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A novel integrated modelling framework to assess the impacts of climate and socio-economic drivers on land use and water quality

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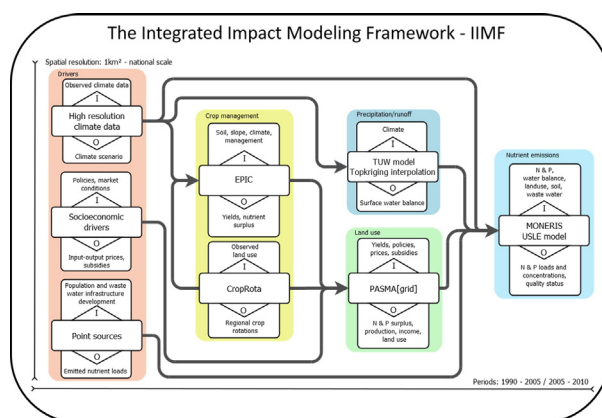
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HIGHLIGHTS

- Developing an integrated impact modelling framework (IIMF) with six models.
- Application of the IIMF at various scales from 1 km pixel to the Austrian territory.
- Pollution impacts are assessed along policy-climate-agriculture-water interfaces.
- Deviations between model results and observations are assessed and discussed.
- The IIMF enables risk assessment for future water quality development.

GRAPHICAL ABSTRACT



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ABSTRACT

Changes in climatic conditions will directly affect the quality and quantity of water resources. Further on, they will affect them indirectly through adaptation in land use which ultimately influences diffuse nutrient emissions to rivers and therefore potentially the compliance with good ecological status according to the EU Water Framework Directive (WFD). We present an integrated impact modelling framework (IIMF) to track and quantify direct and indirect pollution impacts along policy-economy-climate-agriculture-water interfaces. The IIMF is applied to assess impacts of climatic and socio-economic drivers on agricultural land use (crop choices, farming practices and fertilization levels), river flows and the risk for exceedance of environmental quality standards for determination of the ecological water quality status in Austria. This article also presents model interfaces as well as validation procedures and results of single models and the IIMF with respect to observed state variables such as land use, river flow and nutrient river loads. The performance of the IIMF for calculations of river nutrient loads (120 monitoring stations) shows a Nash-Sutcliffe Efficiency of 0.73 for nitrogen and 0.51 for phosphorus. Most problematic is the modelling of phosphorus loads in the alpine catchments dominated by forests and mountainous landscape. About 63% of these catchments show a deviation between modelled and observed loads of 30% and more. In catchments dominated by agricultural production, the performance of the IIMF is much better as only 30% of cropland and 23% of permanent grassland dominated areas have a deviation of >30% between modelled

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and observed loads. As risk of exceedance of environmental quality standards is mainly recognized in catchments dominated by cropland, the IIMF is well suited for assessing the nutrient component of the WFD ecological status.

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1. Introduction

Climate change is one of the major challenges of our time and adds considerable stress to the human society and environment (UNEP, 2010). A change in climate is not only restricted to a shift of seasonal weather patterns like increasing winter precipitation in Northern Europe and decreasing summer precipitation in Southern and Central Europe, but can also lead to more frequent occurrence of extreme weather events such as intense rainfall or drought (IPCC, 2007; Jentsch and Beierkuhnlein, 2008; IPCC, 2014). The most important changes in the climate system related to water resources are increases in air temperature, shifts in precipitation patterns and snow cover, and potentially an increase in the frequency of flooding and droughts (EEA, 2007). In Austria, weather station data of the last decades show a rising air temperature trend but significant changes in annual precipitation sums have not been detected in the period 1975 to 2007 (Strauss et al., 2013). For the decades to come, increasing precipitation in winter and decreasing precipitation in summer as well as increases in extreme weather events are expected (APCC, 2014). However, uncertainties and spatial heterogeneity are large, particularly in the alpine region (Gobiet et al., 2014).

Climate change has direct effects on water resources. Rising water temperatures influence biological processes and chemical conditions in surface waters, e.g. decreasing oxygen solubility, increasing growth rates of aquatic organisms and consequently increasing variability of pH-values. Since the influence of temperature and water availability is closely connected, longer dry periods leading to severe low-flow situations might affect the quality of surface waters adversely. Climate change also induces land use changes, i.e. autonomous or planned adaptation, resulting in indirect impacts on water resources. Agriculture is one of the major water consumers through either rain-fed production or irrigation, and contributes to surface and ground water pollution. Increasing yield potentials from extended vegetation periods and elevated CO₂ concentration may lead to adjustments of land cover (e.g. conversion of grassland or natural habitats to cropland, land abandonment), land use and management (e.g. choices of crops and cultivars, irrigation, fertilization, adjusted planting dates) (Olesen et al., 2011). Furthermore, climate change is accompanied with changes in socio-economic production conditions such as agricultural policy reforms and international market dynamics.

