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Prediction of Saturated Hydraulic Conductivity Dynamics in an Iowan Agriculture Watershed

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***Abstract*—**In this study, a physically-based, modeling framework was developed to predict saturated hydraulic conductivity (K_{sat}) dynamics in the Clear Creek Watershed (CCW), Iowa. The modeling framework integrated selected pedotransfer functions and watershed models with geospatial tools. A number of pedotransfer functions and agricultural watershed models were examined to select the appropriate models that represent the study site conditions. Models selection was based on statistical measures of the models' errors compared to the K_{sat} field measurements conducted in the CCW under different soil, climate and land use conditions. The study has shown that the predictions of the combined pedotransfer function of Rosetta and the Water Erosion Prediction Project (WEPP) provided the best agreement to the measured K_{sat} values in the CCW compared to the other tested models. Therefore, Rosetta and WEPP were integrated with the Geographic Information System (GIS) tools for visualization of the data in forms of geospatial maps and prediction of K_{sat} variability in CCW due to the seasonal changes in climate and land use activities.

***Keywords*—**Saturated hydraulic conductivity, pedotransfer functions, watershed models, geospatial tools.

I. Introduction

WHEN infiltration rate into soil reaches a steady state condition, it is defined in the literature as the saturated hydraulic conductivity, also known as K_{sat} [1]. K_{sat} directly influences the amount of runoff and eroded surface soil that are delivered to local waterways, thereby affecting both in-field soil and in-stream water quality [2], [3]. K_{sat} is also one of the key input variables for the majority of the physically-based watershed models used for the assessment of the impacts of the land uses and management practices on the dynamic behavior of soil and water [4]. Therefore, accurate estimate of K_{sat} and its statistical properties is of paramount importance for predicting hydrologically-driven processes and making catena assessments in landscapes [5], [6].

K_{sat} exhibits large nonlinear spatial and temporal variability at both large and small scales due to various combinations of the intrinsic soil properties (e.g., texture, bulk density) and extrinsic factors such as land use, vegetation cover, and precipitation [7].

Spatial variability of K_{sat} due to regional differences is controlled by intrinsic soil properties, while the added seasonal variability of K_{sat} within a region is due to the extrinsic factors [8].

The main objective of the proposed study was to introduce an integrative modeling method to make adequate predictions of K_{sat} under different intrinsic and extrinsic factors at scales where management and policy decisions must be made (e.g., watershed, township, county, state, etc.). A geospatial-physically based, modeling framework was developed within which geographic, climatic, and land uses data can be incorporated. The model integrated pedotransfer functions (PTFs) and watershed models (WSMs) along with the Geographic Information System (GIS) tools to predict K_{sat} as a function of some intrinsic soil properties and extrinsic factors. The ultimate goal of this study was to utilize the proposed modeling framework in the Clear Creek Watershed (CCW), Iowa by adapting it to site-specific parameters. The model predicted K_{sat} dynamics in a subwatershed of the CCW due to the seasonal changes in climate and land use activities. The study incorporated also selective field measurements for models calibration.

II. Modeling Framework Development

A physically-based, modeling framework within which different geographic, climatic, and land uses data can be incorporated was developed by integrating selected PTFs and WSMs with the Geographic Information System (GIS) tools to predict K_{sat} dynamics. Selection of the appropriate PTFs and WSMs that provide consistent predictions with the field measurements was based on statistical criteria. The predictions of the integrated models were compared to the field measurements at selected locations in the CCW.

A. K_{sat} Models

The predicted K_{sat} from the PTFs is defined as the baseline saturated hydraulic conductivity. The main assumption underlying most PTFs is that textural properties dominate the hydraulic behavior of soils [9], [10].

WSMs that account for extrinsic factors [4] typically adjust the values obtained from the PTFs, for variables such as vegetation cover, land use, management practices, and precipitation. The main assumption underlying most of the WSMs is that extrinsic factors can alter K_{sat} values for soils exhibiting the same surface texture [4], [11].

B. Models Selection

The first step towards developing the modeling framework was the selection of the appropriate models that represent the study site conditions [12]. The models were examined against the field data collected from previous studies [13]. The

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accuracy (the deviation between observed and predicted values) of a number of PTFs and WSMs was examined through statistical measures of the models' errors [14]. Standard criteria such as the root mean square error (*RMSE*) and Akaike Information Criterion (AIC) were considered in this study to evaluate each model's performance [15], [16]. Both the RMSE and AIC are negatively-oriented scores that range from 0 to ∞. The lower their values, the closer the agreement between the predicted and measured values is. The geometric mean error ratio (GMER) and the geometric standard deviation of the error ratio (GSDER) were also considered in the evaluation to account for the log-tailed distribution of K_{sat} [12], [17]. The predicted values are overestimated if GMER > 1.0 and underestimated if GMER < 1.0. Perfect agreement between the predicted the measured values is obtained when the GSDER = 1.0.

