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Biogeomorphological floodplain dynamics along a degradation gradient of an Alpine river

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Abstract

Channel migration, furcation, and vegetation succession are characteristic processes of braided gravel rivers in Alpine regions. These are associated with a frequent turnover of large parts of the active floodplain. However, more than one century of river regulation has reduced or destroyed most of these ecosystem dynamics. More recently, there have been attempts to restore at least some sections of degraded rivers, while there is little monitoring of the biogeomorphological dynamics of such rivers. Thus, we did a four-year analysis of four representative sections of the upper River Isar in Southern Germany differing in their degree of naturalness. Dynamics of channels, gravel bars, and vegetation were recorded by drone images, and braiding and gravel indices were calculated. When comparing the near-natural, semi-natural, degraded or restored sections, there was a gradient of decreasing channel migration, gravel bank expansion, and bank erosion due to a reduced turnover frequency. Biogeomorphological variation among years correlated with log peak discharge within the four sections. In addition, the cover and height growth of vegetation increased with river degradation, and channel migration was positively related to the braiding index. The total turnover of the active river corridor and of the vegetation were positively correlated with log peak discharge within the four sections. The floodplain dynamics of the restored section were improved compared to the degraded section but did not reach a near-natural state. Thus, Alpine river sections with contrasting degrees of naturalness differ in terms of habitat turnover and vegetation succession, and these characteristics can only partially be restored by local measures.

KEYWORDS

braided river, channel migration, floodplain turnover, gravel index, patch dynamics, river restoration

1 | INTRODUCTION

Patch dynamics is an important driver of biodiversity and ecosystem functions (Allan & Castillo, 2007; Pickett et al., 1999). Braided rivers are an example of an ecosystem in which patch dynamics play a critical role (Hohensinner et al., 2018). The main causes of this habitat turnover are regular flood pulses and their peak discharge (Ward & Stanford, 1995), and braided rivers are characterized by frequent changes in their biogeomorphological patterns (Tockner et al., 2010). Bedload transport and channel migration create and destroy low gravel bars, and major floods eliminate most vegetation due to high bedload transport (Ashmore et al., 2011; Belletti et al., 2017; Stanford et al., 1996; Surian, 1999). Both vegetation and deadwood contribute to shaping river biogeomorphology (Bertoldi et al., 2009), with deadwood supporting furcation and braiding, and succession counteracting these processes. High and dense vegetation supports the stabilization of gravel bars and leads to a narrowing of the active river corridor (ARC, or "braidplain"), that is, the gravel-dominated part of the active floodplain that is not covered by alluvial forest (Warburton, 1996). Old, high, and often densely vegetated islands, terraces, and banks may be removed through bank erosion, which reactivates stabilized gravel and contributes to the preservation of a wide and open active river corridor.

Whereas channel migration, furcation, erosion and sedimentation increase floodplain turnover (Tockner et al., 2006), the development of vegetation accumulates and stabilizes sediments (Gurnell et al., 2001; Kollmann et al., 1999). Therefore, habitat turnover and vegetation succession are the main factors that determine the specific mosaic of channels, bars and islands, and they are controlled by stream power, sediment composition, discharge variability, and vegetation structure (Ashmore et al., 2011; Bertoldi et al., 2009). Within a reach, stream power and sediments are more or less constant and determine braiding intensity, while discharge and vegetation vary over years and thus are decisive for habitat availability. Together with floods and more small-scale inundation of the riparian zone, these processes maintain a diverse, constantly changing mosaic of more or less open habitats that support metapopulations of specialized animal and plant species (e.g., Woellner, Bräuchler, et al., 2022).

Over the past century, human interventions have negatively affected river morphology, for example, in Central Europe (Tockner et al., 2022; Woellner, Wagner, et al., 2022). Alterations to the discharge characteristics of a river or changes to its geomorphological basis such as modifications of the channel morphology, bedload relocation, or the incision of the watercourse affect biogeomorphical complexity including vegetation and ecosystem services (Cullum et al., 2008; Jaehnig et al., 2022; Wu & Loucks, 1995). Channelization and dikes alter drainage patterns and discharge regimes, and limit the active river corridor and its spatio-temporal variability (Scorpio et al., 2018; Surian & Rinaldi, 2003). Water withdrawals and discharge regulation for flood protection reduce the frequency, peak height, and extent of floods, leading to temporal water deficiency, reduced inundation of the riparian zone, less transport of bedload and deadwood, and decreased habitat turnover (Bristow & Best, 1993; Tonolla et al., 2021). Dams and other transverse structures hold back the sediments and cause bedload shortages downstream, sometimes aggravated by gravel mining (Batalla, 2003; Gilet et al., 2023). The missing bedload and reduced habitat turnover, often combined with eutrophication and prolonged growth period of the vegetation, favor woody succession that further stabilizes and narrows the active river corridor (Picco et al., 2017). Suppressed processes that maintain a dynamic habitat mosaic, reduce valuable early-successional habitats, and the associated populations of specialists disappear. Alpine rivers, with their fluctuating discharge regime, flood risks, steep bed slope, and deep valleys, are particularly suitable for hydropower, and thus are mostly in poor conditions (Woellner, Wagner, et al., 2022).

In Europe, various restoration efforts have been made under the Water Framework Directive with the aim of improving naturalness of rivers. However, restoration measures are often done without the reestablishment of bedload transport and of a natural discharge regime (Wohl et al., 2015). The focus has been almost exclusively on structural features and the aquatic fauna, while efforts to restore terrestrial ecosystem processes have been limited (Carvalho et al., 2019), and many projects have not been successful (Habersack & Piégay, 2007; Woellner, Wagner, et al., 2022). Moreover, current monitoring of restoration success covers mainly floodplain structure and fish fauna. In addition, most restoration projects have included river sections of a few 100 m, due to constraints such as the availability of land, flood protection of infrastructure, or costs. Small-scale measures show limited success, whereas large-scale measures lead only to short-term improvements of the respective section (Woellner, Wagner, et al., 2022; Scorpio et al. 2020), while few projects have restored bedload continuity or the original discharge regime.

Unfortunately, scientific data on the original, degraded or restored states are lacking for most Alpine rivers. It is, therefore, not possible to monitor success in terms of restoring the original ecosystem processes, while the restored sections can be compared to the last remaining reference rivers, that is, the Tagliamento in North East Italy (Tockner et al., 2003) or the Upper Isar in Southern Germany (Woellner, Wagner, et al., 2022). The latter is an instructive example with near-natural, degraded, and restored sections that allow disentangling the drivers of biogeomorphological floodplain dynamics along a gradient of naturalness.

Thus, we studied bedload turnover and successional processes in four contrasting sections of the Upper Isar over 4 years. Three sections ranged from near-natural to heavily impacted due to straightening, discharge control, embankment fortification, and bedload deficiencies. The fourth section was a 6.5-km long stretch with embankment removal and implementation of a residual discharge.

Our study addresses the following questions:

1. How do Alpine river sections with different degrees of naturalness differ in terms of habitat turnover and vegetation succession?
2. How does annual variation in discharge affect these two drivers of floodplain dynamics within a section?

3. To what extent can turnover processes be reinforced by improving local river morphology without restoring the discharge and bed-load regime?

2 | METHODS AND MATERIALS

2.1 | Study sections

The Upper Isar extends from its source in the Karwendel mountains to Bad Tölz in the forelands of the Bavaria Alps (Figure 1). Within the past centuries, some sections of this reach were subject to extensive regulations for flood protection and hydropower generation (Maier et al., 2021). For our study, we selected three sections, each roughly 3 km in length and in different states of naturalness, and a fourth section that was degraded but has been restored in 1996 (Table A1).

The near-natural section ("Vorderriss") is situated between the Vorderriss bridge and the bedload barrier at the Sylvenstein reservoir. It is affected by water abstraction and reduced gravel transport at the Kruener weir. Thus, peaks of high floods are reduced, small floods are not passed on, and flood duration is moderated. However, the missing bedload is partially compensated for by the Rissbach, which provides substantial bedload input upstream of this section. The active river corridor takes up almost the entire valley.

