Assessing fluvial and riparian vegetation dynamics as indicators of sustainable river management: A bio-geomorphological analysis of the Rio Mareta restoration project (2010-Present)

Évaluation des dynamiques fluviales et de la végétation riparienne en tant qu'indicateurs d'une gestion durable des rivières : Une analyse bio-géomorphologique du projet de restauration du Rio Mareta (2010-Présent)

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RÉSUMÉ

Cet article examine les impacts bio-géomorphologiques et l'efficacité du projet de restauration de la rivière Mareit dans les Alpes italiennes, lancé en 2008 pour remédier aux graves impacts anthropiques tels que l'extraction de gravier et l'incision du lit fluvial. Le projet visait à renforcer la résilience écologique grâce à l'élargissement du lit, à la réintroduction d'un schéma en tresses et à l'enrichissement des habitats pour les espèces ripariennes. La photogrammétrie, la méthode Structure-from-Motion (SfM) et des indices géomorphologiques tels que le MQI et le GUSI ont été utilisés pour évaluer les changements dans la morphologie de la rivière et la diversité des unités géomorphologiques. De plus, le Modèle Numérique de Différence d'Élévation (DoD) et les données historiques de débit (1955 à aujourd'hui) ont permis d'analyser les évolutions hydromorphologiques. Les résultats ont montré des améliorations de la qualité morphologique et de la diversité géomorphologique, notamment dans les sections restaurées par rapport aux sections non restaurées, mettant en évidence les bénéfices pour la rivière. Malgré ces succès, des recherches supplémentaires sont nécessaires pour évaluer l'efficacité du projet dans l'atténuation des vagues de crues. Cette étude apporte des éclairages précieux sur la gestion durable des rivières dans les écosystèmes alpins, en mettant l'accent sur des stratégies adaptatives et des méthodes innovantes d'évaluation de la restauration dans le contexte des changements climatiques et des pressions humaines.

ABSTRACT

This paper examines the bio-geomorphological impacts and effectiveness of the Mareit river restoration project in the Italian Alps, launched in 2008 to address severe anthropogenic impacts like gravel mining and channel incision. The project aimed to improve ecological resilience through channel widening, reintroducing a braided pattern, and enriching habitats for riparian species. Photogrammetry, Structure-from-Motion (SfM), and geomorphological indices such as MQI and GUSI were employed to evaluate changes in the river's morphology and geomorphic unit diversity. Additionally, Digital Elevation Model of Difference (DoD) and historical discharge data (1955-present) enabled the analysis of hydromorphological changes. Results showed improvements in morphological quality and geomorphic diversity, particularly in restored reaches compared to unrestored ones, highlighting benefits to river. Despite these successes, further research is needed to determine the project's effectiveness in mitigating flood waves. The study contributes valuable insights into sustainable river management in alpine ecosystems, emphasizing adaptive strategies, and innovative restoration evaluation methods in the context of climate change and human pressures.

KEYWORDS

Alpine rivers, Geomorphic Unit, River restoration, River Morphology, Morphological Quality Index.
Rivières alpines, Unité Géomorphologique, Restauration des rivières, Morphologie de la rivière, Indice de Qualité Morphologique.

1. INTRODUCTION

River systems are facing significant anthropogenic pressures, particularly in the European Alpine region, where centuries of human activities like gravel extraction, dam construction, and channelization have drastically altered river dynamics (Campana et al., 2014). These interventions have led to biodiversity loss, groundwater lowering, and geomorphological imbalances (Comiti et al., 2011). The implementation of the Water Framework Directive in 2000 marked a shift in European river management, emphasizing ecological restoration and integrated approaches to water management (Hoornbeek, 2004). River restoration has since gained prominence, addressing physical, ecological, and socio-economic challenges by reintroducing natural features like braided channels and removing barriers (Brierley & Fryirs, 2005). Effective monitoring of such efforts relies on geomorphological indices like the Morphological Quality Index and Geomorphic Unit Survey Indices (Belletti et al., 2015; Rinaldi et al., 2016). The Rio Mareta, profoundly affected by gravel extraction and narrowing during the 70s, serves as a case study for alpine river restoration. Restoration efforts began in 2008 to enhance habitat complexity and ecological connectivity through channel widening and removal of artificial structures (Scorpio et al., 2020). This research evaluates the effectiveness of these measures, focusing on bio-geomorphological changes post-restoration and exploring indicators for sustainable monitoring of river health.

2. MATERIAL AND METHODS

2.1 Study Area

The Mareit River is a tributary of the Eisack River in South Tyrol, Italy, flowing through a U-shaped valley indicative of past glacial activity. Its catchment spans 212 km², with elevations ranging from 3000 m to 935 m at the confluence with the Eisack River. Intense gravel mining from the mid-20th century reduced the channel width from 300 m to 40 m and incised the riverbed by up to 8 m, disrupting longitudinal and lateral connectivity and lowering the groundwater table (Scorpio et al., 2020). The study area encompasses three reaches located between Mareta and Casateia, forming a representative segment for evaluating restoration effectiveness. The interventions initiated in 2008 targeted reaches 2 and 3, focused on channel widening, reintroducing a braided pattern, and enhancing longitudinal connectivity (Autonomous Province of Bolzano, 2018).