Table I summarizes the performance of the PTFs and WSMs. The overall performance of the PTFs and WSMs were evaluated using the following scoring rule: one point was assigned for each criterion shown in Table I to give a total of seven points. The scores were relative on a linear scale and based on the close agreement between the measured and predicted values. The score for the different examined PTFs and WSMs are given in Table I along with the total score. The last column in the table shows the overall performance in percentage. The table shows that Rosetta and WEPP predictions provided the best agreement to the measured K_{sat} values in the CCW.

TABLE I
PTFS AND WSMS PERFORMANCE

	Criterion* / Author	Mode	Min.	Max.	AIC	RMSE	GMER	GSDER	Total	Ω (%)
PTF	[18]	0.8	0.82	0.18	0.85	0.89	0.6	0.71	4.85	69
	[19]	0.87	0.98	0.42	0.54	0.68	0.36	0.71	4.56	65
	[20]	0.85	0.97	0.4	0.51	0.66	0.39	0.72	4.5	64
	[21]	0.32	0.72	0.23	0.96	0.95	0.89	0.86	4.93	70
	[22]	0.02	0.02	0.37	0.35	0.47	0.02	0.14	1.40	20
	[23]	0.73	0.94	0.08	0.21	0.15	0.1	0.65	2.86	41
	[24]	0.51	0.68	0.37	0.93	0.93	0.83	0.78	5.03	72
	[25]	0.74	0.91	0.03	0.12	0.1	0.02	0.53	2.45	35
	[9]	0.85	0.92	0.12	0.33	0.42	0.09	0.5	3.23	46
	[26]	0.83	0.91	0.42	0.66	0.81	0.61	0.55	4.79	68
	Rosetta BD [27]	0.59	0.83	0.79	0.79	0.91	0.93	0.76	5.6	**80**
	Rosetta [27]	0.91	0.72	0.17	0.73	0.88	0.67	0.78	4.86	69
WSM	KINEROS [11]	0.67	0.53	0.18	0.88	0.88	0.58	0.69	4.41	63
	WEPP [4]	0.86	0.98	0.38	0.99	0.97	0.92	0.84	5.94	**85**
	CAESAR [28]	0.35	0.89	0.28	0.88	0.88	0.58	0.69	4.55	65

*AIC = the Akaike Information Criterion, RMSE = the root mean square error, GMER = the geometric mean error ratio, GSDER = the geometric standard deviation of the error ratio, Ω = the overall performance in percentage, BD = the bulk density.

C. Models Integration

Rosetta and WEPP were integrated with the GIS tools to develop a physically-based, modeling framework within which different geographic, climatic, and land use data can be incorporated. ArcGIS, developed by the Environmental Systems Research Institute (ESRI), Redlands, CA, was used for graphical representation of the models outputs. The modeling framework allowed for visualization of the data in forms of geospatial maps for the prediction of K_{sat} dynamics.

Geospatial data for both Rosetta and WEPP models were obtained from open-access Internet sources. An algorithm was developed to facilitate the compilation of different geospatially distributed data from registries of the data and computational resources of the models into the ArcGIS interface. The data were downloaded, transmitted to the computational resources of the models, and converted with the developed code into a format that can be implemented into ArcGIS [29]. ArcMap, a subcomponent of ArcGIS, was used to convert the soil vector maps into raster maps, develop maps for different variables describing the models, and convert the raster maps into data points for statistical analysis.

III. MODEL IMPLEMENTATION

A. Study Site

Model implementation and infiltration measurements were conducted in a representative watershed in southeastern Iowa, namely the South Amana Subwatershed (SAS) in the Clear Creek Watershed (CCW), Iowa (Fig. 1). The SAS is located in the northwest corner of the CCW and encompasses approximately 10% of the total CCW drainage area, which is about 270 km^2. The SAS has two sub-basins, both containing first order tributaries. The average slope is 4% with a range that varies from 1% to 10%.

There are four main soil series mapped across the SAS [30] comprising approximately 80% of the total acreage. The uplands are comprised of the Tama series, which is the most prominent in the southern sub-basin, and the Downs series, which is prominent in the northern subbasin. Both soils are well-drained and are formed from Peorian loess. They are considered, respectively, the end members of a prairie-forest biosequence. Floodplains are comprised of mostly Ely and Colo soil series. These soils are derived from alluvium. The Ely and Colo soils are poorly drained.

Currently in the SAS, there are nine main land uses. Six of the land uses represent various corn-soybean rotations. Each rotation involves a unique set of the following management practices: no-till, reduced spring tillage and conventional fall tillage with secondary tillage in the spring. Three of these rotations encompass over 80% of the watershed acreage. Hay farming, pastures, and fields enrolled in the Conservation Reserve Program are the remaining land uses. The growing season lasts about 180 days in Southeast Iowa.