The semi-natural section ("Wallgau"), extends 3 km upstream of the Rissbachduekker. Like the near-natural section, it is affected by

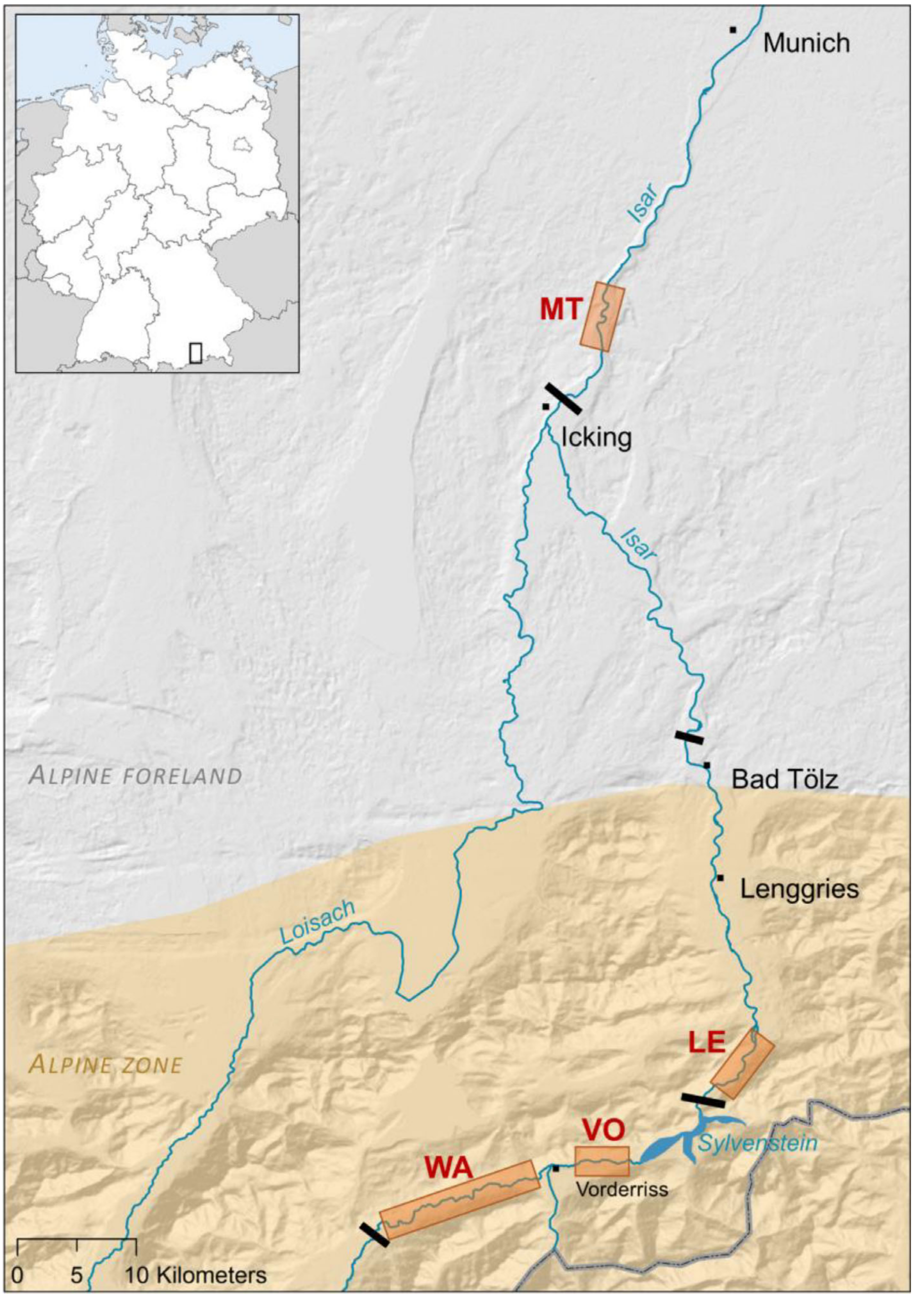

FIGURE 1 Study sections on biogeomorphological dynamics of River Isar within the Bavarian Alps. The near-natural section Vorderriss (VO) and the semi-natural section Wallgau (WA) are influenced by the Kruener Weir (black bar) and the tributary Rissbach. The degraded section Lenggries (LE), downstream the Sylvenstein reservoir, and the restored section Muehltal (MT) north of the weirs of Bad Tölz and Icking, are both affected by discharge regulation and sediment deficits. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Slope, daily mean, maximum, and peak discharges (Q > MHQ) for the four study sections of the River Isar in the years 2018–2021. Discharge measurements were taken from the nearest river gauge stations "Rissbachdüker" (ID 16001303), "Abfluss Sylvenstein" (ID 16002500) and "Puppling" (ID 16004403); daily discharge data of the respective stations was obtained from the Bavarian State Institute of the Environment (LfU Gewässerkundlicher Dienst, 2023).

Name	Section	Slope [°]	Mean discharge MQ [m^3]	Mean maximum discharge MHQ [m^3]	Peak discharge 2018–2019 [m^3]	Peak discharge 2019–2020 [m^3]	Peak discharge 2020–2021 [m^3]
Vorderriss	Near-natural	0.0051	4.8	101	130	157	361
Wallgau	Semi-natural	0.0054	4.8	101	130	157	361
Lenggries	Degraded	0.0064	15.1	154	131	165	222
Mühltal	Restored	0.0022	38.5	299	624	405	263

the Kruener weir, but the retained gravel is not compensated for, and it is strongly affected by water withdrawal and sediment shortage. The active river corridor is narrowed, and large parts have been subject to succession and are densely vegetated.

The degraded section ("Lenggries") is situated below the Sylvenstein dam. The dam acts as a bedload trap and is an effective discharge modifier. During the past century, the river channel has been repeatedly straightened, and the embankments partially fortified (Heckmann et al., 2017). Following the erection of the dam, large parts of the active river corridor became immobilized resulting in rapid succession. The remaining active river corridor leaves only a little space for gravel bars.

The restored section ("Muehltal") was straightened as a diversion channel with a fortified embankment in 1927. Since the 1950s, it has been additionally affected by the regulatory measures upstream and the Sylvenstein reservoir. In the year 1995, the embankments were removed along a 6-km stretch, and a residual discharge was established. Thus, this section represents one of the largest river restoration sites in Europe. Despite these improvements, it still suffers from massive bedload deficits due to the upstream Sylvenstein dam and the discharge control, while the effectiveness of restoration has not been quantified (Binder et al., 2015; Maier et al., 2021).

2.2 | Discharge data

The amount of transported bedload depends on the stream power, which is a function of bed slope and discharge (Ferguson, 2005). Bed slope is ca. 5% in three sections, while the restored section has a slope of ca. 2% (Table 1). Peak discharge is a major determinant of gravel transport (Vázquez-Tarrío et al., 2019). To account for multiple flood events per year, periods above mean maximum discharge (MHQ) were determined, and the peak discharges of each period were summed. Mean discharge (MQ), mean flood discharge (MHQ) and the respective annual peak discharges during the study period varied among the four study sections, depending on rainfalls, tributaries, and degree of discharge regulation.

2.3 | UAV data acquisition

In the summers of 2018–2021, geotagged *nadir* aerial images were produced for each study section using a DJI Phantom 4pro UAV with a standard RGB camera. All flights were done at mean water level to allow comparisons among years. Mission planning was done with MapPilot pro App; flight height was 40 m above ground, speed 4 m/s, and image overlap was 80%.

The processing software AgiSoft Metashape 1.8.2 was used to stitch orthomosaics and generate digital terrain (DTM) and digital surface models (DSM) via the surface from motion approach, following the "Best Practice Tutorial DJI Phantom 3 Professional" (Woellner & Wagner, 2019). Ground points were automatically identified by MetaShapes ground point classification tool (Röder et al., 2017) with a maximum distance set to 0.1 m, angle set to 20°, cell size 10 m, and an erosion radius of 0.02; all data were projected to UTM32. The resulting orthomosaic had a resolution of ca. 2 cm/px, the elevation and terrain models had a horizontal resolution of ca. 5 cm/px, and a vertical resolution of ca. 7 cm/px.

