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RESEARCH ARTICLE

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Spatio-temporal patterns in degradation and restoration of gravel bars along Alpine rivers

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Abstract

Braided reaches were common along near-natural Alpine rivers, and the associated habitat dynamics supported plant and animal species specialized on early-successional stages. The extensive riparian zones could mitigate climate change by absorbing floods and by retaining water during droughts. Human impacts largely reduced active river corridors through altered discharge and construction of dykes, while recent restoration projects aim at increasing river dynamics. The causes and consequences of Alpine river degradation are well understood, but there are only few quantitative studies on floodplain degradation and restoration. Thus, we have reconstructed historical changes of gravel bars along five Alpine rivers (Iller, Inn, Isar, Lech, and Wertach) in Southern Germany in the period 1808–2009, based on historical maps and aerial images. We found losses of >90% in gravel bar area along these rivers since the mid-19th century. The decline was caused by a reduction of the active river corridor and by ongoing succession of the remaining open habitats. Within the past 30 years, at the Isar River, restoration measures were realized with the aim to widen the active river corridor and to recreate gravel bars. In four restored reaches, we found that 5% of the historical gravel bar area recovered, and that the proportion of restored gravel bar area was highest after intermediate flooding. We conclude that the active river corridors of German Alpine rivers are almost completely lost, and that more extensive restoration needs to be done to preserve the habitat dynamics and biodiversity of these systems, and to adapt Alpine rivers to climate change.

KEYWORDS

active river corridor, Alpine rivers, degradation, gravel bar dynamics, remote sensing, river restoration

1 | INTRODUCTION

Freshwater habitats are experiencing a major biodiversity crisis, and despite their high conservation value, they face critical threats (Dudgeon et al., 2006; He et al., 2019; Reid et al., 2019). Besides reduced water quality, hydromorphological alterations are the dominant causes of river degradation (Belletti et al., 2018; Wohl, Lane, & Wilcox, 2015). This is also seen in Alpine rivers and their associated riparian zones that are particularly dynamic under near-natural conditions, with high spatio-temporal habitat turnover (Hauer et al., 2016; Kollmann, Vieli, Edwards, Tockner, & Ward, 1999). Strong fluctuations in water discharge, sediment erosion, and deposition lead to the formation of braided-sections

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[The copyright line for this article was changed on 1 March 2022 after original online publication] with a diverse habitat mosaic (Driscoll & Hauer, 2019). The active channel of a braided river is affected by low and medium flow events and consists largely of open gravel and sand bars, and islands with pioneer vegetation (Edwards et al., 1999; Surian et al., 2015).

Before river regulation, braided Alpine rivers maintained extensive gravel plains reaching far into the foreland. During the past 200 years, their course was straightened and the remaining channels became confined between dykes (Comiti, 2012; Scorpio et al., 2018; Surian & Rinaldi, 2003). Thus, large parts of the once extensive floodplains were cut off, the no longer flooded areas were converted to forests or arable land (Herrmann & Sieglerschmidt, 2017; Jürging & Patt, 2005), and gravel extraction became common practice for obtaining building material. Thus, the altered discharge and the remaining narrow active river corridor (Campana, Marchese, Theule, & Comiti, 2014; Piégay, Alber, Slater, & Bourdin, 2009) no longer support wide and dynamic gravel plains. Furthermore, dams erected for hydropower inundate former floodplains, prevent flooding downstream, cause hydropeaking, and disrupt sediment transport (Brenna, Surian, & Mao, 2020), thus, further reducing the historical river dynamics, and fixing the remaining gravel bars (Liébault & Piégay, 2002; Picco, Comiti, Mao, Tonon, & Lenzi, 2017). Together, all these measures have led to a reduction in the natural dynamics of Alpine rivers and to a shrinking of the active river corridor, causing huge losses in quality and quantity of gravel bars. This development is particularly evident for the total length of braided reaches within the 20th century, that is, -95% in Austria, −70% in France, −70% in Germany, −35% in Italy, −52% in Slovenia, and − 83% in Switzerland (Gurnell, Surian, & Zanoni, 2009; Hohensinner, Egger, Muhar, Vaudor, & Piégay, 2021). In unregulated Alpine rivers, multi-channel reaches constitute about a third of their length, while today only 15% of these rivers still show braided patterns (Hohensinner et al., 2021).

The widespread constriction of active river corridors and the decrease of the associated gravel bars reduces ecosystem resilience against floods and droughts under climate change (Death, Fuller, & Macklin, 2015; Kiedrzyńska, Kiedrzyński, & Zalewski, 2015). At the same time, it represents a significant loss of habitats and hence a severe reduction in biodiversity (Bravard et al., 1997; Schindler et al., 2016). Several aquatic and terrestrial animal and plant specialists depend on dynamic gravel bars with frequent flooding and desiccation. Consequently, the reduction in the amount of gravel area and hence habitat diversity causes a dramatic decrease in the abundance of floodplain species, including gravel spawning fish (Kondolf, 1997), benthic invertebrates, ground beetles (Langhans & Tockner, 2014), and pioneer plants (Sitzia et al., 2016; Woellner, Bräuchler, Kollmann, & Wagner, 2021; Woellner, Müller, Reich, Wagner, & Kollmann, 2019). Moreover, less frequent flooding, lower groundwater levels, and a modified sediment composition (Kondolf, 1997) result in rapid succession (Bravard et al., 1997), thus, further degrading the quality of the remaining habitats, and also negatively affecting the resilience of rivers and their communities under climate change.

Therefore, increasing efforts are made to improve the hydromorphological structure of European rivers in response to the Water Framework Directive (WFD) (Arnaud et al., 2015; Campana et al., 2014; Wohl et al., 2015), and here floodplain restoration along braided Alpine rivers has high priority. Most restoration projects along Alpine rivers aim to improve the flow regime, the channel structures, or aquatic habitat conditions, while improving sediment fluxes is difficult (Habersack & Piégay, 2007; Kurth & Schirmer, 2014). Comparing 20 restoration projects across Europe, Muhar et al. (2016) found river widening through embankment removal to be more successful compared to other restoration measures, such as, for instance, re-meandering or instream modifications. Riparian habitat diversity, availability of open habitats, specialized arthropods, macrophytes, and many riparian plants benefit from river widening (Göthe, Timmermann, Januschke, & Baattrup-Pedersen, 2016; Januschke, Jähnig, Lorenz, & Hering, 2014; Kail, Brabec, Poppe, & Januschke, 2015; Muhar et al., 2016). In case of re-braiding or river widening interventions, floodplain habitats and plant communities are best suited for indicating the immediate effects of restoration (Jähnig, Brunzel, Gacek, Lorenz, & Hering, 2009). Though, monitoring of river restoration should not be based on a snapshot, since development of habitat features and riparian vegetation require some time (Geist & Hawkins, 2016). Still, time since restoration is rarely considered, and it is not well understood in which time frame a new equilibrium can be reached after restoration (Januschke et al., 2014; Leps, Sundermann, Tonkin, Lorenz, & Haase, 2016).

In river restoration, the questions arise whether, for example, an increase in gravel bars can persist in the long term or will be lost due to succession or erosion after a few years (Bauer, Harzer, Strobl, & Kollmann, 2018; Scorpio et al., 2020; Zerbe, Rohrmoser, Scorpio, & Comiti, 2019). Thus, hydromorphological indicators have to be selected that can be easily applied across large scales (González del Tánago, Gurnell, Belletti, & García de Jalón, 2016). Open gravel and sand bars are suitable indicators for near-natural flood and sediment dynamics, because they respond rapidly to river regulation (González del Tánago et al., 2016), and have a high significance for biodiversity (Picco, Sitzia, Mao, Comiti, & Lenzi, 2016). In addition, in contrast to detailed surveys of species or communities, gravel bar monitoring can be easily done based on aerial images over large spatio-temporal scales. Thus, these landscape elements are appropriate for evaluating degradation and restoration of multiple river sections and over long time spans (see Surian et al., 2015), and comparing it to historical developments at catchment scale (González del Tánago et al., 2016).

While there are multiple studies describing channel changes (e.g., Choi, Yoon, & Woo, 2005; Comiti et al., 2011; Scorpio et al., 2018; Ziliani & Surian, 2012), there are only few publications that quantitatively addressed the changes in riparian habitats of Alpine rivers (but see Driscoll & Hauer, 2019; Heckmann, Haas, Abel, Rimböck, & Becht, 2017; Rollet, Piégay, Dufour, Bornette, & Persat, 2014; Škarpich, Macurová, Galia, Ruman, & Hradecký, 2020 for instance), and even fewer studies investigated the hydromorphological patterns after restoration aiming at widening the active river corridors of Alpine rivers. Therefore, we carried out an analysis of historical and recent aerial images along rivers of the European northern Alps to address the following questions:

1. How has the extent of gravel bar area in Alpine rivers changed since the 19th century?
2. Which structural alterations within the active river corridor are related to these changes?
3. How did recent restoration influence recovery of the gravel bars?

