Geomorphology 413 (2022) 108327

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology

Modelling restoration of natural flow regimes in dam impaired systems: Biomorphodynamic effects and recovery times

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ARTICLE INFO

Keywords:
Dam removal
Flow alteration
River restoration
Riparian vegetation
River morphodynamics
Bio-geomorphology

ABSTRACT

Dams affect the natural flow regime by altering the magnitude, timing and frequency of high and low flows. Many river ecosystems impaired by dams are currently being restored. Restoration success is difficult to quantify and is often assessed by comparing the restored system to an unimpaired static 'reference' system. However, restoring a river to past environmental conditions and assessing restoration success by comparing it to a static situation neglects natural system dynamics and non-linear, adaptive system responses. With this modelling study we evaluate long-term changes in river morphology, morphodynamics, riparian vegetation cover and habitat suitability of two fish species and two types of wetland vegetation in a meandering gravel bed river after removal of an upstream dam and complete restoration of the natural flow regime. We assessed the ecological and hydromorphodynamic recovery of systems impaired by two different dam operating regimes and three different time periods the dam was present by comparing these to a dynamic undisturbed situation. Modelling results show that recovery potential depends on how much the system has been changed by the dam and the system state at the start of the restoration, rather than the duration of the pressure. Even if the conditions shortly after restoration are comparable to pre-disturbance conditions, there can still be a time-lag in the system response where the future state of the restored system continues to deviate from the undisturbed situation. When this happens, the system can develop into an alternative dynamic equilibrium where recovery becomes increasingly difficult. These results stress the importance of considering natural variability in restored systems as well as in reference systems, requiring detailed spatio-temporal monitoring to assess restoration effects.

1. Introduction

Natural flow dynamics are important to maintain a bio-diverse fluvial system (Naiman and Decamps, 1997; Richter and Thomas, 2007). The flood pulse determines the frequency and magnitude of overbank flooding and is the main driving force behind ecosystem productivity, the creation of suitable habitats and interactions between hydro-morphodynamic processes and fluvial species (Junk et al., 1989; Tockner et al., 2000). It dictates the connectivity between the main channel and floodplain that is important for movement of fish and macro-invertebrates to complete their life-cycles (Rolls et al., 2012).

Many river systems have been impaired by humans, and flow regimes have been significantly altered from their natural state to protect people against flooding, for hydropower production, to facilitate navigation or to manage water supplies (Nilsson et al., 2005). Tockner and Stanford (2002) found that in Europe and North-America, 90% of the floodplain areas have lost their natural functions and interactions. Reservoir dams affect the magnitude, timing and duration of high and low flows, which in turn may dramatically alter river hydromorphodynamics and associated habitat suitability of species depending on natural flow dynamics (Clarke et al., 2008; Poff et al., 2010). Species can be affected differently according to the timing of their critical life-history stages (Bunn and Arthington, 2002; Poff et al., 2010). This can influence habitat suitability in opposite directions for species with contrasting seasonality in their important life events (Van Oorschot et al., 2018). The river shape, lateral confinement and river

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https://doi.org/10.1016/j.geomorph.2022.108327
Received 31 March 2021; Received in revised form 14 April 2022; Accepted 7 May 2022

entrenchment due to limited upstream sediment supply determine the sensitivity of a river system to the flow alteration (Cienciala and Pasternack, 2017; Kleinhans et al., 2018). This suggests that large changes in river geomorphology during dam operation might hamper system recovery.

Public awareness on the ecological deterioration of our rivers and floodplains has grown in the last decade, and large-scale restoration guidelines, plans and projects have been initiated world-wide. One of the most elaborate regulation instruments is the EU Water Framework Directive (WFD). This directive aims to improve the chemical, ecological and hydro-morphodynamic quality of river systems to preserve aquatic ecology, valuable habitats and socio-economic values of natural water resources (WFD, 2000). Currently, many river restoration projects are carried out across Europe to improve the quality of river systems and to meet the WFD requirements (Rijke et al., 2012; Kail et al., 2015). A large scientific challenge remains in quantifying the biological, physical and chemical responses after restoration, whilst this is necessary to set restoration objectives (Hart et al., 2002; Jähnig et al., 2011). The current state of water bodies is assessed by comparing it to an ‘unimpaired’ or ‘reference’ system. However, assessing ecological quality of a system is mostly based on comparison to a reference condition at one moment in time. This approach has been increasingly criticized because it does not consider internal system dynamics (Friberg et al., 2011). Hence, it becomes difficult to make a distinction between system changes due to human impact on the one hand versus natural variability inherent to the system on the other hand (Bouleau and Pont, 2015). Furthermore, river hydro-morphodynamics and vegetation change dynamically over time in a non-linear way with multiple interactive adaptation scales (Solari et al., 2016; van Oorschot et al., 2016; Garofano-Gomez et al., 2017; Van Oorschot et al., 2018). Due to these effects, simply restoring the past environmental boundary conditions of a river system, to restore a river system to a desired reference ‘state’ is not straightforward, and often impossible (Dufour and Piegay, 2009).

With this study we want to gain understanding of how river hydro-morphodynamics and ecology may evolve in response to dam removal and restoring the natural flow regime in a system where the flow regime was previously modified by reservoir dams. We evaluate whether and to what extent hydro-morphodynamic and ecological conditions along a river stretch of a meandering gravel bed river can return to values within the dynamic equilibrium range of the undisturbed state, and how long that takes. Additionally, we assess whether the magnitude, i.e. how much the system has been changed by the flow alteration compared to the natural situation, and duration of the dam operation prior to flow restoration, i.e. pressure duration, influences the restoration success and whether there are hysteresis effects or irreversible changes that hamper restoration. Only alteration of the flow is assessed, since the dams are assumed to be relatively far upstream so there is no direct sediment supply limitation.

A biomorphodynamic model including the dynamic interaction between hydro-morphodynamic processes and riparian vegetation (van Oorschot et al., 2016, 2017) was used to evaluate long-term changes in river morphology, morphodynamics and riparian vegetation cover. Ecological response was further assessed by transferring the model output to ecological response models of fish and wetland vegetation to calculate habitat suitability for these ecological indicators. The effect of restoration from two types of flow alterations caused by dams was studied with one scenario with a reservoir to attenuate peak discharges and one scenario with attenuated peak discharges combined with a reversed seasonality of the flow. The effect was evaluated for three different durations, i.e., 10, 50 and 100 years of dam operation. All dam scenarios were compared to a reference situation where the discharge sequence is equal except during the dam operation. This allows us to isolate the effect of the flow alteration and therefore investigate the actual dam effect instead of an effect caused by the natural variability in the system.

2. Methods

2.1. Biomorphodynamic model

The dimensions of the modeled river stretch were loosely based on the Allier River in France (see van Oorschot et al., 2016, for details on the model dimensions). This is an intermediate sized, gravel bed river with a mean annual discharge of 140 m^3/s and an active meandering planform which has been well studied over the last years (Geerling et al., 2006; Kleinhans and van den Berg, 2011; Van Dijk et al., 2014). Our goal was not to exactly replicate the Allier river, but to use its characteristics to model the behavior of a natural, meandering gravel bed river and to study patterns and trends in river morphology and vegetation affected by flow regulation and river regulation. To speed up the initialization phase, the initial model river morphology was based on the average sinuosity and dimensions of the Allier River. In the reference scenario, we used real discharges of the Allier River over 27 years which we randomly sampled per calendar year, such that the sequence of discharge years is random, but the flow seasonality is represented and maintained. We assume a uniform sediment distribution, which is sufficient to obtain the patterns in river morphology and the dynamic vegetation development. Previous work showed that in rather high sediment mobility conditions, as the case here, sediment mixtures and spatial sorting does not change the relevant characteristics of river morphology (Wilcock and Southard, 1989; Kleinhans and Van Rijn, 2002; Parker and Toro-Escobar, 2002; Baar et al., 2019).

