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Review

Erosion and Sediment Transport Modeling: A Systematic Review

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Abstract: Soil erosion and sediment transport have significant consequences, including decreased agricultural production, water quality degradation, and modification to stream channels. Understanding these processes and their interactions with contributing factors is crucial for assessing the environmental impacts of erosion. The primary objective of this review is to identify a suitable soil erosion and sediment transport model for catchment-scale application. The study considers various model selection processes, including model capability and the spatial and temporal domains for assessing spatiotemporal distributions. The review acknowledges the limitations, uncertainties, and unrealistic assumptions associated with soil erosion and sediment transport models. Models are usually developed with a particular objective, which demands an assessment of capabilities, spatial, and temporal applicability, and catchment-scale applicability. Distributed models are often preferred for catchment-scale applications, as they can adequately account for spatial variations in erosion potential and sediment yield, aiding in the evaluation of erosion-contributing elements and planning erosion control measures. Based on the findings of this study, the authors encourage utilizing models (such as Soil and Water Assessment Tool (SWAT) or Automated Geospatial Watershed Assessment Tool (AGWA)) that can forecast net erosion as a function of sediment output for catchment erosion and sediment yield modeling. This review helps researchers and practitioners involved in erosion and sediment modeling by guiding the selection of an appropriate model type based on specific modeling purposes and basin scale. By choosing appropriate models, the accuracy and effectiveness of sediment yield estimation and erosion control measures can be improved.

Keywords: models; model applicability; sediment transport; soil erosion; sediment yield

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1. Introduction

Land and water resources are often threatened due to population growth that causes deforestation, overgrazing, and soil erosion [1]. Soil erosion, land degradation, and sediment transport are common issues within catchments [2,3]. Soil erosion can be a significant environmental concern in cultivated areas [4], as nutrients such as phosphorus attached to sediment particles reach a river system and affect the water quality of the receiving water bodies [5]. Water-induced soil erosion is still a worldwide issue reducing soil productivity and water carrying capacity [6–8]. Increased upland erosion causes sediment deposition in river channels and downstream reservoirs that reduces the water carrying capacity of channels and reservoirs [9]. Furthermore, the decrease in carrying capacity of river channels can increase the frequency of bank overflow and inundation of the surrounding area. Sediment deposition in reservoirs and other water bodies may lead to a reduction in the optimal use of reservoirs and growth of seagrass, and increase the threat of eutrophication that endangers aquatic life [10].

Predicting erosion and sediment transport requires a comprehensive understanding of sediment transport processes in surface water systems [11]. Sediment yield assessment provides valuable information about the quantity and rate of sediment deposition in estuaries and other surface water bodies [12]. This information is crucial for guiding natural resource development and informing management strategies. The transport capacity of sediment particles in moving water controls their erosion, transport, and deposition [13]. The spatially distributed and regional-scale nature of sedimentation processes makes it challenging to measure sediment movement accurately. This difficulty not only hampers the identification of sediment sources and sinks, but also makes it challenging to validate the results of sediment transport models [14]. The investigation of erosion and deposition processes has been greatly improved by the advance of remote sensing technologies, allowing for the assessment of spatial and temporal changes in sediment transport and providing valuable data for sediment modeling and management [15].

Sediment begins in the upstream channel network and upland areas as erosion, and moves downstream when the channel has sufficient stream power. The amount of sediment transported by water to downstream areas is directly related to the flow rate [16]. Higher flow rates result in greater sediment transport capacity. Smaller flood events can transport fine suspended particles, while larger flood events are needed to move larger sediment particles such as gravel, cobbles, and boulders. During moderate-intensity storms, large sediment particles are commonly trapped in the channel bed, leading to the formation of sediment bars along the channel. These bars are accumulations of sediment that can affect channel morphology. The detachment process of sediment from the catchment and the transport capacity of the channel system influences the sediment load at a particular location [17]. These factors are influenced by flow characteristics (such as flow velocity and discharge), channel shape, and human activities. It is important to assess the impact of flow characteristics, channel shape, and human activities on soil erosion and sediment transport [18].

Erosion models are mostly used in agricultural fields to anticipate typical rates of soil loss from a specified area such as a plot, a field, or a catchment/watershed. Sediment transport models, on the other hand, concentrate on numerical modeling of sediment mobilization, transportation, and settling in fluids [11]. Soil erosion models are crucial tools for understanding erosion processes and their interactions with the contributing factors [19]. They help assess the environmental impacts of erosion and sedimentation, providing valuable insights for land management and planning. Soil erosion models can be categorized into three groups based on their complexity and the level of dynamic physical processes they incorporate: empirical, conceptual, and physical based models [8]. The selection of a suitable model depends on the intended application and the characteristics of the landscape under study. It is important to assess the strengths, limitations, and uncertainties associated with each model and evaluate how well they align with study objectives [20], because different models may perform better in different environmental circumstances or spatiotemporal scales. This enables researchers and practitioners to make more informed decisions when selecting a model that best meets their objective.

Reviews of existing erosion models with different dimensions have been conducted by several scholars [13,21–26]. However, these have limitations in terms of selecting the best-fit erosion model. For example, the review conducted by De Vente et al. [27] focused specifically on models that were used for predicting soil erosion and sediment yield at regional scales. This indicates a limited scope in terms of the spatial scale considered in the review. Similarly, Pandey et al. [25] limited their review to physical soil erosion and sediment yield models, excluding empirical and conceptual models. These limitations highlight the need for a comprehensive review that considers various dimensions and types of soil erosion model. It is important to evaluate the practical application and selection of the best-fit erosion model based on a range of criteria, including model capabilities, spatial and temporal scale applicability, data requirements, and uncertainties. As a result, the objective of this review paper is to evaluate soil erosion and sediment transport models, and recommend a suitable model for catchment-scale application. The review was carried out by analyzing the existing scientific publications on erosion and sediment transport modeling, by selecting publications based on the relevance of the abstract, keywords, title, and main document text. The following questions were addressed by this review: What are the current soil erosion and transport models in various parts of the world? What are the spatial and temporal scale applicability of the models? What erosion processes are represented by the chosen model? This review helps streamline the model selection process, saving time and effort for researchers and catchment management professionals embarking on sediment modeling studies. By considering the characteristics and requirements of their modeling task and case study basin, researchers can refer to the review to identify suitable models that align with their objectives. A clearer understanding of the available models and their strengths and limitations can enhance the accuracy and reliability of sediment modeling studies. This promotes consistency and comparability across different studies, and contributes to advancing knowledge and understanding in the field of erosion and sediment transport.

