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Watershed models for assessment of hydrological behavior of the catchments: a comparative study

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Abstract

Hydrological parameters like overland flow, soil loss and nutrient losses can be studied by using different watershed models. However, all these models vary significantly in their analysis of parameters, input and output flexibility, scale accountability, processing ability, computational efficiency and capability of modeling the changes in catchments. This paper reviews different watershed models used for analyzing overland flow, soil loss and sediment yield with their shortcomings and strengths. These watershed models are described briefly along with their capabilities and shortcomings with their examples of applications, results and comparisons. An outcome of these discussions is presented in tabular format as a screening tool to allow the researchers and decision makers to choose the appropriate watershed model for the specific purpose.

Key words: hydrological parameters, nutrient losses, overland flow, soil loss, watershed modeling

INTRODUCTION

Soil loss is a grave issue due to its severe effects on economic productivity and environmental consequences leading to land disintegration. Studies show that 2–15 million hectares of total cultivable land are affected every year due to soil erosion, making it incongruous for any kind of productivity (Den Biggelaar *et al.* 2004). Soil disintegration is mostly influenced by normal variables; for example, atmosphere, soil, geography, vegetation and anthropogenic exercises, for example, soil protection measures furthermore, culturing frameworks (Kuznetsov *et al.* 1998).

Watershed behavior and hydrologic cycle are to be wholly examined so as to discover the variability in environmental and economic conditions. The reliable prediction of the various hydrological parameters becomes tedious and time consuming by conventional methods. Currently, many hydrological models have been developed over the world to determine and analyze the effect of land use, climatic conditions and soil characteristics on hydrology. Each watershed model has got its own attributes to carry out the different processes and capability to analyze the parameters. The data utilized by these different and diverse models are precipitation, air temperature, soil properties, geology, vegetation cover, hydrogeology and other physical parameters. Improved comprehension of how each of these elements affect water chemistry and quality requires improved capacities to comprehend fundamental procedures and their influence on water accessibility and use. This involves utilizing all encompassing methodologies which coordinate hydrologic forms at the watershed scale to decide a general watershed reaction to changing atmosphere (Singh & Woolhiser 2002).

TYPES OF MODELS

Based on the applications of watershed models in analyzing physical parameters, the simulation processes and algorithm, models are primarily classified in three categories named empirical models, conceptual models, and physically based models. Experimental models rely on actual observations and characterizing different data responses with less computational necessities (Wheater *et al.* 1993). The conceptual model represents a catchment as a progression of internal storages. These models use semi-empirical equations and evaluate the model parameters from field observation as well as by model calibration. These models incorporate a general depiction of the catchment, thereby avoiding point by point data necessities and represent a catchment as a progression of internal storages (Sorooshian 1991). These models fill a gap between empirical and physically based models and thus play a transitional role (Beck 1987).

Physical models are based on solutions of various physical equations to define and analyze the various hydrological parameters like runoff and sediment yield. These models use the various physical characteristics of a catchment like topography, land cover, flow characteristics, soil characteristics and basin geology for the assessment of the hydrological behavior of the catchment. The standards equations used in these models are based on conservation of mass and momentum for flow estimation.

BRIEF DESCRIPTION OF A FEW WATERSHED MODELS

A watershed model estimates various hydrological parameters with a comprehensive methodology compared to other models, which principally center on individual procedures at field-scale without full incorporation of a watershed area (Oogathoo 2006).Watershed models are considered to be the most vital tools in the current era, which assess the hydrological behavior of any catchment and the impact of different changing factors on the hydrology of the catchment. The various models reviewed are summarized in Tables 1 and 3 with the governing equations of these models shown in Table 2.

SHETRAN (System hydrologique europian transport model)

It is a spatially distributed physical model that analyses the various processes of the hydrological cycle (Ewen *et al.* 2000). SHETRAN utilizes the Rutter equation (Rutter *et al.* 1971) to obtain the interference and transpiration is represented by a root density function. Runoff is estimated either by calculating the rainfall excess over infiltration capacity or by analyzing saturation excess. Surface runoff is estimated by routing Saint-Venant equations and transport capacity can be determined either by Yalin's equation (Yalin 1963) or Engelund-Hansen's equation (Engelhund & Hansen 1967).

AGNPS (Agricultural non point source model)

It is a distributed watershed model capable of estimating the maximum of hydrological parameters (Young *et al.* 1989) and uses a modified version of the Universal Soil Loss Equation (Wischmeier & Smith 1978) for prediction of soil loss and the Soil Conservation Services runoff curve method for estimating surface runoff. Sediment yield is divided into different classes and the process includes sediment transport and deposition relations depicted by Bagnold (1966), Foster *et al.* (1981) and Lane (1982). The model also analyses the chemical transport by the procedure given by Frere *et al.* (1980).

KINEROS (Kinematic runoff and erosion model)

It is a single storm event based distribution model that incorporates kinematic wave equations for estimating surface runoff and mass balance equations along with sediment transport equations for analysis of sediment yield (Woolhiser *et al.* 1990). KINEROS is improved into KINEROS2, which incorporates a new method for redistribution of soil water during rainfall interruptions and has an infiltration algorithm that can handle a two layer soil profile.