Orthomosaics were georeferenced to match the respective images from 2018. The identified reference points were subsequently applied to the respective elevation and terrain models. To match the heights of the different terrain models, further reference points were used.

2.4 | GIS data preparation

Based on the orthomosaic, the active river corridor and water channels were manually delineated, digitized, and converted to raster data. Vegetation cover was derived from the RGB orthomosaics by calculating the excessive green vegetation index (E × G) and applying Otsu's thresholding as described by Woellner and Wagner (2019), resulting in a binary raster with cells with vegetation coded by 1, unvegetated cells by 0. Vegetation height was calculated by subtracting the DSM from the DTM model and dividing the results by the raster with vegetation cover. Thereby, raster cells that do not represent vegetation became "no data" and were ignored during resampling.

For further analysis, the resulting raster data for turnover, cover, and vegetation height were finally aggregated by applying average function into congruent rasters with 5 m × 5 m resolution. Rasterized active river corridor and river surface of the respective years were resampled to match the raster data, and used as masks for further analyses.

2.5 | Analysis of braiding and turnover

Mosley's braiding index (BI), that is, the total channel length per length of the main channel (Egozi & Ashmore, 2009; Mosley, 1981) was calculated for the individual years and sections, and the river courses were overlaid to visualize the river dynamics. Three aspects of floodplain turnover were quantified, that is, bank erosion, changes of the river course, and height changes of existing gravel bars or terraces (for a summary of the terms and parameters used in this study, see Appendix, Table A2). Changes of contiguous cells from land to water that were in direct connection with the river were classified as "bank erosion;" other changes from water to land and vice versa were classified as changes of the river course ("channel migration"). Height changes of existing gravel bars and terraces were classified as "surface changes." Here, elevation changes of <10 cm were ignored due to the resolution of the elevation models. In general, negative changes (erosion, abrasion, change from land to water) were coded by "−1," positive changes (accumulation, change from water to land) by "+1," and unchanged cells were set to "0." The turnover frequency of each cell was determined by summing up all changes (either positive or negative) during the study period.

Finally, the changes in densely vegetated gravel bars were traced because their turnover is particularly important for maintaining the active river corridor. Cells with >20% vegetation cover were selected, the percentage of cells that were turned over each year was determined, and the average yearly turnover probability for a cell within the respective section was calculated. Yearly total turnover (in percent of active river corridor) and the proportion of cells with >20% vegetation turnover each year were related to the logarithm of the summed peak discharge and slope, and the fit was determined using simple linear regression.

2.6 | Quantifying vegetation succession

To characterize successional processes in each section, the changes in vegetation cover and height were recorded. Based on the original, non-aggregated cover raster data, annual changes in vegetation cover, and the gravel index (see Woellner, Wagner, et al., 2022) were calculated. The gravel index is the proportion of non-vegetated area of the active river corridor minus the proportion of vegetated area and ranges from 1 (100% open area) to −1 (100% vegetation), water courses are not included. The height increase of the vegetation was determined by subtracting the vegetation height at the end of the study period (2021) from the beginning (2018), and selecting all cells with values ≥0. The total increase was calculated as the average of all selected cells. Furthermore, the increase in vegetation height of the areas with different turnover frequencies (never, once, twice, thrice) was quantified.

2.7 | Correlations among environmental factors

The correlations of discharge values (MQ, MHQ, peak discharge, annual peak discharge sum), turnover (total turnover, bank erosion, channel migration, surface change), and succession (increase in vegetation cover and vegetation height) were calculated with non-parametric Spearman rank analysis.

3 | RESULTS

3.1 | Differences in braiding of the four river sections

Gravel relocation areas with furcation patterns were only found in the near-natural section and to a lesser extent in the semi-natural one. Very limited braiding occurred in the restored section, and practically no braiding in the degraded section (Figure 2). The BI of the study sections remained largely stable in the years 2018–2021 (Table A3), with the highest values (1.6–1.7) in the near-natural section and lowest values in the degraded one (1.2–1.4).

The active braided plain was restricted to the river sections with low gravel banks that make up about 50% of the area of the active river corridor in the restored and the degraded sections. Higher islands and terraces (>1 m above MQ) were fixed and only occasionally flooded without gravel relocation but infrequent overgraveling (Figure 3b). Changes in these areas were mainly caused by side erosion. Inactive side channels were flooded during high discharge (Figure 2).

3.2 | Habitat turnover

The highest total gravel relocation occurred in the near-natural section, with a total turnover rate of 30% per year (Table 2); >18% of the active river corridor was turned over by channel migration. Aggradation and degradation on existing gravel bars and terraces were high, comprising almost 10% of the active river corridor; in contrast, bank erosion was low (ca. 1%).

The overall turnover of the semi-natural section was with ca. 18% also relatively high, but clearly lower compared to the near-natural one. Bank erosion was low, as were surface changes. Areas of de- and aggradation were in balance and affected small sections of existing (mostly) low gravel bars. Minor aggradation and overgraveling occurred on the older terraces (Figure A1) but did not result in larger surface changes.

Overall turnover of the restored section was as high as in the semi-natural section but was essentially due to bank erosion that occurred along the cut banks and at the edge of the older terraces. The resulting widening of the active river corridor was up to 15 m per year (Figure 2). However, there was considerable surface relocation on the existing younger gravel bars.

The degraded section showed the lowest turnover, that is, only 4% of the active river corridor was affected per year. In this section, the position and shape of most gravel bars remained largely unchanged and there was almost no bank erosion. Dominant turnover was due to smaller channel migrations.

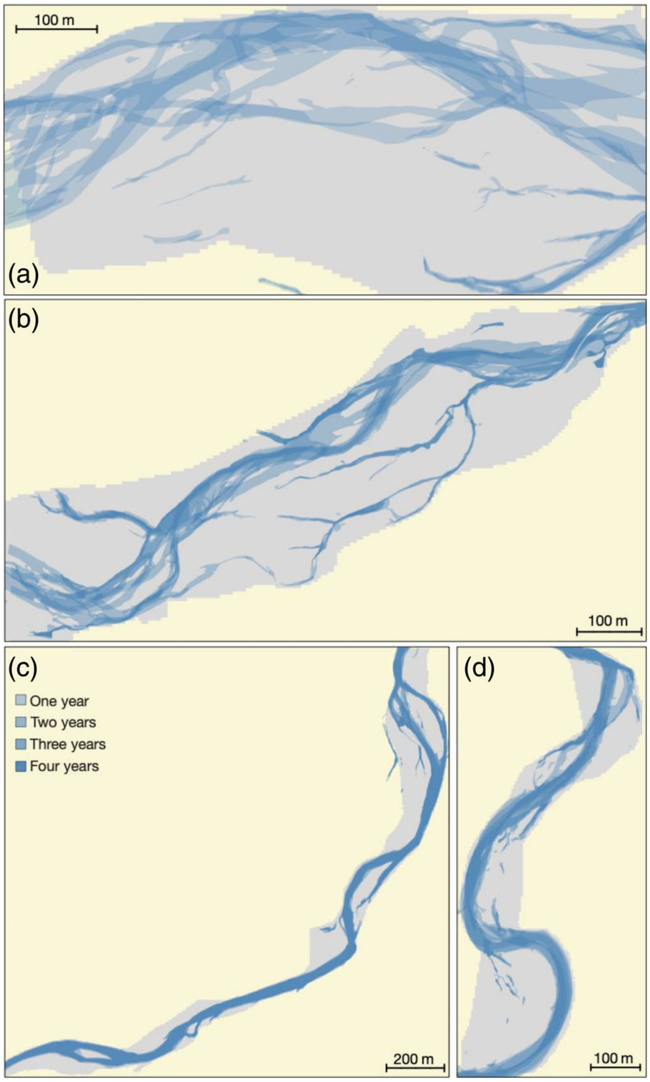

FIGURE 2 Shifting course of the River Isar in four study sections in the years 2018–2021. The near-natural (a; Vorderriss) and semi-natural section (b; Wallgau) showed furcation patterns while in the degraded section (c; Lenggries) and the restored section (d; Mühltal) only low braiding intensity occurred. Darker blue indicates that river channels more frequently occupy this area, while a gray background marks the active river corridor. [Color figure can be viewed at wileyonlinelibrary.com]

Turnover probability was highest for the near-natural section with almost a third, followed by semi-natural and restored sections with 0.16 and 0.17, and lowest in the degraded section with only 0.05 (Table 3). Broken down to turnover frequency classes (Table A4), the near-natural section again showed the highest numbers and frequencies of relocations; here, 10% of the active river corridor changed every year. However, almost half of the area of the active river corridor remained completely unchanged within the study period. The semi-natural section had considerably lower turnover frequencies and the degraded section had the lowest turnover. Turnover in the restored section was intermediate between the near-natural and the semi-natural sections, and most of the change was caused by single events, with multi-turnovers being rare. Regardless of the turnover frequency, in all study sections, the relocation areas occurred almost exclusively in the active braidplain (Figure 3).

