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Research papers

Improving model prediction reliability through enhanced representation of wetland soil processes and constrained model auto calibration – A paired watershed study

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A B S T R A C T

Process based, distributed watershed models possess a large number of parameters that are not directly measured in field and need to be calibrated, in most cases through matching modeled in-stream fluxes with monitored data. Recently, concern has been raised regarding the reliability of this common calibration practice, because models that are deemed to be adequately calibrated based on commonly used metrics (e.g., Nash Sutcliffe efficiency) may not realistically represent intra-watershed responses or fluxes. Such shortcomings stem from the use of an evaluation criteria that only concerns the global in-stream responses of the model without investigating intra-watershed responses. In this study, we introduce a modification to the Soil and Water Assessment Tool (SWAT) model, and a new calibration technique that collectively reduce the chance of misrepresenting intra-watershed responses. The SWAT model was modified to better represent NO_3 cycling in soils with various degrees of water holding capacity. The new calibration tool has the capacity to calibrate paired watersheds simultaneously within a single framework. It was found that when both proposed methodologies were applied jointly to two paired watersheds on the Delmarva Peninsula, the performance of the models as judged based on conventional metrics suffered, however, the intra-watershed responses (e.g., mass of NO_3 lost to denitrification) in the two models automatically converged to realistic sums. This approach also demonstrates the capacity to spatially distinguish areas of high denitrification potential, an ability that has implications for improved management of prior converted wetlands under crop production and for identifying prominent areas for wetland restoration.

1. Introduction

Process-based, distributed watershed models have been increasingly used in recent years for assessment of environmental policies and best management practices, both challenging tasks (Arnold et al., 2015). Policy makers and stakeholders often make important decisions based on predicted model responses and perhaps more critically for jurisdictional regulation of nonpoint source pollution associated with agriculture. It is common knowledge that distributed, process-based models have a large number of parameters, partly due to the complex nature of the physical and biogeochemical processes that they characterize, and partly in an attempt to represent watershed spatial heterogeneity (Whittaker et al., 2010). Most of these parameters are not directly measured *in situ* and need to be calibrated, in most cases through matching modeled in-stream fluxes (e.g., streamflow and nutrient loads) with monitored data (Beven, 2011; Yen et al., 2014a). The calibration process is either performed manually, or using an autocalibration program that employs an optimization scheme for maximizing an objective function, which is based on statistics that reflect goodness of fit between model results and field observations. In this

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conventional calibration practice, it is assumed that the model reflects true system behavior when the "global" model responses at the outlet of the watershed (in-stream fluxes) adequately match the field observations (Yen et al., 2014a). Adequacy of this match is subjective; however, there are publications, such as Moriasi et al. (2007), which offer ranges of acceptable goodness of fit statistics, measured using Nash-Sutcliff efficiency and percent bias for flow and other predicted water quality constituents.

Recently, considerable concern has been raised regarding the reliability of conventional calibration practices (Arnold et al., 2015; White et al., 2014; Yen et al., 2015a). This concern stems from the fact that so called adequately calibrated models (given the conventional standards described above) may contain input data errors not readily identifiable by model users (White et al., 2014), or may not realistically represent intra-watershed responses or fluxes (e.g., crop yield, decomposition, denitrification, and NO_3 leaching) (Yen et al., 2014a). Such shortcomings are a result of the large number of calibration parameters, the broad range that each parameter adopts, and the use of an evaluation criteria that is based solely on global in-stream responses of the model and not intra-watershed responses (Cassidy and Jordan, 2011; Yen et al., 2014a). In other words, conventionally calibrated models might be producing results that perfectly match in-stream field observations, and at the same time over/under estimate intra-watershed responses by several orders of magnitude. Such flaws can be substantial, and lead to erroneous predictions when models are used to predict effects of conservation programs, pollution control strategies, best management practices or future climate scenarios. In response to the shortcomings of conventional calibration methods, some techniques and recommendations have been developed and suggested by the scientific community. White et al. (2014) developed a screening tool named "SWAT Check" that monitors SWAT model (Soil and Water Assessment Tool – Arnold et al., 2012) outputs and alerts users if simulated budgets (i.e., water, sediment and nutrient) are not realistic and outside of typical ranges. Yen et al. (2014a) incorporated extra measures in their autocalibration routine to check for some intra-watershed responses (i.e., denitrification and nitrogen lost to tile flow) and penalize simulations that produced unrealistic responses. The result was a calibrated model that not only matched available in-stream monitoring data, but produced realistic internal watershed behavior. Arnold et al. (2015) reviewed calibration strategies of 25 model application studies at different scales and provided recommendations for calibration/validation of watershed models. The recommendations include a four step process that embraces use of "hard data" – measured discharge and water quality at the outlet of a watershed – and "soft data" – estimations of intra-watershed responses and other average estimations of physical evidence, such as groundwater depth, and baseflow ratios (Yilmaz et al., 2008; Seibert and McDonnell, 2003).

