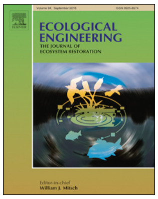
Ecological Engineering 120 (2018) 329–344

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Combined effects of climate change and dam construction on riverine ecosystems

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ARTICLE INFO

Keywords:
Climate change
Dams
Flow alteration
Bio-geomorphology
River morphodynamics
Riparian vegetation

ABSTRACT

River morphology and riparian vegetation continuously adapt to changing discharge conditions, which makes it a challenge to distinguish long-term development driven by natural discharge variation from the impacts of flow alteration due to climate change and due to dams. The aim of this study was to investigate how such flow alterations affect bio-geomorphological processes and habitat suitability of several fluvial plant and animal species. This is done with a numerical model representing dynamic interactions between morphodynamic processes and riparian vegetation coupled to habitat suitability models of fluvial species. We compared a control run with natural flow regime to altered flow for two scenarios with different dam operating regimes, two scenarios with climate change, and for combinations of dams and climate change. Results show that flow stabilization leads to incision, acute reduced seedling recruitment and decline of riparian vegetation. Climate change generates a gradual response, where high flow extremes counteract an otherwise reduced seedling recruitment of pioneer vegetation, while drying reduces riparian vegetation recruitment and causes vegetation shifts towards lower elevations on the floodplain. Modelled habitat availability for facilitated plant and animal species declines most when the synchronicity between critical life history events and habitat requirements is disrupted by altered flow conditions, with opposite effects for different species. Dynamic interactions between bio-geo-morphological processes with somewhat different characteristic timescales create non-linear and adaptive behaviour of morphology, habitat patterns and facilitated species habitat. This implies that only models that include bio-geomorphological feedbacks can forecast impacts of multiple flow alteration pressures, whereas addition of single-pressure regime effects is overly simplistic.

1. Introduction

Humans have been altering river systems for centuries to fulfill their water needs and for protection against floods. Dams have been constructed to secure water supply, regulate river flow for navigation and to generate power. Consequently, the flow regime of many rivers has been dramatically altered from their natural flow regime (Dynesius and Nilsson, 1994; Nilsson et al., 2005). Flow alteration by dams can affect the magnitude, timing and duration of high and low flows (Clarke et al., 2008). In addition to these direct human alterations, climate change is beginning to affect the hydrological regime as well. Multiple climate models forecast a general trend towards lower discharges and an increase of precipitation in winter and spring in Europe (Dankers and Feyen, 2008; Van Vliet et al., 2013). Both these direct regulation-associated and climate driven alterations will likely continue to affect rivers for the coming decades, potentially having dramatic and unpredictable impacts on their morphodynamics and associated ecosystems.

Riparian species closely depend on river flow and have adapted their life-history processes to flow regimes (Karrenberg et al., 2002). Consequently, flow regimes and associated bio-morphological interactions determine the distribution pattern of riparian species. Therefore, alteration of the flow regime inevitably leads to shifts in riparian ecosystem dynamics.

Changing timing of peak flows can decrease the colonization success of riparian plant species when it results in a mismatch between the seasonal flow and the timing of seed release (Poff et al., 2010). A decrease in high flows reduces the connectivity of the main channel to the floodplain, thereby restricting movement of specific fish and macroinvertebrate species between different habitat types that are essential to complete their life-cycle (Rolls et al., 2012). Furthermore, a decrease in inter-annual discharge variation will lead to a decline in richness of

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https://doi.org/10.1016/j.ecoleng.2018.05.037
Received 16 March 2017; Received in revised form 17 May 2018; Accepted 22 May 2018

riparian species and fish species (Poff et al., 2010). Less frequent overbank flooding due to, for instance, dam construction may lead to an increase of vegetation and vegetation development within or adjacent to the river channel (Williams and Wolman, 1984; Dolores Bejarano et al., 2011), aging of riparian vegetation (Azami et al., 2004), reduced recruitment success of riparian trees, and eventually a decline in softwood forest extent (Rood and Mahoney, 1990, 1995; Polzin and Rood, 2000). Additionally, the riparian ecosystem can become more vulnerable to competing effects of invasive alien species that can faster and better adapt to new conditions than native species, e.g. invasive species that rapidly elongate their root systems to cope with dryer conditions after dam construction (Stromberg et al., 2007; McShane et al., 2015). Hydrological change also affects riparian ecosystems by rearranging the habitat mosaic through changes in river morphology (Nilsson and Svedmark, 2002). In turn, this influences the settlement locations of pioneer eco-engineering species and all other species depending on the conditions created by these engineering species (Williams and Wolman, 1984; Gurnell, 2014).

The bio-geomorphological response of rivers to impoundment by dams depends on a variety of factors, such as sediment load and grain size, dam operating regime, climatic region, type of vegetation and inherited channel form (Williams and Wolman, 1984). This large variability makes it difficult to predict the rate and sequence of changes in river morphology (Petts and Gurnell, 2005). There are some conceptual frameworks that generalize effects of dams in terms of changes in channel dimensions, roughness and slope due to changes in discharge and sediment load (Ward and Stanford, 1995; Petts and Gurnell, 2005). For instance, in rivers where discharge is strongly reduced, the channel width and channel conveyance are reduced (Petts and Gurnell, 2005). The time that is necessary for rivers to reach a new dynamic equilibrium after the flow alteration can range from less than 10 years in systems with high sediment loads and fast vegetation development to well over 200 years in environments that are less dynamic (Williams and Wolman, 1984). For instance, in an intermediate-sized meandering sand-bed river, Merritt and Cooper (2000) found channel narrowing in the first decade after dam construction followed by channel widening and vegetated mid-channel bars in subsequent years.

