A distributed model for estimating erosion and deposition of sediment in the Yellow River basin

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Abstract In this paper, a spatially distributed model for simulating the water budget and estimating erosion is discussed and applied to the basin of the Wei River, the largest tributary of the Yellow River. A digital elevation model (DEM) is created from the elevation data using the ArcView GIS software package. Routing of the water and sediment to the basin outlet is performed using the simplified equations of continuity and momentum for both water and sediment. The model is calibrated by using available field data on precipitation and other climatological observations in the study area. The numerical simulation shows that the proposed mathematical model is able to adequately simulate the water and sediment budgets in the drainage basin. The model results also show that the combination of GIS and a spatially distributed model has greatly improved the capability for simulating streamflow, erosion and transport of sediment at the basin scale.

Key words China; distributed hydrological model; drainage basin; erosion; GIS; sediment; Wei River; Yellow River

INTRODUCTION

Simulating erosion, transport and deposition of sediment involves representing complex interactions of precipitation, surface and subsurface hydrological processes, soil properties, land cover and topography. For this kind of complex spatial process, conventional lumped rainfall–runoff models are of limited use. Conversely, GIS and spatially distributed models have a great potential for improving humankind's capability to understand hydrological and sediment transport processes. Although great achievements have been made in the field of hydrological research during the past several decades, the issue of how to reliably predict the erosion and deposition of sediment in ungauged river basins is still a great challenge. In the Yellow River basin, obtaining information on hydrological processes such as evapotranspiration, streamflow, and, especially, erosion and transport of sediment is also a great challenge and a key issue for integrated water resources management.

Simulating erosion and sedimentation usually requires prediction of spatially variable hydrological processes at a fine resolution. Overland flow generally detaches and transports large amounts of sediment, depending on ground slope, soil characteristics, vegetation coverage, and conservation practices, and usually varies significantly in space, even in small river basins. These and other aspects provide the argument for a finer resolution in the simulation of erosion processes. In a spatially distributed model, the spatial variability within the basin may be properly accounted for (Wigmosta *et al.*, 1994; Bemporad *et al*., 1997). Although a number of physically-based erosion models have been developed, most of them are primarily aimed at relatively small drainage basins, and few existing models can be applied to large scales where the model should account not only for hillslope and channel erosion and transport processes, but also for the integrated surface and subsurface hydrological responses which provide energy for carrying the eroded sediment (Wicks & Bathurst, 1996).

The need to reliably estimate the sediment yield in the Yellow River basin mainly arises from the necessity to control sediment deposition in reservoirs as well as in the downstream portion of the main stream. The major hydrological phenomena driving erosion and sedimentation are investigated by schematically representing the basin as a raster of square cells in this study. The requirement to represent the physical principles of erosion while maintaining an acceptable level of practicality, led to the development of a conceptually-based, distributed model, which is based on the conservation of momentum and the continuity equations of water and sediment. The drainage area is subdivided into small homogeneous square grids. The Coupled Hortonian and Dunne Flow and Sediment (CHDFS) model is proposed as a conceptually-based, spatially distributed erosion and sediment transport model at the basin scale. Application of the CHDFS to the Wei River basin shows relatively good reproduction of the observed temporal variations in sediment yield. Application to the period from 1995 to 1997 shows good reproduction of observed sediment loads, but some discrepancy in the timing of the simulated discharge peak. The resulting predictions are relatively satisfactory considering the large basin area. The following sections of this paper describe the basic assumptions leading to the CHDFS model, as well as the application of the model to the basin of the Wei River, the largest tributary of the Yellow River.

MODEL FORMULATION

The main physical processes relevant to the transport of water and sediment may be analysed by sub-dividing the computation domain into five zones: the interception zone, the storm flow zone, the subsurface zone, the groundwater zone, and the drainage zone. According to this schematic description, rainfall is partially or entirely intercepted in the interception zone. Vegetation cover is usually a major factor in such processes. In the study area, this zone also includes the snow cover, depleted according to the surface thermal energy balance (Bemporad *et al*., 1997). The soil zone is conceptually subdivided into two sub-zones, the storm flow zone and the subsurface soil zone. Water exchanges between the interception zone and storm flow zone determine evapotranspiration and the erosion and deposition of sediment. Water exchanges between the storm flow zone and the subsurface zone determine the overland flow resulting from saturation excess overland flow and infiltration excess overland flow. Saturation excess overland flow occurs when the storm flow zone becomes saturated, and infiltration excess or Hortonian overland flow occurs when rainfall intensities exceed infiltration rates. From the subsurface zone, water reaches the groundwater zone through percolation and baseflow is generated; it represents the water exchange between the groundwater zone and the drainage zone.