2. Methods

This paper provides a review of the applicability, reliability, strengths, and limitations of sediment transport models at different spatial and temporal scales using a systematic literature review approach. The study employed two well-known databases, Scopus and Web of Science, as well as the Google Scholar search engine, to gather relevant information. These databases were chosen for their comprehensive coverage of academic literature [28] and relevance to the study objectives. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 approach, suggested by Page et al. [29], was utilized during this study to screen and identify relevant articles. This technique provides a structured framework and visual representation that helps track the selection process of articles during a systematic review, ensuring transparency and reproducibility. Using inclusion and exclusion criteria, the relevant and required published literature was acquired from the selected relevant databases. The search criteria used were: (“catchment scale” OR “watershed scale”) AND (“sediment yield” OR “erosion” OR “sediment transport” AND model*), and the year of publication ranged from 1990 to 2022. By using a combination of specific keywords and restricting the search to a defined timeframe, the study aimed to identify relevant papers that focus on catchment- or watershed-scale sediment yield, erosion, and sediment transport modeling.

The study followed a three-stage screening process (Figure 1). The initial screening involved removing the duplicate records and evaluating the relevance of articles based on their titles, abstracts, and keywords. Out of the total number of the articles considered, approximately 154 were deemed relevant for further screening. The analysis removed 22 entries based on the relevance of the abstracts. The final level of screening includes a comprehensive review of the full text of the remaining articles. Following a review of the full text, 18 papers were removed based on the relevance and scope of the study. Following this screening process, 112 articles that met the criteria and scope of the study remained for further analysis and inclusion in the research. It is important to go through a systematic screening process to ensure that the selected articles align with the research objectives and criteria set forth by the study. This helps in maintaining the quality and relevance of the literature review or research synthesis.

The increasing trends observed in the use of keywords and publication types reflect the growing interest in soil erosion and sediment yield studies (Figure 2). The three types of papers included in this review were research articles, reviews, and conference papers. In terms of publication type, researchers publish more research articles than reviews (Figure 2). However, assessing prior studies is necessary to provide critical evaluations of current literature, identify research gaps, and contribute to the consolidation of knowledge on a specific area.

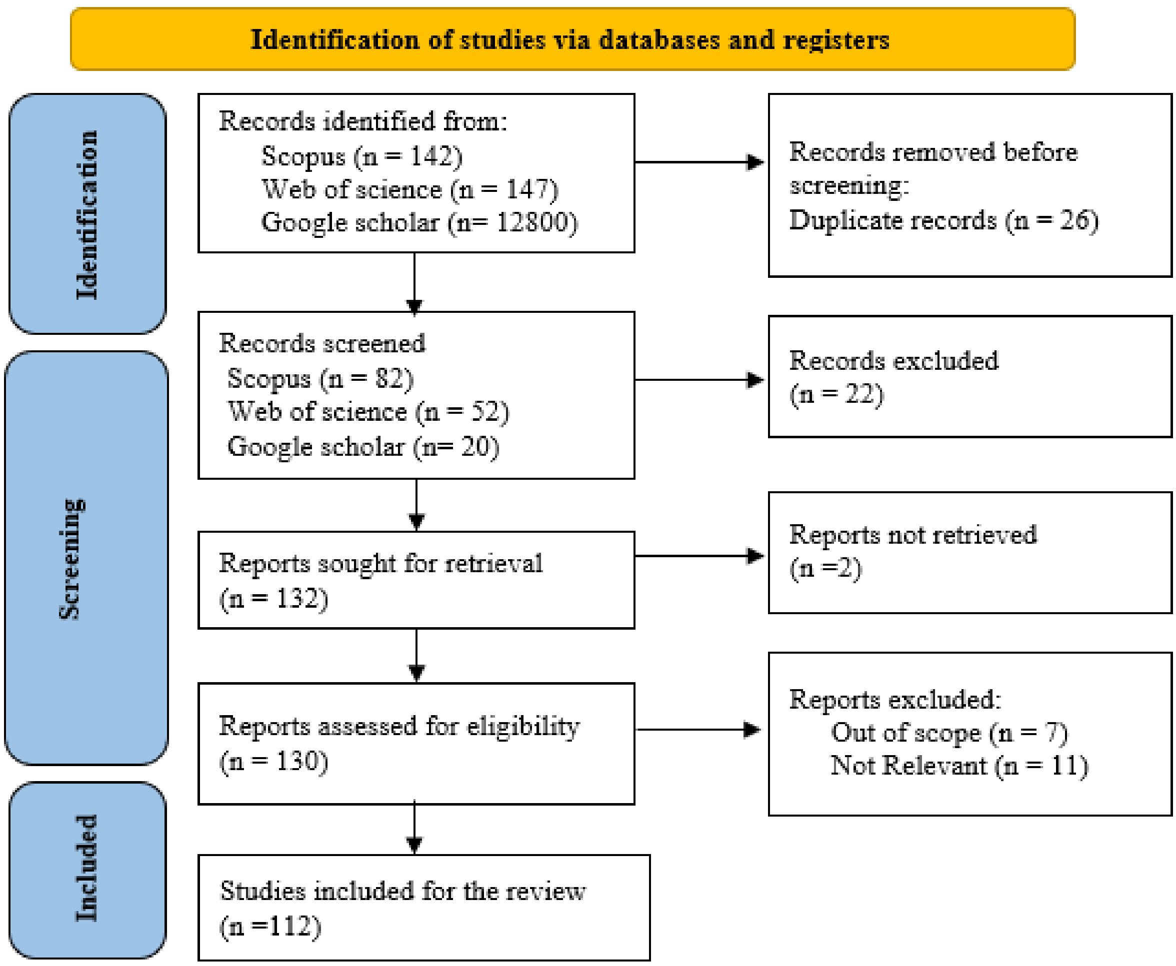

Figure 1. Data search and screening procedure applied in this study based on PRISMA 2020 (adapted from Page et al. [29]).