For numerical hydro-morphological calculations, Delft3D was used with depth averaged flow velocities and bed level updates (see Lesser et al., 2004; Schuurman et al., 2013, and Table 1 for details on morphodynamic equations and processes).

This model was interactively coupled to a riparian vegetation model that calculates vegetation colonization, growth and mortality. In the model, riparian vegetation acts as ecosystem engineers that dynamically interact with river morphodynamics. Vegetation actively affects the flow path by providing resistance to the flow and affecting flow velocities within and around vegetated areas. In turn, the flow regime affects the vegetation survival by burial through sedimentation, scour by erosion, uprooting due to high flow velocities, anoxia due to flooding and

Table 1
Table with morphodynamic and vegetation parameter settings.

Parameter	Value	Unit	Reference or motivation
Hydrodynamic timestep	0.2	*min*	Based on grid cell size and flow velocity
Morphological scale factor	30	–	Schuurman et al. (2013)
α Koch and Flokstra bed slope parameter	0.70	–	Schuurman et al. (2013)
β Koch and Flokstra bed slope parameter	0.50	–	Schuurman et al. (2013)
Timestep bed level change	6	*min*	
Timestep vegetation	21,900	*min*	To capture main ecological processes
Vegetation types	willows and poplars	–	main European riparian trees
Grid size (*width* × *length*)	1000 × 3600	*m*	Covering a few meanders
Cell size (*width* × *length*)	25 × 25	*m*	Compromise between resolution and model efficiency
Chezy value bare substrate	25	$m^{\frac{1}{2}}/s$	Van Dijk et al. (2014)
D50	5×10^{-3}	*m*	Van Dijk et al. (2014)
Sediment transport predictor	Engelund-Hansen	–	Schuurman et al. (2013)
Initial sinuosity	1.3870	–	Geerling et al. (2006)
Slope	0.000833	*m/m*	Crosato and Saleh (2011)
Channel width (at low flow)	50	*m*	Google Earth at 27/9/2018

desiccation due to water deprivation.

Riparian vegetation characteristics were based on the eco-engineering species of temperate lowland rivers, i.e. willow and poplar trees. Willow and poplar types are modeled as separate vegetation types and include different age classes with different height and stem densities. Hydraulic roughness by vegetation was calculated by the Baptist et al. (2007) relation. Riparian trees can only colonize on bare substrate, i.e. when there is room left in the grid-cell. Competition between vegetation types, other than for space, was not included in this study. Details on the vegetation model and vegetation characteristics are described in van Oorschot et al. (2016). This study uses the same vegetation model as described in Van Oorschot et al. (2018) with two-weekly feedbacks to the hydro-morphodynamic model and measured Allier discharge sequences. This means that vegetation characteristics and vegetation location are updated every two weeks based on hydrodynamic and morphodynamic parameters and are fed back into the hydro-morphodynamic model. Fig. 1 shows an example of a typical simulated river morphological shape of the situation without dams and with vegetation development of different age classes.

The model has been applied and validated in several studies. The general modeled patterns and dynamics in river morphology and vegetation have been compared to satellite data (van Oorschot et al., 2016; Van Oorschot et al., 2018). The model reproduced distinct morphological features that are relevant for the interactions with vegetation, such as chute cut-offs and oxbow lakes. Likewise, the dynamics of native riparian trees in the vegetation model create a cover, landscape diversity, vegetation distribution and vegetation age distribution that is comparable to the available empirical data. In van Oorschot et al. (2017) we showed that the model produces plausible spatiotemporal results on the expansion of an invasive riparian herb, from which valuable insights on the ecological processes of facilitation and propagule pressure were derived.

2.2. Setup of scenarios

Two different types of dams were used to create the restoration scenarios: 1) a dam acting as a buffer to attenuate peak flows in winter and increase the minimum flow in summer for water abstraction downstream, 2) a dam with a seasonally reversed flow regime which represents an extreme situation that aims at increased water provisioning during the dry season and storage of water in the high flow season. Details on the construction of these flow regimes are described in Van Oorschot et al. (2018). From these two dam operating regimes, six restoration scenarios were designed by totally restoring the natural flow regime after three different durations of dam presence: 10, 50 and 100 years (Fig. 2b-d, Table 2). This allows testing the effect of pressure duration. Note that all scenarios represent a total removal of the dams.

Following the period of dam operation, the natural flow regime was restored for 180 years. To compare the results after restoration to the undisturbed situation, we created one scenario with undisturbed flow conditions for each pressure duration. These scenarios contained a similar sequence of discharges from the moment of restored flow regime onwards (Fig. 2a). Each scenario is composed of the following sequence of discharge time series: 1) a 100-year period of natural discharges as the model spinup, which is used as the starting point for all scenarios and allows the river morphology and vegetation patterns to develop, followed by 2) a period of altered discharge due to the dam release scheme for a period of 10, 50 or 100 years and then followed by 3) a 180-year period of restored natural discharge, which is the same for all scenarios. All undisturbed scenarios therefore have different simulation times, i.e. 290 years for the 10-year run, 330 for the 50-year run and 380 years for the 100-year run. By using similar hydrographs before and after the period of dam operation, we fairly compare the results of the three durations of dam operation since we excluded the effect of inter-annual and intra-annual discharge variation. However, a second effect of the different dam operation periods is that the river morphology and vegetation pattern at the end of the dam operation can differ among the scenarios, which creates different initial conditions at the start of the flow restoration period.

For all scenarios, only the upstream discharge boundary was adjusted. All other settings, including sediment concentration and parameters for vegetation remained unchanged. With this method, we assume the dam was constructed so far upstream that the river is able to pick up sufficient sediment downstream of the dam. This prevents model instabilities due to steep sediment gradients and is a valid assumption since changes in water flow regime have a direct impact over longer distances compared to the sediment deprivation effects immediately downstream of the dam (Ribberink and Van Der Sande, 1985; Middelkoop et al., 2015). The model only includes bed-load transport since the Allier is a typical sand-gravel bed river type. Furthermore, we assume that a potential reduction in wash load transport due to the dam has insignificant impact on this stretch.

2.3. Habitat suitability models

Two types of fish and two types of wetland vegetation were selected to evaluate the ecological response to river restoration: macrophytes, helophytes, Atlantic salmon (spawning and egg incubation), and pike (spawning). These species were selected as ecological indicators that inhabit different parts of the river system and depend on river hydromorphodynamics for their growth and survival. In our study area these fish species and wetland vegetation do not operate as ecosystem-engineers in the fluvial system, and thus do not interact with the higher scale biomorphological processes that build their habitats. Their occurrence is ‘facilitated’ by the habitat conditions resulting from the bio-morphological processes. This means that these species are

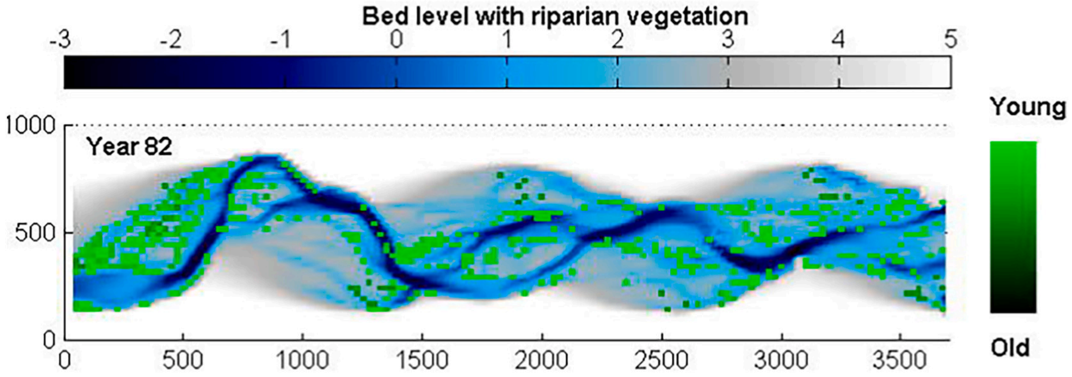

Fig. 1. Example of river morphology and vegetation development in the natural situation without flow alteration. It shows a meandering planform with cut-offs and oxbow lakes and a typical age distribution of vegetation across the floodplain with older vegetation at higher elevations and younger vegetation close to the channel.

