Evaluation of the morphological quality index in the Cordevole river (BI, Italy)

Emanuel Rigon, Johnny Moretto, Riccardo Rainato, Mario Aristide Lenzi, Andrea Zorzi

Department of Land, Environment, Agriculture and Forestry, University of Padua, Italy

Abstract

The European Union (EU) Water Framework Directive (WFD, 2000/60/EC), which came into force in Italy under Decree Law no. 152 of 3rd April 2006, has as its objectives the protection and improvement of aquatic ecosystem status, promoting the sustainable use of water resources and mitigating the effects of floods and droughts. According to this Directive, the ecological classification of a watercourse should be considered in addition to physical-chemical and biological aspects of its hydromorphological condition, in order to define the deviation of the present condition from a pre-defined reference state. The Italian National Institute for Environmental Protection and Research has promoted a methodology called IDRAIM for the hydromorphological analysis of streams. This is an integrated approach aimed at implementing both WFD and EU Flood Directives (2007/60/EC). In this paper, we describe the application of the morphological quality index (MQI) protocol, which is part of the IDRAIM, used for evaluating the morphological quality of the Cordevole River, Province of Belluno, northeastern Italy. General settings and segmentation of the water network through the use of semi-automatic GIS techniques were presented. The MQI data derived from the application of 28 indicators in 42 reaches were then analysed. Most (48%) of the analysed reaches have a good quality status; 38% have a moderate quality status and poor morphological conditions (14%) are due to the presence of artificial elements and to the limited connectivity between hill-slopes and the river corridor.

Correspondence: Emanuel Rigon, Department of Land, Environment, Agriculture and Forestry, University of Padua, Italy.
E-mail: emanuel.rigon@unipd.it

Key words: hydromorphology, river network segmentation, morphological recovery, Water Framework Directive, Cordevole river, Italy.

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Introduction

Many European rivers have suffered the negative consequence of different degrees and types of pressure from human activities that have modified their morphology and altered their hydrological processes (Liébault and Piégay, 2001; Gurnell *et al*., 2009). In recent years, the need has been recognised for a tool able to assess the ecological, morphological, hydrological conditions and the degree of alteration from the reference conditions of rivers. The main purpose of this tool is to define strategies of morphological recovery and plan river restoration management. The European Union (EU) Water Framework Directive (WFD; European Commission, 2000) and the EU Flood Directive (European Commission, 2007), define a series of innovative criteria and actions necessary for the ecological classification and management of European rivers. The WFD introduces the term *hydromorphology* that requires an interface among different topics and analyses the physical processes for river management actions and strategies (Vaughan *et al.,* 2009). In this context, the modifications in flow and sediment regimes, morphology and lateral channel mobility must all be considered. It is still not clear which of the components are more strictly related to the ecological state, but it is now well known in the literature that the geomorphological processes promote the functionality of aquatic and riparian ecosystems (Palmer *et al*., 2005). The equilibrium of a river is the result of sedimentological and hydrological regimes, and can be modified by human action both directly by the alteration of these components or indirectly on the control variables (*e.g.* climate, forest area, etc.). The evaluation of the morphological and hydrological alteration allows the anthropic changes to the water channel to be assessed, and defines the evolutionary trends. River restoration strategies can then be defined. The evaluation of the morphological quality is particularly significant for rivers in Italy that, as in many other European countries, are characterised by a very high level of human pressure (Surian *et al.,* 2009; Rigon *et al.,* 2012b; Moretto *et al*., 2012).

The WFD that came into force in Italy under the Decree Law no. 152 of 3rd April 2006 regulates the achievement by 2015 of a *good ecological status* for all natural water bodies, and the Italian Institute for Environmental Protection and Research (ISPRA) has recently promoted a new methodology, called IDRAIM, for the hydromorphological evaluation, analysis and monitoring of Italian streams. All local governments in Italy are working to implement the procedure, but the WFD objectives may not be achieved, especially for heavily modified water bodies (HMWB). The regulations provide for the deadline to be extended to achieve *good ecological status*. Currently in Italy the morphologi-

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cal evaluation procedure has been applied to around half of the regions, and the Region of Veneto is expected to apply it to its entire river network. In addition to the 102 river reaches analysed in the index test phase (Rinaldi *et al.,* 2013), there are still very few publications available on the morphological evaluation carried out with this new methodology (Cencetti *et al*., 2010; Vangelista, 2011). ISPRA has now developed an initial screening procedure for the identification of HMWB. Only water bodies at risk of not achieving a *good ecological status* will be analysed by IDRAIM.

In this paper, we describe the application of the morphological quality index (MQI) protocol, which is part of IDRAIM (Rinaldi *et al.,* 2013), in the Cordevole River (Belluno, northeastern Italy), one of the main tributaries of the Piave River. The first phase of the MQI procedure (general setting and segmentation) was implemented for the whole catchment area, and remote sensing and GIS techniques have been used to detect and classify the 132 segments between the 6th and 4th order (Horton-Strahler classification; Strahler, 1964). The 28 indicators contained in the evaluation forms were applied in the second phase for 42 reaches (*i.e.* approx. 32% of the total river network). In addition, we propose a methodology for a semi-automatic calculation of lateral confinement (defined by *Degree of Confinement* and a *Confinement Index*) in order to reduce the period of time required for river network segmentation. Part of the GIS analyses, and in particular the field surveys, were developed as part of two Bachelor degree theses (Zorzi, 2013; Loreggian, 2013).

Materials and methods

Study area

The Cordevole River (Figure 1) is approximately 79 km long and runs for its entirety in the Province of Belluno (northeastern Italy). It rises from the Pordoi pass (1919 m asl) in the municipality of Livinallongo del Col di Lana, and it flows into the Piave river near the town of Mel, (275 m asl). Its main tributaries are the Fiorentina and Pettorina (near the village of Caprile), the Biois (near Cencenighe), and the Tegnas (near Taibon). Downstream of Agordo, the stream continues along a narrow valley where the water flow decreases considerably, due to the derivations created for hydroelectric production. A few kilometers from its confluence in the Piave River, it receives the Mis stream.

