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Research article

Comparing two tools for ecosystem service assessments regarding water resources decisions

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ABSTRACT

We present a comparison of two ecohydrologic models commonly used for planning land management to assess the production of hydrologic ecosystem services: the Soil and Water Assessment Tool (SWAT) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) annual water yield model. We compare these two models at two distinct sites in the US: the Wildcat Creek Watershed in Indiana and the Upper Upatoi Creek Watershed in Georgia. The InVEST and SWAT models provide similar estimates of the spatial distribution of water yield in Wildcat Creek, but very different estimates of the spatial distribution of water yield in Upper Upatoi Creek. The InVEST model may do a poor job estimating the spatial distribution of water yield in the Upper Upatoi Creek Watershed because baseflow provides a significant portion of the site's total water yield, which means that storage dynamics which are not modeled by InVEST may be important. We also compare the ability of these two models, as well as one newly developed set of ecosystem service indices, to deliver useful guidance for land management decisions focused on providing hydrologic ecosystem services in three particular decision contexts: environmental flow ecosystem services, ecosystem services for potable water supply, and ecosystem services for rainfed irrigation. We present a simple framework for selecting models or indices to evaluate hydrologic ecosystem services as a way to formalize where models deliver useful guidance.

1. Introduction

Hydrologic ecosystem services (HESs) are beginning to influence land management decisions through both regulations and investments targeted at protecting and improving water resources (Le Maitre et al., 2007; Gordon et al., 2010; Goldman-Benner et al., 2012). HESs are the goods and services that ecosystems provide to people related to various uses of water, and include water availability for municipal, agricultural, and commercial use, the reduction of the magnitude and frequency of flow peaks to prevent floods, the reduction of sediment and nutrients in water, and the value of natural hydrologic systems for recreation (Brauman et al., 2007; Keeler et al., 2012; Brauman, 2015). Land managers use HESs to support investments and meet regulatory requirements around water resources in both developing countries (Goldman, 2009) and developed countries (Lautenbach et al., 2010; Logsdon and Chaubey, 2013). To support investments or meet regulations, scientists and managers assess HESs under expected future conditions based on some model of the landscape and ecosystem response; the landscapes are then managed to restore, retain, or optimize HESs and thus improve the status of the water resources. Scientists and managers assess HES provision in distinct decision contexts-combinations of investment and regulatory goals and institutional structures-which may decide both which models are applied and how model outputs are used to make decisions.

Scientists and managers often have different focuses when assessing HESs for inclusion in land management and water resources decisions. Scientists focus on formally linking ecosystem status and function to the goods and services they provide, while managers want models and results that can be easily included in the decision-making process. Clearly the best decisions can be made when both scientists' and managers' criteria are met; however, there is often a gap between advanced models, which are often more complex, and ease of inclusion in the decision-making process. Linking ecosystem function to services presents a

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challenge because models of ecosystem structure and function around water remain complex, and provide uncertain results (Kirchner, 2006; Beven, 2009). The simplest analyses rely solely on correlation or lookup tables to link ecosystem structure and function to these goods and services (Costanza et al., 1997, 2014). These simple approaches may be problematic in hydrologic systems where downstream interactions can be complex and nonlinear, especially on relatively short timescales that may be crucial for many water resource decisions. It is difficult to generalize which models can be included in the decision process because model results and their presentation can vary depending on the decision and institutional contexts. Various HES analyses have provided results at different levels of complexity and with different presentation strategies (Lautenbach et al., 2010), from overlay maps (Jackson et al., 2013) to scenario analysis (Van Liew et al., 2007) to explicit landscape optimization (Bekele and Nicklow, 2005; Lautenbach et al., 2010; Vogl et al., 2012; Cibin and Chaubey, 2015) and adaptive optimization (Kalcic et al., 2015b).

Simple HES models have been developed by several groups to provide managers with estimates of HESs for land and water resource management decisions. These models attempt to link ecosystem structure and function to the water resource goods and services provided by the ecosystem. Models to assess HESs have been developed by groups including the Natural Capital Project (the Integrated Valuation for Ecosystem Services and Tradeoffs, or InVEST model suite; Tallis and Polasky, 2009), the ARtificial Intelligence for Ecosystem Services (ARIES) project (Bagstad et al., 2013), and Polyscape (Jackson et al., 2013), while the Investment Framework for Environmental Resources (INFFER) (Pannell et al., 2012) uses an expert elicitation approach to estimate the biophysical production of HESs. All of these groups work to increase the use of ecosystem service (ES) approaches in land management and water resources decisions by making it easy to include them in the decision process. Therefore, these groups' models use simple approaches to ease the assessment of multiple ESs by non-experts in the developing world where data may be scarce. These groups hope that their models will be more widely used in decision-making than currently available hydrologic models and that the models will be used by people outside the hydrology research community. However, even among themselves, these models differ significantly in their simulation of biophysical complexity and the linkages of ecosystem structure to HESs. For example, InVEST uses relatively simple biophysical models developed from the hydrology literature to assess the landscape response under distinct scenarios, while INFFER uses expert opinion about landscape response.