2 | METHODS

2.1 | Study rivers

Our study was located within the pre-Alpine and Alpine regions of Germany and included all major rivers in this area, that is, Iller, Inn, Isar, Lech, and Wertach (Figures 1 and A1) that originate in the calcareous or central Alps and are tributaries of the Danube River. Typical for Alpine rivers, their discharge is highest in late spring and early summer due to snow melt and heavy rainfalls, while the lowest discharge occurs during winter (Table A1). The bedload of these rivers is dominated by gravel of various sizes, with an occasional portion of boulders and sand (Pottgiesser & Sommerhäuser, 2004).

River regulation in Bavaria started at the end of the 19th century as protection against flooding and for generating hydropower (Müller, 1995). All rivers suffer from moderate to heavy modifications through damming and channelization over the past centuries, with Lech River and Inn River being the most affected due to numerous hydropower plants, and, as regards the Inn River, also by its function as a former shipping route (Figure A2). Especially at the Lech River, downstream of the large reservoir "Forggensee" near the Austrian border, there are numerous dams and reservoirs, and almost no free-flowing reaches remain (von Pfeuffer, 2014); just between 1943 and 1972, 20 dams were built along the Lech River from the Austrian border to Augsburg. The rivers Iller and Wertach are mainly modified through channelization and smaller weirs, while the Isar River hosts some near-natural braided reaches around Vorderriss, upstream the "Sylvenstein" reservoir. Construction of that reservoir was finished in 1959 and resulted in an artificial discharge regime, which reduces flood peaks to 390–600 $m^3\ s^{-1}$ (Heckmann et al., 2017). Thus, the reach between this reservoir and Munich further suffers from a disrupted sediment transport; it is moderately modified through channelization but contains some sections where a wider active river corridor is preserved. Before the 20th century, gravel mining took place only at a small scale in all study rivers; later, larger gravel mining was restricted to the cut-off floodplains and older terraces of these rivers.

Based on European directives (WFD and 92/43/EEC) and national water development plans several restoration projects have been carried out at Alpine rivers in Southern Germany since 1990. Most restoration projects have so far been realized at Isar River, because it is the least degraded.

We focused on the "active river corridors" that comprises channels, islands, gravel bars, and the floodplain. In contrast, "historical river corridor" is the historical extent of the active river corridor in the 19th century, before major hydraulic engineering measures, straightening, and dyking.

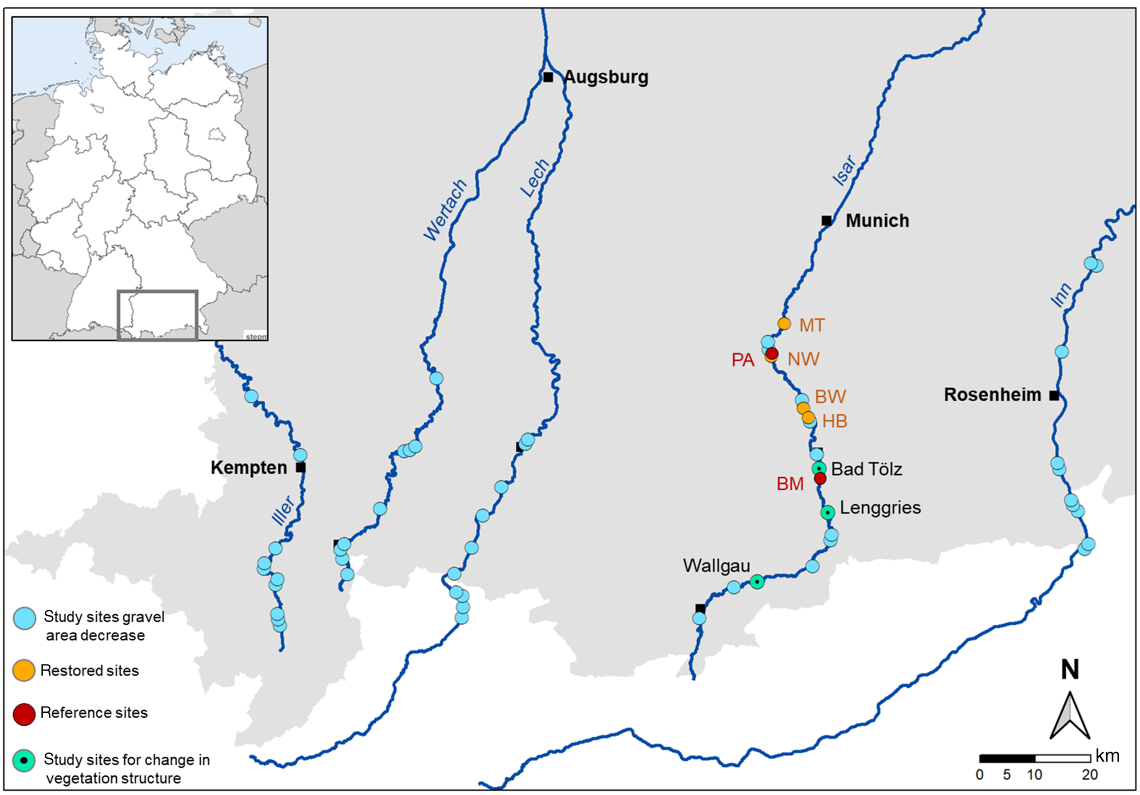

FIGURE 1 Study sites for the historical analysis of active river corridors of the five major Alpine rivers in Southern Germany (blue dots). A more detailed analysis was done on changes in gravel bar area and vegetation in the sites "Bad Tölz", "Lenggries", and "Wallgau", and effects of river restoration were studied in four sites ("BW 'Bairawies," HB "Hechenberg," MT "Mühltal", and NW "Nantwein") and compared with two reference sites (PA "Puppling" and BM "Biebermühle") [Color figure can be viewed at wileyonlinelibrary.com]

2.2 | Reconstructing historical gravel bar change

First, we quantified the overall decline in gravel bar area at the five study rivers. For this purpose, 10 sites were randomly selected at each of the five rivers, with five sites in the alpine and pre-alpine zone, respectively (Figure 1). Dams, bridges, and other modifications as well as current restoration efforts were excluded. All historical maps mentioned in this paragraph were hand-crafted at the end of the 19th century and visualized at a 1:25,000 scale. Other aerial images were from official aerial surveys (1:800) (Figure 2). To ensure comparability of the floodplain surveys, only aerial photographs taken at times of mean discharge were used. The historical river corridor and the different habitat types of water, gravel bars, willow shrub, and riparian forest were delineated by drawing polygons around each habitat element in ESRI ArcGIS 10.1. To quantify the overall change in gravel bar area over the 19th and 20th century, two-time steps were considered, that is, historical (1808–1900) and recent gravel bars (2009–2010) within circles of 1-km diameter. Digitalization was

