Unraveling the Response of a Mountain basin to a Large Disturbance

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ABSTRACT

This work studies the effects of a severe and rare natural disturbance named Vaia (27-30 October 2018) on a mountain basin. It unravels the hydrological, geomorphological and sedimentological responses of the Rio Cordon Basin (Dolomites, Italy) by integrating the findings obtained from three past studies with different spatial scales and focuses of analyses. It combines information about three main topics: (i) identification of geomorphic changes along the channel network, (ii) evolution of the step-pool morphology and (iii) changes in sediment flux and yields. The geomorphic changes registered intense streambed remobilization, boulder mobility, incision and lateral erosion. The step-pool morphology featured a complete disruption, but a fast recovery to the stable condition in just two years. The suspended sediment dynamics, instead, surprisingly showed fluxes and yields (42 t km^{-2} $years^{-1}$) that were in line with those registered before the Vaia event (40 t km^{-2} $years^{-1}$). Thus, the integration of such findings, obtained through pre- and post-event remote and field-based data, proved to be a valuable approach to comprehend the hydrological and sedimentological responses of a mountain basin affected by an extreme event. Therefore, based on the current morphological and sedimentological condition, it can be concluded that the Rio Cordon is now heading back to the pristine state but with a new dynamic equilibrium since (i) the morphology of the system changed during the Vaia event and (ii) the sediment fluxes and stability of the step-pool configuration resulted in line with the prior event conditions.

KEY WORDS: Vaia storm, Geomorphic changes, Sediment transport, Step-pool evolution, Cascading processes

INTRODUCTION

The dynamic nature of mountain rivers and their responsiveness to perturbations are influenced by geological, climatic, hydrological, and hydraulic factors (Lenzi, 2001; Rainato et al., 2017). Factors such as sediment sources, channel bed composition, and hydraulic forces (Mao et al., 2008; Cavalli et al., 2013) govern sediment transport processes in mountain streams. Suspended sediment transport prevails as the dominant mechanism in mountain streams (Lane and Borland, 1951), while bedload processes entail the movement of coarser sediment particles along the riverbed (Einstein et al., 1940). Colluvial transport, encompassing mass movements like debris flows, also contributes to sediment transport within mountain basins (Martinsen, 1994). The concept of a "graded" stream denotes a state of dynamic *equilibrium* where the stream's transport capacity aligns with the sediment supply (Mackin, 1948). However, disturbances, both natural and anthropogenic, can disrupt this equilibrium and induce alterations in the morphology of mountain streams. Climate change is anticipated to amplify the frequency and magnitude of disturbances, thereby further complicating the comprehension of sediment dynamics (Hirschberg et al., 2020). Major disturbances such as hurricanes, floods, windstorms and earthquakes, referred to as Large Infrequent Disturbances (LIDs) (Turner and Dale, 1998), significantly reshape the landscape; nevertheless, their impacts remain inadequately investigated. The imperative for comprehensive analysis and monitoring of LIDs to comprehend their influence on sediment dynamics and mitigate associated risks is thus needed. In this case, the Vaia storm (Davolio et al., 2020) serves as an example of extreme event that perturbed the dynamic *equilibrium* of mountain basins, resulting in secondary processes (Brenna et al., 2020; Rainato et al., 2021; Macchi et al., 2022). Therefore, this work has the aim of unravelling the primary impacts and the ongoing cascading morphological and sedimentological processes of a mountain basin affected by Vaia. To do so, the study integrates the findings obtained from three different studies (Pellegrini et al., 2021; Rainato et al., 2021; Pellegrini et al., 2023), with different spatial scales and focuses of analyses.

MATERIAL AND METHODS

The following sections, besides characterizing the study area, aim at summarizing the three different methodological approaches applied in the three studies from which the results concerning the impacts of the Vaia storm were taken (Pellegrini et al., 2021; Rainato et al., 2021; Pellegrini et al., 2023). Specific attention is devoted to the geomorphic changes, to the evolution of the step-pool morphology and to the changes in suspended sediment dynamics.

