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Eco-hydrologic model cascades: Simulating land use and climate change impacts on hydrology, hydraulics and habitats for fish and macroinvertebrates

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HIGHLIGHTS

- A recently developed model cascade is applied in different scenario simulations.
- Impact of climate and land use change on hydrology and biota is assessed.
- Climate change affects hydrology, hydraulics and fishes.
- Abundance of macroinvertebrates is influenced by land use and climate change.
- Direction and intensity of impact on habitat suitability is highly species-dependent.

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ABSTRACT

Climate and land use changes affect the hydro- and biosphere at different spatial scales. These changes alter hydrological processes at the catchment scale, which impact hydrodynamics and habitat conditions for biota at the river reach scale. In order to investigate the impact of large-scale changes on biota, a cascade of models at different scales is required. Using scenario simulations, the impact of climate and land use change can be compared along the model cascade.

Such a cascade of consecutively coupled models was applied in this study. Discharge and water quality are predicted with a hydrological model at the catchment scale. The hydraulic flow conditions are predicted by hydrodynamic models. The habitat suitability under these hydraulic and water quality conditions is assessed based on habitat models for fish and macroinvertebrates. This modelling cascade was applied to predict and compare the impacts of climate- and land use changes at different scales to finally assess their effects on fish and macroinvertebrates.

Model simulations revealed that magnitude and direction of change differed along the modelling cascade. Whilst the hydrological model predicted a relevant decrease of discharge due to climate change, the hydraulic conditions changed less.

Generally, the habitat suitability for fish decreased but this was strongly species-specific and suitability even increased for some species. In contrast to climate change, the effect of land use change on discharge was negligible. However, land use change had a stronger impact on the modelled nitrate concentrations affecting the abundances of macroinvertebrates.

The scenario simulations for the two organism groups illustrated that direction and intensity of changes in habitat suitability are highly species-dependent. Thus, a joined model analysis of different organism groups combined with the results of hydrological and hydrodynamic models is recommended to assess the impact of climate and land use changes on river ecosystems.

1. Introduction

Climate and land use changes are intrinsic drivers of hydrological processes (Blöschl et al., 2007; Juckem et al., 2008; Li et al., 2009). These processes are summarized in the river discharge which reflects various kinds of changes in the catchment (Ceola et al., 2014). Several model

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studies analysed the individual or combined effects of climate or land use change on hydrology (e.g., Niehoff et al., 2002; Hesse et al., 2008; Juckem et al., 2008; Tu, 2009; Li et al., 2009; Setegn et al., 2011; Santos et al., 2014), sediment or nutrients (e.g., Huang et al., 2009; Tu, 2009; Li et al., 2011; Martinkova et al., 2011; Bieger et al., 2013) at the catchment scale.

Catchment-wide hydrological changes also impact conditions at smaller scales ranging from in-stream hydraulics in river segments to habitat conditions of biota at the reach scale (Kiesel et al., 2009, 2013). Aquatic biota is strongly impacted by large-scale environmental pressures as revealed recently by several empirical studies (Dahm et al., 2013; Marzin et al., 2013). It was emphasised that catchment-scale pressures such as land-use or climate are more relevant in controlling occurrences and abundances of macroinvertebrate and fish communities in comparison to pressures at smaller spatial scales (Roth et al., 1996; Allan and Johnson, 1997; Hughes et al., 2008; Stephenson and Morin, 2009; Sundermann et al., 2013).

The importance of pressures acting at different spatial scales and the vulnerability to changes of the abiotic conditions differ between organism groups such as fish and macroinvertebrates (Hering et al., 2006; Pander and Geist, 2013; Müller et al., 2014). Abundance and diversity of fish species are highly affected by habitat degradation and habitat loss at local scale (Hering et al., 2006; Kail and Wolter, 2013), species-specific dispersal and fragmentation (Radinger and Wolter, 2014, 2015), and by alterations of natural flow velocity patterns and natural flow regimes (Logez et al., 2013; McManamay and Frimpong, 2014).

Distribution and composition of macroinvertebrates on the catchment scale are primarily affected by water quality and land use change at the catchment scale (e.g., Feld and Hering, 2007; Sundermann et al., 2013; Valle Junior et al., 2015). Increased nitrogen loads lead to an increase in biomass and productivity of primary producers. The resulting accumulation of organic material degrades water quality and leads to a loss of habitats resulting in shifts in community compositions (Camargo and Alonso, 2006).

