq 51$), high ($52 \leq AI \leq 64$) or very high ($AI \geq 65$) artificiality. The spatial distribution of AI values along the analyzed Sabato R. reaches is shown in Figure 7D.

Table 12. Scores assigned to the Artificiality indicators. A1 = Upstream alteration of flows; A2 = Upstream alteration of sediment discharges; A3 = Alteration of flows in the reach; A4 = Alteration of sediment discharge in the reach; A5 = Crossing structures; A6 = Bank protections; A7 = Artificial levees; A8 = Artificial changes in river course; A9 = Other bed stabilization structures; A10 = Sediment removal; A11 = Wood removal; A12 = Vegetation management; AI = Total Artificiality Indicator ($= \sum_{i=1}^{12} A_i$); $\text{Max}(\text{SA}_{\text{tot}})$ = Sum of the highest possible scores of all the Artificiality indicators (i.e., A1 to A12); $\text{SA}_{\text{max}} = \text{Max}(\text{SA}_{\text{tot}})$ minus the sum of highest possible scores of the indicators not considered.

Reach	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	AI	SA _{max}	Max (SA _{tot})
5.1	0	0	0	4	3	3	0	0	3	0	0	5	18	72	72
5.2	0	0	0	6	2	6	0	0	3	0	0	2	19	72	72
5.3	0	0	3	6	2	3	3	0	0	0	0	2	19	72	72
5.4	0	0	6	12	2	3	6	0	0	3	0	0	32	72	72
7.1	0	0	0	6	3	3	0	2	3	0	0	2	19	72	72
7.2	0	0	0	6	0	3	0	0	3	0	0	2	14	72	72
7.3	0	0	0	4	2	3	0	2	0	0	2	0	13	72	72
7.4	0	0	0	0	2	3	3	0	0	0	2	2	12	72	72
7.5	0	0	6	6	2	0	3	2	0	3	2	2	26	72	72
8.2	0	0	0	4	0	0	0	0	3	3	0	2	12	72	72
9.1	0	0	6	6	3	3	0	0	6	3	0	2	29	72	72
9.2	0	0	0	0	0	0	0	0	3	0	2	2	7	72	72
9.3	0	0	0	4	2	0	0	0	3	3	2	2	16	72	72
9.4	0	0	0	4	2	0	0	0	0	0	2	0	8	72	72
9.6	0	0	0	6	3	0	12	0	3	0	2	2	28	72	72

Regarding channel adjustments for the 1955–2023 period, scores are reported in Table 13, while their spatial distribution is shown in Figure 8. Channel adjustment scores (CAI) have been derived from the sum of indicators related to adjustments in channel pattern (CA1), channel width (CA2), and bed level (CA3). CAI values have ranged from 4 to 13 among the analyzed RRs. Values equal to 4 have been obtained in RRs 7.1 and 7.3, whereas the highest CAI values (13) have been obtained in four RRs, namely 7.5, 9.2, 9.3 and 9.4. The subdivision of the CAIs range into classes has shown that most of the RRs (i.e., 6 out of 15) have displayed a moderate-low CAI (i.e., $8 \leq CAI \leq 11$). Similarly, 5 RRs have fallen into the “low” CAI values class ($4 \leq CAI \leq 7$) and the remaining 4 RRs into the “moderate-high” CAI values class ($12 \leq CAI \leq 15$).