Table 1 | A list of few watershed models and their details

S. No	Model name	Description	Inputs	Governing equations for sediment estimation	Governing equations for runoff estimation	Model capability and shortcommings	Model remarks
1.	SHETRAN (System HydrologiqueEuropian Transport)	Ewen *et al.* (2000)	Soil characteristics, Soil topography, climatic data, vegetation cover etc.	1. Sediment continuity equation. 2. Sediment transport capacity.	1. Interception is calculated using Rutter equation. 2. Evapo-transpiration is calculated by Penman equation or Pan evaporation. 3. Infiltration by Richard's equation. 4. Transpiration by root density function. 5. Overland flow by Saint-Venant's equations.	This model is capable of estimation and simulation of various hydrological parameters like runoff, peak runoff rate, soil loss and solute transport. However, it doesn't calculate the flow through unsaturated zone.	It is a spatially distributed basin scale simulation model capable of predicting the climate change and land use impacts.
2.	AGNPS (Agricultural non-point source model)	Young *et al.* (1989)	Meteorological data, soil data, land use/land cover, management factors, soil slopes etc.	1. Steady State Continuity Equation. 2. Universal Soil Loss Equation.	Curve Number Method	The model is capable of estimating soil loss and runoff. However the model relies on single storm event and is data intensive. Further, it cannot predict sub-surface flow.	It is an event based distributed watershed model.
3.	KINEROS (Kinematic Runoff & Erosion model)	Woolhiser *et al.* (1990)	River geometry, climate data, topography, vegetation cover etc.	1. Mass balance equation. 2. Sediment transport capacity.	Kinematic wave equations $Q = ah^m$	The model is capable of estimating runoff, peak runoff rate as well as soil loss simulation etc. However it relies on single storm event and it doesn't carry the simulation of chemical elements and sub-surface flow	It is a process oriented distributed model which can be used for un-gauged watersheds. It is a single storm event based watershed model.
4.	RHEM (Range-land Hydrology and Erosion Model)	Nearing *et al.* (2011)	Climatic data, soil characteristics, land use, topographic data etc	Splash erosion and transportation equations	1. Kinematic wave equations with method of characteristics 2. Green & ampt.,Mein-Larson model for infiltration	This model has a great ability for analyzing hydrological parameters of small agricultural catchments and rangelands but it relies on single storm event.	It is a single event based rangeland analyzing tool

(*Continued.*)

Table 1 | Continued

S. No	**Model name**	**Description**	**Inputs**	**Governing equations for sediment estimation**	**Governing equations for runoff estimation**	**Model capability and shortcommings**	**Model remarks**
5.	SWM (Stanford Watershed Model)	Bicknell *et al.* (1993) and Crawford & Linsley (1966)	Land use/land cover, soil characteristics, topography, climatic data etc	Overland sediment uses power relations. Channel sediment utilizes cohesive and non-cohesive sediment transport concept.	Semi-empirical equations.	It is a long term watershed simulation model which uses variable time steps on daily basis. However calibration of its parameters is a tedious practice.	It is a continuous model based on different processes and designed to predict overland flow and soil loss along with other hydrological parameters.
6.	SWRRB (Simulator for Water Resources in Rural Basins)	Williams *et al.* (1985)	Weather data, soil data, vegetation cover etc.	1. Modified Universal Soil Loss Equation. 2. Sediment-Balance Equation	SCS Curve Number for surface runoff.	This model is capable of simulating hydrological cycle and other parameters based on daily time steps. However, it incorporates different assumptions and has extensive data requirements	It is a process oriented watershed simulation model suitable for analyzing complex rural watersheds.
7.	SEDIMOT III (Sedimentology and Distributed Modeling Technique)	Barfield *et al.* (2006)	Meteorological data and water characteristics	CREAMS uses MUSLE equation SLOSS Routing for soil loss/sediment estimation.	SCS Curve Number method for surface runoff. The channel flow is routed between structures and to them by Muskingum's routing method	This model is capable of flood and sediment estimation in transition from undistributed to distributed conditions. However, it is suitable for small field scale catchments only and it relies on single storm event.	It is a single -event based field scale model.
8.	ANSWERS (Areal Non-Point Source Watershed Environment Response Simulation)	Beasley *et al.* (1980)	Land-use/land-cover, BMPs, soil characteristics, drainage data, climatic data.	1. Universal Soil Loss Equation 2. Yalin's modified equation and steady-state sediment continuity equation	1. SCS Curve Number for surface runoff. 2. Greeen&Ampt. Equations for other hydrological processes.	This model is capable of estimating runoff, peak runoff rate, nutrient, sediment yield and other hydrological parameters. However, it relies on single storm event and is data intensive. Sub-surface flow component can't be estimated.	It is a distributed hydrological model based on events.
9.	TOPMODEL (Topography Based Hydrological Model)	Beven & Kirkby (1979)	Hydrological data, soil characteristics, topography etc	Sediment transport capacity equations	1. Hydrological similarity theory. 2. Probability distribution function. 3. Darcy's law and topography indices.	This model is capable of simulating surface and sub surface flows as well as sediment yield and solute transport. However, it is suitable for catchments with shallow homogenous soils with very few dry periods.	It is a distributed, continuous watershed scale simulation model.

