Continuous Simulation of Water and Soil Erosion in a Small Watershed of the Loess Plateau with a Distributed Model

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Abstract: A physically based distributed hydrological model (THIHMS-SW, TsingHua Integrated Hydrological Modeling System-for Small Watershed) was developed and applied to a 187 km^2 watershed in the severe soil erosion region of the Loess Plateau. In the model, calculations of water and sediment transport were coupled in each grid, and the modeling of water and soil conservation measures, especially the silt-trapping dam, was also included. Continuous simulation for a period of eight years undisturbed by human activities was carried out and the results indicate that the model worked well in terms of estimating water/sediment peak discharge, time to peak, and total volume at different locations. Continuous simulation for three years after the installation of hundreds of silt-trapping dams was also carried out and fairly good results were obtained. The model is physically based and can be used in water resources planning, land use management, flood control, as well as water and soil conservation planning in small watersheds.

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Introduction

The Yellow River is world famous for its exceptionally high sediment load, on average the river carries as much as 37 kg of sediment per cubic meter of water in its lower reaches. Approximately 90% of the high sediment load originates from the Loess Plateau, which is located in the middle Yellow River Basin. Severe erosion and high sediment load are responsible for many of the major problems in the basin, like flooding, water quality, reservoir operation, and decrease in agricultural productivity and water retention. The Chinese government has acknowledged the erosion problem and has made great strides to promote erosion and flood control approaches such as hillside terracing, afforestation, silt-trapping dam construction (YRCC 2002).

It is planned that hundreds of thousands of silt-trapping dams be constructed on tens of thousands of gullies in the coming decades (MWR 2003). The Loess Plateau will witness a big change. Efforts have been made through site observations and numerical modeling to quantify the impact of such construction on erosion control as well as the hydrological cycle. However, up until now no consistent conclusion could be reached as different investigations have yielded different results, some of them being opposite, making it difficult for rendering sound decisions in the planning and implementation of water and soil conservation strategies.

In the past decades, a number of empirical methods have been proposed to evaluate the effects of soil and water conservation measures, including the soil and water conservation, the hydrologic, and the analog methods. The limitations and shortcomings of these traditional methods are clarified and some improvements are made (Ran et al. 2000; Xu and Niu 2000; Chen et al. 2004). Wang and Jiao (2002) took the heterogeneity of the sediment yield into account by using the hydrology-geomorphology method, in which the whole Loess Plateau was discretized into 292 erosion units to evaluate the effect of water and soil conservation measures on sediment control.

Mathematical modeling of the whole integrated hydrologic process in a watershed has been employed to address a wide spectrum of environmental and water resource problems in recent decades. Singh and Woolhiser (2002) gave a comprehensive summary of the development and application of the representative global hydrologic models. Some investigators have tried to apply their hydrologic models in the Loess Plateau. Yang et al. (2005) developed a grid-based model and applied it to a small watershed, Chabagou, of the Loess Plateau. The model was calibrated and validated by some flood events from 1970 to 1989, and good simulations for runoff forecasting was obtained. Liu (2005) developed a digital watershed model for the Yellow River Basin, which was discretized into subbasins with similar hydrologic properties. Both water and soil erosion processes were considered in each subbasin. The Limburg Soil Erosion Model (LISEM, version 1.63) was applied by Hessel et al. (2003) to the Danangou watershed, which is a 3.5 km^2 typical small watershed in the severe soil erosion region of the Loess Plateau. In the study, a finite difference solution of the vertical one-dimensional Richards equation was used to simulate infiltration with a 10 m grid discretization. It was concluded that the model can, in principle, be

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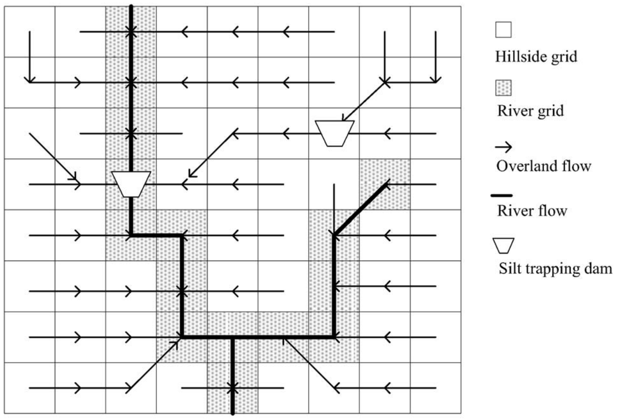

Fig. 1. THIHMS-SW structure in horizontal plane

applied to the Chinese Loess Plateau. However, the results also show that separate calibrations are needed for low- and high-magnitude events and probably even for each event. This limits the usefulness of LISEM as a predictor of future discharges.