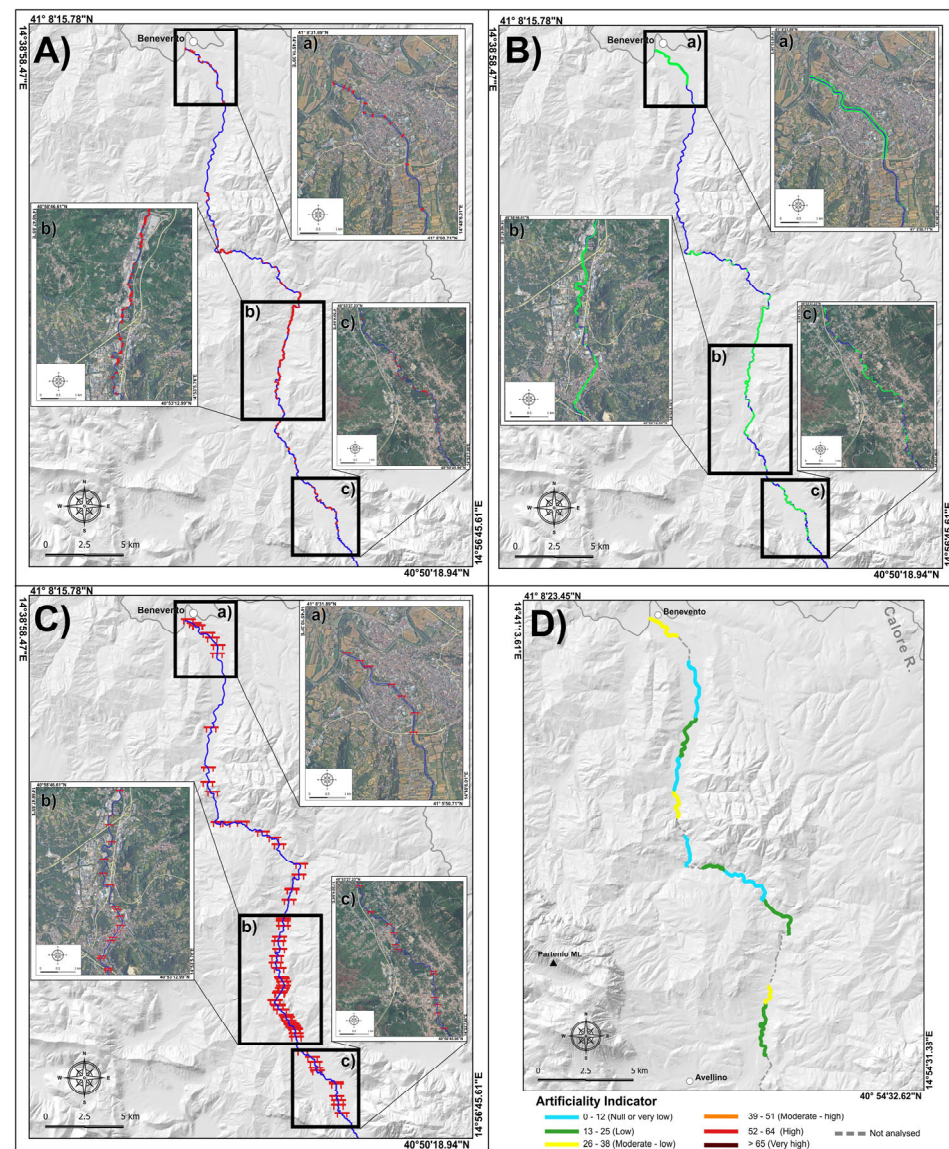


Figure 7. Spatial distribution of the main anthropogenic infrastructures along the Sabato River. (A) Location of weirs (in red) along the main channel, with insets (a–c) showing representative sectors in detail. (B) Distribution of artificial levees (in green); insets a–c are enlargements of significant sectors. (C) Location and density of bridges (in red) along the river, with detailed views of some selected sectors (a–c). (D) Distribution of the Artificiality Indicators along the analyzed Sabato RRs.

Table 13. Scores assigned to the channel adjustments indicators. CA1 = adjustments in channel pattern; CA2 = adjustments in channel width; CA3 = bed-level adjustments; CAI = total channel adjustment indicator ($= \sum_{i=1}^3 CA_i$); Max(SCA_{tot}) = sum of the highest possible scores of all the channel adjustment indicators (i.e., CA1 to CA12); and SCA_{max} = Max(SA_{tot}) minus the sum of the highest possible scores of the indicators not considered.

RR	CA1	CA2	CA3	CAI	SCA _{max}	Max (SCA _{tot})
5.1	0	6	4	10	24	24
5.2	0	6	4	10	24	24
5.3	0	6	4	10	24	24
5.4	0	6	4	10	24	24
7.1	0	0	4	4	24	24
7.2	0	3	4	7	24	24
7.3	0	0	4	4	24	24
7.4	0	6	4	10	24	24

Table 13. Cont.