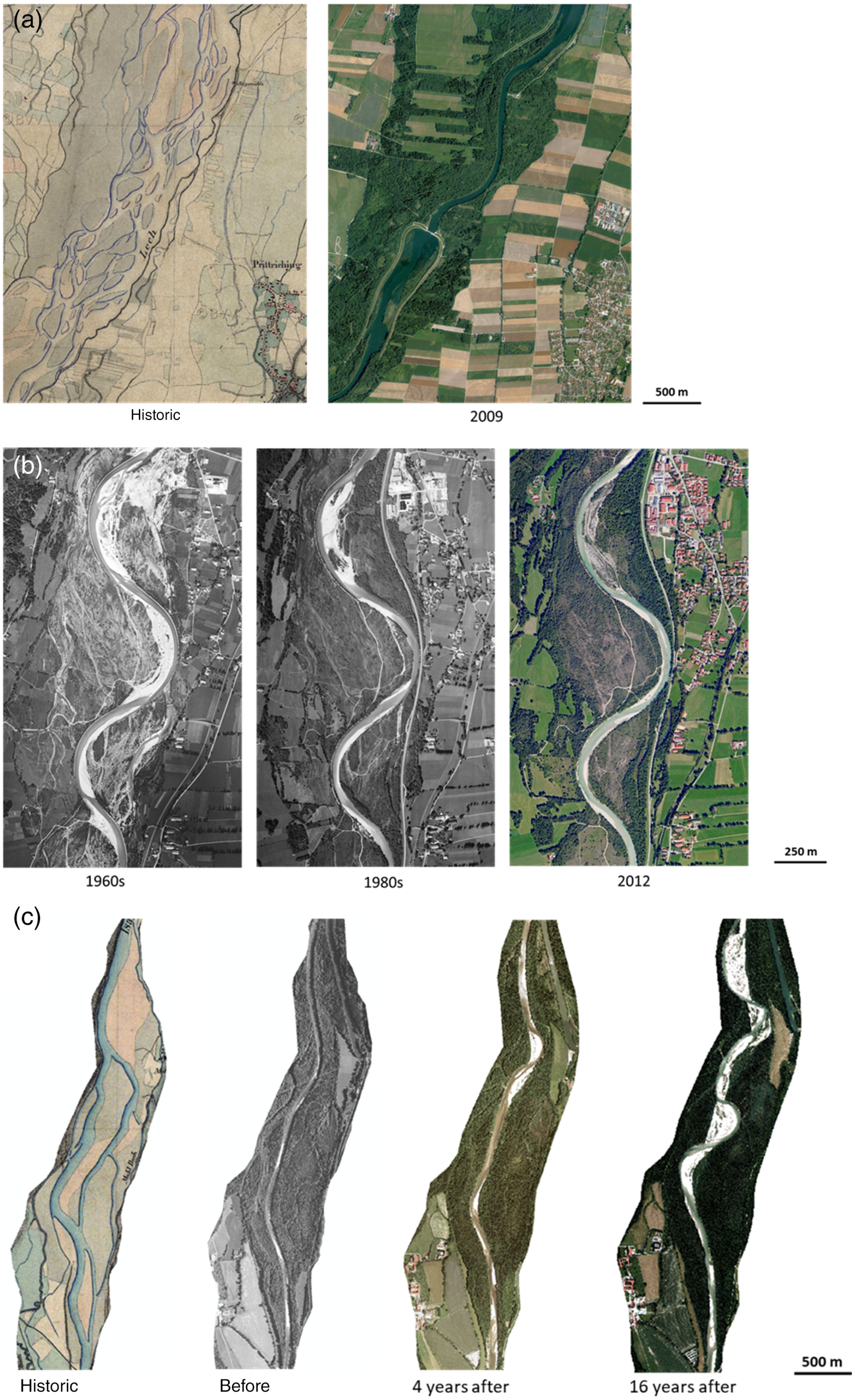

FIGURE 2 Historical maps and aerial photographs of the study sites demonstrating changes in river corridor structure and gravel bar area: (a) comparison of historical and current state at Lech River; (b) change of the active river corridor within the 20th century near "Bad Tölz" at Isar River; and (c) increase in gravel bars at the restored site "Mühltal" at Isar River (Bayerische Vermessungsverwaltung Nr. 2103–4375) [Color figure can be viewed at wileyonlinelibrary.com]

done within the same circular sample, so that the total area was identical and percentage of open gravel bars could be calculated and compared among reaches. In total, 100 samples of the active river corridors of five rivers were included in the analysis, that is, 10 sites × 5 rivers × 2 time periods.

2.3 | Analysis of historical change in floodplain habitats

For a more detailed analysis on how gravel bar area change is associated with vegetation succession, three representative sites were chosen along the Isar River, that is, "Wallgau," "Lenggries," and "Bad Tölz." The site "Wallgau" was located upstream of the Sylvenstein reservoir, whereas the other sites were situated downstream of the reservoir; the studied segments at these sites were 2.6 ± 0.4 km long. We considered four time periods, that is, 1864, 1960, 1983, and 2012, reflecting different types and intensities of hydro-engineering: While the first period was dominated by channelization and, to a lesser extent, gravel mining, the changes of the active river corridor between 1960s and 1980s was mainly driven by damming and building of large reservoirs. Since the 1980s, river management has changed to a more sustainable approach, including river restoration (Morandi, Kail, Toedter, Wolter, & Piégay, 2017). For each site, the polygons of open gravel bars, pioneer vegetation (low vegetation with mean coverage <10%), willow shrub, riparian forest, and water were mapped. The proportions in total active river corridor, gravel bar, and vegetated area relative to their historical (year 1864) extent were calculated for the respective site.

2.4 | Monitoring gravel bar restoration

To select suitable sites for assessing the impact of restoration measures on gravel bars, the results of an extensive compilation of river restoration projects within the study area were used (Woellner et al., 2019). Most information had to be obtained from the relevant authorities as there was no central database for restoration, and many projects were not well documented or too small-scale to derive reliable results. Detailed documentation on location, dimension, and date of restoration was necessary for selecting suitable study sites. Furthermore, the intervention should have occurred >10 years earlier to properly evaluate changes over time. A further selection criterion was the type of restoration measures, insofar as they had to be suitable to improve the gravel bar situation, and should preferably be a single intervention, such as the removal of longitudinal shoring in contrast to repetitive measures such as gravel inputs, scrub clearing, or grazing. Moreover, embankment removal is most effective to increase hydromorphological diversity (Habersack & Piégay, 2007).

The extent of the study sites was defined as the length of the restoration measure plus 1 km downstream, including the entire historical river corridor. Only four sites along the Isar River between Bad Tölz and Munich matched these criteria (Figures 1 and A3), and no suitable sites were available at the four other rivers. "Bairawies" (BW) and "Hechenberg" (HB) were the smallest restoration sites, where the bank protection was removed over 0.2 km in 1987 (BW) and 1989 (HB). The largest restoration site "Mühltal" (MT) is a residual water stretch, and here embankment was removed over about 6.7 km; moreover, river hydromorphology was further improved by dead wood insertion and increasing discharge from about 2 to 15 m^3 s^{-1} (Binder, Gröbmaier, & Lintzmeyer, 2015). Along the site "Nantwein" (NW), embankment was removed irregularly over 1.2 km in 1990 and 1995; a road bridge crossed the river halfway in this study site, with no measures nearby. Further, two reference sites were selected for comparing the restoration effects with background changes in river corridor structures, that is, a channelized, unrestored stretch "Biebermühle" (BM), and a near-natural stretch "Puppling" (PA).

On the six sites, aerial photographs from different time periods (1987–2015) were chosen to investigate the change in gravel bar area before and after restoration. As far as possible, images from the same years were used for the different study sites to ensure comparability, but according to the availability of official aerial images time spans were 3–6 years. Overall, there were four (MT), five (BM), six (NW), and seven (PA, BW, HB) time periods supporting this approach, using aerial images 1–3 years before restoration. Six habitat types were distinguished and digitized, with the same method as previously described, that is, water, gravel, pioneer vegetation, willow shrub, riparian forest, and others.

2.5 | Data analysis

For quantifying the historical loss in gravel bar area, we calculated relative numbers for the historical and current state of the active river corridor of the 10 sites for each of the five rivers. For significant differences between historical and current gravel bar area per river, a pairwise permutation *t*-test was used (package *RVAideMemoire*) (R Core Team, 2019). The loss was estimated as the proportion of the current to the historical gravel bar area.

In order to visualize the quantitative change of the active river corridor of the Isar River at the sites "Wallgau," "Lenggries", and "Bad Tölz," the relative area of the active river corridor in relation to the historical river corridor was plotted. Further, the difference of relative gravel bar area and vegetated area within the active river corridor was calculated for the different times. The resulting "gravel index," ranging from $+1$ for river corridors with 100% gravel and -1 for totally vegetated river corridor was plotted against time, to visualize succession at the respective sites.

The same representations were applied to the restored sites but here with the active river corridor (instead of the historical) at the time immediately before the restoration as reference, to highlight the widening of the active river corridor after restoration and to show the vegetation development within the corridor. In addition, the proportion of gravel bars in proportion to the historical river corridor area was calculated. The change in the proportion of gravel bar area was then related to flood events that occurred within five time periods (1991–1996, 1997–1999, 2000–2003, 2004–2009, 2010–2015) to assess their contribution to the restoration of gravel bars. Discharge data were taken from the nearby gauge “Pupplinger Au,” provided by the Bavarian Flood Information Service (Figure A4). With the exception of the period 2000–2003, exactly one flood higher than the mean high water occurred in each period studied. However, the duration and discharge of the floods differed (Table A2), with the discharge of the flood largely being proportional to the maximum discharge. Only during the flood between 2004 and 2009, the maximum discharge was over-proportionally high in relation to the total discharge. Hence, for intuitiveness, we related the changes in proportion of gravel bar area against the maximum discharge of the respective flood. Pearson correlations between the change in proportion of gravel bar area and highest discharge were calculated for five time periods.