The Loess Plateau is characterized by steep slopes, thick loess, crisscrossed landform, less vegetation cover, intensive rainfall in a short period, and severe water and soil loss. With the large scale construction of the water and soil conservation measures, especially the silt-trapping dams, great changes will take place in the basin. It brings long term effects on both soil erosion and hydrologic cycle. With these in mind, in this study, a physically based distributed hydrological model (THIHMS-SW, TsingHua Integrated Hydrological Modeling System-for Small Watershed) was developed to adapt to the special conditions of the Loess Plateau, focusing on soil moisture movement in saturated–unsaturated zone to accurately simulate infiltration and runoff, and couple water and sediment. The study aims to develop a tool to evaluate the effects of water and soil conservation measures, especially that of the silt-trapping dams.

THIHMS-SW

General Characteristics

THIHMS-SW is grid based, its structure in horizontal and vertical plane is shown in Figs. 1 and 2. For simulation the watershed is discretized into grids, which are further categorized as hillside, river, and silt-trapping dam grids, according to their relation to the river and the silt-trapping dam. The mosaic method (Avissar and Porlke 1989; Jia et al. 2002) is adopted to treat the heterogeneity in a grid. Rivers and dams are in a separate simulation domain, which overlay on the top of a watershed and have water interchange with the corresponding grids. In the vertical direction, each grid is further divided into top soil, deep soil, and groundwater zones.

Main hydrologic processes include interception, unsaturated flow, groundwater flow, overland, and channel flow routing. Flow processes calculated in the unsaturated zone consist of infiltration, evaporation, percolation, interflow, and return flow, etc. A finite difference solution of the Richards equation is employed to obtain an accurate simulation of soil moisture movement in the unsaturated zone, with finer discretization for the top soil layer (root zone) and a coarser one for the deep soil zone to save the calculation time (Ni et al. 1994). The node spacing varies with depth.

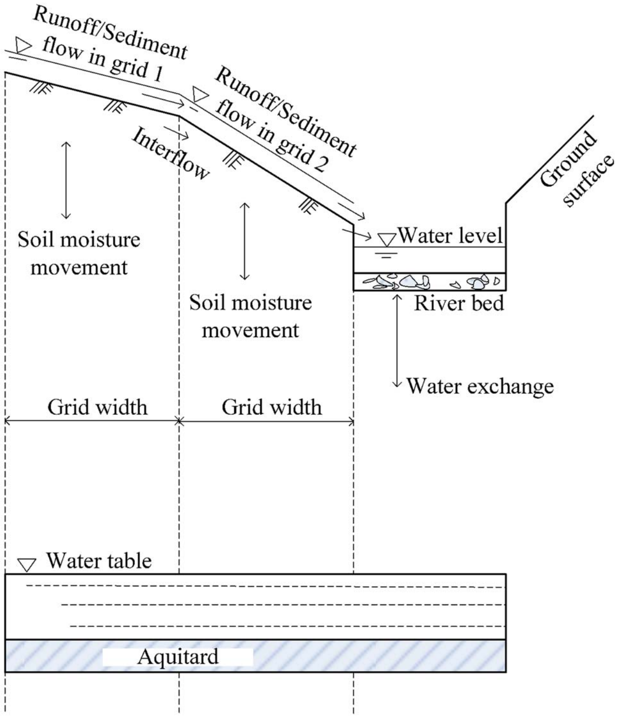

Fig. 2. THIHMS-SW structure in vertical plane

Interflow along the slope is introduced to render the simulation semi-two-dimensional. According to the data collected, actual evapotranspiration can be either calculated directly by using the Penman–Monteith equation, or estimated from the potential evapotranspiration by a coefficient, which is a function of the state of crop growth and the soil moisture (Lei et al. 1988). Overland flow is routed by using the kinematic wave method to one of its eight adjacent grids along the steepest direction. If a river flows through or a silt-trapping dam exists, overland flow of the grid will flow into the river or dam. Either kinematic or dynamic wave method can be chosen for river flow simulation. Groundwater flow simulation is carried out with a three-dimensional model and solved using the alternating direction implicit difference method. Anthropic water utilization, such as domestic water supply, sewerage leakage, and groundwater abstraction are also considered in the model.