RR	CA1	CA2	CA3	CAI	SCA _{max}	Max (SCA _{tot})
7.5	6	3	4	13	24	24
8.2	0	3	4	7	24	24
9.1	0	6	4	10	24	24
9.2	3	6	4	13	24	24
9.3	3	6	4	13	24	24
9.4	3	6	4	13	24	24
9.6	0	3	4	7	24	24

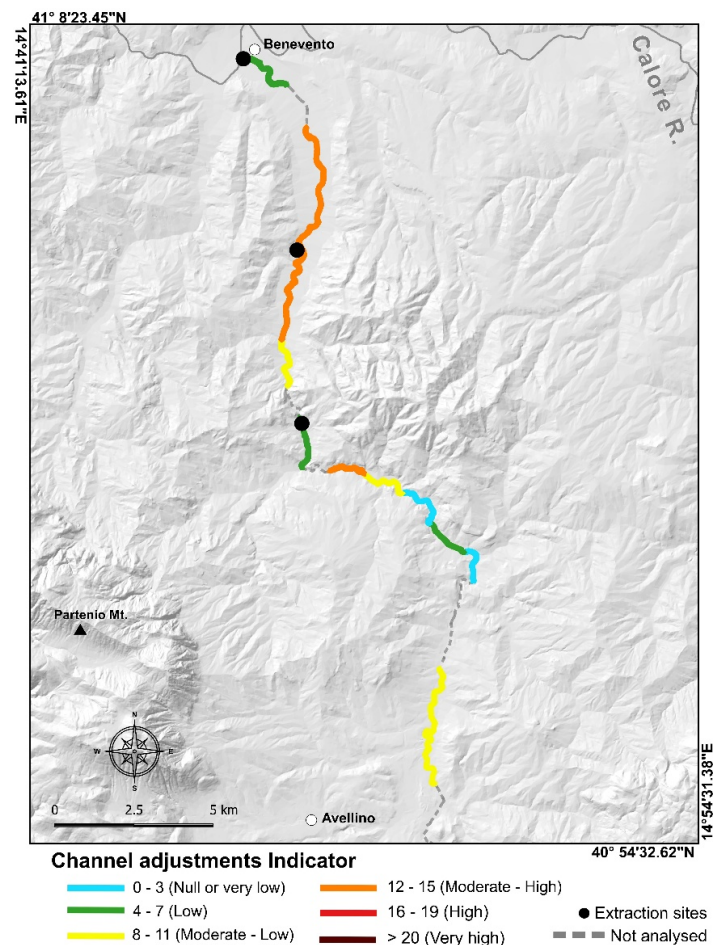


Figure 8. Distribution of the channel adjustments indicators. The locations of the sediment extraction sites are also reported.

The Morphological Quality Index (MQI) has been calculated by normalizing the sum of the scores (S_{tot}) against the maximum possible deviation (S_{max}), set to 46 for functionality, 72 for Artificiality and 24 for channel adjustments [29–32]. The ratio S_{tot}/S_{max} , defined as the Morphological Alteration Index (MAI), has been used to compute the MQI, which is complementary to MAI (i.e., $MQI = 1 - MAI$). According to the IDRAIM classification scheme, the MQI values obtained for the investigated river reaches (RRs) are reported in Table 14 and spatially represented in Figure 9. Five RRs (7.2, 7.3, 8.2, 9.2 and 9.4) have displayed a “Good” morphological quality, eight RRs (5.1, 5.2, 5.3, 7.1, 7.4, 7.5, 9.1 and 9.3) have fallen within the “Moderate or sufficient” morphological quality class, and, finally, two RRs (5.4 and 9.6) displayed a “Poor or scarce” morphological quality. The MQI values have ranged between 0.46 and 0.84. The mean MQI value calculated for the entire set of

investigated reaches has been equal to 0.64, corresponding to a “Moderate or sufficient” morphological quality class.

Table 14. Morphological Quality Index (MQI) for the investigated Sabato River reaches. $S_{tot} = FI + AI + CAI$ (see Tables 11–13); $S_{max} = SF_{max} + SA_{max} + SCA_{max}$ (see Tables 11–13); MAI = Morphological Alteration Index see Equation (4); MQI = Morphological Quality Index (see Equation (5)).

Reach	S_{tot}	S_{max}	MAI	MQI	Morphological Quality Class	Mean MQI
5.1	46	133	0.35	0.65	Moderate or sufficient	0.64
5.2	55	139	0.40	0.60	Moderate or sufficient	
5.3	57	139	0.41	0.59	Moderate or sufficient	
5.4	69	133	0.52	0.48	Poor or scarce	
7.1	49	139	0.35	0.65	Moderate or sufficient	
7.2	34	139	0.24	0.76	Good	
7.3	30	139	0.22	0.78	Good	
7.4	48	139	0.35	0.65	Moderate or sufficient	
7.5	63	134	0.46	0.54	Moderate or sufficient	
8.2	42	139	0.30	0.70	Good	
9.1	67	139	0.48	0.52	Moderate or sufficient	
9.2	38	139	0.27	0.73	Good	
9.3	48	139	0.35	0.65	Moderate or sufficient	
9.4	31	139	0.22	0.78	Good	
9.6	68	133	0.51	0.49	Poor or scarce	