2.2 Methods

Photogrammetry and the Structure-from-Motion (SfM) methods were employed to reconstruct a 3D terrain model starting from images captured using a Unmanned Aircraft System (UAS). Ground Control Points measured with a RTK DGPS ensured accuracy and georeferencing (Westoby et al., 2012). Frames were processed using Agisoft® Metashape® software. The final model errors were below 0.05 m and 0.5 pixel. The Geomorphic Unit Survey method was applied to classify and analyse macro-unit and unit using a combination of remote sensing and field surveys (Belletti et al., 2017). The GUS Indices about richness and density quantified morphological complexity and tracked changes over time. The Morphological Quality Index was used to evaluate the physical and morphological conditions of the Mareit River in 2024 (Rinaldi et al., 2015c). Indicators were scored using field observations and historical data, with results translated into qualitative classes, ranging from poor to excellent morphological quality (Rinaldi et al., 2016). The DEM of Difference method was applied to quantify topographic changes in the reach 3 from 2016 to 2018 by using the Geomorphic change detection (GCD) software of Riverscapes (http://gcd.riverscapes.xyz/; Wheaton et al., 2010a; 2010b). Errors were minimized through the application of 0.20 m as minimum level of detection (LoD), ensuring reliable measurements of morphological changes. Hydrological trend was investigated studying historical drainage and precipitation data from 1955 to present obtained from local monitoring stations.

3. RESULTS

3.1 Geomorphic unit survey, indices and the morphological quality index

The GUS analysis revealed notable improvements after restoration in geomorphic diversity and complexity of the restored reaches (2 and 3). The distribution of geomorphic units, including sedimentary features and vegetated patches, significantly increased in both richness and density. Restored reaches showed a balanced mix of geomorphic units, with enhanced connectivity between channel and floodplain features, supporting diverse habitats. In contrast, the unrestored reach (1) exhibited limited geomorphic variability and lower indices of richness (GUSI-R) and density (GUSI-D)(Fig.1). Over time, the restored areas demonstrated a positive trajectory in geomorphic unit development, indicating the effectiveness of restoration in enhancing morphological and ecological conditions (Fig.2). The Morphological Quality Index (MQI) evaluation showed significant improvements in the restored reaches (2 and 3) of the Mareit River. The MQI class result was “Moderate” for

both the restored reaches. Key indicators, including sediment transport continuity, floodplain connectivity, and reduced artificiality, contributed to higher scores in these reaches. Restoration measures such as channel widening and removal of artificial structures enhanced geomorphological functionality. In contrast, the unrestored reach (reach 1) retained lower MQI scores due to persistent morphological alterations and limited natural dynamics. The MQI class of this reach was “Poor” through the analysed period. The results underscore the restoration's success in improving the river's morphological quality and aligning it more closely with natural reference conditions.

Figure 1. GUSI-R (left) and GUSI-D (right) over the nine years of investigation

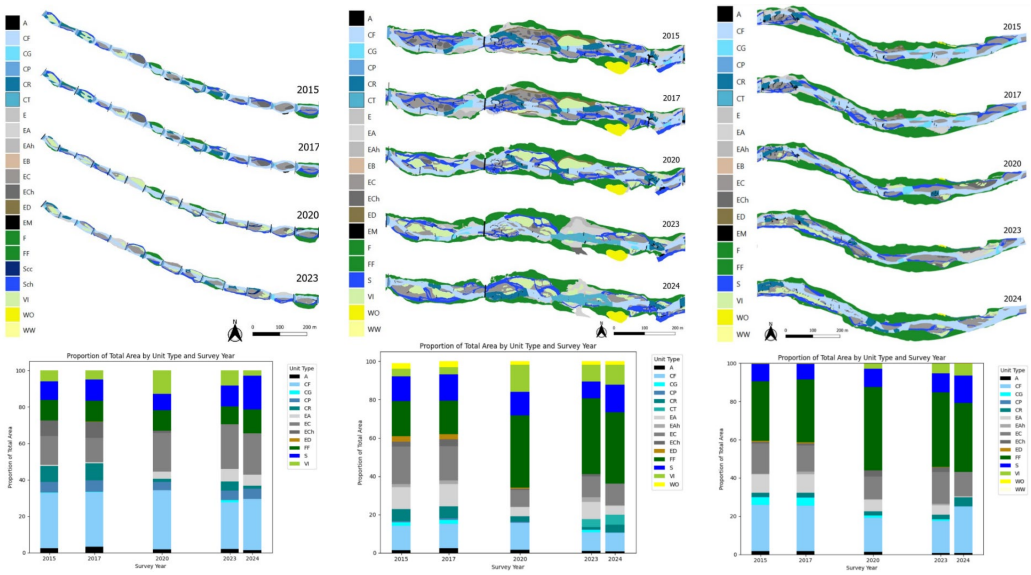

Figure 2. From left to right: reach 1, reach 2 and reach 3 GUs distribution (top) and proportion of total area by unit type and survey year (bottom)