3.3 | Vegetation dynamics

Changes in the cover and height of vegetation within the active river corridor showed different trends depending on the degree of naturalness of the four sections (Figure 3). With about 15% vegetation cover, the near-natural section was gravel-dominated, while the others ranged between 37% and 56% (Table 3). Vegetation cover remained stable or even decreased slightly in the near-natural and semi-natural sections, but it markedly increased in the degraded section from about 37% to 44% in the years 2018–2021, and even more pronounced in the restored section from 44% to over 56% (Table A5). While the active river corridor here was still gravel-dominated in 2018, vegetation clearly prevailed after 4 years at the end of the study period (Figure 3), and a widening of the active river corridor occurred mostly via erosion of the impact slopes (Figure A2).

In the near-natural section, the average gain in vegetation height was only 0.04 ± 0.06 m in 2018–2021 (Table 3), with the increase being slightly greater on non-overturned areas than on multiple overturned areas. In areas that had turned over each year, the increase practically was zero (Table A6). In the semi-natural section, the average increase of vegetation height was 0.26 ± 0.72 m, whereby the increase in the stable areas with ca. 40 cm was clearly higher than in areas with multiple turnovers, while in the degraded section, the average increase was similar (ca. 0.23 m), but largely independent of turnover frequency. The highest height increments occurred in the restored section, where the average increase was ca. 1 m. In this section, the most significant growth occurred in the areas that were never turned over during the study period, and the height increment reached ca. 2 m. Even in the case of areas that have been turned over only once or twice, the increase is significantly higher than in the other sections. This development is documented by the aerial photos of the respective sections (Figure 3).

3.4 | Turnover and succession in relation to braiding and discharge

There was a close correlation between BI and channel migration (Figure 4), and weaker one between BI and surface change or total turnover (Table A7). No correlation existed between BI and bank erosion, vegetation cover, and vegetation growth.

Across the different river sections, none of the discharge parameters correlated with the different turnover classes. Within each section, however, there was a positive relationship between the peak discharge and total turnover. No clear relationship existed between bank erosion and surface changes. There were also no correlations between vegetation cover, height, turnover, or discharge.

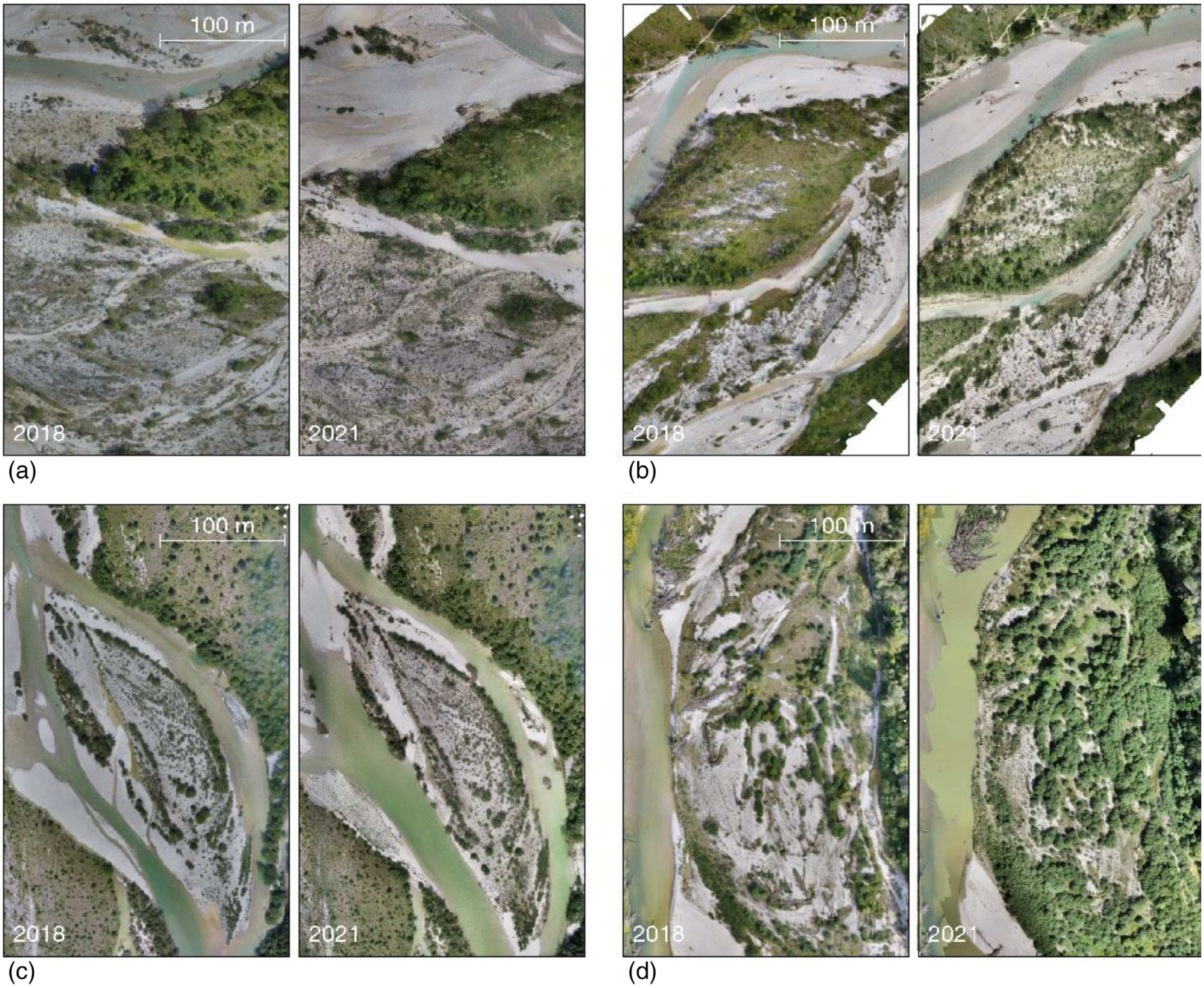

FIGURE 3 Examples of biogeomorphological dynamics of four sections along the River Isar in the years 2018 and 2021 (a) The near-natural section (Vorderriss) with minor increase in vegetation cover but marked bank erosion at the older, densely vegetated terrace; (b) the semi-natural section (Wallgau) with marked bank erosion and obvious decrease in cover due to over-graveling on the older terraces; (c) the degraded section (Lenggries) with only slight bank erosion and hardly any increase in cover and height; and (d) the restored section (Muehltal) with the pronounced increase both in vegetation cover and vegetation height. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Habitat turnover of four sections at the River Isar in the years 2018–2021. The average proportion of the area of the active river corridor that is overturned per year in total and broken down according to the different relocation processes, that is, channel migration, gravel bank expansion, and bank erosion (means ± SD).

Name	Section	Migration (%)	Expansion (%)	Erosion (%)	Total (%)
Vorderriss	Near-natural	18.7 ± 4.3	10.4 ± 3.2	1.2 + 0.6	30.3 ± 4.1
Wallgau	Semi-natural	13.3 ± 3.0	2.9 ± 0.8	1.5 ± 0.9	17.8 ± 4.2
Mühltal	Restored	8.3 ± 2.8	6.0 ± 1.1	4.3 ± 1.3	18.6 ± 5.0
Lenggries	Degraded	2.9 ± 0.1	1.3 ± 0.4	0.2 ± 0.3	4.3 ± 0.5

TABLE 3 Probability of habitat turnover, braiding index, vegetation cover, and height increment within the four sections of the River Isar in the years 2018–2021 (means ± SD).

