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Channel degradation and restoration of an Alpine river and related morphological changes

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A B S T R A C T

River degradation and thus necessity for restoration are major issues worldwide. However, adequate methodologies to assess morphological variations linked to these actions and the morphological success of restoration interventions are still to be determined. The Ahr River (South Tyrol, Italian Alps) was characterized until the mid-twentieth century by an anabranching and meandering pattern, but starting from the 1960s it underwent intense channel degradation in terms of narrowing, incision, and floodplain disconnection. In the period 2003–2011, several reaches of the Ahr River were restored by widening and raising the channel bed. The planimetric changes that occurred historically in the Ahr River were determined by the interpretation of 10 maps and aerial photos covering the period 1820–2011. The estimation of the incision that occurred during the degradation phase was assessed by the difference in elevation between gravel surfaces, whereas the changes introduced by restoration interventions in two reaches were evaluated through the comparison of topographic cross sections surveyed in year 2000 and a high-resolution bathymetric LiDAR survey flown in late 2012. The MQI (Morphological Quality Index) was applied to different reaches in order to test how assessment methodologies respond to degradation and restoration actions. The combined analysis of planform and vertical changes indicates that gravel mining has been the largest pressure for the river, but a change in sediment/flow regimes probably led to the channel adjustments that occurred during the early twentieth century. The restoration measures have locally increased channel width, elevation, and morphometrical diversity compared to the unrestored reaches, as well as the morphological quality assessed by MQI. However, the extent of the modifications brought about by restoration works differs between the two restored reaches, pointing out the need for a quantitative analysis of the historical evolution of each river reach before designing and implementing restoration actions and to the necessity to monitor the subsequent morphological adjustments.

1. Introduction

In order to enhance the environmental conditions of fluvial systems, river restoration projects have begun to spread worldwide (Marston et al., 1995). In Europe, river restoration has become an important topic for water authorities and river managers to match the objectives set by the Water Framework Directive (European Community, 2000), which aims at preserving and improving the ecological quality — determined from physicochemical water quality, stream hydromorphology, and biological elements — of aquatic ecosystems. River remediation from organic pollution, acidification, and eutrophication is generally understood and effective measures are available (Hynes, 1960); whereas the same cannot be said for restoration of hydromorphological river characters, which represents now the most dominant alteration in European river systems (Petts et al., 1989; Moss, 1998), particularly in the Alps (Comiti, 2012). Hydromorphological degradation implies multiple factors such as river straightening, flow regulation, sediment load alteration, and river disconnection from the floodplain, which create varying effects in different river types (Montgomery and Bolton, 2003). Over the last two centuries, the great majority of rivers in the European Alps have undergone significant hydromorphological modifications from flood mitigation, land reclamation, hydropower production, and gravel mining (Liébault and Piégay, 2002; Jähnig et al., 2008; Surian et al., 2009; Comiti et al., 2011; Comiti, 2012).

However, only a few large-scale restoration works have been carried out so far in the Alps. Among the most relevant examples are as follows: the creation of secondary channels and floodplain compartments reflooding along the Rhine River (Simons et al., 2001; Lachat et al., 2012; Schmitt et al., 2012), the reconnection of the main channel with the side-arm system in the Danube River (Tockner et al., 1998), the widening (and also side-arm reconnection) of the Drau River in Austria and

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of the Mur and Thur rivers in Switzerland (Rohde, 2004), and the reconnection of cutoff channels and dredging of isolated pools within the channels of the Rhone River (Castella et al., 2012). Most of the river restoration projects in the Alps have focused on channel widening and on reconnection and reconstruction of former secondary channels. More limited are the cases where bank erosion and bedload supply processes were favored or enhanced (Habersack and Piègay, 2008).

A proper monitoring of river restoration outcomes is generally lacking worldwide (Palmer et al., 2007). In particular, the monitoring of the hydromorphological consequences of river restoration actions over time and their analysis in the context of each river's evolutionary trajectory (Surian et al., 2009) ararerely accomplished. Indeed, consensus is growing also among biologists that biological elements used to assess river quality (i.e., typically macroinvertebrates and fish) do not adequately respond to hydromorphological modifications, thus making the monitoring of hydromorphological variations — relative to prior natural and human-induced variability — associated to restoration even more relevant. A vast number of methods are in use in different countries to assess the ecomorphological status of streams. Methods similar to the River Habitat Surveys (RHS; Raven et al., 1997) are appropriate to characterize the presence and diversity of physical characteristics at the habitat scale but do not permit an assessment based on hydrological and geomorphological processes of streams. The Danish National Physical Habitat Index (Pedersen et al., 2006) in Denmark, the French SEQ (Agences de l'Eau, 1998), and the Italian CARAVAGGIO method (Buffagni et al., 2005) fall into this category.

