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Biogeomorphic tipping point in braided rivers: vegetation development at a restored Upper Drava River section (Austria)

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Abstract We determined how the interaction between geomorphic processes and vegetation development enables tipping points in braided rivers. We performed vegetation monitoring and succession modelling on the restored Kleblach side channel at the Upper Drava River (Austria) to assess long-term trends in vegetation succession and landform development. Two alpine pioneer plant species, the German Tamarisk (*Myricaria germanica*) and the Dwarf bulrush (*Typha minima*), were used to assess the ecosystem consequences of succession. Vegetation rapidly developed on initially open sites; 14 years after restoration, approximately 60% of the study area was characterized by stable succession phases. Even a major flood event in the near future would not reduce the dense vegetation cover. This indicates that a stable, dense vegetation cover can lead to a permanent transition from a dynamic braided to a stable single-channel river without major morphological changes, which we interpret as "biogeomorphic tipping point". The result is a significant reduction in the indicator species' habitats, preventing them from maintaining a resilient population in the long term. Thus, maintaining process regimes with high hydro- and morphodynamics is critical for preserving the valuable braided river ecosystems. The idea of "biogeomorphic tipping points" contributes to the process-based conservation and restoration of braided rivers globally.

Keywords River restoration · Vegetation succession · Succession model · Indicator species for river dynamics · *Myricaria germanica* · *Typha minima*

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Introduction

In river corridors, fluvial landforms and hydrogeomorphic processes drive the evolution of riparian plant communities. At the same time, vegetation also largely controls geomorphic processes and the

emergence of landforms (Osterkamp & Hupp, 2010). Once pioneer species germinate on open sites and grow to a certain size, interactions between vegetation and hydromorphology begin, leading to the co-evolution of plant communities and geomorphic landforms. This reciprocal influence of plants and geomorphic processes has gained increasing interest over the past years within the emerging field of biogeomorphology (Corenblit et al., 2007; Gurnell, 2014; Viles, 2020; Larsen et al., 2021). As the inter-dependence of river morphology and plant communities is crucial for riverine landscape development, rivers have been referred to as "biogeomorphic ecosystems" (Balke et al., 2014).

Throughout the world, gravel-bed rivers, and in particular braided rivers, are ecosystems of exceptional ecological value (Tockner et al., 2006). Braided rivers are characterized by "having a number of alluvial channels with bars and islands between meeting and dividing again and presenting from the air the intertwining effect of a braid" (Lane, 2016). They occur in various environments associated with high-energy and coarse sediment. As their main features, an abundant sediment load exceeding the transport capacity, erodible riverbanks, extensive discharge variability, and steep slopes are highlighted (Church, 1983; Maier et al., 2022).

The extreme morphodynamics, frequent flood peaks, and intermittent severe droughts in braided river systems allow only for the survival of highly adapted, stress-tolerant species (Egger et al., 2022), which is why their riparian vegetation is generally sparse and underdeveloped (Ashmore, 2013). The vegetation development in combination with the hydrogeomorphic conditions of rivers can be described by the "fluvial biogeomorphic succession" concept, linking fluvial landforms and riparian vegetation community evolution in a bidirectional manner by five succession phases (after Corenblit et al., 2007, 2015; Gurnell et al., 2016): (1) the permanent water phase, (2) the geomorphic phase on open gravel banks after floods, (3) the pioneer phase, with the beginning of vegetation establishment, (4) the biogeomorphic phase, where the interaction between vegetation and hydrogeomorphological processes dominates, and (5) the ecological phase, characterized by stable and established geomorphic structures, the establishment of a floodplain forest, and stable biotic interactions. In a natural braided river system, the highly dynamic succession phases consisting of the permanent water phase (1), the geomorphic phase (2), and the pioneer phase (3) have the highest area shares due to the high river dynamics (Gurnell, 2014). All succession phases are in a "pseudo-equilibrium" (Phillips, 2011) at the reach scale and quasi-stable in the long term considering that due to the inhering disturbance regime of rivers, the temporal variation of an area can be high (Phillips, 2011; Fuller et al., 2019).

In general, vegetation growth leads to an increased roughness, fine sediment deposition, and substrate stabilization. As a consequence, the site is elevated by sediment accumulation which, in turn, greatly reduces or prevents flood (Osterkamp & Hupp, 2010). Once pioneer species germinate on open sites and grow to a certain size, interactions lead to an increased roughness, fine sediment deposition, and substrate stabilization. As a consequence, the site is elevated by sediment accumulation which, in turn, greatly reduces or prevents flood. Here, especially the self-reinforcing effect (positive feedback) of some plant species influencing the landforms results in the development of biogeomorphic structures such as vegetated banks, islands, or floodplains, leading to the designation of these plant species as "ecosystem engineers" (Jones et al., 1994; Gurnell, 2014). Their influence on the hydrogeomorphic processes leads to an increase in vegetation cover on formerly open sites in braided river systems (Wagner et al., 2024), which promotes channel narrowing (Liébault & Piégay, 2002) and leads to a shift in habitat conditions.

Braided rivers respond rapidly and comprehensively to changes in habitat parameters and are highly sensitive to planform changes in response to extreme floods (Burkham, 1976). In recent decades, due to the impacts of human activities, such rivers have become highly endangered (Tockner et al., 2008; Hauer et al., 2016). A reduction in morphodynamics caused by human activities, such as channel sediment extraction, channelization, torrent control, and dam closure, can result in a considerable reduction in sediment availability (Kondolf et al., 2002; Marston et al., 2003; Surian & Rinaldi, 2003) and, consequently, altered flow and flood regimes (FitzHugh & Vogel, 2011; Mittal et al., 2015), disturbing the equilibrium. River systems are shaped by disturbances that can occur as pulse (induced by a single event), press (long term and continuous), or ramp disturbance (increasingly strong) (Lake, 2000; Piégay et al., 2020). The

systems stay as long in their former state as they can resist the disturbance or can recover from the effects of the disturbance event. However, if the system's resilience is exceeded and the boundary conditions reach a certain river-specific threshold, they will enter a new system state (Church, 2002; Fuller et al., 2019; Piégay et al., 2020).