3 | RESULTS

3.1 | Historical gravel decline at Alpine rivers

The five study rivers showed a marked decrease in gravel bars (−83% on average) when comparing the historical and recent river corridors (Figure 3, Table A3). This corresponded to a historical average proportion of 13.8% gravel that varied among rivers ranging from 1.6% (Wertach) to 27.3% (Isar). Gravel bar area decreased to 2.1% on average, with a range from 0.0% (Inn) to 7.4% (Isar). The proportional decrease in gravel bar area ranged from −67.4% (Isar) to −99.9% (Inn), and the total loss in gravel bars ranged from −10 ha (Wertach) to −157 ha (Isar). The extent of changes in total gravel bar area per site varied widely within rivers, from +15 to −46 ha at Isar River.

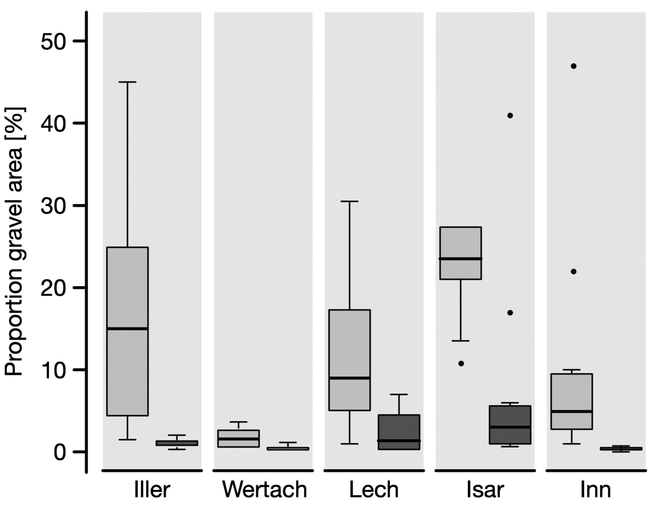

FIGURE 3 Change in the proportion of gravel bar area within the active river corridors between historical near-natural state (mid-19th century; left column) and 2009 (right column) for 10 study sites along the Alpine rivers Iller, Wertach, Lech, Isar, and Inn, respectively. The difference between the two time periods was significant for all rivers (permutation *t*-test, $p < .01$)

3.2 | Historical floodplain changes at Alpine rivers

The overall decrease in proportion of gravel bars was −76%, −94%, and −97% between historical maps and the year 2012 for the sections “Wallgau,” “Lenggries”, and “Bad Tölz,” respectively, that we used for a more detailed analysis (Figure 4). The largest decline in gravel bar area occurred before the 1960s in all sites (decrease of −45–80%), as well as the largest decrease in the active river corridor area (decrease of −6–43% between historical maps and the 1960s, Figure 5a). At the upstream site “Wallgau,” the gravel and active river corridor area remained unchanged between 1960 and 1983, but this was followed by a great loss of gravel bars between the years 1983 and 2012 (−31% of the historical gravel bar area), while the active river corridor remained overall stable during this time (Figure 5a). In contrast, the lowest decrease in gravel bar area was observed between 1983 and 2012 at the two sites downstream of the reservoir (−7 and −2% of the historical gravel bar area, respectively). While the greatest change happened before the 1960s, our results indicate that the gravel bars continued to decrease within the late 20th century (on average − 22% of the relative gravel bar area per decade between the 1960 and the 1983, −16% per decade between the 1983 and 2012).

In the historical state, all active river corridors were gravel-dominated with a similar ratio of gravel and vegetated areas (Figure 5b). At all sites, the gravel index shifted markedly toward a vegetation-dominated corridor until 1960. In 2012, the sites “Lenggries” and “Wallgau” remained at a similar level, while “Bad Tölz” showed the lowest ratio (gravel index = 0.11). There was a further notable increase in vegetated area between 1983 and 2012 at the upstream site “Wallgau.” While the increase in vegetated areas over the late 20th century was mostly due to an expansion of willow shrub at this site (+25% between 1960 and 2012; Table A4), the increase near Bad Tölz was caused by an extension of riparian forest (+22% between 1960 and 2012; Table A4).

3.3 | Effects of embankment removal on the active river corridor area and gravel bars

In the restoration sites, re-expansion of the active river corridor seems to be insignificant (Figure 6a, Table A5). Only the active river corridor at the “Mühltal” site doubled in size within 20 years, while the active river corridor increased less than 1.5-fold at the other sites, even after more than 25 years. Note that the natural site at “Puppling” also showed a slight increase of the active river corridor to the same extent as the restoration sites. However, the active river corridor at the dyked reference site remained largely the same. With exception of the “Mühltal” site, the widening of the active river corridor area after the embankment removal progressed only slowly at the restoration sites. At “Bairawies” after a short-term improvement within the first 10 years, the situation even worsened again, so that the active river corridor area in 2015 only comprised 70% of the corridor before the restoration.

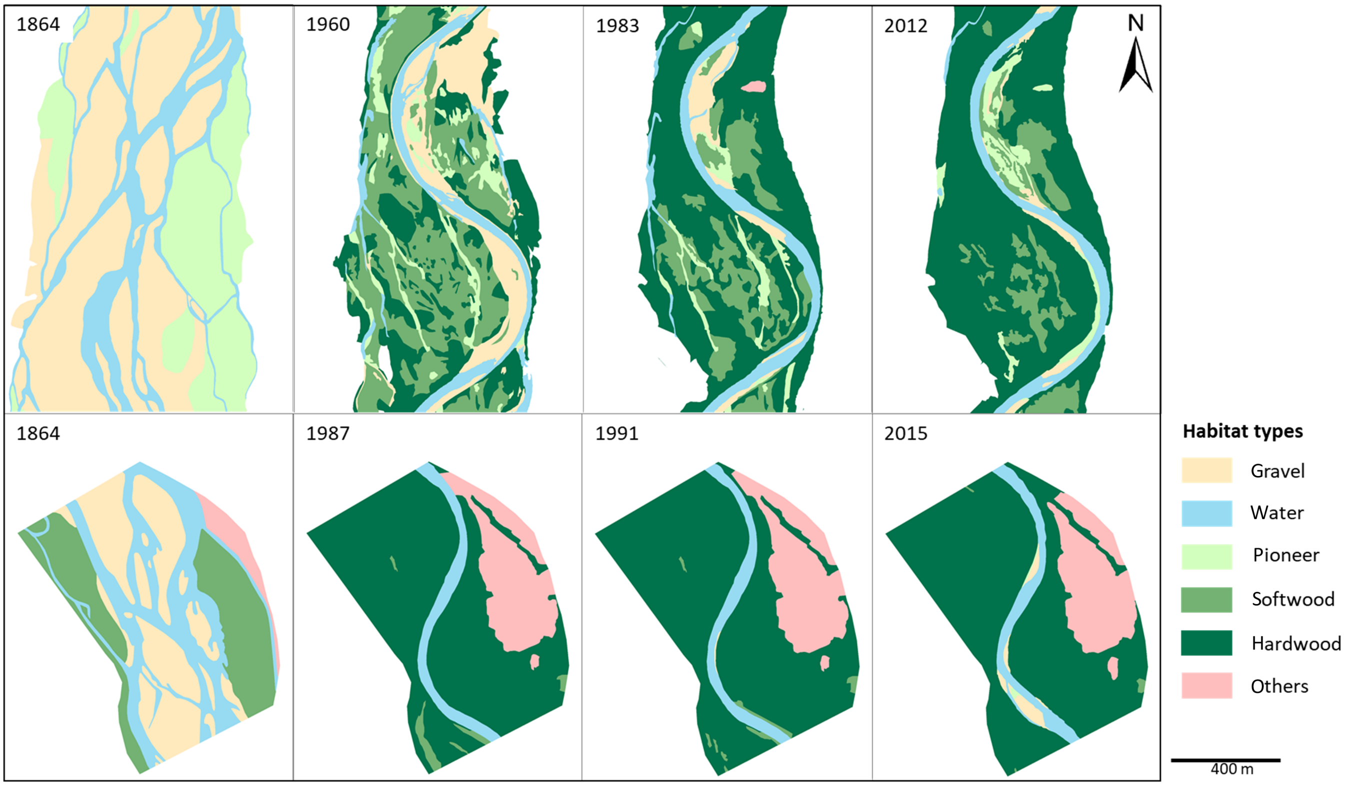

FIGURE 4 Changes in habitat type composition at the unrestored site "Bad Tölz" since mid-19th century (above), while at the restored site "Hechenberg" (below) only small gravel bars developed after embankment removal in 1989. Positions of the sites at Isar River are shown in Figure 1 [Color figure can be viewed at wileyonlinelibrary.com]

