CHAPTER 4

SOIL EROSION AND SEDIMENT TRANSPORT MODELING

4.1 Introduction

Natural processes of soil erosion and sediment transport are highly complex. Computational modeling of these processes has been a very challenging but important task for hydro-scientists and engineers, and thus many numerical models have been developed since 1950s. Merritt et al. (2003) noted that most of the erosion and transport models can suffer from a range of problems including over-parameterisation, unrealistic input requirements, unsuitability of model assumptions or parameter values to local conditions and inadequate documentation of model testing and resultant performance. Therefore, a clear understanding of a model is important for its appropriate use. The present report is an effort in achieving a greater understanding of soil erosion and sediment transport modeling.

In the present work, an effort has been made to review various aspects of erosion and sediment transport modeling, available approaches for modeling these processes, existing models and the concepts behind these models. The review is expected to be of interest to researchers, watershed managers and decision-makers while searching for models to study erosion and sediment transport phenomena and related processes such as pollutant and nutrient transport.

4.2 Brief Review of Soil Erosion and Sediment Transport Modeling Approaches

The processes, controlling sediment detachment, transport, and deposition on the hill slope scale, lumped under the term erosion processes, are complex and interactive (Lane et al., 1988). This complexity leads to the need for upland erosion models as tools in resource management. Since runoff is the main carrier of sediment, the erosion models are used in combination with a hydrologic model to estimate the sediment yield at the outlet of the watershed. A wide range of models exists for use in simulating sediment erosion, transport and associated pollutant transport. Bryan (2000) carried out a review on the water erosion modeling on hillslopes while Zhang et al. (1996a) reviewed modeling approaches used for the prediction of soil erosion in catchments. Merritt et al. (2003) provided a comprehensive review of specific models based on model input–output, model structure, runoff, erosion/transport and water quality modeling, and accuracy and limitation of the model. Borah and Bera (2003a) reviewed mathematical basis of eleven watershed scale hydrologic and nonpoint-source pollution models. Most recently, Aksoy and Kavvas (2005) carried out a review of hillslope and watershed scale erosion and sediment transport models.

Available models can be classified according to different criteria that may encompass process description, scale, and technique of solution (Singh, 1995). Some models may be similar because they are based on the same assumptions and some may be distinctly different.

4.3 Classification of Models

In general, models may be classified into three main categories, depending on the physical processes simulated by the model, the model algorithms describing these processes, and data dependence of the model: (i) empirical (ii) conceptual, and (iii) Physically-based. The models may also contain a mix of modules (Merritt, et al, 2003). For example, while the rainfall-runoff component of a water quality model may be physics-based or conceptual, empirical relationships may be used to model erosion or sediment transport.

4.3.1 Empirical models

Empirical models are generally the simplest of all three model types. The computational and data requirements for such models are usually less than for conceptual and physics-based models, often being capable of being supported by coarse measurements.

Wischmeier and Smith (1965), based on over 10,000 plot years of natural and simulated runoff data, presented Universal Soil Loss Equation (USLE), expressed as,

$$A = R\ K\ LS\ C\ P \qquad (4.1)$$

where A is the annual potential soil erosion (t ha^{-1} $year^{-1}$); R is the rainfall erosivity factor (MJ mm ha^{-1} hr^{-1} $year^{-1}$) taken as the long term average of the summation of the product of total rainfall energy (E) and maximum 30 minute rainfall intensity (I_{30}), i.e. EI_{30}; K is the soil erodibility factor (t ha hr ha^{-1} MJ^{-1} mm^{-1}); LS is the slope length and steepness factor (dimensionless); C is the cover management factor (dimensionless); and P is the supporting practice factor (dimensionless). The dimensions used here are consistent with the work of Renard et al. (1991).

Three major limitations of the USLE restricted its application in many modeling analysis. First, it was not intended for estimating soil loss from single storm events (Haan et al., 1994); second, it was an erosion equation, and consequently did not estimate the deposition (Wischmeier, 1976); and third, it did not estimate gully or channel erosion.

Since 1965, efforts have been to improve the USLE and it has been expanded for additional types of land use, climatic conditions and management practices. Williams (1975) presented a Modified Universal Soil Loss Equation (MUSLE) for predicting sediment yield from individual storm events. Renard et al. (1991) proposed revised USLE (RUSLE) incorporating a method for computing kinetic energy of rainfall for individual storm events using the equation proposed by Brown and Foster (1987).

4.3.2 Remarks on empirical models

The major weakness of the empirical models is that they only provide a limited insight in the relative importance of the various variables and their sensitivity in different environments. The major weaknesses of empirical modeling include: (i) the spatial and temporal resolution and extent are limited by the data available; (ii) their lack of process explicit process representation can limit predictive ability outside the study area or measured range of environmental characteristics; (iii) the heterogeneity of catchment characteristics such as rainfall, topography, lithology and land use is not usually represented in spatially lumped models; this reduces predictive ability, given the significant spatial correlations, and nonlinear dependencies, between slope gradient, runoff and other driving variables of erosion (iv) the absence of source and sink process representations in empirical sediment yield models can limit the number of different types of data which can be meaningfully assembled. The advantage with empirical models, however, is that they can be implemented in situations with limited data and parameter inputs and are particularly useful as a first step in identifying sources of sediment and nutrient generation.

USLE so far remains the well accepted and most widely used empirical approach for estimation of upland erosion despite the development of a number of conceptual and physically process based models (Lane et al., 1988; Narula et al., 2002). Researches and investigators have applied USLE with suitable modifications for estimation of annual soil loss and sediment yield as well as its temporal variation on single storm event basis, and to study the effect of various parameters that affect the soil loss.

4.4Conceptual Models

Conceptual models are based on spatially lumped forms of continuity equations for water and sediment and some other empirical relationships. These models include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information (Sorooshian, 1991). They consist of a number of interconnected reservoirs which represents the physical elements in a catchment in which they are recharged by rainfall, infiltration and percolation and are emptied by evaporation, runoff, drainage etc. Semi empirical equations are used in this method and the model parameters are assessed not only from field data but also through calibration. Large number of meteorological and hydrological records is required for calibration. The calibration involves curve fitting which makes the interpretation difficult and hence the effect of land use change cannot be predicted with much confidence. Many conceptual models have been developed with varying degree of complexity. To summarize, conceptual models of sediment are analogous in approach to those of surface runoff, and hence, embody the concepts of the unit hydrograph theory.

