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Research article

Evaluating the impacts of agricultural land management practices on water resources: A probabilistic hydrologic modeling approach

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ABSTRACT

Evaluating the effectiveness of agricultural land management practices in minimizing environmental impacts using models is challenged by the presence of inherent uncertainties during the model development stage. One issue faced during the model development stage is the uncertainty involved in model parameterization. Using a single optimized set of parameters (one snapshot) to represent baseline conditions of the system limits the applicability and robustness of the model to properly represent future or alternative scenarios. The objective of this study was to develop a framework that facilitates model parameter selection while evaluating uncertainty to assess the impacts of land management practices at the watershed scale. The model framework was applied to the Lake Creek watershed located in southwestern Oklahoma, USA. A two-step probabilistic approach was implemented to parameterize the Agricultural Policy/Environmental eXtender (APEX) model using global uncertainty and sensitivity analysis to estimate the full spectrum of total monthly water yield (WYLD) and total monthly Nitrogen loads (N) in the watershed under different land management practices. Twenty-seven models were found to represent the baseline scenario in which uncertainty of up to 29% and 400% in WYLD and N, respectively, is plausible. Changing the land cover to pasture manifested the highest decrease in N to up to 30% for a full pasture coverage while changing to full winter wheat cover can increase the N up to 11%. The methodology developed in this study was able to quantify the full spectrum of system responses, the uncertainty associated with them, and the most important parameters that drive their variability. Results from this study can be used to develop strategic decisions on the risks and tradeoffs associated with different management alternatives that aim to increase productivity while also minimizing their environmental impacts.

1. Introduction

Land management practices have been implemented in the United States for over 80 years to mitigate land degradation and environmental impacts of traditional agricultural practices (Richardson et al., 2008). The U.S. Department of Agriculture (USDA) has promoted the application of these practices like cover crops, riparian buffers, or no-tillage, and landowners receive financial incentives to implement them (Tomer and Locke, 2011). However, the actual environmental benefits of these practices, especially at watershed scale where the primary public benefit is observed, remain unknown (Richardson et al., 2008; Tomer and Locke, 2011). Some factors such as inaccessibility of privately owned agricultural lands for monitoring, the complexity linked to agro-production, the elevated cost of long-term data collection, and the difficulty to conduct physical experimentation at farm production scales, limit field testing of these land management practices at larger scales (Gassman et al., 2007). Experimentation at smaller scales, for instance, field or plot scale, and controlled conditions, are more accessible but results may not properly upscale with expected benefits at the watershed scales (Tomer and Locke, 2011).

A better understanding of land management practices impacts on water resources, including water quality, may also be assessed if the physical processes are understood and the possible water quality outcomes to alternative future scenarios can be reasonably predicted. This may be achieved through long-term monitoring and

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use of environmental models that can represent the responses of the system (Gassman et al., 2007; Starks et al., 2014a; Tomer and Locke, 2011). However, the development and use of environmental models (hydrologic and water quality) are accompanied by inherent uncertainties from different sources that can hinder the interpretation and use of the results. Uncertainty can be present in input data (climate data, elevation, land cover, soil, etc.), data processing (rainfall and runoff data aggregation and interpolation), model parameters, spatio-temporal discretization, and model structure (Guzman et al., 2015a) that can be propagated nonlinearly to the model outputs for example runoff, nutrient concentration, and sediment load.

Parameterization that involves calibration can introduce another layer of uncertainty in model outputs while trying to improve model performance metrics. Multiple acceptable parameter combinations for a set of model inputs may exist that can represent the observed watershed systemic behavior, that is, equifinality. Equifinality makes it difficult to determine whether or not the selected set of parameters is the most appropriate to represent the system response. However, Beven (2006) argued that evaluation of equifinality should be given serious consideration not because of the difficulty of identifying parameter values but as an indication of multiple functional hypotheses about how the system is working. In most cases, no a priori knowledge of the number of acceptable model outputs is available and thus outputs generated from a single optimized set of parameters are considered the “true” solution. Using an optimized model to represent baseline conditions of the system, limits the applicability and robustness of the model to properly represent future or alternative scenarios. This is especially critical when model results are used to evaluate the impacts of environmental decisions or to formulate new policies. It is crucial that the results are interpreted in light of the risk associated with model output uncertainty (Cariboni et al., 2007; Guzman et al., 2015a) in which long-term systemic responses are better understood if the full spectrum of system behavior is considered.