The catchment area (Figure 1), which accounts for 843 km^2 (see the hydro GIS analysis below) is made up of mountainous terrain and this creates a hydrographical network with a complex morphology typical of Alpine basins. The hydrographical network extends for approximately 1440 km (calculated by ArcGIS, setting a minimum drainage area of 160,000 m^2) with a drainage ratio of 1.7 m^{-1}. Woodlands cover approximately 40% of the territory, most of which is occupied by spruce trees, and the local climate is influenced by altitude and exposure (mean annual temperature is approx. 7°C and mean annual precipitation is approx. 1100 mm).

The geology of the area is very complex. The higher parts of the basin are generally composed of dolomite, limestone, and volcanic rocks forming subvertical cliffs, whereas the lower slopes, deeply incised by rivers, are formed by highly erodible sedimentary rocks and quaternary deposits, with diffuse mass wasting processes (Picco *et al*., 2012).

The flow regime is characterised by a high runoff during the snowmelt period (May-June) with also significant summer storms, and low flows during the coldest months (January-February). In autumn, intense rainfall of short duration is common and subsequent flash floods are frequent events. Part of the basin lies within the Belluno Dolomites National Park and there are several areas of Regional interest and natural beauty.

Intervention has led to the construction of artificial infrastructures in the stream (*e.g.* check-dams, transversal structures, bank protections) (Figure 2) and these are often located near villages and roads. Many of these were built in the years following the 1966 flood that showed just how dangerous these areas can be (for further information see Castiglioni, 1974; Malaguzzi *et al.,* 2006). Cross structures, such as the check-dams, are currently filled with sediment, and are, therefore, no longer functional. In recent years, there has been a tendency to apply methods taken from river restoration engineering, but overall, there has been little human intervention and infrastructures have only been built in cases of extreme necessity to respond to problems of hydrogeological safety. The infrastructure constructed for hydroelectric power production, already designed in 1930 with the presence of two natural basins (Marmolada Glacier and Alleghe Lake) (Figure 2B), are mainly represented by the Masarè spillway (Alleghe), the Ghirlo dam (Cenceninghe) and the 91 m high Mis dam (Figure 2C).

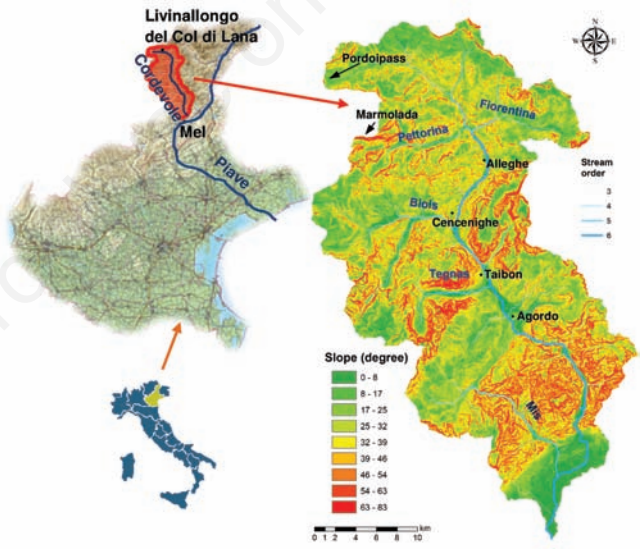

Figure 1. Map of the Cordevole river basin, stream order and slope.

Figure 2. The study area. A) Alleghe Lake and Cordevole river. B) Check-dam in the upper part of the Cordevole river. C) Mis Dam.

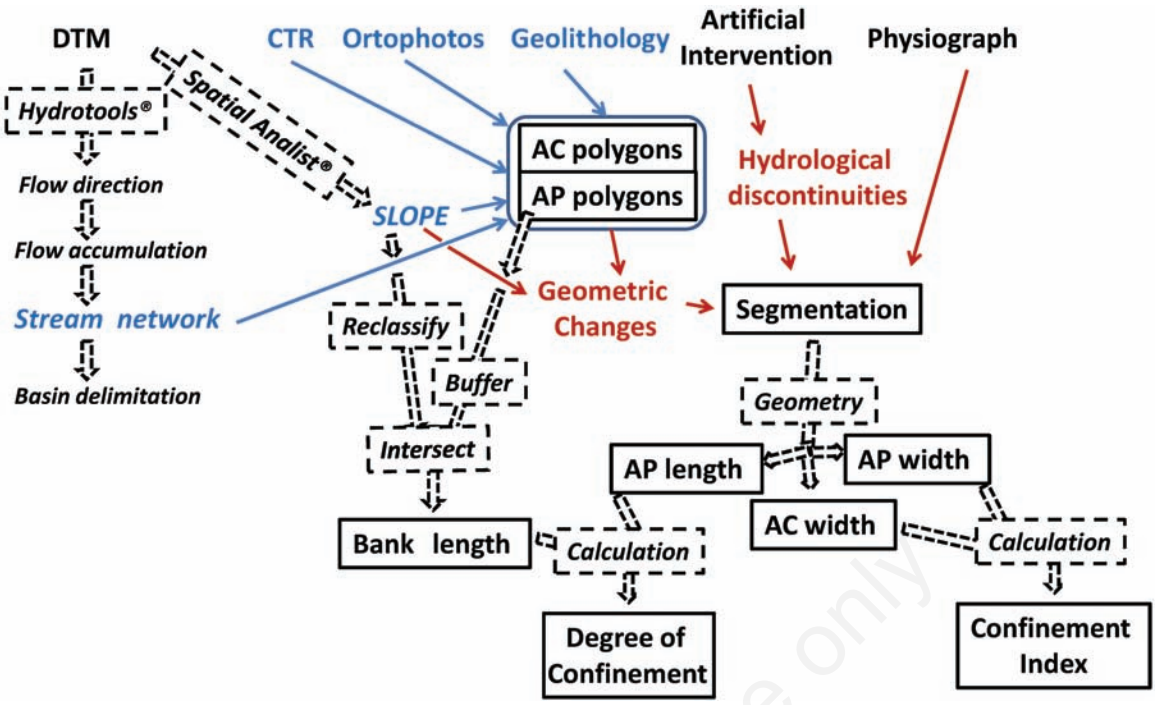

Figure 3. Flowchart that describe the procedure of semi-automated GIS model for segmentation and calculation of parameters. Data souces are on top line. Automated processes have been highlighted with dotted boxes. See text for description. AP, alluvial plain; AC, active channel.