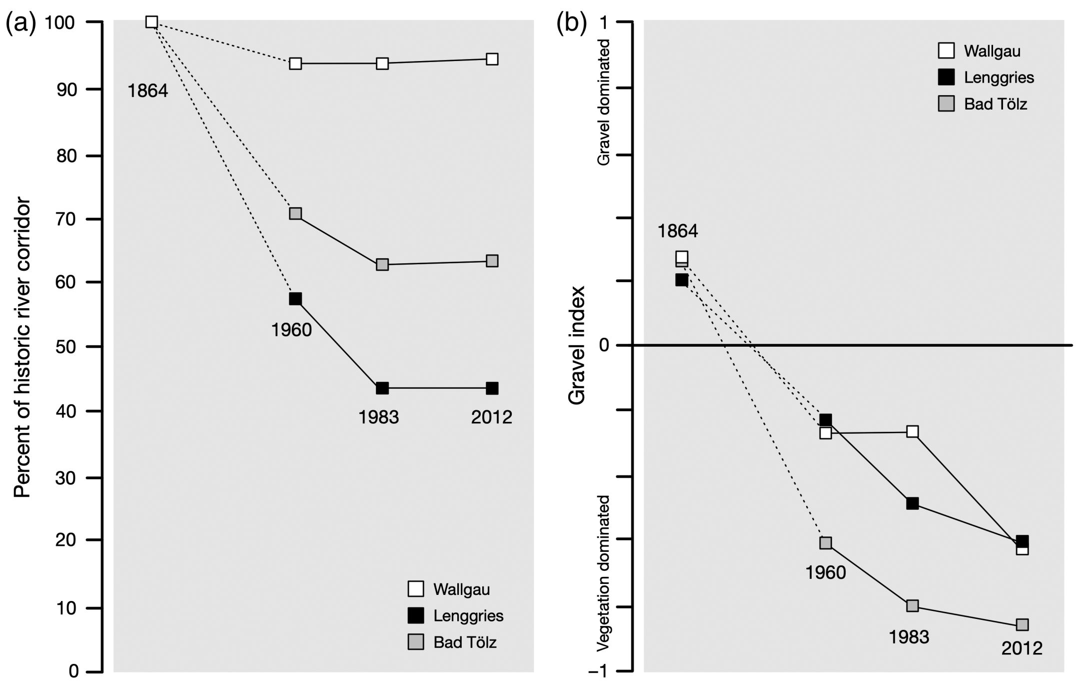

FIGURE 5 (a) Historical changes in active river corridor area at the Isar River since 1864 for the sections "Wallgau," "Lenggries," and "Bad Tölz." (b) Changes in the gravel index (i.e., difference of the percentage of gravel and vegetated areas within the active river corridor) in the same sites

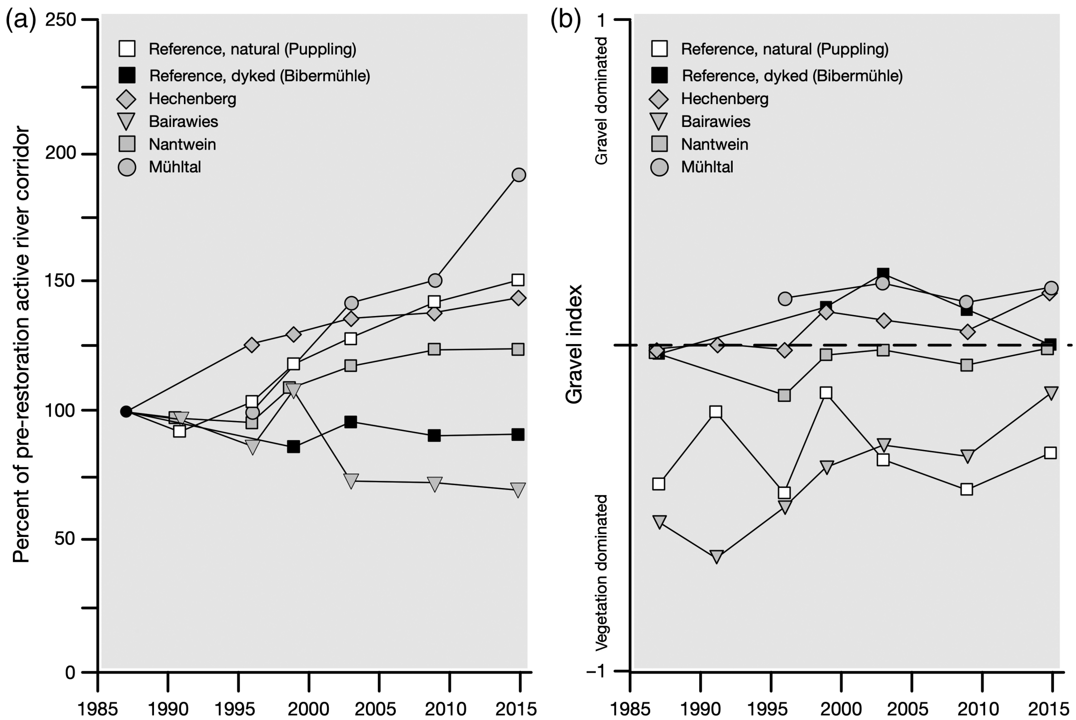

FIGURE 6 (a) Recent changes in active river corridor area since 1987 at the Isar River with four restoration and two reference sites; and (b) changes in the gravel index (difference of the percentage of gravel bar areas and vegetated areas within the active river corridor) in the same sections

Though the restoration measures led to a widening of the active river corridor, the proportions of gravel and vegetation did not show a clear trend and remained largely the same over time, except for "Bairawies" (Figure 6b). For the dyked reference site and the restoration sites "Hechenberg," "Nantwein" and "Mühltal" the ratio of vegetation and gravel was balanced, with a slight and stable dominance of gravel at the "Mühltal." The natural reference site "Puppling" was clearly dominated by vegetation with temporarily higher proportions of gravel. The restoration site "Bairawies" was initially also dominated by vegetation but developed increasingly in the direction of balanced gravel-vegetation ratio.

At all sites, the gravel bar area increased only slightly, when comparing the pre-restoration state with the year 2015: "Hechenberg" (+1.6%) (Figure 4), "Bairawies" (+1.2%), "Nantwein" (+0.9%), and "Mühltal" (+4.7%) (Figure A3). Two sites ("Nantwein," "Bairawies") showed even a slight decrease between 1999 and 2015. The unrestored site "Biebermühle" showed a decrease over the entire time period 1987–2015 (−0.7%), while the gravel bar area proportion at the near-natural site "Puppling" increased (+4.2%). At the restored sites, the proportion of gravel bar area decreased by 91–100%, comparing the historical and pre-restoration states at the Isar River, which is similar to the overall loss detected along the five rivers (Figure 3). The amount of gravel after the restoration measures reaches only less than 5% of the historical gravel bar area proportion, except at the largest restored site ("Mühltal," 36%).

When comparing the average change in gravel bars over all sites and flood events within the years after restoration, large discharge events were associated with a stronger increase in gravel bars (Figure 7). The flood in 2005 was an exception; between 2003 and 2009, no general increase could be detected for the restored sites despite the highest flood event within the study period. Two sites ("Bairawies," "Nantwein") even showed a decrease within this time step. Excluding this exceptional time step, discharge height and amount of gravel bar change were significantly correlated ($r = .97$, $p < .05$).

4 | DISCUSSION

4.1 | Drivers of historical gravel bar decrease

Our study revealed a dramatic loss of almost −80% of gravel bars along all major German Alpine rivers over the past century. This decrease was most pronounced along the largest rivers with a historically wide active river corridor. The loss in gravel bars varied considerably among rivers (−65–100%), depending on the degree of modification and the resulting impairments. While the losses were smaller for the less modified sites close to the Alps, the loss of gravel bars reached up to −100% at more heavily impacted sites in the alpine foreland. Along the other rivers, the remaining gravel bars are either fragmented or restricted to a narrow strip in a confined river course, as seen in other studies (Comiti et al., 2011; Scorpio et al., 2018; Surian, Ziliani, Comiti, Lenzi, & Mao, 2009).

