Science of the Total Environment 621 (2018) 253–264

Contents lists available at ScienceDirect

Science of the Total Environment

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

Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark)

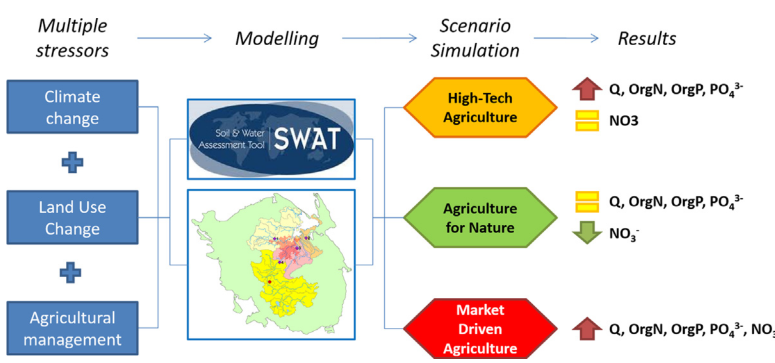
Eugenio Molina-Navarro *, Hans E. Andersen, Anders Nielsen, Hans Thodsen, Dennis Trolle

Department of Bioscience, Aarhus University, Silkeborg, Denmark

HIGHLIGHTS

- We calibrated a SWAT model for discharge and four nutrients in the Odense catchment.
- We downscaled three future storylines focusing on climate and land use changes.
- Changes in land use alone showed an impact on NO_3^- loss due to changes in fertilization.
- Discharge, organic nutrients and PO_4^{3-} loads will increase under high emissions.
- Both land use and climate changes will interact regarding nitrate loads.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 May 2017
Received in revised form 7 November 2017
Accepted 21 November 2017
Available online xxxx

Keywords:
Catchment management
Climate change
Eco-hydrological modelling
Nutrients
Scenario simulation
SWAT

ABSTRACT

Water pollution and water scarcity are among the main environmental challenges faced by the European Union, and multiple stressors compromise the integrity of water resources and ecosystems. Particularly in lowland areas of northern Europe, high population density, flood protection and, especially, intensive agriculture, are important drivers of water quality degradation. In addition, future climate and land use changes may interact, with uncertain consequences for water resources. Modelling approaches have become essential to address water issues and to evaluate ecosystem management. In this work, three multi-stressor future storylines combining climatic and socio-economic changes, defined at European level, have been downscaled for the Odense Fjord catchment (Denmark), giving three scenarios: High-Tech agriculture (HT), Agriculture for Nature (AN) and Market-Driven agriculture (MD). The impacts of these scenarios on water discharge and inorganic and organic nutrient loads to the streams have been simulated using the Soil and Water Assessment Tool (SWAT). The results revealed that the scenario-specific climate inputs were most important when simulating hydrology, increasing river discharge in the HT and MD scenarios (which followed the high emission 8.5 representative concentration pathway, RCP), while remaining stable in the AN scenario (RCP 4.5). Moreover, discharge was the main driver of changes in organic nutrients and inorganic phosphorus loads that consequently increased in a high emission scenario. Nevertheless, both land use (via inputs of fertilizer) and climate changes affected the nitrate transport. Different levels of fertilization yielded a decrease in the nitrate load in AN and an increase in MD. In HT, however, nitrate losses remained stable because the fertilization decrease was counteracted by a flow increase. Thus, our results suggest that N loads will ultimately depend on future land use and management in an interaction with

* Corresponding author at: Department of Bioscience, Aarhus University, Vejlsøvej 25, 8600 Silkeborg, Denmark.
E-mail addresses: emna@bios.au.dk, eugenio.molinanavarro@gmail.com (E. Molina-Navarro).

https://doi.org/10.1016/j.scitotenv.2017.11.251
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climate changes, and this knowledge is of utmost importance for the achievement of European environmental policy goals.

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1. Introduction

Water pollution and water scarcity are among the main challenges faced by the European Union. The continuing presence of a range of pollutants (e.g., creating excessive nutrient levels) and the possible consequences of climate change constitute a threat to water resources and their associated ecosystems (Kristensen, 2012). The main aim of the EU water policy, anchored in the European Water Framework Directive (WFD), is to ensure that a sufficient quantity of good quality water is available for people's needs and for the environment. The Directive committed the EU member states to achieve good ecological and chemical status of all surface water bodies by 2015, which involved fulfilling certain quality and quantity standards (European Parliament and Council, 2000). However, according to Europe's first generation of River Basin Management Plans, many water bodies failed to achieve this target. Thus, the EU has planned a revision of the WFD by 2019 and set the new deadline for achieving the overall WFD targets by 2027 (Hering et al., 2015).

In northern Europe, multiple stressors compromise the integrity of water resources and ecosystems. In lowland areas, high population density, intensive agriculture and flood protection have been important drivers of water quality degradation, and freshwater streams and lakes, as well as transitional (estuaries) and coastal waters are severely affected by eutrophication and pollution (Hering et al., 2015). Eutrophication is a recurrent issue in the Baltic Sea and the affected countries have therefore adopted various counteracting measures, like the Baltic Sea Action Plan (HELCOM, 2007). In Denmark, one of the world's most intensively farmed countries, diffuse nutrient losses from agriculture to water bodies, especially nitrogen, are of particularly great concern (Kaspersen et al., 2016). As a result of the undertaking of Danish water action plans, the total contents of nitrogen and phosphorus in the streams have decreased by approximately 43% and 40%, respectively, since 1989 (Thodsen et al., 2016). However, further reductions are required to ensure successful implementation of the WFD.