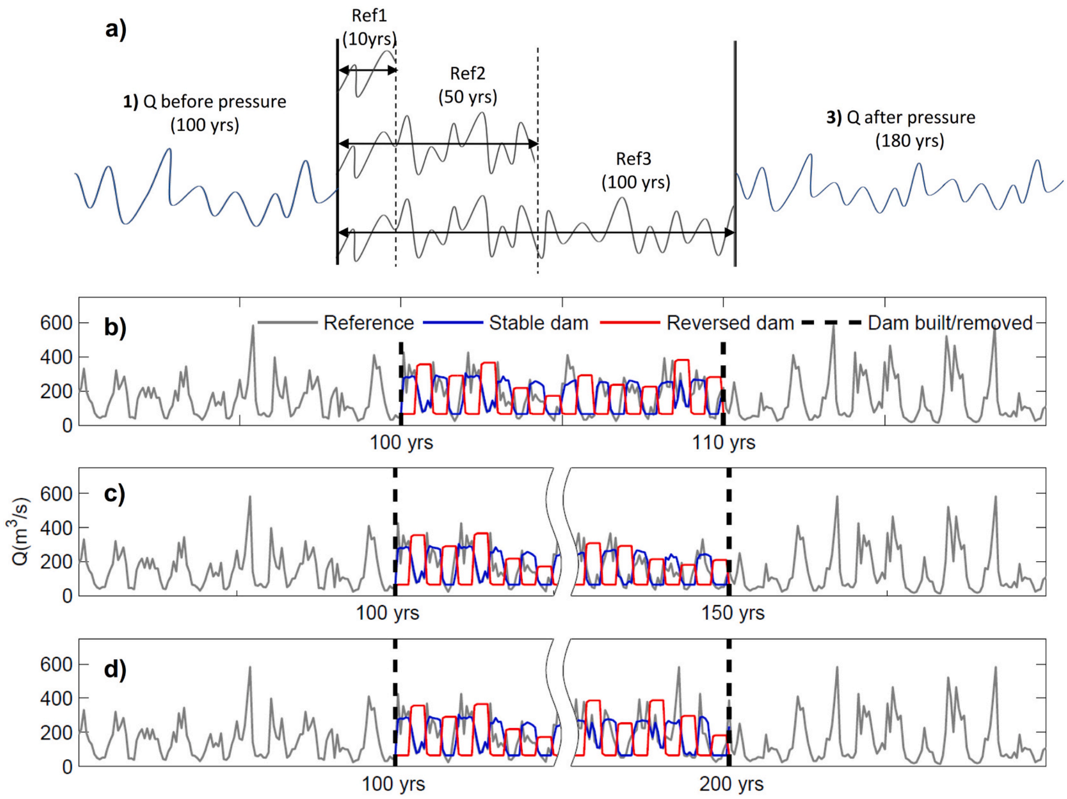

Fig. 2. a) Schematic representation of the construction of the hydrographs for the three scenarios without disturbance, starting with a similar discharge sequence, followed by discharge sequences of three different time intervals corresponding to the three pressure durations and ending again with a similar sequence of discharges from the point of restoration onwards. The time frame after recovery is 180 years for all scenarios, independent of the pressure duration. b-d: actual hydrographs for the stable dam and reversed dam for three different durations compared to the undisturbed hydrograph. For optimal visualization only 10 years during the pressure and after restoration are shown in the figure.

Table 2
Restoration scenarios.

Scenario	10 yr	50 yr	100 yr
Dam stable	S10	S50	S100
Dam reversed	R10	R50	R100

dependent on the hydro-morphodynamic conditions, but do not actively influence them. For each of the fish and wetland vegetation types, habitat suitability models were established in the spatial analysis tool HABITAT (Haasnoot and van de Wolfshaar, 2009). Relevant annual hydro-morphological statistics, serving as input for the habitat suitability models, were calculated after the eco-hydromorphodynamic model simulations were completed. These are annually calculated statistics for flow velocity, water depth and morphodynamic activity. Each species has its own set of habitat requirements and related statistics to serve as input for the habitat suitability models. These statistics served as the boundaries of environmental conditions for the expected presence of the species depending on the time frame of the modeled processes, e.g. maximum and minimum flow velocity in November and December for salmon spawning. Details on the statistics, timing and response curves of the ecological indicators can be found in Table 4 in Van Oorschot et al. (2018). We included habitat stability requirements and population dynamics in the habitat suitability analysis. For both wetland vegetation types the conditions have to be suitable for 5 consecutive years (Geest and Teurlincx, 2010). Pike longevity requires 1 suitable year in 8 years to enable successful reproduction (De Laak and Van Emmerik, 2006). Most salmon die after spawning, so for this species habitat conditions were calculated for each separate year and do not depend on conditions in previous years. This method is simplified in the sense that we do not consider population size and biomass. Competition between species was not considered in this study. More details on the calculation of the population response data can be found in Van Oorschot et al. (2018).

2.4. *Response analysis*

For the response and recovery analysis, three different hydro-morphodynamic variables and one ecological variable were selected with different adaptation times: i) sediment transport rate as a parameter directly responding to changes in discharge, ii) channel depth as a variable with a longer response time and dynamic conditions with a longer periodicity, iii) sinuosity as an overarching variable without clear periodicity that is determined by meander migration and chute cutoffs, and iv) habitat suitability for all ecological indicators (riparian trees, fish and wetland vegetation). Before data analysis, all bed level data was detrended and the boundary conditions were removed as described in van Oorschot et al. (2016). Hydro-morphodynamic data and riparian vegetation data was extracted at the end of each year and statistics were calculated over all grid cells, excluding the boundaries. Sediment transport rate was calculated as the 95*th* percentile and channel depth was calculated as the 5*th* percentile. Sinuosity was calculated each year as the length of the path with maximum flow-velocity per cross-section divided by the valley length. Riparian vegetation area was calculated as the sum of all vegetation fractions over all grid cells and both vegetation types at the end of the year. A more detailed description of the data analysis for sinuosity is described in van Oorschot et al. (2016). Habitat suitability for selected species was calculated as the total area with a suitability higher than 0.5 for each year. This resulted in a timeseries of hydro-morphodynamic and ecological statistics for each year. A more detailed description of the habitat suitability calculations is described in

Van Oorschot et al. (2018).