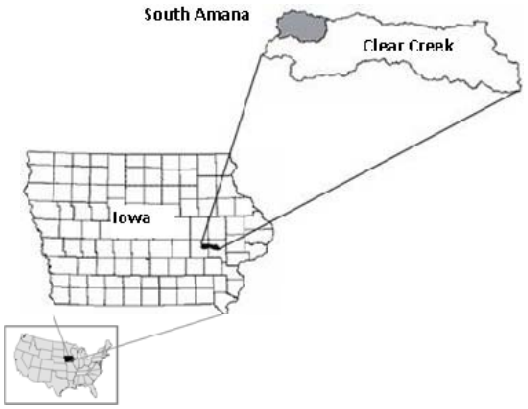

Fig. 1 The Clear Creek Watershed and the South Amana Subwatershed, Iowa

Due to the mid-continental location of Iowa, the SAS climate is characterized by hot summers, cold winters, and wet springs [31]. Summer months are influenced by warm, humid air masses from the Gulf of Mexico, while dry Canadian air masses dominate the winter months. Average daily temperature is about 10ºC, ranging from an average July maximum of 29ºC to an average January minimum of -13ºC. Average annual precipitation is approximately 889mm/yr with convective thunderstorms prominent in the summer, and snowfall in the winter, which averages 762mm annually.

B. Input Variables

Soil, land use, and precipitation data were collected from different databases as inputs for Rosetta and WEPP. The soil data were obtained from the Soil Survey Geographic (SSURGO) databases of the Iowa Department of Natural Resources (IDNR). The databases provide information regarding the soil series, major soil area, taxonomic classification (order and suborder), hydrological group, soil textures, surface and subsurface bulk density, organic matter, cation exchange capacity, and soil pH. The soil information obtained from the SSURGO database was confirmed via the soil cores collected from the South Amana Subwatershed (SAS). About 85% of the soil pedons classified as the same series identified in the published soil survey databases.

Detailed maps of land uses and management practices of the SAS were obtained from IDNR. The land use maps of 2002, which is the latest survey conducted by the IDNR, was used as input for the models. There were insignificant changes in the current land uses in the SAS, when compared to the IDNR maps of 2002. The extensive management practices database of the WEPP model was used to estimate the random roughness based on the IDNR inventory.

The precipitation depth and intensity were obtained from the Iowa Environmental Mesonet (IEM) of the Department of Agronomy at the Iowa State University. The rainfall radar data obtained from the IEM was compared to the tipping bucket data from different stations of the National Climate Data Center (NCDC) in the SAS. The deviation between the radar and tipping bucket data was less than 10%.

C. K_{sat} Dynamic Maps

The collected data from the databases were incorporated into Rosetta and WEPP, and imported as layered information into ArcGIS to generate K_{sat} dynamic maps for the SAS (Fig. 2). As can seen from the figure, the models predicted the seasonal variation of K_{sat} in the SAS showing low K_{sat} values in the winter, moderate values in the spring and autumn seasons, and high values in summer. These trends were expected because the change in vegetation cover and rainfall intensity are believed to affect K_{sat} considerably.

IV. Summary

The proposed modeling framework was able to successfully capture the spatial and temporal variability of K_{sat} of the South Amana Subwatershed (SAS). Among the tested K_{sat} models, Rosetta and WEPP predictions provided the best agreement to the measured values in the SAS. Therefore, Rosetta and WEPP were integrated with the Geographic Information System (GIS) tools to develop K_{sat} dynamic maps for the SAS. The developed maps of the SAS showed seasonal variation in K_{sat} values due to change in the vegetation cover and rainfall intensity.

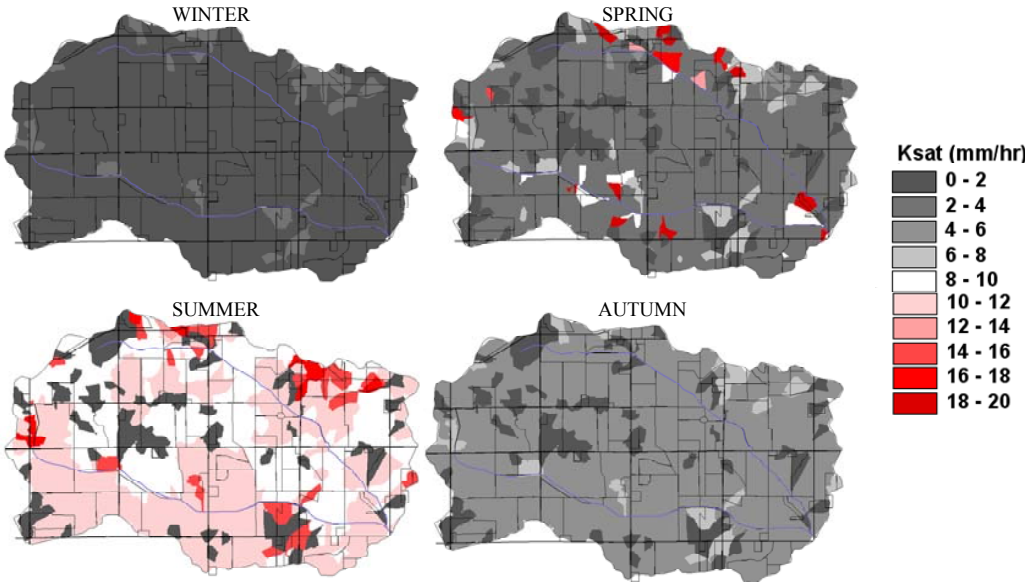

Fig. 2 Seasonal variation of K_{sat} in the SAS, IA

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