Canyoning simplifies benthic macroinvertebrate communities in Mediterranean canyons: evidence from Sierra y Cañones de Guara Natural Park

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Keywords: canyoneering, outdoor sports, river management, tourism impact, trampling on rivers.

Statements

Data availability statement

Data are available from the authors upon reasonable request.

Funding

This study was funded by the Government of Aragón (Spain) and the European Regional Development Fund (ERDF/FEDER). Funding was provided through contract HB32044 from the Department of Environment and Tourism, and contracts HB72020, HB02010, HB12028 and HB22031 from the Department of Environment of the Government of Aragón.

Conflict of interest

The authors declare that they have no competing financial or personal interests that could have influenced the work reported in this paper.

Ethics approval

Ethical approval was not required for this study because it involved only unregulated aquatic invertebrates and did not include vertebrate animals or protected species.

Abstract

1. Recreational activities in freshwater ecosystems are increasing worldwide, yet their ecological consequences remain poorly understood. Canyoning is one of the most popular nature-based sports in Mediterranean rivers, but quantitative assessments of its effects on aquatic communities are scarce, particularly in protected areas where conservation and recreation coexist. Here, we evaluated how canyoning affects benthic macroinvertebrate communities and whether recreational intensity and hydrogeomorphological characteristics influence ecosystem vulnerability.
2. We evaluated the impact of canyoning on benthic macroinvertebrate communities in six canyons of the Sierra y Cañones de Guara Natural Park (NE Spain). At each canyon, control and disturbed sites were sampled using Surber samplers, and community descriptors, ecological quality indices and taxonomic composition were compared. We also assessed whether the magnitude of the impact was related to visitor pressure and hydrogeomorphological characteristics.
3. A total of 53 taxa were identified across all samples. When sites were pooled, 47 taxa were recorded in control sites and 29 in disturbed sites. Canyoning reduced macroinvertebrate abundance by 69% on average, and 24 families recorded at control sites were absent from disturbed sites. Community composition differed significantly between control and disturbed sites and was characterised by marked declines in sensitive groups, particularly Trichoptera, Coleoptera and Odonata. Visitor pressure influenced the percentage impact on abundance, with high-use canyons showing reductions exceeding 85%. In contrast, richness, diversity and ecological quality indices showed no clear relationship with visitor pressure. Some impact metrics were also associated with hydrogeomorphological characteristics, particularly bankfull width.

4. Our results demonstrate that canyoning can substantially simplify benthic macroinvertebrate communities and reduce ecological quality in Mediterranean canyons. The severity of these effects is influenced not only by visitor pressure but also by local hydrogeomorphological conditions.
5. This study provides new evidence that recreational disturbance can substantially alter benthic macroinvertebrate communities in Mediterranean canyon ecosystems. It also suggests that local environmental characteristics may contribute to differences in ecosystem vulnerability, highlighting the importance of considering ecological context when assessing the sustainability of recreational activities in freshwater ecosystems.

Introduction

The promotion of tourism in rural and remote regions over recent decades has led to increasing visitor pressure in protected areas (Seguin et al., 2024). This has contributed to social and economic development, but has also generated a range of unintended environmental consequences (Stone & Nyaupane, 2016). Tourism and recreational activities are recognised as important drivers of ecological change in protected areas, affecting habitat quality, species behaviour and community structure (Cohen, 1978; Meyer, 2021). Increasing evidence suggests that some ecosystems are insufficiently resilient to accommodate current levels of recreational use (Sayan & Atik, 2011; Malik & Bhat, 2015; Zhang et al., 2015). The magnitude of these impacts depends not only on visitor numbers but also on factors such as the duration and type of activity, as well as the vulnerability of the affected ecosystem and biological communities (Cole, 1995; Cole & Landres, 1996). Numerous studies have examined visitor characteristics, patterns of use in protected areas and the general consequences of recreational disturbance (Leung & Marion, 2000; Sayan & Atik, 2011; Escarpinati et al., 2014), yet relatively few have focused on the effects of specific outdoor sports (Farías Torbidoni, 2011; Huddart, 2019).

Despite this limited knowledge, existing studies suggest that recreational activities can affect ecosystem structure and functioning through a variety of mechanisms. For example, they may alter predator–prey dynamics, reduce the frequency of bird perches and modify patterns of vegetation succession (Webb & Blumstein, 2005; Ballantyne et al., 2014; Geffroy et al., 2015). Similar effects have also been documented in freshwater ecosystems, where recreational activities may directly disturb aquatic habitats and biological communities. Aquatic macroinvertebrate communities may be affected through trampling, substrate disturbance and habitat alteration. Previous studies have reported reductions in abundance, taxon richness and diversity, as well as shifts in community composition and the loss of sensitive taxa in response to human disturbance in freshwater ecosystems (e.g. Hardiman & Burgin, 2011; Morales-Armijo *et al.*, 2024).

The growth of nature-based tourism has been accompanied by increasing participation in canyoning, a recreational activity that involves descending natural water canyons through a combination of walking, swimming, jumping and abseiling. Canyoning has become increasingly popular worldwide, with the Alps and the Pyrenees representing two of the most important destinations in Europe.

The few studies that have investigated the ecological effects of canyoning and related freshwater recreational activities have focused primarily on benthic macroinvertebrate communities (Escarpinati et al., 2014). Nevertheless, information on the ecological consequences of canyoning remains scarce (Caires et al., 2010; Hardiman & Burgin, 2011) and is virtually absent in Europe (Huddart & Stott, 2019). This knowledge gap is particularly important in the context of global change because canyon ecosystems, many of which are intermittent or temporary, may be especially vulnerable to the cumulative effects of multiple anthropogenic stressors (Birk et al., 2020; Bruno et al., 2022). Consequently, they may face disproportionately high biodiversity losses compared with terrestrial ecosystems (Dudgeon et al., 2006).

This study examines the effects of canyoning on benthic macroinvertebrate communities across six Mediterranean canyons located within an internationally renowned canyoning destination. Using a combination of community descriptors, biological indices and community composition analyses, we assess the ecological consequences of recreational disturbance and investigate the environmental factors underlying variation in ecosystem vulnerability. Specifically, our objectives were to: (1) evaluate the effects of canyoning on benthic community structure and ecological condition across six canyons within a protected natural area; (2) compare community composition between impacted and control sites; and (3) determine whether hydrogeomorphological characteristics influence community vulnerability to recreational disturbance. Addressing these objectives will improve our understanding of how recreational disturbance affects benthic communities and how local environmental conditions modulate ecosystem vulnerability in Mediterranean canyon systems, thereby providing a scientific basis for assessing the ecological sustainability of recreational use in canyon ecosystems.