From a geomorphological perspective, Piégay et al. (2020) define thresholds as turning points of channel responses between two equilibrium states, resulting in altered system characteristics. Church (2002), however, identified the flow regime, the sediment regime (quantity and grain size), and the topography as main settings of a geomorphic threshold in river systems. However, growth and spread of the riparian vegetation are also dependent on the river disturbance regime. When the disturbance regime shifts, such as through a reduction in disturbance intensity and/or frequency, the system responds with enhanced vegetation growth (Garófano-Gómez et al., 2017). Apart from the abiotic conditions, the riparian vegetation also largely influences the river conditions via bank stabilization or channel narrowing (Piégay et al., 2020), leading to "biogeomorphic thresholds". In a braided river section, such thresholds are surpassed as shifts occur in the area proportions of the succession phases, driven by increasing vegetation cover and density. If the species inventory is unchanged, this can be caused by a change in the disturbance regime, such as water diversions or sediment removal, by changes in the catchment area, such as altered flow regimes due to changes in precipitation caused by climate change, or by human intervention. Invasive alien species, given that they are able to change the growing patterns, can also induce state changes (Fei et al., 2014; Polvi & Sarneel, 2018).

In the case of continuous and long-term disturbances (press or ramp disturbance), a so-called tipping point can be reached (Notebaert et al., 2018; Piégay et al., 2020). In terms of river ecosystems, Phillips (2018) describes a tipping point as a transformation of a river reach with a major and qualitative alteration of the river structure and function. Such transitions typically occur over a timescale of decades or less and persist for decades and longer (Phillips, 2018). There are four possible categories of tipping points in fluvial systems, which are (1) planform change, e.g. the transition between a single-channel and a multi-channel planform, (2) qualitative sediment budget shifts, which are related to shifts in sediment supply versus transport capacity relationships, (3) sediment transport regimes, which include qualitative changes in dominant bed material or transformations in shares between coarse or suspended river substrate, or (4) biogeomorphic states, considering state changes associated with biotic–abiotic interactions between vegetation and sediment transport or storage (Phillips, 2018). We define the exceeding of irreversible river system thresholds by the impact of the riparian vegetation, which stabilizes side channels and can lead to a planform change of a multi-channel braided river to a single-channel river as "biogeomorphic tipping point". Such tipping points occur due to a complex interplay of growth-inhibiting stressors (morphodynamics, hydrodynamics, drought), growth-promoting site parameters (water balance, light), and vegetation-related properties (germination and establishment, root and shoot growth, resilience, and resistance to disturbance).

A tipping point is not defined as static condition but rather as a persistent and permanent state change of a river or river reach (Delong et al., 2024). Notably, even if the original conditions are restored, the natural reversion of this process is no longer possible (Phillips, 2018). Consequently, the former highly dynamic braided river landscape dominated by large, open gravel banks with permanent sediment relocation ultimately becomes a stabilized floodplain forest landscape ("from White Rivers to Green Rivers", Egger et al., 2012), which is associated with a loss of flora and fauna specific to pristine braided rivers.

In the context of analysing if the biogeomorphic tipping point of a river reach has been reached, the key issue is the extent to which different flood events will affect vegetation development and the emergence of specific system states in the long term. Will extensive regressions occur again, and will the river ecosystem return to its original state? Or has the tipping point been reached, and will stable succession phases remain dominant? One way to answer these questions is the use of succession models. These models depict the interaction between hydraulics and vegetation and allow forecasts of long-term vegetation development (Egger et al., 2012, 2013).

In the European Alps, human pressure on braided rivers appears to have pushed numerous rivers beyond the biogeomorphic tipping point. Here, the historical river types have largely been altered, i.e.

the proportion of braided river sections has been reduced from approximately 30–15% (Hohensinner et al., 2021). In Austria, for example, the Drava River was channelized in the twentieth century, which also destroyed braided river sections. To improve the ecological status of the river, more than 30% of the upper course of the Drava River, characterized by local braiding in the past, has been restored in recent decades (Muhar et al., 2019). One example is the creation of an artificial side channel at the Upper Drava near Kleblach in 2002. By widening and reactivation of the riparian zone, this side channel represented a small braided river section with a high proportion of open sites. The restoration programme was accompanied by extensive monitoring studies, which provided the opportunity to investigate vegetation succession and feedback with hydrogeomorphic processes (Egger et al., 2023). One restoration goal was to re-establish habitats for the two alpine riparian species German Tamarisk (*Myricaria. germanica* (L.) Desv.) and Dwarf bulrush (*Typha minima* Funck ex Hoppe) (Egger et al., 2019). However, during vegetation succession, the development of willow–tamarisk shrubs resulted in increased roughness and sand deposits, which further improved the growth conditions and massively accelerated succession (Egger et al., 2023). After approximately 14 years, a large part of this area had been transformed into white willow and grey alder forests, and the side channel can no longer be classified as a braided river section.

The overall aim of the study is to determine the conditions leading to biogeomorphic thresholds in braided rivers and, consequently, to the biogeomorphic tipping point, which can change multi-channel braided rivers into single-channel rivers. To achieve this aim, we analysed vegetation monitoring data and applied a biogeomorphic succession model for addressing the following research questions, using the Kleblach side channel of the Drava River as an example: (1) How can vegetation development be used to confirm if biogeomorphic thresholds have been reached? (2) Can the long-term trend confirm that the biogeomorphic tipping point has been reached? (3) What are the ecological consequences?

Our results allow a deeper understanding of the global responses of braided rivers to enhanced stable succession phases that lead to biogeomorphic tipping points. This facilitates the development of effective restoration measures and the protection of these valuable ecosystems (Dufour & Piégay, 2009).

Materials and methods

Study area

The study area is an artificial side channel of the Upper Drava River near Kleblach (Austria) in the south of the Central Alps at 570 m above sea level (Politti et al., 2014) (Fig. 1). The hydrological regime of the Upper Drava River is nivo-glacial, with maximum monthly discharges in June and July and low-flow periods during winter (Mader et al., 1996). The characteristic hydrological values for the Drava River at Sachsenburg gauge include a mean annual discharge of 69.69 m^3/s (MQ). The highest annual discharge is approximately 310 m^3/s (HQ_1), the highest decadal discharge is approximately 590 m^3/s (HQ_{10}), the highest discharge of a 30-year-interval is approximately 790 m^3/s (HQ_{30}), and the highest annual discharge of a 100-year-interval is approximately 1050 m^3/s (HQ_{100}) (Fig. 2) (Amt der Kärntner Landesregierung, 2024). In the period from 2002 to 2018, no flood event of HQ_5 or higher occurred.