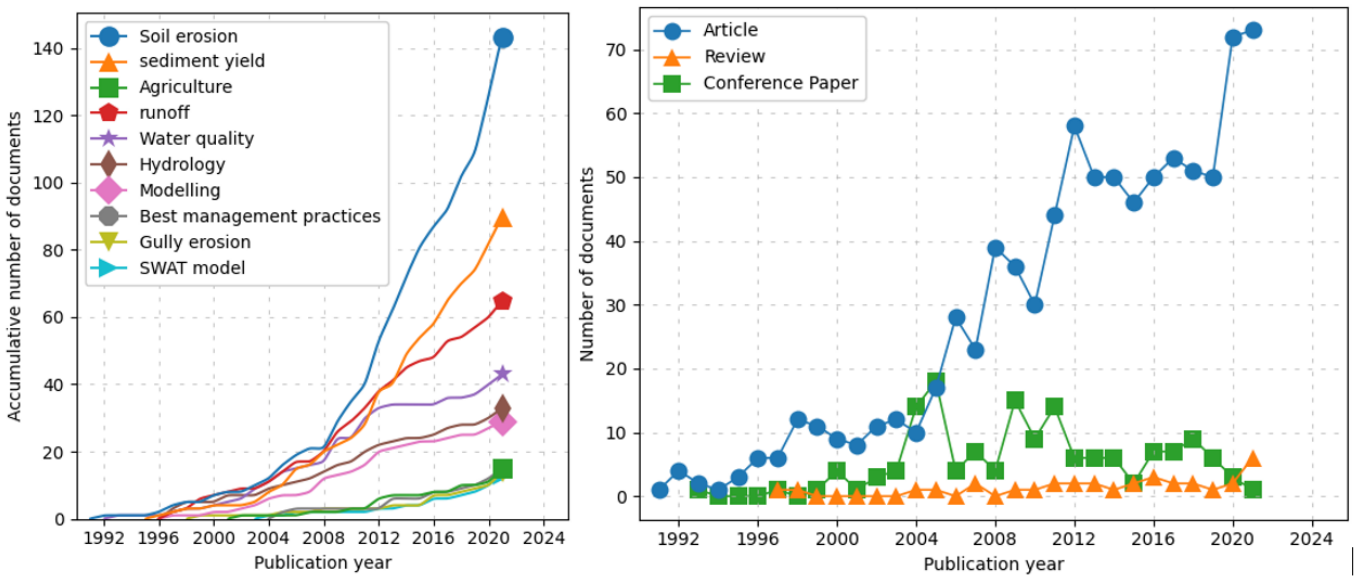

Figure 2. The total number of documents that utilized erosion-related keywords (on the **left**) and the total number of publications by document type (on the **right**).

Our review approach employs first- and second-stage model selection to identify the appropriate model that can be applied to most catchments. The first-stage model selection was based on modeling purpose, whereas the second-stage model selection follows the intercomparison of the first-stage-selected models according to watershed/catchment applicability, as well as spatial and temporal applicability.

3. Results and Discussion

3.1. Erosion and Sediment Modeling

The processes of erosion, sediment delivery, and transport of sediment constitute essential components and measurements of the earth system's functioning [30], which necessitate modeling and assessing its significance for potential management alternatives. Investigating the amount of silt entering the water system allows for the optimum long-term management approach for the utilization of the water resource [2]. The detachment and transportation of soil particles by flowing water to downstream locations is a common phenomenon [31]. These emphasize the need for sustainable land management practices, erosion control measures, and integrated water resource management to mitigate the negative impacts of water erosion and preserve the health of both terrestrial and aquatic ecosystems. To understand and plan management strategies, it is crucial to have models that can accurately model the effects of changes in agricultural land use, farming practices, and conservation measures [32,33]. In addition to modeling approaches, experimental investigations [34,35] are commonly used to study erosion and sediment transport. Experimental methods involve conducting physical experiments in controlled laboratory settings or in the field to measure erosion rates, sediment yields, and other related parameters [36,37]. Experimental investigations provide valuable data that can be used to validate and compare with model-based estimations [38]. By comparing the results obtained from experiments with those from erosion models, researchers can assess the accuracy and reliability of the models and refine their parameters or assumptions. However, it is worth noting that experimental methods for erosion and sediment yield estimations can be expensive and time-consuming.

3.1.1. Description of Erosion and Sediment Models

Many models have been developed to estimate and evaluate erosion and sediment yield problems [39] due to the model uncertainty, the assumptions and parameters that are unsuitable for local conditions [8]. Erosion models are designed for describing the erosion process and controlling factors with a specific model objective and output. The fundamental erosion process induced by water includes the detachment, transport, and deposition that can be described using models [40]. To understand how this occurs, process-based or physics-based models are built [18]. Generally, based on the physical process and other criteria, erosion and sediment transport models are classified into three types: empirical, conceptual, and physically-based [8].