To evaluate and compare the effect of flow alteration by dam operation to the situation after restoring the natural flow regime, three criteria were determined that represent different effects on ecology and hydro-morphodynamics:

1. Pressure effect, calculated as the ratio between median values of model output variables during the period of altered flow and the median values under the natural undisturbed flow regime with the same time duration. This is a comparison between the reference situation with undisturbed flow and the period of flow alteration. Values smaller than 1 indicate lower values in the disturbed state than in the undisturbed state, values higher than 1 indicate higher values in the disturbed state and a value of 1 is no difference between disturbed and undisturbed. In exceptional cases the value can get 0 when the value in the disturbed situation becomes 0. As an equation this reads:

$$Pressure\ \ effect = \frac{Median\left(Disturbedflow_{pressure\ \ interval}\right)}{Median\left(Undisturbedflow_{pressure\ \ interval}\right)}$$

Pressure interval is the time period of flow alteration, i.e. 10, 50 or 100 years.

2. Restoration effect. This was calculated in a similar way as the pressure effect, but now using the median values over the 180 years after restoring the natural flow regime of the pressure scenarios and the median reference values in the same time interval. As an equation this reads:

$$Restoration\ \ effect = \frac{Median(Disturbedflow_{restoration\ \ interval})}{Median(Undisturbedflow_{restoration\ \ interval})}$$

Restoration interval is the time period after restoration of the flow.

3. Recovery time. This was calculated as the number of years that is needed for the variables to return within the bandwidth between the 25*th* and the 75*th* percentile of the undisturbed situation. For this calculation the values were smoothed with a moving average over 10 years to exclude the effects of single floods and large intra-annual variations.

To evaluate to what extent hysteresis effects occurred in the scenarios the *ecological* deviation from the undisturbed situation was plotted against the *morphological* deviation from the undisturbed situation (Fig. 3). This gives insight in the magnitude and pathways of individual (straight arrows) and interacting ecological and hydro-morphological processes (oblique arrows) during pressure and recovery compared to the undisturbed situation. We plot cause, i.e. the morphological change caused by flow alteration against the effect, i.e. habitat suitability of the ecological indicators and visualize the pathways between different dynamic equilibria. In this sense, we can define this as ‘hysteresis' pathways because the way towards a certain system state after disturbance, differs from the way back after the disturbance is removed (Beisner et al., 2003).

3. Results

3.1. Hydro-morphodynamic recovery

All dam operation scenarios deviate from the undisturbed situation in sediment transport, channel depth and sinuosity (Fig. 4). Results for sediment transport contrast between both dam scenarios, showing initially higher transport and subsequent stabilization for the stable dam scenario, whereas the transport under the reversed dam scenario is consistently lower and more stable. After a short initial increase in channel depth, the bed level of all scenarios increases, which means that channels become shallower over time. This increase is constant and rapid in case of the stable dam and irregular in case of the reversed dam. The sinuosity shows an irregular pattern in the stable dam scenario, due to river migration and chute cutoffs, while the sinuosity remains relatively stable in the reversed dam scenario, likely due to the development of wider and shallower channels. This is most likely due to a reduction of vegetation in combination of vegetation development at higher elevations, causing more diffusion of flow over the floodplain and less flow velocity in the channel, leading to increased sedimentation and shallower channels, as shown in Van Oorschot et al. (2018).

After restoring the natural flow regime, sediment transport recovers within 5 years to values within the range of the natural dynamic equilibrium for both dam operation schemes (Fig. 4, left panels and Table 3). However, channel depth shows a deviating trend after restoration compared to the undisturbed situation (Fig. 4, middle panels). In the stable dam scenario, the channel depth follows a similar trend, but with a delayed response in increasing channel depth when compared to the undisturbed situation. During the period of disturbance, there is a steadily decreasing channel depth, while in the undisturbed situation, it

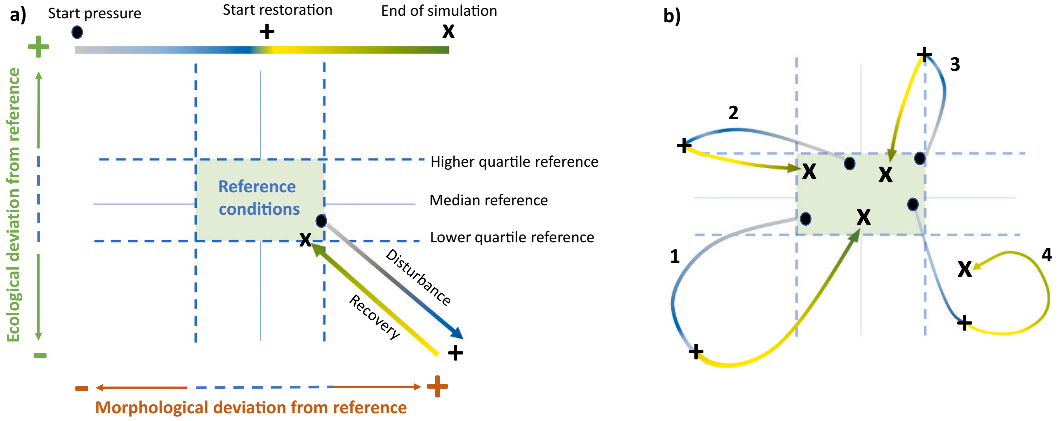

Fig. 3. a) Concept figure explaining the meaning and interpretation of the hysteresis figures of the morphological and ecological deviation from the undisturbed situation. The dashed lines indicate the range of the dynamic equilibrium around the undisturbed situation calculated as the quartiles for ecological and morphological variables over the whole simulation. The green box represents reference conditions for both ecology and morphology. b) four examples of typical hysteresis loops: 1) a situation where the morphological and the ecological deviation are both large during the disturbance, but after restoration there is a fast response towards values within reference conditions; 2) a large deviation in hydro-morphodynamic conditions with a small ecological effect; 3) a large deviation in ecological conditions with small hydro-morphodynamic effects 4) a deviation in both hydro-morphodynamics and ecology ending in an alternative dynamic equilibrium state outside reference conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

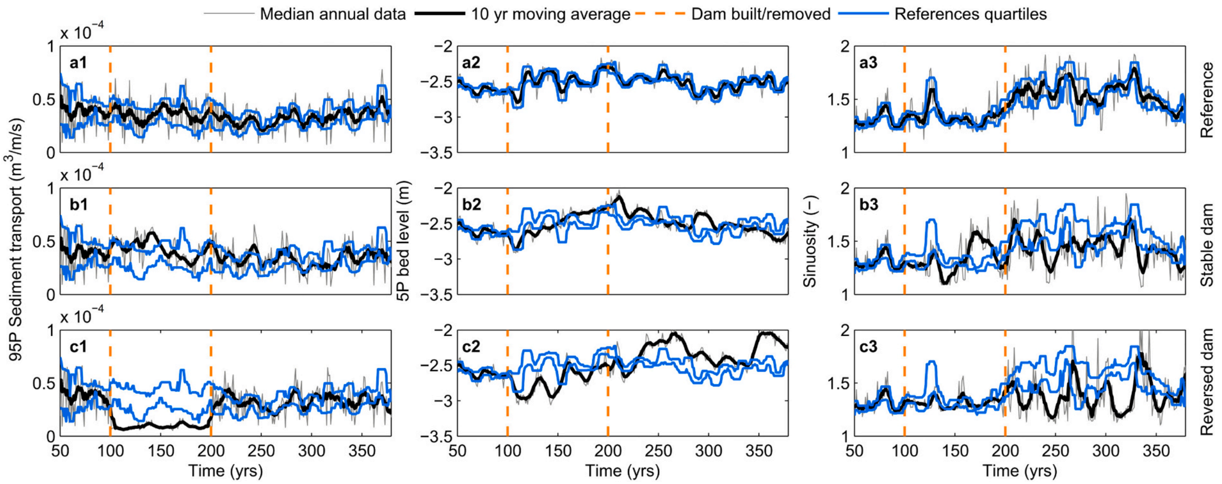

Fig. 4. Temporal statistics for sediment transport (left panels), channel depth (middle panels) and sinuosity (right panels) of runs with 100-year pressure duration. a) the undisturbed situation, b) stable dam scenario, c) reversed dam scenario. Data are shown for annual values (grey line) and for values smoothed over 10 years (black line) to remove effects of individual floods and to show the general trend. The blue lines indicate the quartiles of the undisturbed situation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Values for hydromorphological recovery for sediment transport, bed level and sinuosity for all scenarios. Pressure and restoration effects are the median deviations from reference conditions and recovery time is the time needed to reach dynamic equilibrium conditions. The scenario names are explained in Table 2.