Methods

IDRAIM is a method of analysing and monitoring hydromorphological alteration that was created to support river management through the integration of environmental quality objectives and risk mitigation. It consists of two indexes: i) the alteration of the hydrological regime index (IARI); and ii) the MQI that defines stream morphological quality. The MQI procedure (Rinaldi *et al*., 2012) is made up of three phases: i) general setting and segmentation; ii) evaluation of the current morphological condition of river reaches in terms of functionality, artificiality, and recent channel changes; iii) monitoring of the morphological quality variation. The evaluation of the current morphological condition and deviation from the reference state is performed by applying a set of 28 indicators that assess the continuity of river processes, channel morphological conditions, and riparian vegetation. The reference state is represented by a river reach in dynamic equilibrium with undisturbed geomorphic processes, and where the artificiality does not significantly change the dynamics of the river, allowing it to perform its expected morphological functions (Rinaldi *et al*., 2013). The methods of investigation are characterised by an integrated approach to perform remote sensing analyses and field surveys, with sufficiently large spatial and temporal scales in relation to the various aspects analysed (*e.g.* longitudinal continuity).

During the river network segmentation, various tools and scripts were used to reduce the application time, *e.g.* semi-automatic calculation of the indexes needed to define the degree of confinement. The second phase consists in the analysis of the information collected from the first phase and the MQI evaluation. Moreover, in this phase, 42 reaches were investigated by field surveys, with the support of the evaluation forms, in order to define the geomorphic functionality, artificiality and channel adjustments for each reach.

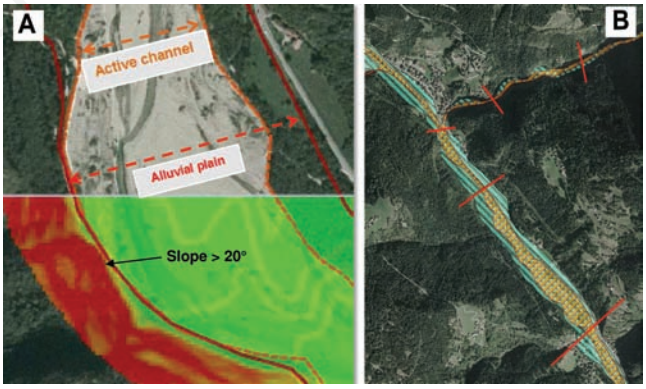

Figure 4. Calculation of confinement indexes (A); profiling of the active channel and alluvial plain, and segmentation (B).

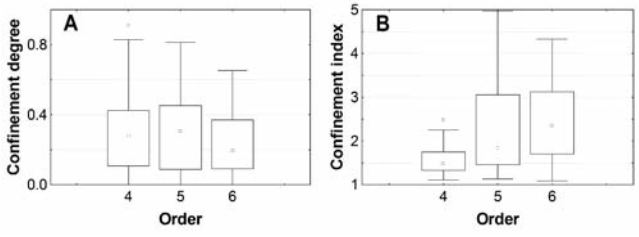

Figure 5. Degree (A) and confinement index (B) in relation to order of the 132 reaches identified through the segmentation phase of morphological quality index protocol. The square within each box indicates the median value, box ends are 25th and 75th percentiles, whiskers are the non-outlier extreme.

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Table 1. Characteristics of the 4th order reaches obtained in the segmentation phase of morphological quality index protocol. The last row shows the average values.

Reach ID	Stream name	Stream order	Length (m)	Mean width		Mean elevation (m asl)	Degree of confinement	Confinement index	Mean channel slope (m/m)	Drainage area (km^2)
				Alluvial plain (m)	Active channel (m)					
40144	Cordevole	4	742	40	18	1131	0.40	2.22	0.03	70.2
40145	Cordevole	4	1270	19	11	1164	0.66	1.73	0.03	68.8
40146	Cordevole	4	1046	19	12	1203	0.23	1.58	0.04	66.3
40147	Cordevole	4	1375	30	21	1255	0.22	1.43	0.05	56.3
40148	Cordevole	4	1181	20	12	1312	0.17	1.67	0.04	46.5
40149	Cordevole	4	1098	11	9	1433	0.68	1.22	0.18	14.8
40150	Cordevole	4	619	28	15	1582	0.22	1.87	0.16	9.8
40211	Mis	4	1282	29	20	700	0.35	1.45	0.04	31.4
40212	Mis	4	877	28	25	752	0.69	1.12	0.06	15.5
40213	Mis	4	1536	18	15	877	0.53	1.20	0.13	10.8
40301	Tegnas	4	1262	72	48	906	0.35	1.50	0.10	21.5
40302	Tegnas	4	1625	33	20	984	0.49	1.65	0.02	17.2
40401	Biois	4	1826	25	13	1077	0.19	1.92	0.05	53.7
40402	Biois	4	1840	40	20	1158	0.03	2.00	0.04	44.3
40501	Fiorentina	4	1750	22	15	1210	0.19	1.47	0.07	38.2
40502	Fiorentina	4	1150	40	28	1321	0.28	1.43	0.08	27.4
40503	Fiorentina	4	1257	22	17	1396	0.28	1.29	0.05	24.2
40504	Fiorentina	4	1063	19	13	1466	0.19	1.46	0.08	14.0
40505	Fiorentina	4	1259	15	12	1536	0.05	1.25	0.05	10.3
40601	Pettorina	4	978	23	16	1027	0.12	1.44	0.05	52.5
40602	Pettorina	4	826	28	19	1066	0.04	1.47	0.04	49.8
40603	Pettorina	4	690	27	16	1106	0.30	1.69	0.07	47.8
40604	Pettorina	4	795	13	9	1162	0.25	1.44	0.08	46.2
40605	Pettorina	4	1477	17	10	1218	0.02	1.70	0.03	43.5
40606	Pettorina	4	612	8	6	1258	0.23	1.33	0.05	37.4
40607	Pettorina	4	1507	16	10	1350	0.62	1.60	0.10	32.4
40608	Pettorina	4	1907	9	7	1488	0.05	1.29	0.07	27.1
40701	Codalunga	4	1282	20	18	1224	0.47	1.11	0.12	13.5
40702	Codalunga	4	910	35	21	1351	0.25	1.67	0.11	12.5
40703	Codalunga	4	965	23	14	1475	0.28	1.64	0.15	10.4
40801	Bordina	4	1486	18	8	998	0.63	2.25	0.20	11.4
40901	Sarzana	4	1180	39	20	622	0.49	1.95	0.09	25.2
40902	Sarzana	4	1124	23	16	751	0.65	1.44	0.14	24.0
40903	Sarzana	4	1515	18	12	879	0.44	1.50	0.07	19.5
40904	Sarzana	4	1187	11	9	983	0.65	1.22	0.09	16.7
41001	Rova	4	609	29	26	587	0.02	1.12	0.05	20.1
41002	Rova	4	990	29	26	634	0.07	1.12	0.06	19.4
41003	Rova	4	775	20	15	692	0.31	1.33	0.07	18.0
41004	Rova	4	345	16	8	737	0.28	2.00	0.10	17.5
41101	Missiaga	4	1816	25	10	640	0.25	2.50	0.08	23.9
41201	Liera	4	1626	13	9	969	0.09	1.44	0.05	40.7
41202	Liera	4	963	13	7	1039	0.02	1.86	0.06	37.7
41203	Liera	4	813	13	10	1090	0.00	1.30	0.05	35.4
41204	Liera	4	1020	23	12	1140	0.02	1.92	0.06	32.2
41205	Liera	4	879	15	12	1206	0.00	1.25	0.08	27.5
41206	Liera	4	950	20	14	1265	0.00	1.43	0.05	26.6