In 2002, the 40- to 60-m-wide and 530-m-long side channel was created during a restoration programme as a braided river section including an island with a size of approximately 3 ha. The left bank of the side channel is protected with groynes. In the beginning, the gravel banks of the geomorphic phase and the pioneer phase dominated, and later succession phases occurred only on elevated sites. During the restoration measures in 2002, *Typha minima* and *Myricaria germanica* were reintroduced into the study area. The establishment success of both species is generally low, and they are almost extinct in their original distribution area. This is due to their low competitive ability compared to willows and grey alder (Bill et al., 1997), along with their short germination period and slow juvenile growth (Bill, 2000; Baur et al., 2017) This makes them highly sensitive indicators of ecological conditions of alpine rivers (Harzer et al., 2018). In 2002, *T. minima* was planted in the study area. Over time, it formed several small stands from which it spread in new, open sites, while the older stands were gradually overgrown by willow shrubs. In 2003, three mature individuals of *M. germanica*

Fig. 1 Drone image of the Drava side channel near Kleblach in 2021. The formerly open areas are largely covered by floodplain forest and shrubbery, leaving only one to two temporary side channels (base map: basemap.at)

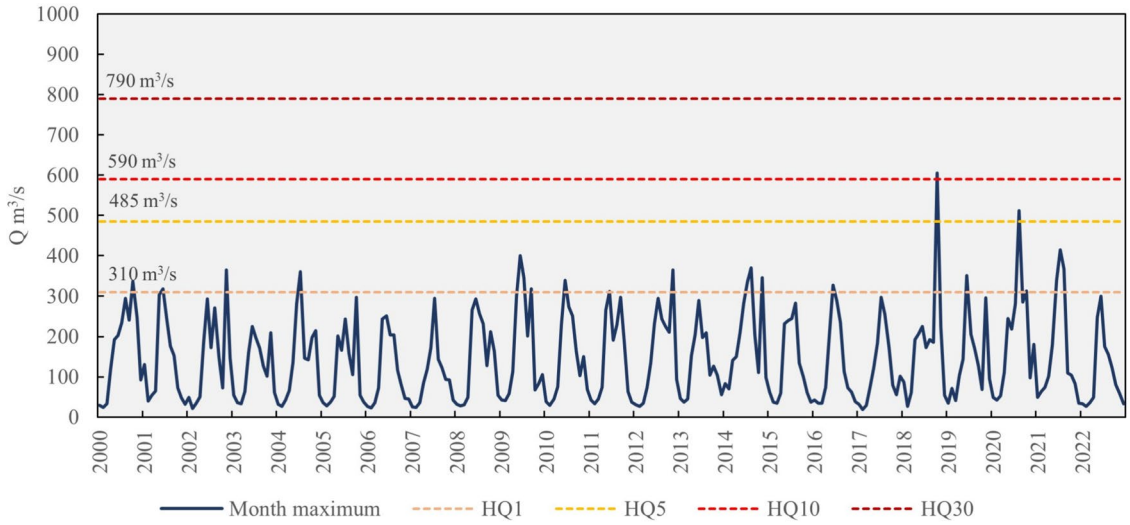

Fig. 2 Monthly maximum discharge volumes from 2000 to 2022 and discharge of the following recurrence intervals: annual (HQ_1), 5 years (HQ_5), 10 years (HQ_{10}), and 30 years (HQ_{30}) (Sachsenburg gauge; HQ = highest discharge during equal intervals (years); data source: Amt der Kärntner Landesregierung, 2024)

were planted at the beginning of the side channel, and the species spread in the active channel of the upper study area over the years (Egger et al., 2019). To date, *M. germanica* populations occur along the edges.

Determining biogeomorphic thresholds and the tipping point via vegetation monitoring

As mentioned above, increased vegetation growth is a response of an altered disturbance regime, leading to biogeomorphic thresholds. We consider such thresholds as detectable, albeit reversible, steps of changes and trends in vegetation succession that, in the absence of disturbance events, initiate an irreversible biogeomorphic tipping point. We defined the first threshold on the way to a biogeomorphic tipping point as the gradual decrease in the highly dynamic succession phases consisting of the water, geomorphic phase, and pioneer phase. As a second threshold, we defined the emergence of the ecological phase. The latter confirms decreased river dynamics since the later succession phases cannot be destroyed by the frequent morphologically active floods ($HQ_{1.5}$–HQ_2; (Leopold, 1997). This leads to the definition of a biogeomorphic tipping point as a point that is reached when a major flood event cannot retrogress the vegetation. For this purpose, the vegetation development of the study area between 2002 and 2021 was investigated to compare the area shares of the different succession phases and identify decreases in the highly dynamic succession phases and increases in the stable ecological phase.

Monitoring took place in 2002, 2003, 2005, 2007, 2008, 2009, 2010, 2011, 2013, 2014, 2016, 2017, 2018, and 2021 (Egger et al., 2023; Table 1). Thereby, the vegetation types were pre-defined using a current orthophoto, in the course of an area-wide mapping, the vegetation boundaries were checked in the field, and the segments were assigned to the respective succession phases (according to Corenblit et al., 2007) and vegetation types (Schiebel, 2019; Dolamic, 2022).

Simulating the long-term succession trend by vegetation modelling

Long-term vegetation succession in the side channel was analysed using the spatially explicit model CASiMiR vegetation (hereafter CASiMiR; Benjankar et al., 2011). It is an expert rule-based, dynamic succession model that accounts for key riparian ecosystem processes such as recruitment, succession, and disturbances induced by flood events. Thereby, biotic drivers and disturbances are coupled to replicate the disturbance regime approach (Formann et al., 2014). The model simulates the growth and spatial distribution of floodplain succession phases based on the interaction of disturbance impacts and the sensitivity of riparian vegetation. The succession phases transition from one phase to the next in a predetermined order (succession series), based on the site conditions and influenced by their minimum and maximum age. Disturbances can delay or disrupt the transition process. Their impact is generally determined by factors such as elevation above the mean water level, shear stress, and flood duration (Formann et al., 2014).