Methods

Study area

We selected one of the most intensively used canyoning destinations in Europe. The Sierra y Cañones de Guara Natural Park (SCGNP) is located in one of the principal outer ranges of the Pyrenees in Aragón, Spain. It comprises a core area (47,453 ha) and a surrounding buffer zone, covering a total of 80,739 ha, making it the largest protected area in the Aragón region. The park's pronounced altitudinal gradient, together with the widespread occurrence of limestone and conglomerates, has shaped a complex system of karstic canyons. These geological formations have long represented a key resource for tourism and recreational activities. The park contains approximately 20 canyons with moderate to high levels of recreational use, concentrated during the summer season from June to October (Lacosta Aragüés, 2002). Although recent regulations governing recreational activities within the natural park have been introduced (DGA, 2014), a significant lack of scientific knowledge remains regarding the ecological disturbances associated with canyoning. This knowledge gap hampers the effective regulation of canyoning, as its overall effects on aquatic communities have not yet been comprehensively assessed.

The Sierra de Guara is located in a transition zone between Mediterranean and Atlantic climatic influences and experiences highly variable weather conditions. Winters are cold with frequent frost, spring is characterised by rainfall and strong winds, and summers are warm but often affected by thunderstorms and hail. Annual precipitation at the highest elevations reaches approximately 1500 mm (Cuchí Oterino, 2006). The rivers investigated share broadly similar climatic and geological characteristics. They are tributaries of two main river systems, the Alcanadre and Flumen catchments (Table S1).

To characterise the hydrological setting of the study area, Table S1 includes discharge statistics for the period 2018–2023 derived from gauging stations located within the corresponding catchments. Because discharge measurements were not available for the individual study sites, these values should be interpreted as catchment-scale descriptors rather than site-specific hydrological conditions. In contrast, bankfull depth, width and discharge were estimated for each canyon by Ollero Ojeda *et al.*, (2010) and were used to characterise differences among study sites.

Methods

Hydrogeomorphological characteristics of canyons

Mean annual precipitation was obtained from historical precipitation records (CHE, 2022), whereas three hydrogeomorphological variables (channel length, mean slope and basin area) were derived using Geographical Information System tools (QGIS Development Team, 2022).

Sampling design and protocols

This study includes six canyons, sampled in different years between 2018 and 2023. Each canyon was surveyed once during this period, with sampling conducted between 20 July and 5 October, encompassing the period of highest recreational use (Fig. 1). Recreational activity peaks during July and August, although canyoning generally continues until mid-October, depending on hydrological conditions. During this period, the most popular canyons are descended daily and often by multiple groups per day. Consequently, sampling was generally conducted while canyoning activity was ongoing or within a few hours of the last descent.

Daily visitation of canyons was assessed using a direct method: *in situ* counts conducted by SCGNP staff. For less accessible canyons, maximum daily visitation was estimated based on expert knowledge obtained through personal communications with experienced canyon guides Omar Catalá and Alex Castro. Based on park monitoring records, canyons were classified into low-use and high-use categories according to natural breaks in maximum daily visitation. When visitor numbers were ordered, the first major discontinuity occurred between 40 and 99 visitors day^{-1}, separating low-use canyons (6–40 visitors day^{-1}) from high-use canyons (99–343 visitors day^{-1}). This data-driven classification was consistent with field observations and previous management descriptions distinguishing technical, less accessible canyons from more accessible routes used by larger numbers of visitors (Benayas et al., 1996). This distinction reflects the structure of recreational use within the Natural Park, where high-use canyons are generally easier, more accessible and commonly used for initiation activities, whereas low-use canyons are more technical, have longer or more difficult access routes and are used by a smaller proportion of visitors. In the present study, this classification was supported by the recorded visitor numbers.

Within each canyon, two sites were sampled (one control and one disturbed). One site was located in an undisturbed river reach, preferably upstream of the recreational descent route, where canyoning activity was absent or negligible (control). Control sites were selected as close as possible to disturbed sites in order to minimise environmental differences and ensure comparable geomorphological and hydrological conditions. Their lack of recreational use was due to their position outside the established descent route rather than to any environmental constraint. In most canyons, access is provided by a single entry point and the recreational route follows the downstream course of the canyon, making access to upstream sections uncommon during canyoning activities. The second site was located within the recreational section subjected to trampling by canyoners (disturbed). Specifically, the disturbed site was positioned along the main route used by canyoners, between the habitual entry and exit points, ensuring consistent exposure to trampling. Canyons with multiple entry and exit points were avoided in order to standardise the monitoring design.

Samples were collected with the assistance of the Aragón Government's specialised canyon surveillance team (GRUBA), as access to the study sites required descending the canyons using the same techniques employed by canyoners. All samples were collected by the same trained researcher throughout the study, ensuring consistency in field procedures among sites and years. Sampling focused on gravel substrates, as these represent the main mobile fraction of the streambed, whereas larger substrates are often stabilised by carbonate precipitation. At each site, three Surber samples were collected from representative mesohabitats in order to capture the spatial heterogeneity of the benthic community. These samples were used as within-site sampling units and not as independent experimental replicates.

Macroinvertebrates were collected using a 500 µm mesh Surber sampler. The sampling protocol consisted of disturbing and cleaning gravel and cobble substrates within a 30 × 50 cm area upstream of the Surber net. Substrate particles were thoroughly examined and the streambed was disturbed until bedrock was reached, allowing the current to carry dislodged organisms into the net. Samples were preserved in 70% ethanol until analysis. Taxonomic composition was determined using a Leica S9D stereomicroscope and the dichotomous keys of Oscoz, Galicia & Miranda (2011). Taxa were identified to family level whenever possible, except for Oligochaeta and Nematoda, which were recorded at higher taxonomic levels.