Empirical models, often referred to as black box models, are based on observed data and rely on mathematical equations, such as regression relationships, to represent the relationships between input variables and the predicted output [41]. The process of computation is straightforward and the data requirement of empirical models is lower than other models [8,21]. Furthermore, empirical models may make unrealistic assumptions about the physics of the catchment system. These models often overlook the heterogeneity of inputs such as rainfall patterns and soil types within a catchment. These simplifications can affect the accuracy and reliability of the model's predictions, particularly in situations where the catchment exhibits significant spatial variability [8,21]. Despite these limitations, empirical models still have practical utility, especially in cases where data availability is limited or when only a quick assessment of erosion or sediment transport is required. Therefore, it is essential to carefully consider the specific context and limitations of empirical models when applying them in different regions or for more detailed analyses.

Conceptual models, which are more general in nature, serve as a bridge between empirical and physically-based models. The sediment continuity equation and spatially lumped water forms are used to create these models. Conceptual models predict sediment yield primarily using the unit hydrograph concept. Conceptual models combine broad descriptions of catchment processes by incorporating the detailed catchment characteristics, physical processes of runoff generation and sediment transport into their conceptual structure. The limitation of these models is their poor representation of physical processes [39].

Physically-based models are created using physical equations to predict runoff and soil loss, using the local distribution of runoff and sediment during rainfall [41]. These models are designed to denote the key mechanisms that control erosion using the majority of the factors that influence erosion with temporal and spatial variability, and subprocesses and their interconnections [39]. Approximately 55% of the models reviewed in this study were physically-based models, whereas 27% and 18% of the models were conceptual and empirical, respectively. Physically-based models are critical for identifying important erosion processes and determining sediment concentration in space and time that allows for the identification of erosion-prone areas.

Table 1 lists the models described in the studies this review examined and provides details on their capabilities and limitations. According to a recent study by Borrelli et al. [22], RUSLE, SWAT, and WaTEM/SEDEM are increasingly being employed worldwide.

3.1.2. Erosion Modeling Capability

Models have been developed to simulate one or more factors of erosion, including sediment yield, sediment budget, stream bank erosion, riparian erosion, sheet, and rill erosion. These modeling aspects predict either gross or net erosion within the study catchment. In this review, 53 models were investigated and categorized depending on the kind of erosion and modeling focus (Table 2). Several models, including AGNPS, AGWA, AnnAGNPS, ANSWERS, STREAM, SWAT, and SedNet, have been used for sediment yield modeling to estimate net erosion. Furthermore, models capable of simulating sediment yield and runoff are essential for developing the relationship between sediment yield and runoff because runoff is the primary contributor to the sediment transport process.

Table 1. List of erosion and sediment transport models reviewed, with their capability and limitations indicated.

Model Acronym	Space Domain		Time Domain		Scale		GIS Integration	Modeling Capability	Model Limitation	Model Type	Source
	L	D	C	E	F	W					
AGNPS		✓		✓		✓	High	Er, SY, R, nutrient	Suitable for catchments, simulates only single rainfall events	Conceptual	[42]
AnnAGNPS		✓	✓			✓	High	SY, R, nutrient	Requires large data input, does not allow for spatial variablity of rainfall	Conceptual	[43]
LASCAM		✓	✓		✓	✓	High	SL, R, salt fluxes	Low prediction capacity during calibration	Conceptual	[44]
MMMF	✓		✓		✓			ER, R, SY, SD		Conceptual	[45]
RillGrow		✓		✓	✓		Low	Rill formation	Simulates only single rainfall events	Conceptual	[46]
SedNet		✓	✓			✓		SS, SD, overland flow		Conceptual	[47]
STREAM		✓		✓		✓		Er, ST	Simulates only single rainfall events	Conceptual	[48]
SWAT		✓	✓	✓		✓	High	Er, SY, R, nutrient	Requires large data input, low capacity in stream channel erosion and deposition analysis	Conceptual	[49]
SWIM		✓	✓			✓	High	SL, R, nutrient	Does not simulate gully erosion, relatively complex	Conceptual	[50]
SWM/HSPF	✓		✓			✓	High	SL, R, nutrient	Requires calibration of several parameters	Conceptual	[51]
SWRRB	✓		✓	✓		✓	Moderate	sediment, R, nutrient and pesticide	Uncertainty in model parameter estimations	Conceptual	[52]
TOPMODEL		✓	✓	✓		✓	High	SY, R	Suitable only for shallow homogenous soil watersheds	Conceptual	[53]
USPED	✓			✓	✓			Er		Conceptual	[54]
WATEM/SEDEM		✓	✓		✓		Moderate	Er, Dp, ST	Requires large data input	Conceptual	[55]
EGEM		✓	✓	✓	✓	✓	High	Gully formation	Requires large data input	Empirical	[56]
EPIC	✓		✓	✓	✓		Low	SL, nutrient	Limited to field-scale application only	Empirical	[57]
EPM		✓	✓		✓			EI, SP, ST	Model performance subjected to specific characteristics and sedimentary regime	Empirical	[58]
MUSLE	✓		✓			✓	High	Er, SY	Complexity for calibration	Empirical	[59]
PSIAC	✓		✓			✓		Upland and channel Er, Dp	Model is sensitive to changes of different factors	Empirical	[60]
RUSLE	✓		✓			✓	High	Er, process-based	Does not simulate gully or stream-channel erosion, not suitable for slope length factor more than 25	Empirical	[61]
SEDD	✓		✓			✓		SY	Reliability of model decreases from the annual scale to the event scale	Empirical	[62]
TMDL		✓	✓			✓		SL, nutrients	Needs conversion of transport capacity into erosion coefficient, factor determination is difficult	Empirical	[63]
USLE	✓		✓			✓		Er	Does not simulate events that are likely to result in large-scale erosion	Empirical	[61]
AGWA		✓	✓			✓	High	Er, SY, R, nutrients		Physically-based	[64]