Succession modelling starts with a germination submodel, based on the recruitment box model of Mahoney & Rood (1998), which has been expanded to include woody species. Germination only occurs on open sites, and germination success depends on elevation above the mean water level as an indicator of soil moisture (Politti et al., 2014). Germination is followed by plant growth, simulated in the succession progression submodel, which adheres to the defined order of succession phases. Succession may be disrupted by disturbances in the regression submodel. These include mechanical disturbances, modelled using maximum annual shear stress as a proxy for morphodynamic disturbance, with each succession phase assigned a critical shear stress threshold. Disturbance by flood duration (Egger et al., 2013) was considered but omitted in this study (Politti et al., 2014) since only short flood events occur in the study area. Instead, the rearrangement of the sand and gravel bars emerges as the decisive process influencing the riparian vegetation along braided rivers. A detailed description of this simulation method is provided in Benjankar et al. (2011) and Egger et al. (2013).

For our case study, we used a pixel size of 1×1 m (Politti et al., 2014). For each pixel, vegetation survival during an annual maximum flood event was simulated, considering the relationship between flood disturbance intensity and vegetation resistance. The model simulates succession in annual time steps and uses the results as input for the following year. Input parameters include raster maps of the topography,

Table 1 Area shares of the vegetation types in the study area (%) in the monitoring years and their classification to the succession phases (after Corenblit et al., 2007; extended by Gurnell et al., 2016; data modified from Egger et al., 2023)

Vegetation type	2002	2003	2005	2007	2008	2009	2010	2011	2013	2014	2016	2017	2018	2021
Succession phase 0: Permanent water phase														
Kleblach side channel	46.0	46.0	27.4	7.0	9.7	8.4	27.0	18.1	32.2	25.9	10.2	18.7	18.0	20.1
Still waters	4.0	4.0	4.0	2.9	2.1	2.1	2.5	2.3	2.3	2.3	2.6	2.7	2.6	2.4
Succession phase 1: Geomorphic phase														
Gravel and sand banks	36.5	19.1	22.1	19.3	25.1	20.1	10.9	24.3	1.5	10.8	23.3	12.3	7.4	13.0
Riprap	1.1	1.1	1.1	0.9	1.2	0.9	1.2	1.3	0.6	0.5	0.0	0.5	1.0	0.5
Succession phase 2: Pioneer phase														
Pioneer herb vegetation	0.0	0.0	5.1	33.0	13.5	8.8	2.3	0.0	3.2	0.8	1.3	3.8	6.4	3.8
Pioneer shrubs	1.5	7.6	23.6	18.4	23.5	1.5	7.8	7.6	10.7	8.3	2.7	0.5	0.2	0.5
Succession phase 3: Biogeomorphic phase														
Dead wood	0.1	0.1	0.1	0.4	1.4	1.0	1.1	1.5	0.8	1.4	1.7	1.9	3.0	2.4
Reed vegetation	0.0	0.0	0.2	1.0	5.2	10.5	6.9	8.0	2.1	3.1	3.2	3.1	5.7	2.5
Typha minima reed	0.0	0.0	0.0	0.0	0.0	0.0	0.8	1.3	1.6	2.7	0.4	0.4	0.7	0.3
Shrubs with *T. minima* reed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.3	0.3	0.0
Willow–tamarisk shrubs	0.0	0.0	0.0	1.7	1.8	7.8	9.2	7.6	10.0	9.0	11.0	11.5	11.1	7.8
Willow shrubs	0.3	0.3	5.9	5.9	7.5	30.3	18.0	13.5	21.1	22.7	3.4	4.3	1.8	2.0
Forbs and ruderal vegetation	3.7	15.0	3.7	1.7	2.1	1.6	0.9	4.1	2.5	1.8	2.0	2.0	2.0	0.1
Succession phase 4: Ecological phase														
Salix alba floodplain forests	0.0	0.0	0.0	0.0	0.0	0.0	6.9	1.2	1.7	1.1	16.8	16.7	16.4	19.2
Alnus incana floodplain forests	6.8	6.8	6.8	7.7	7.0	7.0	4.5	9.0	9.5	9.5	20.5	21.2	23.4	25.5
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

mean water level, delineation of the three zones water, bank zone and floodplain zone, and mapped vegetation types for each succession series. The expert-based rules regarding the sensitivity of the succession phases against morphodynamics were calibrated by comparing the simulated and mapped vegetation types from 2002 to 2018 (Schiebel, 2019). In the calibration period, topography was surveyed seven times (2003, 2005, 2007, 2008, 2009, 2011, and 2018) and used as new input for a stationary calculation of the water levels, employing a 2D hydrodynamic model (Schiebel, 2019).

To assess the crossing of the biogeomorphic tipping point in the long term, we simulated vegetation succession from 2002 to 2050. For the long-term simulation, the annual discharge maxima of the Drava River (Sachsenburg gauge) were used for the calibration period from 2002 to 2018. For the period from 2019 onwards (30 years), the maximum discharges were transferred from 1986 to 2017 to the model period from 2002 to 2050 (Scenario 1) (Schiebel, 2019).

No major floods higher than HQ_{10} occurred in the reference period from 1986 to 2018. To be able to determine the effect of a catastrophic flood on vegetation, in a second scenario, a (hypothetical) HQ_{100} in 2019 was assumed (Scenario 2).

In both scenarios, the topography of the study area was assumed to be stable throughout the simulation period since the studied side channel is bordered by stable riparian forest patches, where only extreme flood events could significantly alter the topography. We assumed stable conditions for our simulations as the focus was on determining whether a regression would occur due to a flood event and not on the vegetation development afterwards. Structural changes in the study area were accounted for through vegetation growth as older and more stable vegetation types are less vulnerable to shear stress.

For both simulated scenarios, the biogeomorphic tipping point was defined as the point at which the study area is dominated by stable succession phases in the long term.

Nature conservation assessment of biogeomorphic tipping point consequences

The ecological conditions were assessed based on the occurrence of the two indicator plant species *M. germanica* and *T. minima*, which are highly sensitive to river alterations. *M. germanica* is the indicator species of the willow–tamarisk shrub and *T. minima* of the *Typha minima* reed. The distribution of the two indicator species was also recorded with the mapping of vegetation types from 2002 to 2021 and simulated via CASiMiR modelling (Scenarios 1 and 2) from 2019 to 2050.