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General setting and segmentation

The initial setting and river network segmentation into relatively homogeneous reaches was carried out as part of a geographical information systems (GIS) project (ArcGIS 10, ESRI®). We considered the valley form, slope, flow and sediment load conditioning (Brierley and Fryirs, 2005) derived from analysis of the following metadata: i) digital colour orthophotos for the years 2000, 2003, and 2006 available in Web Map Service mode on the national Geoportal (http://www.pcn.minambiente.it/GN/); ii) Digital Terrain Model (DTM) (ascii format) down-loaded from the regional Geoportal (http://idt.regione.veneto.it/app/metacatalog/index?deflevel=165) and subsequently converted to raster with a cell size of 5 m; iii) regional technical maps (Carta Tecnica Regionale, Region of Veneto, from the regional Geoportal); iv) regional physiographical units map available from the website of the Agency for Environmental Protection and Prevention of Veneto (ARPAV) (http://www.arpa.veneto.it/temi-ambientali/suolo); v) regional geolithological map (down-loaded from the regional Geoportal); vi) artificial intervention database (watershed management and torrent control structures) of the Province of Belluno, provided by the Regional Hydrological Service.

These last metadata are organised according to types of structures, in different shaped files that report essential information (*e.g.* year of construction, geometric dimensions, etc.) both for the first and the second phase of the MQI evaluation.

Definition of the catchment area and the identification of the synthetic hydrographical network was made with the Arc Hydro Tools (ESRI®) setting the blue line threshold value to 160,000 m^2. Slope and exposure maps were derived from the DTM. This geospatial information, together with the 2006 orthophotos, were used for photo-interpretation (Figure 3) and for editing the active channel and alluvial plain (which is defined as the maximum width of the river region under study). This editing was carried out throughout the river network from the 4th to the 6th order (Horton-Strahler classification; Strahler, 1964) because in the reaches located in the upper part of the basin, interpretation of the photographic material was problematic due to the quality of DTM and images, and disturbance (see below).

The segmentation methodology was based on the MQI protocol application (Rinaldi *et al*., 2012), but has been applied following a slightly different step sequence for which some semi-automatic GIS processes were used. Figure 3 presents the simplified flow chart that summarises the GIS processing performed. Automated processes have been highlighted with dotted boxes. The alluvial plain and active channel editing was carried out following the validated stream network (hydrotools®) detected by photo interpretation, but also taking into account the geolithology, slope and the CTR. A first segmentation (editing of lines) was then created considering the physiographical units, hydrological discontinuities (from hydrological elaboration and artificial intervention database), significant geometric changes, and variations in geolithology (Figure 4). The active channel and alluvial plain shapes

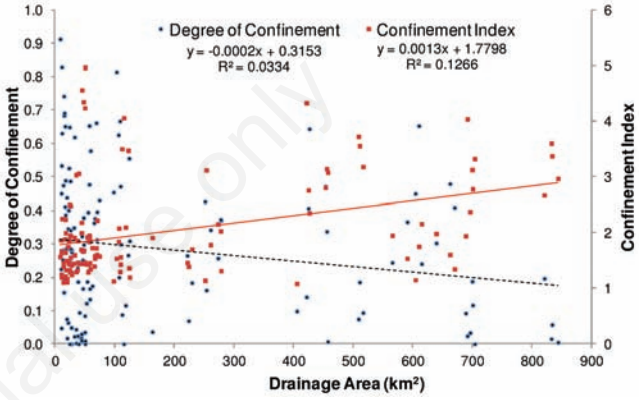

Figure 6. Degree and confinement index in relation to the drainage area.

Table 1. Continued from previous page.