In contrast to the relatively extreme and acute effect of dams, climate change leads to a more gradual change in conditions depending on geographical location. Potential adverse effects of climate change for fish and macro-invertebrates are often attributed to altered chemical composition and increasing water temperature (Brucet et al., 2012; Mantyka-Pringle et al., 2014; Santiago et al., 2016). However, also changes in low flows and high flows can disrupt critical life history processes. For instance, lower flows reduce the available spawning and incubation habitat for salmon, while increased peak flows can destroy salmon eggs through scouring (Battin et al., 2007) and change the general abundance and community composition of fish and macro-invertebrates (Death et al., 2015). Yet, few studies have addressed the effects of climate change on riparian vegetation. In the case of more extreme events in high- as well as low flows, Mosner et al. (2015) predict a general decrease in habitat for hardwood forest and softwood forest in the River Rhine. Other studies involving climatic predictions with a general drying trend, predict a decrease in early succession phases and a trend towards aging of vegetation and replacement of softwood species with more drought-tolerant species (Rood et al., 2008; Stromberg et al., 2010; Rivaes et al., 2014).

Bio-geomorphological impacts of altered flow regimes are controlled by the interactions between vegetation and morphodynamics, which are non-linear and comprise both negative and positive feedbacks. In an intermediate-sized river where vegetation and morphodynamics regularly interact, vegetation density as well as vegetation location on the floodplain strongly influence the morphodynamics of the system (van Oorschot et al., 2016). Dense vegetation development reduces morphodynamic activity and can lead to avulsions, while more sparsely distributed vegetation leaves room for chute cut-offs and dynamic meandering, which locally cause vegetation mortality and at other locations creates new suitable sites for settlement (van Oorschot et al., 2016). Since vegetation and river pattern both adapt to altered discharge conditions, it is a challenge to distinguish effects of the natural discharge variation from the effect of climate change and dams (Petts and Gurnell, 2005).

This study aimed at determining and understanding how altered flow regimes affect bio-geomorphological processes and habitat suitability of representative fluvial plant and animal species and species groups. To this end, we tested effects of two types of flow alterations: acute flow alteration related to dam construction and gradual flow alteration caused by climate change as well as combinations of both pressures. This was done by simulating the bio-geomorphological interactions in a river stretch using a numerical model for morphodynamic processes that was dynamically linked with a model for vegetation colonization and growth processes. Although this coupled model is computationally expensive, it allows us to investigate the complex and dynamic bio-geomorphological patterns and dynamics that emerge on the timescale of decades. We ran in total 9 scenarios: a control, two different dam scenarios, two opposing climate scenarios and all combinations between dam and climate change scenarios. One dam scenario represented preservation of flow seasonality, the other completely reversed flow seasonality. The climate change scenarios comprise one with a general drying trend and one with increased low and high flows. All scenarios and combinations of scenarios were compared to a reference scenario with an unaltered, natural flow regime for evaluation of trends and changes in ecosystem response.

2. Methods

We conducted modelling for several flow alteration scenarios with a detailed hydro-morphological model coupled to our vegetation model, detailed below. The model represents intermediate-sized meandering rivers: this condition was chosen such that the surface cover is created by interacting fluvial morphodynamics and vegetation, and that neither dominate the resulting landscape in the reference situation. The scenarios are idealised in the sense that they represent typical conditions as found in the literature, but the scenarios are also realistic in the sense that we retained the natural discharge variability necessary for the expected settling, growth and mortality of the riparian tree species. Results for these scenarios were compared in vegetation age and cover properties. Furthermore, we applied habitat suitability rules for representative fluvial plant and animal species of several taxonomic groups to assess wider ecological implications of the changing river conditions and landscapes.

2.1. Eco-morphodynamic model

We loosely based our modelled river stretch on the Allier River in France, which is a medium sized, dynamic meandering gravel bed river of which the morphodynamics and vegetation have been well documented over the last years (Geerling et al., 2006; Kleinhans and van den Berg, 2011; Van Dijk et al., 2014). The eco-morphodynamic model contains the morphodynamic model Delft3D for numerical calculation of depth-averaged flow velocities and bed level updates (see Lesser et al., 2004; Schuurman et al., 2013, for details on morphodynamic equations and processes) and an interactively coupled riparian vegetation model based on van Oorschot et al. (2016), containing vegetation colonization, growth, prediction of hydraulic resistance and mortality through flooding, desiccation, uprooting, scour and burial. Initial model settings and parameterization of hydro-morphodynamic model parameters, except the discharges, were similar to those described in van Oorschot et al. (2016). The vegetation model from van Oorschot et al. (2016) has been updated and re-calibrated at several points. The current model version calculates and updates vegetation growth and mortality in two-weekly time steps, as opposed to once a year in the