Johnson (1943) was perhaps the first to derive a distribution graph for suspended sediment concentration employing the hypothesis analogous to that embodied in the unit hydrograph. Rendon-Herrero (1978) extended the unit hydrograph method to directly derive a unit sediment graph (USG) for a small watershed. Williams (1978) extended the concept of an instantaneous unit hydrograph (IUH) to instantaneous unit sediment graph (IUSG) to determine the sediment discharge from an agricultural catchment. The concept of USG has been also employed by Singh et al. (1982), Chen and Kuo (1986), Kumar and Rastogi (1987), Raghuwanshi et al. (1994), Banasik and Walling (1996), among others, for the purpose of estimating the temporal variation of sediment yield. Kalin et al. (2004) developed a modified unit sedimentograph approach for identification of sediment source areas within a watershed.

4.4.1 Concluding remarks on conceptual models

Spatial lumping of model domains into morphological units or sub-catchments, and application of lumped parameter values across units and time scales is common in conceptual models. Therefore, the main limitations of the conceptual models lie in the poor physical description of the processes which, among other things, results in distortion of parameter values determined by calibration (Elliot et al., 1994). Because the parameter values are determined through calibration against observed data, conceptual models tend to suffer from problems associated with the identifiability of their parameter values (Jakeman and Hornberger, 1993).

4.5Physically-Based Models

Significant research and understanding of basic processes of erosion and sediment transport led to the development of more complicated, physically-based sediment models. These models have been developed in a coupled structure such that the algorithms for computing runoff are combined with the algorithms for computing sediment detachment, deposition and their transport. The physically-based sediment models involve solutions to the simultaneous partial differential equations of mass, momentum and energy conservation for simulation of hydrological and erosion processes which are non-linear in nature.

The fundamental relationship normally used in overland flow erosion model is given as follows (Bennett, 1974; Foster and Meyer, 1975).

$$\frac{\partial q_s}{\partial x} + \rho_s \frac{\partial (C_s h)}{\partial t} = D_i + D_r \quad (4.2)$$

Where q_s = sediment discharge [$ML^{-1}T^{-1}$], ρ_s = mass density of the sediment particles [ML^{-3}], C_s = concentration of the sediment being transported [L^3L^{-3}], h is the depth of flow [L], D_i = detachment by raindrop impact [$ML^{-2}T^{-1}$] and D_r = detachment by flow [$ML^{-2}T^{-1}$]. The term $\partial q_s / \partial x$ is build-up or loss of sediment load with distance and $\rho_s \, \partial (C_s h) / \partial t$ is storage rate of sediment within the flow depth and D_r and D_i are the contributions from lateral flow.

When quasi-steady sediment transport is assumed, the mass continuity equation (Equation4.1) for down slope sediment transport is expressed as follows (Curtis, 1976; Thomas, 1976; Foster and Huggins, 1977).

$$\frac{dq_s}{dx} = D_r + D_i \quad (4.3)$$

where, q_s is sediment load per unit width per unit time (sediment flux); x is down slope distance; D_r is the net rate of rill flow detachment or deposition, i.e., rill erosion; and D_i is the rate of soil particles detached by inter-rill erosion. Rill detachment (or deposition), D_r, may be assumed to be as given by Equation (4.3) (Foster and Meyer, 1975).

$$D_r = \alpha \cdot (T_c - q_s) \quad (4.4)$$

where, α is the first order reaction coefficient for deposition [L^{-1}], and T_c is the transport capacity [$ML^{-1}T^{-1}$]. The Equation (4.2) may be rewritten as (Foster and Meyer, 1972):

$$\frac{D_r}{D_{rc}} + \frac{q_s}{T_c} = 1 \quad (4.5)$$

where $D_{rc} (= \alpha \, T_c)$ is the rill erosion detachment capacity rate [$ML^{-1}T^{-1}$]. The first order reaction coefficient for overland deposition can be computed using Equation (4.5).

$$\alpha = \varepsilon \cdot V_s / q \quad (4.6)$$

where V_s is the fall velocity $[LT^{-1}]$ and q is the discharge per unit width $[L^2T^{-1}]$. The value of ε for overland flow can be taken as 0.5 and 1.0 for channel flow (Foster, 1982).

The physically-based erosion models generally separate the ground surface into inter-rill and rill erosion areas (Wu et al., 1993; Meyer et al., 1975; Kothyari and Jain, 1997). As such, these models consist of three major component processes viz. inter-rill erosion, rill erosion and transport process as discussed below.

4.5.1 Inter-rill erosion process

Raindrop impact on soil surface, and velocity and depth of flow over the surface are the factors that affect the amount and rate of inter-rill and rill erosion in a catchment. Both detachment and transport of sediment particles occur on inter-rill and rill areas. Since Ellison (1947), many researchers have investigated this process and related it with the physiographic, land use, soil characteristics, management practices such as contouring etc. and proposed the relationships for modeling in the watershed. The important relationships proposed by various researchers for computation of inter-rill erosion are summarized by Tyagi (2007).

4.5.2 Rill erosion process

Erosion in rills has been attributed to component processes including scour, head-cutting, sidewall sloughing, and slaking (incipient failure, or mass erosion). Equations that describe rill erosion have generally been limited to describing the scouring process through relation of flow, shear, and slope. Almost all natural soil surfaces where flow occurs are irregular causing shear stress concentrations. If stress at these concentrations is greater than the soil's critical shear stress, soil erosion occurs. Total rill erosion on an area can be modelled by describing soil erosion in each individual rill (Foster and Meyer, 1975). To date, physically-based rill erosion models have been based almost exclusively on shear stress excess concept (Haan et al., 1994). The relationships developed for the rill erosion process in the watersheds are summarised by Tyagi (2007).

4.5.3 Transport process

Once sediment particles are detached, they become part of the overland flow and are transported downstream to distances varying from a few millimetres to hundreds of kilometres. The distances so traversed are dependent on the sediment transport capacity of the flow, which in-turn depends on sediment characteristics and hydraulic parameters associated with flow path (Haan et al., 1994). No single sediment transport equation is said to be superior to others as all these equations require calibration for representing sediment transport by overland flow (ASCE, 1975). A summary of the important relationships for overland flow transport capacity are given in Tyagi (2007).

4.5.4 Concluding remarks on physically-based models

Physically-based models are expected to provide reliable estimates of sediment transport. In theory, the parameters used in physically-based models are measurable and so are 'known'. However, in practice, the large number of parameters involved and the heterogeneity of important catchment characteristics require that these parameters must often be calibrated against observed data (Beck et al., 1995; Wheater et al., 1993). This creates uncertainty in parameter values. Given the large number of parameter values needed to be estimated using such a process, problems with a lack of identifiability of model parameters and non-uniqueness of 'best fit' solutions can be expected (Beck, 1987; Wheater et al., 1993).