Reach ID	Stream name	Stream order	Length (m)	Mean width		Mean elevation (m asl)	Degree of confinement	Confinement index	Mean channel slope (m/m)	Drainage area (km^2)
				Alluvial plain (m)	Active channel (m)					
41207	Liera	4	525	20	15	1307	0.00	1.33	0.06	24.2
41208	Liera	4	563	28	16	1327	0.06	1.75	0.01	21.7
41209	Liera	4	1176	20	17	1482	0.29	1.18	0.26	20.1
41210	Liera	4	1610	67	48	1727	0.28	1.40	0.11	13.9
41401	Nottole	4	924	15	9	861	0.45	1.67	0.11	10.3
41501	Listolade	4	1391	67	27	747	0.34	2.48	0.11	25.4
41502	Listolade	4	1565	69	37	934	0.53	1.86	0.14	23.0
41503	Listolade	4	1494	56	25	1162	0.39	2.24	0.16	17.2
41601	No name	4	1189	11	7	544	0.91	1.57	0.20	8.4
41701	No name	4	1361	27	12	773	0.74	2.25	0.17	14.5
41801	Caiada	4	651	6	5	1064	0.83	1.20	0.08	11.1
41901	Andraz	4	1246	17	12	1178	0.28	1.42	0.10	27.2
41902	Andraz	4	1093	14	9	1308	0.29	1.56	0.13	25.7
41903	Andraz	4	606	16	11	1421	0.40	1.45	0.14	22.4
41904	Andraz	4	1298	17	9	1544	0.41	1.89	0.12	16.4
41905	Andraz	4	541	18	8	1655	0.15	2.25	0.11	14.5
62 Reaches		Mean	1147	25	16	1111	0.31	1.59	0.09	28

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have been subdivided into various polygons with the segmentation line intersection (Figure 4). The outer area alluvial plain polygons (buffer 20 m) was intersected with the slope map, and the percentage of banks directly in contact with the hill-slopes was calculated automatically (identified as the terrain portions with a slope greater than 20°) (Figures 3A and Figure 4A). The Degree of Confinement has been defined for each reach. Other automatic processes were used to calculate the geometry of each polygon from which it was possible to evaluate the relationship between the alluvial plain and the active channel width (Figure 4A) (Confinement Index) (Zorzi, 2013). The lateral confinement could be computed by putting together these two indexes (for more details see Rinaldi *et al*., 2012, 2013). According to this lateral confinement, appropriate adjustments were then calculated on the initial division. The river morphology was then defined, taking into account the specific Italian Alpine context (Lenzi *et al.*, 2000).

Evaluation procedure

After the segmentation phase, the data and information needed to apply the evaluation procedure were summarised for each reach identified. The field surveys were carried out in the period August 2012-May 2013 and the evaluation forms were also used. Of the 42 reaches analysed, 31 are located in the upper part of the Cordevole catchment

Table 2. Characteristics of the 5th order reaches obtained in the segmentation phase of morphological quality index protocol. The last row shows the average values.

Reach ID	Stream name	Stream order	Length (m)	Mean width		Mean elevation (m asl)	Degree of confinement	Confinement index	Mean channel slope (m/m)	Drainage area (km^2)
				Alluvial plain (m)	Active channel (m)					
50138	Cordevole	5	858	67	35	1013	0.04	1.91	0.03	163.0
50139	Cordevole	5	458	36	23	1028	0.30	1.57	0.01	109.6
50140	Cordevole	5	485	33	23	1044	0.47	1.43	0.05	109.4
50141	Cordevole	5	968	52	40	1066	0.67	1.30	0.02	108.7
50142	Cordevole	5	1047	37	24	1095	0.81	1.54	0.04	102.9
50143	Cordevole	5	555	60	53	1120	0.45	1.13	0.02	97.9
50201	Mis	5	1058	142	35	332	0.00	4.06	0.01	115.1
50202	Mis	5	1670	84	24	345	0.09	3.50	0.01	112.2
50203	Mis	5	747	35	19	365	0.63	1.84	0.04	106.2
50204	Mis	5	1162	79	50	453	0.43	1.58	0.02	74.1
50205	Mis	5	811	90	56	471	0.31	1.61	0.01	69.8
50206	Mis	5	895	54	35	491	0.38	1.54	0.04	66.5
50207	Mis	5	1136	45	26	511	0.17	1.73	0.01	62.3
50208	Mis	5	860	62	46	533	0.58	1.35	0.04	59.3
50209	Mis	5	1145	39	20	581	0.65	1.95	0.05	57.2
50210	Mis	5	1360	126	29	643	0.38	4.34	0.05	47.5
50301	Tegnas	5	404	164	33	615	0.00	4.97	0.03	50.3
50302	Tegnas	5	619	114	23	631	0.01	4.96	0.04	50.3
50303	Tegnas	5	1194	89	21	671	0.08	4.24	0.05	49.8
50304	Tegnas	5	890	82	18	720	0.32	4.56	0.04	44.8
50305	Tegnas	5	1426	188	86	754	0.01	2.19	0.02	44.2
50306	Tegnas	5	678	107	35	779	0.00	3.06	0.03	39.3
50307	Tegnas	5	1940	91	30	817	0.04	3.03	0.03	35.1
50401	Biois	5	785	24	20	768	0.31	1.20	0.04	124.8
50402	Biois	5	951	52	38	802	0.55	1.37	0.04	124.1
50403	Biois	5	1544	59	17	849	0.27	3.47	0.04	122.4
50404	Biois	5	1282	42	20	904	0.12	2.10	0.04	118.1
50405	Biois	5	1017	25	12	959	0.20	2.08	0.06	107.0
50406	Biois	5	577	21	15	1010	0.36	1.40	0.08	65.2
50501	Fiorentina	5	440	28	15	1004	0.13	1.87	0.04	58.2
50502	Fiorentina	5	643	54	37	1024	0.17	1.46	0.04	58.1
50503	Fiorentina	5	726	35	19	1056	0.48	1.84	0.06	57.2
50504	Fiorentina	5	1054	44	34	1111	0.39	1.29	0.07	55.1
33 Reaches		Mean	948	69	31	764	0.29	2.38	0.03	82

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(76% of reaches identified in the segmentation phase) while the 11 other reaches are representative of the downstream area. The water conditions while measurements were being taken were characterised by low flow rates with no significant floods reported in the periods previous to the study.

As required by the protocol, different indexes of geomorphological functionality, artificiality, and channel adjustments were analysed. Channel adjustments were investigated only for two reaches that have a channel width over 30 m. The evaluation of the 28 indicators was completed with the application of two types of MQI evaluation forms: i) one for confined channels; and ii) one for semi-confined and unconfined channels (Rinaldi *et al.*, 2013). These two types of evaluation forms have different numbers and types of indicators.

Most attention was paid to the analysis of the continuity (lateral and

Table 3. Characteristics of the 6th order reaches obtained in the segmentation phase of morphological quality index protocol. The last row shows the average values.