Name	Section	Turnover [*p*]	Braiding index	Vegetation cover [%]	Vegetation height increase [m]
Vorderriss	Near-natural	0.27	1.65 ± 0.05	14.0 ± 1.8	0.04 ± 0.06
Wallgau	Semi-natural	0.16	1.49 ± 0.05	51.4 ± 2.0	0.26 ± 0.72
Mühltal	Restored	0.17	1.28 ± 0.05	49.4 ± 5.6	0.92 ± 1.04
Lenggries	Degraded	0.05	1.21 ± 0.01	39.5 ± 3.4	0.23 ± 0.45

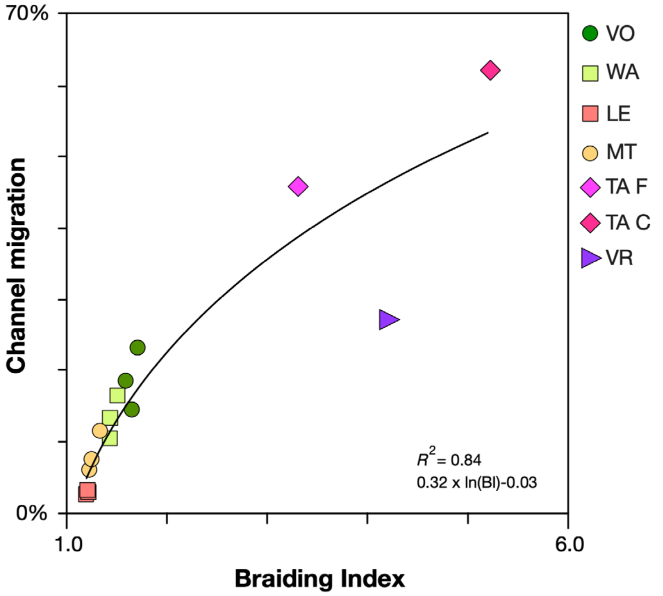

FIGURE 4 Percentage of turnover of the active river corridor that is caused by channel migration for the Isar sections (VO, near-natural; WA, semi-natural; LE, degraded, MT, restored) and for two reference sections of the Tagliamento River (TA F, TA C; Welber et al., 2012) and Val Roseg (VR; Zah et al., 2001). The line corresponds to the respective logarithmic linear model; the formula and R^2 are given. [Color figure can be viewed at wileyonlinelibrary.com]

Apart from the degraded section, all sections exhibited a positive, quasi-linear relationship between the proportion of turnover and log peak discharge in the respective section and period (Figure 5). While the slopes of the semi-natural and near-natural sections were similar, the turnover rate in the restored section increased more steeply. In the degraded section, an increase in discharge did not lead to a significant increase in the turnover rate.

4 | DISCUSSION

4.1 | How are bedload turnover and succession affected by river degradation?

The four study sections of the River Isar showed clear differences regarding the extent and frequency of habitat turnover and development of vegetation. A lower degree of naturalness was associated with reduced turnover and more succession, and human interventions caused a reduction in the width of the active river corridor that is associated with lower braiding intensity, less channel migration, and turnover, similar to other rivers in the Alps (Picco et al., 2017; Surian et al., 2009; Surian & Rinaldi, 2003). At river Isar even in the near- or semi-natural sections, the active braidplain was limited by older, stable terraces and islands leading to a braiding area of 30%–50% of the active river corridor (degraded section 15%). The BI was <2, and well below the values for reference sections of the Tagliamento with 3–7 (Van der Nat et al., 2003; Welber et al., 2012).

Bedload turnover was almost completely restricted to the active river corridor. Channel migration, surface changes, and bank erosion were differently related to the braiding intensity. The annual turnover probability decreased with degradation and correlated with the BI and channel migration rate. Irrespective of the section, most turnover was through channel migration, affected sparsely vegetated lower gravel bars, and directly related to braiding. The intensity of bank erosion and surface changes was less connected to braiding. Turnover by channel migration in the near-natural section, though, reached only 18% of the braidplain, while it was 46%–62% at the Tagliamento (Welber et al., 2012).

Surficial changes, that is, erosion and aggradation, were generally very low in all sections. The highest proportions were found in the near-natural one, where roughly 10% of the active river corridor (mostly lower gravel bars) was affected. The lack of significant surface changes in the other study sections may be explained by a narrow active river corridor leading to incision and a more direct run-off, and the bedload deficit caused by the Kruener weir and the Sylvenstein dam. In the near-natural section, the bed load deficit was partially compensated for by the tributary Rissbach that supplies larger amounts of gravel. There the braidplain widens so that the flow velocity decreases and the sediment becomes deposited. These regular deposits support braiding, and the associated regular turnover prevents large-scale succession in this section. Though some overgravelling and sediment deposition were visible on high terraces, this was not reflected in measurable elevation change, probably due to the accuracy of elevation data of ±10–15 cm. Nevertheless, even these slight but often large-scale overgraveling contributes to the creation of new open areas for the establishment of early-successional plant specialists, such as *Chondrilla chondrilloides* or *Myricaria germanica* (Woellner, 2023).

The older, mostly higher, and densely vegetated gravel bars and terraces were mostly eroded by bank erosion (Figure 3a). This occurred to a notable extent on the impact slopes. The extent of bank erosion in the respective sections was generally low. For example, in Wallgau, only about 2500 m^2 of a 13,000 m^2 vegetated island were removed by bank erosion within 3 years. It would therefore take at least 15–20 years for this island to get completely eroded. Along the restored section, the massive erosion of the densely forested banks resulted in a large input of dead wood that accumulated on the gravel bars (Figure 3b). However, the deadwood released did not promote furcation, as could be expected for island formation processes in natural rivers (Gurnell et al., 2001). Apart from the widening of the active river corridor through bank erosion, channel migration was low.

There were also large differences in turnover frequencies between the study sections: while in the near-natural section turnover of the active river corridor takes on average 4 years, it takes 6 years in the semi-natural, and more than 18 years in the degraded section, with marked consequences for vegetation development. Turnover rates at the Isar thus remained significantly below the turnover rates of ca. 50% within 5–6 years observed at the Tagliamento (Surian et al., 2015). The near-natural section was clearly gravel-dominated (Figure 3a) caused by the large active river corridor and braidplain, high turnover, and high bedload availability. Here, the gravel index corresponded well to the

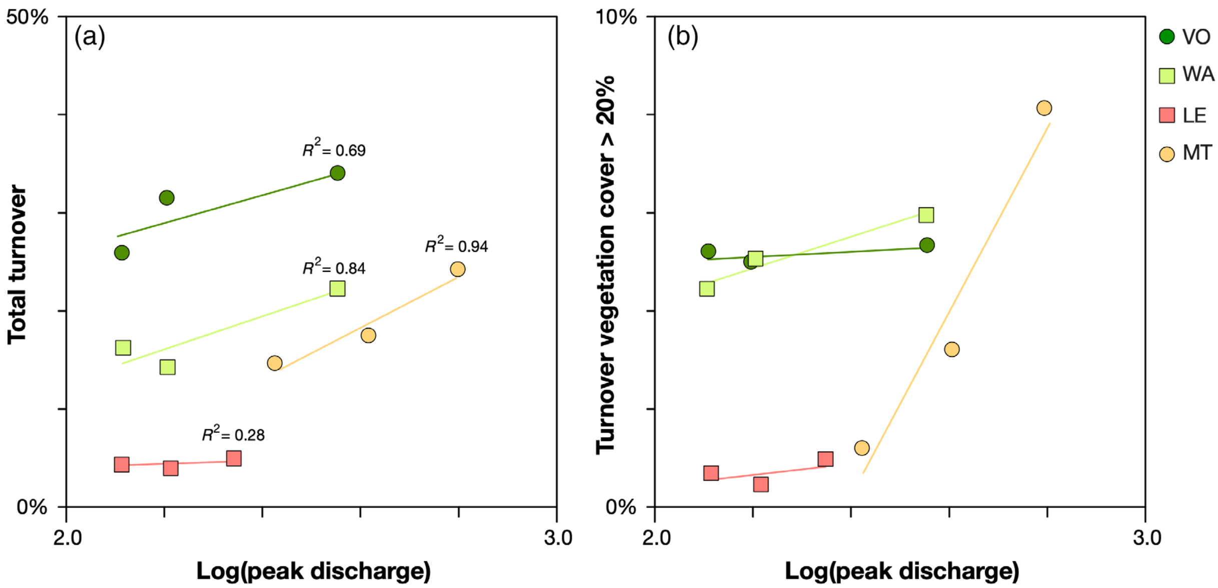

FIGURE 5 Turnover in relation to discharge in differently degraded sections of the Isar: near-natural (VO, Vorderriss), semi-natural (WA, Wallgau), degraded (LE, Lenggries), and restored section (MT, Muehltal). (a) Proportion of overturned area of the active river corridor in relation to the log of the peak discharge during the year; and (b) proportion of overturned area with a vegetation cover of more than 20%. [Color figure can be viewed at wileyonlinelibrary.com]