The physics behind the model structure are generally based on laboratory or small-scale in-situ field experiments, and hence are affected by the nature of the experiments themselves. Extrapolation to larger (e.g. catchment) scales often involves the assumption that the physical processes and properties are independent of scale, raising uncertainty about their applicability (Beven, 2004). To reduce computational burden and data requirements, simplified physics are sometimes used to represent the physics (e.g. simplified St. Venant equations, the Green-Ampt equation [Green and Ampt, 1911; Mein and Larson, 1973)], leading to deviation from the physical basis and additional questionability.

The practical applications of physically-based models are still limited in developing countries because of large number of input parameters, uncertainty in specifying model parameter values and also due to the difference between the scales of application i.e. a catchment versus a field (Wu, et al., 1993).

4.6 Selecting an Appropriate Model

All types of mathematical models are useful but in somewhat different circumstances. Each has its own effectiveness, depending upon the objective of study, the degree of complexity of the problem, and the degree of accuracy desired. There is no conflict between these models; they represent different levels of approximation of reality. In their review of erosion and sediment transport models, Merritt, et al. (2003) have presented important aspects that need to be considered in selecting an appropriate model and some of them are produced below for the benefit of model users.

4.7 Model Structure

Choice of a suitable model structure relies heavily on the purpose that the model needs to serve. Within the literature, the preferences of researchers for certain model types over others largely reflect two main viewpoints: emphasis on the processes at work or emphasis on the output (Merritt et al., 2003). For example, Thorsen et al. (2001) considered that 'the predictive capability of empirical and conceptual models with regards to assessing the impacts of alternative agricultural practices is questionable, due to the semi-empirical nature of the process description'. Yet, other authors argue that simple conceptual models, or empirical models, when used within the developed framework, can be more accurate than models with more complicated structures (e.g. Ferro and Minacapilli, 1995; Letcher et al., 1999). Perrin et al. (2001) noted that models with a larger number of parameters generally yield a better fit to observed data during the calibration period than more simple models, although in the verification phase this trend of improved performance is not apparent. Simpler models tend to be more robust, thus providing more stable performances than more complicated models. Overly complicated models with large numbers of processes considered, and associated parameters, run the risk of having a high degree of uncertainty associated with the model inputs which are translated through to the model outputs. The ultimate factor determining a model's value is its simplicity relative to its explanatory power (Steefel and Van Cappellan, 1998).

4.8 Spatial Representation

Traditionally, models have treated input parameters as lumped over the area of analysis. In the last two decades, however, lumped models have been challenged by distributed hydrologic models. Distributed hydrologic models, with the capability to incorporate a variety of spatially-varying land characteristics and precipitation forcing data, are thought to have great potential for improving hydrologic forecasting. However, uncertainty in the high resolution estimates of precipitation and model parameters may diminish potential gains in prediction accuracy achieved by accounting for the inherent spatial variability. In distributed models, parameters need to be defined for every spatial element and for each process representing equation. In principle, parameter adjustment should not be necessary for this type of model because parameters should be related to the physical characteristics of the surface, soil and land use. However, in practical applications, calibration procedures are required for both lumped and distributed models; consequently, the models require effective or equivalent values for some parameters. Despite these difficulties, there has been a strong surge in the use of distributed modeling specially for soil erosion and sediment transport modeling over the last decade. Ferro and Minacapilli (1995) argue that the dependence of the sediment delivery process on local factors, such as sediment detachment and flow transport travel time, emphasises the need to use a spatially distributed approach for modeling this phenomenon. However, in most practical applications, little geographical and spatial information is available.

A compromise between fully distributed methodologies and lumped models are the semi-distributed models that break a catchment down into a group of sub-catchments or other biophysical regions over which the model is applied. Ultimately the choice between lumped or distributed models depends on the desired output of the model. Increasingly, resource managers are requiring knowledge of the origin of the major sources of pollutants or sediments. Distributed models have the potential to assist management in this situation if the data requirements do not inhibit model application.

4.9 Temporal Resolution

A key consideration in determining an appropriate model for application is the timing of the events or processes that the model user wants to predict. Sediment-associated water quality or erosion models tend to have been developed from two opposed viewpoints. Event-based models were developed to look at the response of the modelled area to single storm events. For each event, the model time-step is of the order of minutes to hours. The model algorithms that describe these processes were often developed for application to small plots or grid cells in a catchment. Alternatively, a larger temporal resolution was used and models were applied to explore broad trends over time to changes in rainfall, vegetation or land management. A third approach was to use a continuous time step, usually daily, that is responsive to, for example, the development and recession of saturated zones or other processes that can be captured at this time step, yet does not capture responses to high intensity and short duration events.

4.10 Review of Popular Erosion and Sediment Yield Models

A multitude of erosion and sediment transport models are available now a day that differ in complexity, the processes modelled, the treatment of the sediment generation, transport and deposition processes, the scale to which they are applied, and assumptions on which they are based. Some of the commonly used models are reviewed in this Section.

4.10.1 Universal Soil Loss Equation (USLE) and Modifications

The USLE (Wischmeier and Smith, 1965) is the most widely used and accepted empirical soil erosion model Equation (4.1). It predicts the long-term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system and management practices. USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion. Model outputs are both spatially and temporally lumped. This erosion model was created for use in selected cropping and management systems, but is also applicable to non-agricultural conditions such as construction sites. The USLE can be used to compare soil losses from a particular field with a specific crop and management system to "tolerable soil loss" rates. Alternative management and crop systems may also be evaluated to determine the adequacy of conservation measures in farm planning.

Five major factors are used to calculate the soil loss for a given site as explained in sub-section 3.1.1. Each factor is the numerical estimate of a specific condition that affects the severity of soil erosion at a particular location. The erosion values reflected by these factors can vary considerably due to varying weather conditions. Therefore, the values obtained from the USLE more accurately represent long-term averages.

Although developed for application to small hill-slopes, the USLE and its derivatives have been incorporated into many catchment scale erosion and sediment transport modeling applications. Due to the identified limitations of the USLE, a number of modifications and revisions to the basic format have been proposed in the literature. These include the modified USLE (Williams, 1975), the revised USLE (Renard and Ferreira, 1993; Renard et al., 1994), and the USLE-M (Kinnell and Risse, 1998). These continue to improve components of the model making it more process-based.

