Journal of Environmental Informatics 19(1) 30-37 (2012)

Journal of Environmental Informatics

www.iseis.org/jei

Application of Loosely Coupled Watershed Model and Channel Model in Yellow River, China

L. He[1,*], G. Q. Wang[2], and C. Zhang[3]

[1]*Institute of Geographical Sciences and National Resources Research, Chinese Academy of Sciences, PEK 100101, China*
[2]*State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, PEK 100084, China*
[3]*School of Renewable Energy, North China Electric Power University, PEK 102206, China*

Received 3 August 2010; revised 2 September 2011; accepted 13 September 2011; published online 12 March 2012

ABSTRACT. Insufficient flow and excessive sediment supply in the Middle Yellow River lead to persistent sedimentation and rising flood levels in the lower river channel. Better understanding of the relationship between sediment erosion, transportation, and deposition can help in the decision making of soil and water conservation in the Coarse Sediment Source Area (CSSA) and sediment reduction works in the lower channel. A linked simulation can help elucidate the interrelationship. The goal of the current research is to simulate the whole sediment process from the CSSA to the downstream channels of the Yellow River. To achieve this goal, we use the Digital Yellow River Model (DYRM), a watershed hydrology and sediment yield and transportation model plate, coupled with a one-dimensional (1D) unsteady model for the hyper-concentrated sediment-laden flow in complex sections, to study the sedimentation process in the entire watershed. The performance of the simulation of flood in year 1977 was evaluated using the percent bias, Nash-Sutcliffe statistics of the residuals, and percentage difference. Simulation of the sediment process in 1977 shows that linked simulation can describe the hydrographs of discharge and sediment concentrations, especially flood in the downstream main channels. Compared with the underestimated discharge and sediment load in the main channel, the discharge of most tributaries is overestimated, whereas most of the sediment load is underestimated. The inconsistency indicates that more efforts are required to conduct better simulation, including data input and data processing, and both DYRM and 1D models.

Keywords: linked simulation, Digital Yellow River Model, one-dimensional unsteady model, Yellow River

1. Introduction

Traditional hydrologic modeling approaches generally focus on either the watershed or the channel system. Watershed models are designed and calibrated with emphasis on water and sediment yield in the watershed. Channel models focus on the deformation of channel beds and flood propagation in channels, with water and sediment yield as the boundary conditions. The coupling of both approaches can model the entire hydrologic system, as well as investigate the interaction between watershed and channel. Loose model coupling and complete model coupling are two ways of coupling simulation. Complete model coupling is defined as coding the equations of one model completely within the framework of another model [e.g., Kyrsanova et al. (1998); Carroll et al. (2008); Papanicolaou (2008)]. Loose model coupling is a process in which output from one model is used as input to another model [e.g., Chen and Chen (2010); Barth et al. (2005)]. For example, Bdour and Papanicolaou (2008) developed an integrated watershed hydrologic/sedimentation framework for mountainous watersheds to simulate upland (macro level) and instream (micro level) processes. The loosely coupled model of Barth et al. (2005) can simulate the complex hydrological processes in a mesoscale watershed. The link between the surface water model PRMS and the groundwater model MODFLOW is the PRMS parameter, which provides recharge estimates. Migliaccio et al. (2007) analyzed the prediction performance of the loosely coupled model and completely coupled model of the SWAT and QUAL2E models. The case results imply that neither modeling method was significantly better. Consequently, a loosely coupled modeling approach of the watershed model and hydraulic channel model has been adopted to simulate the complex hydrological processes in the Yellow River.

The Yellow River is unique in the world because of its extremely high sediment concentration and rapid sedimentation rate in its lower reach. Insufficient flow and excessive sediment supply in the Coarse Sediment Source Area (CSSA), which is located in the Middle Yellow River, lead to persistent sedimentation and rising flood levels in the lower channel (Qian et al., 1980; Xu and Niu, 2000). The Digital Yellow River Model (DYRM) has been created to simulate rainfall-runoff and sediment erosion in CSSA (Wang et al., 2007). The selected one-dimensional (1D) unsteady model is capable of describing the propagation of hyper-concentrated sediment-laden flow in se-

* Corresponding author. Tel.: +86 10 64888151; fax: N/A. *E-mail address:* heli@igsnrr.ac.cn (L. He).

ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.201200206

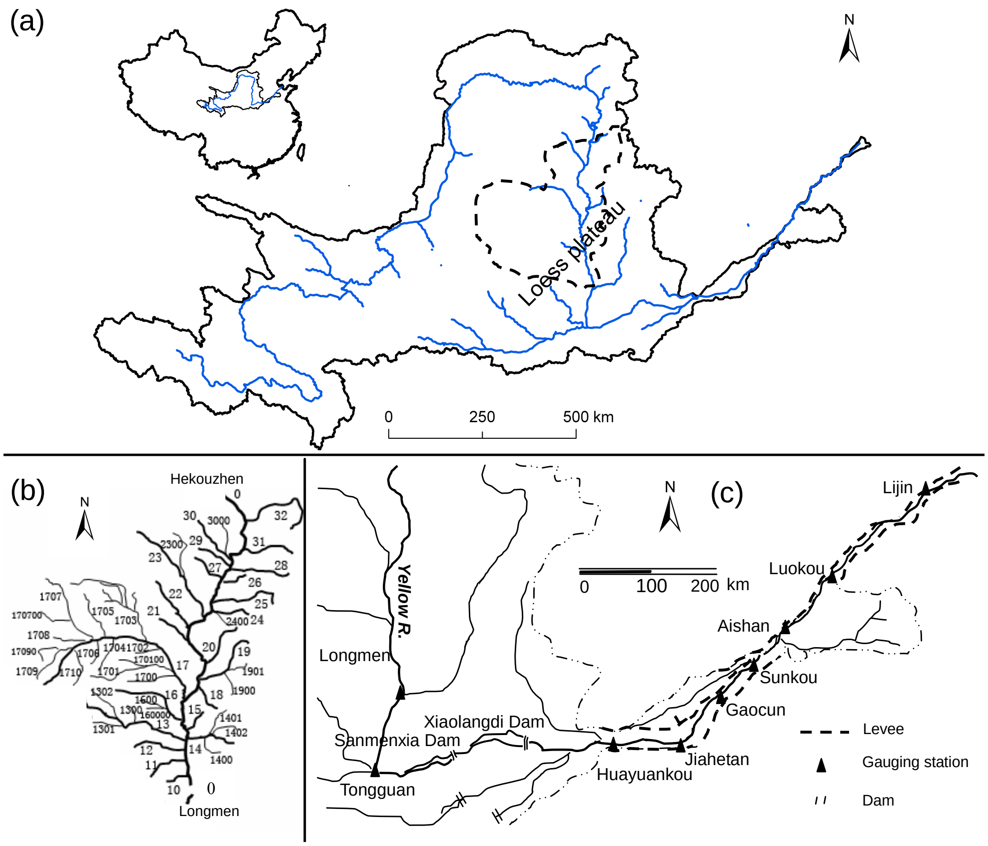

Figure 1. Sketch map of CSSA (Coarse Sediment Source Area) and downstream channel in the Yellow River watershed . (a) map of the Yellow River and CSSA (the dashed area), (b) digital drainage network of CSSA in DYRM (c) details of the middle and lower reaches.

condary-perched cross sections in the Lower Yellow River (He, 2008). The year 1977, which is characterized by a large amount of sediment yield, high sediment concentration, and severe deposition, was simulated to evaluate the performance of loosely coupled DYRM and 1D unsteady model. The performance was evaluated with percent bias (PBIAS), Nash-Sutcliffe (NS) statistics of the residuals, and percentage difference (PD). Analysis shows that linked simulation can describe the hydrographs of discharge and sediment concentration, especially in the main channel.

2. The Yellow River

The Yellow River (Figure 1) is the second largest river in China, with a drainage area of 752,000 km^2 (including 42,000 km^2 of internal drainage basin) and length of 5,464 km. It is divided into the upper, middle, and lower reaches. The upper reach (from the headwater to Hekouzhen) is 3,472 km long with a relief of 3,496 m. The drainage area of the upper reach is about 0.39 million km^2. The middle reach (from Hekouzhen to Tiexie) has a drainage area of 0.34 million km^2, length of 1,206 km, and relief of 890 m. Below Tiexie, the river flows out the mountainous region and enters the Northern China Plain.