The more detailed analyses of the changes of the active river corridor at the Upper Isar since the 19th century highlighted that the

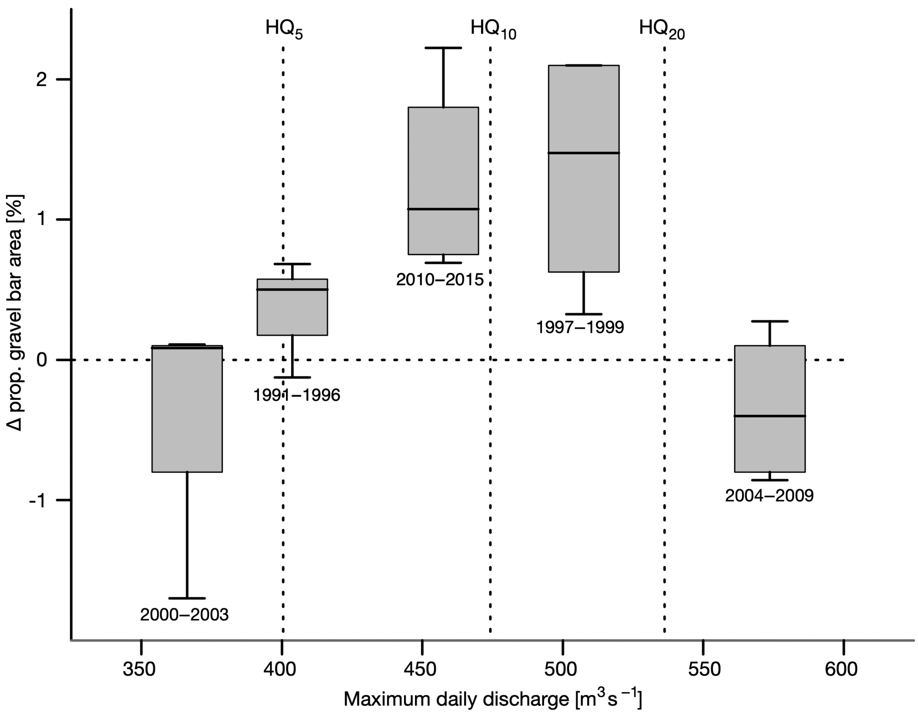

FIGURE 7 Changes in gravel bar area between two time periods averaged over the four restoration sites at Isar River as correlated with the maximum daily discharge within the respective time periods (gauge "Pupplinger Au"). Except for the time period 2003–2009 (HQ_{20} flood in 2005), higher floods were associated with an increase in gravel bar area. Within the studied periods there was one event in 2002 below the HQ_5 value (400 $m^3\ s^{-1}$), one in 1995 and 2013 between HQ_5 and HQ_{10} (470 $m^3\ s^{-1}$), and one in 1999 between HQ_{10} and HQ_{20} (540 $m^3\ s^{-1}$)

gravel decline was associated with two major changes, that is, reduced total area of the active river corridor and encroachment with willow shrub and later the formation of riparian forest. Embankment, canalization, and hence the reduction of the active river corridor were particularly pronounced near settlements, where up to 60% of the historical river corridor zone was lost.

As for other rivers in the Alps (Arnaud, Schmitt, Johnstone, Rollet, & Piégay, 2019; Comiti et al., 2011; Hohensinner, Jungwirth, Muhar, & Schmutz, 2014), the Upper Isar showed the greatest reduction of the active river corridor area between 1860 and 1960. During this period, the most extensive straightening and dyking measures along the Isar River had taken place (Heckmann et al., 2017; Speer, 1977). These interventions led to a strong (and fast) channel incision of almost 2.5 m, indirectly measured by the decrease in annual mean low water level at the gauge "Puppling." The construction of the Sylvenstein reservoir in the 1950s and further smaller channel forming measures resulted again in a significant incision of about 1 m until the 1970s (Heckmann et al., 2017). Still, in 1980 no further reduction of the active river corridor was observed. Gravel mining, which until then had only taken place on a small scale in the riverbed, was restricted to the area of the former floodplain.

However, the gravel bars continued to decrease after 1980. The reason here is progressive succession on the gravel bars due to flood regulation at the Sylvenstein reservoir constructed in 1959. Reduced flooding led to a lower turnover of gravel bars and thus to scrub and forest establishment with negative feedback effects (Tonolla, Geilhausen, & Doering, 2021; van Oorschot, Kleinhans, Buijse, Geerling, & Middelkoop, 2018). From the 1860s to the 1960s, the altered discharge and channel narrowing due to dyking changed Upper Isar from a gravel- to a vegetation-dominated river corridor. While the succession at the reaches downstream the Sylvenstein reservoir continued until recently, at the near-natural stretch between Wallgau and Vorderriss the succession increased strongly after 1980. This site is a residual water stretch and was almost completely dried out until an increase of the residual flow rate was agreed in 1990. This resulted in a marked vegetation development that previously was suppressed due to drought (Juszczyk, Egger, Müller, & Reich, 2020; Reich, Bargiel, & Rühmkopf, 2008).

4.2 | Effectiveness of gravel bar restoration

Restoration measures did result in a moderate widening of the active river corridor in most of the study sites and did not differ from the widening observed for the near-natural site at the Pupplinger Au. However, it can be assumed that without embankment removal no expansion would have taken place here at all. Even after almost 30 years, the width of the active river corridor hardly increased more than 50%, and the reduced increase over the past years suggests that an equilibrium is reached.

The reasons for these results are probably a combination of factors: the canalization of river courses leads to increased incision. At the same time, flood regulation with altered discharge and bedload trapping (by the Sylvenstein reservoir) reduce the erosivity and energy of floods. The resulting succession then leads to additional stabilization of banks and floodplains, so that after the removal of the embankment, the floodplains must first be recreated (Scorpio et al., 2020).

In contrast, the largest restoration site "Mühltal," with almost 6-km length, performed slightly better. Here the active river corridor doubled within 20 years and the continuing steep increase suggests that an equilibrium is not yet reached and a further expansion of the corridor is likely. In general, restoration sites showed a better development of active river corridor area than the unrestored reference site, indicating a positive effect of the embankment removal on riverbank dynamization, also reported in Campana et al. (2014) and Januschke et al. (2014). Still, gravel bar area proportion increased only slightly over 20 years at all sites. Again, the largest restoration site was exceptional as it showed an increase of more than 5%, similar to the near-natural reference site. The counteracting process of succession resulted in a more or less stable gravel-to-vegetation ratio, as expressed by the gravel index at all sites independent of the widening in the active river corridor area. While gravel bars extended with time, there was a simultaneous increase in vegetation on these open sites (also in Januschke et al., 2014). At the "Bairawies" site immobilization of an alluvium and further succession to riparian forest even led to a loss of one-third of the active river corridor area.

Generally, longer sections of embankment removal perform better, with a higher expansion rate and higher saturation level, due to more space for erosion and depositional processes. This has serious implications for river restoration and the removal of river embankment, as it makes clear that such measures are only sufficiently successful at large scales. Also in our study, the success of spatially confined restoration measures is limited by further factors at large scales, like disrupted sediment transport, or flood regulations that are not addressed by standard measures so far (Campana et al., 2014). Consequently, current restoration approaches should be revised and future measures need to focus on longer stretches (Belletti et al., 2018; Schmutz et al., 2014) to support floodplain dynamics at the reach scale. However, in terms of successful river restoration, the process of un-assisted widening of the active river corridor is disappointingly slow and the actual improvements in gravel, particularly in relation to the gravel bar area of the historical river corridor, are marginal.

4.3 | Flood effects on gravel restoration

Floods and the associated transport of bedload and deadwood, the turnover of habitats and the interaction of the discharge with the floodplain are crucial processes for maintaining Alpine rivers and their open gravel bars (Gurnell et al., 2015; Surian et al., 2015). With reduced flood frequency and heights, caused by water withdrawal and hydroelectric dams that also serve to mitigate downstream flood peaks, the turnover of older alluviums becomes less likely (Church, 1995; Comiti et al., 2011). Their immobilization and stabilization are further supported by the advanced successional stages (van Oorschot et al., 2018). The decisive role of floods is evident in our findings, causing erosion and formation of gravel bars in restored sites only in connection with flood events.

At the restored sites, floodings with a 5–10 years return period lead to relocation and sedimentation of gravel bars, and simultaneously a partial reversal of the succession state. In time periods with lower or larger floods, the gravel bar area was not at all or even negatively affected. This calls for a new perspective on the role of floods for vegetation development and bar migration (Adami, Bertoldi, & Zolezzi, 2016; Surian et al., 2015), since not only large floods (every 10–20 years) can cause significant vegetation erosion but also the combination with intermediate, more frequent floods (2–3 years) (Tonolla et al., 2021). In our case, the largest flood event (HQ_{20}) even resulted in a decrease in gravel bars. However, this could be an artifact because of the larger time span between 2003 and 2009 compared to the other time steps, so vegetation had more time to develop. Otherwise, Belletti, Dufour, and Piégay (2014) found morphology of reaches with impacted sediment load did not respond to large floods, as their river dynamics were mainly driven by 1–10-years flood events, whereas Lenzi, Mao, and Comiti (2004) found that during extreme floods the bed is the main source of sediment transport. Consequently, larger floods may even destroy existing gravel bars in reaches with small active river corridors. In our study region, the Sylvenstein reservoir holds back most sediments, and there are no unregulated tributaries with significant sediment load. Thus, gravel and sand of the restored sections must originate from lateral or bed erosion of these sites or of less embanked river stretches upstream.

