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Physically based soil erosion and sediment yield models revisited

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ABSTRACT

A plenty of models exist for study of the soil erosion and sediment yield processes. However, these models vary significantly in terms of their capability and complexity, input requirements, representation of processes, spatial and temporal scale accountability, practical applicability, and types of output they provide. The present study reviews 50 physically based soil erosion and sediment yield models with respect to these factors including shortcomings and strengths. The literature generally suggests the use of models like SWAT, WEPP, AGNPS, ANSWERS and SHETRAN for soil erosion and sediment studies. Most of the developed soil erosion and sediment yield models are capable of simulating soil detachment and sediment delivery processes at hillslope scale; a limited development was found in the field of reservoir siltation and channel erosion processes. The study proposes a guideline for selection of an appropriate model to the reader for a given application or case study. The future research suggested to improve the simulation and prediction capability of physically based soil erosion and sediment yield models, and should focus on incorporation of improved global web based weather database, inclusion of sediment associated water quality and gully erosion simulation module, and improvement in reservoir siltation and channel erosion simulation processes.

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1. Introduction

Soil erosion is a major concern for environment and natural resources leading to the reduction in field productivity and soil quality resulting to land degradation. The process of soil erosion includes removal of soil material from one location via natural erosive agents such as water, wind, ice, waves and bioturbation or human-induced erosive agents such as ploughing, fertilizing, overgrazing, building, fires, off road vehicles etc. and their transportation to another location where it is deposited. Thus, erosive agents influence the process of detachment, transportation, and deposition of soil materials (Foster and Meyer, 1972). About 0.3–0.8% (2–12 million hectares) of the world's arable land is affected by excessive soil degradation every year making soil unsuitable for agricultural production (den Biggelaar et al., 2004a). According to den Biggelaar et al. (2004b), there will be additional requirement of 200 million ha of cropped area to feed the increasing population over the next 30 years. Thus to meet the world's future needs good management to protect the soil against further degradation is critical.

Soil erosion is mainly affected by natural factors, such as climate, soil, topography, vegetation and anthropogenic activities, such as soil conservation measures and tillage systems (Kuznetsov et al., 1998). Surface sealing and crusts significantly decrease infiltration, and increase runoff and erosion (Moore and Singer, 1990). Erosion is also increased by the soil water repellency i.e., hydrophobicity (Pires et al., 2006). Crucial information about erosion patterns and trends can be obtained by modelling of water-induced soil erosion which allows scenario analysis in relation to current or potential land uses (Millington, 1986). With the development of algorithm and computational capabilities supported with newly available distributed databases, like high resolution digital elevation models (DEM), radar rainfall, remotely sensed satellite data and space technology, a number of models have been developed and these are available for applications to a variety of water resource problems.

Soil erosion (water-induced) research was started in early 20th century when it was identified as severe problem in the United States (Chapline, 1929). Application of equations and models for soil erosion prediction started when a relationship between water-induced soil erosion and land slope and length was developed by Austin Zingg (Zingg, 1940), followed shortly by a relationship developed by Smith (1941) that expanded this equation to incorporate conservation practices. Expansion of this work along with large experimental plot data, formed the basis for Universal Soil Loss Equation (USLE), perhaps the paramount achievement in the field of soil erosion modelling (Wischmeier and Smith, 1965, 1978). Stanford Watershed Model (SWM) was probably the first physical model developed in 1966 capable of modelling the entire hydrologic cycle and the entire watershed (Crawford and Linsley, 1966), which was later modified as Hydrological Simulation Program-Fortran (HSPF) by incorporating Fortran version and adding water-quality processes (Bicknell et al., 1993).

1.1. Necessity and constraint of models

It is difficult to describe the rate of soil erosion in the watershed over spatial and time scales due to limitations in the field measurements for each part of the watershed. In order to ensure that measurements are not biased by a few years of abnormally high rainfall or an extreme event, long-term measurements are required to build a sufficient data base. Long-term measurements are also needed in order to investigate the response of erosion rates to alterations in climate and land use or the efficiency of erosion control measures. To counter these difficulties, computer based physical models can be used for erosion prediction over a wide range of conditions. To ensure model validity, simulation results can be compared with field measurements. Although, before validation, practically these models also require model calibration with field data and then validated model can be used for simulation of erosion in other areas of similar conditions. Models can only work when they are applied to conditions (correct spatial and temporal scales considering model accountability for erosion processes) for which they have been calibrated and, if possible, validated (Govers, 2011). A desirable model should satisfy the requirements of universal acceptability; reliability; robustness in nature; ease in use with a minimum of data; and ability to take account of changes in land use, climate and conservation practices.

1.2. Objectives of the study

The main objective of this study is to identify and review the most popular physically based soil erosion and sediment yield models and their applications in different parts of the world for performance evaluation, considering: (a) identification and brief description of existing popular physically based soil erosion and sediment yield models encompassing model developer(s)/author(s), year of development/study, input variables required, governing equation(s) used, future development ideas, capability, shortcoming and strength of the model; (b) description of algorithm or governing equations used in the models; (c) classification of models on the basis of space and time domains, scale, model accountability and their potential for integration with Geographic Information System (GIS); and (d) presentation of a few available case studies from different parts of the world, including information on study area and catchment/watershed size, land use, topography, purpose of the study, reference data used, method(s) used for performance evaluation, sensitivity analysis and findings of the study. It is believed that this study will be helpful in the selection of a suitable physically based model according to the problem at hand, conditions or situations. The current study is restricted to physically-based models incorporating soil erosion and sediment yield aspects although it is worth noting that practically no models are absolutely physical based, as large number of assumptions and empirical/conceptual procedures were usually considered in mathematical expressions describing individual processes in these models.

1.3. Benefits of physically-based models

A number of physically based soil erosion hydrological models have been developed worldwide for prediction of soil erosion and sediment yield although practically no models exist that are 100% physically based. Mathematical expressions describing individual processes in these models are based on and large number of assumptions and consideration of empirical/conceptual approaches. Physically based spatially distributed models can be used to identify critical areas by providing the output at any desired location within the watershed with increased accuracy of simulation compared to empirical or conceptual models. Specifically, when time and money are constraints, it is not possible to estimate soil erosion and sediment yield by considering the entire catchment area/watershed at the same time for implementing erosion control measures. In such a situation, physically based modelling not only helps to identify priority areas on the basis of sediment yield but also helps to evaluate the best management practices (BMPs) for the priority sub-watersheds in a short time and with minimum investments. Erosion and sediment yield models represent a powerful tool to predict the effect of man-induced as well as natural environmental changes and impacts on the sediment dynamics, however potential of most of these models to be applied to evaluate scenarios of changing land use management or climate is not too high (de Vente et al., 2013). The present generation of erosion and sediment yield models vary significantly in data handling, computational requirements and sophistication and are quite diverse and comprehensive. Due to large diversity and quite comprehensive nature of models, there exist a multitude of models to address any practical problem and the same model can be applied to a range of problems. In most cases, models mimic quite well the physics underlying hydrological processes and are also distributed in time and space. The main contributions of