The main state variables of the model include canopy water storage, soil water content of each layer, groundwater heads of each aquifer, water level, and discharge. The canopy interception capacity, hydraulic conductivities of soils and aquifers, the Manning roughness of hillside and gully are the main coefficients, of which most can be determined or estimated based on the field data of land use, hydraulic properties of soils and aquifers, whereas some coefficients need to be calibrated against observed discharge and groundwater table.

Sediment Yield and Transportation

An empirical formula proposed by Cai et al. (2004) to couple the sediment and runoff calculation for a subwatershed is employed to simulate sediment yield and transportation in a grid. As experimental data show a strong correlation between sediment yield and discharge, this model is expected to perform well for estimating sediment load at each grid. The equation is given as

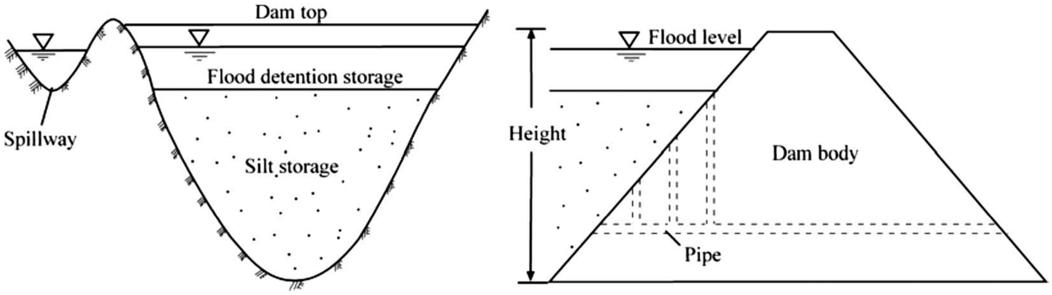

Fig. 3. Schematic diagram of the silt-trapping dam

$$M_s = kH^{\alpha}Q^{\beta} \tag{1}$$

where M_s=sediment yield of the grid (kg); H=water depth of overland flow (m); Q=overland flow discharge ($\mathrm{m^3/s}$); and k, α, and β=coefficients that need to be calibrated for each subwatershed.

The erosion and deposition in a river are determined by the flow conditions, and calculated as the transport deficit and surplus, respectively. For sediment transportation in gully, the one-dimensional transportation capacity is estimated by the following equation, known as the Zhangruijin formula (CHES 1992)

$$S_* = K(U^3/gR\omega)^m \tag{2}$$

where S_*=sediment transport capacity ($\mathrm{kg/m^3}$); K=dimensional coefficient ($\mathrm{kg/m^3}$); U=mean velocity (m/s); R=hydraulic radius (m); ω=sedimentation velocity of sediment particles (m/s); g=gravity acceleration ($9.8\ \mathrm{m/s^2}$); and m=index needed to be calibrated.

The ratio of the sediment yield to that transported by gullies in the Loess Plateau has been discussed for several decades, as noted by Meng et al. (1996). By simply assuming the ratio as 1, the sediment transportation in a gully can be written as

$$W_{si} = q_{si} + W_{s(i-1)} \tag{3}$$

where W_{si}=sediment transportation of the present reach (kg); q_{si}=lateral sediment inflow into the reach (kg); $W_{s(i-1)}$=sediment inflow from upper reach (kg); and i denotes river reach.