4.10.2 AGNPS

The Agricultural Non-Point Source (AGNPS) model (Young et al., 1987) is a single-storm event model. It simulates surface runoff, soil erosion, and transport of sediment, nitrogen (N), phosphorous (P), chemical oxygen demand (COD), and pesticides from non-point and point sources resulting from a single rainfall event. The model generates total or average responses for a storm event considering the storm duration as one time step. The watershed is divided into uniform square areas (cells).

AGNPS computes runoff volume using the SCS runoff curve number method. Peak runoff rate for each cell is computed using an empirical function of drainage area, channel slope, runoff volume, and watershed length-width ratio. Computation of soil erosion due to rainfall is based on the USLE. Detached sediment is routed using sediment transport and depositional relations based on a steady-state sediment continuity equation, effective sediment transport capacity, particle fall velocity, and Manning's equation. A modification to Bagnold's stream power equation is used for the effective sediment transport capacity.

AGNPS simulates chemical transport in soluble and sediment-adsorbed phases. Nutrient yield in the sediment adsorbed phase is empirically calculated using sediment yield, nutrient (N or P) content of the soil, and an enrichment ratio. Soluble N or P contained in runoff is computed simply by multiplying an extraction coefficient of N and P, the mean concentration of soluble N or P at the soil surface during runoff, and total runoff. AGNPS uses an N decay factor when simulating N movement through stream channels. COD is calculated based on runoff volume, with average concentration in that volume as the background concentration obtained from the literature.

AGNPS accounts for nutrient and COD contributions from point sources, such as feedlots, springs, and wastewater treatment plants, and estimated sediment contributions from stream bank, stream bed, and gully erosion as user input values. AGNPS simulates impoundments and their impacts on reducing peak discharges, sediment yield, and yield of sediment-attached chemicals.

AGNPS contains a mix of empirical and physically-based components. It is spatially distributed but temporally lumped, and is relatively robust with runtime estimates in minutes; it is suitable for both sediment and nutrient Total Maximum Daily Loads (Borah et al. 2006).

4.10.3 AnnAGNPS

The Annualized Agricultural Non-Point Source (AnnAGNPS) model (Bingner and Theurer, 2003) is a batch-process, continuous simulation watershed model developed from the single event Agricultural Nonpoint Source (AGNPS) model. AnnAGNPS was designed by the USDA Agriculture Research Service (USDA-ARS) and the USDA Natural Resources Conservation Service (USDA-NRCS) to evaluate nonpoint source (NPS) pollution from agriculturally dominated watersheds. The model simulates the same processes as AGNPS (surface runoff, soil erosion, and transport of sediment, nutrients, and pesticides) plus snowmelt, irrigation, subsurface flow, tile drain flow, feedlots, and gullies at continuous daily or sub-daily time steps.

AnnAGNPS allows the user to select either a grid (or cell) spatial representation or a hydrologic response unit spatial representation, with the selected unit being characterized by homogeneous land and soil properties. AnnAGNPS hydrologic simulations are based on a simple water balance approach. The runoff volume is computed using the SCS runoff curve number method, and the sediment yield routine is upgraded to the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) for erosion computations. Refereed AnnAGNPS applications are predominantly for sites in the U.S. (e.g., Yuan et al., 2001; Yuan et al., 2002; Polyakov et al., 2007); however, applications in other countries have also been published, e.g., Australia (Baginska et al., 2003), Canada (Das et al., 2006), and China (Hong et al., 2005).

4.10.4 ANSWERS

The ANSWERS (Areal Nonpoint Source Watershed Response Simulation) model (Beasley et al., 1980) includes a conceptual hydrological process and a physically based erosion process. The erosion process assumes that sediment can be detached by both rainfall and runoff but can only be transported by runoff. ANSWERS model divides a watershed into small, independent elements. Within each element the runoff and erosion processes are treated as independent functions of the hydrological and erosion parameters of that element. In the model, surface conditions and overland flow depth in each element are considered uniform. No rilling is considered (Aksoy and Kavvas, 2005). The effect of rills is assumed to be described by the roughness coefficient of the Manning equation used in the model. According to ANSWERS subsurface return flow and tile drainage are assumed to produce no sediment. A detached sediment particle is reattached to the soil, if it deposits. Detachment of such a particle requires the same amount of energy as required for the original detachment. Channel erosion is negligible. In the erosion part, the differential equation given by Foster and Meyer (1972) is used. Preparing input data file for ANSWERS is rather complex (Norman, 1989) as it is the case for many physically based hydrology and erosion and sediment transport models. The model can be considered a tool for comparative results for various treatment and management strategies (Beasley et al., 1980).

The applicability of ANSWERS is limited in many catchments by the large spatial and temporal input data requirements of the model. Given the lack of such data in most catchments, parameters may need to be calibrated, raising problems with model identifiability and the physical interpretability of model parameters. There are also other potential problems with the model. Fisher et al. (1997) concluded from a spatial sensitivity analysis on the model that many outputs were insensitive to changes in the spatial distribution of input variables to the model. The authors proposed three possible explanations: lack of variability of important parameters in the study catchment; key model components were unaccounted for; or variables not subjected to spatial mixing in any run may swamp the effect of mixing. These findings indicate the possible shortcomings of the model in effectively modeling the processes addressed by the model (Fisher et al., 1997).

4.10.5 CREAMS

The CREAMS (Chemical, Runoff and Erosion from Agricultural Management Systems) model (Knisel, 1980) model was developed as a tool to evaluate the relative effects of agricultural practices on pollutants in surface runoff and in soil water below the root zone. The model consists of three major components namely, hydrology, erosion-sedimentation, and chemistry and target non-point source pollution. The hydrology component estimates runoff either by SCS curve number method or by the Green-Ampt infiltration equation depending upon the availability of data. The erosion component considers the processes of detachment, transportation and deposition. Detachment is described by a modification of USLE for a single storm event. Transport capacity of overland and channel flow is derived from Yalin's sediment transport equation. It assumes that sediment load is controlled either by the losses at transport capacity or by the amount of sediment available for transport. In simulating the nutrients, nitrogen and phosphorous attached to the soil particles are lost with the sediment; soluble nitrogen and phosphorous are lost with the surface runoff, and; soil nitrate is lost by leaching with percolating water or by plant uptake. The pesticide component estimates pesticide concentration in runoff, and the total mass of pesticide carried from the field for each storm during the period of interest.