(*Continued.*)

Table 1 | Continued

S. No	Model name	Description	Inputs	Governing equations for sediment estimation	Governing equations for runoff estimation	Model capability and shortcommings	Model remarks
10.	WESP (Watershed Erosion Simulation Program)	Lopes (1987)	Channel characteristics, soil characteristics, climatic data, topography etc	Unsteady and spatially varying erosion/deposition process.	1. Green &ampt for infiltration. 2. Unsteady overland flow for kinematic wave approximations.	This model is capable of prediction of runoff and soil loss. However it relies on single storm event. It also lacks the information on erosion and deposition parameters.	It is a distributed, event based, non-linear numerical model.
11.	SWIM (Soil and Water integrated model)	Krysanova *et al.* (1998) and Krysanova *et al.* (2000)	Soil characteristics, land cover, crop cover, climatic data	Modified Universal Soil Loss Equation	Modification of Curve Number Method. Potential evapo-transpiration is calculated using Priestley-Taylor through a method of Penman-Moteinth.	Capable of utilizing key hydrological processes by utilizing daily time steps. However, model is quite complicated and gully erosion cannot be simulated.	It is a spatially distributed watershed model designed to analyze water quality and other parameters at river basin scale.
12.	EUROSEM (European Soil Erosion Model)	Morgan *et al.* (1993) and Morgan (1994)	Land use/land cover, soil characteristics, topography etc.	Mass balance equation of erosion.	1. Based on KINEROS Code with some minor additions. 2. Net rainfall is calculated using a dynamic approach. 3. Mass conservation and simplified form of Saint-Venant equation is used in runoff routing..	This model is capable of simulation of sediment yield, runoff, erosion and deposition. However, it is suitable for small catchments only.	It is a single event distributed model.
13.	GUEST (Griffith University Erosion System Template)	Misra & Rose (1996)	Topography, soil characteristics, climatic data, runoff data etc	Transportation and depositions equations.	Water Balance Model.	This model is capable of evaluating temporal fluctuations of sediment concentration, runoff etc. However, it relies on single storm events and has low potential for GIS integration.	It is a steady state, process oriented and event based erosion model.
14.	LISEM (Limburg Soil Erosion Model)	De Roo *et al.* (1996a, 1996b)	Soil characteristics, land use, climatic data, erosion and deposition etc	Generalized form of erosion-deposition mass balance equation.	Kinematic Wave solution by taking into view the parameters affecting the process i.e., precipitation, interception, infiltration, soil depression, storage and sheet flow.	This model is capable of simulating runoff and soil erosion loss/sediment yield. However, it relies on single storm events and requires extensive data.	It is a single storm event based, distributed simulation model

(*Continued.*)

Table 1 | Continued

S. No	Model name	Description	Inputs	Governing equations for sediment estimation	Governing equations for runoff estimation	Model capability and shortcommings	Model remarks
15.	WEPP (Water Erosion Prediction Project)	Laflen *et al.* (1991)	Topography, soil data, climatic data, channel impoundment, cultural practices.	Steady-state sediment continuity equation	Kinematic Wave equation.	Capable of evaluating almost every hydrological parameter utilizing daily time steps. However, it requires extensive input data.	It is a process oriented, distributed, continuous simulation.
16.	SWAT (Soil and Water Assessment Tool)	Arnold *et al.* (1998)	Meteorological data, land use/land cover, soil data etc	1. Modified Universal Soil Loss Equation. 2. Bagnold's stream power concept.	Soil Conservation Number method. Green-ampt method.	Capable of simulating hydrological processes in large basins using daily or sub-daily input data. However, it does not evaluate the peak floods efficiently probably due to snow-melt simulation	It is a semi-disturbed continuous simulation model and can be integrated with GIS interface and large databases.
17.	HEC-HMS/ HEC-RAS	U.S.Army Corps of Engineer's Hydrologic Center (Thakur *et al.* (201)7)	Hydrological data, soil characteristics, vegetation cover etc.	Modified Universal Soil Loss Equation.	SCN method	Capable of evaluating overland flow and soil loss but requires careful consideration for representation of grain size and settling depth.	HEC-HMS/HEC-RAS is a one dimensional model.

Table 2 | Governing equations for runoff and erosion used in different models.[a]

Title equations	Name	Algorithm	Model
Governing equations for for water flow	De Saint-Venant's (1871) kinematic wave equations	$\frac{\partial y}{\partial t}+\frac{\partial F}{\partial x}=q_w; S_0=S_f$	RHEM, CREAMS, WESP, KINEROS, WEPP
	Manning's equation (1891)	$\mathrm{F}=\frac{1}{n}AR^{2/3}S_0^{1/2}$	SWAT, ANSWERS, CREAMS
	SCS Curve Number (1985)	$Q_d=\frac{(p-I_{a)}^2}{(p-I_{a)+S}}$	SWAT, AGNPS, CREAMS, SWRRB, SEDIMOT, SWIM, SWAT
Governing equations for sediment transport on hill-slopes	Universal Soil Loss Equation, USLE (Wischmeier 1965)	$S_L=IELS_fC_fP_c$	AGNPS, ANSWERS, SWRRB
	Modified version of Universal Soil Loss Equation (Williams & Berndt 1977)	$S_Y=a(Q{*}q_p)^bIELS_fC_fP_c$	CREAMS, SEDIMOT, SWRRB, SWIM and SWAT
	Foster equation by Foster *et al.* (1977)	$\frac{\partial q_s}{\partial x}=D_{rn}+D_{in}$	WEPP, AGNPS, ANSWERS, CREAMS RHEM
	Bennett mass balance equation (Bennett 1974)	$\frac{\partial(AC_s\ \ )}{\partial t}+\frac{\partial(QC_s\ )}{\partial x}=e(x,t)=q_s(x,t)$	KINEROS
	Erosion-deposition mass balance (Morgan *et al.* 1992)	$E=Ds+Df-Dp$	EUROSEM, LISEM
	Wicks equation (1988)	$Dr=k_rF_{wd}(1-C_{ng}-C_{lr})(Mr+Md)$	SHETRAN
Governing equations for sediment transport in channels	Rose *et al.* (1983a, 1983b) and Hairsine & Rose (1992a, 1992b)	$\frac{\partial q_{si}}{\partial s}+\frac{\partial(C_sh)}{\partial x}=D_S+D_{ds}+D_f+D_{df}+R_{gi}-D_p$	GUEST
	Bagnold's stream power concept (1977)	$C_{\max}=V_{\max}^{spexp}$	SWAT
	Engelhund & Hansen (1967)	$Z_t=0.04\frac{(S_0h)^{3/2}}{(S-1)^2\ d_{50}g^{1/2}}u^2=0.04\left(\frac{2g}{f}\right)1/6\frac{(s_0q)^{3/2}}{(s-1)^2d_{50}\,g^{1/2}}$	SHETRAN
	Yalin's equation (1963)	$\frac{\mathrm{T_c}}{(\mathrm{SG})\mathrm{d}\rho_w^{\frac{1}{2}}\tau_s^{1/2}}=0.635\sigma\left[1-\frac{1}{\partial},\ \ln(1+\partial)\right]$	ANSWERS, CREAMS