Variable	Scenario	Pressure effect	Recovery time (yr)	Restoration effect
Sediment transport	S10	1.28	0	
	S50	1.44	2	0.99
	S100	1.21	0	1.01
	R10	0.18	4	1.06
	R50	0.23	4	1.05
	R100	0.23	4	0.99
Bed level	S10	0.92	0	0.96
	S50	0.95	54	1.00
	S100	1.00	0	1.00
	R10	0.97	0	0.93
	R50	0.87	5	0.98
	R100	0.92	11	1.08
Sinuosity	S10	0.94	5	0.98
	S50	0.94	20	1.01
	S100	0.98	0	0.92
	R10	0.97	0	0.98
	R50	0.95	2	0.98
	R100	0.99	0	0.86

shows more variation without a clear trend. For the reversed dam scenario, channel depth decreases to values higher than the undisturbed situation after return of the natural flow regime, which seems a continuation of the pressure effect. Values immediately fall within the range of the dynamic undisturbed situation after recovery of the natural flow regime. This seems rather coincidental in this case, there is a clear time-lag effect where channels become increasingly shallower and continue to remain shallower than in the undisturbed situation (Fig. 4). This shows that conditions after restoration can become very different, while general statistics such as the recovery time suggest that the system rapidly recovers. For sinuosity, we find a similar irregular pattern for both dam operations after recovery (Fig. 4, right panels). However, sinuosity naturally follows an irregular pattern that is more difficult to compare among different situations.

The recovery time is longer when the direction of change during the period of disturbance at the start of the restoration is opposite to the direction of change in the undisturbed situation, which is the case for instance in the channel depth of the stable dam scenario for the 50 year pressure duration (Fig. 4 b2). Here, there is a relatively steep upward trend during the pressure, while the undisturbed system shows little change. When the flow regime is restored, the upward trend that was visible under the disturbed flow regime continues several years after restoration. This shows that a disturbance could initiate a disruption that modifies the whole trend in hydro-morphodynamics, not only generating a deviation from the undisturbed situation but also causing longer recovery times.

The recovery times of sediment transport and channel depth are generally short (Table 3). Recovery time of these variables does not seem to be linked to the magnitude and duration of the pressure. More important seems the direction of change during the pressure period. If this is opposite to the undisturbed situation, this could create a different system state at the start of the restoration and therefore longer recovery times.

3.2. Ecological recovery

Both dam operating regimes have a negative effect on riparian tree cover (Van Oorschot et al., 2018). After restoring the natural flow regime, riparian trees recover rapidly, i.e. within 11 years, to values within the dynamic equilibrium of the undisturbed situation (Fig. 5). Although the vegetation cover of the disturbed and undisturbed situation show differences, the values do not differ by more than 10%. This shows that the extent of the riparian pioneer trees recovers rapidly after the natural flow regime is restored.

A similar rapid recovery in habitat suitability occurs for both fish species (e.g. salmon in Fig. 6c), but the response of wetland vegetation is more variable (e.g. helophytes in Fig. 6a and b). Wetland vegetation types benefit from the reversed flow regime and the time to return to the state that occurs under undisturbed conditions, with lower habitat suitability, in this scenario is longer (Table 4). Helophytes show the strongest response under the reversed dam flow regime (Fig. 6a and b). In the 50-year and 100-year pressure duration runs, a new dynamic equilibrium seems to appear after recovery; after the 50-year pressure duration, the total habitat suitability is higher than in the undisturbed situation, whereas it is lower after a 100-year pressure duration. This suggests that in some cases, both the *magnitude* of the pressure and the *timing* of the restoration could cause an alternative dynamic equilibrium after restoration. Similar to the hydro-morphodynamics, the pressure *duration* does not seem to affect the recovery time and the restoration effect.

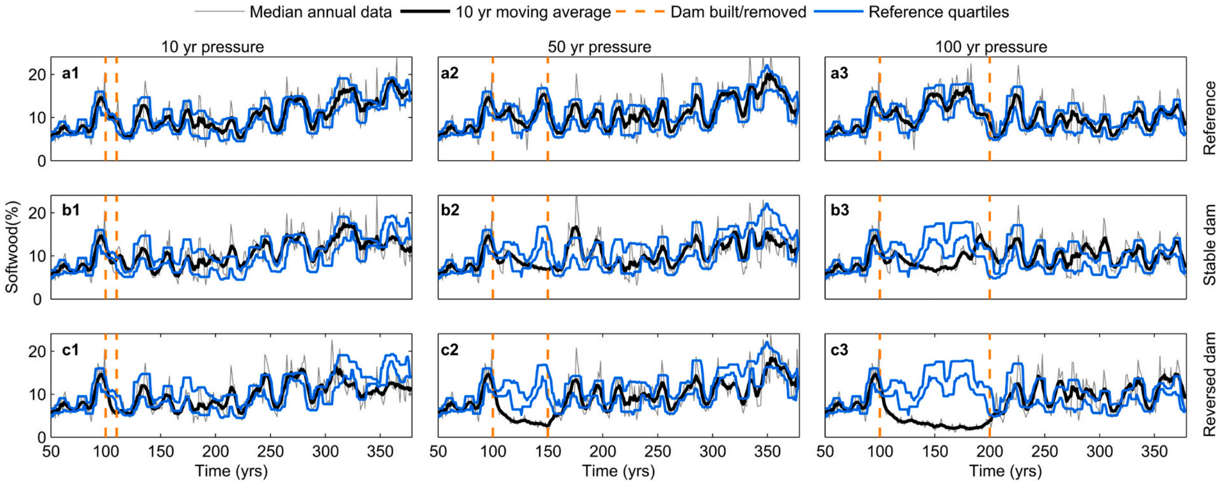

Fig. 5. Temporal softwood development expressed as the percentage of vegetated cells for a) undisturbed situation, b) stable dam scenario, c) reversed dam scenario for three different periods of dam operation. Data are shown for annual values (grey lines) and for values smoothed over 10 years (black lines) to remove effects of individual floods and to show the general trend. The blue lines indicate the quartiles of the undisturbed situation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