The spatial domain is sub-divided into many elementary cells, and each cell is modelled by solving the equations of continuity and momentum. Overland flow is responsible for most of the sediment transport in the upland area. Sediment transport mainly depends on soil characteristics, vegetation coverage, slope, and soil conservation practices. A detailed representation for the hydrological aspects of the model has been given by Xu *et al*. (2001). The mathematical relationships governing the main hydrological processes relevant to sediment transport and the basic relationships governing erosion and sedimentation in the drainage basin are briefly described below.

Storm flow zone

The equation for the conservation of mass of water in the storm flow zone is represented as:

$$\frac{\partial h}{\partial t} = \begin{cases} q_f - E_p - Q_s - q_s\,, & S_{s\max} \le h \\ q_f - \dfrac{h}{S_{s\max}} E_p - q_s\,, & S_{s\min} \le h < S_{s\max} \\ q_f - \dfrac{h}{S_{s\max}} E_p\,, & h \le S_{s\min} \end{cases} \tag{1}$$

in which q_f is effective rainfall, E_p is potential evapotranspiration, Q_s is saturated excess flow, q_s is deep percolation to the groundwater storage, and $S_{s\min}$ and $S_{s\max}$ are the minimum and maximum capacity of the surface storage, respectively. The rate of overland flow is calculated as:

$$Q_s = \frac{1}{n} i^{1/2} L (h - S_{s\max})^{5/3} \tag{2}$$

in which n is the roughness coefficient of the ground surface and i the slope of the ground surface. Once the rate of overland flow is obtained, the erosion and deposition rates may be estimated. The equation describing the sediment mass balance in the storm flow zone is:

$$\frac{\mathrm{d}V_s}{\mathrm{d}t} = \sum_{i=1}^{n} P_{ss}^{(i)} + AW_s - P_s \tag{3}$$

in which P_s is the sediment outflow from the hillslope cell, V_s is the sediment content, $P_{ss}^{(i)}$ is the ith sediment inflow routed to the cell from the n adjacent cells and W_s is the erosion rate per unit area. The sediment output from a cell is calculated as:

$$P_s = g_s \cdot L \tag{4}$$

in which L is the width of the grid, and g_s is the sediment flow rate per unit width, according to Jing *et al*. (1997):

$$g_s = \Phi \cdot q_s^{1.7} \tag{5}$$

in which q_s is the flow discharge per unit width, and:

$$\Phi = 15.54 \frac{S_0^{1.65}}{n^{0.3} D} \tag{6}$$

in which S_0 is the slope of the cell, n the Manning's roughness coefficient, and D the mean diameter of the sediment particles which may be taken as 0.025 mm < D < 0.05 mm in the midstream section of the Yellow River.

According to Mitas & Mitasova (1998), the net erosion rate of sediment may be expressed as:

$$W_s = \Psi \cdot \left(T_c - |g_s|\right) \tag{7}$$

in which Ψ is the first order reaction coefficient dependent on soil and cover properties, and T_c is the sediment transport capacity, estimated as:

$$T_c = \zeta \cdot (\rho_w g h \sin \beta)^p \tag{8}$$

in which ζ is the effective transport capacity coefficient, ρ_w the mass density of water, g the gravitational acceleration, and β the slope angle in degrees.

Drainage zone

The continuity equation for water in the drainage zone is expressed as:

$$LB \frac{\partial h}{\partial t} = \sum Q_{di} + R - E_p - Q_d \tag{9}$$

in which L is the length of the drainage area, B is the width of the channel, Q_{di} is the inflow from the ith neighbouring grid cell, and Q_d is the outflow from the cell of interest. The continuity equation for sediment in the drainage zone is expressed as:

$$\frac{\mathrm{d}V_d}{\mathrm{d}t} = \sum_{i=1}^{n} P_{ds}^{(i)} + \sum_{j=1}^{m} P_{dd}^{(j)} + P_d - P_r \tag{10}$$

in which V_d is the cell sediment content, $P_{ds}^{(i)}$ is the ith sediment inflow routed to the cell from the n adjacent hillslope cells, $Q_{dd}^{(j)}$ is the jth sediment inflow routed to the cell from the m adjacent drainage cells, and P_d is the drainage cell sediment output estimated with a formula similar to equation (4). The sediment detachment from the drainage cell is expressed as:

$$P_d = W_D \cdot A \tag{11}$$

in which A is the area of the grid cell, and W_D the detachment capacity of the flow which is estimated as follows:

$$W_D = \varsigma \cdot (\bar{\tau} - \tau_{cr})^q \tag{12}$$

in which ς is the erodibility factor, τ_{cr} the critical shear stress, q the exponent, and $\bar{\tau}$ the average shear stress of the flow in the channel acting on the soil, with:

$$\bar{\tau} = \rho_w \cdot R_s \cdot S_f \tag{13}$$

in which R_s is the channel hydraulic radius due to the soil, and S_f the friction slope, both of which are estimated as (Govindaraju & Kavvas, 1991):

$$R_s = \left(\frac{V \cdot n_c}{1.49\sqrt{S_f}} \right) \tag{14}$$

$$S_f \approx S_0 - \frac{\partial h}{\partial x} \tag{15}$$

in which n_c is the Manning's n for bare channel conditions, and V the channel velocity.

Hillslope sediment routing depends on the downslope transport of the eroded sediment by overland flow. The physically-based sediment transport model should simulate the process by comparing the transport capacity of overland flow with the amount of sediment made available for transport by upstream supply and local erosion. As long as the flow is carrying less than its capacity, local erosion can continue. Once the flow reaches its transport capacity, any excess sediment will be deposited (Wicks & Bathurst, 1996). The sediment yield of a drainage basin depends on the availability of sediment along the channel system and on the transport of the sediment to the outlet. Sediment availability for transport relies on local bed and bank erosion, sediment inflow from upstream, and sediment input by overland flow. Sediment routing involves a comparison of the availability of sediment with the transport capacity of the flow.

STUDY AREA AND DATA DESCRIPTION

The loess plateau is the most important topographic feature of the Yellow River basin. It consists of a thick layer of wind-blown deposits, with a thickness of several hundred meters. Located in the middle reach of the Yellow River, the Wei River basin is accredited as the "cradle of Chinese civilization", and constitutes the most densely populated areas of the region together with the Fen River valley. In and around the Wei River basin, the loess plateau is badly eroded by thousands of deep gullies and is the main source of sediment, contributing over 90% of the sediment yield of the Yellow River.

GTOPO30, a set of 30-arc-sec (approximately 1 km) DEMs, was used for the hydrological analysis because it is the highest resolution raster topographic data set available for the study area. The DEM simulation was carried out by applying spatial analysis functions integrated in the ArcView software. A network that represents the flow paths was produced by identifying the downstream pixel adjacent to each terrain pixel, and a unique path can be traced from each pixel to the basin outlet, as shown in Fig. 1. The DEM data were spatially aggregated to a 1512 × 1849 m resolution, resulting in a finite difference overland flow grid with 48 146 cells. The selected grid resolution provides an adequate representation of the spatial variability of soil textures and land use cover. Soil textural classifications for the basin are obtained from the United Nation's Food and Agriculture Organization (FAO). The drainage basin characteristics, taken together with the predominance of fine soil textures, indicate that the infiltration excess runoff production mechanism is dominant in the Wei River basin.

Land-cover and soil properties are considered homogeneous within each grid cell, and a single set of parameters is used to represent the hydrological processes in each cell. The first layer consists of a land-cover classification. The following four main land-cover classes are distinguished in the study area: grassland (36.1%), open shrubland (14.7%), cropland (11.9%), and wooded grassland (11.8%), as illustrated in Fig. 2. The second layer consists of soil information derived from the FAO Soil

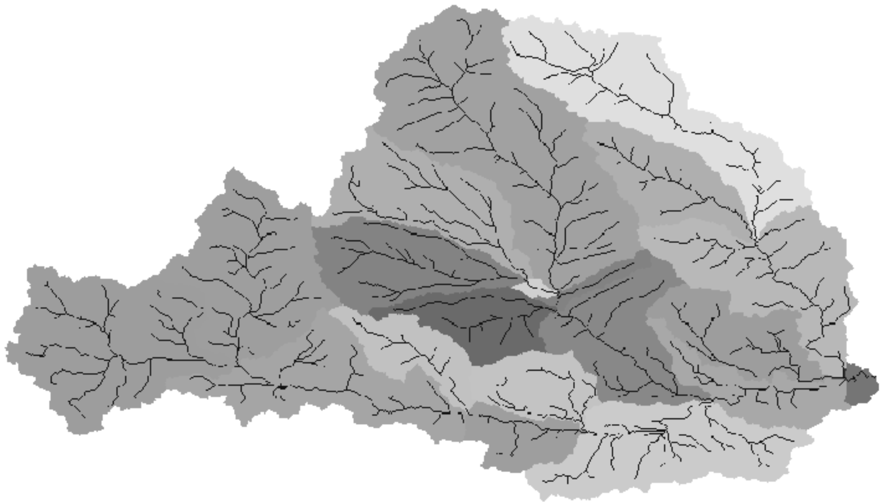

Fig. 1 Flow network in the Wei River basin from the GTOPO30 DEM.