The major drawbacks of CREAMS are its complexity, intensive data requirements, and its reliance on modified USLE relationships and parameters. This degree of empiricism employed in the CREAMS model makes it useful for planning purposes and immediate application to field conditions, but limits its use for research in the physical processes causing erosion.

The CREAMS model has been used in many parts of the world with varying degree of success. Algorithms in CREAMS have been used in numerous other models of erosion and water quality (e.g. PERFECT model, WEPP model). Model outputs are computed temporally on a daily or event basis for a field sized catchment assumed uniform in soil, topography and land use.

4.10.6 HSPF

The Hydrologic Simulation Program - Fortran (HSPF) was developed based on the 1960s Stanford Watershed Model, for the simulation of watershed hydrology and water quality (nitrogen, phosphorus, suspended sediment and other toxic organic or inorganic pollutants) (Walton and Hunter, 1996). The model is a catchment scale, conceptual model and performs typically at an hourly time step and produces a time history of water quantity and quality at any point in a watershed. The watershed is divided into sub-watersheds, each conceptualized as a group of pervious and impervious land uses all routed to a representative stream segment or a mixed reservoir. Routing is performed by assuming that the sub-watersheds, streams, and the reservoirs (impoundments) are a series of one-dimensional reservoirs.

HSPF uses a comprehensive, physically based water budgeting procedure with interaction among the various storages and processes. It accounts for interception, infiltration, evapotranspiration, snowmelt, surface runoff, interflow, groundwater loss and recharge, and base flow; these are mostly represented by empirical equations. HSPF allows routing of in-stream flows and can simulate reservoir behavior as well.

Pervious land surface erosion and transport are modelled using exponential relationships for soil detachment, detached sediment washoff, and gully erosion. Sediment from impervious areas is also modeled with buildup/washoff routines. In-stream sediment transport, deposition, and scour of sediment are simulated for each of three particle-size classes (sand, silt, and clay) based on physical properties and using published equations.

HSPF includes very detailed subroutines of nutrient dynamics and calculates individual nutrient balances at a user-specified time step, representing a series of storages and phases with transport either by runoff in the dissolved phase or attached to sediment in the particulate phase. HSPF allows for detailed inputs of field operations and fertilization rates (management activities) through its special actions module. It simulates in-stream fate and transport of a wide variety of pollutants, such as nutrients, sediment, tracers, DO, biochemical oxygen demand, temperature, bacteria, and user-defined constituents, including pesticides.

BMPs can be simulated either through land use changes, a variety of special action functions that include direct reductions of input source loads and distributions, or through the Best Management Practice (BMPRAC) module. The BMPRAC module simulates simple removal fractions for a wide variety of constituents, including sediment and many forms of nutrients. These removal fractions can vary monthly or be constant.

Primary strengths of HSPF include: flexibility, ability to simulate a wide range of user-configurable inputs, modular structure that allows use of only those components needed for a specific application, and USEPA and USGS support (Borah et al. 2006). HSPF's limitations include large input data requirements and the need of monitored data for calibration for parameterisation (Walton and Hunter, 1996).With the relatively large number of parameters required to be calibrated this raises problems associated with parameter identifiability, and the physical meaningfulness of model parameters.

4.10.7 IHACRES-WQ

The IHACRES-WQ model contains the rainfall runoff model of the IHACRES (Jakeman et al., 1990) and the STARS model (Green et al., 1999; Dietrich et al., 1999). The input data include time series data for stream flow, rainfall and, depending on the version of IHACRES, also include temperature or evapotranspiration. The STARS model requires upstream and downstream concentration for calibration purposes. Based on the instantaneous unit hydrograph, the IHACRES model is a hybrid metric-conceptual model using the simplicity of the metric model to reduce the parameter uncertainty inherent in hydrological models.

The IHACRES model is a lumped model providing outputs at the catchment outlet on daily basis. However, when linked with a model such as STARS, it can be applied in a distributed manner with IHACRES applied to individual sub-catchments and the runoff generated from each sub-catchment routed through to the catchment outlet by STARS. The STARS model, while it is distinguished from empirical models by explicitly considering the processes of particle settling, deposition and re-suspension of sediments, describes these processes with conceptual algorithms.

The main objective of the IHACRES model is to characterise catchment-scale hydrological behaviour using as few parameters as possible. The model has been applied for catchments with a wide range of climates and sizes (Croke and Jakeman, 2004). It has been used to predict stream flow in un-gauged catchments to study land cover effects on hydrologic processes and to investigate dynamic response characteristics and physical catchment descriptors. The small number of model parameters in both IHACRES and STARS suggests that the models are less likely to suffer from problems of identifiability than more complex models. However, parameters values must be calibrated against observed data. By linking the IHACRES and STARS models, the runoff and in-stream components of catchment scale sediment transport and deposition are accounted for. However, there is no land surface erosion component to the model that predicts the sediment generation due to overland erosion and the contribution of this sediment into the stream network. Likewise, contribution from gully erosion is not considered.

4.10.8 MIKE-11

MIKE 11, developed by the Danish Hydrologic Institute (DHI), is a software that simulates flow and water level, water quality and sediment transport in rivers, flood plains, irrigation canals, reservoirs and other inland water bodies. It is a 1-dimensional river model. The basic modules are a rainfall-runoff module, a hydrodynamic module, a water quality module, and a sediment transport module. MIKE-11 contains a mix of conceptual and physics-based modules.

The rainfall-runoff module includes (i) the unit hydrograph method (UHM) to simulate the runoff from single storm events, (ii) a lumped conceptual continuous hydrological model (NAM) that simulates overland flow, interflow and base flow as a function of the moisture content in each of four storages namely, the snow, surface, root zone and groundwater storages, and (iii) a monthly soil moisture accounting model. It includes an auto-calibration tool to estimate model parameter based on statistic data of comparison of simulated water levels/discharges and observations.

The hydrodynamic module provides fully dynamic solution to the complete nonlinear1-D Saint Venant equations, diffusive wave approximation and kinematic wave approximation,Muskingum method and Muskingum-Cunge method for simplified channel routing.

The erosion and transport module includes a description of the erosion and deposition of both cohesive and non-cohesive sediments (http://www.dhisoftware.com/mike11). Erosion and deposition are modelled as source or sink terms in an advection–dispersion equation. The advection–dispersion module is based on the one-dimensional equation of conservation of mass of dissolved or suspended materials. It is also possible to simulate non-cohesive sediments with the A-D module. For non-cohesive sediments, the erosion and deposition terms are described by conventional sediment transport formulations.