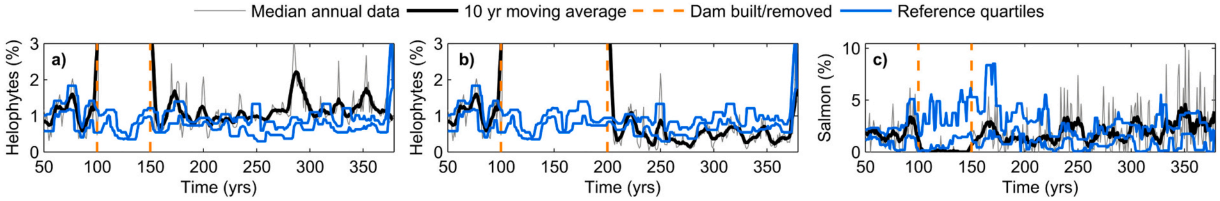

Fig. 6. a) Temporal habitat suitability expressed as percentage of habitat suitability higher than 0.5. Data are shown for annual values (grey lines) and for values smoothed over 10 years (black lines) to remove effects of individual floods and to show the general trend. The blue lines indicate the quartiles of the reference scenario. a) helophytes during and after the reversed dam scenario with 50 years of dam operation, b) helophytes during and after the reversed dam scenario with 100 year of dam operation c) Salmon during and after the reversed dam scenario with 50 years of dam operation. Note that in panels a) and b) the maximum values reach up to 8% during the pressure, but are cut off for visualization purposes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Recovery pathways

Habitat suitability of fish and wetland vegetation depends on hydrology and on the river morphology, for which we use channel depth as a proxy. In this study, the flow regime is the primary driver that was altered by the dam and then by restoring the natural flow regime, while the river morphology is the longer-term consequence of the hydro-morphological interactions in response to the flow changes. The interactions may in turn also affect the pathway of restoration after the period of disturbed flow, leading to hysteresis in the disturbance-recovery response.

Results show a clear effect of different pressure durations on riparian vegetation by increasing ecological segregation between the pressured state and the recovering state when pressure duration is longer (Fig. 7). In the scenarios with a 50-year and 100-year pressure duration, a clear response loop is visible for riparian vegetation during the period of pressure that generally illustrates initially deteriorating conditions during the pressure linked to lower channel depth. Via several shifting states, the loop is advancing towards undisturbed ecological values after the natural flow regime was restored. This indicates a partial recovery effect and shows the non-linear relation between channel depth and riparian vegetation. So even though the morphology is not yet in the pre-disturbed state, the pioneer trees have the flexibility to quickly adapt to these new circumstances.

Also during recovery, there are loops in the relations between these state variables, although they are less pronounced and overlap within the undisturbed space. Interestingly, in the 50-year and 100-year reversed dam scenario the morphological state shows an opposite morphological response after recovery. At the moment of flow restoration, the channel is deeper in the 50-year pressure duration scenario than in the 100-year pressure duration scenario (data and figures in Van Oorschot et al. (2018)). This is shown by the different locations of the restoration loops, which is on the left side of the reference box for the 50-year pressure duration and on the right side for the 100 year pressure duration. This confirms the inference made above, that the moment of restoration is important in directing the system state after restoration.

The increasing segregation during the pressure period is also found for fish and wetland vegetation and most clearly in the reversed dam scenario (Fig. 8). For wetland vegetation we find similar behavior: lower bed level values during the pressure are linked to higher habitat suitability, for both fish species there is an opposite trend with lower habitat suitability. The recovery loops are less clear due to the large spread in data, leading to non-coherent paths. This might be caused by the fact that for fish and wetland vegetation the absolute habitat suitability was calculated via post-processing and is therefore more directly linked to bed level as boundary condition, which could cause a more scattered pattern. This means there is no strong evolving pattern that depends on conditions in preceding years, which is the case for riparian vegetation. Still, for helophytes, macrophytes and pike, the population response was considered and therefore a certain amount of historical information (i.e. the habitat suitability during preceding years) was included. For salmon no historical information was taken into account since it is a migratory species of which the habitat suitability does not depend on the preceding year, and this translates into fast ecological recovery times (Table 4).

Table 4
Values for ecological recovery for all scenarios and all species. Pressure and restoration effects are the median deviations from reference conditions and recovery time is the time needed to reach dynamic equilibrium conditions. The scenario names are explained in Table 2.

Species	Scenario	Pressure effect	Recovery time (yr)	Restoration effect
Softwood	S10	0.96	0	1.08
	S50	0.76	4	0.99
	S100	0.73	15	1.11
	R10	0.62	3	0.92
	R50	0.36	10	0.97
	R100	0.26	3	1.04
Macrophytes	S10	0.97	16	1.13
	S50	1.05	0	1.07
	S100	0.95	0	0.91
	R10	3.93	5	1.08
	R50	2.51	13	1.43
	R100	2.79	7	0.69
Helophytes	S10	0.82	0	1.26
	S50	1.25	0	0.92
	S100	1.12	16	0.74
	R10	8.41	6	1.21
	R50	7.24	13	1.61
	R100	7.49	6	0.60
Salmon	S10	1.38	0	0.92
	S50	0.51	0	0.91
	S10	0.53	0	1.08
	R10	0.00	0	1.01
	R50	0.00	2	0.82
	R100	0.00	0	1.21
Pike	S10	0.98	0	0.92
	S50	0.77	15	0.94
	S100	0.70	14	1.14
	R10	0.80	15	0.90
	R50	0.07	17	0.87
	R100	0.08	10	1.17

The differences in dynamic equilibria between reference and pressure period, shown in Fig. 4 and Table 4, become clearly apparent in the hysteresis loops for helophytes (Fig. 8a and b), and to a lesser extent for macrophytes during the 50-year pressure scenarios and for pike (Fig. 8d) in the reversed dam scenario with 100-year pressure duration. Overall, the ecological and morphological deterioration is more severe in the reversed dam scenario, showing large deviations from under undisturbed conditions for both fish species and vegetation types.

Recovery pathways of sinuosity and sediment transport give different results than channel depth (Figs. 8e and f versus Fig. 7). For sinuosity, most values during pressure and recovery stay within or close to the boundaries of the undisturbed situation (Fig. 8e). This is due to the relatively large natural variation in sinuosity, which is characterized by periodic chute cutoffs and meander migration, which causes a large spread in the data. In contrast, there is a strong response in sediment transport during the pressure and a fast recovery during restoration (Fig. 8f). This is because local sediment transport is an immediate responder to changes in flow regime.

These results show that impaired systems follow different pathways than restored systems and also restored pathways differ, depending on the system state and the direction of change of the system at the start of the restoration. In all scenarios there is an overshoot response during the pressure, which means that there is an immediate large response, followed by a relatively fast rebound. The loops during the pressure periods are clearly visible and show a variety of pathways that are less visible during recovery. For riparian trees, we find clear hysteresis loops during the pressure period. For the habitat suitability of fish and wetland species the patterns are more scattered, which is due to the limited dependence on historical conditions and the absence of direct interactions with river dynamics. Here, the species without historical dependence, i.e. salmon, shows the most scattered response pattern, while the pike, of which the response depends on 8 antecedent years,