Survey. This survey was originally conducted on the basis of a 10 km grid for the whole study area, and disaggregated to a resolution of approximately 2 km. Soil types were converted to soil physical parameters.

Daily precipitation and other climatological data such as air temperature, relative humidity, and wind speed was obtained for the stations within or near the Wei River basin from the US National Climatic Data Center (NCDC) for the period of 1995 to 1997. The average annual precipitation over this period was 522 mm.

MODEL APPLICATION

The spatially-distributed parameters in the CDHFS model include topography, soil characteristics, evapotranspiration parameters, and channel location. Initial estimates of the hydraulic properties of the soil, such as wilting point water content, were obtained from surrogate published values. Owing to the lack of spatially distributed soil moisture data, initial soil moisture input values were derived solely by calibration. Model parameters with unknown spatial distributions are assumed to be spatially uniform over the entire basin. Values of the albedo are assigned based on land-cover classification, and initial values were obtained from published literature. The calibration process is tightly constrained in that maintaining realistic values of all model parameters is considered paramount in the context of physically-based modelling. The most sensitive parameters are varied in a systematic fashion within each common land-use/soil type classification in an attempt to match the simulated hydrograph.

Figure 2 shows the estimated daily rainfall, streamflow, and sediment discharge for the period 1995–1997. It is clear that the CHDFS model provides satisfactory approximations of runoff and sediment predictions and spatial runoff/sediment generation dynamics. Using the proposed model, it is possible to estimate where in the basin sediment production is higher as a result of the soil and land-cover characteristics. The advantage of the present distributed approach over conventional lumped methods in the analysis of sediment yield is evident.

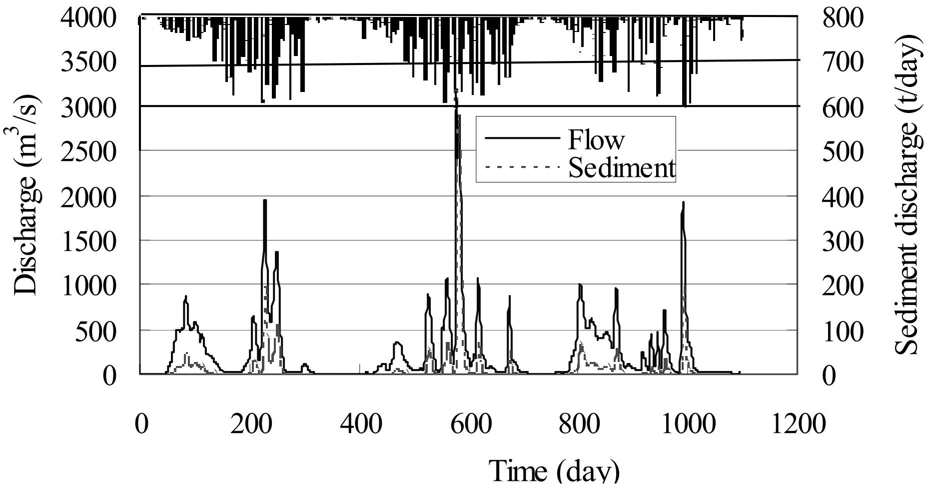

Fig. 2 Simulated streamflow and sediment discharge at Huaxian gauging station.

CONCLUSIONS

Sediment production and transport is an important issue for integrated water resources management in the Yellow River basin. This study uses a distributed model for sediment yield estimation in the basin of the Wei River, the largest tributary of the Yellow River. The present study shows how to analyse the sediment yield at a cell scale. Using the present approach, it is possible to determine in which portions of the basin erosion was higher, as well as in which regions accumulation was more likely to occur. This is an obvious advantage with respect to conventional lumped approaches, where only the total amount of sediment yield at the drainage basin outlet can be estimated. Such an attempt is particularly suitable for simulating the impacts of land-use and climate change on erosion and sediment yield, and for identifying drainage basin management strategies that minimize unwanted effects, both on the hillslopes and along the channel system. However, a possible deficiency of the sediment transport model is the description of the initial bed conditions and sediment sources along the channel. Observed variations at short temporal and spatial scales are less well reproduced, suggesting that localized sediment supply effects in the form of sediment waves may not easily be accounted for with the current model structure or with readily available data. In the future, it is the intention to enhance the capability of the model for simulating hillslope erosion by accounting for possible landslides and gully erosion.

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