J. Resour. Ecol. 2014 5 (2) xxx-xxx
DOI:10.5814/j.issn.1674-764x.2014.02.XXX
www.jorae.cn

Article

Representation of Agricultural Best Management Practices in A Fully Distributed Hydrologic Model: A Case Study in the Luoyugou Watershed

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Abstract: Agricultural Best Management Practices (BMPs) are effective ways to reduce agricultural nonpoint source pollution from their source area to receiving water bodies. Characterization of BMPs in a watershed model is a critical prerequisite for evaluating their impacts on water quantity and water quality in a complex system. However, limited research has reported about the representation of BMPs in fully distributed models. This paper presents a stepwise procedure for representation of several BMPs and assessment of their hydrologic impacts with a fully distributed model, SEIM (Spatially Explicit Integrated Modeling). A case study is conducted in the 73 km^2 Luoyugou watershed located in the Loess Plateau of China, where rainstorm erosion accounts for more than 60% of annual sediment load in average. Three BMPs are selected in this study including (i) conversion from farmland to forest, (ii) terrace, and (iii) no-till farming. These management practices are represented in the model through the alteration of model parameters characterizing their physical processes in the field. The results of scenario assessment for a historical storm event showed that the maximum sediment reduction after terrace is about 97.3%, the average sediment reduction after no-till farming is about 9.5%, and the average sediment reduction after conversion from farmland to forest is75.6%.

Key words:best management practice; erosion; watershed model; representation of BMPs; SEIM

1 Introduction

Flooding, hillslope soil loss and stream bank erosion by storm events are critical land degradation problems and environmental hazards in agricultural watershed both in China and worldwide (Borah *et al*. 2004; Edwards and Owens 1991; Kang *et al*. 2001). Agricultural conservation practices, which often are called best management practices (BMPs)(Logan 1993), are effective ways to reduce erosion, nutrients, pesticides, animal waste, and other pollutant loadings from their source area to receiving water bodies within the complex processes. Watershed models that simplify and simulate these complex processes are useful analysis tools for BMPs assessment and providing an estimation of their impacts on soil erosion (Arabi *et al*. 2006). Therefore, characterization and representation of BMPs in watershed models are critical prerequisite for evaluation of soil and water conservation measures in a complex system (Arabi *et al*. 2008).

Generally, the representation of BMPs in watershed models can be classified into two ways. One is by modifying the model parameters to reflect the impacts of the practice on the processes simulated in the model, which is commonly used to represent agricultural BMPs in the SWAT model for long-term BMPs evaluation (Engel *et al*. 2006; Nejadhashemi *et al*. 2011; Tuppad *et al*. 2010). The other is through a BMP

Received: 2014-01-20 **Accepted:** 2014-04-08
Foundation: the Major Science and Technology Program for Water Pollution Control and Treatment (No. 2013ZX07103006-005) and the National Science and Technology Support Program (No. 2013BAC08B03-4).
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module, which provides a process-based simulation of flow and pollutant transport routing using a combination of fundamental algorithms to represent the BMPs. This approach was used in Lee's study for representation of BMPs in an urban watershed for stormwater management (Lee *et al*. 2012).

Intense single-event storms are significant when most of the yearly loads of sediment and pollutants are carried by storm floods, especially on Loess Plateau of China (Liu *et al*. 2012). In addition, due to the time scale of single-event storms, the model must enable to provide location-specific outputs and simulate the movement of water and sediment explicitly along flow paths. Therefore, fully distributed hydrologic models are preferable for an event-based evaluation of agricultural BMPs. However, limited research has reported about the representation of agricultural BMPs in the fully distributed models.

The aim of this paper is to illustrate a stepwise procedure for the representation of several BMPs and the assessment of their hydrologic impacts within a fully distributed model. A case study is conducted in Luoyugou watershed with about 73 km^2, located in Loess Plateau of China, where soil loss has been a critical environmental problem in the region. Three BMPs are selected in the case study including (i) conversion from farmland to forest, (ii) terrace, and (iii) no-till farming. They have been commonly used in the Luoyugou watershed for soil and water conservation. The model used here is the SEIM (Spatially Explicit Integrated Modelling) model (Liu *et al*. 2014), which is a modular-based, fully distributed hydrologic model. Two scenarios including a baseline scenario and a test scenario are evaluated with the model in a historical storm event, and compared with each other to investigate the impacts of the BMPs on infiltration, runoff and soil erosion after these practices implemented.