section of the Tagliamento at Cornino (0.66) but did not reach the values at Flagogna (0.81) or Spilimbergo (0.95; all T.C. Wagner, unpubl. data). The changes in the gravel index were only slight in the study period (Figure A3).

In contrast, the proportion of vegetated and open areas in the semi-natural section was balanced. Despite the relatively high turnover rates, large parts of the active river corridor were taken up by densely vegetated islands. Here, reduced discharge and bedload deficit result in moderate incision (Reich, 1991), and the formation of a narrower braidplain. Since the increase in the residual water flow in 1990, high and dry areas (previously sparsely vegetated) were supplied with sufficient groundwater and grew over rapidly. However, the stable values of the gravel index indicate that this succession has come to a halt today. In fact, the situation slightly improved during the study period. Despite these improvements, however, the bedload deficit largely prevents the remobilization of the older islands and the creation and subsequent maintenance of a wider braidplain (see Gurnell et al., 2009).

Also, in the degraded section open areas dominated, even if the braidplain and the active river corridor were narrow. Channelization of this section causes gravel bars to flood more frequently and the little sediment transported was carried along with the flood, preventing the emergence of denser vegetation on the gravel bars.

4.2 | How does discharge affect floodplain dynamics?

Independent of the different turnover characteristics of the river sections of Upper Isar, there was a clear relationship between total turnover and peak discharge in Wallgau and Vorderriss (Figure 5): The turned-over area increased logarithmically with the peak discharge. In the degraded section, this correlation was missing. Bank erosion and surficial changes also showed no correlation to discharge values. Here, the bedload deficit caused by the upstream dam and the channelized morphology hindered mobilization of larger gravel areas even by high discharges. So, in channelized rivers with alternating bar morphologies, the highest migration rate of gravel bars is found under intermediate discharges and floods rather than causing a flattening of the bars (Adami et al., 2016).

Increased discharge, which might be expected to cause erosion of older terraces, had no effect on areas with >20% vegetation cover. This shows the interaction between vegetation and turnover (Serlet et al., 2018). On the one hand, undisturbed succession can only take place in more stable areas; on the other hand, high and dense vegetation also increasingly leads to the stabilization of these areas so that their turnover frequency decreases. This initiates a positive feedback loop that can then only be stopped by major erosion events, usually by extreme flooding. This problem is exacerbated within sections with bedload deficits, where abrasion of vegetation is low due to the low sediment load, even during larger floods.

Over the study period, the semi-natural and near-natural sections showed slight improvements as reflected by an increase in turnover and the proportion of open area, while the degraded section showed a slight degradation. This could be because flood discharge is moderated by the Sylvenstein reservoir, while discharge peaks are capped but passed on unchanged in time by the Kruener weir.

4.3 | Could floodplain dynamics be restored by river widening?

Twenty years after embankment removal and recreation of gravel bars, the restored section had a similar turnover as the near-natural one, with a yearly turnover of 18% of the active river corridor. However, a detailed examination showed that bank erosion accounted for a large part of the turnover, while channel migration and surface changes were low. The strong lateral erosion continued the trend of widening the active river corridor (Binder et al., 2015; Woellner, Wagner, et al., 2022) and indicates that the river has not yet reached its equilibrium after the removal of the embankment fortifications. As the channels create space for themselves, densely vegetated banks are eroded, thus explaining the high turnover rates of vegetated areas. This resulted in large amounts of dead wood, which accumulated on the gravel bars. However, unlike at the Tagliamento (Kollmann et al., 1999), it did not contribute to furcation and braiding but additionally protects the existing gravel banks in the slip-off slope from erosion.

Bank erosion created new space, but this did not lead to the formation of a wide braidplain, and the BI remained similar to the degraded section (about 1.2). Instead, the river started meandering, whereby the gravel banks in the slip-off slope became immobilized, vegetated, and were hardly turned over again. Reasons for the development of a meander morphology instead of widening the braidplain could be (i) lower bed slope (2%) compared to the other sections (5%), (ii) discharge regulation, and (iii) the bedload deficit. Altered discharge and bedload availability as a result of the dams and barriers upstream lead to further incision. The gravel bars in the slip-off slope were thus high above the water, less frequently inundated, and can lastly only be eroded by bank erosion (Serlet et al., 2018).

The resulting succession was also accelerated by the high content of fine sediments in the lower sections, and the high nutrient content of the water due to inflows from wastewater treatment plants. Thus, the sections moved from a gravel-dominated to vegetation-dominated braidplain during the study period, while the gravel index remained almost stable from 1995 to 2015 (Woellner, Wagner, et al., 2022). Strong vegetation development both in terms of cover and height reduces the large open areas and pioneer habitats (Binder et al., 2015), and the active river corridor is narrowing again.

In contrast to the degraded section, high discharge increased the turnover rate significantly. It can be explained by the high proportion of bank erosion along the restored reach that was positively affected by floods, while gravel bar formation or migration was more influenced by medium floods that support restoration success regarding gravel bar establishment (Woellner, Wagner, et al., 2022). With an average turnover every 5–6 years, the frequency of turnover was also relatively low compared to the Tagliamento (Surian et al., 2015).

4.4 | Implications for restoration

The historic interventions at Upper Isar with respect to discharge regime, bedload balance, and river morphology had massive negative effects on ecosystem processes, turnover, and succession. However, with a wide active river corridor, a gravel index of ca. 0.65, and a percentage of open space of over 85%, the appearance of the Vorderriss section corresponds most closely to what would be expected in a natural Alpine river, similar to the Tagliamento between Cornino and Flagogna. Thus, this section can be used as a reference for the restoration of River Isar. Additionally, the comparable natural morphology of this section, although impaired by water withdrawal, demonstrates the value of sediment input from the smaller tributaries. Where the longitudinal fluxes of the main river are disrupted by larger check-dams and their removal is unlikely, reconnecting tributaries and restoring their continuum can support the restoration of sections along the main river (Blackburn et al., 2023; Marteau et al., 2020).

Embankment removal is often applied with the assumption that the riverbed will subsequently widen by itself. For this, however, the restoration measures must be applied over a long stretch, and much time is needed to achieve results (Woellner, Wagner, et al., 2022). The studied restoration section was shifted to an ecologically better state but still is far from its original and reference state. The consequent re-installment of the natural discharge regime and the compensation of the gravel deficits caused by barriers and dams is an indispensable prerequisite to successfully restoring the natural river ecosystem following the paradigm of restoring not only structures but also processes (Palmer & Ruhi, 2019). Their absence leads, as in the presented example, to short-term improvements and subsequently through unprevented succession through a new equilibrium. Conservational measures, such as artificial diverters deflecting the flow and creating new impact slopes on older, stable terraces would initiate erosion and turnover processes.