[a] Abbreviations used in above equations.

q_w, flow per unit width ($m^2\ s^{-1}$); u, velocity of flow (m/s); S_0, bed slope (mm^{-1}); S_f, energy gradient (mm^{-1}); t, time (s); x, longitudinal distance (m); F, flow rate ($m^3\ s^{-1}$); g, acceleration due to gravity (m s-); A, flow area (m^2); n, Manning's coefficient of roughness; I, hydraulic radius (m); Q_d, depth of runoff (m); P, rainfall (m); S, Potential retention after runoff starts (m); I_a, initial abstraction (m); E, average annual soil loss (tons ha^{-1}); R, rainfall erosivity factor; y, flow depth (m); E, soil erodibility factor; L, length of the slope; S_f, slope factor; C_f, crop management factor; P_c, conservation practices factor; S_Y. sediment yield for an individual storm(tones); q_p, peak flow rate (($m^3\ s^{-1}$); $\frac{\partial q_s}{\partial x}$, sediment rate per unit width of rill channel; D_{rn}, rill net detachment or deposition rate; D_{in}, inter-rillnet detachment or deposition rate); S_L, Erosion; D_s, Detachment by rain drops; D_{ds}, rainfall re-detachment; D_f, detachment by runoff; D_{df}, runoff re-entrainment; D_p, Deposition; Dr, rate of soil detachment; F_{wd}, protective effect of surface water layer in reducing the energy imparted to the soil by rain drop and leaf drip impact; C_{ng}, proportion of ground shielded by near ground cover; C_{lr}, proportion of ground shielded by ground level cover; M_r, momentum squared of raindrops reaching the ground per unit time per unit area; M_d, momentum squared of leaf drip reaching the ground per unit time per unit area; R_{gi}, gravity process rate; C_{max}, maximum sediment concentration that can be transported by water (kg/L or ton/m^3); $V_{\max}$, peak channel velocity (m/s); spexp, an exponent defined by user; Z_t, amount of transported sediment ($m^2\ s^{-1}$); s, ratio of the specific weight or density of sediment to water; d_{50}, median grain diameter (m); T_c, sediment transport capacity; SG, specific gravity; ρ_w, mass density of water; τ_s, shear stress acting to detach soil; σ, ∂, empirical parameters.

RHEM (Rangeland hydrology and erosion model)

It is an event based analyzing tool designed to help with surveying rangeland preservation practice impacts. It uses semi-analytical solution to the kinematic wave equations for routing runoff. Sediment calculations utilize splash erosion and transportation equations (Nearing *et al.* 2011).

SWM (Stanford watershed model)

It is a continuous simulation model that uses semi-empirical equations for estimation of surface runoff and utilizes separate methods for evaluating overland and channel sediment (Crawford & Burges 2004).

SWRRB (Simulator for water resources in rural basins)

It is a semi-distributed model used in complex rural watersheds capable of simulating hydrology and soil loss on daily time steps. Overland flow is evaluated using Soil Conservation Service curve number method (SCS 1985) while Modified Universal Soil Loss Equations (Williams & Berndt 1977) and sediment balance equations are used for sediment calculations. This model was created to analyze the hydrological behavior of complex rural basins (Williams *et al.* 1985). Improvisations to the model were made for application of large rural basins by allowing simultaneous computations on several sub-basins and with a few other modifications to the CREAMS model (Knisel 1980). Ritchie's evapo-transpiration model (Ritchie 1972) is utilized for estimating evapo-transpiration. Precipitation and temperature data can be simulated using a weather generator (Nicks 1974) if the actual data is unavailable, which makes the model applicable to ungauged rural watersheds.

SEDIMOT (Sedimentology and distributed modeling technique)

It is a field-scale model based on single events that uses the SCS curve number method for simulation of runoff and SLOSS routing for sediment estimation. The rill and inter-rill components are calculated using the same methodology as used in the CREAMS model (Barfield *et al.* 2006).

ANSWERS (Areal non-point source watershed environmental response simulator)

It is an event based model that relies on a single storm event and is capable of estimating runoff, peak runoff rate and soil loss. It uses the SCS curve number method for simulating surface runoff and Green& Ampt. equation for calculating other hydrological processes. Universal Soil Loss Equation and modified Yalin's equations are used for soil loss and its transportation and deposition (Beasley & Huggins 1982).

TOPMODEL (Topography based hydrological model)

It is a distributed watershed model that uses hydrological similarity, probability distribution function, Darcy's law and topographic indices for simulation of overland flow (Beven & Kirkby 1979). The distribution of topographic indices used for hydrologic similarity is explained in detail by Beven *et al.* (1995).