In this study, we introduce a modification to the SWAT model, and a new calibration technique that collectively reduce the chance of misrepresenting intra-watershed responses, especially those related to wetlands. The proposed modification to the SWAT model concerns the resolution at which nutrient biogeochemical exchanges occur. In particular, this study focused on the simulation of denitrification – one of the major mechanisms for removal of NO_3 in terrestrial ecosystems. In the SWAT model, denitrification occurs at each soil layer when soil moisture of that layer is above a certain threshold value; and the amount of NO_3 lost to denitrification is calculated as a function of NO_3 concentration, soil organic carbon content and a global (basin wide) denitrification rate which is adjusted for local temperature effects. With this current SWAT protocol minimal distinction is made between poorly drained hydric soils that likely have higher potential for denitrification and better drained soil types. The modification that we propose in this study includes expanding the influence of the denitrification coefficient, by assigning various denitrification rates for various hydrologic response units as opposed to one rate for the whole basin, and allocating higher rates for soils with greater denitrification potential. Soil denitrification potential is extracted from a readily available source (i.e. the Soil Survey Geographic Database [SSURGO]).

Furthermore this study introduces a new calibration technique that has the capacity to calibrate paired watersheds simultaneously using a single framework. The term "paired watersheds" typically refers to a case where two (or more) independent watersheds are monitored for discharge and water quality. Paired watersheds are usually within the same physiographic region, are more or less about the same size, have many similar properties, but possess some distinctive characteristics that make the comparison of their outflows compelling. The purpose of monitoring paired watersheds is to understand how differences in soil properties, physiographic attributes, or land management practices affect hydrology and nutrient cycling within the paired watersheds. The common practice of modeling paired watersheds involves the construction of individual models for each watershed, which are calibrated independently without paying attention to the shared characteristics of the paired watersheds. In the new method proposed in this study, the calibration of paired watersheds is not performed independently, but on one platform that uses an optimization algorithm for autocalibration. In this new approach, the user identifies calibration parameters that should be held constant between the two watershed models, according to the shared properties of the two watersheds. The rest of the parameters are allowed to adopt independent values. Accordingly, the autocalibration code generates one value for shared parameters, and two values for independent parameters.

The objectives of this study were to: (1) introduce a modification to the SWAT model that enhances the representation of soils at different hydric states without introducing new parameters; (2) introduce and test a new calibration technique for paired watershed experiments, that constrains model parameters which represent shared processes between watersheds; and (3) combine both methods to see whether implementing them in combination results in reasonable estimates of intra-watershed responses using automated calibration.

2. Methods

2.1. Study area

The methodology proposed in this study was applied to two adjacent watersheds located within the upper region of the Choptank River basin, on the Delmarva Peninsula (Fig. 1). The study watersheds, namely Greensboro and Tuckahoe, are roughly the same size and have similar crops and agricultural management practices, but possess distinctive soil properties. The Greensboro watershed (290.1 km^2) originates in Kent County, Delaware and extends southwest towards the township of Greensboro, Maryland (Caroline County), where a U.S. Geological Survey (USGS) gauging station (#01491000) has been monitoring river stage since 1948. The Tuckahoe watershed (220.7 km^2) is located within Queen Anne's and Caroline counties in Maryland, and flows south towards Tuckahoe State Park. USGS has been continuously monitoring flow at the outlet of the Tuckahoe watershed since 2000 (USGS Station # 01491500).

A combination of two facts has motivated extensive research and monitoring in the Choptank River basin in recent years (e.g., McCarty et al., 2008; Denver et al., 2014; de Guzmán et al., 2012; Whitall et al., 2010; McCarty et al., 2014): (1) the Choptank River has been classified as impaired under the Clean Water Act