Reach ID	Stram name	Stream order	Length (m)	Mean width		Mean elevation (m asl)	Degree of confinement	Confinement index	Mean channel slope (m/m)	Drainage area (km^2)
				Alluvial plain (m)	Active channel (m)					
60101	Cordevole	6	2140	920	310	287	0.00	2.97	0.01	843.8
60102	Cordevole	6	885	715	212	296	0.06	3.37	0.00	833.6
60103	Cordevole	6	1550	778	216	303	0.02	3.60	0.01	832.5
60104	Cordevole	6	1878	483	181	316	0.20	2.67	0.01	820.8
60105	Cordevole	6	1198	362	109	329	0.00	3.32	0.01	703.9
60106	Cordevole	6	1108	164	59	340	0.12	2.78	0.01	700.5
60107	Cordevole	6	1540	125	40	348	0.19	3.13	0.00	699.8
60108	Cordevole	6	1158	107	45	363	0.03	2.38	0.02	696.2
60109	Cordevole	6	1883	432	107	378	0.02	4.04	0.00	691.5
60110	Cordevole	6	2923	342	176	403	0.09	1.94	0.02	688.8
60111	Cordevole	6	2322	345	256	426	0.41	1.35	0.00	670.0
60112	Cordevole	6	2078	291	181	438	0.48	1.61	0.01	662.3
60113	Cordevole	6	2130	262	132	463	0.30	1.98	0.01	639.4
60114	Cordevole	6	1713	175	81	488	0.24	2.16	0.01	614.8
60115	Cordevole	6	1952	72	41	524	0.65	1.76	0.02	610.3
60116	Cordevole	6	1817	91	79	549	0.45	1.15	0.00	604.2
60117	Cordevole	6	1413	74	48	550	0.37	1.54	0.00	590.8
60118	Cordevole	6	1097	123	63	563	0.24	1.95	0.02	565.5
60119	Cordevole	6	1275	356	112	588	0.09	3.18	0.02	516.6
60120	Cordevole	6	905	160	45	601	0.19	3.56	0.00	510.8
60121	Cordevole	6	619	175	47	613	0.07	3.72	0.04	508.9
60122	Cordevole	6	594	120	39	626	0.01	3.08	0.00	457.4
60123	Cordevole	6	613	110	35	638	0.34	3.14	0.04	455.6
60124	Cordevole	6	882	115	41	663	0.47	2.80	0.03	453.5
60125	Cordevole	6	970	106	45	688	0.64	2.36	0.03	426.4
60126	Cordevole	6	1016	80	29	709	0.41	2.76	0.02	424.9
60127	Cordevole	6	2007	160	37	738	0.14	4.32	0.02	421.6
60128	Cordevole	6	881	50	46	766	0.10	1.09	0.02	405.4
60129	Cordevole	6	786	58	44	776	0.37	1.32	0.00	278.4
60130	Cordevole	6	1078	61	30	789	0.37	2.03	0.02	277.6
60131	Cordevole	6	1456	56	26	813	0.26	2.15	0.02	273.1
60132	Cordevole	6	1308	66	37	838	0.34	1.78	0.02	260.7
60133	Cordevole	6	719	131	42	853	0.16	3.12	0.01	253.6
60134	Cordevole	6	868	40	35	915	0.43	1.14	0.11	251.4
60135	Cordevole	6	1414	133	78	976	0.18	1.71	0.00	229.4
60136	Cordevole	6	1208	113	81	988	0.07	1.40	0.02	223.8
60137	Cordevole	6	465	101	69	1001	0.27	1.46	0.00	221.5
3	Reaches	Mean	1347	218	88	593	0.24	2.43	0.02	522

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longitudinal) of river processes, channel morphological conditions, and vegetation. Most of the applied indexes were evaluated from the information obtained during the first phase of general settings and segmentation. Three classes are generally defined for each indicator, with a score of 0 in the case of absence or negligible presence of alteration, 2-3 for intermediate alteration, and 5-6 the highest alteration score. In cases of an extremely dense and dominant presence of artificial elements, additional points of alteration are assigned. The final score is calculated as the ratio between total deviation from non-altered conditions (assigned to all indicators applied in the reach) and the maximum possible deviation for the given stream typology. Following this logic, the morphological alteration index (MAI), with values ranging from 0 to 1, was calculated. MQI is complementary to MAI (MQI=1-MAI). It is also possible to calculate the sub-vertical score of functionality (MQI_F), artificiality (MQI_A) and channel variation (MQI_V) in order to identify the critical points of the reaches analysed.

Results

Segmentation

The segmentation phase has identified 62 reaches of 4th, 33 of 5th, and 37 of 6th orders. For each of them, the average values of the following parameters were calculated in a GIS environment:

- segment length (m);
- width of the active channel (m);
- width of the alluvial plain (m);
- mean elevation (m asl);
- Degree of Confinement (methodology as above);
- Confinement Index (methodology as above);
- average channel slope derived from the DTM (m/m);
- drainage area at the outlet of the reach from hydrological analysis (km^2).

All data were included in a GIS project database and parameters for the reaches of the Cordevole River are reported in Table 1 (reaches of 4th order), Table 2 (reaches of 5th order), and Table 3 (reaches of the 6th order).

The results show that the average length of the obtained river segments ranges from 948 m (5th order) to 1347 m (6th order). The average length of reaches of 4th order are (1147 m) slightly higher than that relating to the 5th order reaches. This may be affected by the presence of large areas with homogeneous morphological and physiographical characteristics. The average width of the active channel is strictly linked to the reach order and changes from 16 m (4th order), to 31 m (5th order) and 88 m for the reach of 6th order, as is the average widths reported for the floodplain of 25 m, 69 m and 218 m, respectively. Near the confluence with the Piave, the Cordevole River greatly increases in size with a fluvial plain of approx. 920 m (reach 60101) (Table 3). The average slope shows values ranging from 0.02 m/m (6th order) to 0.09 (4th order) with a maximum of 0.26 in the Liera stream (reach 41209)

Table 4. Morphological quality index results for the 42 reaches analyzed. Contains the name of the river, reach order, the class of confinement, morphological quality index of functionality, morphological quality index of alteration, and morphological alteration index (see Figure 7 for the distribution into the river network of morphological quality class evaluated).