WESP (Watershed erosion simulation program)

It is a non-linear numerical model that relies on a single storm event and utilizes unsteady overland flow for kinematic wave approximations and offers Green and Ampt. equations for estimating infiltration.

SWIM (Soil and water integrated model)

It is a spatially distributed watershed model capable of modeling at river basin scale. Potential evapotraspiration is calculated using a method given by Priestley & Taylor (1972), soil evaporation and transpiration by Ritchie (1972) approach and the snowmelt by a simple degree-day equation (Knisel 1980). Surface runoff is calculated by a modified Soil Conservation Service curve number method given by King *et al.* (1999). The Cinematic storage model developed by Sloan *et al.* (1983) is utilized for interflow and lateral subsurface flows. The Muskingum method (Maidment 1993) gives the procedure of flow routing from one sub-basin to another.

EUROSEM (European soil erosion model)

It is a dynamic distributed model that depends on single storm events and operates for short time intervals of one minute to evaluate the physical description of hydrological processes in small catchments (Morgan *et al.* 1998). The erosion process is based on the KINEROS code with some minor additions (Woolhiser *et al.* 1990). Runoff estimation utilizes mass conservation and a simplified form of Saint-Venant equations while a dynamic mass balance equation of erosion is used for predicting soil loss.

GUEST (Griffith university erosion system template)

It is an erosion model based on events and capable of simulating temporal fluctuations of sediment concentration and it utilizes the concept of the water balance model for overland flow estimation. The settling velocity characteristic defined by Lovell & Rose (1988) defines the influence of various factors on the rate of deposition.

LISEM (Limburg soil erosion model)

It is a single storm, event based simulation model that analyses runoff by taking the results of kinematic wave equations (De Roo *et al.* 1996a, 1996b). Sediment yield analysis is carried out by generalized erosion and deposition mass balance equations. The parameters like infiltration and vertical movement can be analyzed through various methodologies such as:-

- SWATRE sub-model for all kinds of surfaces (Belmans *et al.* 1983).
- SWATRE sub-model for surface with wheel tracks (Belmans *et al.* 1983).
- SWATRE sub-model for crusted and non-crusted surfaces (Belmans *et al.* 1983).
- One layer Green & Ampt infiltration equation (Green & Ampt 1911).
- Two layer Green & Ampt infiltration equation (Green & Ampt 1911).
- Holtan infiltration equation (Holtan 1961; Overtone 1964).
- Assumption of zero infiltration for testing.

Equations given by Onstad (1984) and Linden *et al.* (1988) are utilized for calculating surface storage depression. To allow the spatial variation, LISEM is integrated with a raster Geographic Information System called PC Raster (Van Deursen & Wesseling 1992).

WEPP (Watershed erosion prediction project)

It is a physical simulation model capable of simulating hydrological parameters on an event or continuous steps using daily time steps (Laflen *et al.* 1997). WEPP is considered as one of the finest watershed models, capable of estimating overland flow and other hydrological parameters with high level of precision (Lane *et al.* 1997). A detailed description of the various analysis procedures performed by WEPP can be found in the model documentation given by Flanagan & Nearing (1995).

SWAT (Soil and water assessment tool)

It is a physical model designed to simulate the hydrological parameters in all the basins including hills and areas with larger databases (Arnold *et al.* 1998; Setegn *et al.* 2008). SWAT can simulate the overland flow using two completely different methodologies. The SCS curve number method is the most used method but Green and Ampt. method is less data intensive (Fontaine *et al.* 2002).

HEC-HMS/HEC-RAS (Hydrologic engineering center-hydrologic modeling system and river analysis system)

These models are designed by U.S Army corps of Engineer's Hydrologic Center to simulate the hydrologic behavior and carry out the simulation processes by utilizing modified universal soil loss equation and SCS curve number methods for sediment and runoff respectively (Tahmasbinejad *et al.* 2012).

DISCUSSION

A huge number of watershed modeling tools have a capability to simulate the hydrological behavior realistically and with fair precision and can be applied to predict the effect of various factors on the hydrologic characteristics of catchment and can be used to address other environmental problems. However, all these models vary in analyzing the watershed parameters and need proper evaluation before applying any of these models for a particular purpose. In order to evaluate if the model has the ability to produce the desired results, 17 watershed models worldwide were reviewed and their results are summarized in Table 3. The performance of the model depends largely on the data utilized to support the model for the prediction process. Validating the results of the calibrated model is essential in determining the quality of the model, which requires comparison of its predicted values with the observed or measured values. Then the validated model can be used for predicting the hydrological parameters of other areas with similar characteristics. Furthermore, some cases have been added in Table 4 to compare different models to check the better model in the same set of conditions.

SELECTION OF A MODEL

Each model has its own processing capabilities to analyze the hydrological behavior of a catchment. Their application depends on the aims and objectives as well as the degree of precision needed. On the basis of the review work, it is suggested that the following points should be considered before selection of any watershed model.