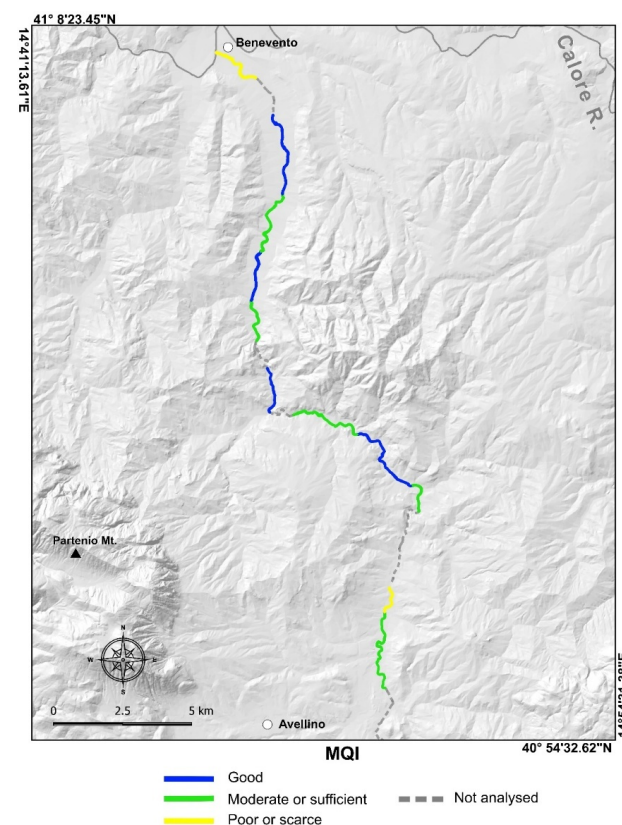


Figure 9. Distribution of the MQI in the investigated Sabato R. reaches.

4. Discussion

From many different standpoints (e.g., experienced mid- and short-term channel adjustments, dimensions, geomorphological setting, anthropogenic impacts), the Sabato R. shows several similarities with some fluvial systems within the broader Mediterranean morphoclimatic context [42,47,53]. Thus, the data we obtained in this study can be meaningfully compared with those produced for other Mediterranean rivers with the aim of

assessing their hydromorphological state, planning restoration activities and supporting integrated analyses, including those related to flood hazard and risk. To this latter aim, our data could be usefully integrated with hydraulic modeling, analysis of extreme flows, and flood inundation to complement, rather than replace, conventional flood risk analysis.

However, such representativeness should be interpreted with caution, as it is based on a single case study, and further validation across multiple catchments is required to extend these findings to the entire Mediterranean region.

In fact, on one hand, it is true that the method we have used (i.e., IDRAIM: [29,30,32]) has been specifically designed for Italian rivers, but on the other hand, the above-mentioned similarities between Italian and most Mediterranean rivers suggest that the method may be applied, subject to appropriate validation, to rivers located in other Mediterranean countries.

The combined analysis of Artificiality (AI), functionality (FI), channel adjustments (CAI) and the resulting Morphological Quality Index (MQI) has provided a clear and internally consistent framework for interpreting the hydromorphological conditions of the Sabato R. Overall, the investigated RRs of the Sabato R. have resulted to be characterized by generally low levels of artificiality (Table 12; Figure 7D), widespread channel adjustments over the period 1955–2023, that have been particularly intense from the standpoint of CMW variations (Table 10; Figure 8) but not from those of both riverbed degradation [42] and channel morphology (Table 9; Figure 3); and predominantly moderate-high degrees of functional alteration (Table 11; Figure 6). The marked spatial variability observed among RRs (Figures 3, 6 and 7D) has reflected the heterogeneous distribution of morphological alterations along the river and confirms the strong influence of local conditions on morphological quality.

