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# A spatially distributed risk screening tool to assess climate and land use change impacts on water-related ecosystem services

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ABSTRACT

To support the implementation of the European Water Framework Directive (WFD), and as part of a tiered approach to prioritise detailed modelling, a high-level screening methodology has been developed to assess the vulnerability of water-related ecosystem services (ES) to future change. The approach incorporates a range of spatially distributed scenarios of land use and climate, which are used as inputs to a qualitative risk assessment model underpinned by expert opinion. The method makes use of widely available datasets and provides a structured way of capturing and "codifying" expert knowledge, as well as for assessing the degree of consensus between different expert groups. The range of model output reflects uncertainty in both the expert-derived assumptions and the climate & land use simulations considered. The approach has been developed in collaboration with the Scottish Environment Protection Agency (SEPA) and applied in Scotland to support the second cycle of River Basin Management Planning.

## Software availability

Python code and additional resources for the analysis presented are available here: https://github.com/JamesSample/ecosystem_services_impacts.

## 1. Introduction

Land use and water resources are closely interlinked (Howden et al., 2010). In Scotland – as in many countries – diffuse pollution from agriculture is among the main causes of failure to meet water quality targets (SEPA, 2014a, 2007), while urban expansion and afforestation may affect water quantity by changing infiltration and evapotranspiration rates. In addition, climate change is expected to lead to an intensification of the hydrological cycle (Huntington, 2006), resulting in further changes to both water quantity and quality. Meeting the food, water and energy demands of an expanding population in the face of global climate and land use change is therefore considered to be one of society's biggest challenges (Godfray et al., 2010).

Across the globe, water provides a diverse range of valuable ES (Brauman et al., 2007), from drinking water provision to opportunities for recreation and the dilution of industrial discharges. Future changes to the availability and quality of water resources may therefore affect the capacity of natural systems to provide these services (Metzger et al., 2006; Schröter et al., 2005). This has been recognised in water policy and, under the obligations of the WFD, SEPA is required to undertake a process of River Basin Management Planning (RBMP), with the aim of maintaining or improving waterbody status while also safeguarding water-related ES. Details of the second cycle of RBMP are due for publication in 2015 (SEPA, 2014a), and to support this process there is a need to identify waterbodies where ES may be negatively affected by future change.

Estimating the likely effects of land use and climate change on ES is not straightforward, as each service may respond differently to a range of factors. Physically-based, conceptual models are capable

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*Abbreviations:* ES, Ecosystem Service(s); EU, European Union; FF, Future Flows; IPCC, Intergovernmental Panel on Climate Change; LCA2050, Land Capability for Agriculture 2050; LCF, Land Capability for Forestry; LCM2007, Land Cover Map 2007; LCMS1988, Land Cover Map of Scotland 1988; PET, Potential Evapotranspiration; RBMP, River Basin Management Plan(ning); SEPA, Scottish Environment Protection Agency; UKCP09, United Kingdom Climate Projections 2009; WFD, Water Framework Directive.

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of simulating some of these factors (Arnold et al., 2012; Lindstrom et al., 2010) and a variety of studies have explicitly considered the effects of future change on specific ES, for example by modelling hydropower potential (Christensen and Lettenmaier, 2007; Lehner et al., 2005) or water quality (Mehdi et al., 2015; Wilby et al., 2006) under a range of future scenarios. However, the skill of existing hydrological and water quality models is strongly dependent on the variable(s) being simulated (Gassman et al., 2007) and many models are complex and highly parameterised, making them time-consuming to setup even for narrowly focused studies. The quality of the simulated results is also influenced by uncertainty in the model structure, parameterisation, initial conditions and input & calibration datasets (Uusitalo et al., 2015). Complex physically-based models with large numbers of "free" parameters are especially prone to "over-fitting" the data, which makes their predictive power difficult to assess (Kirchner, 2006). For adaptation studies, a number of authors have also questioned whether the best climate scenarios currently available are good enough to be used in quantitative decision support (Frigg et al., 2013; Smith and Petersen, 2014), especially in cases where they are used to drive lengthy modelling chains to assess mitigation options. These authors argue instead for a more pragmatic approach, making use of quantitative modelling only where the numerical detail can be justified.

Given time, knowledge and financial constraints, it may be impossible to obtain the measured data required to robustly parameterise complex, physically-based models (Vrana et al., 2012). Where quantitative modelling is not feasible, qualitative approaches based on expert or stakeholder opinion may be a useful way of bridging knowledge gaps and supporting high-level decision making (Heathwaite, 2003; Rowan et al., 2012), particularly if used in a hierarchical framework to identify areas worthy of more detailed (quantitative?) investigation (Volk et al., 2010). The current state-of-the-art concerning modelling with stakeholders is reviewed by Voinov et al. (2016), who state that "participatory modelling" is now one of the mainstays of environmental management and decision support. A variety of authors have also noted that the process of stakeholder elicitation can itself be beneficial, leading to better engagement and reduced levels of conflict, thereby improving the decision making process (e.g. Krueger et al., 2012).

