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A stochastic dynamic model to assess land use change scenarios on the ecological status of fluvial water bodies under the Water Framework Directive

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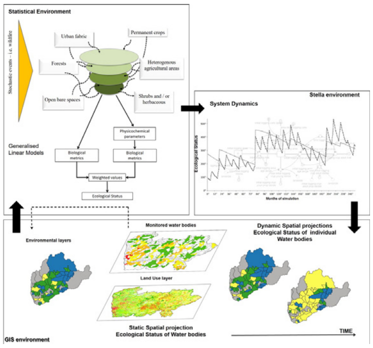
HIGHLIGHTS

- The dynamic model framework tests land change scenario effects on surface water ecological status.
- Spatial projection of output from simulations using open source Geographical Information System.
- Model provides both temporal and spatial patterns of change in surface water bodies.
- The two tested land use scenarios produce difference degrees of response
- Dynamic tool suitable for Water Framework Directive planning and extrapolation.

GRAPHICAL ABSTRACT



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ABSTRACT

This method development paper outlines an integrative stochastic dynamic methodology (StDM) framework to anticipate land use (LU) change effects on the ecological status of monitored and non-monitored lotic surface waters under the Water Framework Directive (WFD). Tested in the Alto Minho River Basin District in North West Portugal, the model is an innovative step towards developing a decision-making and planning tool to assess the influence impacts such as LU change and climate change on these complex systems. Comprising a series of sequential steps, a Generalized Linear Model based, competing model Multi Model Inference (MMI) approach was used for parameter estimation to identify principal land use types (distal factors) driving change in biological and physicochemical support elements (proximal factors) in monitored water bodies. The framework integrated MMI constants and coefficients of selected LU categories in the StDM simulations and spatial projections to simulate the ecological status of monitored and non-monitored lotic waterbodies in the test area under 2 scenarios of (1) LU intensification and (2) LU extensification. A total of 100 simulations were run for a 50 year period for each scenario. Spatially dynamic projections of WFD metrics were obtained, taking into account the occurrence of

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stochastic wildfire events which typically occur in the study region and are exacerbated by LU change. A marked projected decline to "Moderate" ecological status for most waterbodies was detected under intensification but little change under extensification; only a few waterbodies fell to "moderate" status. The latter scenario describes the actual regional socio-economic situation of agricultural abandonment due to rural poverty, partly explaining the projected lack of change in ecological status. Based on the WFD "one out all out" criterion, projected downward shifts in ecological status were due to physicochemical support elements, namely increased phosphorus levels. Little or no change in status was driven by Intercalibrated Biological Quality Elements, indicating innate resilience and raising questions concerning uncertainty, the effect of pressures other than land use and metric redundancy and the WFD classification process.

1. Introduction

Catchment level management of water resources and associated ecosystems encapsulates the concept of social ecological systems. Human well-being and provision of ecosystem services within this geographical unit is sustained by adaptive forward looking planning. River catchments are extremely complex and dynamic systems (see Cilliers et al., 2013) with hierarchically organised biophysical and anthropogenic processes that vary and interact in time and space via complex, often non-linear pathways (Frissell et al., 1986; Cortes et al., 2013). Catchment level Land Use (LU) and Land Cover (LC) change is influenced by underlying socio-ecological interactions related to governance, economic development, technological advances and climate together with natural stochastic events like wildfire (D'Andrea et al., 2011) or flood events (Rosso and Rulli, 2002). Thus socioeconomic phenomena, that often start at a global level, exert their influence via changes in LU down to the local scale via complex direct and indirect processes and different spatial and temporal scales (see Lambin and Meyfroidt, 2011; Turner et al., 2007). These processes ultimately influence water resources, ecosystems and the services they provide (Sandin, 2009) which is reflected in bioindicator and support element response.

The Millennium Assessment Report recognises the fundamental, holistic links between ecological processes and human well-being, (Reid et al., 2005), a concept also common to the Water Framework Directive (WFD), which "promotes sustainable water use through long-term protection of available water resources, progressively reduces discharges of hazardous substances in ground and surface waters, and mitigates the effects of floods and droughts" (Green et al., 2013). The WFD has revolutionised integrated water management across Europe by recognising that sustainable governance of sustainable water resources must embrace catchment complexity as a socio-ecological system. As a result, integrated ecological assessment and classification of surface waterbodies and public participation in catchment level River Basin Management Plans (RBMP) are now mandatory (Balana et al., 2011; Hering et al., 2010; Steyaert and Ollivier, 2007). A main WFD objective is to ensure that all waterbodies achieve "Good" overall status by the end of the first six year planning cycle ends (December 2015) and the second begins. RBMP must set out Programmes of Measures (PoM) for waterbodies falling below this benchmark to improve their status and become compliant over subsequent planning cycles.