The overall significant number of anthropogenic infrastructures, such as weirs (Figure 7A), artificial levees (Figure 7B) and bridges (Figure 7C), seems not to be fully reflected by the obtained values of AI (Table 12). In fact, these values have ranged between 7/72 and 32/72, where 72 is the highest possible value of the sum of the Artificiality Indicators or $\text{Max}(\text{SA}_{\text{tot}})$ (Table 12). The overall low values of AI can be explained by the very low values of several artificiality indicators such as A1, A2, A8 and, subordinately, A11 (Table 12). In other words, the low AI we have calculated for the investigated Sabato RRs is in good accordance with the absence of dams, transversal infrastructures that alter sediment discharge, artificial changes in river course and wood removal. Thus, both the values and the distribution we have obtained for AI indicate that, according to the IDRAIM method, anthropogenic alterations are generally low and spatially discontinuous along the investigated RRs of the Sabato R., with only localized RRs characterized by more significant artificiality.

As concerns channel adjustments, CAI values range from 4/24 to 13/24 (Table 13), where 24 is $\text{Max}(\text{SCA}_{\text{tot}})$. Among the CA indicators, a brief discussion is devoted to CA3. In fact, the IDRAIM method requires assigning each reach to a class of channel-bed elevation change, i.e., (A) ≤ 0.5 m; (B) 0.5 to 3 m; (C1) 3 to 6 m; (C2) >6 m, rather than determining exact incision values. According to the literature [42], no channel-bed elevation changes greater than 3 m have been observed over a 47-year period along the Sabato R. Furthermore, at the regional scale, Scorpio et al. [47] have demonstrated that incision values exceeding 3 m are quite rare in rivers of Southern Italy. Thus, both the classes (C1) and (C2) and the associated values of the indicator (i.e., 8 and 12) have been excluded for the analyzed reaches of the Sabato R. Similarly, field survey also allowed us excluding a channel bed elevation change lower than 0.5 m, so also class (A) and associated indicator value (i.e., 0) has been excluded. This is the reason why the value of 4 has been assigned to the indicator

CA3 in all the investigated reaches, notwithstanding that the CA3 indicator has been derived from literature and based on a single hydrometric station's data.

The lowest CAI values, i.e., falling into the “low” CAI class, have been limited to five RRs out of 15. Moderate-low CAI values have characterized six RRs out of 15, suggesting that channel adjustments of moderate-low intensity, mainly related to CMW variations rather than to morphological changes and riverbed degradation, have been the most widespread along the river. Moderate-high CAI values occur in four reaches out of 15, reflecting locally more intense channel adjustments. These relatively more intense channel adjustments could have been linked to local conditions that favored river morphological changes, such as lower confinement or outcropping of more erodible fluvial deposits. Overall, the spatial distribution of CAI has indicated that channel adjustments have been irregularly distributed across the investigated RRs of the Sabato R. (Figure 8).

Functionality Indicators have ranged between 10/43 and 30/43 (Table 11), where 43 is the Max (SF_{tot}). Nine reaches out-of-fifteen have displayed a moderate-high or high functional alteration, highlighting a quite worrying situation for the analyzed Sabato R. from the standpoint of river functionality. In addition, functional alterations have resulted in low three RRs only.

No linear or systematic relationships have emerged between artificiality and functionality. In fact, only in four RRs out-of-15, significant functional alterations have been coupled with high values of AI and vice versa. In all the remaining RRs, functionality and artificiality have shown contrasting values of associated indicators (Tables 11 and 12). Similarly, the most intense channel adjustments, highlighted by the highest CAIs (Table 13), have not systematically occurred in RRs that have displayed the highest AIs, as they have also affected RRs with low or moderate-low artificiality. This suggests that recent morphological changes have not been promoted and/or controlled by anthropogenic impacts only, but also by climatic changes and local river conditions (e.g., confinement, bedrock erodibility, riparian vegetation).

Among the considered parameters, functionality seems to be the one that controls the morphological quality more strictly. This has been suggested by the fact that both the two RRs displaying the worst morphological quality, i.e., RR 5.4 and 9.6 (Table 14), have displayed high values of FI, indicating a high functionality disturbance. In both these two reaches, artificiality is moderate-low. Similarly, channel adjustments have been moderate-low in RR 5.4 and even low in RR 9.6, suggesting a minor control on morphological quality by the experienced channel adjustments compared mainly to functionality and, subordinately, artificiality. However, further quantitative analyses (e.g., statistical or sensitivity-based approaches) would help to better constrain the relative contribution of functionality compared to the other indicators.

On the other hand, the combination of low or very low artificiality and low or moderate channel adjustments has proved to be fundamental in reducing the negative effects of functionality alterations in determining a good morphological quality: this has been the case of all the RRs displaying a “good” morphological quality. Among these, RR 9.2 and 9.4 have both experienced relatively more significant (i.e., moderate-high) channel adjustments, but the negative effects of these latter on morphological quality have been obliterated by both a low/very low artificiality and a low or moderate-low functionality alteration.