Results

Biogeomorphic tipping point thresholds at the Kleblach side channel after the restoration measure up to 2021

In the first period after the restoration measures in 2002, more than 50% of the study area was covered by water and approximately 40% by gravel banks (Fig. 3a). On the riverbanks, there were small areas with pioneer vegetation. One year later, the biogeomorphic phase, represented by the establishment of ruderal species, was dominant on the higher terraces, approximately 2 m above the mean water level. In the side channel itself, no vegetation was present due to the high morphodynamics in the active channel. The side channel was characterized by continuous lateral erosion, and after 3 years, the riverbed of the side channel had widened to a width of 70–80 m (Formann et al., 2014). Following the first initial years, between 2005 and 2008, the side channel still had high area shares of the highly dynamic succession phases but with higher shares of pioneer vegetation (Period 2 in Fig. 3a). With a decrease in morphodynamic processes, woody pioneer species, mainly *Salix alba* and *Alnus incana*, established, especially on the newly formed gravel islands and banks. This trend continued in 2007. With further succession, the first *M. germanica* shrubs developed. Between 2008 and 2009, the former pioneer vegetation developed into shrubs, which became dominant (beginning of Period 3 in Fig. 3a). Approximately 10 years after the restoration (2009–2014), the succession phases seemed to be quasi-stable. However, the vegetation on the site became denser, with the highest area shares in the biogeomorphic phase. In large parts of the side channel, the sediment was stabilized by vegetation. The increased roughness caused by vegetation establishment led to massive sand sedimentation,

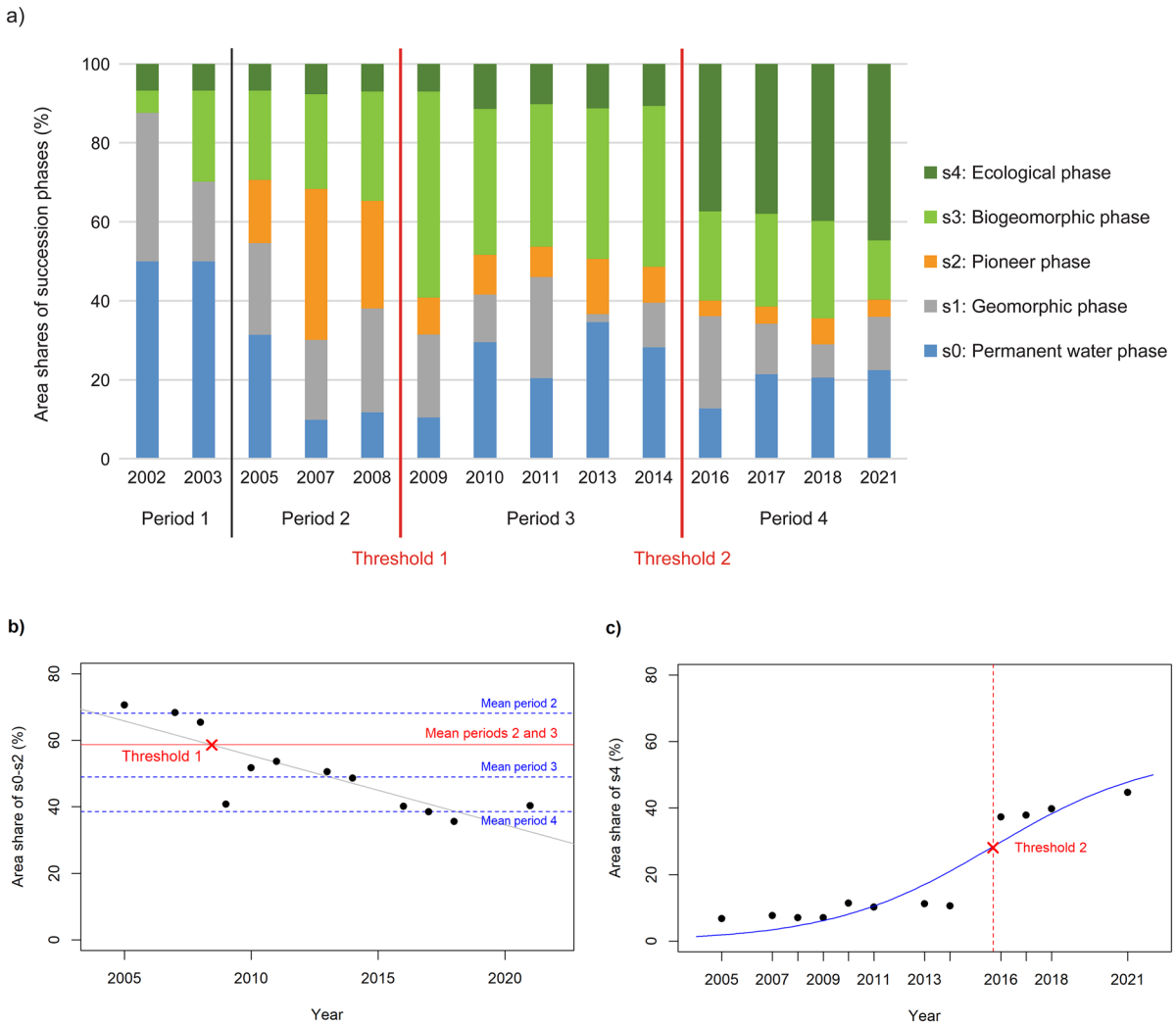

Fig. 3 Area shares of the succession phases at the Kleblach side channel after the restoration measures in 2002 with **a** all succession phases throughout the monitoring period (adapted from Egger et al., 2023), and the two biogeomorphic thresholds **b** biogeomorphic threshold 1: decline in the highly dynamic succession phases (water, geomorphic phase, pioneer phase), and **c** biogeomorphic threshold 2: development of the ecological phase showing a logistic trend with its inflection point shortly before 2016

which in turn further accelerated succession (Egger et al., 2023). The most dynamic areas up to this time were the inflow area of the side channel and the adjacent riverbank due to the flow of the Drava. In 2016, the first riparian forest patches were established in the active channel (mainly white willow and grey alder forests). Thereafter, the softwood forest cover, which represents the ecological phase, became more prominent and eventually dominated (Period 4 in Fig. 3a). In the autumn of 2018, the first major flood event (HQ_{10}) since 2002 occurred, which caused side erosion and created new gravel banks in the inflow area of the side channel (for a vegetation type map of the Kleblach side channel, see Supplementary Fig. S1).