The PoM process implicitly requires adaptive stakeholder capacity to implement effective plans, based on the ability to anticipate change in ecological status as a result of realistic scenarios of LU change within defined waterbodies. This can be achieved by testing scenarios using predictive modelling methods based on system dynamics (Jørgensen and Bendoricchio, 2001) which can be used as management tools to reproduce the complex and dynamic processes that shape real systems (Bastos et al., 2016; Lambin and Meyfroidt, 2011). Dynamic models, usually tested on a small subset of data for a given geographical area for demonstration purposes, are an effective way to assess how key drivers in complex ecosystems can influence change in an ecological system such as the WFD catchment based approach. Results obtained from different scenarios allow managers to identify circumstances that may need urgent attention (e.g. water bodies that may fail to meet "Good" status) and plan accordingly in a way that is free from partiality that can arise from "expert judgement" (Cortes et al., 2013).

Predictive modelling methods have been used to address many different issues in freshwater systems. The Stochastic Dynamic Methodology (StDM) is a sequential modelling protocol that combines statistical and dynamic modelling techniques to assess the outcome of scenarios of change in altered ecosystems (Santos and Cabral, 2004). The StDM modelling process is built upon "the premise that general statistical patterns of ecological phenomena are emergent indicia of complex ecological processes", minimising problems inherent in model creation "such as parameterization, model complexity and variables choice" (Santos et al., 2013). The StDM has been used to predict change in altered terrestrial and aquatic ecosystems under different case relevant scenarios (Bastos et al., 2012; Cabecinha et al., 2009b; Cabral et al., 2007; Fernandes et al., 2013; Santos et al., 2011). The StDM outputs can provide a versatile visual tool to support strategic decision making when coupled with Geographical Information Systems (Bastos et al., 2012).

Previous StDM studies on freshwater systems have addressed aspects of land use change on the ecological status of reservoirs (Cabecinha et al., 2009a; Cabecinha et al., 2009b; Cabecinha et al., 2009c; Cabecinha et al., 2009d) and drivers of change in selected benthic macroinvertebrate bioindicator metrics in lotic systems (Cabecinha et al., 2004; Cabecinha et al., 2007). The lotic StDM studies have been limited to a small number of river catchments and although they have tested benthic macroinvertebrate metric response, many are not WFD compliant and WFD status has not been directly assessed. The StDM is particularly suited to the WFD planning process because each share a holistic socio-ecological approach that is suited to address the inherent complexity of aquatic ecosystems (Cabecinha et al., 2004; Cabecinha et al., 2009a; Hughes et al., 2012). This demonstration focussed paper recognises the need to take the StDM another step, to develop an operational framework for the WFD planning process that can cover larger areas such as River Basin Districts, to test scenarios of change such as land use and the response of stipulated WFD biological and support quality elements used to determine ecological status.

This method development article outlines an integrative stochastic dynamic model based framework, to predict change in the ecological status of WFD lotic waterbodies under different LU scenarios. We apply two different LU change scenarios, reflecting different underlying socio-economic situations, to illustrate the potential range and influence of land use pathways on indicator response and WFD status in the study area. The model framework is tested in the Alto Minho River Basin District, situated in North West Portugal. Land abandonment (usually due to rural poverty) and wildfire are regularly occurring phenomena in southern Europe, including the Alto Minho region; wildfire occurrence is exacerbated as a result of climate change (Birot, 2009; Mayor et al., 2007; Moreira et al., 2011).

The ultimate aim of the model framework method is to assess change in WFD indicator response and ecological status under different types of scenarios, including climate change, to provide stakeholders with a tool that informs whether water bodies will meet the required "good" status over WFD planning cycles. The European Commission's 2012 assessment of Member States' RBMPs concluded that "that a more determined effort is needed to ensure achievement of WFD objectives in 2015, 2021 and 2027 cycles" (European Commission, 2012a). However, the timing and deadlines for specific POMs and subsequent compliance will differ between Member States and River