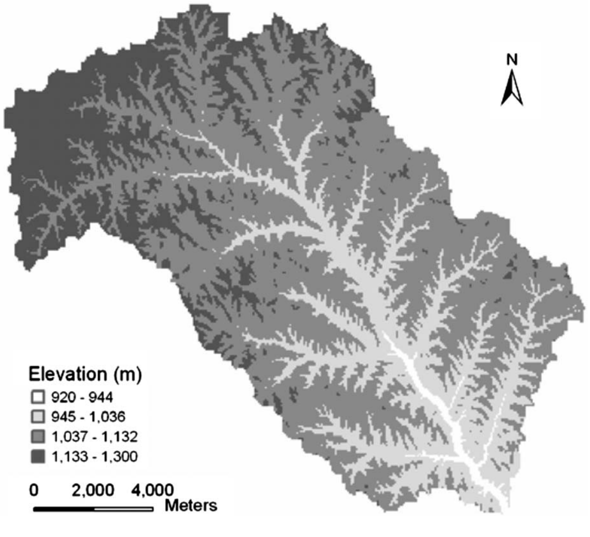

Fig. 4. Elevation map of the Chabagou watershed

Modeling of a Silt-Trapping Dam

Silt-trapping dams usually are earth dams of 2–5 m high, trapping sediment from eroded topsoil behind them and forming high-yield plots within a few years. The basic unit to plan erosion and flood control approach is a small watershed, with a draining area of several square kilometers to several hundred square kilometers, called a small watershed rehabilitation program. In a small watershed, all the silt-trapping dams are considered as a whole system. Small low dams are built to trap sediment, control floods, and create productive agricultural land within the valleys, whereas major or key dams, which are higher and with larger reservoir capacities, are built on major gullies to withstand exceptional flood runoff. In this way, sediment plots created downstream from the key dams are protected from heavy runoffs, whereas those created upstream from the key dams in the branch gullies trap sediment from reaching the reservoir.

A silt-trapping dam, as shown in Fig. 3, usually consists of a dam body, spillway, and discharge pipe and serves to trap sediment behind and forms a highly productive agricultural plot. At the same time it functions as a reservoir or detention storage to protect the downstream area from floods. When a flood occurs, the mud water is detained as long as there is enough detention storage, and silt is then trapped. If the water level is over the discharge pipe inlet, clear water (or water of lower sediment concentration) will flow through the pipe to the downstream area. In this case, the water depth and discharge through the pipe are calculated as

$$H' = 0.5\left(\left(H - \frac{2V_rS}{HB}\right) + \sqrt{\left(\frac{2V_rS}{HB} - H\right)^2 + \frac{8V_iS}{B}}\right) \tag{4}$$

$$Q = \mu \cdot \omega \cdot \sqrt{2gH'} \tag{5}$$

where H'=water depth (m); H=height from dam top to silt level (m); V_i=flood volume ($\mathrm{m^3}$); V_r=storage capacity left ($\mathrm{m^3}$); S=reach slope; B=reach width (m); Q=discharge through pipe ($\mathrm{m^3/s}$); μ=discharge coefficient; ω=area of the pipe inlet ($\mathrm{m^2}$); and g=gravity acceleration ($9.8\ \mathrm{m/s^2}$).

When the flood detention storage capacity is full, the coming flood water will flow via spillway or overflow on the dam top if no spillway is constructed. In this case, sediment cannot be

Table 1. Calibrated Coefficients of Sediment Yield

Coefficient	Value scope
k	188,000–1,819,250
α	0.56–0.92
β	0.36–0.67

Table 2. Comparison of Observed and Simulated Runoff in the Flood Season

Year	Gauge		Largest peak discharge (m^3/s) Sim.	Largest peak discharge (m^3/s) Obs.	Error in time to peak (h)	Nash coefficient
1960	Main stream	Dujiagoucha	62.4	54.1	0	0.76
		Caoping	56.5	53.7	0	0.74
1961	Tributary	Sanchuankou	41.9	43.8	+1	0.70
		Shejiagou	4.5	5.1	0	0.93

trapped anymore and will directly flow to the downstream area. The discharge through spillway is calculated as (Zheng et al. 2004)

$$Q = MBh^{1.5} \tag{6}$$

where Q=discharge through spillway (m^3/s); M=corresponding discharge coefficient; B=spillway width (m); and h=water depth in the spillway (m).

Model Calibration

Study Area and Data

The Chabagou watershed is situated in the severe soil erosion region of the Loess Plateau, with a draining area of 187 km^2. The average annual rainfall was 388 mm over the period from 1959 to 2000. About 80% of rain falls in the period from June to September, often with heavy storms, where rains of very high intensity fall in a short period.

Detailed data as topography, land use of both present and past conditions, and the state of each silt-trapping dam are available, as well as long term meteorological and hydrological data for modeling. In addition, experimental data of soil hydraulic properties are also collected. Before 1969 there were seven flow gauges in the watershed, of which three are on the main stream, i.e., Xizhuang, Dujiagoucha, and Caoping, and four are on tributaries, i.e., Tuoerxiang, Sanchuankou, Shejiagou, and Tianjiagou. Only the Caoping gauge, which is at the watershed outlet, remains after 1969.