From a management perspective, the integrated interpretation of AI, FI, CAI, and MQI has allowed the identification of RRs where hydromorphological quality is the worst and most sensitive to anthropogenic alteration. In the most critical RRs, such as RR 5.4 and RR 9.6, characterized by the lowest MQI values (0.46 and 0.49, respectively), potential improvements in hydromorphological quality would require actions aimed at improving functional conditions and further reducing artificiality. Field surveys have proven that most

of the existing weirs are damaged by undermining processes (Figure 5b), partly associated with the riverbed degradation that occurred from the 1950s onwards, thus confirming the observations by Martucci et al. [42]. These damaged weirs could be the first to be removed to improve hydromorphological quality, as they do not work efficiently anymore from a hydraulic standpoint and only alter ecological conditions. As concerns the removal or modification of the other existing structures, it may be difficult, as such elements often still play a role in flood protection and channel stability. This has highlighted the need for management strategies that balance hydraulic safety with the preservation or recovery of hydromorphological quality, avoiding interventions that could further increase functional alteration in already critical RRs.

Sediment extraction management has represented another key issue. Although in-channel sediment extraction has been illegal in Italy since the 1990s, the presence of past extraction sites may still contribute to artificiality and reduced hydromorphological quality. Furthermore, some observations emerged during the field surveys (e.g., anomalous accumulations of sediments in the active channel located at the end of “fresh” pathways, with tracks of mechanical vehicles, that connect the sediment extraction site with the Sabato R.) have not allowed to fully exclude that, at least in some sites, extractions of sediments from the riverbed could still be active.

Overall, the results have confirmed that hydromorphological degradation along the investigated reaches of the Sabato R. is mainly linked to the cumulative effect of several concurrent pressures, while moderate to good morphological quality can persist where functional conditions are preserved and artificiality remains limited, even in the presence of significant short-term channel adjustments.

5. Conclusions

This study has applied the IDRAIM methodology to assess the hydromorphological quality of the Middle and Lower Sabato R. through the calculation of the Morphological Quality Index (MQI), providing a spatially explicit overview of the current hydromorphological conditions in an anthropized river system of Southern Italy. The results have contributed to addressing the limited number of MQI applications available for Mediterranean rivers and offered a structured basis for interpreting morphological conditions within the framework of European water and restoration policies.

The results have indicated that the investigated reaches of the Sabato R. are generally characterized by a moderate or sufficient morphological quality. The three components we have considered—artificiality, functionality and channel adjustments—have contributed to MQI values with different relative importance. Functionality and, to a lesser extent, artificiality have tended to be more closely associated with lower MQI values, whereas channel adjustments have not systematically corresponded to reduced morphological quality.

Lower MQI values have been mainly observed in river reaches where high functionality alterations and moderate artificiality have coexisted, not necessarily coupled with marked channel adjustments. Overall, these findings have suggested that morphological quality reflects the combined influence of multiple components, with functionality appearing to play a particularly relevant role, although this evidence has been identified on a descriptive basis and would require further statistical support.

The integrated evaluation of artificiality, functionality and channel adjustments has proved to be useful in identifying river reaches where hydromorphological conditions are more compromised and where management or restoration actions may be prioritized. In this sense, the spatial distribution of MQI provides a valuable support for river management strategies aimed at improving hydromorphological quality, in line with the objectives of the WFD [21] and the EU Nature Restoration Law [34].

Although the IDRAIM approach is not intended to replace hydraulic modeling or flood risk assessment methods, the analyses we have conducted in this study has provided complementary information on channel conditions and recent morphological adjustments that may be relevant for river management and for identifying reaches that may deserve further investigation also in relation to flood-related processes, in coherence with the EU Floods Directive [40]. Overall, the results have confirmed that MQI is a reliable diagnostic tool for describing present morphological conditions and for supporting integrated river management in complex and anthropized settings.

Even if the results are based on a single case study and therefore should be generalized with caution, they could provide useful insights for some similar Mediterranean rivers. Future research should build on this assessment by integrating MQI-based analyses with investigations of morphological dynamics, multi-site validation, and event-scale processes, in order to improve the understanding of the links between short-term channel adjustments, hydrological extremes and flood hazard in some similar Mediterranean river systems.

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