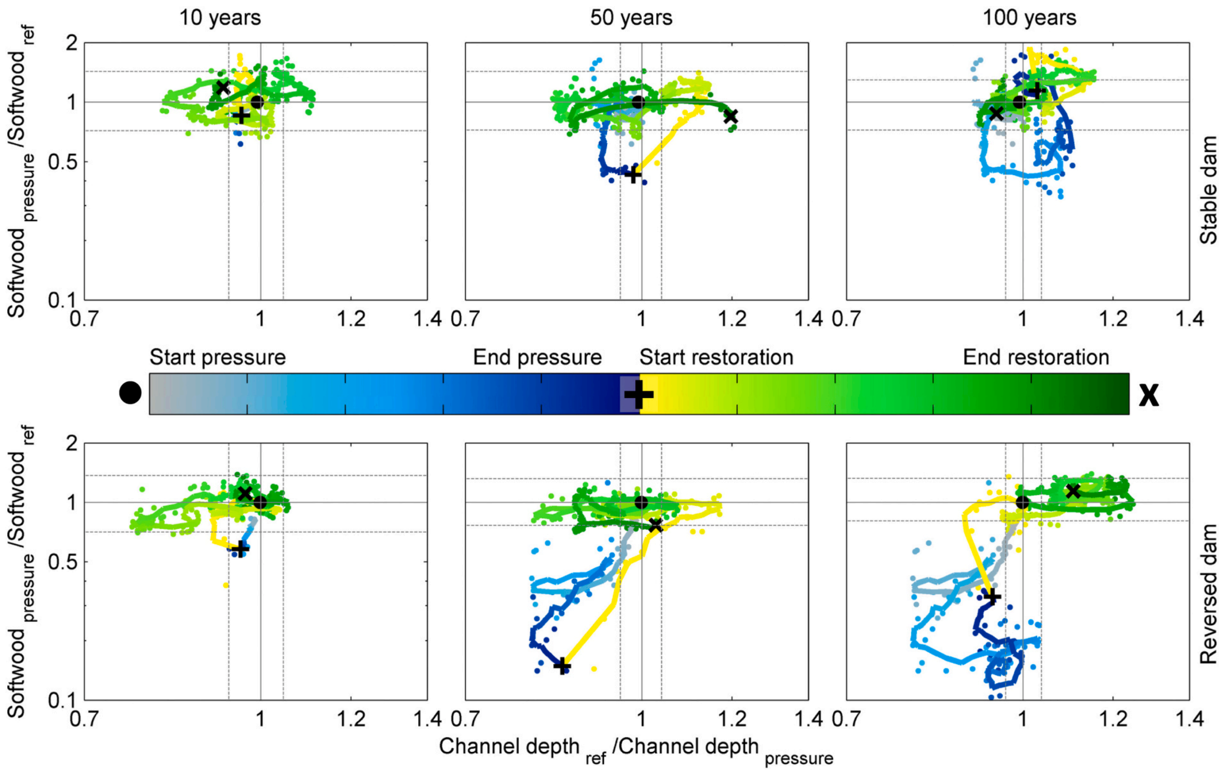

Fig. 7. The pressure and recovery pathway for riparian trees plotted as the ecological against the morphological (5P bed level) deviation from the undisturbed situation for three different pressure durations. The colored lines represent time during pressure in grey-blue and time during restoration in yellow-green calculated as a moving average of 10 years. Note that the axes are logarithmic. For detailed explanation and symbols see Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

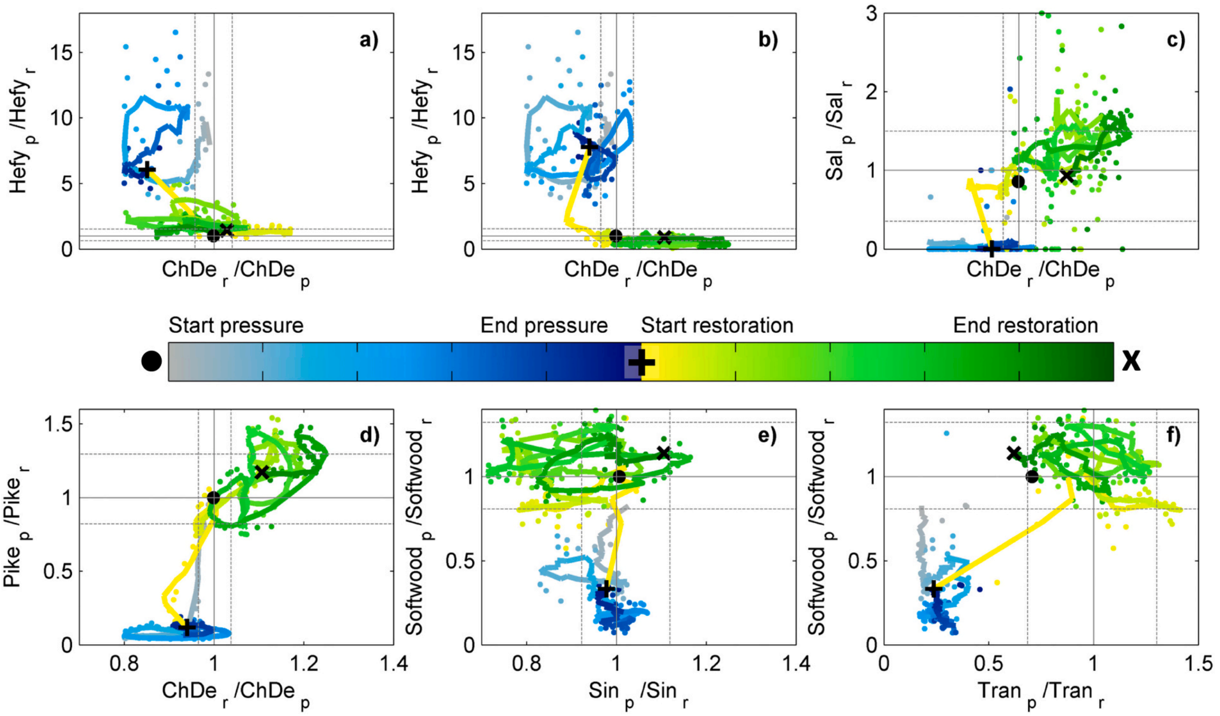

Fig. 8. Selected pressure and recovery pathways for habitat suitability of fish and wetland vegetation plotted as the ecological against the morphological deviation with the clearest and most relevant signals. Helophytes versus channel depth in the reversed dam scenario for the 50 year (a) and the 100 year (b) pressure duration, salmon versus channel depth (c) and pike versus channel depth (d) in the reversed dam scenario for the 100 year pressure duration, softwood versus sinuosity (e) and softwood versus sediment transport (f) for in the reversed dam scenario for the 100 year pressure duration. The colored lines represent time during pressure in grey-blue and time during restoration in yellow-green calculated as a moving average of 10 years. Note that the axes are logarithmic. Hefy = helophytes, Sal = Salmon, p = pressure, r = undisturbed, ChDe = channel depth, Sin = sinuosity, Tran = sediment transport. For detailed explanation and symbols see Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shows the smoothest response. Especially for helophytes, we find alternative dynamic equilibria after recovery, which indicate a change of their habitat beyond the undisturbed situation.

4. Discussion

4.1. Ecological and hydro-morphodynamic recovery

The modelling approach adopted in our study enabled us to evaluate the variability of the restored system versus the natural variability of an undisturbed situation with a similar hydrograph. Therefore, we could define the undisturbed situation in a dynamic equilibrium and assess ecological- and hydro-morphological restoration success as a quantitative deviation from the undisturbed situation in an exact similar discharge setting. Furthermore, this enabled us to quantify to what extent the system returned to a natural state after flow restoration, by comparing the restored state to the bandwidth of the natural state.

Our model results show that when natural flow is restored in dammed systems, the recovery potential depends on the magnitude of the pressure and timing of the restoration, rather than the duration of the pressure. We find relatively short hydro-morphodynamic and ecological recovery times, generally less than 20 years, expressed here as the time to reach values within the dynamic undisturbed situation (Tables 3 and 4). This relatively quick recovery to pre-dam hydro-morphodynamic conditions was also found in studies by Pizutto (2002); Doyle et al. (2005) and Foley et al. (2017).