ID	60102	60103	60119	60120	60124	60133	60134	60135	60136	60137	50138	50139	50140	50141
Collector	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Cord
Order	6	6	6	6	6	6	6	6	6	6	5	5	5	5
Conf. class	S-NC	S-NC	S-NC	S-NC	S-NC	S-NC	C	S-NC	S-NC	C	S-NC	S-NC	C	C
MQI_F	0.74	0.86	0.19	0.44	0.81	0.74	0.76	0.47	0.51	0.78	0.58	0.35	0.70	0.86
MQI_A	0.71	0.80	0.36	0.58	0.85	0.68	0.19	0.71	0.80	0.72	0.59	0.56	0.79	0.79
MAI	0.26	0.17	0.63	0.43	0.17	0.30	0.52	0.38	0.32	0.27	0.38	0.47	0.27	0.17
MQI	0.74*	0.83*	0.37°	0.57#	0.83*	0.70*	0.48°	0.62#	0.68#	0.73*	0.62#	0.53#	0.73*	0.83*
ID	**50142**	**50143**	**40144**	**40145**	**40146**	**40147**	**40148**	**50201**	**50202**	**50203**	**50204**	**50501**	**50502**	**50503**
Collector	Cord	Cord	Cord	Cord	Cord	Cord	Cord	Mis	Mis	Mis	Mis	Fior	Fior	Fior
Order	5	5	4	4	4	4	4	5	5	5	5	5	5	5
Conf. class	C	C	S-NC	C	C	C	C	S-NC	S-NC	S-NC	S-NC	S-NC	C	C
MQI_F	1.00	0.84	0.81	0.92	0.78	0.78	0.86	0.84	0.35	0.77	0.93	0.49	0.65	0.65
MQI_A	1.00	0.89	0.86	0.96	0.79	0.75	0.93	0.73	0.59	0.56	0.77	0.51	0.60	0.58
MAI	0.00	0.12	0.16	0.05	0.25	0.25	0.11	0.22	0.46	0.33	0.17	0.49	0.41	0.44
MQI	1.00§	0.88§	0.84*	0.96§	0.76*	0.75*	0.89§	0.78*	0.54#	0.67#	0.83*	0.51#	0.59#	0.56#
ID	**50504**	**40501**	**40502**	**40503**	**40504**	**40505**	**40601**	**40602**	**40603**	**40604**	**40605**	**40606**	**40607**	**40608**
Collector	Fior	Fior	Fior	Fior	Fior	Fior	Pett	Pett	Pett	Pett	Pett	Pett	Pett	Pett
Order	5	4	4	4	4	4	4	4	4	4	4	4	4	4
Conf. class	C	C	C	C	C	S-NC	C	C	C	C	S-NC	C	C	C
MQI_F	0.72	0.68	0.84	0.76	0.84	0.93	0.35	0.46	1.00	0.46	0.42	0.41	0.70	0.73
MQI_A	0.62	0.61	0.75	0.67	0.96	0.91	-0.02	0.49	0.75	0.46	0.63	0.44	0.65	0.51
MAI	0.39	0.33	0.20	0.33	0.12	0.11	0.89	0.54	0.19	0.56	0.49	0.59	0.31	0.38
MQI	0.61#	0.67#	0.80*	0.67#	0.88§	0.89§	0.11^	0.46°	0.81*	0.44°	0.51#	0.41°	0.69#	0.62#

Cord, Cordevole; Conf. class, class of confinement; S-NC, semi-confined/unconfined; C, confined; MQIF, morphological quality index of functionality; MQIA, morphological quality index of alteration; MAI, morphological alteration index; MQI, morphological quality index; Fior, Fiorentina; Pett, Pettorina. Quality class in MQI: *good; °poor; #moderate; §very good; ^very poor.

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(Table 1). The average drainage area is 28 km^2 in the 4th order reaches, 82 km^2 in the 5th order reaches, and 522 km^2 in the 6th order reaches. The Degree of Confinement, calculated with semi-automatic GIS methods, has a median value of 0.2-0.3 with a maximum of 0.9 (90% of channel in contact with the slopes) in the smaller streams (Figure 5A). Figure 6 shows the relationship between the Degree of Confinement and the drainage area (R^2=0.0034). It shows that there is no correlation with the dimensions of the collectors. The Confinement Index (alluvial plain *vs* bankfull width ratio) is, instead, directly proportional to the stream order, with median values of 1.5 in the 4th order reaches, 1.8 in the 5th order reaches, and 2.4 in the 6th order reaches (Figure 5B), although higher values are to be found among 5th order reaches. The relationship between the Confinement Index and the drainage area for each reach was found to be better than the previous one (Figure 6), even though values were relatively low (R^2=0.1266).

Morphological quality index evaluation

Filling in the MQI evaluation forms took approximately 3 h for each reach analysed, for a total of 15 days of work. Ten reaches of 6th order (27% of reaches of this order identified in the segmentation phase), 14 of 5th order (42%), and 18 of 4th order (27%) were analysed. The results derived from the application of various indexes have been organised in the summary sheets (one for each reach) that contain tables with the general settings (location, confinement and morphology), scores attributed to each indicator, and the calculation of the MQI with the corresponding class quality. These data are summarised in Table 4 with the name of the river, reach order, the class of confinement, MAI, MQI, MQI_F and MQI_A. The MQIs obtained were also used in the GIS database from which a layout summary was obtained (Figure 7) where the quality classes are shown in different colours for each reach analysed.

These results show that 48% of the reaches analysed are of a good or high quality and these are mainly located in the High Cordevole or in the less hydrographical network (Figure 8A-D). Thirty-eight percent were of moderate quality, and, in particular, this concerned different reaches of the Fiorentina, Cordevole from Caprile to Alleghe and Pettorina (Figure 8E and F). Only 14% are of poor or very poor quality, *e.g.* the Pettorina reach immediately upstream of the confluence with the Cordevole (Figure 8G and H).