Study area

The Rio Cordon catchment (Fig. 1) is a 5 km^2 area located in the eastern Alps of Italy, specifically in the Agordino valley. With consistent annual precipitation of about 1180 mm, it has a typical alpine climate (Rainato et al., 2018). The basin experiences a nivo-pluvial climate, with late fall, winter, and early spring seeing the majority of snowfalls and the rest of the year seeing brief but powerful rainfalls. Dolomites, limestones, volcanic conglomerates, and calcareous-marly rocks make up the Rio Cordon's substratum. Only 7% of the basin is covered by vegetation, mostly made up of spruce and larch trees. The remaining 93% is made up of bare rocks, bushes, and grasslands. The Rio Cordon main channel displays Cascade, Step-pool and riffle-pool morphologies (Comiti et al., 2007; D'Agostino and Lenzi, 1999), with a notable waterfall acting as a natural area of disconnection in the middle section of the basin. In the Lower Rio Cordon, the bankfull discharge is approximately 2.3 $m^3\ s^{-1}$ with a mean channel width of 5.3 m, and the average slope around 17% (Lenzi et al., 2006).

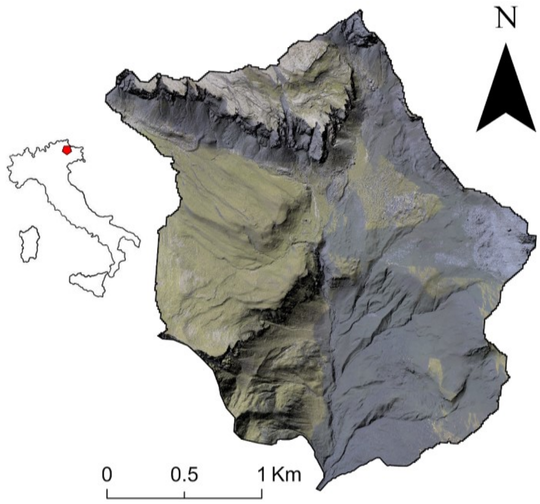

Fig. 1 – The Rio Cordon basin, located in the eastern Italian Alps.

Geomorphic changes

By comparing pre (2006) and post-event (2019) Digital Elevation Models (DEMs), the Geomorphic Change Detection (GCD) tool was used to determine volumetric changes (Wheaton et al., 2013). By taking into account uncertainty in the DEMs and error propagation in the resulting Difference of DEMs (DoD), this tool aids in separating true changes from noise (Neverman et al., 2016; Cavalli et al., 2017). To take into consideration various point densities, a set of FIS rules were employed (Rainato et al., 2021). The GCD output provided a quantification of sediment volumes displaced during the flood and identified areas of deposition and erosion (Wheaton et al., 2013). The DoD was performed over a polygon of 4200 m^2.

Step-pool morphological evolution

In order to analyse the step-pool structure in the Rio Cordon, the longitudinal profile of a 320 m-long study reach was surveyed. A laser rangefinder and target prism were used to survey the longitudinal profile before, after, and under the current circumstances in order to gauge the relative height and distance of significant discontinuities in the bed topography. Analyses focused on identifying step pool units (Church and Zimmermann, 2007; Lenzi, 2001; Turowski et al., 2009). Only step pool units with heights above the D_{84} (358 mm) limit of the particle size distribution were considered. A step-pool sequence has been identified as a cluster of three or more consecutive step-pool units separated by a distance of at least twice the average bank width (Lenzi, 2001). Slopes and dimensionless slopes were calculated using specific equations (Abrahams and Atkinson, 1995).

Suspended sediment transport after Vaia

Discharge and sediment monitoring were conducted at the outlet of the Rio Cordon. Turbidity was monitored using a multiparameter water quality sonde (HL4), and water levels were measured using pressure transducer sensors. Rainfall data was collected using a rain gauge sensor. Rating curves were established between water level and discharge based on salt dilution measurements, resulting in a discharge range of 0.07-1.54 m^3/s. Empirical relationships between turbidity (NTU) and suspended sediment concentration (SSC - g l^{-1}) were derived using water samples collected during rainfall events (Mao and Carrillo, 2017). The monitoring period lasted for 16 months, from August 2020 to November 2021.

RESULTS

Geomorphic changes

Regarding the geomorphic changes, the results showed moderate responses of the hillslopes where (re)activation of sediment sources was limited. Only a few of them served as a sediment source for the main channel. Instead, the channel network responded positively (net erosion of 6979 $m^3 \pm 2059$ m^3), and the Rio Cordon was greatly altered by widening laterally, deepening the riverbed, removing armoured layer

Fig. 2 – Bank erosion and channel widening featured by the Rio Cordon during the Vaia storm.

and eroding the banks (Fig. 2). Hydraulic (Q_P = 16.36 ± 1.14 m^3 s^{-1}, Rainato et al., 2021) and geomorphological forcing caused by the October 2018 floods caused massive bed remobilization and boulder mobility, resulting in massive sediment transport.