Table 1. *Cont.*

Model Acronym	Space Domain		Time Domain		Scale		GIS Integration	Modeling Capability	Model Limitation	Model Type	Source
	L	D	C	E	F	W					
ANSWERS		✓		✓		✓	High	Er, SY, R, nutrients	Consider erodibility as a time-constant parameter	Physically-based	[65]
CAESAR		✓		✓		✓		Er, ST	No rainfall–runoff interaction	Physically-based	[66]
CASC2D		✓	✓	✓		✓	Low	SY, Er/Dp	Does not simulate sub-surface flow, reservoir flow and channel sediment, and relies on a single storm event	Physically-based	[67]
CREAMS		✓	✓	✓	✓		Low	Er, Dp		Physically-based	[68]
DWSM		✓		✓		✓	Moderate	Er, SY, R, flood, agrochemical transport	Slow computing speed, uncertainties in input parameter data	Physically-based	[69]
EROSION-2D/3D		✓		✓		✓	High	Sediment dynamics	Needs maximum computational efforts	Physically-based	[70]
EUROSEM		✓		✓	✓		High	Er, SY, R	Lesser precision for large catchments	Physically-based	[71]
GLEAMS	✓		✓	✓	✓		Low	Er, SY	Uncertainty in model validation and parameter estimation	Physically-based	[72]
GSSHA		✓	✓	✓		✓	High	Er, Dp, ST, detachment, raindrop impact	Does not simulate the sub-surface flow component	Physically-based	[73]
GUEST		✓		✓	✓		Low	SS, R	Requires large data input	Physically-based	[74]
HEM		✓		✓	✓		High	Er, SY, R, SC	Need specific conditions	Physically-based	[75]
KINEROS		✓		✓	✓	✓	High	Er, SY, R	Sub-surface flow is not considered for estimating runoff	Physically-based	[76]
LISEM		✓		✓		✓	High	SY, R	Requires large data input physical parameters	Physically-based	[77]
MEDALUS	✓	✓		✓	✓		Moderate	Er, impact of land use changes	Relies on recent data inputs only	Physically-based	[78]
MIKE11		✓	✓	✓		✓	High	SY, R	Requires large data input and physical parameters, use of 1D equations to represent 3D processes	Physically-based	[79]
MIKE-SHE		✓		✓	✓			Er, SY		Physically-based	[80]
OPUS		✓	✓		✓		High	Er, SS, R, nutrient		Physically-based	[81]
PEPP-HILLFLOW		✓		✓	✓		Moderate	Er, Dp, sediment and phosphorous transport	Simulates only single rainfall events, large data input requirement	Physically-based	[82]
PERFECT	✓			✓	✓		Low	Er, SY, R	Require detailed information on crop management and tillage practices	Physically-based	[83]
PESERA	✓		✓			✓	High	Er, R	Flow routing is not well developed	Physically-based	[84]
RUNOFF		✓		✓		✓	High	Er, R, crop yield	Uncertainties in input parameter estimations and model validation	Physically-based	[85]
SHE/SHESED		✓	✓	✓		✓	High	Er, SY, R	Does not simulate gully erosion	Physically-based	[86]
SHETRAN		✓		✓		✓	High	SY, Er/ Dp, pollutants transport	Uses very large grids and does not simulate flow through an unsaturated zone	Physically-based	[87]

Table 1. *Cont.*

Model Acronym	Space Domain		Time Domain		Scale		GIS Integration	Modeling Capability	Model Limitation	Model Type	Source
	L	D	C	E	F	W					
TOPOG		✓		✓		✓	Moderate	Erosion hazard, water logging, solute transport	Requires large data input and physical parameters	Physically-based	[88]
WEPP		✓	✓	✓		✓	Moderate	Er, SY, R	Requires large data input, does not simulate in permanent channels	Physically-based	[89]
WESP		✓		✓		✓	Moderate	Er, SY, R	Intensive computation of input parameters	Physically-based	[90]
APEX		✓	✓		✓		High	Er, land Management strategy, soil quality	Suitable only for field-scale and small catchments, less developed sub-surface drainage and water table fluctuation routine	Physically-based	[91]
IDEAL	✓			✓		✓	Low	SY, Er	Simulates only single rainfall events	Physically-based	[92]
MEFIDIS		✓		✓		✓	Low	Er, R	Soil erosion is based on extreme rainfall events, low potential for GIS integration	Physically-based	[93]

L = lumped, D = distributed, C = continuous, E = event, F = field, W = watershed/catchment, Er = erosion, EI = erosion intensity, SY = sediment yield, SP = sediment production, R = runoff, ST = sediment transport, SS = Suspended Sediment, Dp = Deposition, SC = sediment concentration, SD = sediment distribution, SL = sediment load.

Table 2. Modeling capability and erosion type modeled by erosion and sediment models.

Modeling Focus	Erosion Type	Model Name
Sediment yield	Gross erosion	GLEAMS, GUEST, HEM PERFECT, PESERA, RUSLE, SWIM, USLE
	Net erosion	AGNPS, AGWA, AnnAGNPS, ANSWERS, APEX, DWSM, EPM, HSPF, KINEROS, LISEM, MEDALUS, MEFIDIS, MMF, MUSLE, PSIAC, RUSLE/SEDD, RUSLE-SDR, SedNet, SHESED, SHETRAN, STREAM, SWAT, TOPOG, USLE2D, WEPP
Sediment budget	Gross erosion	DWSM, RMMF/SEDD, SEDEM, USLE
	Net erosion	CAESAR, EPM, Erosion2D/3D, EUROSEM, MUSLE, RUSLE-3D, RUSLE-SDR, SedNet, STREAM, SWAT, USLE-SDR, WEPP-Road
Stream bank erosion	Gross erosion	USLE, RUSLE
	Net erosion	WEPP, RUSLE-SDR, LISEM
Riparian erosion	Gross erosion	MIKE-SHE, USLE, PESERA, RUSLE
	Net erosion	GLEAMS, SWAT
Rill erosion	Gross erosion	RUSLE, EPIC
	Net erosion	USLE-SDR, RHEM
Sheet and rill	Gross erosion	CREAMS, Erosion 3D, GLEAMS, PEPP, PERFECT, PESERA, RUSLE, RUSLE-SEDD, STREAM, USLE,
	Net erosion	APEX, EPIC, HSPF, LISEM, MEDALUS, MMF, OPUS, RUSLE/SEDD, RUSLE-SDR, SED, SEDD, SEDEM, SLEMSA, USLE-SDR, WEPP
Gully erosion	Gross erosion	CREAMS, EGEM, WEPP, AnnAGNPS-REGEM