4.5 | Methodological limitations

Though our results refer to the peak discharge, the frequency, time course, and also height of normal water level fluctuations vary and may thus affect the rates of succession and probably, but to a lesser extent, the bedload transport. The complex situation of different tributaries and the discharge control at the Kruener weir, Sylvenstein dam, and the Ickinger weir are further confounding factors. Also, the sections are to some extent interrelated in terms of bedload sedimentation. While the bedload deficit of the semi-natural section caused by the Kruener weir is still being compensated for in the near-natural one, the bedload blockage of the Sylvenstein dam continues from the degraded section to the restored section. In the restored section, the currently high bank erosion can compensate for sediment deficiency at present. Further, the increased discharge of nutrient-rich wastewater along the river course has an amplifying influence on succession. Additionally, the slightly warmer climate can lead to greater succession in the downstream, restored section. It also cannot be ruled out that geographical factors such as a greater slope or the respective valley geometry may affect flow velocity and, thereby, turnover rates.

The observation period of 4 years is relatively short for a dynamic river ecosystem with highly fluctuating discharge situations. However, there is no data with sufficient quality available for the preceding years. The resolution of aerials is insufficient, the coverage is patchy and not always available for the growth period, LiDAR data is lacking.

There is also a lack of studies with quantitative and comparable data on the condition of the respective sections. However, with the exception of two unusually high floods (>HQ50) in 1999 and 2005, the observed peak discharges cover practically the whole discharge range between 1990 and 2021 and can be seen as representative of low, medium, and high peak discharge rates.

5 | CONCLUSIONS

Rivers worldwide experience anthropogenic interventions and modifications (e.g., Tockner & Stanford, 2002). Despite the growing awareness of dire ecological consequences and increasing restoration efforts, a fundamental intensification of river regulation, for example, for power generation, is to be expected against the background of global change (Nilsson et al., 2005). The changing climate will alter precipitation distributions and thus discharge peaks, flood frequencies, and flood times. So, the need for more effective river restorations must be faced by considering these changing factors more carefully (Davies, 2010).

Our case study highlights the importance of flooding and peak discharge for the maintenance of turnover processes and thus short- to mid-term habitat formation of Alpine rivers. The effects of floods and discharge on habitat turnover were reduced in the degraded section by interventions in the river morphology, such as straightening and canalization or bedload deficits caused by the upstream dam and weirs. Consequently, restoration measures only focusing on removing embankment fortifications and restoring morphological aspects but not including the re-establishment of the former natural flood and bedload regime are less able to improve the ecological situation (Lorang et al., 2005; Stanford et al., 1996). In addition, the preceding impairment often leads to irreversible legacies such as channel incisions or fixed and densely vegetated terrasses that exercise a certain resilience against further ecological improvements (Corenblit et al., 2015; Wohl et al., 2015). Thus, restoration of Alpine rivers has to be implemented within entire reaches including all critical factors that drive biogeomorphical patch dynamics.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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APPENDIX A

TABLE A1 Characteristics and intervention of the four study sites at River Isar. The river sites differ in their active river corridor width (mean and standard deviation) and their gravel index, that is, the ratio between gravel bar area and active river corridor area, and thus a measure for intact river dynamics.

Name	Section	Interventions and impact	Habitats
Vorderriss VO	Near-natural	Most natural bed-load and discharge regime through Rissbach tributary, residual water stretch	Large open gravel bars dominant, natural turnover and succession
Wallgau WA	Semi-natural	Bed-load retention at Kruener weir, residual water stretch	Large gravel bars, high habitat diversity, reduced turnover, proceeded succession
Lenggries LE	Degraded	Channelization, bed-load retention, and discharge regulation by Sylvenstein reservoir	Few, consolidated gravel bars, sediment sorting, reduced turnover, proceeded succession
Muehltal MT	Restored	Embankment removed 1990, bed-load retention and discharge regulation by upstream dam and weirs, residual water stretch	Increased side erosion and development of gravel bars, reduced turnover, progressing succession through incision

TABLE A2 Parameters and terms used in the study, their definition (as used in this study), method applied for the determination and, if applicable, reference to the respective source.

Parameter	Description	Source/method
Annual peak discharge	Highest daily discharge during a year	Hochwassernachrichtendienst Bayern
Active river corridor (ARC)	Braidplain, that is, gravel-dominated part of the active floodplain that is not covered by alluvial forest	Warburton (1996), Woellner, Wagner, et al. (2022)
Annual peak discharge sum	Sum of daily discharges for days with discharge >MHQ	Hochwassernachrichtendienst Bayern
Orthomosaic	Orthorectified mosaic of UAV aerial images	UAV aerials
Digital surface model (DEM)	Height of surface (including vegetation)	Surface from motion; aerial UAV images
Digital terrain model (DTM)	Height of ground (without vegetation)	Surface from motion; aerial UAV images; automatic ground point identification
Vegetation cover	Vegetation cover (%)	Excessive green index (E × G), thresholding; derived from RGB orthomosaic; aggregated to 5 × 5 with average function
Vegetation height	Vegetation height (cm)	DEM-DTM
Terrain height above water level at mean discharge	Height above MQ (cm)	DTM-water level
Mosleys braiding index	The sum length of all channels related to the length of the main channel	Derived from orthomosaic
Gravel index	The proportion of the non-vegetated area of the active river channel minus the proportion of vegetated area; range −1 (100% vegetation) … +1 (100% gravel)	Derived from vegetation cover; Woellner, Wagner, et al., 2022
Bank erosion		Changes of cells adjacent to the water course that changed to water
Surface changes (aggradation, degradation)	Changes in surface elevation between years	Erosion, degradation, change from land to water: −1; accumulation, aggradation, change from water to land) by +1; unchanged cells 0
Channel migration	Change of the location of the water channels	Changes of cells that are not directly connected to the watercourse from water to land or vice versa
Turnover frequency	Number of turnovers during the study period	
Turnover probability		Derived from turnover frequency/time period
Overgraveling	Deposition of gravel on existing, vegetated gravel bars without measurable aggradation	Change from vegetated to gravel without measurable surface level change
Gravel relocation	Surface level change of unvegetated area	
Densely vegetated areas	Vegetation cover >20%	Raster with vegetation cover; cells >0.2
Active floodplain	Regularly flooded area, including vegetated/forested areas	

TABLE A3 Braiding Index of the four study sections of the River Isar in the years 2018–2021, ordered by decreasing naturalness.

Name	Section	2018	2019	2020	2021
Vorderriss	Near-natural	1.66	1.72	1.60	1.62
Wallgau	Semi-natural	1.44	1.45	1.53	1.54
Muehltal	Restored	1.35	1.27	1.24	1.24
Lenggries	Degraded	1.21	1.22	1.21	1.21

TABLE A4 Frequency of habitat turnover within the four sections of the River Isar in the years 2018–2021. Distribution of the turnover frequency classes within the different river sections and overall probability of yearly turnover.

Name	Section	Never [%]	Once [%]	Twice [%]	Thrice [%]
Vorderriss	Near-natural	47.1	23.0	20.3	9.6
Wallgau	Semi-natural	65.7	19.2	11.2	3.9
Muehltal	Restored	58.8	28.5	10.8	1.9
Lenggries	Degraded	86.8	8.9	3.5	0.7

TABLE A5 Vegetation cover [%] within the four study sections of the River Isar in the years 2018–2021.

Name	Section	2018	2019	2020	2021
Vorderriss	Near-natural	16.6	14.1	12.6	12.9
Wallgau	Semi-natural	53.9	52.1	49.5	50.2
Muehltal	Restored	44.4	45.6	51.1	56.5
Lenggries	Degraded	36.6	37.6	39.6	44.3

TABLE A6 Increase in vegetation height [m] within the four study sections of the River Isar in the years 2018–2021. Total increase and variation among four classes of habitat turnover.