The middle part of the side channel was characterized by strong morphodynamics, facilitating the continuous development of new pioneer sites. Until 2021, this section was characterized by driftwood deposits as well as willow and tamarisk shrubs. In the lower part, from the beginning on, massive sand deposits were typical, resulting in the rapid establishment of

willows. In the more unobstructed areas, *T. minima* could establish large populations (Baur et al., 2017). However, with the increasing density of the willow shrubs, these populations gradually disappeared. *M. germanica* never established itself along the lower section of the side channel. After only a few years, the sediment banks in the lower section were completely occupied by reed and willow stands.

During the 20-year vegetation mapping period, the cover of dynamic habitats on sites with high turnover rates (including water, gravel banks, and pioneer habitats) decreased from approximately 90–40%. As a result, the coverage of stable habitats with little possibility of retrogression increased from 10% to approximately 60%. By analysing the succession phase development in detail (Fig. 3b, c), the general decrease in the highly dynamic succession phases (water, geomorphic, and pioneer phase) became visible, with a distinct decline after 2008. By taking the means of the shares of these highly dynamic succession phases of each period (Fig. 3a) and intersecting them with the general linear decrease in these phases over the whole monitoring period, we determined the first biogeomorphic threshold on the way to a biogeomorphic tipping point in the study area for the year 2008 (intersection at 2008.4, Fig. 3b). On the contrary, the ecological phase remained on a similar level for the first two periods before sharply increasing between 2014 and 2016. The inflection point of the curve can be seen as a second biogeomorphic threshold (inflection point at 2015.8; Fig. 3c). The areas covered by vegetation of the biogeomorphic phase slightly increased up to 2014 before decreasing due to areas growing and being then classified as being in the ecological phase (Fig. 3a).

Long-term vegetation succession from 2018 to 2050

The long-term future development of the study area is characterized by ongoing succession processes (Table 2; Supplementary Fig. S2). By 2030, progression is predicted to have reduced the open areas to 11% in favour of pioneer vegetation and shrubs typical for the biogeomorphic phase. This state is stable for the remaining model period. By 2040, most of the area (more than 60%) will have developed into softwood forests, representing the ecological phase, with small patches of the biogeomorphic phase. Until the end of the modelling period in 2050, the trend will likely continue, and there will be only small dynamic open areas directly along the side channel and the adjacent ecological succession phase.

Scenario 2 with a (hypothetical) major flood in 2019 also shows that even a HQ_{100} would only cause a short-term and small-scale increase in young succession phases. The HQ_{100} would destroy a total of approximately 6% of the shrubs and young riparian forests (biogeomorphic and ecological phases), and the number of young succession phases would increase accordingly in the short term (Table 2). After just 6 years (after 2024), however, all young succession phases would have developed back into shrub phases and, after a further 12 years, into a stable ecological phase analogous to that in Scenario 1 without a major flood event. This demonstrates that even a HQ_{100} will not lead to any further regression in the medium term.

Indicator species development

Within 5 years after restoration, pioneer vegetation had established in the study area, followed by willow and grey alder shrubs (Fig. 4). At approximately 7 years after the planting of *M. germanica*, willow–tamarisk shrubs already covered approximately 10% of the study area. They remained at approximately the same level until the end of the monitoring period in 2021. *T. minima* reeds covered approximately 1% of the study site after 7 years and 3% after 12 years. However, the establishment of the willow shrubs and softwood forest largely reduced the *T. minima* populations, and as of 2021, the species only occurs in small areas along the Kleblach side channel (Egger et al., 2023).

Discussion

Fluvial biogeomorphic succession at the Kleblach side channel: Has the biogeomorphic tipping point been reached?

Analysis of the vegetation development from 2002 to 2021 shows that the first biogeomorphic threshold in the study area was reached in 2008 with the decline in the areas characterized by highly dynamic succession phases. The second biogeomorphic threshold could be detected for the time point just before 2016, when

a fundamental change in succession direction was initiated and stable succession phases prevailed. This could also be confirmed by the modelling of long-term future vegetation development. Even a simulated catastrophic flood in 2019 (3 years after the inflection point) would not have reversed the long-term development. These results, including the indication from the long-term simulation, suggest that the biogeomorphic tipping point was reached between 2015 and 2019.

Lateral erosion, although it cannot be modelled by CASiMiR, has the potential to create new open gravel bars. A HQ_{30} flood event, which occurred in autumn 2018 after vegetation mapping, created few new open areas. These retrogression processes are limited to the inflow area of the side channel. Also, along the cut banks, continuous lateral erosion during the smaller annual floods leads to a slow shift of the river course. However, this is not sufficient to prevent vegetation development or to mitigate the crossing of the biogeomorphic tipping point.

Minor floods, such as events with annual or biannual recurrence interval, play an important role in riverbed formation and shape the stream morphology through the rearrangement and deposition of sediment and thus have a considerable impact on vegetation development. If such events occur frequently, they can prevent the large-scale establishment of pioneer vegetation as the development of communities capable to resist flood disturbance takes approximately 3–4 years (Egger et al., 2012). As a consequence, the crossing of the biogeomorphic tipping point would be prevented. In case the time between two pulse disturbance events is too long, the vegetation is able to establish and form resilient communities, leading to channel narrowing (Piégay et al., 2020). This is exactly what happened at the Kleblach site, where no flood event of HQ_5 or higher occurred between 2002 and 2018. After this long stable period, even a major flood event, such as the hypothetical HQ_{100} in 2019, could no longer destroy already established vegetation. Thus, at this site, the biogeomorphic tipping point has clearly been crossed, leading to a resilient, vegetated state which offers only very limited habitat for species of conservation value, such as *M. germanica* or *T. minima*.