- **Recognition of problem:** The initial step in watershed modeling is to be well aware of the ideal results you require from the simulation process, so as to limit the danger of utilizing the wrong tools for any activity.
- **Selection of models:** Before model determination, one should realize what sort of system is to be modeled and what components need to be modeled. Furthermore, a researcher or a decision

Table 3 | Details of applications of some selected physical based runoff, soil erosion and sediment yield models in different parts of the world

S. No	Model name	Researcher	Region	Area	Method of performance evaluation	Aim of work	Results/Conclusion
1	SHETRAN	De Figueiredo & Bathurst (2007)	Basin of Sume and Taua in a sem-iarid region of Brazil	13,740 ha	R^2	Capability of SHETRAN for runoff and sediment yield prediction.	Model performed quite well, good for the observed runoff with R^2 as 0.8 and sediment yield with R^2 as 0.46. The containments with overall mean of 76%, observed runoff mean of 86% and sediment yields mean of 67% suggests that the model can predict the hydrological parameters satisfactorily in other ungauged basins.
2.	AGNPS	Jianchang *et al.* (2008)	Jiulong river watershed, Fujian Province, China	95,600 ha	R	Performance of AGNPS as a predictor of runoff, peak runoff rate, sediment yield and nutrient losses.	Model performed well with coefficient of correlation as 0.99 and 0.98 for runoff, 0.94 and 0.95 for peak runoff rate of the large catchment and small catchment with correlation coefficient of 0.76 for sediment, 0.98–0.99 for nutrient losses.
		Mohammed *et al.* (2004)	Kori watershed, South Wollo zoneEthiopia	108.2 ha	PD	Capability of AGNPS for predicting runoff and sediment yield	Model calibration gave satisfactory results with model efficiencies of 0.73 for runoff; 0.53 for peak runoff rate and 0.90 for sediment yield.
		Haregeweyn & Yohannes (2003)	Augucho catchment, western Hararghe, Ethiopia	234.00 ha	R	Evaluation of AGNPS for runoff, peak runoff rate and sediment yield	Model performed well for peak runoff rate and sediment yield but lagged its performance in predicting runoff volumes. Coefficient of correlation for runoff were 0.59 & 0.58; 0.96 and 0.95 for peak runoff rate; 0.97 & 0.97 for sediment yield for 100 and 200 m grids, respectively.
3.	KINEROS	Smith *et al.* (1999)	Catsop catchment in south Limburg	41.2 ha	Comparison graphs	Efficiency of KINEROS	KINEROS2 performed well in simulating runoff and sediment in the given catchment. However, certain difficulties in modeling sediment were highlighted in this study.
4.	RHEM	Al-Hamdan *et al.* (2015)	Idaho & other watershed s	260 m^2 etc.	R^2, NSE	Efficiency of RHEM as a runoff predictor	The coefficient of determination ($R^{2)}$ and Nash–Sutcliffe efficiencies were 0.78 and 0.71 respectively, which indicates predicting power of KINEROS as a successful tool.
5.	SWM	Egbuniwe & Todd (1976)	Malendo Watershed, Nigeria	3,480 square miles	Correlation Coefficient (R)	Efficiency of Nigerian version of SWM with observed data	Annual and monthly correlation of 0.97 and 0.91 respectively were found for Malendo watershed.

(*Continued.*)

Table 3 | Continued

S. No	Model name	Researcher	Region	Area	Method of performance evaluation	Aim of work	Results/Conclusion
6.	SWRRB	Arnold *et al.*(1987)	White Rock lake Dam	256,800 ha	Tables of measured and simulated values.	To evaluate the effect of urbanization on water and sediment entering the lake using SWRRB	Comparison of simulated and observed values of water yield, peak flow rates and sediment yield was carried out. The comparisons showed that the model can be used as a suitable tool in predicting the effect of urbanization on these parameters.
7.	SEDIMOT	Mirzai *et al.* (2014)	Latian Dam Watershed (Roodak, Kond and Afjeh basins)	403 km^2 58 km^2 31 km^2 respectively	Model Precision in Percentage	Efficiency of model for simulation of sediment yield estimation	Model precision of 86.8%, 86% and 55% for Roodak, Kond & Afjeh basins respectively was found.
8.	ANSWERS	Singh *et al.* (2006)	Banha Watershed, India	1,613 ha	NSE	Evaluation of ANSWERS for simulation of runoff, peak flow, and sediment yield data	Model showed satisfactory performance with NSE of 0.991, 0.741 and 0.965 for surface runoff, peak flow and sediment yield simulations respectively.
		Ahmadi *et al.* (2006)	College of Agriculture, Shiraz University, south of Iran	3.63 ha	CE, PD	Comparison of ANSWERS and revised Yalin's sediment transport equations	Simulated sediment concentration was more consistent with original sediment transport equation than Yalin's equation
9.	TOPMODEL	Beven *et al.* (1984)	Crimple Beck, Hodge Beck, Wye Headwater watersheds in U.K.	8 km^2, 36 km^2, 10.5 km^2 respectively	Model Precision in Percentage	Efficiency of TOPMODEL as a predictor of runoff.	The model succeeded in coping with variety of hydrologic conditions with long term model precision efficiencies of 67% and 58% for Crimple and Hodge Beck, rising to 84% for the Wye. Monthly efficiencies are 97.2% for Crimple Beck, 64.4% for Hodge Beck and 98.3% for the Wye.
10.	WESP	Srinivasan & Galvão (1995)	Two erosion plots and two micro-basins located in the semiarid region of the State of Paraiba in Brazil.	Micro-basins (0.48 to 1.07 ha each). Erosion plots of 100 m^2 each.	Graphical plots	Efficiency of model as runoff and soil loss predictor.	The agreement between the calculated and measured runoff is quite good. However, the measured and simulated erosion showed large discrepancies, probably due to lack of proper input data.