The water quality module simulates the reaction processes including the degradation of organic matter, photosynthesis and respiration of plants, nitrification and the exchange of oxygen with the atmosphere.

The model requires large data for its application which means that the model is likely to suffer from problems caused by error accumulation and from a lack of identifiability of model parameters in situations where model parameters must be calibrated.

4.10.9 SWAT

SWAT, Soil and Water Assessment Tool (Arnold et al., 1998) emerged mainly from SWRRB (Arnold et al., 1990), and contains features from CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1984), and ROTO (Arnold et al., 1995). It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment and agricultural chemical yields in large un-gauged watersheds or river basins. It is a continuous model and operates on a daily time step. Model components include weather, hydrology, erosion/sedimentation, plant growth, soil temperature, nutrients, pesticides, agricultural management, channel routing, and pond/reservoir routing. The model is intended for long term yield predictions and is not capable of detailed single-event flood routing.

SWAT contains a mix of empirical and physically-based components. It is a watershed scale model that uses spatially distributed data on topography, land use, soil, and weather. SWAT subdivides a watershed into a number of sub-basins for modeling purposes. Each sub-basin delineated within the model is simulated as a homogeneous area in terms of climatic conditions, but additional subdivisions are used within each sub-basin to represent different soils and land use types. Each of these individual areas is referred to as a hydrologic response unit (HRU) and is assumed to be spatially uniform in terms of soils, land use, and topography.

SWAT requires a significant amount of data and empirical parameters for development and calibration (Benaman et al., 2001). It requires specific input on weather, soil properties, topography, vegetation, and land management practices to model hydrology and water quality in a watershed. Model output include all water balance components (surface runoff, evaporation, lateral flow, recharge, percolation, sediment yield, nutrients and pesticides) at the level of each sub-basin at daily, monthly or annual time steps.

The daily water budget in each HRU is computed based on daily precipitation, runoff, evapotranspiration, percolation, and return flow from the subsurface and ground water flow. Runoff volume in each HRU is computed using the SCS runoff curve number approach. A recent addition to the model is the Green and Ampt (1911) infiltration equation to compute runoff volume. Peak runoff rate is computed using a modification to the Rational formula. Lateral subsurface flow is computed using the Sloan et al. (1983) kinematic storage model and ground-water flow using empirical relations.

The sediment from sheet erosion for each HRU is calculated using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The transport of sediment in the channel is controlled by simultaneous operation of two processes: deposition and degradation. Whether channel deposition or channel degradation occurs depends on the sediment loads from the upland areas and the transport capacity of the channel network.

The transformation and movement of nitrogen and phosphorus within an HRU are simulated in SWAT as a function of nutrient cycles consisting of several inorganic and organic pools. Losses of both N and P from the soil system in SWAT occur by crop uptake and in surface runoff in both the solution phase and on eroded sediment. Simulated losses of N and P can also occur in percolation below the root zone, in lateral subsurface flow including tile drains, and by volatilization to the atmosphere.

Pesticides are simulated as per the GLEAMS model (Leonard et al., 1987), which is based on plant leaf-area-index, application efficiency, wash-off fraction, organic carbon adsorption coefficient, and exponential decay according to half lives. The in-stream kinetics used in SWAT for nutrient routing are adapted from QUAL2E (Brown and Barnwell, 1987).

Borah and Bera (2003b) reviewed seventeen SWAT applications found in the literature. They noted that the model requires a significant amount of data and empirical parameters for development and calibration. The model was found suitable for predicting yearly flow volumes, sediment and nutrient loads. Monthly predictions were generally good, except for months having extreme storm events and hydrologic conditions. Daily predictions were generally not good.

Gassman et al. (2007) reviewed a large number of peer-reviewed published applications of SWAT. The ability of SWAT to replicate hydrologic and/or pollutant loads at a variety of spatial scales on an annual or monthly basis was confirmed in numerous studies. However, the model performance was found inadequate in some studies, especially when comparisons of predicted output were made with time series of measured daily flow and/or pollutant loss data. These weaker results underscore the need for continued testing of the model, including more thorough uncertainty analyses, and ongoing improvement of model routines. Some users have addressed weaknesses in SWAT by component modifications, which support more accurate simulation of specific processes or regions, or by interfacing SWAT with other models.

4.10.10 SWRRB/SWRRB-WQ

The Simulator for Water Resources in Rural Basins (SWRRB, Arnold et al., 1990) was developed by the Grassland, Soil, and Water Research Laboratory of the Agricultural Research Service (ARS) of the USDA. SWRRB is designed to predict the effect of various types of watershed management practices on water and sediment yield in un-gauged agricultural watersheds. The major processes reflected in the model include precipitation, surface runoff, percolation, lateral sub-surface flow, evapotranspiration, pond and reservoir evaporation, erosion and sedimentation, soil temperature, crop growth, and irrigation. Precipitation may be either inputted or developed by the model as a Markov process using inputted probabilities. SWRRB is conceptual in framework although its components utilise both physically-based and empirical algorithms to describe the major processes. SWRRB operates on a continuous basis. A watershed, based on soil, land use, and climatic characteristics, may be divided in to as many as ten sub-watersheds. The soil profile can also be divided in to as many as ten layers. The hydrologic computations are based on the water balance equation. The SCS Curve Number method is used to compute runoff volume. Sediment yield is determined using the modified universal soil loss equation and a sediment routing model.

The Simulator for Water Resources in Rural Basins – Water Quality (SWRRB-WQ) was developed by adding water quality modeling capabilities to SRRB. SWRRB-WQ simulates weather, hydrology, erosion, sediment yield, nitrogen and phosphorous cycling and movement, pesticide fate and movement, crop growth and management, pond and reservoir management and other processes (Arnold et al., 1991).

SWRRB-WQ has been used by the Agricultural Research Service, Soil Conservation Service, Environmental Protection Agency and other agencies to assess the effects of land management on off-site water quantity and quality, pollution of coastal bays and estuaries, reservoir sedimentation, and registration of pesticides.

4.10.11 WEPP

WEPP (Water Erosion Prediction Project) (Nearing et al., 1989) was developed to be used by the USDA Soil Conservation Service, USDA Forest Service, and USDI Bureau of Land Management, and other organizations involved in soil and water conservation and environmental planning and assessment. WEPP is a physically-based, continuous simulation model to predict soil erosion and sediment delivery from fields, farms, forests, rangelands, construction sites and urban areas. Although WEPP was original developed to simulate hill slopes, WEPP now includes the abilities to simulate small watersheds (500 ha or less). The WEPP model includes the following components: climate generation, winter processes, irrigation, hydrology, soils, plant growth, residue decomposition, hydraulics of overland flow, and erosion. Spatial differences in land characteristics are designated in WEPP using "strips" or overland flow elements (OFEs). Each OFE represents a region of homogeneous soils, cropping, and management.