The following biological metrics and ecological quality indices were calculated to evaluate their sensitivity to canyoning disturbance: abundance, taxon richness, evenness, Shannon diversity (Shannon & Weaver, 1949), EPT (Ephemeroptera, Plecoptera and Trichoptera taxa), EPT/(EPT+OCH) [the ratio between EPT and OCH (Odonata, Coleoptera and Heteroptera)] (Bonada et al., 2006), and the abundance of individual macroinvertebrate orders. In addition, IBMWP (Iberian Biological Monitoring Working Party) and IASPT (Iberian Average Score Per Taxon) indices were calculated following Alba-Tercedor & Sánchez-Ortega (1988).

Ecological status was assessed using the Iberian Biological Monitoring Working Party index (IBMWP). Observed IBMWP values were compared against reference conditions for the corresponding river typology to calculate the Ecological Quality Ratio (EQR), defined as the ratio between observed and reference values. Reference conditions were established according to the criteria defined in national regulations implementing the Water Framework Directive (e.g. MAGRAMA, 2015). Ecological status was subsequently classified into status classes (high, good, moderate, poor and bad) based on the corresponding EQR thresholds.

Data statistical analysis

Each canyon comprised one control and one disturbed site, and each site was characterised using three Surber samples collected from representative habitats. These samples were used to quantify within-site variability in biological metrics. However, for the calculation of the IBMWP index used to assess ecological status according to regulatory standards, the three Surber samples collected within each site were pooled to obtain a single integrated value per site and sampling occasion.

Statistical analyses were conducted using R software (R Core Team, 2018). Prior to analysis, normality and homoscedasticity were assessed using the Shapiro–Wilk and Levene tests, respectively. Differences in response variables (e.g. abundance and community metrics) were tested using two-way ANOVA, with canyon and treatment (control vs. disturbed) as fixed factors. When assumptions were not met, a non-parametric alternative (Kruskal–Wallis test) was applied.

The impact of canyoning on each biological index was quantified as the percentage change between control and disturbed sites, calculated as [(Control − Disturbed) / Control] × 100.

In addition, taxon-specific responses were quantified using log-response ratios (LRR), calculated as the natural logarithm of the ratio between disturbed and control abundances. Mean LRR values and their 95% confidence intervals were estimated across sites. Confidence intervals were calculated using the t-distribution as mean ± t × SE, where SE is the standard error of the mean and t corresponds to the 0.975 quantile with n−1 degrees of freedom. These values were used to construct a forest plot summarising the magnitude and variability of responses among taxa.

Multivariate analyses were performed on square-root-transformed abundance data using Bray–Curtis dissimilarities. Patterns of variation in community composition were visualised using NMDS. Differences between control and disturbed sites were tested using PERMANOVA with

999 permutations, and the contribution of individual taxa to compositional differences was assessed using SIMPER analysis. Multivariate analyses were conducted using PAST software (Hammer et al., 2001).

Results

Basin characteristics and daily use levels

Information on basin characteristics and visitor pressure, which had not previously been reported for these canyons, was compiled and is presented in Table 1. The studied canyons exhibited substantial variation in length, slope, basin area and visitor pressure.

Visitor pressure varied markedly among canyons, with maximum daily visitation ranging from 6 to 343 visitors per day (Table 1). Two broad groups could be distinguished: high-use, easily accessible canyons used by large numbers of visitors (99–343 visitors day^{-1}), and more technical canyons with longer access routes and substantially lower visitor numbers (6–40 visitors day^{-1}).

Characteristics of the undisturbed benthic community

A total of 4,060 individuals were collected and identified to family level in control sites across the six canyons. Taxon richness averaged 11.8 ± 3.4 families per Surber sample (range: 8–17), while abundance averaged 1503.7 ± 1174.6 individuals m^{-2} per Surber sample (range: 431–3648.9). Taxon richness, abundance and diversity varied among canyons, but none of these differences was statistically significant (ANOVA; Table 2).

The number of EPT taxa averaged 5.8 ± 2.0 (range: 4–8) and did not differ significantly among canyons. The EPT/(EPT+OCH) ratio averaged 0.7 ± 0.1 (range: 0.4–0.9) and differed significantly among sites. The highest values were observed in Mascún, whereas Gorgas

Negras showed the lowest EPT/(EPT+OCH) ratio. Integrated IBMWP values averaged 117.0 ± 36.6 (range: 73.0–157.0), corresponding to ecological status ranging from moderate to very good across all canyons.

Effects of disturbance: comparison of the benthic community between disturbed and control sites

A total of 853 individuals were collected and identified from disturbed sites across the six canyons. Mean abundance was 315.9 ± 226.0 individuals m^{-2} per Surber sample (range: 151.1–744.4). Ecological status, assessed using the IBMWP index, was classified as moderate or poor in all disturbed sites except Formiga, which maintained good ecological status. Although some variation among canyons was observed, abundance, taxon richness and diversity remained consistently low across disturbed sites. No significant differences among canyons were detected for any of the variables analysed (ANOVA; Table 3).

All indices analysed were lower in disturbed sites (Table 4). Total abundance decreased by 70% in disturbed sites compared with controls, while taxon richness and IBMWP were reduced by 46% and 50%, respectively. Shannon diversity decreased by 25%. The number of EPT taxa was reduced by 53%. In contrast, the EPT/(EPT+OCH) ratio did not differ significantly between treatments. Similarly, the evenness and IASPT indices did not differ significantly between treatments (Table 4).

The NMDS ordination revealed differences in macroinvertebrate community composition between control and disturbed sites, although some overlap between groups was observed (Fig. 2). Samples from disturbed sites tended to cluster separately from control samples along the first ordination axis, indicating a consistent shift in community composition associated with canyoning disturbance. This pattern was supported by PERMANOVA ($F_{1,10} = 2.71$; $p = 0.005$), which detected significant differences between control and disturbed communities. However, multivariate dispersion did not differ significantly between treatments (PERMDISP: $F_{1,10}$ = 0.81, p = 0.39), indicating that the observed differences were due to shifts in community composition rather than differences in within-group variability.

A total of 53 taxa were identified across all samples. When data from all canyons were pooled, 47 taxa were recorded in control sites and 29 taxa in disturbed sites. Communities in both disturbed and control sites were dominated by the same four families (Chironomidae, Elmidae, Leuctridae and Baetidae). Compared with control sites, 24 families were absent from disturbed sites, while 16 additional families exhibited lower mean abundances (Table 5). In contrast, 12 families were more abundant in disturbed sites than in control sites, particularly Ceratopogonidae, Gammaridae and Lymnaeidae, and six taxa were recorded exclusively in disturbed sites (e.g. Chaoboridae, Cordulegastridae and Oligochaeta). The dominant families collectively accounted for 34% of the dissimilarity between disturbed and control communities, whereas taxon losses were primarily associated with less abundant families (Table 5). Overall, these changes resulted in a simplification of community structure in disturbed sites.