Careful examination of the sub-indexes (Table 4) shows that the reach with the worst quality (ID 40601) has a negative MQI_A and this is due to the continuous presence of bank protections and check-dams in the reach that causes the assignation of additional scores in some indicators. The reach no. 60134 (Cordevole 6th order) is heavily penalised for the same reason. Many other segments are affected by the presence of other artificial structures, *e.g.* the segment no. 50203 (MQI_A=0.56), where the Mis dam is located and no. 40608 (MQI_A=0.51), characterised by interventions for hydroelectric power production. In contrast, 19 of 42 reaches have a quality functionality index lower than the quality alteration index, *e.g.* segment no. 60119 (MQI_F=0.19) and no. 50202 (MQI_F=0.35) which have a limited floodplain, poor variability of the section, and little presence or complete absence of functional vegetation in the fluvial corridor.

If we observe the MQI values obtained in the different collectors analysed (Figure 9A), we can see that the lowest median value is found

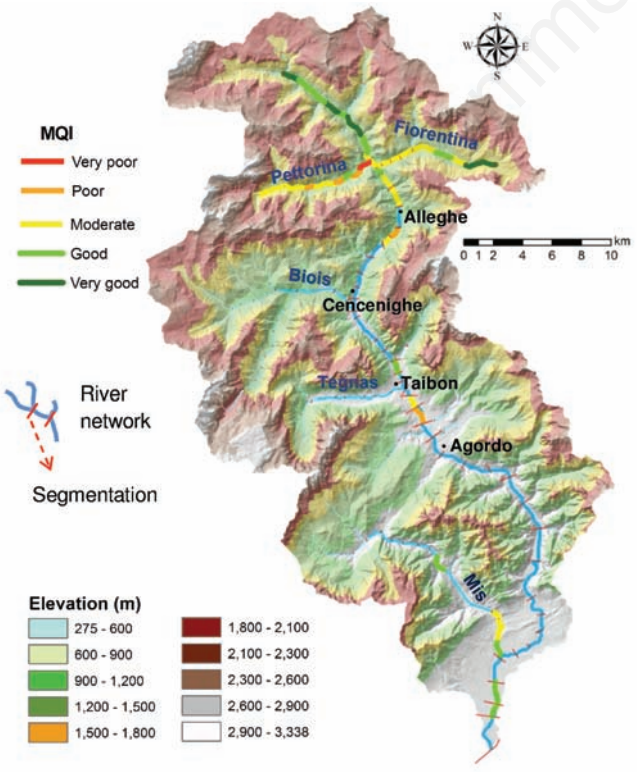

Figure 7. Elevation of Cordevole basin, hydrograph segmentation and morphological quality index evaluation results.

Figure 8. Some of the reaches evaluated and morphological quality index results.

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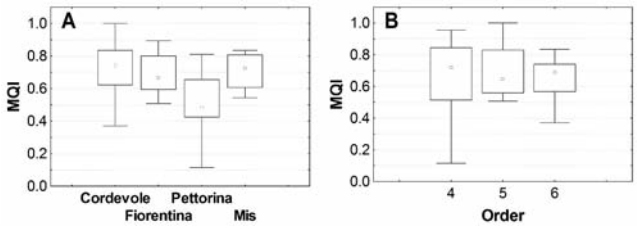

Figure 9. Morphological quality index evaluation results of the different streams (A) and in relation to order (B) for the 42 reaches analysed. The square within each box indicates the median value, box ends are 25th and 75th percentiles, whiskers are the non-outlier extreme.

for the Pettorina stream (0.49), followed by the Fiorentina (0.67), the Mis (0.72) and then by the Cordevole (0.75), although in this last stream we have a very wide distribution of data (21 reaches analysed with MQI between 0.37 and 1). The distribution of morphological quality in relation to the stream order (Figure 9B) shows that the median value of 4th order reaches is higher (0.71), although in this category there are segments with the worst morphological characteristics. The 5th order reaches have a median MQI of 0.64 while the 6th order reaches have a median MQI of 0.69.

Discussion

This paper shows the successful use in a Dolomite basin (Torrente Cordevole, Province of Belluno), of the new MQI protocol evaluation (Rinaldi *et al*., 2013). The use of some semi-automatic GIS tools has allowed us to greatly speed up the first phase of the general setting and segmentation. It was also possible to determine some indicators of alteration in the laboratory. We are currently planning to implement this methodology in an ArcGIS tool (through the model builder) also applicable to non-expert users in other areas. However, active channel and alluvial plain should always be edited manually. Some limitations or problems arising during this first phase were: i) the need for high standards of GIS analysis and editing; ii) the limitations of spatial analysis linked both to the quality of the DTM and images, and to the strong disturbance (shadows, vegetation, narrow valleys). In the case study analysed, the hydrographical network lower than the 4th order are difficult to analyse; iii) the need for a complete and up-dated Artificial Intervention Database. Not all the artificial interventions are catalogued in this database. Also big infrastructure, such as the Mis dam (Figure 2C), are not included.

The second phase of indicator implementation has highlighted the non-availability of some information required for the evaluation, such as the management of artificial structures and river clearcut operations, as well as information regarding the morphometric changes of the last 50 years in the great reaches. Some indicators are extremely simplified, as shown by the MQI Authors (Rinaldi *et al.,* 2013), and there is a strong subjectivity in the scoring of the indexes in relation to the experience and training of the operators. In order to accomodate this, the survey was carried out by a team of 3 researchers.

The sub-reaches that have the greatest degree of morphological alteration present: i) poor connectivity between hill-slopes and river corridor (mainly caused by the presence of roads) that is very important for the natural input of sediment and large wood from the slopes; ii) absence of vegetation in the river corridor due to human alteration, that is functional to a range of geomorphic processes; iii) presence of artificial elements, such as bed-load interception structures in the catchment, bank protection along the reach, and the removal of sediment, large wood and vegetation, already highlighted in Rigon *et al*. (2012a). The MQI has allowed us to assess the morphological condition for 42 reaches of the Cordevole Basin. In order to identify possible strategies of mitigation, we need to apply the MQI procedure to the entire water network, as required by the Protocol. However, partial restoration of the reaches with lower MQI values could be achieved by converting the old interception structures in new constructions designed by the criteria of river restoration engineering. In addition, it would be desirable to carry out an analysis of priorities, and implement intervention only where really necessary, possibly with low-impact structures such as wood retention structures with rope nets or rakes.

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