The digital elevation model is digitized from 1/50,000 topographic map, and the land use data digitized from 1/10,000 land use map. As shown in Fig. 4, elevation in the watershed ranges from 920 to 1,300 m, with a slope angle of up to 42°. The main land use in the watershed is wildland, taking account of 84%, followed by cropland (10%) and forestland (4%). The whole basin is discretized into 74,108 grids of 50 m, and 61 subwatersheds considering the position of past and existing flow gauges.

Calibration Results

The period from 1960 to 1961 was chosen for model calibration, annual rainfall in 1960 was near average, whereas 1961 had more rain than usual. Continuous simulation with half an hour time step was carried out for 1960–1961, and model parameters were calibrated by comparing the simulated results with the observed ones. All the flow and sediment discharge data at the seven gauges were used for model calibration. Model was calibrated first on the runoff depth and the total sediment yield at each gauge and after that an adjustment was made to obtain the correct shape of the hydrograph at each gauge. The base flow was separated from the total stream discharge by using the streamflow filter and the recession method (Arnold and Allen 1999).

It is found that the saturated conductivity is the most important and sensitive parameter to infiltration, runoff, and soil erosion. The calibration results show that, in general, the saturated conductivity increases from upstream to downstream, with a few exceptions where land uses or soil types are obviously different. The calibrated coefficients used in Eq. (1) of grid sediment yield are given in Table 1. Strong spatial variation of coefficient k can be seen, whereas α and β are relatively stable.

Comparison between observed and simulated results of runoff and sediment in the flood season within the calibrated period is made for all seven gauges. The Nash coefficient is used to assess the model performance. High Nash coefficients indicate that the simulated results match well with the observed ones, in general, and vice versa (Legates and McCabe 1999). Some of the comparisons are shown in Tables 2 and 3. At different gauges in different years, in main stream as well as in tributaries, simulated results fit the observed ones very well in terms of peak discharge, time to peak, and total amount. The results indicate that the model can simulate well both runoff and sediment yield. Compared to runoff, sediment yield is simulated less well as can be seen from Table 2. This is expected due to the complicated nature of sediment transport processes.

Table 3. Comparison of Observed and Simulated Sediment Discharge/Yield in the Flood Season

Year	Gauge	Largest daily sediment discharge (kg/s) Sim.	Largest daily sediment discharge (kg/s) Obs.	Total sediment yield (10,000 ton) Sim.	Total sediment yield (10,000 ton) Obs.
1960	Sanchuankou	1,451	1,917	25.6	24.7
	Tianjiagou	1,201	1,061	11.4	13.5
1961	Xizhuang	5,120	4,246	84.8	87.0
	Tuoerxiang	150	206	4.74	4.99

Table 4. Nash Coefficients Based on the Results of Runoff Simulation

Year	1962	1963	1964	1965	1966	1967	Average
Nash coefficient	0.70	0.87	0.71	0.77	0.84	0.89	0.82

Long-Term Continuous Simulation

Keeping all the calibrated parameters unchanged, but using different meteorological and land use data, long-term continuous simulations were carried out for 1962–1967 and 1979–1981 to evaluate model performance. During 1962–1967 the land use did not significantly change, and no silt-trapping dam was built, whereas the 1979–1981 simulation involved hundreds of silt-trapping dams.

Simulation without Silt-Trapping Dam

The period from 1962 to 1967 was chosen for simulation, as detailed hydrological data were available and the watershed was still in a relatively original natural state. The Nash coefficients at the outlet gauge were calculated for each year, as shown in Table 4.

In 1962 the rainfall was small and the simulation result gave the lowest Nash coefficient of 0.7 at the Caoping gauge, where comparison between simulated results and the observed ones for both runoff and sediment yield are shown in Figs. 5 and 6, respectively. Comparison of runoff is made for hourly data, whereas comparison for sediment is made for daily data. As a dry year, the total runoff and sediment yield of 1962 are much less than those of other years. Simulated results show that some small peak discharges match less well, such as the case for the Shejiagou tributary, bringing out the effect on the sediment simulation results. Observation errors in small discharges are considered to be one of the main reasons.