Some models, such as RUSLE, SWAT, GLEAMS, PESERA, LISEM, MMF, STREAM, and WEPP, can execute multiple modeling tasks. Similarly, the models PERFECT, APEX, DWSM, EPM, HSPF, MEDALUS, MUSLE, and SedNet can simulate two modeling focuses. The rest of the models are solely designed to model a single function. By considering the specific requirements of the study, such as the available data, study area characteristics, and research objectives, researchers can make an informed decision regarding the most appropriate model to use. The purpose of erosion and deposition studies is primarily on understanding the processes and estimating net erosion or sediment deposition in a watershed [94]. There are several models that can simulate erosion and deposition processes at different scales and levels of complexity. The majority of erosion models fail to explain the gully formation process [95]. Different models have different strengths, weaknesses, and application areas that must be understood before employing them for a certain task. As a result, understanding the nature of the model and selecting a suitable model for a certain case study is crucial in order to produce accurate and dependable results.

3.1.3. Spatial Scale of Models

The spatial representation of physical features, such as land cover, topography, soil types, and hydrological networks, allows for a better understanding of hydrological and sedimentological processes by capturing the spatial variability of erosion-contributing elements within the catchment [18]. This information can help identify erosion hotspots, prioritize management interventions, and assess the effectiveness of erosion control measures [18,96,97]. By considering spatial variability, decision makers can make informed choices regarding the allocation of resources and the implementation of erosion control practices at specific locations. Models such as SWAT, RUSLE, AGNPS, and SedNet are widely used in erosion studies incorporating spatially distributed information and provide outputs that depict erosion rates, sediment transport, and deposition with spatial variability [27,98].

As noted earlier, erosion models can be applied at multiple scales, including plot or field, catchment, watershed, basin, regional, and continental scales. When selecting a model to perform a specified task, the spatial applicability of the model should also be considered, as some models, such as PERFECT, APEX, EUROSEM, and GLEAMS, are developed only for plot- or field-scale (small size catchment) application (Table 1). Watershed-scale erosion models are more accurate at forecasting average soil loss per year, month, or across a series of occurrences than they are at forecasting event-scale sediment yield. The spatial heterogeneity in erosion-contributing factors and the random nature of the erosion process produces variabilities in erosion and sediment yield [25].

The vast majority (36 of the total 53 models) of the erosion and sediment models studied in this review were found to be distributed (Table 1). Lumped conceptual models necessitate reasonably precise rainfall and runoff data, as well as the average areal physical properties. Lumped models did not represent the various physical catchment characteristics that influence model simulation and feature representation [23,65,99]. Some important physical catchment parameters that distributed models consider include soil properties, land use/land cover, geology, and topography, hydrometeorological data, and water abstraction. The spatial representation of the physical features of the catchment aids in demonstrating spatial monitoring and management practices based on model results. Distributed models divide the catchment into smaller spatial units or grid cells, allowing for the assessment of localized variations and the spatial patterns of erosion-contributing factors. However, the successful application of distributed models relies on the availability of relevant data. Distributed models enable the identification of erosion hotspots, the assessment of spatial variations in sediment transport, and the evaluation of management practices at localized scales. As a result, distributed models could be used in studies that concentrate on the spatial effects of erosion-contributing elements.

3.1.4. Temporal Scale of Models

The temporal scale of model simulation is an important consideration when selecting a model for erosion and sediment yield studies. Continuous models are designed for long-term simulations and allow for the analysis of temporal variations over extended periods. These models require a continuous approach to initialization, which involves running the model during a warm-up phase to allow for the model states to reach values that are no longer influenced by arbitrarily specified initial conditions. In this case, the model states achieve equilibrium and are no longer dependent on initial values [100]. On the other hand, event-based models are specifically designed to simulate individual events or short-duration occurrences. These models require a unique method for generating initial values of model states for each event. The initial values can be determined based on recent measurements, values derived from climatology, or other relevant data sources that represent the measurable physical properties of the system. Approximately 18 models were identified as continuous models, primarily suitable for long-term simulations, while around 24 models were classified as event-based models, designed for capturing short-duration events (Table 1). Additionally, there were 12 models that can operate at both continuous and event scales, providing flexibility in addressing different temporal scales as needed. Considering the appropriate temporal scale for the specific modeling objectives and the availability of data at different time scales is crucial for selecting the most suitable model. Continuous models are advantageous for analyzing long-term trends and changes, while event-based models excel at capturing individual events and their associated impacts.

By understanding the temporal characteristics of different models and matching them with the temporal variations in the erosion and sediment yield processes of interest, researchers can make informed decisions regarding model selection and ensure that the chosen model aligns with their desired temporal scale of analysis.