Odense Fjord, located on the island of Funen (Denmark), is one of the ecosystems affected by environmental pollution. Thus, elevated nutrient input levels have led to hypoxia, algal blooms and disappearance of seabed vegetation and fauna (Conley et al., 2007; Miljøministeriet, 2011). The fjord has a catchment area of approx. 1100 km^2, including rivers and lakes. The integrity of water ecosystems in the area has been damaged due to urbanisation and use of fertilizers and pesticides derived from the industrialisation of the agricultural sector, extensive channelisation of rivers, summer droughts and groundwater abstraction (Miljø- og Fødevareministeriet, 2016a). For Funen as a whole, Henriksen et al. (2008) reported an abstraction slightly over the sustainable yield, with the highest over-exploitation taking place in the Odense Fjord catchment, probably due to abstraction for water supply of Funen's largest city, Odense.

Climate and land use changes may interact and thus have combined effects on water resources, and the consequences of this are uncertain. To take into account the effects of climate change on the availability of freshwater is one of the main challenges to water administrators in Europe (Kristensen, 2012). Despite this, climate change was not consistently considered in the first generation of European River Basin Management Plans. The latest assessment elaborated by the Intergovernmental Panel on Climate Change (IPCC) has reported a general warming trend all over Europe, with the strongest warming projected for Southern Europe in summer and Northern Europe in winter (Kovats et al., 2014). For precipitation, climate projections show a general increase in Northern Europe, mainly during winter, while precipitation may decrease in summer with the associated risk of drought due to enhanced evapotranspiration. Consequently, climate change is projected to affect the hydrology and conditions of agricultural production in the Nordic-Baltic region (Jensen and Veihe, 2009; Øygarden et al., 2014; Trolle et al., 2015). In lowland catchments, most studies predicted an increase in average flow, generally due to the higher precipitation during winter, including also an increase of extreme events (e.g. Karlsson et al., 2015; e.g. Thodsen, 2007; van Roosmalen et al., 2009). The occurrence of high flows may, however, decrease in spring due to reduced snowpack and earlier melt as a result of the higher temperatures (Arheimer and Lindström, 2015). Increased temperatures will prolong the length of the growing season, potentially up to 2–4 months in some Nordic locations, and milder winters will allow more productive cultivation of winter crops (Jensen and Veihe, 2009; Øygarden et al., 2014).

The changes in precipitation and runoff, as well as temperature increases, will expectedly lead to an increase in nutrient loadings to surface water bodies in Northern Europe. Several studies have predicted profound effects of climate change on nutrient loading and eutrophication (e.g. Andersen et al., 2006; Jeppesen et al., 2009; Trolle et al., 2011), but better understanding of how nutrient losses will be influenced by the climate-induced changes in hydrology and agricultural management practices is essential. For the Nordic-Baltic region, higher temperatures influencing nutrient mineralisation, and increased precipitation will expectedly result in enhanced nutrient losses outside the growing season (Øygarden et al., 2014). Predictions for the growing season are more uncertain since climate change effects may influence agricultural decisions about land use and management (Jensen and Veihe, 2009), and many factors (duration of the growing season, weather conditions, changes in fertilization and yields, mineralisation, plant survival, future policies) may affect nutrient losses (Øygarden et al., 2014). Trolle et al. (2015) suggested that it will not be possible to obtain 'good' ecological status required by the EU WFD without interfering substantially with land use and crop production.

Considering the multiple stressors on water resources, a holistic and multidisciplinary approach is needed to understand how these may interact and explore what might be done to mitigate the undesirable effects. For this purpose, simulation models have proven to be useful tools (Devia et al., 2015; Trolle et al., 2012). In particular, catchment-scale models are valuable in addressing water quantity and quality issues, to evaluate ecosystem management practices and ultimately to develop river basin management plans (Arnold et al., 1998; Schoumans et al., 2009). One of those models is the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998), a physically-based eco-hydrological model developed by the US Department of Agriculture (USDA) and the Texas A & M University. SWAT is used worldwide and >2500 papers in international journals have been published based on its application and ongoing development.

The SWAT model has already been set up for the Odense catchment (Thodsen et al., 2015) and may thus be used as a platform to address water issues in the area. Some studies have also endeavoured to assess the impact of future climate scenarios in the Odense catchment. For example, Thodsen (2007) studied the influence of the IPCC A2 scenario on stream flow (2071–2010 vs. 1961–1990), and Karlsson et al. (2015) and Trolle et al. (2015) assessed the impacts of an extreme 6 °C warming scenario on future runoff and nutrient exports.

In this study, three storylines, combining climate and land use change (socio-economic) scenarios, were developed to help differentiate the effects of multiple stressors on water quality and availability. The main objective was to run multi-stressor scenarios with the SWAT

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