Name	Section	Stable	One turnover	Two turnovers	Three turnovers
Vorderriss	Near-natural	0.07 ± 0.17	0.06 ± 0.14	0.04 ± 0.14	0.00 ± 0.03
Wallgau	Semi-natural	0.41 ± 0.90	0.37 ± 1.19	0.13 ± 0.43	0.10 ± 0.19
Muehltal	Restored	2.34 ± 1.76	0.56 ± 0.86	0.32 ± 0.59	0.22 ± 0.46
Lenggries	Degraded	0.23 ± 0.47	0.22 ± 0.45	0.21 ± 0.47	0.24 ± 0.48

TABLE A7 Spearman rank correlations between floodplain variables at the four study sections of River Isar (colored, rs >0.7). [Color table can be viewed at wileyonlinelibrary.com]

	Veg cover	Veg height	Total turnover	Bank erosion	Channel migration	Surface change
BI	−0.25	−0.39	0.87	0.28	0.95	0.76
MQ	0.15	0.63	−0.43	0.31	−0.66	−0.20
MHQ	0.16	0.63	−0.43	0.31	−0.66	−0.20
Peak discharge	0.00	0.50	0.20	0.59	0.00	0.27
$\sum$ Q > MQ	0.15	0.59	−0.37	0.34	−0.61	−0.18
Vegetation cover	-	0.80	−0.38	0.32	−0.25	−0.40
Vegetation height	-	-	−0.28	0.60	−0.32	−0.19
Total turnover	-	-	-	0.48	0.91	0.93
Bank erosion	-	-	-	-	0.32	0.60
Channel migration	-	-	-	-	-	0.76

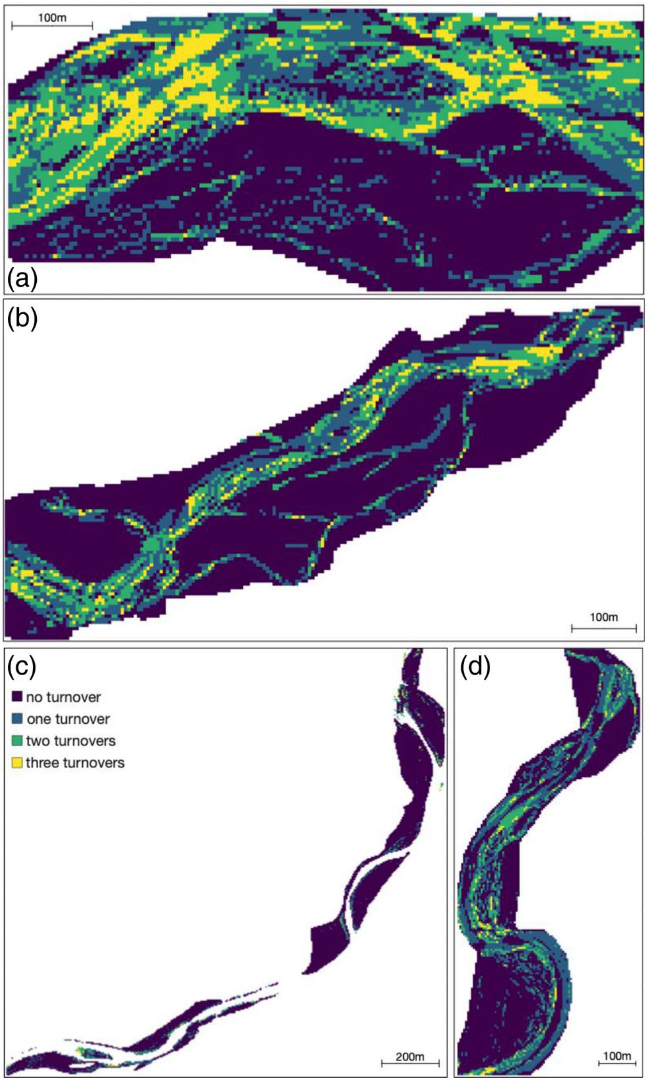

FIGURE A1 Distribution of turnover frequencies between 2018 and 2021 in the different river sections of the River Isar. Large-scale, frequent turnover in the near-natural section, covering approximately 50% of the active river corridor (a, Vorderriss); frequent but more restricted turnover in the semi-natural section (b, Wallgau), low turnover in the degraded section (c, Lenggries) and in the restored section (d, Muehltal). [Color figure can be viewed at wileyonlinelibrary.com]

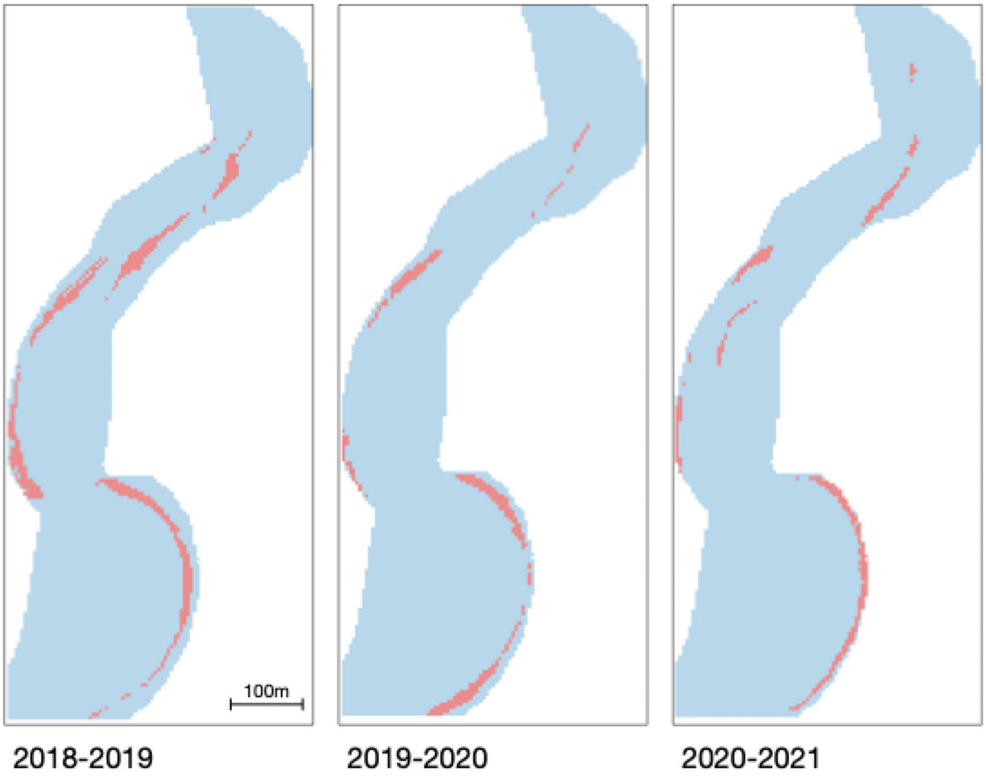

FIGURE A2 Bank erosion in the restored section (Muehltal) between 2018 and 2021. It is evident that only a widening of the active river corridor occurs via the attack of the impact slopes. [Color figure can be viewed at wileyonlinelibrary.com]

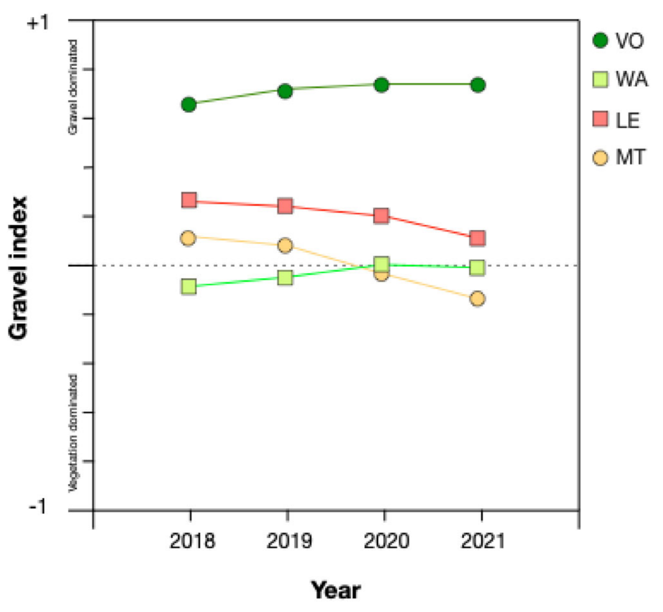

FIGURE A3 Changes of the gravel index of four contrasting sections of the River Isar in the years 2018–2021 near-natural (VO, Vorderriss), semi-natural (WA, Wallgau), degraded (LE, Lenggries) and restored section (MT, Muehltal). A value of 1 indicates 100% gravel cover, and a value of −1 that all land areas of the active river corridor are 100% covered by vegetation. [Color figure can be viewed at wileyonlinelibrary.com]