Rainfall excess is predicted using the Green-Ampt Mein-Larson (GAML) infiltration equation. The soil water status is updated on a daily basis and is required to obtain infiltration and surface runoff volumes, the driving force in the detachment by flowing water in rills and channels. The water balance component uses information about climate, plant growth and infiltration to estimate daily potential evapotranspiration and soil and plant evaporation. WEPP divides runoff between rills and inter-rill areas. Consequently, it calculates erosion in the rills and inter-rill areas separately. The steady-state sediment continuity equation is used to predict rill and inter-rill processes (Nearing et al., 1989). Rill erosion occurs if the shear stress exerted by flow exceeds the critical shear stress while sediment load in the flow is smaller than the transport capacity of flow. Inter-rill erosion is considered to be proportional to the square of the rainfall intensity. Inter-rill area delivers sediment to rills. The model solves the non-dimensional (normalized) detachment and deposition equations. The normalized load is calculated and then is converted to the actual load.

It was found by Zhang et al. (1996b) that the model was reliable in predicting long term averages of soil loss under cropped conditions. Refereed articles of the catchment form of the WEPP model are not as numerous as applications of the hillslope WEPP model. However, some catchment applications include Cochrane and Flanagan (1999) and Covert et al. (2005) in the U.S., Ampofo et al. (2002) and Saenyi and Chemelil (2002) in Africa, and Raclot and Albergel (2006) in the Mediterranean.

4.10.12 LASCAM

A continuous (daily time interval), conceptual sediment generation and transport algorithm was coupled to an existing water and salt balance model, LASCAM (Viney and Sivapalan, 1999). LASCAM was originally developed to predict the effect of land use and climate change on the daily trends of water yield and quality in forested catchments in Western Australia. The model uses gridded topographic information to define a stream network and to disaggregate the catchment into a series of interconnected sub-catchments of area 1-5 km^2. The sub-catchments are the basic building blocks of the model. It is at the sub-catchment scale that the hydrological processes are modelled, before being aggregated to yield the response of the entire catchment.

Sediment generation in the sub-catchments is assumed to occur by erosion processes associated with surface runoff. The model is a conceptualization of the universal soil loss equation (USLE), giving daily hillslope sediment generation. Sediment transport involves the processes of channel deposition and re-entrainment, and bed degradation. The model assumes that these processes are governed by a stream sediment capacity that is a function of stream power. The developed sediment transport algorithm does not discriminate between sediment size classes. Viney et al. (2000) later coupled a conceptual model of nutrient mobilisation and transport to the LASCAM.

The inputs to the model are daily rainfall (distributed), pan evaporation and land use information (e.g. leaf area index, which is allowed to vary with time), while topographic data are needed to define the sub-catchments and the stream network. The outputs from the model, for each sub-catchment and for the total catchment, are surface and subsurface runooff, actual evaporation, recharge to the permanent groundwater table, base flow and measures of soil moisture. The model has shown considerable potential as a sediment yield model (Viney and Sivapalan, 1999) and has been used to predict water yield, salinity, sediments, nitrogen and phosphorus for the entire Swan-Avon River Basin in Western Australia.

4.10.13 KINEROS

KINEROS (KINematic EROsion Simulation) (Smith, 1981; Woolhiser et al., 1990) is composed of elements of a network, such as planes, channels or conduits, and ponds or detention storages, connected to each other. KINEROS is an extension of KINGEN, a model developed by Rovey et al. (1977), with incorporation of erosion and sediment transport components. The kinematic wave theory was initially used for estimation of runoff, and then some correction was done on infiltration section, regarding basin element, erosion and sediment transportation estimation and finally the model was named as KINEROS. KNEROS is a physically-based distributed model.

The KINEROS model components include infiltration, infiltration at the end of rain, surface flow of Hortan, flow in channels, flow in the storage, erosion and sediment transportation, channel erosion, and sedimentation in the basin. The sediment component of the model is based upon the one dimensional unsteady state continuity equation. Erosion/deposition rate is the combination of raindrop splash erosion and hydraulic erosion/deposition rates. Splash erosion rate is given by an empirical equation in which the rate is proportional to the second power of the rainfall. Hydraulic (runoff) erosion rate is estimated to be proportional to the transport capacity deficit, which is the difference between the current sediment concentration in the flow and steady state maximum concentration. Hydraulic erosion may be positive or negative depending upon the local transport capacity. A modified form of the equation of Engelund and Hansen (1967) was used for determining the steady state flow concentration. A single-mean sediment particle size was used in the formulation. KINEROS does not explicitly separate rill and inter-rill erosion. Channel erosion is taken the same as the upland erosion except for the omission of the splash erosion as it is no longer effective on erosion in the channel phase. Soil and sediment are characterised by a distribution of up to five size class intervals in the new version of the model, KINEROS2 (Smith et al., 1995). Smith et al. (1999) applied the model to a catchment in the Netherlands. It was also applied to a catchment in Northern Thailand to see its applicability for unpaved mountain roads (Ziegler et al., 2001).

4.10.14 SHESED

SHESED (Wicks, 1988) is the sediment transport component of the SHE hydrological model (Abbott et al., 1986 a, b). SHESED considers erosion as the sum of erosion by raindrop and leaf drip impacts and that by overland flow. Erosion takes place in the channel bed too. The eroded sediment is transported by overland flow to channels. Once the eroded sediment gets to the channel, it is further transported downstream. Soil erosion by raindrop and leaf drip impacts is given by an equation based on the theoretical work of Storm et al. (1987). The overland flow soil detachment is given by an equation accounting for inter-rill areas and rills together. Therefore, rills are not accounted for explicitly in the model. Ground cover, given in the raindrop detachment equation, is low-lying cover, which shields the soil from raindrop impact erosion. Canopy cover refers to taller vegetation, which shields the soil from the direct impact of the raindrops but allows the rainwater to coalesce on its surface and fall to the ground as large leaf drips (Wicks and Bathurst, 1996).

