Journal of Hydrology 517 (2014) 1008–1018

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Use of Fuzzy rainfall–runoff predictions for claypan watersheds with conservation buffers in Northeast Missouri

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ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form 12 May 2014
Accepted 16 June 2014
Available online 1 July 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Fi-John Chang, Associate Editor

Keywords:
Agroforestry buffers
Contour upland grass buffers
Fuzzy logic
Genetic algorithm
Field-scale watersheds
Membership function optimization

SUMMARY

Fuzzy rainfall–runoff models are often used to forecast flood or water supply in large catchments and applications at small/field scale agricultural watersheds are limited. The study objectives were to develop, calibrate, and validate a fuzzy rainfall–runoff model using long-term data of three adjacent field scale row crop watersheds (1.65–4.44 ha) with intermittent discharge in the claypan soils of Northeast Missouri. The watersheds were monitored for a six-year calibration period starting 1991 (pre-buffer period). Thereafter, two of them were treated with upland contour grass and agroforestry (tree + grass) buffers (4.5 m wide, 36.5 m apart) to study water quality benefits. The fuzzy system was based on Mamdani method using MATLAB 7.10.0. The model predicted event-based runoff with model performance coefficients of r^2 and Nash–Sutcliffe Coefficient (NSC) values greater than 0.65 for calibration and validation. The pre-buffer fuzzy system predicted event-based runoff for 30–50 times larger corn/soybean watersheds with r^2 values of 0.82 and 0.68 and NSC values of 0.77 and 0.53, respectively. The runoff predicted by the fuzzy system closely agreed with values predicted by physically-based Agricultural Policy Environmental eXtender model (APEX) for the pre-buffer watersheds. The fuzzy rainfall–runoff model has the potential for runoff predictions at field-scale watersheds with minimum input. It also could up-scale the predictions for large-scale watersheds to evaluate the benefits of conservation practices.

1. Introduction

Estimation of surface runoff is fundamental for predicting sediment and pollutant transport, and mitigation of contaminants from agricultural watersheds (Yu and Yang, 2000; Tayfur and Singh, 2006). Numerous physically-based models have long been employed to model surface flow from watersheds in water quality studies. These models permit calculation of temporal and spatial variations of flow and velocity over land surfaces, which are important for erosion, sediment and solute transport evaluations (Tayfur and Singh, 2006). Physically-based models are process driven and mimic the system and its behavior in a physically realistic manner (Lohani et al., 2010). Despite numerous benefits of physically-based models, they require large amount of site specific data for parameterization and significant time for construction (Tayfur et al., 2003). The drawbacks in physically-based models have led to the search for alternative methods of estimating runoff when detailed modeling is not required or detailed data are not available.

Over the past decade, artificial intelligence (AI) techniques such as artificial neural networks (ANN) and fuzzy logic (FL; Zadeh, 1965) algorithms, which mimic human perception, learning, and reasoning to solve complex problems, have increasingly become popular in rainfall–runoff modeling. The ANN technique has been used for rainfall–runoff modeling (Shamseldin, 1997), flood forecasting (Dawson and Wilby, 1998; Rajurkar et al., 2002) and monthly river flow prediction (Tokar and Markus, 2000).

In classical hydrologic modeling, there is no facility to include expert understanding of hydrological processes in linguistic form.

Abbreviations: AGF, agroforestry; APEX, Agricultural Policy Environmental eXtender model; CGS, contour grass strips; FR, fuzzy rules; FL SYSTEM, fuzzy logic system; GA, genetic algorithm; MF, membership functions; NSC, Nash–Sutcliffe coefficient; Pbias, percent bias.

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http://dx.doi.org/10.1016/j.jhydrol.2014.06.023
0022-1694/

Data driven fuzzy inference systems (FIS; Mamdani, 1974) based on fuzzy set theory (Zadeh, 1965) offers a unique way to incorporate such expert understanding into the internal structure of modeling through fuzzy sets. Other advantages of the FIS include the ability to account for uncertainty of environmental variables, a relatively simple approach applicable to complex systems, the robustness of the system due to the ability to account for imprecise and incomplete input data and results that are readily interpretable and communicable (Openshaw and Openshaw, 1997).

Fuzzy logic models have been applied to simulate river discharges (Hundecha et al., 2001), predict runoff (Xiong et al., 2001; Sen and Altunkaynak, 2005; Jacquin and Shamseldin, 2006; Lohani et al., 2010), and forecast water supply from snow melt (Mahabir et al., 2003). Hybrid systems such as neuro-fuzzy systems combine ANN and fuzzy systems to compensate for weaknesses in individual systems. Aqil et al. (2007) used ANN to optimize parameters of Takagi–Sugeno rule-base of a neuro-fuzzy model and compared the performance of it with two other ANN models to predict the flow of the Cilalawi River in Indonesia. The neuro-fuzzy model has outperformed the other ANN models. A fuzzy expert model for estimating the index water yield and index flow (the index flow is the median flow for the lowest flow month of the flow regime) of ungauged streams in Michigan was also reported as the most robust method among other models tested: multiple linear regression, fuzzy regression, and adaptive neuro-fuzzy inference models (Hamaamin et al., 2013).