3.1.5. Model Performance Evaluation

Model performance evaluation is crucial for ensuring that the simulated results align with observed data and achieving a desired level of accuracy. Uncertainties in modeling are common due to the representation in hydrological process, biased model structure, data accuracy, and discrete location measurements [97]. Therefore, model calibration and validation by comparing the simulated and observed results are required for attaining a certain desired accuracy. Runoff calibration and validation are required prior to sediment yield because runoff is the primary agent for sediment transport. Manual or automatic calibration and verification techniques can be employed using a set of model performance evaluation parameters. Statistical indicators for runoff and erosion estimation such as Nash–Sutcliffe efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE), percent bias (PBIAS), and RMSE–observations standard deviation ratio (RSR) have been used to evaluate model performance. These indicators provide quantitative measures of how well the model reproduces the observed data [101]. NSE and R^2 are the most used performance evaluation statistics in hydrological and water resource research. Models may include a built-in automated or manual calibration and validation tool. SWAT, WEPP, APEX, EPIC, KINEROS, AGWA, HSPF, and MIKE-SHE models can be evaluated either manually or automatically; however, SWIM, GLEAMS, and LISEM can only be evaluated manually [102]. Sediment yield and erosion studies using the SWAT model evaluated the model's performance in various case study catchments using R^2, NSE, RSR, and PBias [103–105]. The model performance evaluation findings of SWAT, WaTEM/SEDEM, and LISEM are provided with improved calibration and validation results [22]. As a result, while selecting a model, it is vital to determine whether the model performance can be evaluated.

3.2. Model Selection

It is important to note that selecting the best-fit model is not a one-size-fits-all approach. It requires careful evaluation, validation, and calibration of the model against observed data and local conditions. Additionally, expert judgment and understanding of the specific case study area play a significant role in the model selection and interpretation of results. For the adoption of sustainable watershed management strategies, long-term continuous simulations and studies of hydrological changes are necessary [106]. The model that best fulfils the objectives of study must be carefully selected. The spatial (field, catchment, hillslope, and regional) and temporal scales of the model should be given careful consideration during the model selection process, since these are essential elements in selecting an appropriate tool for a specific study. Approved and verified models are considered ideal for simulating erosion and sediment processes under similar physiographic and climatic circumstances. Furthermore, precise data are essential for erosion and sediment prediction systems to produce credible results [8]. An erosion model must include all components that contribute significantly to the erosion process at the geographical, temporal, and local levels where the model is used. The following factors should be considered when selecting a model: dataset requirements, fundamental assumptions, accuracy and validity, objectives and capabilities, components, user-friendliness, model output scales, and model hardware requirements [8,21,27].

During the initial stage of the model selection, the model's ability to estimate sediment output and net erosion was used. In the first screening, 23 models that satisfied the initial selection criteria developed throughout this enquiry were identified (Table 3). The preliminary models were subjected to additional testing in terms of temporal and spatial domain applicability. Models with a distributed spatial domain, continuous time domain, and watershed-scale applications were chosen for modeling erosion and sediment yield in the second stage of screening.

Table 3. First-stage-selected sediment yield models with the net erosion output.

Sediment Yield Models (Net Erosion)	Space Domain	Time Domain	Scale	Model Type	Source
SWAT	Distributed	Continuous	Watershed	Physically-based	[49]
AGWA	Distributed	Continuous	Watershed	Physically-based	[64]
AnnAGNPS	Distributed	Continuous	Watershed	Conceptual	[43]
SedNet	Distributed	Continuous	Watershed	Conceptual	[47]
WEPP	Distributed	Continuous	Watershed	Physically-based	[89]
SHESED	Distributed	Continuous	Watershed	Physically-based	[86]
EPM	Distributed	Continuous	Watershed	Empirical	[58]
APEX	Distributed	Continuous	Field	Physically-based	[91]
DWSM	Distributed	Event	Watershed	Physically-based	[69]
SHETRAN	Distributed	Event	Watershed	Physically-based	[87]
AGNPS	Distributed	Event	Watershed	Conceptual	[107]
ANSWERS	Distributed	Event	Watershed	Physically-based	[65]
TOPOG	Distributed	Event	Watershed	Physically-based	[88]
KINEROS	Distributed	Event	Watershed	Physically-based	[76]
LISEM	Distributed	Event	Watershed	Physically-based	[77]
MEDALUS	Distributed	Event	Plot	Physically-based	[78]
MEFIDIS	Distributed	Event	Watershed	Physically-based	[93]
MMF	Lumped	Continuous	Watershed	Conceptual	[108]
MUSLE	Lumped	Continuous	Watershed	Empirical	[59]
PSIAC	Lumped	Continuous	Watershed	Empirical	[60]
RUSLE/SEDD	Lumped	Continuous	Watershed	Empirical	[62]
HSPF	Lumped	Continuous	Watershed	Empirical	[51]
STREAM	Distributed	Event	Watershed	Conceptual	[48]

During the second stage of the model selection, five models were identified with the ability to model sediment yield at the watershed scale (Table 4). However, due to the constraints listed in Table 4, this comparison suggests using either the AGWA or SWAT model for modeling sediment yield for watershed-level investigations. The SWAT model can predict overland and in-stream sediment formation, transport, and deposition, as well as rainfall runoff and chemical-associated sediment transport [8].

Table 4. Second-stage-selected sediment models.

Sediment Yield Models	Net Erosion	Distributed	Continuous	Watershed	Process	Remark
AGWA	✓	✓	✓	✓	Physically-based	
AnnAGNPS	✓	✓	✓	✓	Conceptual	Does not provide information about deposition in reaches
SedNet	✓	✓	✓	✓	Conceptual	Applicable to areas > 3000 km^2
SHESED	✓	✓	✓	✓	Physically-based	
SWAT	✓	✓	✓	✓	Physically-based	
WEPP	✓	✓	✓	✓	Physically-based	Applicable to areas < 2 km^2

The comparison of the selected models suggests that either the AGWA or SWAT model can be used for modeling sediment yield at the watershed scale, considering the constraints listed. AGWA, SHESED, and SWAT are physically-based and distributed models that can simulate diverse sediment processes with high GIS integration, and discretize the watershed into sub-watersheds [109]. Their capacity to analyze land-use and climate change impacts on flow and sediment processes at different temporal and spatial scales adds to their attractiveness as a modeling tool [49].