Recently, there has been a growing development of new methods that contain a greater consideration of geomorphological processes at multiple spatiotemporal scales, whereby current morphological patterns are analyzed in the context of the historical river dynamics and within the whole river basin. Some new methodologies developed in Spain (Ollero Ojeda et al., 2007), in France (method SYRAH, Chandesris et al., 2008), and in Italy (MQI, Morphological Quality Index, Rinaldi et al., 2013) follow such rationale. The MQI is the official method to assess the hydromorphological quality of Italian streams for the Water Framework Directive (WFD) and is part of a broader methodology called IDRAIM that pursues an integrated analysis of morphological quality and hazards (Rinaldi et al., 2013). The MQI is applied at the reach-scale by an integration of remote sensing/GIS analysis and field survey. It includes a set of 28 indicators assessing longitudinal and lateral continuity, channel pattern, cross section configuration, bed structure and substrate, and vegetation in the riparian corridor. These characteristics are evaluated in terms of three components, i.e., geomorphological functionality, artificiality, and channel adjustments. The evaluation is based on a scoring system, considering that reference conditions are identified with a river reach in dynamic equilibrium, performing those morphological functions that are expected for a specific morphological typology, and where artificial elements and pressures are absent or do not significantly affect the river forms and processes. Although MQI was developed to assess the loss of morphological quality (i.e., degradation) over relatively long time scales, it could be potentially applied — with some modifications as explained later — to river restoration interventions as well.

The general aim of this work is to analyze the morphological changes determined by the recent restoration interventions carried out in the Ahr/Aurino River (Italian Alps), and frame them within the context of their evolutionary trajectory over the last two centuries. Specifically, we want to (i) quantify the historical channel variations (planform, width, elevation) that occurred over this period in the study river, linking them to natural and human-related pressures, and (ii) assess the extent to which restoration actions have modified river morphology, by performing a morphometrical analysis of the river bed and by applying the Morphological Quality Index. The more significant outcomes from these two objectives will be generalized in the discussion section, and their implications relevant for river restoration actions will be remarked in the conclusions.

2. Study area

The study area is the Ahr — following the local German name, whereas it is Aurino in Italian — River basin (drainage area 629 km^2), located in south Tyrol, Italian Alps. The Ahr River, with its 53 km of length and 15.2 m^{3}s^{-1} of annual mean water discharge (30–50 m^{3}s^{-1} during the summer), is the most important tributary of the Rienz/Rienza River (Fig. 1). The basin is mostly composed of metamorphic (gneiss, micaschists) and magmatic (tonalite) rocks. The lower valley features a typical U-shaped section caused by Pleistocene glacial erosion, and the present-day glaciers (about 25 km^2, <50% of their extent at the end of the Little Ice Age) are still responsible for the nivo-glacial regime of the Ahr River. Since the late 1950s, many large and small hydraulic structures have been built along the tributaries of the river, including two hydropower dams — trapping a total basin area of about 100 km^2 (Fig. 1) — 742 check-dams (retention and consolidation) and 87 bed sills.

The river segment analyzed here lies in the lower, wider Ahr valley (Fig. 2), where the channel features mostly partly confined conditions punctuated by debris flow fans determining shorter confined reaches. Gravel mining occurred in this river stretch from the 1950s to the 1980s. Bed incision became evident during the second half of the twentieth century, leading to a morphological and hydrological discontinuity between the channel and its floodplain, the latter being now a terrace flooded only by events with recurrence intervals >30–50 years, depending on the location. Bed incision has also caused a lowering of the water table, likely limiting growth and dynamics of riparian forest dominated by gray alder (*Alnus incana*) but surely favoring conditions for agriculture and bed armoring.

In 2003 the Department of Hydraulic Engineering of the Autonomous Province of Bolzano started a river restoration program with the purpose of ameliorating the ecological functionality of the river. In particular, the reestablishment of more suitable soil moisture conditions for the remaining riparian forest patches and the increase of morphologic diversity in the channel were the main goals, but these were not to determine a substantial increase in flood hazard and excessive soil moisture within the cultivated part of the valley. The restoration actions were planned within the river segment between the confluence with the Mühlwalder/Selva dei Molini Creek near the town of Sand in Taufers/Campo Tures and the confluence with the Rienz River (14.9 km in length; Fig. 1). The river restoration program consists mainly in the removal of river bank protections, channel widening, raising of the riverbed by introducing the sediments taken from the banks, and creation of islands. The planimetric design of these interventions was based on the recognition that gravel bars, secondary channels, and islands were present in this segment in the nineteenth century, for a much wider active river corridor, but it had to cope with the very limited areas nowadays at the disposal of the Province and with the constraints posed by agriculture and transport routes. Indeed, the restoration works actually realized are a compromise resulting from intense discussions between the Dept. of Hydraulic Engineering of the Autonomous Province of Bolzano and the local stakeholders.

The two analyzed restored reaches (both partly confined) (Fig. 2) lie at an altitude between 830 and 850 m asl and are located near the villages of Mühlen in Taufers/Molini di Tures (about 800 m in length, average slope 0.2%, carried out in late 2003) and of Gais (about 1000 m in length, average slope 0.1%, carried out between 2005 and 2011) (Fig. 2). An unrestored reach (about 4500 m in length, average slope 0.3%) lies between the two restored ones (Fig. 2). The downstream part of this unrestored reach (labeled hereafter as unrestored confined) is confined by alluvial fans, whereas the upper part (between the villages of Unterheim/Villa Ottone and Mühlen in Taufers, about 2 km in length) is partly confined (hereafter unrestored partly confined) and thus only this length has been analyzed in terms of evolutionary trajectory and used as a control against the restored reaches for channel variations.