Non-point source pollution from agricultural watersheds is a major problem of claypan soils in the Midwestern U.S. Claypan soils is distributed over 3 * 10^6-ha area in Missouri, Illinois, and Kansas states in U.S. and majority of the area are under agriculture with row-crop or pasture (Jamison et al., 1968). A claypan is an impermeable layer within the 0.1–0.5-m depth with an abrupt increase in clay content (75–100% increase) over the above layer and consists of smectitic clays (with 350–600-g kg^{-1} clay content; Miles and Hammer, 1989). The textural class of the clay pan soils belongs to silty clay or clay (Blevins et al., 1996). Blanco-Canqui et al. (2002) found that the argillic horizon of Missouri soils acts as a barrier to the vertical flow of water and enhances lateral flow through the shallow topsoil layer. The saturated hydraulic conductivity (K_{sat}) of the claypan horizon was very low (0.002 mm h^{-1}) relative to that of the surface horizons (70 mm h^{-1}) under pasture management (Blanco-Canqui et al., 2002), Mudgal et al. (2010) also reported similar K_{sat} values for the claypan horizon with lower permeabilities for the surface layers of a crop field. Therefore, the existence of a perched water table and ponded conditions are common for these soils. These characteristics of claypan soils contribute to excessive runoff and pollutant loadings from agricultural watersheds during large precipitation events (Blevins et al., 1996; Blanchard and Donald, 1997; Blanco-Canqui et al., 2002). Comprehensive, long-term hydrologic data sets for watershed systems are valuable for model development, calibration, and validation; and for assessment of change over time. Senaviratne et al. (2013) used a long-term data set from three adjacent row-crop watersheds in the claypan region of Northeast Missouri for the model assessment by a physically-based distributed hydrological model, the Agricultural Policy Environmental eXtender (APEX; Williams et al., 1998). They successfully parameterized the model to simulate the claypan watersheds to predict event-based runoff with r^2 and Nash–Sutcliffe Coefficient (NSC) values ranging between 0.86–0.88 and 0.71–0.87, respectively.

Most of the fuzzy rainfall–runoff applications have been developed for forecasting flood or river flow discharge over large catchments using continuous stream flow data. Tayfur and Singh (2006) developed a FL system to predict rainfall–runoff peak discharge hydrographs based on measured event data from laboratory flume and experimental plots. They found that the developed FL model satisfactorily predicted peak-discharge hydrographs of a large watershed with an area of 8.4 km^2 s and the predictions were comparable with those of a physically-based kinematic wave approximation (KWA) model for the same watershed.

Application of FL logic model to estimate runoff volumes at field-scale watersheds with intermittent discharges are not reported earlier. However, most of the experimental studies for assessing the effectiveness of conservation practices on water quality are being conducted at field-scale. A FL model calibrated for a watershed with conservation practices could be a useful tool to predict the environmental benefits of such conservation practices on other watersheds even with the absence of physical details. The goals of this study were to (1) develop, calibrate, and validate a FL system to predict long-term event-based runoff using event-based rainfall from three adjacent field scale corn-soybean (*Zea mays* L. – *Glycine max* L.) watersheds before and after the establishment of upland vegetative buffers in the claypan soils of Northeast Missouri, (2) compare the model performance with results of Agricultural Policy eXtender model (APEX) model from a previous study (Senaviratne et al., 2013) for the same watersheds, and (3) use the model to simulate runoff of two large watersheds.

2. Study watersheds

The rainfall–runoff data for the study were obtained from three adjacent field-scale watersheds with catchment areas of 1.65 ha (East), 4.44 ha (Center) and 3.16 ha (West), established in early 1991 at the University of Missouri Greenley Memorial Research Center in Knox County in the claypan region of Missouri, USA (40°01N, 92°11′W; Fig. 1a; Udawatta et al., 2002). The three watersheds had grass waterways (swales) and were monitored for a 6-year period prior to the establishment of the main treatments in two of the watersheds: upland contour agroforestry (trees + grass) and grass buffers. In 1997, 4.5 m [15 ft.] wide contour grass–legume strips (CGS) consisting of redtop (*Agrostis gigantean* Roth), brome grass (*Bromus* spp.) and birdsfoot trefoil (*Lotus corniculatus* L.) were established at 36.5 m apart (at lower slope positions 22.8 m) in the West and Center watersheds (Udawatta et al., 2011). Along the center of the grass strips, a tree line of pin oaks (*Quercus palustris* Muenchh.), swamp white oaks (*Q. bicolor* Willd.) and bur oaks (*Q. macrocarpa* Michx.) were planted alternately at 3 m intervals to establish the agroforestry buffers (AGF) in the Center watershed. The East watershed was maintained as the control. Each watershed's grass waterway leads to a concrete approach structure and an H-flume to measure the flow rate using ISCO (Lincoln, NE, USA) bubbler flow measuring devices for each storm event. Mean annual rainfall (30 year) in the region is 920 mm $year^{-1}$ and 66% of it falls from April to September (Owenby and Ezell, 1992). The 1, 5 and 100 year 24-h storms for the nearby station of Kirksville are 74, 108, and 205 mm (http://hdsc.nws.noaa.gov/hdsc/pfds/index.html). Daily rainfall data were obtained from the Novelty weather station (http://agebb.missouri.edu/) located within 500 m of the watersheds.

Two large watersheds located close to the Greenley Research Center with similar soils, slopes and management were used to test the FL system predictions for larger scale watersheds. The large watersheds 300 (140 ha) and 301 (259 ha) are located in the Long Branch Watershed in Macon and Adair Counties Missouri, USA. (39°50′N to 40°05′N and 90°32′W to 92°20′W; Fig. 1b; Udawatta et al., 2006). Land-use details of these watersheds are listed in Table 1 and further description can be found in Udawatta et al. (2006).

3. Soils

Major soils of the watersheds at the Greenley Memorial Research Center are Putnam silt loam (fine, smectitic, mesic Vertic