4.4 | Implications for biodiversity and flood control

The reduced gravel bar area has also serious implications for the ecosystems of regulated rivers. In the study region, many riparian pioneer species, such as the plants *Chondrilla chondrilloides* and *Myricaria germanica*, *Formica selysi* (ant) or *Bryodemella tuberculata* (grasshopper), and even a number of gravel-breeding bird species—all of them endangered and red-listed today (Reich, 1991; Woellner et al., 2019, 2021)—rely on the open and frequently disturbed gravel habitats. In many cases, the remaining gravel bars are fixed and immobilized, and affected by shrub encroachment, and thus do not provide the historical habitat quality of a natural alpine river. Hence, the overall loss of more than 80% in gravel bar area along the major alpine foreland rivers can be directly related to a habitat loss for these specialist species. At least the "Mühltal" restoration has succeeded in restoring habitats to such an extent that a spontaneous colonization of the threatened pioneer shrub *Myricaria germanica* occurred in 2014 (Binder et al., 2015). The establishment most likely followed the summer flood in 2013, when fresh sediments and seeds were deposited along the restored reach (Binder et al., 2015).

This underlines the importance of an adequate discharge regime for creation of suitable habitats, and this is (most likely) also necessary to allow the dispersal of characteristic species with source populations several kilometers away (Fink & Scheidegger, 2018). For creating pioneer habitats on gravel bars, it is not enough to restore the geomorphic structures, but their quality and functionality have to be taken into account (Wohl et al., 2015). This includes the adaptive management of sediment supply, flow regime, and functional (longitudinal) connectivity combined with restoration measures like embankment removal (Gostner, Paternolli, Schleiss, Scheidegger, & Werth, 2017; Wohl et al., 2015).

The reduction of the active river corridors, particularly from the 1800s until the early 20th century has also serious implications for the resilience of floodplains against extreme flood events, since gravel bars and riparian forests moderate discharge peaks and the extent of flooding. Already today, floods in the lower reaches of regulated rivers are higher and reach their peak faster, causing more severe flooding downstream (Kiedrzyńska et al., 2015). As the frequency of such extreme events will increase with climate change, it becomes clear that a removal of dykes and the widening of active river corridors are urgently needed (see Scorpio et al., 2020).

5 | CONCLUSIONS

Our study demonstrates a strong decline in the proportion of gravel bar area for virtually all large German Alpine rivers. The loss is associated with a reduction of the active river corridors as a consequence of increasing human intervention over the past century. More recently, increased vegetation succession on immobilized gravel bars drives a further decline of open gravel bar areas. With the removal of longitudinal shoring and the thereby associated widening of the active river corridor, these losses can partially be reversed. However, the success of these measures depends on sufficiently large spatial extent of the implemented measure and a series of medium to high floods. Thus, floodplain restoration is basically able to revert the loss of gravel bars, but this is only effective if the restored sections are large, and measures are coordinated along the river. Considering that river restoration is a hot topic especially against the background of the European WFD, climate change and the aspects of conservation associated with the loss of gravel bars, the poor results and the slow improvements achieved by smaller restoration measures found in our study, in the future more and more extensive approaches are needed.

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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

FIGURE A1 Impressions of typical regulated sections of the study rivers taken in 2019: (a) Iller River near Ferthofen; (b) Inn River near Wasserburg, (c) Lech River near Kissing, south of Augsburg; (d) Wertach River near Bobingen, south of Augsburg; (e) largely natural section of the Isar River near Wallgau; (f) slightly modified section of the Isar River near Fleck, south of Bad Tölz [Color figure can be viewed at wileyonlinelibrary.com]

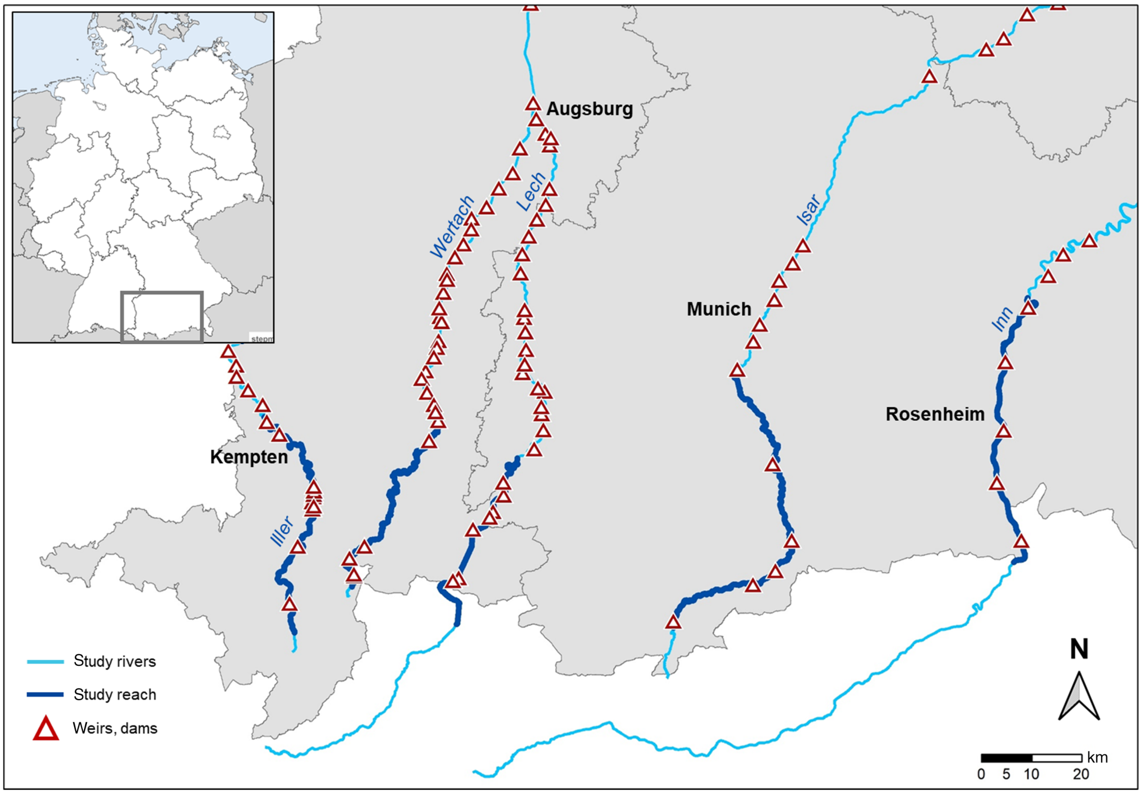

FIGURE A2 Position of weirs and dams along the five study rivers in S Germany. *Source:* Bavarian Federal Office for Environment 2018 [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE A3 Photographs of reference sites and passively restored sites along the Isar River: (a) Unrestored reference site: canalized stretch of river with fortified river banks near Biebermühle; (b) "Pupplinger Au," one of the two still existing naturally braided sections of the Isar River downstream of the Sylvenstein Reservoir. Note the unnaturally high and dense vegetation on large parts of the river islands due to the altered flood regime caused by the reservoir and consequently heavy succession. (c) River section near Hechenberg with 200 m embankment removal; (d) River section near Bairawies with 200 m embankment removal, the righthand side of it a steep bank; (e) heavily straightened and canal-like section near Nantwein with partial embankment removal on both sides of the river; (f) "Mühltal" restoration site with embankment removal on both sites over a length of 6.7 km and increased average discharge 4 years after the restoration (*Source:* Wasserwirtschaftsamt München). Photographs of the "Mühltal" were taken in June 2020, all other photographs in August 2021 at mean water level facing downstream along the respective site [Color figure can be viewed at wileyonlinelibrary.com]