Mean log response ratios (LRR) calculated for the major macroinvertebrate orders were negative in all cases (Fig. 3). Negative LRR values correspond to lower abundances in disturbed than in control sites. Trichoptera exhibited the strongest response to disturbance, followed by Coleoptera, whereas Diptera and Heteroptera showed comparatively smaller declines. The remaining orders (Odonata, Ephemeroptera and Plecoptera) showed intermediate responses. Despite variability among canyons, the negative mean LRR values observed for all orders indicate a general reduction in macroinvertebrate abundance associated with canyoning activity.

Influence of use intensity and hydrogeomorphological characteristics on canyoning impact

Across the six canyons, mean abundance decreased by 69% ± 24% (range: 36–95%), taxon richness by 46 ± 14% (range: 26–66%), and IBMWP scores by 50 ± 13% (range: 37–74%). Site-specific responses varied among canyons, with the strongest effects generally observed for abundance and ecological quality metrics (Fig. 4).

The percentage impact on abundance differed significantly between high-use and low-use canyons (ANOVA: $F_{1,5} = 8.5$, $p = 0.043$). No significant effects of use intensity were detected for any of the other biological indices analysed.

Correlation analyses revealed significant relationships between bankfull width and the percentage impact on Plecoptera abundance ($r = -0.85$, $p = 0.032$) and Shannon diversity ($r = 0.85$, $p = 0.032$). Basin surface area was negatively correlated with the percentage impact on Trichoptera abundance ($r = -0.88$, $p = 0.020$). No other significant relationships were detected. However, the relationship between bankfull width and the percentage impact on total abundance approached significance ($r = -0.79$, $p = 0.060$), as did the relationship between bankfull depth and the percentage impact on Shannon diversity ($r = -0.78$, $p = 0.058$).

Discussion

Changes in community descriptors due to disturbance

Under control conditions, abundance, taxon richness and diversity did not differ significantly among canyons, suggesting comparable macroinvertebrate community structure across the study area. According to the IBMWP index, the ecological status of the studied canyons ranged from good to moderate under control conditions. In contrast, the ecological status of the main river channels in the region is frequently classified as good or very good in terms of both physicochemical and biological quality (CHE, 2022). These differences suggest that the classification of canyon ecosystems within current regulatory frameworks may require improved reference conditions or the development of a specific typology for canyon environments. The limited availability of reference information probably reflects the logistical difficulties associated with sampling these systems, which are generally accessible only through canyon descent.

When disturbed sites were analysed, all indices describing community composition and ecological status were lower than those recorded at control sites. Moreover, disturbed sites dropped by one ecological status category. Lower abundance, diversity and taxon richness were observed in disturbed sites, consistent with previous studies reporting the effects of instream recreational activities and, more specifically, with the limited number of studies investigating trampling (Escarpinati et al., 2014; Kidd et al., 2014) and canyoning impacts (Hardiman & Burgin, 2011). The number of EPT taxa was also significantly lower in disturbed zones. Although this index includes taxa considered sensitive to pollution 38, it also appears to be affected by canyoning disturbance.

Benthic community composition under canyoning disturbance

Our results showed that canyoning altered community composition across all studied canyons, consistently simplifying community structure through substantial losses in both abundance and taxonomic richness. Twenty-three taxa found in control sites were absent from disturbed sites and a further 20 showed marked reductions in abundance. The strongest declines were observed in Trichoptera, Coleoptera and Odonata. These orders are typically associated with stable benthic habitats and well-oxygenated flowing waters, making them particularly vulnerable to substrate disturbance and drift. Many Trichoptera larvae are closely associated with the substrate through fixed retreats or portable cases, increasing their susceptibility to direct trampling and substrate disturbance (Escarpinati et al., 2014). Similarly, many aquatic Coleoptera depend strongly on benthic and periphytic resources and are therefore likely to be affected by reductions in biofilm biomass associated with recreational disturbance (Mičetić Stanković et al., 2018; Fenoglio et al., 2020). Odonata may also be indirectly affected through trophic pathways. As many odonate larvae are generalist predators, the marked reductions in abundance observed across multiple macroinvertebrate groups may decrease prey availability and contribute to their decline in disturbed sites. Together, these mechanisms suggest that the effects of canyoning extend beyond direct physical disturbance and may also propagate through trophic interactions and habitat-mediated processes.

Dominant families, particularly Chironomidae, Elmidae and Leuctridae, remained abundant in disturbed communities, although their abundances were generally lower than in control sites. Their persistence may partly reflect their initially high abundances, but also biological traits commonly associated with disturbance resistance, including broad ecological tolerance, flexible feeding strategies and adaptations that reduce drift or facilitate refuge within the substrate (Syrovátka et al., 2009; Picazo et al., 2012; Mičetić Stanković et al., 2018; Dorić et al., 2024).

In contrast, Baetidae and Gammaridae were more abundant in disturbed sites, and a few taxa were recorded exclusively in disturbed sites (e.g. Chaoboridae, Cordulegastridae and Oligochaeta). The success of these groups may be related to their high ecological plasticity and rapid recolonisation capacity. The increase in Baetidae abundance may reflect life-history traits commonly associated with resilience to disturbance, including rapid development, high mobility and efficient recolonisation of disturbed habitat patches (Matthaei et al., 1996), whereas Gammaridae may benefit from broad feeding niches and opportunistic resource use (Macneil et al., 1997). Consequently, these taxa may be able to exploit habitat patches and resources made available following the decline of more disturbance-sensitive organisms.

The family Leuctridae deserves special attention because it contributes strongly to ecological quality assessments through the IBMWP index. Although several species within this family are considered sensitive to environmental degradation, *Leuctra geniculata*—the dominant leuctrid species in this study—remained abundant in disturbed sites. This persistence may be related to biological traits such as a generalist diet, burrowing behaviour and adaptation to naturally variable flow conditions (Hynes, 1941; Pařil et al., 2008). As a consequence, IBMWP scores in disturbed sites remained higher than expected based on the magnitude of the observed reductions in abundance and richness. These findings highlight the need for caution when interpreting biotic indices developed primarily to detect water quality degradation in the context of physical disturbances such as canyoning.