2 Material and methods

2.1 Study area

Luoyugou watershed is located in the north suburb of Tianshui City, Gansu Province in northwestern China. The watershed covers an area of approximately 73 km^2 with remarkable conditions of climate, terrain and soil erosion, and forms the boundary between the Longxi Loess Plateau hill-ravine region and the Longnan Mountains (see Fig.1). The gully system is feather-shaped and the length of the main channel is about 21.8 km. The watershed is characterized by high mountains and steep slopes with an average slope of 18°, Average annual temperature is around 10˚C, and annual precipitation is about 560mm. The representative storm events in the history were on July 7, 1965, August 7, 1988, and August 17, 1999, with maximum precipitation of 100, 116 and 151mm, respectively. Soil erosion caused by storm events accounts for more than 60% of annual sediment loading in average (Wang *et al*. 2008a). Soil types in the watershed are reclassified as sandy loam, silt loam and loamy sand soils. Land uses in the watershed are slope farmlands (68.8%), forest (10.7%), grass land (8.6%) and others. Intensive agricultural activities have seriously led to soil loss in the watershed.

2.2 SEIM model

SEIM is a grid-based, flexible, object-oriented, and parallelized fully distributed model (Liu *et al*. 2014). The assumptions of the model are: (i) a watershed can be divided into grid cells for which hydrological processes can be simulated to a level of detail desired; (ii) In each grid, land use and soil type are assumed homogeneous to represent the landscape in digital form; (iii) Each grid can be assigned with a 1-dimentional topography-based flow direction derived from the DEM. Compared to lumped and semi-distributed models, it provides location-specific outputs, and is suitable for various watershed management purposes. It can simulate major watershed processes including precipitation distribution, snowmelt, evapotranspiration, infiltration, surface runoff, subsurface runoff, groundwater recharge, soil water content, plant growth, soil erosion, nutrient cycle, and water and pollutant movement on land surface and in streams in a spatial explicit manner using process-based algorithms and at different time intervals (i.e. minutely, hourly, and daily). Thus, it has capabilities of both storm event and long term simulation. The model uses an object-oriented, modular-based structure to perform dynamic modeling routines supported by five databases including geographical, BMP,

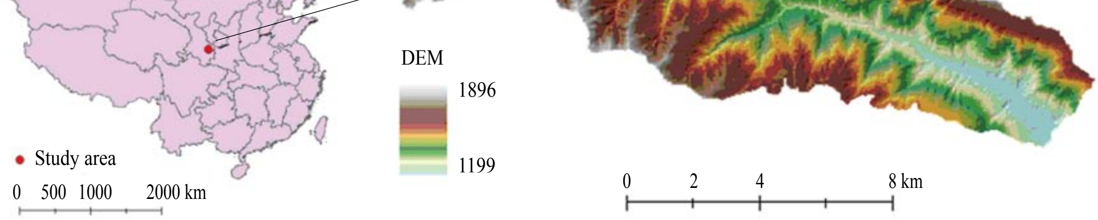

Fig. 1 Location and elevation maps for Luoyugou watershed.

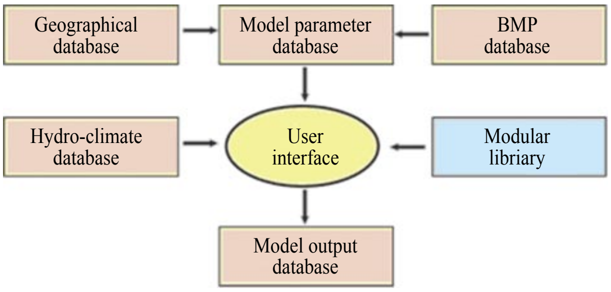

Fig. 2 Structure of the modeling system (SEIM).

parameter, hydrometeorological, modular, and output database (Fig. 2). It provides a framework for users to apply or develop new algorithms for specific purposes. Inputs to the model are geospatial data of DEM, soil, and land use, and climate data of precipitation and temperature, while outputs of the model are time series and spatial distribution of hydrologic variables at user defined location, spatial and time scales.

Table 1 lists the methods/algorithms selected for the model to simulate storm events hydrologic and erosion processes in the Luoyugou watershed. The method for interception process is the mass balance method taken from the WetSpa model (Liu and De Smedt 2004). The Green-Ampt method is used to simulate infiltration and surface runoff processes. The algorithm selected for overland flow, interflow and erosion processes is the one-dimensional kinematic wave method, which can simulate the movement of water and sediment explicitly along flow paths. Because of the fully distributed model structure, water and sediment could be trapped at the BMP sites on the way to streams.