Ecosystem consequences of biogeomorphic tipping points in braided rivers

At the restored Kleblach side channel, open sites were dominant in large parts a few years after restoration, providing germination sites for the two indicator species *M. germanica* and *T. minima*. In the Alps, the formerly connected populations have largely declined within the last 150 years because of habitat alterations, such as river regulation and the establishment of dams and power plants. Both species have a high tolerance for stressful habitat conditions and colonize the edges of their ecologic amplitude to avoid inter-species competition since they are highly sensitive to shading (Kudrnovsky & Höbinger, 2015; Egger et al., 2019, 2023). After planting a few individuals of these indicator species in the study area, they spread rapidly, which is a great success from a nature conservation perspective

Table 2 Differences between the area shares of succession phases (abbreviations see Fig. 3a) in Scenario 2 (HQ_{100} event in 2019) and Scenario 1 (no HQ_{100} event in the model period; in %, based on total study area) (based on data from Schiebel, 2019)

Year	s0	s1	s2	s3	s4	Sum
2018	0.0	0.0	0.0	0.0	0.0	0.0
2019	0.0	6.4	-0.5	-5.8	-0.1	0.0
2020	0.0	6.7	-0.7	-6.0	-0.1	0.0
2021	0.0	4.7	1.4	-4.8	-1.3	0.0
2022	0.0	0.6	6.1	-5.0	-1.7	0.0
2023	0.0	0.4	4.3	-3.0	-1.7	0.0
2024	0.0	0.5	0.1	1.1	-1.7	0.0
2025	0.0	0.5	0.0	1.6	-2.1	0.0
2030	0.0	0.3	0.2	6.3	-6.7	0.0
2040	0.0	0.3	0.0	0.2	-0.5	0.0
2050	0.0	0.3	0.0	0.0	-0.3	0.0

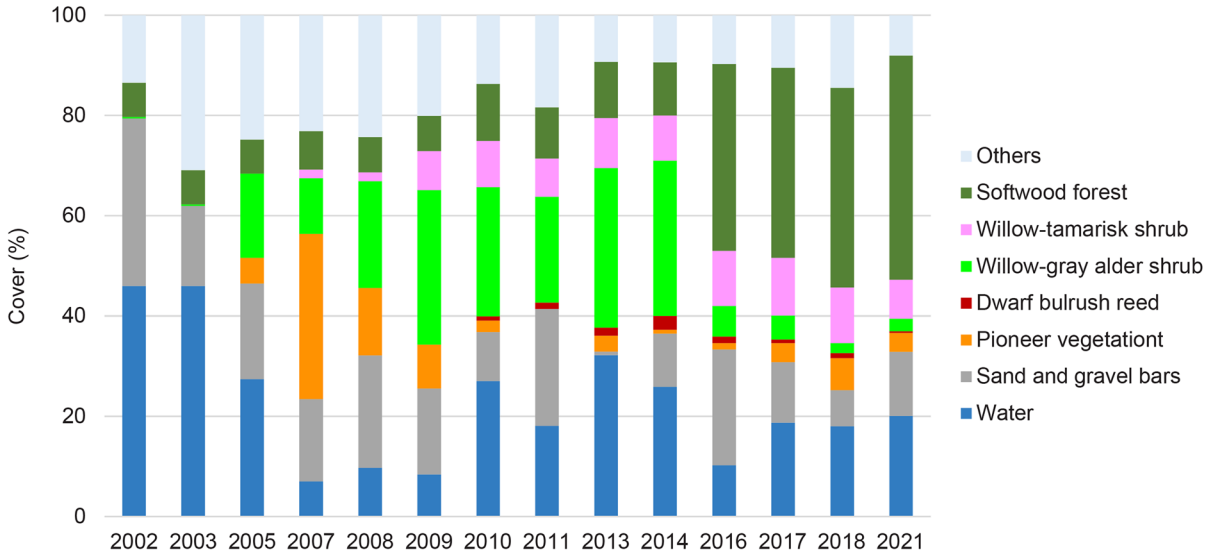

Fig. 4 Development of selected vegetation types and indicator species vegetation types (Dwarf bulrush reed and willow–tamarisk shrub) in the study area from 2002 to 2021 (after Egger et al., 2023)

(Harzer et al., 2018). However, the planting of fructifying plants was a prerequisite for establishment as both species were locally extinct (Egger et al., 2023). Due to the massive spread of the softwood forest from 10% to almost 40% after 12 years, the *M. germanica* occurrences were restricted to the sites with higher light availability at the edge of the dense willow and alder stands, and the population seemed to decrease due to shading (see also Egger et al., 2023). As our modelling results predict the further spread and dominance of softwood forests, *M. germanica* will probably only survive on the edges of vegetated islands and softwood patches. The species is likely to thrive in the study area due to its high capacity to withstand floods (Egger et al., 2019). *T. minima* populations, in contrast, are likely to decline or even disappear as this species is more sensitive to flood events with sedimentation or high traction (Müller, 1991). Our findings are in line with other species conservation planting projects (Latzin & Schratt-Ehrendorfer, 2005; Wittmann & Rücker, 2006) which also highlighted the importance of river dynamics to provide suitable germination sites and decrease management actions but also the danger of eroding the planted individuals.

Our findings from the Upper Drava can be transferred to most other European rivers affected by anthropogenic modification of process dynamics, many of which are moving towards a biogeomorphic tipping point. For example, the decline of the two indicator species *M. germanica* and *T. minima* can also be seen, for example, in the Upper Isar River (Germany). Here, the Sylvenstein dam alters hydrodynamics and retains sediment, threatening the *M. germanica* population in the Pupplinger Au downstream of the dam (Harzer et al., 2018). Upstream of the dam, there is still a viable population of *M. germanica*, despite water dispersion for a hydropower plant for several decades, leading to the continuous increase in vegetation cover but leaving sufficient open germination sites (Juszczyk et al., 2020).

Furthermore, the Kleblach case study can be seen as representative of many braided river sections. Braided rivers are highly sensitive to changes in their sediment supply and water flow (Grant et al., 2013). According to the findings of early laboratory experiments, increased vegetation cover and density in braided streams reduce the number of river channels and their lateral migration, increase bank stability, and narrow and deepen channels (Gran & Paola, 2001). Flood-resilient plants such as trees highly influence the development of riparian landform structures in the active corridor of braided rivers, and their growth rate plays a critical role in vegetation recovery after flood events and the development of the root system that traps and stabilizes the sediment

(Bertoldi et al., 2011). Dam construction and operation often lead to drastic increase in vegetation cover and coverage rate downstream of the dam due to flood reduction and changes in the hydroregime including groundwater lowering and soil moisture content decrease (e. g. Choi et al., 2005). Furthermore, riverbank vegetation tends to grow more homogenously (Yi et al., 2019). These effects can lead to planform changes, as reported by other authors (Gordon & Meentemeyer, 2006), who observed an increase in riparian vegetation by 72% 17 years after dam construction in a braided river in northern California and the transition to a single-thread meandering river.