Taken together, these patterns indicate that canyoning modifies community composition through the combined effects of taxon loss, changes in relative abundance and species replacement.

Beyond visitor pressure: hydrogeomorphological drivers of canyoning impact

Studies evaluating the effects of different levels of canyoning intensity on aquatic communities remain extremely scarce, with most available evidence derived from experimental trampling studies (Hardiman & Burgin, 2011; Escarpinati et al., 2014). Our results indicate that visitor pressure plays an important role in determining ecological impacts on benthic communities. High-use canyons exhibited the strongest responses, with reductions in total abundance exceeding 85%. Similar patterns were reported by Hardiman & Burgin, (2011), who found that the effects of trampling increased rapidly with disturbance intensity and approached saturation at high trampling levels. Nevertheless, abundance was the only biological metric significantly related to canyon use intensity. In contrast, richness, diversity and IBMWP showed substantial reductions in disturbed sites but were not significantly associated with visitor pressure.

The weak relationship between visitor pressure and most biological indices suggests that the ecological response to canyoning cannot be explained solely by recreational intensity. Our results indicate that hydrogeomorphological characteristics may also influence the magnitude of the disturbance effect. Among the variables analysed, bankfull width showed significant relationships with the percentage impact on Plecoptera abundance and Shannon diversity, as well as a near-significant relationship with the percentage impact on total abundance. The percentage impact on total abundance and Plecoptera abundance was lower in wider canyons, whereas the percentage impact on Shannon diversity was greater. The contrasting responses of these variables may explain this apparently opposite pattern, as reductions in the abundance of dominant taxa can increase diversity by promoting a more even distribution of individuals among taxa. In addition, basin surface area was negatively correlated with the percentage impact on Trichoptera abundance. Larger catchments may support greater habitat availability and recolonisation potential, thereby reducing the impact on sensitive taxa such as Trichoptera. Alternatively, larger catchments are also likely to sustain higher discharges, which may favour the persistence of Trichoptera populations. Unfortunately, discharge data were not available for all canyons, preventing a direct evaluation of this hypothesis. This interpretation is further supported by the marginally significant relationship between bankfull depth and the impact on diversity ($p = 0.058$). Deeper canyons contain a greater proportion of habitat that is inaccessible to trampling and direct contact with the substrate, a situation comparable to that expected under higher discharge conditions.

Taken together, these findings indicate that the ecological effects of canyoning are context dependent and may vary according to local channel and catchment characteristics. The observed patterns suggest that community simplification is influenced not only by recreational pressure itself, but also by the capacity of taxa to resist disturbance and persist under altered habitat conditions (Brooks & Boulton, 1991; Miyake et al., 2005). Plecoptera and Trichoptera are generally considered among the most disturbance-sensitive components of Mediterranean stream communities (Bonada et al., 2006; Bonada & Resh, 2013). In canyon ecosystems, however, their vulnerability may be further increased by their close association with the benthic substrate, which is directly affected by trampling and other canyoning-related disturbances. This vulnerability may be particularly pronounced in Mediterranean rivers, where peak recreational use typically coincides with summer low-flow conditions. Under these circumstances, reduced discharge, habitat contraction and increased trampling intensity may act synergistically, amplifying the effects of disturbance on sensitive benthic taxa. The significant relationships detected for these groups therefore suggest that hydrogeomorphological characteristics may play an important role in determining the persistence of sensitive taxa under recreational pressure. Consequently, management strategies based solely on visitor numbers may overlook important differences in ecosystem vulnerability among canyons.

Regulation of canyoning

The observed reductions in abundance, richness and ecological quality indicators highlight the need for management measures aimed at reducing ecological pressure in heavily used canyons. Monitoring programmes combining biological indicators and visitor pressure data may help identify vulnerable sites and support adaptive management. Because the magnitude of the impact varied among canyons and was partly related to hydrogeomorphological characteristics, management strategies should consider local environmental conditions in addition to visitor numbers. Our results suggest that a single carrying-capacity threshold may not be appropriate for all canyon systems. Instead, management actions should account for differences in ecosystem vulnerability associated with channel morphology, habitat availability and hydrological conditions. Wider and deeper canyons may provide greater refuge opportunities for aquatic communities, whereas narrower systems may be more susceptible to recreational disturbance. Consequently, visitor limits, temporal restrictions and conservation measures should be adapted to the characteristics of individual canyons rather than applied uniformly across protected areas.

Long-term ecological monitoring is particularly important in Mediterranean rivers, where recreational pressure is concentrated during the low-flow season and may interact with natural hydrological stress. Integrating ecological indicators into canyon management plans would improve the capacity to detect early signs of degradation and support conservation strategies that balance biodiversity protection with the socio-economic benefits associated with nature-based tourism.

Acknowledgments

The authors gratefully acknowledge the invaluable support of GRUBA (Canyoning Unit), the specialised canyoning team of the Nature Protection Officers (Agentes de Protección de la Naturaleza, APN) of the Government of Aragón, whose expertise and assistance were essential for the safe descent of the canyons and field sampling. We also thank the Environmental Sciences students from the University of Zaragoza who contributed to this work through internships and undergraduate research projects within the Ecological Restoration research group. Their dedication and commitment greatly enriched this study. Finally, we are grateful to the canyoning guides Omar Catalá and Alex Castro for their collaboration and continued support of this research.

The authors used ChatGPT (OpenAI) during the manuscript revision stage to improve the clarity, grammar and scientific writing of the text. All scientific content, data analysis, interpretation of the results and final editorial decisions were performed and verified by the authors.

Author contribution statement: Conceptualisation: RLF, DGO. Developing methods: RLF, DGO, DME, MG. Data analysis: RLF, DME, MG. Preparation of figures and tables: RLF, DME, MG. Conducting the research, data interpretation, writing: RLF, DGO.

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Figures

Figure 1. Location of the six canyons of the Sierra y Cañones de Guara Natural Park (SCGNP) included in the study (Aragón, Spain).