Empirical linkages, however, do not explain the underlying processes ranging from hydrological and hydraulic processes to the occurrence and dispersal of biota (Beechie et al., 2011). Thus, process-based models are required for reliable predictions under changing conditions. These process-based models are commonly applied to hydrology or hydraulics but rarely to biota.

To obtain a fundamental and holistic understanding of the functioning of habitat-species interactions, all dominant processes from hydrology to biota have to be represented at their relevant scales and analysed together in an integrated abiotic–biotic model cascade. A model cascade is a sequence of consecutively combined models where one model provides the input for another model as presented by Kiesel et al. (2009). Whilst process-based model cascades spanning from global change to biological processes are commonly applied in lakes (Mooij et al., 2010), the use of such models in rivers is still underdeveloped (Kiesel et al., 2009).

Kiesel et al. (2009) and Kiesel et al. (2013) developed a first prototype, which couples an eco-hydrological and 1D hydrodynamic model to predict discharge at the catchment scale and the resulting water level at the downstream end of a study reach. They predicted the respective flow and substrate conditions using a 2D morphodynamic model. The suitability of these habitats for macroinvertebrates was assessed based on habitat models (Kiesel et al., 2015). This modelling cascade was recently further developed by including morphological and dispersal models by Kail et al. (2015). In this model framework, fish were considered besides macroinvertebrates to test the applicability of such an integrated modelling framework for different organism groups. This modelling framework consists of separate models for the major processes and depicts the different habitat characteristics of fish and macroinvertebrates. The principal applicability of their modelling framework was demonstrated in Kail et al. (2015).

Applying this modelling framework in scenario simulations enables the assessment of the effects of changing climate and land use on abiotic conditions and related biota. Scenario simulations were performed to estimate potential effects of changes as a basis for restoration of freshwater habitats. The effects of climate and land use change on biota act through intertwined and complex dependencies. These connections can be disentangled by using the modelling framework.

Therefore, this study used the modelling framework presented by Kail et al. (2015) to investigate consecutive impacts of land use and climate change on hydrology, hydrodynamic and biota. Two different process chains were analysed for considering the specific habitat preferences of fish and macroinvertebrates, respectively. It is therefore one of the first attempts to simulate the abundance and occurrence of riverine species, resulting from a chain of processes from the catchment hydrology down to local habitat suitability under climate and land use change.

The main objectives of this study are:

1. to simulate the impact of climate and land use changes along the whole modelling framework from catchment scale hydrology to reach scale hydrodynamics on habitat suitability for fish and macroinvertebrates.
2. to compare the relevance of predicted climate and land use changes for future eco-hydrology (river discharge, nutrient concentration), hydrodynamics (flow velocity, water depth) and selected fish and macroinvertebrates species.

2. Material and methods

2.1. Design of the model cascade

The single parts of the applied integrated modelling framework developed by Kail et al. (2015) are presented briefly step-by-step in the order of decreasing spatial scale (Table 1) and the model cascade is then described in detail in Section 2.3.

Due to the different environmental requirements of the two selected organism groups, two process chains were modelled. The first process chain analyses the impact of hydraulic habitat conditions on fish, whilst the second process chain analyses the effects of water quality, i.e., nitrate concentrations, for macroinvertebrates (Fig. 1).

Both process chains start with the eco-hydrological model SWAT (Arnold et al., 1998) (a in Fig. 1), which provides discharge and water quality time series at the catchment scale. The modelled time series as simulated with the SWAT model in the climate and land use scenarios are the initial input to the scenario simulations in both model process chains.

In the fish process chain, the 1-D hydraulic model HEC-RAS (USACE, 2002) (b in Fig. 1) was used to develop a rating curve for the downstream end of the study reach to predict the water level for given discharges. Discharge and water level are necessary input parameters for the 2-D hydrodynamic model iRIC-FaSTMECH (c in Fig. 1), which predicts depth-averaged flow velocity and water depth for all raster cells of a two-dimensional computational grid. The suitability of these hydraulic habitat conditions in each raster cell was assessed using a fish habitat model (d in Fig. 1). The estimated values were weighted by the respective grid cell area and summarized as Weighted Usable Area [WUA] (Bovee and Cochnauer, 1977; Payne, 2003), a single value of habitat suitability for the entire study reach.

In the macroinvertebrate process chain, the SWAT model provides nitrate time series. This nitrate concentration was included in a further development of the recently published habitat evaluation tool (HET, e in Fig. 1) (Kiesel et al., 2015), which models the presence and abundance of macroinvertebrates for a defined spatial unit on the reach scale. Thus, changes in the nitrate concentration affect the abundances of macroinvertebrates.