In SHESED, overland flow and sediment transport are based upon the two-dimensional mass conservation equations. Either the Ackers and White (1973) equation or the Engelund and Hansen (1967) equation is used in determining the transport capacity of flow. Selection of the transport capacity equation in SHESED is based upon a trial and error technique, and is chosen in the calibration stage of the model. Also the raindrop and overland flow erodibility coefficients are calibrated. The sediment yield simulations showed sensitivity to the erodibility coefficient. Therefore, accurate calibration is needed (Wicks et al., 1992). Particle size distribution is not considered. The equation is solved by an explicit finite difference method (Bathurst et al., 1995). Channel erosion in SHESED includes local bed erosion (bed load plus suspended load) in the channel, sediment inflow from upstream, and sediment flow from overland flow. A one-dimensional transport equation is used. Inputs of the channel component are overland flow and rainfall conditions, supplied by either SHE or taken directly from measurements. Gullying, mass movement, channel bank erosion, or erosion of frozen soil are not considered in the SHESED (Aksoy and Kavvas, 2005). It does not feedback to SHE, meaning that change at the channel bed elevation due to erosion is not given as input to SHE, as the change is very small.

4.10.15 EUROSEM

The European Soil Erosion Model (EUROSEM) is a single event process-based model with modular structure for predicting water erosion from fields and small catchments. The model is the result of 25 scientists 'attempts from 10 European countries. The catchment is split into elements for which uniform properties are assumed, these are then linked together to form a network of planes and channels. Each element requires 37 parameters that describe its soil, vegetation, micro-topography, size and slope. Rainfall is entered as break point data and different rain gauges can be assigned to different elements within the catchment.

The model simulates erosion, sediment transport and deposition over the land surface by rill and interrill processes. Runoff is routed over the soil using the kinematic wave equation. Continuous exchange of particles between water flow and soil surface is balanced within the model. Soil loss is computed as sediment discharge by a dynamic mass balance equation. Model output includes total runoff, total soil loss, the storm hydrograph and storm sediment graph. Compared with other erosion models, EUROSEM has explicit simulation of interrill and rill flow; plant cover effects on interception and rainfall energy; rock fragment (stoniness) effects on infiltration, flow velocity and splash erosion; and changes in the shape and sizes of rill channels as a result of erosion and deposition. The transport capacity of runoff is modelled using relationships based on over 500 experimental observations of shallow surface flows. Most of the work to date on evaluating EUROSEM has been concentrated in Europe.

4.10.16 Summary of Models

The foregoing review reveals that the erosion and sediment transport models are extensions of hydrological models. Therefore, erosion and sediment transport equations are coupled to existing hydrological algorithms. In such a coupling, output of the hydrological model becomes input for the erosion part of the model. A multitude of erosion and sediment prediction models have been developed by various researchers that vary significantly in the processes they represent, the manner in which these processes are represented and the temporal and spatial scales of application for which they were developed. Some models represent sediment erosion only while others include sediment deposition as well as their transport. Some models also have explicit representation of the processes to estimates soil loss from permanent gullies. Table 4.1 provides a summary of some of the models and the processes they explicitly represent.

4.11 Way Forward

Erosion is a very important natural phenomenon ending with soil loss. As a result, modeling of soil erosion and sediment transport has advanced tremendously. As is clear from the foregoing sections, a large number of models that range from simple to complex in nature are available for use in soil erosion and sediment transport modeling. Each model has got its own unique characteristics and respective applications. Some of them are comprehensive and uses the physics of underlying hydrological processes and are distributed in space and time. Determining the appropriate model for an application requires consideration of the suitability of the model to local catchment conditions, data requirements, model complexity, the accuracy and validity of the model, model assumptions, spatial and temporal variation, components of the model, and the objectives of the model user(s).Therefore, a model user must fully understand the background, potentials, and limitations of a model before using it.

The catchment managers require spatial aspects of soil erosion and sediment transport. Therefore, research efforts are required for the development of a distributed model of relatively low complexity and plausible physical basis. Alternatively, the existing models, for example SWAT and MIKE-11, which have physical basis and also incorporate land surface and in-stream processes including water quality, offer premise for application to small to very large basins for addressing a wide range of sediment and water quality associated problems. SWAT has been widely used in various regions and climatic conditions on daily, monthly and annual basis and for the watershed of various sizes and scales. SWAT has also been successfully used for simulating runoff, sediment yield and water quality of small watersheds for Indian catchments. These two models proposed here can be taken up for further assessment in Indian catchments.

Table 4.1 Summary of processes represented in erosion and sediment models (source: Merritt et al., 2003)

Model	Type*	Scale	Rainfall-runoff	Land surface sediment			Gully	In-stream sediment			Sediment associated water quality	
				G	T	D		G	T	D	Land	In-stream
USLE	Empirical	Hillslope	no	yes	no	no[a]	no	no	no	no	no	no
AGNPS	Conceptual	Small catchment	yes	yes	no	no	yes	yes	yes	yes	yes	yes
ANSWERS	Physically-based	Small catchment	yes	yes	yes	yes	no	no	no	no	no	no
CREAMS	Physically-based	field 40–400 ha	yes	yes	yes	yes	yes	no	no	no	yes	no
EMSS	Conceptual	Catchment	yes	no[b]	no	no	no	yes	yes	yes	no	no
GUEST	Physically-based	Plot	yes	yes	yes	yes	no	no	no	no	no	no
HSPF	Conceptual	Catchment	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
IHACRES-WQ	Empirical/ Conceptual	Catchment	yes	no	no	no	no	yes	yes	yes	yes	yes
LASCAM	Conceptual	Catchment	yes	yes	no	no	no	yes	yes	yes	yes	yes
LISEM	Physically-based	Small catchment	yes	yes	no	no	no	yes	yes	yes	no	no
MIKE-11	Physically-based	Catchment	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
PERFECT	Physically-based	Field	yes	yes	no	no	no	no	no	no	yes	no
SEDNET	Empirical/ Conceptual	Catchment	yes	yes	no	no[a]	yes	yes	yes	yes	yes	yes
SWAT	Empirical/ Physically-based	Catchment	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
SWRRB	Conceptual	Catchment	yes	no	no	no	no	yes	yes	yes	yes	yes
TOPOG	Physically-based	Hillslope	yes	yes	yes	yes	no	no	no	no	no	no
WEPP	Physically-based	Hillslope/ Catchment	yes	yes	yes	yes	no	yes	yes	yes	no	no

*Model classification refers to the over-arching process representation of the model. Model components generally contain a mix of empirical, conceptual and physics-based algorithms.

G: sediment generation; T: sediment transport; D: deposition.

[a] Requires a sediment delivery ratio (SDR) to compute sediment yield from gross erosion.

[b] Uses prescribed loads for a land use type.

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