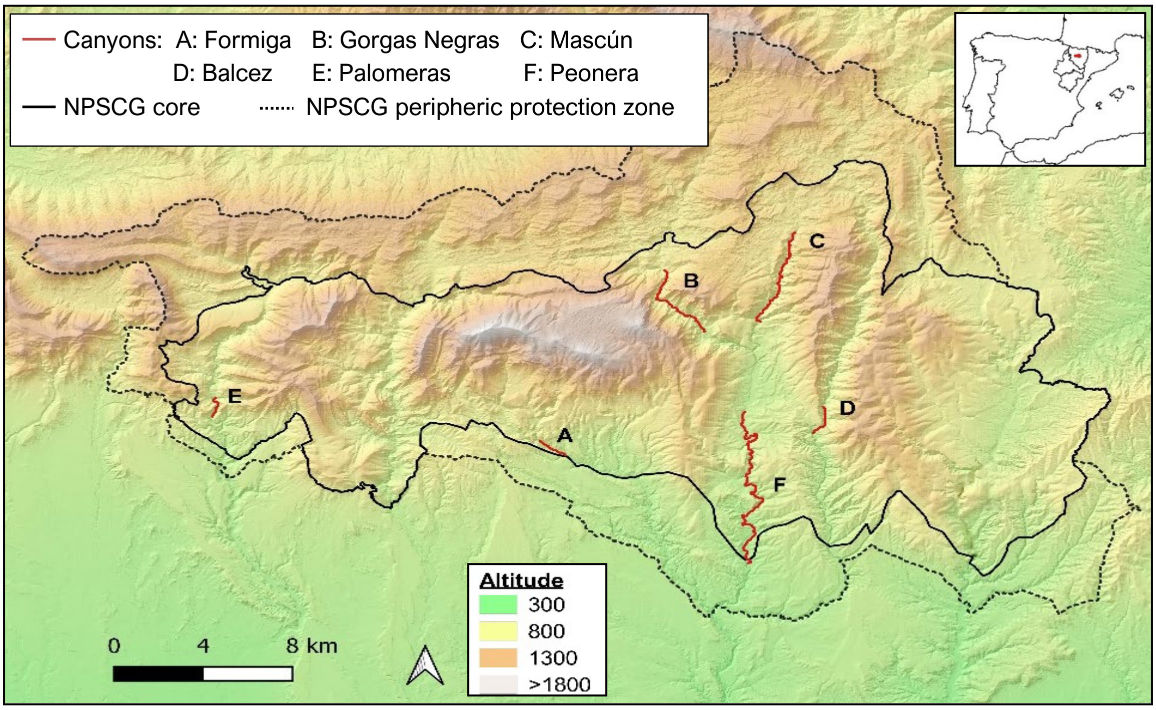

Figure 2. Non-metric multidimensional scaling (NMDS) ordination showing differences in macroinvertebrate community composition between control and disturbed sites (stress = 0.19).

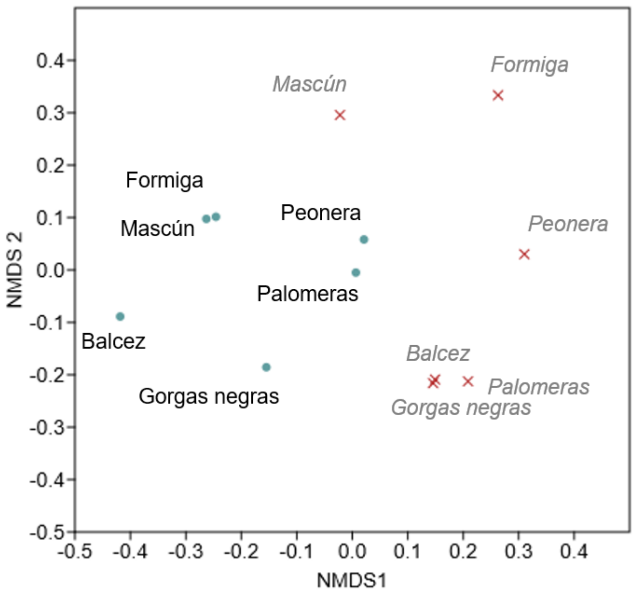

Figure 3. Taxon-specific responses to canyoning disturbance expressed as log response ratios (LRR) of abundance between disturbed and control sites. Points represent mean LRR values across canyons and horizontal bars indicate 95% confidence intervals. Negative values indicate lower abundances in disturbed sites. Taxa are ordered according to effect size.

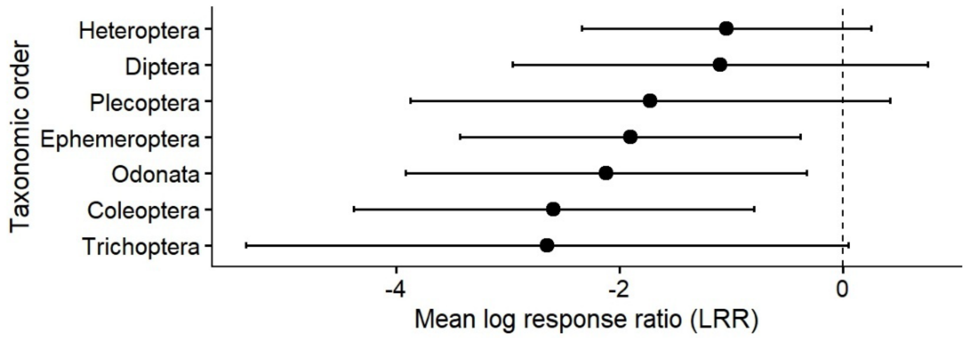

Figure 4. Percentage impact of canyoning on total abundance, taxon richness and IBMWP. Black bars represent high-use canyons and grey bars represent low-use canyons.