2.3 Representation of BMPs

Process-based models should be used where hydrologic impacts of practices are evaluated based on their physical characteristics and spatial locations (Arabi *et al*. 2008). Accordingly, hydrologic and erosion processes that are affected by BMPs need to be identified for their representations in the model. The BMPs selected in this study include terrace, no-till farming and conversion from farmland to forest, which are typical management practices in hillslope farmlands. Implementation of terrace will result in a reduction of surface runoff and erosion by reducing slope and increasing infiltration. Implementation of no-till farming will influence the hydraulic properties of soils and the soil surface conditions, and therefore higher infiltration and lower surface runoff from rainfall and irrigation. Similarly, implementation of conversion from farmland to forest can result in a reduction of surface runoff and soil erosion by increasing infiltration capacity and surface roughness.

Representation of these three practices is implemented through the alteration of parameters characterizing their physical properties in the field. If a BMP is implemented in a field, the location (grids within the field) with altered parameters can be decided. The representation of BMPs for simulating hydrologic and erosion processes in the SEIM model for the Luoyugou watershed is listed in Table 2. For example, if the practice of terrace is implemented in a field, model parameters, such as hydraulic conductivity

Table 1 The processes and methods/algorithms.

Watershed processes	Methods/algorithms
Interception	Mass balance method
Infiltration/surface runoff	Green-Ampt method
Depression storage	Fill and spill method (Liu and De Smedt 2005)
Percolation	Modified Darcy Equation (Liu and De Smedt 2004)
Interflow	One-dimensional kinematic wave (OKW) method (Chow *et al*. 1988)
Overland flow	Same as the interflow
Erosion	Foster equation (Foster 1982) and OKW method (for routing)
Channel flow routing	Muskingum-Cunge method
Channel sediment routing	OKW method

Table 2 Representation of BMPs in the SEIM model for the Luoyugou watershed.

BMP types	Process	Parameters (at grids level)	Suggested value
No-till farming	Infiltration/surface runoff	Conductivity (mm h^{-1})	3 times of the original (Azooz and Arshad 1996)
	Overland flow	Manning's *n*	0.14
	Erosion	USLE_C	0.03
Conversion from farmland to forest	Infiltration/surface runoff	Conductivity (mm h^{-1})	5 times of the original (Yang *et al*. 2006)
	Overland flow	Manning's *n*	0.4
	Erosion	USLE_C	0.05
Terrace	Infiltration/Surface runoff	Conductivity (mm h^{-1})	10 times of the original (Wang *et al*. 2008b)
	Overland flow	Slope	0.001
		Manning's *n*	0.3
	Erosion	USLE_C	0.2

Note: the values of Manning's *n* and USLE_C were taken from SWAT document (Neitsch *et al*. 2005).

(infiltration related parameter), slope, Manning's roughness coefficient and USLE land cover factor (USLE_C) for all grids within the field will be changed. The suggested parameter value in Table 2 is obtained from previous studies. The parameter value can also be obtained from prior experience in the study area, or model calibration if field measurement data are available.

2.4 Model calibration and scenario assessment

A historical storm event on August 7, 1988 was selected to test the model for BMPs simulation. This storm event is selected because it is representative in the region after a historical data analysis. In addition, data of land use, hourly precipitation, and observed flow and sediment loading are available for the model input. The total precipitation is 116 mm from 3 p.m. to 12 p.m. which had caused serious soil erosion in the watershed. The time step in the model simulation is 1 minute. The Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe 1970) was used in the model calibration. The equation for calculating Nash-Sutcliffe efficiency coefficient (ENS) can be written as:

$$ENS = 1 - \frac{\sum_{1}^{n}(O_i - P_i)^2}{\sum_{1}^{n}(O_i - \bar{O})^2} \quad (1)$$

where, O_i is the observed value on day i, P_i is the simulation value, and $\bar{O}$ is the mean of observed values.

After calibration for the baseline scenario, the spatial distribution of infiltration, runoff and erosion (a raster map) can be obtained for the storm event in the Luoyugou watershed. A test scenario then was created by implementing the three BMPs into three separate fields (see Fig. 3). The three representative fields with high erosion rates were created based on the land use map and slope map with land use of crop land and slope higher than 15°. Afterwards, the test scenario was evaluated with the model to obtain the spatial distribution of infiltration, runoff, and erosion for the storm event after implementing the three BMPs. Ideally, implementation of a BMP in the field would result in an increase of infiltration and reduction of surface runoff and erosion. Thus, reduction rate was used in this study to represent the effects of BMPs for different scenarios. The reduction rate was calculated by the baseline results subtracted by the test scenario results, and then divided by the baseline scenario results. Note that the reduction of infiltration is negative, meaning an increase of infiltration rate. Lastly, ArcGIS software was used to calculate the reduction (increase) rate using spatial analysis tools.