Step-pool morphological evolution

The widening (+81% width, +68% area), the creation of a new avulsion and a significant change in number of units (51 pre-event, 22 post-event, 51 current condition) was detected along the downstream active channel of the Rio Cordon after the Vaia storm. Moreover, the current parameters of the step-pool sequence return to pre-event values, attesting the ongoing process of morphological stabilization.

Suspended sediment transport after Vaia

Seasonal and monthly analyses were found to be consistent with results observed before Vaia. As it occurred for the 1994 flood event, the Vaia storm affected the current transport efficiency during near-bankfull events (Fig. 3), but did not affect the ongoing annual sediment production (42 t km^{-2} yr^{-1}) as observed after the last major flood event in September 1994 when the yields increased up to more than three times (149.4 t km^{-2} yr^{-1}) (Rainato et al., 2017). Unexpectedly, the average SSL rate (42 t km^{-2} $years^{-1}$) is comparable to the value (40 t km^{-2} $years^{-1}$) measured in the decade before the Vaia storm (2004-2014).

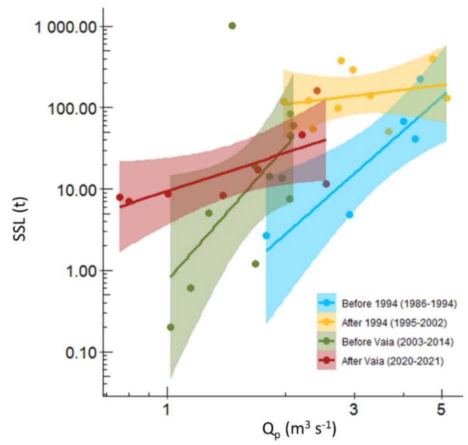

Fig. 3 – Scatter plot and regressions of the SSL and the Qp of the event monitored before (blue, 1986-1994) and after (orange, 1994-2002) 1994 flood, before (green, 2002-2014) and after (red, 2020-2021) the Vaia storm. The data between 1986 and 2014 were retrieved from Rainato et al. (2017).

DISCUSSIONS

The main aim of this work was to unravel the primary impacts and the ongoing cascading morphological and sedimentological processes of a mountain basin affected by Vaia by integrating the findings obtained from three different studies (Pellegrini et al., 2021; Rainato et al., 2021; Pellegrini et al., 2023), with different spatial scales and focuses of analyses. The research focused on catchment-scale and reach-scale analysis using remote sensing and field data. The catchment-scale study (geomorphic changes) examined the effects of the storm on hillslopes and channel network. High-resolution remote sensing data were used to analyze the geomorphic changes. A predominant alluvial response featuring streambed remobilization, boulder mobility, incision, and lateral erosion was detected (Rainato et al., 2021). In the reach-scale analyses, the recovery of the step-pool morphology after the disturbance was investigated (Pellegrini et al., 2021), showing faster recovery compared to a previous large disturbance (September 1994) (Lenzi, 2001). Moreover, hydrological and sedimentological conditions in the Rio Cordon were examined two to three years after the storm, revealing increased transport efficiency for smaller events but similar sediment yield and loads compared to pre-event conditions (Pellegrini et al., 2023). The findings suggested that the Rio Cordon may be in a different resilience stage compared to a previous disturbance occurred in 1994 (Pellegrini et al., 2023). Overall, the research highlighted the impact of large infrequent disturbances on a mountain fluvial system but also the potential for a new dynamic *equilibrium* to emerge as the channel morphology rapidly stabilized and the sediment fluxes registered consistency with the pre-Vaia conditions.

CONCLUSIONS

The results of this study highlight that low-frequency large-scale disturbances disrupt the dynamic balance of river systems in mountainous areas and induce unpredictable secondary processes. This is exemplified by the different secondary responses of the Rio Cordon Basin to different large disturbances. Although the Rio Cordon is now returning to its original state, a new dynamic *equilibrium* is being set up by changes in morphology and sediment fluxes and yields consistent with pre-Vaia conditions.

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