Simulation with the Effects of Silt-Trapping Dams

In the 1970s, hundreds of silt-trapping dams were constructed and more than 10,000 ha of sediment plots were created. However the dam system was not well designed or built to withstand severe storms and many existing dams were damaged by storms in 1977 and 1978. According to field investigations carried out by the local hydrologic bureau, there were 370 silt-trapping dams left in the watershed after the flood season of 1978. The distribution of the dams with remaining storage capacity larger than $10{,}000\ \mathrm{m}^3$ is shown in Fig. 7.

The silt-trapping dams affect the watershed in the aspects of both water and sediment transport, and as it takes several years to trap silt and create a sediment plot, the effects will last for the long term. With the silt-trapping dam investigation result of 1978, dimensions and initial storage capacities of the silt-trapping dams are available and are taken as initial conditions for simulation. A long-term simulation of 1979–1981 was then carried out with reference to the dam operation rules. Table 5 gives simulation results of runoff in the flood season of each year, and Table 6 shows the simulated sediment discharge and yield in each year at the outlet gauge. Tables 5 and 6 show that the Nash coefficients of runoff are lower, and simulated sediment discharges and yield and the observed ones agree less well, compared to those in the 1960s.

The hourly hydrograph and daily sediment discharge in the flood season of 1980 at the outlet gauge are shown in Figs. 8 and 9, respectively. The match between simulated results and observed ones is fairly good. The main reasons for errors are considered to be the accuracy of data on the silt-trapping dams in terms of dimensions and state of function, and the dam collapse mechanism, which is not fully introduced in the model.

Discussions and Conclusions

A distributed hydrological model, THIHMS-SW, is developed with special consideration of hydrologic and geologic conditions