Previous studies have not thoroughly assessed the accuracy of these simple HES models' hydrologic estimates or how applicable their results are to relevant decisions. This is true despite the use of such models in making real decisions and investments (Goldman et al., 2010). Vigerstol and Aukema (2011) compared the inputs and outputs of the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), InVEST (Tallis and Polasky, 2009), ARIES (Bagstad et al., 2013), and the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) but did not compare model results. InVEST's annual water yield model has been compared with the SWAT model (Gassman et al., 2007) in a few studies (Goldman et al., 2010; Rocha, 2012), but none of them have been peer-reviewed. Hamel et al. (2015) did assess the InVEST annual water yield model in one North Carolina watershed against observed flows, but this does not evaluate the accuracy relative to other models, and further assessment is necessary to understand its value for application across many sites. Most of these comparisons have been performed at scales larger than those at which most management or investment decisions are made, making them less useful for real-world application. The ARIES hydrologic models have been assessed theoretically but have not been compared with more sophisticated models (Bagstad et al., 2013). Polyscape has been developed at smaller scales, and have been applied in the Pontbren Catchment in Wales (Jackson et al., 2013), but have not been applied broadly or in the developing world contexts where HES investments may be the most important. These HES models are being used to make decisions (e.g., Goldman-Benner et al., 2012; Goldstein et al., 2012; Jackson et al., 2013), but the decision contexts under which they are useful have not been well-described. In addition, the accuracy of the model estimates will influence the land management contexts under which their use is justified.

Previous studies have used existing hydrologic models to assess HESs for land management and water resources decisions (e.g., Bekele and Nicklow, 2005; Van Liew et al., 2007; Lautenbach et al., 2012; Logsdon and Chaubey, 2013); however, with few exceptions, while these models have been shown to provide useful hydrologic predictions in the hydrology literature, their application in ES decision contexts where there are many service tradeoffs have not been thoroughly described. For example, Logsdon and Chaubey (2013) developed a set of ES indices to describe the integrated services supplied by ecosystems. They tested their indices (hereafter the Logsdon ES indices) by examining simulation of several extreme landscape management scenarios built with the SWAT model, and found that the resulting ESs differed significantly across those scenarios. (Note that the Logsdon ES indices can be calculated based on observation of hydrologic and agricultural processes, in place of simulated outputs, to examine actual ES production rather than the potential of a given scenario). Prior to that, SWAT was used to examine ESs in agricultural areas as part of the Conservation Effects Assessment Project (Van Liew et al., 2007) and a recent review highlighted SWAT's use and utility for ES assessments, especially for evaluating water yield (Francesconi et al., 2016). Other attempts have been made to quantitatively assess HESs; however, as Logsdon and Chaubey (2013) point out, while ESs has become a significant buzzword in the hydrology literature, few quantitative assessment tools or measures for ESs have been developed.

This paper compares one of the simple HES models, the InVEST annual water yield model (hereafter the InVEST water model), against a very widely used ecohydrologic model, SWAT. Our unique contribution is to be the first to compare these models in the peer-reviewed literature, and to carefully consider the spatial and temporal scales at which these models should be selected for use in specific decision contexts. As shown in Fig. 1, we address two major components, corresponding to the different rows in the figure: (1) the spatial distribution of water yield estimates from the InVEST model relative to the SWAT model; and (2) the usefulness for decision-makers of the INVEST annual water yield results versus the results from a SWAT model or ES indices developed by Logsdon and Chaubey (2013), both with and without a hydrologic model to apply the indices at a smaller scale. To address component (1), we ran both the InVEST water model and SWAT in two watersheds in the US with distinct climatic, physiographic, soil, and water use regimes. We investigated the spatial distribution of water yield estimates from InVEST by comparing the subbasin-scale results against those from SWAT. Component (2) can be seen in the second row of Fig. 1; to investigate this, we considered InVEST, SWAT, and the Logsdon ES index outputs and how each would address three distinct decision contexts about land management decisions to meet regulations and inform sustainable resource investments. We assessed each model's usefulness for making decisions in each of these decision contexts. While the considered decision contexts are hypothetical, they are realistic both in terms of the types of tools that people are using to assess the ecosystem response for ES assessments, and for the types of regulations and investments ES approaches are being used to support.