Although qualitative modelling approaches generally provide less detailed information than process-based alternatives, in many real-world applications it is sufficient for decision makers to know only the likely direction of change and an indication of magnitude (Dunn et al., 2015). In such cases, qualitative models may have the advantage of being quicker to develop and apply, so the amount of effort invested in modelling is more proportionate to the utility of the output. An additional advantage is that the assumptions and limitations of qualitative models are typically more transparent and easier to communicate, further enhancing opportunities for engagement and discussion with non-expert stakeholders, and ultimately giving the models greater credibility with users (Hall et al., 2014; Wieland and Gutzler, 2014).

Key considerations when conducting a participatory modelling study include how to effectively elicit information from those taking part and how to aggregate the responses in a way that reduces bias and provides an accurate reflection of group opinion (Krueger et al., 2012; Voinov et al., 2016). One approach for dealing with bias is to use "expert calibration", where participants are first asked to estimate some known quantities so that tendencies towards under- or over-estimation can be identified and subsequently corrected. Other commonly used approaches for eliciting and aggregating group opinion include the Nominal Group (Clemen and Winkler, 1999) and Delphi (Dalkey, 1969; MacMillan and Marshall, 2006) methods, where opinions are initially gathered from each expert independently, but the responses are then pooled and communicated back so that participants have the opportunity to iteratively revise their estimates in the light of feedback. For the Nominal Group approach, feedback takes place face-to-face in a workshop setting, whereas for Delphi the feedback is provided remotely so that participants do not feel pressured into changing their views, for example due to a desire to conform with group norms (Ayyub, 2001).

As with physically-based approaches, it is desirable that qualitative modelling studies (especially those aiming to provide decision support) include an assessment of confidence in the model results. This is particularly the case for climate adaptation studies, where there is considerable uncertainty about both the magnitude and direction of climate change (Jenkins et al., 2009). Researchers investigating impacts on ES potential typically represent climate uncertainty using an ensemble of future simulations (e.g. Schröter et al., 2005), although some authors have stated that the results obtained from such ensembles may be misleading if interpreted incautiously, because they rarely provide a comprehensive representation of the true uncertainty in future climate (Frigg et al., 2014). Similarly, it is important that studies incorporating stakeholder or expert opinion allow for the possibility of uncertainty or lack of consensus in the opinions expressed (Voinov et al., 2016). The Nominal Group and Delphi approaches described above aim to reduce bias by shifting group opinion towards a consensus, but in many cases the disagreement among experts may itself provide important information that should be retained (Krueger et al., 2012). O'Hagan (2012) provides an overview of formal statistical methods for dealing with uncertainties in participatory modelling and Scholten et al. (2013) demonstrate how explicit consideration of the variance in expert opinion can improve posterior inference and decision making. Alternative approaches are described by Page et al. (2012) and Vrana et al. (2012), who present examples based on fuzzy set or possibility theory. All of these techniques represent complicated mathematical models in themselves, and they may therefore be difficult to articulate effectively to non-specialist audiences. As Booker and McNamara (2004) point out, experts involved in participatory modelling usually prefer to express themselves using natural language, rather than in the terminology of mathematical uncertainty. An important challenge is therefore how to translate natural language responses into suitable inputs for subsequent modelling.

Krueger et al. (2012) state that expert elicitation should make use of, "*formal, systematic and transparent procedures*" to capture information. Haines-Young et al. (2012) and Burkhard et al. (2012) encoded their opinions in "lookup tables", which were used to link ES potential to historic land cover data, thereby making it possible to estimate the impacts of land use change on service provision. Haines-Young et al. conclude their methodology provides a useful "rapid assessment" tool for decision makers, complementing more detailed, process-based modelling approaches. Dunn et al. (2015) used a similar elicitation procedure to assess the possible impacts of future change on water quality. Although their study does not explicitly consider ES, their method used "reclassification matrices" (analogous to look-up tables) that were initially proposed by the authors, but subsequently refined during an expert workshop. These matrices provide a qualitative link between changes in climate and land use variables and associated changes in water quality.

At larger spatial scales, several authors have chosen to explore land use and climate change impacts on ES by adopting the qualitative vulnerability assessment framework presented by the Intergovernmental Panel on Climate Change (IPCC) in the Third Assessment Report (IPCC, 2001; see also section 2.3). Schröter et al. (2005) and Metzger et al. (2006), for example, used this method to