The objective of this study was to develop a framework that facilitates model parameterization, that is, the selection of parameters and their values, while evaluating uncertainty to assess the impacts of land management practices at the watershed scale. The model framework was applied to the Lake Creek watershed located in southwestern Oklahoma, USA. A two-step probabilistic approach was implemented to parameterize the Agricultural Policy/Environmental eXtender (APEX) model using global uncertainty and sensitivity analysis (GUSA). A baseline model, consisting of a family of APEX models, was derived and used to estimate the full spectrum of water yield (WYLD) and Nitrogen loads (N) in the watershed under different land management practices.

2. Materials and methods

2.1. Study area

The Lake Creek watershed is one of the three main subwatersheds that composed the Fort-Cobb Reservoir Experimental Watershed (FCREW) located in southwestern Oklahoma. It drains an approximate area of 154 km^2 towards the Fort-Cobb reservoir located near the main FCREW outlet (Fig. 1) (Guzman et al., 2015b). The FCREW region is mostly agricultural land composed of croplands and pastures. Soils are mostly fine silty loams of different erodibility (Steiner et al., 2008). The climate in southwestern Oklahoma is sub-humid with long and hot summers, and short and temperate winters. The mean daily temperature during summer is about 28 °C while in winter is 3 °C. The annual precipitation is approximately 800 mm with the largest monthly average at the end of spring (May–June) and beginning of fall (September–October) (Steiner et al., 2008).

The Fort-Cobb reservoir is an important source of public and domestic water supply. However, it has been added to the list of water bodies that do not meet the water quality standards as given in the Clean Water Act (Steiner et al., 2008). The agricultural practices in this watershed release nutrients, especially Nitrogen (N) and Phosphorus (P), to the surface streams that feed the Fort-Cobb reservoir resulting in eutrophication (Steiner et al., 2008). As a result, several agencies such the Oklahoma Water Resources Board, Oklahoma Department of Environmental Quality, and Oklahoma Conservation Commission recognized the FCREW as an experimental land to improve water quality through land conservation practices. In fact, several agronomic management practices have been adopted in the watershed such as no-tillage management, conversion of cropland to grassland, installation of fencing to exclude cattle from streams, and various structural and water management practices (Storm et al., 2006).

2.2. Model set-up

The Agricultural Policy/Environmental eXtender (APEX) model (Williams et al., 1995) is a conceptual and distributed hydrologic and environmental model. It simulates the different hydrologic processes at a watershed scale while evaluating the impacts of conservation and best management practices (Wang et al., 2012) on water quality. The primary inputs to the model are elevation, soil, land use, and time series of climate variables. The outputs of the model are time series of computed hydrologic variables, nutrients, and crop yields at different temporal resolutions (annual, monthly, and daily) and different spatial scales (subareas or watershed).

The main outputs of APEX used to evaluate the impacts of the land management practices were the WYLD and N. The WYLD (in mm) was computed in APEX model using the Soil Conservation Service (SCS) curve number (CN) equation (USDA-Soil Conservation Service, 1972) given as follows (Williams et al., 2012):

$$WYLD = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

where P is the daily rainfall (mm), and S is a retention parameter (mm). The parameter S implicitly depends on the curve number (CN) expressed as $S = 254(100/CN - 1)$.

The Nitrogen load (in kg/ha) was computed by accounting for the Nitrate lost when water flows through a layer. It was estimated as the change in Nitrogen concentration and was computed separately for surface runoff, lateral flow, quick return flow, and horizontal pipe flow (for drains) using the equation (Williams et al., 2012):

$$N = W\left(1 - e^{-\frac{Q_i}{kV}}\right) \tag{2}$$

where N is the amount of Nitrogen lost from a soil layer at the end of the day (kg/ha), W is the Nitrogen load contained in a layer at the beginning of the day (kg/ha), Q_i is the volume of water percolating through the layer, V is the storage volume occupied by percolating water, and k is the porosity. The Nitrogen load in the stream is the sum of the four components (surface runoff, lateral flow, quick return flow, and horizontal pipe flow).

In this study, the GIS interface for APEX (ArcAPEX) was used to build the model for the Lake Creek. This interface requires three different data layers: the Digital Elevation Model (DEM), soils, and land use. In addition, weather data (precipitation and