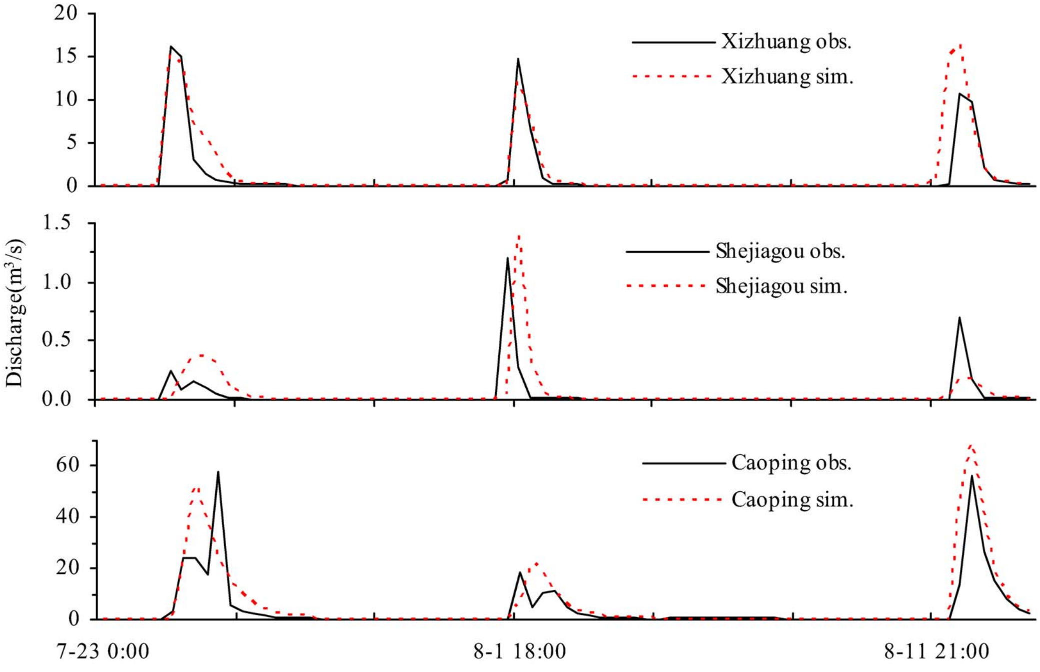

Fig. 5. Hourly hydrograph of 1962 at main stream/tributary gauges

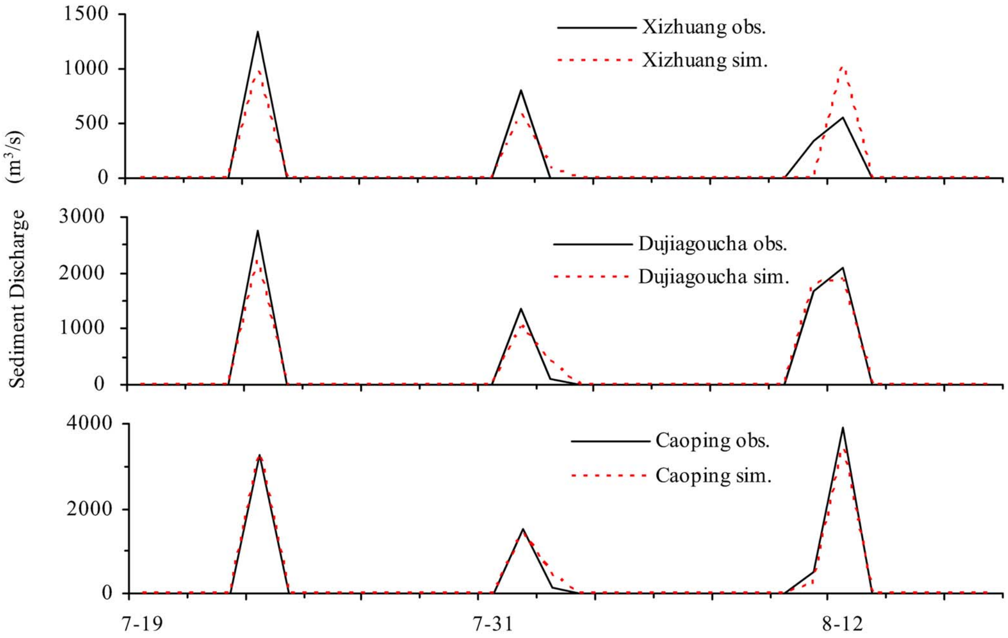

Fig. 6. Daily sediment discharge of 1962 at main stream gauges

of the Loess Plateau. Silt-trapping dams, as one of the major water and soil conservation approaches, are taken into consideration in the model to simulate their effects on the hydrologic cycle and soil erosion. By applying the model to Chabagou watershed (187 km^2), the model performance is evaluated. For the case without a silt-trapping dam, simulations for eight years were carried out and the results show that the model can simulate well both the runoff and sediment yield. On the other hand, the results of a three-year simulation with 370 silt-trapping dams show less agreement between the simulated results and the observed ones. Possible reasons could be the data inaccuracies of silt-trapping dams in terms of dimensions and state of function, and the absence of dam collapse mechanism in the model.

Investigation of silt-trapping dams is a complex and difficult task due to the large number and their wide distribution over the Loess Plateau, which is full of steep slopes and deep gullies. Dam collapse is a special phenomenon in the Loess Plateau. When flood discharge is large and there is little storage capacity of the silt-trapping dam as a result of sedimentation, the dam may collapse instantly due to its simple construction, lack of management or other reasons, with all the stored water and sediment rushing downstream. This phenomenon takes place almost every year, but no detailed studies have been conducted so far (Li and Liu 1995; Li et al. 2003).

Further studies will be conducted on the dam failing mechanism and its incorporation into the model. With these improvements, the model is expected to perform better in evaluating the effects of water and soil conservation measures on the hydrological cycle and soil erosion in the Loess Plateau.

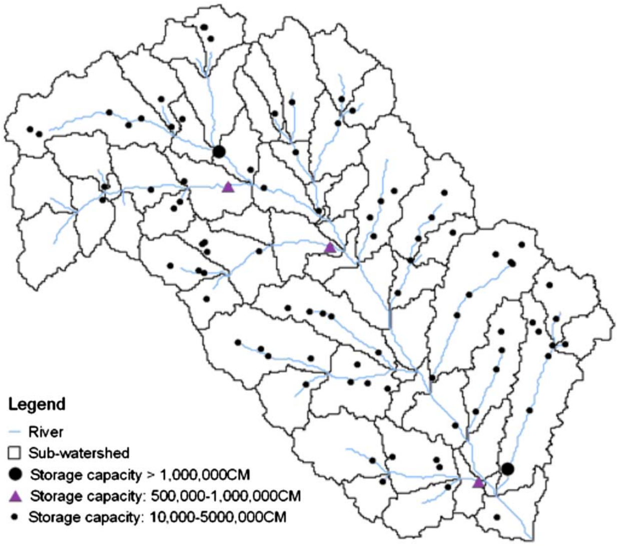

Fig. 7. Distribution of the silt-trapping dams at the end of 1978

Table 5. Hourly Simulation of Runoff in the Flood Season from 1979 to 1981

	Largest peak discharge (m^3/s)		
Year	Sim.	Obs.	Nash coefficient
1979	7.0	23.3	0.53
1980	16.8	22.3	0.64
1981	77.1	61.8	0.63