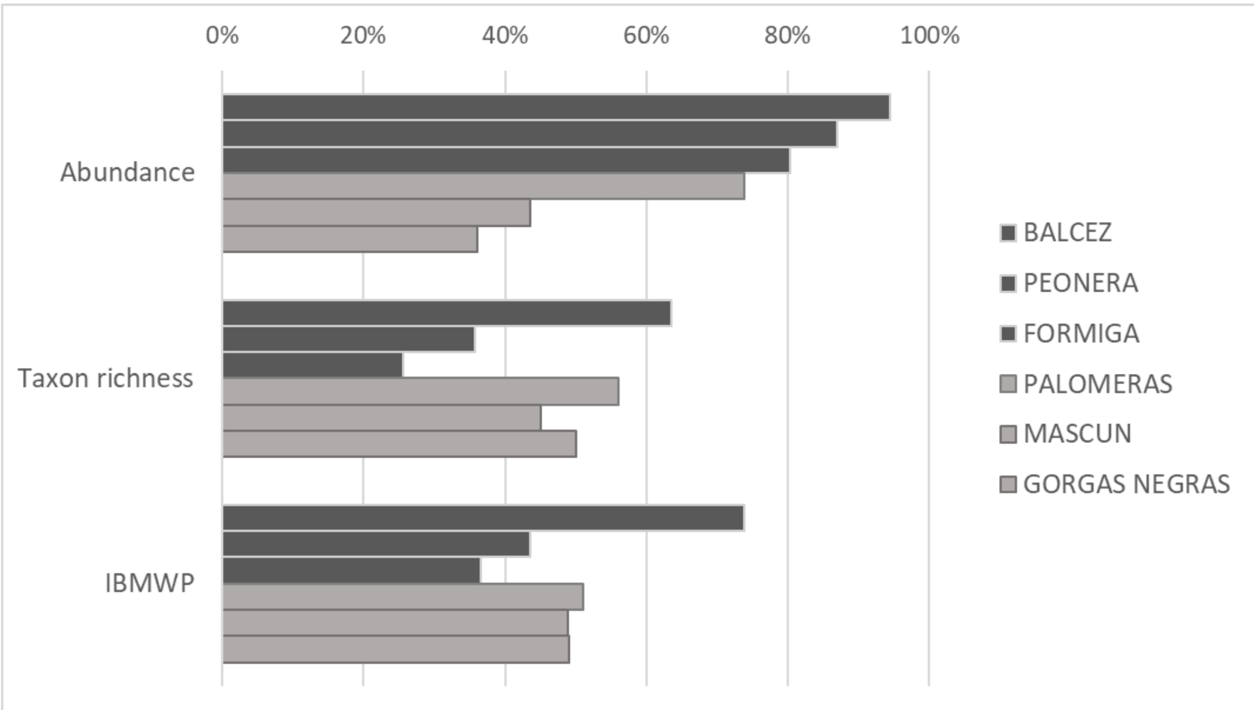

Table 1. Hydrogeomorphological characteristics, precipitation and visitor pressure of the six study canyons.

	Year of sampling	Canyon length (km)	Average Slope (%)	Basin Surface (km^2)	Basin average annual precipitation (mm)	Max daily frequentation registered in high season (seasons 2021-2024)	Use classification
Balcez	2019	1.6	3.5	64.1	789.6	99 (76-99)	High
Formiga	2023	1.5	6.6	23.0	707.0	173 (157-173)	High
Gorgas Negras	2022	11.4	2.2	138.9	768.2	22 (18-22)	Low
Mascún	2018	8.6	3.0	38.8	764.4	40 (25-40*)	Low
Palomeras	2021	1.3	4.0	90.3	719.1	6*	Low
Peonera	2023	12.8	1.2	195.2	739.5	343 (262-343)	High
Mean		6.2	3.4	91.7	748.0		
SD		5.4	1.8	65.1	31.6		

Table 2. Community descriptors and ecological quality indices of macroinvertebrate communities at control sites. Results of ANOVA/Kruskal–Wallis tests for the factor canyon.

Canyon and year	Abundance (ind/m2)	Taxon richness	Shannon H'	Evenness	EPT taxa	EPT/ (EPT+OCH)	IBMWP	IASPT	IBMWP integrated	RD 817/215 Classification (EQR)
Balcez	3648.9	17.3	1.8	0.4	8.0	0.7	101.7	5.9	155.0	Very Good (0,83)
Formiga	1884.4	13.0	1.7	0.5	5.7	0.6	83.7	6.3	134.0	Good (0,72)
Gorgas Negras	431.1	9.3	1.7	0.6	4.0	0.6	51.7	5.7	99.0	Moderate (0,49)
Mascún	1317.8	13.3	1.9	0.6	8.3	0.8	86.0	6.4	157.0	Good (0,77)
Palomeras	584.4	8.3	1.3	0.5	4.0	0.7	46.3	5.4	84.0	Moderate (0,45)
Peonera	1155.6	9.3	1.5	0.6	4.7	0.7	59.0	6.3	73.0	Moderate (0,39)
Mean	1503.7	11.8	1.7	0.5	5.8	0.7	71.4	6.0	117.0	
SD	1174.6	3.4	0.2	0.1	2.0	0.1	22.1	0.4	36.6	
n	18	18	18	18	18	18	18	18	6	
F / Chi^2* (canyon)	6.8*	2.4	8.6*	0.3	3.0	5.1	2.3	6.7*		
p	0.23	0.09	0.13	0.88	0.06	**0.01**	0.11	0.24		
d.f.	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17		

Table 3. Community descriptors and ecological quality indices of macroinvertebrate communities at disturbed sites. Results of ANOVA/Kruskal–Wallis tests for the factor canyon.

Canyon and year	Abundance (ind/m^2)	Taxon richness	Shannon H'	Evenness	EPT taxa	EPT/ (EPT+OCH)	IBMWP	IASPT	IBMWP integrated	RD 817/2015 Classification (EQR)
Balcez	200.0	6.3	1.6	0.9	1.7	0.6	26.7	3.8	52.0	Deficient (0,28)
Formiga	371.1	9.7	1.7	0.7	3.0	0.7	53.0	5.0	102.0	Good (0,55)
Gorgas Negras	275.6	4.7	0.9	0.6	2.0	0.6	26.3	6.1	55.0	Deficient (0,27)
Mascún	744.4	7.3	1.1	0.4	5.0	0.9	44.0	6.0	65.0	Moderate (0,32)
Palomeras	153.3	3.7	0.8	0.7	1.7	0.5	22.7	6.5	38.0	Deficient (0,20)
Peonera	151.1	6.0	1.4	0.7	2.7	0.6	33.3	5.6	45.0	Deficient (0,24)
Mean	315.9	6.3	1.3	0.7	2.7	0.7	34.3	5.5	59.5	
SD	226.0	2.1	0.4	0.2	1.3	0.1	11.8	1.0	22.7	
n	18	18	18	18	18	18	18	18	6	
F/Chi^2* (canyon)	2.3	1.5	2.1	0.1*	2.2	1.5	7.7*	2.5	-	
p	0.11	0.26	0.13	0.29	0.12	0.27	0.17	0.08	-	
d.f.	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17	5, 12,17	-	

Table 4. Community descriptors and ecological quality indices of macroinvertebrate communities at control and disturbed sites. Results of ANOVA/Kruskal–Wallis tests for the factor treatment (control vs. disturbed).