(*Continued.*)

Table 3 | Continued

S. No	Model name	Researcher	Region	Area	Method of performance evaluation	Aim of work	Results/Conclusion
11.	SWIM	Hattermann *et al.* (2005)	Elbe catchment	80,258 km^2	NSE	Efficiency of SWIM model in predicting runoff volumes.	The SWIM model has given good simulation results on a daily time step for after calibration of the river routing factor, global radiation and the groundwater reaction factor and saturated soil conductivity. The validation results were better in mountainous catchments with efficiency of 0.75–0.79 for daily time steps, 0.82–0.84 for monthly time steps than in lowland basins with efficiency of 0.61–0.72 for daily time steps and 0.66–0.86 for monthly time steps.
12.	EUROSEM	Folly *et al.* (1999)	Catsop watershed, The Netherlands.	41.2 ha	Graphical plots	To check the efficiency of EUROSEM for runoff, peak runoff rate and soil loss simulations	EUROSEM showed reasonable results on some validation storms and unsatisfactory results on others primarily due to differences in characteristics between the calibration storms and those in the validation data set.
		Cai *et al.* (2005)	Three Gorges Reservoir areas, China	Experimental plots (2 m × 10 m)	NA	Prediction of runoff and erosion rates	Runoff was predicted quite well but the model lagged in predicting the soil loss.
13.	GUEST	Yu *et al.* (1999)	Experimental sites from China, Malaysia and Thailand	NA	Graphical plots	To predict event soil loss using estimated soil erodibility parameters	An average model efficiency of 0.68 was achieved for selected sites, which makes GUEST a satisfactory model to predict event soil loss.
14.	LISEM	De Roo & Jetten (1999)	Catsop catchment South-Limburg (the Netherlands) and Zululand (South Africa).	45 hectares and 69 hectares respectively	Graphical plots and tables	Calibration and validation of LISEM Model.	A reasonable efficiency of the model was found in simulation of runoff and soil loss. However, the input data needed by LISEM should be of high resolution to produce reliable outcome.
		Hessel *et al.* (2003)	Danangou /Loess Plateau catchment, China	3,500 (total area); 2,000 (upstream of weir)	R, NSE	Discharge calibration and erosion pattern	The model showed unsatisfactory performance because of little resemblance with the actual mapped erosion pattern.

(*Continued.*)

Table 3 | Continued

S. No	Model name	Researcher	Region	Area	Method of performance evaluation	Aim of work	Results/Conclusion
15.	WEPP	Singh *et al.* (2011)	Umroi watershed, India	239.44 hectares	t-tests	To plan/develop best management practices for the given catchment	WEPP gives a satisfactory result for implementation of BMPs (t-test shows 95% significance level for result fits)
		Pandey *et al.* (2008)	Karso Watershed, India	27.93 km^2	R^2	Capability of WEPP as runoff and soil loss simulator	The model performed well with coefficient of determination as 0.86–0.91 for runoff and 0.81–0.95 for sediment yield in the watershed.
		Raclot & Albergel (2006)	Kamech catchment, Cap-Bon, Tunisia	245 hectares	RMSE, NSE, t-test	Predicting capabilities of WEPP on Mediterranean catchment.	Hydrologic outputs were well predicted with errors ranging between 3% - 59% but it showed unsatisfactory results for sediment yield with errors >250%
16.	SWAT	Gull *et al.* (2017)	Lolab watershed of Pohru Catchment	28,162 hectares	R^2	Capability of SWAT model as a predictor of stream flow and soil loss.	SWAT showed better efficiencies for both runoff and soil loss. Hence, SWAT model performs well in hilly areas and is a better tool for assessment of hydrological parameters in general.
		Zhang *et al.* (2014)	Lizixi Watershed, Jialing river basin, China	69,750 hectares	R^2	To study the impact of land use change on soil loss.	Model performed well with the predicted and observed values having a coefficient of determination as 0.78–0.94 for runoff and 0.72–0.88 for sediment yield. Hence, SWAT model is suitable for BMPs.
		Oeurng *et al.* (2011)	Save catchment, Coteaux Gascogne.	1,110 km^2	R^2	Estimation of hydrological parameters and preparation of prioritization/erosion map.	Performance of the model was satisfactory for daily runoff estimation. However, it showed a large variation for some time periods probably due to inconsistent input data. Coefficient of determination values were found as 0.56 for runoff and 0.51 for soil loss.
17.	HEC-RAS/ HEC-HMS	Halwatura & Najim (2013)	Attanagalu Oya and Dee Eli Oya catchment	337,067 hectares	Graphical plots	To evaluate the performance of the model	Model performed quite well for a range of conditions and can be used extensively in other catchments for predicting runoff.

Note: Abbreviations used:

NA, Not Applicable; PD, Percent deviation; BMP, Best Management Practices; R^2, Coefficient of Determination; R, Coefficient of Correlation; NSE, Nash-Sutcliffe Efficiency; RMSE, Root Mean Square Error; CE, Coefficient of Efficiency; ha, hectares.