Table 6. Simulation of Sediment Discharge/Yield in the Flood Season from 1979 to 1981

	Largest daily sediment discharge (kg/s)		Total sediment yield (10,000 ton)	
Year	Sim.	Obs.	Sim.	Obs.
1979	221	2,130	8.6	33.9
1980	2,077	1,350	37.7	28.3
1981	5,049	5,400	1,40.2	72.6

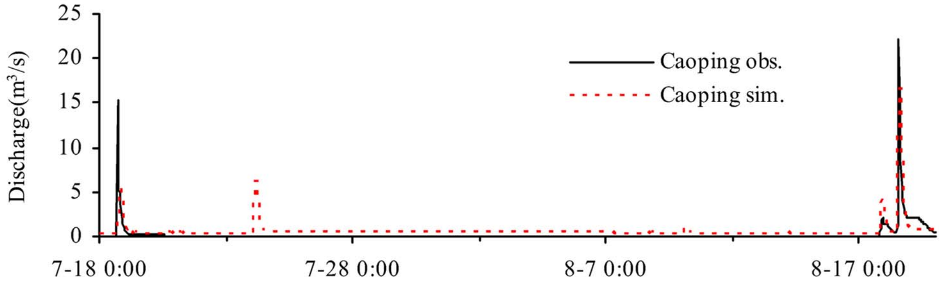

Fig. 8. Hourly hydrograph of 1980

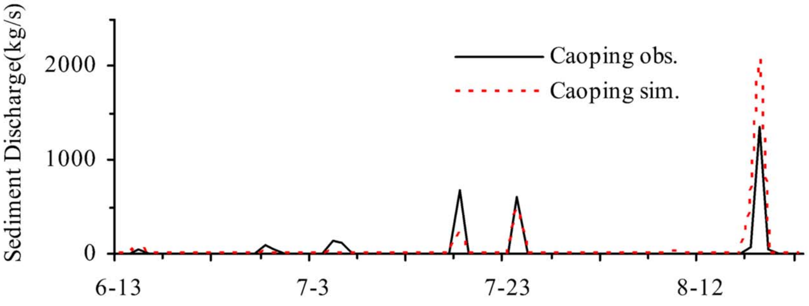

Fig. 9. Daily sediment discharge of 1980

Notation

The following symbols are used in this paper:

B = reach width (m);
B = spillway width (m);
g = gravity acceleration ($9.8\ \mathrm{m/s^2}$);
H = water depth of overland flow (m);
H = height from dam top to silt level (m);
H' = water depth (m);
h = water depth in the spillway (m);
i = river reach;
K = dimensional coefficient ($\mathrm{kg/m^3}$);
k = sediment coefficient of grid;
M = discharge coefficient;
M_s = sediment yield of grid (kg);
m = index;
Q = overland flow discharge ($\mathrm{m^3/s}$);
Q = discharge through pipe ($\mathrm{m^3/s}$);
Q = discharge through spillway ($\mathrm{m^3/s}$);
q_{si} = lateral sediment inflow into the reach (kg);
R = hydraulic radius (m);
S = reach slope;
S_* = sediment transport capacity ($\mathrm{kg/m^3}$);
U = mean velocity (m/s);
V_i = flood volume ($\mathrm{m^3}$);
V_r = storage capacity left ($\mathrm{m^3}$);
W_{si} = sediment transportation of the present reach (kg);
$W_{s(i-1)}$ = sediment inflow from upper reach (kg);
α = sediment yield coefficient of grid;
β = sediment yield coefficient of grid;
μ = discharge coefficient;
ω = sedimentation velocity of sediment particles (m/s); and
ω = area of the pipe inlet ($\mathrm{m^2}$).

Acknowledgments

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