3.3 DEM of difference and trend analysis

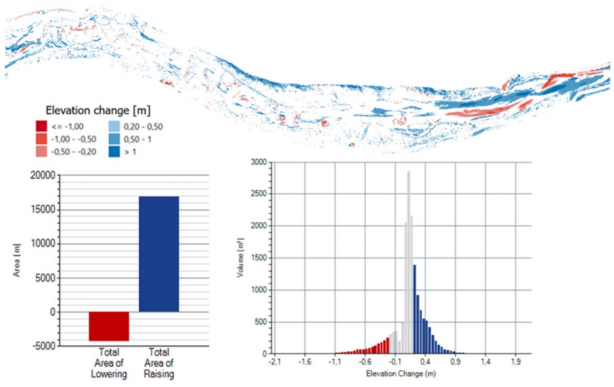

Figure 3. DoD between 2016 and 2018 of the reach 3

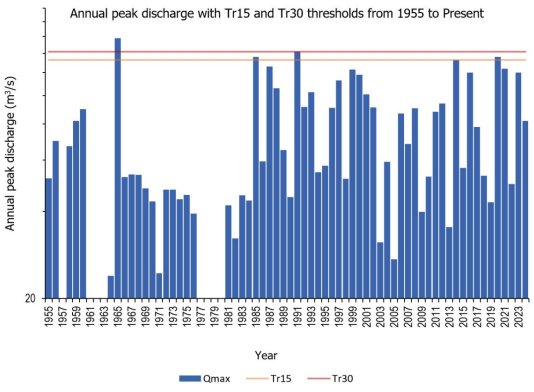

Figure 4. Annual peak discharge with Tr15 and Tr30 thresholds

The Digital Elevation Model of Difference (DoD) analysis quantified topographic changes in the reach 3 of Mareit River from 2016 to 2024. Results exhibited significant sediment deposition, with volumetric changes indicating an accumulation of approximately 5000 m3 over 1600 m3 of erosion. On river bars the average deposition was 28 cm, reaching up to a maximum value of 73 cm. The incision reached up to -133 cm and with a mean value of - 0.46 cm. The DoD results highlighted distinct patterns of sediment redistribution, with erosion prevalent in narrower sections (Fig.3). An initial investigation into the river system's mitigation capability was conducted

through a discharge trend analysis. The results shows that the thresholds for TR15 events were exceeded twice after the restoration interventions (Fig. 4). Additional analyses are required to provide deeper insights.

DISCUSSION

Restoration efforts have substantially improved the morphological and ecological conditions of the Mareit River. The reintroduction of a braided channel and the removal of artificial structures significantly enhanced geomorphic complexity, supporting greater habitat diversity (Belletti et al., 2017). The GUS and MQI analyses demonstrated measurable improvements in morphological quality and unit diversity, particularly in restored reaches. These findings align with previous studies emphasizing the importance of reconnecting channels to floodplains and restoring sediment transport processes to achieve ecological resilience (Comiti et al., 2011; Campana et al., 2014). However, the discussion notes limitations in the restoration, such as the continued presence of erosion in unrestored areas and the challenges of sustaining these improvements under changing hydrological conditions driven by climate change (Scorpio et al., 2020). Hydrological trend analysis revealed an increase in extreme events, which could threaten the stability of restored habitats. The discussion reinforces the need for adaptive management and long-term monitoring, integrating geomorphic and biological indicators to ensure sustainable outcomes (Rinaldi et al., 2016). The study also emphasizes the replicability of methods like photogrammetry and DoD analysis for monitoring restoration projects, offering valuable insights for managing highly modified alpine rivers under future environmental pressures (Belletti et al., 2017).

CONCLUSION

The restoration of Rio Mareta provides a model for sustainable river management in alpine ecosystems. Photogrammetry and morphological indices demonstrated significant improvements, but further evaluations are essential to address future hydrological challenges. These methodologies offer scalable, precise, and cost-effective methods for tracking bio-geomorphological changes, providing valuable data to inform adaptive management strategies (Belletti et al., 2017). Looking forward, a comprehensive and sustainable management approach is essential. This includes regular monitoring to evaluate long-term outcomes, consideration of biological indicators to complement geomorphic assessments, and strategies to mitigate climate-related risks. The Mareit River case study underscores the potential of restoration to enhance ecological resilience in alpine rivers while providing critical insights into methods and strategies for broader applications in similar environments.

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