	Abundance (ind/m^2)	**Taxon richness**	**Shannon H'**	**Evenness**	**EPT taxa**	**EPT/ (EPT+OCH)**	**IBMWP**	**IASPT**	**IBMWP integrated**
Control	1503.7	11.8	1.7	0.5	5.8	0.7	71.4	6.0	117.0
Disturbed	315.9	6.3	1.3	0.7	2.7	0.7	34.3	5.5	59.5
n	36	36	36	36	36	36	36	36	12
F/Chi^2*	11.9*	17.7	8.5	3.8	19.3	0.4*	16.2*	2.3	10.7
p	**0.0006**	**0.0001**	**0.006**	0.06	**0.0001**	0.55	**0.00005**	0.14	**0.01**
d.f.	1, 34,35	1, 34,35	1, 34,35	1, 34,35	1, 34,35	1, 34,35	1, 34,35	1, 34,35	1, 10, 11

Table 5. SIMPER analysis of differences in macroinvertebrate community composition between disturbed and control sites. Shaded taxa were absent from disturbed sites. Taxa in bold were more abundant in disturbed sites. Taxa in bold italics were absent from control sites.

Taxon	Av. dissim	Contrib. %	Cumulative %	Mean CONTROL	Mean DISTURBED
Elmidae	7,26	10,92	10,92	16,60	5,34
Leuctridae	5,93	8,91	19,84	12,60	5,65
Chironomidae	4,67	7,02	26,86	13,40	6,45
Baetidae	**4,48**	**6,74**	**33,59**	**6,24**	**6,31**
Capniidae	4,37	6,57	40,17	6,26	1,70
Leptophlebiidae	3,56	5,36	45,53	5,84	1,80
Gomphidae	3,17	4,77	50,30	5,85	1,18
Caenidae	2,34	3,52	53,82	3,69	1,18
Corixidae	2,21	3,32	57,15	3,00	1,03
Ceratopogonidae	**1,77**	**2,67**	**59,81**	**1,31**	**2,27**
Nemouridae	1,75	2,62	62,44	2,41	0,35
Polycentropodidae	1,74	2,62	65,06	3,18	0,75
Hydraenidae	1,70	2,56	67,62	3,08	0,00
Gammaridae	**1,70**	**2,56**	**70,17**	**0,90**	**1,76**
Lymnaeidae	**1,46**	**2,19**	**72,36**	**1,54**	**2,21**
Hydropsychidae	1,45	2,19	74,54	2,36	0,00
Empididae	1,31	1,97	76,51	2,70	0,00
Heptageniidae	1,24	1,87	78,38	2,33	0,00
Hydroptilidae	1,16	1,74	80,11	2,22	0,25
Philopotamidae	1,12	1,68	81,79	2,24	0,00
Athericidae	0,90	1,35	83,14	1,18	0,70
Aeshnidae	0,87	1,31	84,46	1,28	0,25
Stratiomyidae	0,87	1,30	85,76	1,20	0,00
Ephemerellidae	0,86	1,30	87,06	1,92	0,00
Psychomyiidae	0,79	1,18	88,24	1,18	0,00
Oligochaeta	***0,65***	***0,98***	***89,22***	***0,00***	***0,93***
Gyrinidae	0,60	0,91	90,13	1,11	0,00
Ephemeridae	0,50	0,75	90,87	0,50	0,35
Tabanidae	0,45	0,68	91,55	0,80	0,25
Simuliidae	0,44	0,66	92,21	0,85	0,00
Cordulegastridae	***0,43***	***0,65***	***92,86***	***0,00***	***0,70***
Perlodidae	0,41	0,62	93,48	0,56	0,00
Limoniidae	0,33	0,50	93,98	0,77	0,00
Leptoceridae	0,33	0,49	94,47	0,25	0,25
Hydracarina	0,32	0,48	94,94	0,47	0,25
Calopterygidae	0,28	0,41	95,36	0,50	0,00
Ecnomidae	**0,27**	**0,40**	**95,76**	**0,18**	**0,35**
Chaoboridae	***0,25***	***0,38***	***96,14***	***0,00***	***0,35***
Dixidae	0,25	0,37	96,51	0,43	0,00
Molannidae	0,24	0,36	96,87	0,25	0,00
Crambidae/Pyralidae	0,23	0,34	97,21	0,25	0,00
Gerridae	0,23	0,34	97,56	0,25	0,00
Anthomyiidae	0,23	0,34	97,90	0,25	0,00
Culicidae	**0,21**	**0,31**	**98,21**	**0,10**	**0,25**
Thaumaleidae	0,20	0,30	98,52	0,35	0,00
Physidae	***0,15***	***0,23***	***98,75***	***0,00***	***0,25***
Beraeidae	***0,15***	***0,23***	***98,97***	***0,00***	***0,25***
Nematoda	***0,15***	***0,23***	***99,20***	***0,00***	***0,25***
Tipulidae	0,14	0,22	99,42	0,25	0,00
Chloroperlidae	0,14	0,22	99,63	0,25	0,00
Scirtidae	0,14	0,21	99,84	0,25	0,00
Hydrophilidae	0,06	0,09	99,93	0,14	0,00
Rhyacophilidae	0,04	0,07	100,00	0,10	0,00

Table S1. Hydrological characteristics of the six canyons included in the study. Discharge statistics for the period 2018–2023 were obtained from the SAIH (Automatic Hydrological Information System; CHE, 2022). Bankfull mean depth, bankfull width and bankfull discharge were obtained from Ollero Ojeda et al. (2010).

	Main Basin	**Discharge 2018-2023 (m^3/s)**	**Bankfull Depth (m)**	**Bankfull Width (m)**	**Bankfull Discharge (m^3/s)**
Balcez	Alcanadre	Min (2022) = 49.6 Max (2020)= 157.05 Med=3.89 SD=4.25	1.0	9.0	42.6
Formiga			0.8	13.6	28.2
Gorgas Negras			1.6	2.1	29.3
Mascún			0.4	22	18.0
Palomeras			0.8	8.5	12.7
Peonera	Flumen	Min (2019) = 0.052 Max (2021) = 19.27 Med=0.87 SD=0.98	0.7	10.6	9.7