3 Results and discussion

After calibration, the Nash-Sutcliffe efficiency coefficient in the simulation period was 0.894 and 0.875 for flow and sediment, respectively. This indicates that simulation for stream flow and sediment is pretty good. Fig. 4 shows the distribution of infiltration increase, runoff reduction and sediment reduction after the implementation of three BMPs in the three fields.

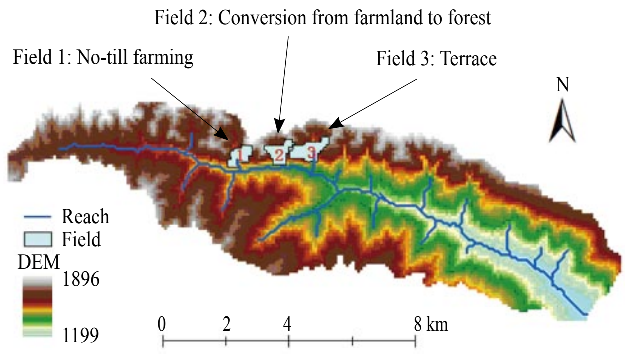

Fig. 3 Location of the three BMPs implemented.

Fig. 4(a) shows the spatial distribution of infiltration increase after the three BMPs implemented. Infiltration increase in Field 3 (68.3% in average) is much higher than that in other two fields (9.1% in Field 1, and 34% in Field 2) as a result of terrace practice in this field. Terrace is the most effective practices of the three BMPs on infiltration increase, because storm water is trapped by the terrace leading to an increase of retention duration and infiltration rate. Fig. 4(a) also indicates that conversion from farmland to forest is more effective than no-till farming on infiltration increase. This result is reasonable that the infiltration rate commonly higher in forest land than in farmland on the loess plateau of China (Liu and Huang 2003).

The spatial distribution of runoff reduction in the three fields is showed in Fig. 4(b). After the implementation of three BMPs, the surface runoff reduction in Field 2 (22.4% in average) and Field 3 (20.6% in average) is much higher than that in Field 1 (7.1% in average). This indicates that, compared with terrace, conversion from farmland to forest could be a more suitable practice in this study area to reduce runoff. No-till farming is limited in runoff reduction in this study area for the test storm event. The simulated maximum runoff reduction of no-till farming in Filed 1 is about 8.3%. This result is close to Lv's study (Lv2003).

The spatial distribution of sediment reduction in the three fields is displayed in Fig. 4(c). The sediment reduction in Field 3 (92.7% in average), much higher than that in other two fields, indicates that terrace might be the most effective practice of the three practices for decreasing erosion in the Luoyugou watershed. The average simulated sediment reduction of no-till farming is about 9.5% in Field 1, and the average simulated sediment reduction after conversion from farmland to forest is 75.6% in Field 2. The simulated maximum sediment reduction of terrace in Filed 3 is about 97.3% for this storm event. This result is close to Wu's study (Wu *et al.* 2004).

In addition, the spatial pattern of infiltration increase, runoff reduction and sediment reduction within each field