Since protecting and restoring aquatic ecosystems is a policy priority in Europe (EC, 2000), uncoordinated autonomous adaptation in agriculture can cause shortages in water supply and affects the compliance of the EU Water Framework Directive (WFD). Nutrient pollution is already considered as a global problem beyond the planetary boundaries (Steffen et al., 2015) and it is suspected that nutrient emissions will exacerbate in vulnerable European aquifers, rivers and estuaries due to climate change (Bindi and Olesen, 2010; Leclère et al., 2013).

The relationship between socio-economic conditions, climate change, agricultural production, water resources and diffuse water pollution are highly complex and require an integrated approach to assess the overall, sectoral and dissipated impacts (Dunn et al., 2012). So far, only limited information is available on the complex interactions between climate change, agriculture and water (Fallon and Betts, 2010). Using impact modelling to investigate the combination of climate change, land use and diffuse water pollution produces divergent conclusions and multiple uncertainties. Dunn et al. (2012) expressed the need for a spatially distributed approach to any large scale modelling. For this purpose, high resolution climate change data and socio-economic scenarios should be integrated in models of land use and fresh water systems for quantification of agricultural production and water resources as well as assessment of water quality. Several studies have analyzed

the impacts of climate change on agricultural production (Brown et al., 2008; Fischer et al., 2005; Olesen et al., 2007) or water resources (Arnell, 2004; Bates et al., 2008; Mimikou et al., 2000; Schöner et al., 2011). A few have dealt with the linkage between agricultural production and water systems (Bindi and Olesen, 2010; Mehdi et al., 2015a; Mehdi et al., 2015b) but do not consistently combine climate change, socio-economic drivers, agricultural land use and water pollution. Though land use is considered in some modelling scenarios (e.g. Karlsson et al., 2016), agricultural land use has been rarely modelled in an integrated modelling framework combined with different climate and political scenario assumptions so far. A methodology for an integrated analysis of tradeoffs between economic and environmental indicators using bio-physical and economic models for agricultural production systems was proposed by Stoorvogel et al. (2004). A unique Australian continental model was presented by Connor et al. (2015) modelling land use change (e.g. food, carbon, water) and biodiversity ecosystem services with food price feedback. Volk et al. (2008) developed an ecological-economic modelling tool, which supports the assessment and 3-dimensional visualization of hydrological, ecological and socio-economic conditions and management effects in river basins. None of these simulation models considered climate change as integrated factor. Barthel et al. (2012) integrated climate change and socio-economic drivers into land use modelling and related nitrogen pollution of groundwater but do not consider phosphorus or surface water quality. An integration of different models combined with existing external constraints as climate change, demographic change and management practices were accomplished by Lautenbach et al. (2009) assessing impacts for the river Elbe though a direct link to climatic and socio-economic drivers was not realized within this study.

This article develops an integrated impact modelling framework (IIMF) to track and quantify direct and indirect pollution impacts along policy-economy-climate-agriculture-water interfaces in Austria. It adds important aspects to previous research by linking climatic and socio-economic boundary conditions via land use optimization and runoff-precipitation modelling to impacts on surface water quantity and quality. The IIMF models adaptation of agricultural production to climatic (e.g. temperature, precipitation) and socio-economic drivers (e.g. market prices, agri-environmental payments) and quantifies related agricultural outputs such as crop and livestock production as well as nitrogen and phosphorus emissions to surface waters, which has not been done before in integrated impact modelling. Agricultural emissions dominate pollution of surface waters in Austria (Schilling et al., 2011) and therefore significantly impact the ecological status of water bodies (BMLFUW, 2015).

The focus of this article is on the description of the IIMF and the interfaces of the single model components (Section 2) as well as the validation against observed data of single models and the IIMF (Section 3). We also quantify and discuss uncertainties relating to individual models and interface options as well as the uncertainty ranges of impacts (Sections 3 and 4). Our conclusions highlight options and procedures for the application of the IIMF in scenario studies (Section 5). A detailed scenarios assessment based on future climatic and socio-economic conditions within the IIMF will be presented in upcoming publications.

2. Material and methods

2.1. Overview of the integrated impact modelling framework (IIMF)

The IIMF has been developed in order to assess climatic and socio-economic impacts on agricultural land use, runoff and nutrient pollution

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