In most alpine rivers in Europe, the tipping point from a multi-channel river with bare gravel bars to a single-channel river with high vegetation cover has been reached, and throughout the Alps, a decline in braided rivers by up to 90% has been reported (Hohensinner et al., 2021), accompanied by the loss of specific fauna and flora. This trend can also be observed on a global scale (Renaud et al., 2013; Notebaert et al., 2018; Phillips, 2018; Delong et al., 2024) and could be shown for different river types by using the CASiMiR model (Benjankar et al., 2011; Egger et al., 2012; 2013; Garcìa-Arias et al., 2013). The application and comparison of findings on the formerly braided Drava River and the two naturally meandering Odelouca River in Portugal and the Mijares River in Spain provided good results, and the CASiMiR model performed in a robust manner (Garcìa-Arias et al., 2013). One well-studied example is the Nakdong River in South Korea (Egger et al., 2012). Here, a dam was first built on the Andong tributary, with little impact on the main active channel. However, after the construction of the second dam, Imha dam, vegetation coverage along the Nakdong River increased significantly. This development was irreversible from the time of the construction of the second dam and triggered by the artificial reduction of the annual maximum flow for several consecutive years, which allowed the vegetation to reach a certain cover and initiate biogeomorphic feedbacks. Based on the CASiMiR modelling results, even a subsequent increase in flood flow would not have been able to decrease the vegetation cover again. The second major trigger was the lack of sediment transport, which further weakened any disturbances of the plant populations. This was finally manifested in the tipping point and the transition from a dynamic to a stabilized river channel.

On the Rhine River, CASiMiR simulation revealed a development similar to that of the Kleblach side channel (Ochs et al., 2019). Approximately 22 years after straightening and channelizing the anabranching Upper Rhine river reaches in 1872, the areas with the dynamic succession phases decreased, and another 16 years later, there was an abrupt rise in areas characterized by the biogeomorphic phase (late successional woodland phase). Due to the altered hydraulic conditions, the disturbance regime was reduced, and after another 54 years, the landscape was dominated by a hardwood forest bordering the artificial single-channel river.

As shown above, the vegetation on many braided rivers covers increasingly more areas in the river corridor and develops towards later succession phases with the lack of flood dynamics. This could be confirmed by CASiMiR modelling on both braided rivers and other river types. The results of our study can therefore potentially be transferred to numerous other rivers and enable a future prognosis of further development. However, one limitation of the succession model is the lack of representation of side erosion, which, in some areas, plays an important role in the development of open germination habitats. In addition, the two biogeomorphic thresholds could be calculated on different rivers to make our results more transferable.

Implications for restoration measures

For braided rivers, it is important to prevent biogeomorphic tipping points by allowing dynamic processes with hydro- and morphodynamics to preserve the habitat conditions for adapted species of conservation value. Morphodynamic processes, such as bank erosion, where the riverbank is washed out and trees are uprooted, can create new habitats for target species. This requires unstabilized riverbanks which need to be a goal for restoration measures (Sambrook Smith et al., 2006; Piégay et al., 2020). To avoid tipping points with channel evolution from braided to single-channel rivers, the runoff and sediment balance need to be largely maintained in their original form. However, once the biogeomorphic tipping point has been reached and the channel

morphology has been stabilized by vegetation, it is crucial to overcome the changes through river restoration measures. Against the background of a nature conservation perspective, the most important aspects for planning and implementing measures are as follows:

(1) The removal of stable vegetation types, especially those of the ecological phase, including the top layer of soil and roots, to allow dynamic processes to take place (Gurnell et al., 2012; Wagner et al., 2024);
(2) The enabling or restoration of hydrodynamics so that annual or at least biennial floods regularly disturb or destroy the pioneer vegetation (Pasquale et al., 2011);
(3) The enabling or restoration of riverbed morphodynamics, including sufficient sediment input and transport, to disturb the vegetation and prevent riverbed incision (Piégay et al., 2006);
(4) The implementation of measures at a scale appropriate to the river type, i.e. for braided rivers, an area where the multi-thread bed can form, and the main channel can shift laterally (e.g. river restoration on the Drave River at Obergottesfeld, Egger et al., 2023);
(5) The planting of endangered species in restored river reaches to promote their occurrence (this is optional), which is only possible once the habitat conditions have been restored (Egger et al., 2010; Baur et al., 2017).

It has to be taken into account that braided rivers are considered a river type that is highly resilient to pulse disturbances since they are shaped by recurring flood events but are, at the same time, highly sensitive to press disturbances (Tockner et al., 2006; Piégay et al., 2020). This has to be considered for restoration measures but also when planning river structures.

Conclusion

According to the analysis of the Kleblach side channel on the Upper Drava River and further CASiMiR vegetation modelling studies on different rivers, it is apparent that the biogeomorphic tipping point occurs once the two biogeomorphic thresholds have been exceeded and that it cannot be reversed without major measures: first, the growth and establishment of the pioneer vegetation due to the reduction of minor floods with an annual or biannual recurrence interval. The missing frequent rearrangement of the substrate and sedimentation, which also shape the stream morphology, enables vegetation growth, with the development of stable communities taking approximately 3–4 years. Second, the extensive consolidation of the biogeomorphic succession phases which are not destroyed even by major flood events. This indicates the reaching of the irreversible biogeomorphic tipping point, making comprehensive and specific restoration measures crucial.

For the Kleblach side channel, the two biogeomorphic thresholds occurred approximately 15 years after the restoration between 2015 and 2019. The indicated biogeomorphic tipping point was confirmed by the CASiMiR long-term succession modelling, which revealed no vegetation regression even in the case of a substantial flood event (HQ_{100}).

Our findings for the restored Kleblach side channel are exemplary for the European Alps. The loss of suitable habitats and the fragmentation of metapopulations of typical riparian species threaten the biodiversity of braided rivers. Hence, the overall site conditions, with continuous water and sediment flow, need to be considered for conservation and restoration of the braided river type in general. The concept of the biogeomorphic tipping point as discussed in this study can provide relevant guidance and contribute to the long-term preservation of these valuable river ecosystems.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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