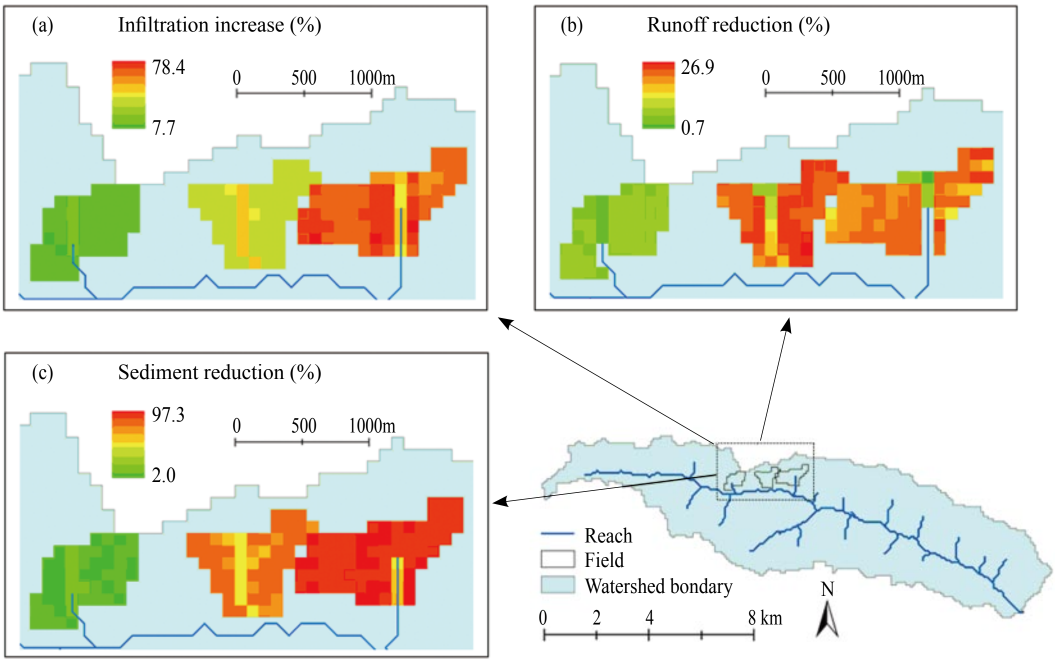

Fig. 4 Distribution of infiltration increase, runoff reduction and sediment reduction after BMPs implemented.

after BMPs implementation was also provided by SEIM model as shown in Fig. 4, while in previous studies a lumped value for the field was estimated. This is a key advantage for BMPs assessment by using a fully distributed model. The reason for such spatial pattern of infiltration increase, runoff reduction and sediment reduction within the fields is rather complex associated with different management practices, land use, topography, and soil types. Further field and modeling studies are required to identify the main reason for the spatial pattern.

Due to the lack of observation data for BMPs in the study area, model validation was not conducted in this study. However, a comparison with previous studies in the same watershed can be a valuable reference for model validation. Besides, some additional parameters, such as practice factor, needed to be added in the representation of BMPs for calibrating the impacts on soil erosion. Future studies shall focus on the identification of appropriate spatial and temporal scales for representation of BMPs on soil erosion, and the assessment of model's sensitivity and uncertainty on the evaluation of BMPs.

4 Conclusion

This paper provides an approach for the representation of three agricultural BMPs including conversion from farmland to forestland, terrace, and no-till farming for soil and water conservation in a fully distributed model. The result of Luoyugou case study indicated that the BMPs parameters used for Luoyugou watershed are acceptable compared with the modelling results from previous studies. In addition, the spatial pattern of infiltration increase, runoff reduction and sediment reduction within each field after BMPs implementation was also provided by the model. This is important information for decision making of BMPs placement at watershed scale. The recommended BMP parameter values were acceptable Luoyugou watershed or watersheds with similar hydrologic and climate characteristics. For watersheds with distinct different climate and landscape conditions, these parameter values could be different significantly. By the proposed approach, other BMPs, such as filter strips, riparian buffers, and sediment deposition ponds could also be represented and evaluated by using a fully distributed model.

The field validation of the model was not conducted for BMPs simulation in this study, because of the lack of field observation data. This is a limitation for spatial validation of fully distributed models, which might result in a high uncertainty of the modelling result in terms of spatial distribution. To limit this uncertainty, information of previous studies, literature, prior experience, and particularly field measurement are essential for validating the model. Besides, additional parameters, such as various land practice factors, need to be accounted for in the model to represent the impact of BMPs appropriately on runoff and soil erosion. Future studies shall focus on the identification of appropriate spatial and temporal scales of the model for representing and evaluating BMP's effect on erosion, and the assessment of sensitivity and uncertainty of the model on the BMP evaluation results.

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农业最佳管理措施在全分布式水文模型中的表达——以罗玉沟流域为例

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摘　要：农业最佳管理措施（BMPs）是为了减少由农业活动引起的非点源污染，防止污染物进入受纳水体的一系列措施。分布式水文模型是流域非点源污染模拟和BMPs评估的重要工具。利用分布式水文模型评估BMPs在水土保持、拦沙减污的有效性，首先要在模型中对BMPs进行刻画和表达。但是，在全分布式水文模型中，如何进行BMPs表达的研究比较缺乏。本文以黄土高原丘陵沟壑区典型小流域罗玉沟流域为例，基于一个全分布式模型，SEIM（Spatially Explicit Integrated Modeling）模型，逐步介绍如何在该模型中进行BMPs的表达，以及评估它们的水文响应。罗玉沟流域面积约为73km^2，流域内侵蚀严重，其中暴雨侵蚀占平均年输沙量的60％以上。本研究选择了3种BMPs，分别是退耕还林、梯田和免耕耕作，并在模型中对这些管理措施进行表达。措施表达的方法是通过修改该措施所在地块的主要物理参数，以此来描述其对流域水文过程的影响。通过在一个暴雨事件的情景模拟，结果表明梯田的减沙效益较高，最大到达97.3%，免耕措施的平均减沙率最小，约为9.5%，退耕还林的平均减沙率介于这两者之间，为75.6%。

关键词：最佳管理措施；土壤侵蚀；流域模型；BMPs的表达；SEIM