4. Summary and Conclusions

In most catchments, problems like rapid population growth, deforestation, overgrazing, soil erosion, sediment deposition, limited storage capacity, and flooding, pose substantial challenges to land and water supplies. The impacts of these factors are evident in the form of soil erosion, land degradation, and sediment transport within catchments. Erosion from upland areas plays a significant role in promoting the deposition of silt in river systems and downstream reservoirs. The decrease in the carrying capacity of river channels due to sediment deposition can lead to bank overflow and inundation of the surrounding areas during periods of high flow. This indicates the importance of maintaining an adequate channel capacity to mitigate the risk of flooding. Understanding sediment movement is crucial for predicting the transport of sediments and contaminants in surface water systems. Sediment yield assessment provides information on the volume and rate of sediment deposition from the watershed to the estuary, and helps quantify the effects of sediment transport on water quality, ecosystem health, and overall watershed functioning.

Soil erosion models are crucial in understanding and analyzing the erosion processes and their interactions with contributing factors. Numerous models have been developed for various erosion and sediment yield modeling tasks. However, no single model has demonstrated an overall integrated approach that encompasses all relevant elements at the required spatial and temporal scales. A variety of aspects must be considered when selecting an appropriate model for modeling erosion and sediment yield in a specific catchment. The modeling aim, spatial and temporal scale output requirements, watershed size, and the availability of other contributing parameters should all considered. It is critical to examine multiple models and select the most suitable based on the specific needs and characteristics of the catchment under consideration.

It is essential for software development to consider the applicability of models, considering the spatially distributed nature of inputs and outputs. This consideration allows for a more accurate representation of processes and dynamics across the catchment. Furthermore, incorporating long-term time series inputs is vital for capturing temporal variability and understanding the long-term effects of erosion and sediment transport. By including historical data, models can account for changes in land use, climate, and other factors that influence erosion processes. The selection of an appropriate model for analyzing high-resolution spatio-temporal data is also important. High-resolution data provide detailed information on the landscape, allowing for a more precise representation of erosion processes. By choosing a model that can effectively handle high-resolution data, researchers can better analyze and understand erosion and deposition patterns and impacts.

The integration of model simulation results with multi-criteria decision analysis is another valuable approach. This integration allows for the consideration of multiple factors and objectives in decision-making processes related to erosion and sediment transport. By combining modeling results with decision analysis, stakeholders can make more informed and effective decisions regarding land and water management strategies. Indeed, continuous and distributed models are often preferred for watershed scale erosion and sediment transport modeling. These models offer the advantage of representing spatially distributed processes and capturing the variability of erosion and sedimentation across the catchment.

This review contributes to future sediment modeling studies by offering insights into various models and their applicability for certain modeling tasks and case study catchments. This helps streamline the model selection process, saving time and effort for researchers who are embarking on sediment modeling studies. By examining the findings of the review, researchers can make informed decisions and select the most appropriate model for their specific needs. Overall, the future improvement of erosion and sediment transport modeling lies in better incorporating model applicability, utilizing high-resolution and quality data, and integrating model results with decision analysis. These advancements will contribute to more accurate and comprehensive assessments of erosion processes, enabling better-informed decision-making and sustainable management of land and water resources. This review, on the other hand, was limited to assessing models focused on soil erosion by water. Future scientific studies should consider model integration and performance employing high-resolution geographic data, which this review did not.

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Abbreviations

Model acronym	Model Name
AGNPS	Agricultural Nonpoint Source Model
AGWA	Automated Geospatial Watershed Assessment
ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation
AnnAGNPS	Annualized Agricultural Nonpoint Source Model
APEX	Agricultural Policy/ Environmental eXtender
CAESAR	Cellular Automaton Evolutionary Slope and River model
CASC2D	CASCade 2Dimentional
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DWSM	Dynamic Watershed Simulation Model
EGEM	Ephemeral Gully Erosion Model
EROSION-2D/3D	No acronym
EPIC	Erosion–Productivity Impact Calculator
EPM	Erosion Potential Method
EUROSEM	European Soil Erosion Model
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
GSSHA	Gridded Surface/ Subsurface Hydrologic Analysis
GUEST	Griffiths University Erosion System Template
HEM	Hillslope Erosion Model
IDEAL	Integrated Design and Evaluation of Loading Models
KINEROS	Kinematic Runoff and Erosion Model
LASCAM	Large-Scale Catchment Model
LISEM	Limburg Soil Erosion Model
MEDALUS	Mediterranean Desertification and Land Use Research Programme Model
MEFIDIS	Modelo de ErosaoFIsico e DIStribuido
MIKE11	Mike (named partially after the author Michael, Mike Abbott)
MIKE-SHE	Systeme Hydrologique Europeen
MUSLE	Modified Universal Soil Loss Equation
MMMF	Modified Morgan, Morgan and Finney
OPUS	No acronym
PEPP-HILLFLOW	Process-Oriented Erosion Prediction Program
PERFECT	Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques
PESERA	Pan-European Soil Erosion Risk Assessment Model
PSIAC	Pacific Southwest Inter-aAency Committee Method
RillGrow	No acronym
RUNOFF	No acronym
RUSLE	Revised Universal Soil Loss Equation
SEDD	Sediment Delivery Distributed
SedNet	Sediment river network model
SHE/SHESED	Systeme Hydrologique Europian/Systeme Hydrologique Europian Sediment
SHETRAN	European Distributed Basin Flow and Transport Modeling System
STREAM	Sealing, Transfer, Runoff, Erosion, Agricultural Modification Model

SWAT	Soil and Water Assessment Tool
SWIM	Soil and Water Integrated Model
SWM/HSPF	Hydrologic Simulation Program, Fortran
SWRRB	Simulator for Water Resources in Rural Basins
TMDL	Total Maximum Daily Load
TOPOG	The Terrain Analysis Hydrologic Model
TOPMODEL	TOPMODEL
USLE	Universal Soil Loss Equation
USPED	Unit Stream Power-Based Erosion Deposition
WATEM/SEDEM	Water and Tillage Erosion Model
WEPP	Watershed Erosion Prediction Project
WESP	Watershed Erosion Simulation Program

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