These results have to be considered within the context of the type of river that was modeled in this study, the possible location of a dam and the type of such a dam. Here, we modeled a dynamic meandering gravel bed river with relatively fast hydro-morphodynamic adaptation times and fast and dynamic development of eco-engineering vegetation that interacts with river morphodynamics. In the scenarios presented here, the dam is assumed to be far upstream, and the sediment balance within the modeled river section remains unchanged. Therefore, the river morphology has presumably been less altered than in areas close to a dam. In such areas for instance, a lateral immobile entrenched river could be formed downstream of the dam due to channel erosion, or large sediment supplies accumulated in the reservoir may be flushed through the system during peak flow release (Doeg and Koehn, 1994; Hart et al., 2002), which might initially hamper recovery after flow restoration. The difference in restoration times between the stable and reversed dam confirm this, since the morphological deviation from the undisturbed situation is strongest in the reversed dam scenario, which showed the largest hydro-morphodynamic deviation during the pressure.

We find that initial conditions at the start of the restoration strongly determine ecological recovery time. These differences in initial conditions firstly are related to the large changes in morphology caused by the preceding pressure, such as in the reversed dam scenario. Additionally, different initial conditions result from natural fluctuations within the system arising from the internal system dynamics and feedbacks, such as the periodic formation of meander bends and subsequent colonization by vegetation. When initiating the restoration at different moments in time, the system state is different, thus giving different initial conditions for the restoration response. In those situations where new restored forcing of the system fits the internal system trend (e.g., the start of a meander development) at the timing of the restoration, recovery to a state similar to the undisturbed system can be rapid. When the restoration occurs on another system state, the response can be much slower. The importance of initial conditions and timing of a temporary disturbance on system response and recovery is also found in other systems, such as atmospheric or post-glacial meltwater pulses on ocean-circulation (Renssen et al., 2002). So this might indicate a more general behavior found in dynamic natural systems.

Even under the complete control of imposed conditions, an alternative dynamic equilibrium was sometimes reached that strongly deviates from the undisturbed situation. This is the case for helophytes in the 50 year and 100 year reversed flow scenario (Fig. 8a and b). This suggests that in these situations, an alternative stable state is reached. This could hamper ecological recovery because it might not be possible to reach good habitat suitability for particular species anymore by only restoring the natural flow regime. In these cases, additional measures might be necessary to actively create suitable niches for affected species. These results are in line with the study from Doyle et al. (2005), who analyzed several case studies with dam removal and assessed how channel changes affect aquatic and riparian species. They found different responses and recovery rates for different species and show with a conceptual model that ecosystem recovery is strongly linked to the potential of the system to return to pre-dam hydro-morphodynamic conditions.

4.2. *Impact on river restoration*

This study shows that when the natural flow regime is restored, the ecological recovery can be fast. This is however an idealized situation with in a very dynamic system where we did not have to take socioeconomic considerations into account. In reality, river restoration projects are often restricted in restoring natural flow dynamics due to the need for water extraction and flood control (Kondolf et al., 2006). Therefore, in many situations totally restoring to natural conditions is not even feasible. Additionally, dam removal initiates a complex sequence of physical, chemical and ecological changes and little is known on how long it takes before biodiversity is restored to natural conditions after the pressure of the dam is removed (Bushaw-Newton et al., 2003). How the river system will evolve after dam removal both morphologically and ecologically is therefore dependent on many factors in and around the river and its catchment (Bellmore et al., 2019). We show that even if the flow regime is totally restored, some vegetation species are not able to recover to pre-disturbance conditions and additional measures might be needed to achieve ecological goals. This calls for nature-based solutions that balance ecological, social and economic interests (Wild, 2020).

We show that comparing restoration success or current state of the river in a static way to a static reference situation, which is the case in for instance the WFD, is likely to either overestimate or underestimate the hydro-morphological and ecological quality, especially in highly dynamic systems. This is also emphasized by Bouleau and Pont (2015) that state that a static method makes it impossible to distinguish natural variability from responses to anthropogenic influences. Even in our situation, where we take a 10-year dynamic reference equilibrium into account, recovery times do not necessarily say something about the long-term deviation from the undisturbed situation. For instance, species with a similar recovery time can show different long-term trends in recovery. Similarly, species with a very long recovery time do not necessarily show large long-term deviations from the undisturbed situation. Also, when an alternative dynamic equilibrium is reached, with conditions on average distinctly different from the undisturbed situation, there are still incidental annual values falling within the boundaries of the undisturbed situation.

In reality it is practically impossible to compare systems to an exact reference condition, unlike in our modelling study, which therefore provides a uniquely well-constrained perspective on how internal system dynamics can affect restoration success. To be able to exclude long-term dynamic effects and accurately verify restoration success, managers should develop long-term monitoring programs and perform monitoring on large spatial scales to assess the natural variability of the system. Subsequently, this data should be compared to a reference situation with dynamic equilibrium conditions instead of using static descriptors that ignore natural variability.

5. Conclusions

Our model results show that when dams are removed and natural flow regimes are completely restored, the recovery potential of eco-engineering vegetation and facilitated fish and wetland vegetation depends on the *magnitude* of the pressure and the *timing* of the restoration, and not directly on the *duration* of the pressure. Recovery time towards the natural range is long when initial conditions at the start of the restoration deviate from the undisturbed situation; these can be due to large morphological differences directly caused by the *pressure*, but also by coincidentally deviating conditions at the start of recovery, due to *natural variability* in fluvial morphology. The recovery time is therefore related to the ability of the river to return to undisturbed hydro-morphodynamic conditions, which can differ between river systems. This study assesses the effect of altered flow in a meandering gravel bed river with fast vegetation development by removal of dams that are relatively far upstream, while keeping the sediment supply in equilibrium. Therefore, other types of river systems might experience different responses in recovery.

Generally, there is a clear segregation of species response during pressure and during restoration. All modeled ecological indicators, i.e. the interacting eco-engineering vegetation and the fish and wetland vegetation, generally respond quickly to flow alterations and also show a swift, recovery in the order of 5 to 10 years towards pre-disturbance conditions. This is related to the fast recovery of sediment transport and channel morphology due to the dynamic nature of the modeled system. However, when the magnitude of the pressure is large and the river morphology has been drastically altered, recovery for some species might become increasingly difficult. This can lead to alternative dynamic equilibria where habitat suitability falls consistently outside the dynamic equilibrium of the undisturbed situation. We found this result most clearly for helophytes in the seasonally reversed flow regime scenario with contrasting effects for different pressure durations, which is related to different starting conditions at the moment of restoration. This suggests that alternative measures might be required to restore hydro-morphodynamic conditions in these types of habitats.

Recovery time is an arbitrary measure since it depends strongly on natural variations in the restored system and the reference to which it is compared. It does not give information about longer-term trends and stability of the restoration success. Even in situations where an alternative equilibrium is reached, there can be a short period right after the restoration where the conditions are within the boundaries of pre-disturbance conditions leading to a short recovery time, while the median conditions during the whole period after restoration shows a large deviation from the undisturbed situation. Therefore, restored systems should be assessed in a dynamic matter and static comparisons between the current state of restored rivers and their reference should be avoided. In turn, monitoring programs should be developed at large spatio-temporal scales to gain more insight in the natural variation of the system to better assess restoration success. Regardless of the difficulty in quantifying restoration success, this paper shows that restoring natural flows in dam impaired system is ecologically beneficial and that in many cases ecosystems have a large flexibility in bouncing back to pre-disturbance conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by REFORM (FP7 Grant Agreement 282656). We thank two anonymous reviewers for valuable discussion and reviewing of the previous version of the manuscript. The authors

contributed in the following proportions to conception and design, model running, analysis and conclusions, and manuscript preparation: MvO (60%, 100%, 60%, 65%), MGK (10%, 0%, 15%, 15%), GG (10%, 0%, 5%, 5%), TB (10%, 0%, 5%, 5%) and HM (10%, 0%, 15%, 10%).

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