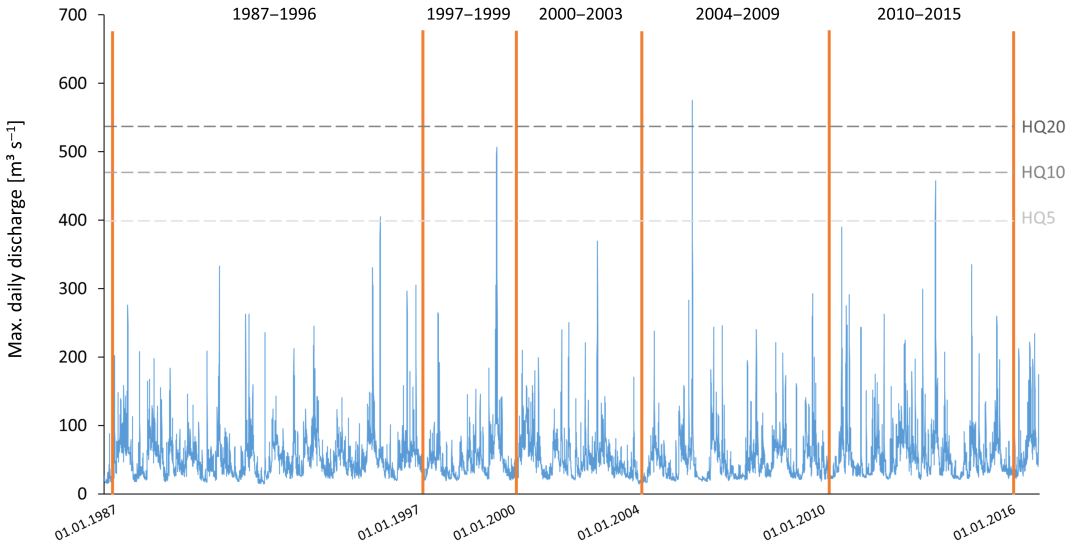

FIGURE A4 Maximum daily discharge (1987–2015) of Isar River at gauge "Puppling" with flood events HQ_5 (400 $m^3 s^{-1}$), HQ_{10} (470 $m^3 s^{-1}$), and HQ_{20} (540 $m^3 s^{-1}$) that were relevant for developments at the restoration sites. Position at the river shown in Figure 1 (data: HND Bayern, Bayerisches Landesamt für Umwelt 2021) [Color figure can be viewed at wileyonlinelibrary.com]

TABLE A1 Overview of the studied five Alpine rivers for analyzing change in gravel bar area from the 19th century until 2009

	Iller	Inn	Isar	Lech	Wertach
Length [km]					
Total	147	517	292	253	141
Study reach	66	65	90	100	62
Catchment area (km^2)	2,152	26,068	8,962	3,919	1,441
Altitude of origin (m a.s.l.)	783	2,484	1,160	1,840	1,078
Mean daily discharge ($m^3 s^{-1}$)	70.1	357.0	48.5	71.0	16.9
Number of power stations upstream the lowest study site	15	11	3	17	5

TABLE A2 Flood events of Isar River recorded at the water gauge "Puppling" during post-restoration monitoring

Time period	Number of floods above mean high water	Duration of flood (days)	Average daily discharge ($m^3 s^{-1}$)	Maximum discharge ($m^3 s^{-1}$)
1991–1996	1	1	356	405
1997–1999	1	3	284	507
			453	
			404	
2000–2003	-	0	156	369
2004–2009	1	2	395	575
			436	
2010–2015	1	2	402	458
			380	

Note: Apart from 2000 to 2003, only one single flood with an average daily discharge higher than mean high water (286 $m^3 s^{-1}$) occurred within each study period. For the respective floods, the duration in days, the average discharge per day, and maximum discharge are shown.

TABLE A3 Average change in total and proportional gravel area for the five study rivers

Study river	Sum change gravel area (ha)	Average loss gravel area (%)	t-value	Mean of differences	*p*-value
Iller	−118.9	−86.5	3.44	0.168	.006
Inn	−80.9	−99.9	2.30	0.103	.008
Isar	−156.5	−67.4	3.02	0.199	.008
Lech	−71.2	−75.8	2.94	0.091	.004
Wertach	−10.1	−85.3	3.87	0.015	.008
All	−437.6	−83.0	5.44	0.116	.002

Note: Permutation *t*-test (999 iterations) indicates significance of changes.

TABLE A4 Proportion of area for each habitat type relative to the total area of the active river corridor

	Wallgau			Lenggries			Bad Tölz		
	1960	1980	2012	1960	1980	2012	1960	1980	2012
Water (%)	12	12	12	23	23	27	11	12	10
Gravel (%)	31	30	13	28	14	7	14	4	2
Pioneer vegetation (%)	24	12	12	8	5	11	9	4	4
Willow shrub (%)	16	28	42	8	13	13	40	24	15
Riparian forest (%)	16	18	20	33	44	42	26	56	68

Note: The historical analysis was done at three sites along Isar River.

TABLE A5 Development of the active river corridor and the gravel bar area at four restored and two reference sites at Isar River in Southern Germany (1987–2015); the latter was the non-restored channelized stretch "Biebermühle," and the near-natural site "Puppling"

Site	Year	Total river corridor (m^2)	Active river corridor (m^2)	Gravel bar area (m^2)	Vegetated area within total river corridor (m^2)	Vegetated area within active river corridor (m^2)	Gravel active river corridor (%)	Vegetated active river corridor (%)	Gravel index
Bairawies	1987	706,498	142,846	8,032	570,668	85,080	0.06	0.60	−0.54
	1991	706,495	138,180	5,050	587,491	95,559	0.04	0.69	−0.66
	1996	706,429	123,443	9,957	580,725	71,749	0.08	0.58	−0.50
	1999	706,458	155,835	24,956	557,286	83,482	0.16	0.54	−0.38
	2003	706,457	105,065	12,991	568,779	45,007	0.12	0.43	−0.30
	2009	706,492	104,000	7,078	566,028	42,829	0.07	0.41	−0.34
	2015	706,693	100,554	16,869	560,229	31,664	0.17	0.31	−0.15
Hechen-berg	1987	598,473	43,476	0	444,372	572	0.00	0.01	−0.01
	1991	598,474	42,339	714	446,049	572	0.02	0.01	0.00
	1996	598,459	41,651	0	448,135	666	0.00	0.02	−0.02
	1999	598,447	47,810	5,343	439,789	0	0.11	0.00	0.11
	2003	598,471	51,257	6,136	445,478	2,133	0.12	0.04	0.08
	2009	598,455	54,094	5,858	442,685	3,658	0.11	0.07	0.04
	2015	598,237	54,289	10,759	440,239	1,530	0.20	0.03	0.17
Mühltal	1996	4,860,833	441,504	73,079	3,539,888	10,902	0.17	0.02	0.14
	2003	4,846,309	627,766	175,006	3,382,522	53,657	0.28	0.09	0.19
	2009	4,861,754	665,947	189,778	3,409,855	105,815	0.28	0.16	0.13
	2015	4,866,607	846,674	299,329	3,269,188	146,381	0.35	0.17	0.18
Nantwein	1987	695,856	62,543	1809	619,732	4,397	0.03	0.07	−0.04
	1996	695,839	79,237	5,306	616,848	17,917	0.07	0.23	−0.16
	1999	695,797	81,776	7,725	603,554	10,004	0.09	0.12	−0.03
	2003	695,300	85,493	8,525	600,340	9,618	0.10	0.11	−0.01
	2009	695,803	86,813	3,462	600,484	9,010	0.04	0.10	−0.06
	2015	695,822	90,428	8,285	596,722	8,687	0.09	0.10	0.00
Bieber-mühle	1987	60,077	110,562	21,086	465,402	23,776	0.19	0.22	−0.02
	1999	600,664	96,309	14,927	450,260	3,599	0.15	0.04	0.12
	2003	603,401	106,933	26,143	441,117	2,322	0.24	0.02	0.22
	2009	600,285	100,678	19,454	453,971	8,607	0.19	0.09	0.11
	2015	600,252	102,187	6,959	451,619	7,460	0.07	0.07	0.00
Puppling	1987	1,260,598	327,747	26,306	1,077,732	169,731	0.08	0.52	−0.44
	1991	1,260,585	306,344	74,198	1,067,224	136,715	0.24	0.45	−0.20
	1996	1,260,656	342,316	45,078	1,100,028	201,304	0.13	0.59	−0.46
	1999	1,260,603	389,385	112,620	1,027,318	168,881	0.29	0.43	−0.14
	2003	1,260,573	422,044	80,006	1,052,652	228,370	0.19	0.54	−0.35
	2009	1,260,145	467,727	56,809	1,041,336	265,051	0.12	0.57	−0.45
	2015	1,259,971	494,399	104,122	1,010,707	263,986	0.21	0.53	−0.32