Table 4 | Comparison between some selected watershed models

S. NO	Researcher	Models in comparison	Area	Remarks
1.	Verma *et al.* (2010)	HEC-HMS and WEPP	Upper Baitarani River basin of Eastern India	HEC-HMS can be used as a good predicting tool for evaluation of daily runoff as it provided reliable results for simulation of total runoff volume with percent deviation ranging between −2.55 and 31%, while it varies from −13.96 to 13.05% for the WEPP model, which makes the WEPP model more authentic for simulating annual flow volumes.
2.	Shen *et al.* (2009)	WEPP and SWAT	Zhangjiachong Watershed, Three Gorges Reservoir Area	The predicted values of runoff and sediment yield were compared with the observed values. Nash and Sutcliffe coefficients for WEPP and SWAT during the calibration period were found to be quite good with values of 0.864 and 0.711 for runoff, and 0.847 and 0.678 for sediment yield, respectively. In the validation period, the Nash Sutcliffe efficiencies values for WEPP and SWAT were 0.835 and 0.690 for runoff, and 0.828 and 0.818 for sediment yield, respectively. The results concluded that both SWAT and WEPP have good capabilities to simulate runoff and soil erosion losses. However, WEPP performs better when it comes to prediction of soil loss in reservoir areas.
3.	Afshar & Hassanzadeh (2017)	WEPP & SWAT	Torogh Dam Watershed basin	Both models showed satisfactory results in simulating predicted values with observed values with Nash- Sutcliffe efficiencies greater than 0.65 for runoff in both the models during calibration as well as validation periods. Efficiencies for calibration and validation periods were found to be above 0.80 for both the models while simulating the soil loss. However WEPP was better in some cases and can be used as a better predictor for quantification of soil loss in watershed of Torogh Dam.
4.	Bingner *et al.* (1989)	CREAMS, SWRRB, EPIC, ANSWERS and AGNPS	Watersheds in Mississippi	Simulated results from all the mentioned models were compared with observed data of runoff and sediment yield on an annual and storm rainfall event basis. The comparisons showed that each model gave unsatisfactory results of runoff and soil loss in all the given conditions. Overall, CREAMS and SWRRB gave better results than the other three models, even though SWRRB is simpler to use with simpler input requirements.
5.	Ghanbarpour *et al.* (2012)	ANN, SWRRB, ARMA, and I-HACRES	Kasilian watershed, north of Iran	The performance of these models was compared on error estimation criteria, which indicated that the IHACRES model gave more reliable results than the other three models.

(*Continued.*)

Table 4 | Continued

S. NO	Researcher	Models in comparison	Area	Remarks
6.	Abdelwahab *et al.* (2018)	SWAT & AnnAGNPS	Carapelle watershed, Southern Italy	The correlation between simulated and actual stream-flow was good in both the modeling approaches. But, AnnAGNPS requires simpler inputs and SWAT works with larger data sets, which makes AnnAGNPS an easier tool to analyze the hydrological parameters of a particular catchment. However, SWAT simulates the base flow too, which lacks in AnnAGNPS, and works better when precipitation doesn't occur for a while.
7.	Duru & Hjelmfelt (1994)	HEC – 1 and KINEROS	30.4 hectare watershed located near Treynor, Iowa.	The results show that HEC-I achieved better results than KINEROS model. However, both models can predict the rainfall-runoff process with good precision when performed with precise calibration.

maker should be exact about the time steps for which the components are to be modeled, spatial and temporal variability and all other factors including the time available for collection of input data. Models that are capable of integration with geographic information systems and Arc softwares are preferred so as to save time to be expended in collection and preparation of input data and make the model more user-friendly. The models with GIS integration capacity are broadly to carry out the tasks of critical significance. The equations used by the model in processing the parameters should be thoroughly studied in order to analyze all the factors that could affect the desired outcome.

- **Model assessment and sensitivity analysis:** The factors that degrade or affect the quality and precision of the model must be identified and streamlined during the model assessment. Sensitivity analysis ensures that the model parameters are well designed to reproduce the desirable yield and determines the effect of these parameters on model execution. Simulation results can be compared to observed or measured values to ensure the model validity, even though these models need to carry sensitivity analysis and model calibration with field data before the validation process.
- **Use of certified/acknowledged analyzing tool:** The validated model can be used for predicting the hydrological behavior and impact of morphology on the other catchments after critical evaluation. However, uncertainties should be thoroughly quantified and evaluated before interpreting the results.

SUMMARY AND CONCLUSIONS

Floods and soil degradation have been recognized as a key problem for human sustainability with adverse economic and environmental impacts that make assessment of these terms of an utmost importance so that proper management practices can be applied to minimize the effect of these threats. The amount of runoff produced by any watershed needs to be appropriately predicted for planning and managing safety measures during the drought and flood conditions. Similarly, the amount of soil loss needs to be predicted and simulated to implement the best management practices to avoid silting of reservoirs and rivers.

This study gives a broad idea to a researcher or a decision maker for selection of an apposite and capable model for a given application. This paper reviewed a few mathematical models that can be used for simulating the hydrological parameters of different catchments across the world. A total of 17 models have been discussed in this study and each model varies in its applicability and analysis procedures. A comprehensive review of these models and their application worldwide revealed that SWAT, HEC-HMS, HEC-RAS, ANSWERS, WEPP and SHETRAN models are the most capable ones for prediction and assessment of various hydrological parameters like runoff, soil yield and nutrient losses, and hence these physical watershed models are more reliable for accomplishing sustainable watershed management practices. However, there are many more models that give good results and can be run for different conditions in different watersheds. Furthermore, a model can perform well in one range of conditions and lack its performance in another set of conditions; therefore, it becomes necessary to choose the appropriate model for the particular watershed after proper evaluation to get the accurate and desired results.

Watershed models reviewed in this paper are summarized in Tables 1 and 3. Research scholars and decision makers can use this study as a screening tool for selecting a watershed model for a given application. Furthermore, researchers can choose the best model suitable for different areas like small agricultural catchments, rangelands, large basins and hilly areas etc. A decision maker can select the model based on the requirements of a study, like analysis of gully erosion, sub-surface flow or flow through unsaturated zone.

DATA AVAILABILITY STATEMENT

The author confirms that the data supporting the findings of this study are available within the article.

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