The river basin is mostly arid and semiarid, with an average annual precipitation of 478 mm, and the long-term average annual runoff depth is 77 mm. The mean annual natural runoff of the Yellow River is normally 58 × 10^9 m^3, the mean annual discharge is 1,822 m^3/s, and the long-term mean annual suspended sediment load measured at Sanmenxia station is 1.6 × 10^9 t, ranking it first among all the world's rivers in terms of sediment load. The riverbed in the lower reach of the Yellow River has elevated from 1.9 to 3.0 m (CHES, 1992) over the past 50 years, thus threatening more serious flood disasters.

Most of the sedimentations in the lower Yellow River channel consist of sediments with a diameter > 0.05 mm in suspended load (Qian et al., 1980). These sediments are mainly derived from areas including the tributaries of the middle Yellow River between Hekouzhen and Longmen, Beiluo River basin, and Malian River (in the Jing River basin), defined as CSSA (Qian et al., 1980; Zhao and Zhou, 1996; Zhang et al., 2002). The average specific sediment yield over this area is 7,170 t/km^2·year (Xu and Niu, 2000), and the fraction of "sandy loess" > 0.05 mm ranges from 31 ~ 57%. Sediment supplied to the Yellow River from the drainage area between Hekouzhen and Longmen stations represents 55.7% of the total sediment, and the > 0.05 mm sediment from this area represents 75% of the total > 0.05 mm sediment of the Yellow River (Xu, 2002).

The CSSA (Figure 1b) in DYRM consists of tributaries in the drainage area between Hekouzhen and Longmen; Beiluo River and Malian River (in the Jing River basin) are excluded because flood from these two tributaries meets the Yellow River in Tongguan. The digital drainage network of CSSA consists of 83,643 channel-slope units; the soil type of the 48.8% channel-slope units is loess (He, 2008). The inlet and outlet of CSSA in DYRM are the Hekouzhen and Longmen hydrology stations, respectively. The Hekouzhen–Longmen reach has a length of 718 km and relief of 611 m. The Longmen–Sanmenxia reach is part of the Middle Yellow River (Figure 1c), with a length is 243 km. Three hydrology stations are located in the Longmen–Sanmenxia reach, namely, Longmen, Tongguan, and Sanmenxia.

3. Model Description and Methods

3.1. DYRM

The DYRM developed by Tsinghua University, which is designed to simulate the whole sediment process in CSSA from slope to rills, is a physically based, distributed-parameter, and continuous erosion prediction model plate at a river basin scale; it can provide hydrographs of discharge and sediment concentrations at the Longmen hydrology station (Wang and Li, 2009; Wang et al., 2007).

DYRM Plate. The DYRM has a data layer, model layer, application layer, and post procession layer. The digital drainage network is a representative form of the river basin in DYRM; it is extracted from the Digital Elevation Model (DEM) (Wang and Li, 2009). The codification and partitioning of the drainage network was developed to help simulate the propagation of sediment-laden flow in the hillslope–channel unit from upstream to downstream. The Message Passing Interface was applied to handle the enormous computation mission (Wang and Li, 2009).

Submodels. The model layer of DYRM is the main part of the integrated simulation of soil erosion process. The watershed sediment processes in CSSA, including water and sediment yield on hillslopes, gravitational erosion in gully regions, and flood propagation in the channel, were simulated by different submodels: runoff and sediment yield model on hillslopes (Li et al., 2009), gravitational erosion model in steep gullies (Xue, 2006), and routing model for hyper-concentrated flood in the channel (Li et al., 2009). Submodels were physically formulated and validated separately, and were applied in each hillslope–channel unit of the digital drainage network (Li et al., 2009).

Data. The parameters acquired were stored in one database. The geometrical parameters were acquired from DEM, and the underlying surface parameters (including vegetation cover, land use, soil type, potential evaporation, etc.) were acquired from remote sensing images (Wang and Li, 2009; Wang et al., 2007). Daily precipitation data were collected from rain gauge stations and were disaggregated to meet the time-step used in *DYRM* (He et al., 2010). The measured hydrographs of the discharge and sediment concentrations at the Hekouzhen hydrology station were used to represent water and sediment yield over the drainage area above Hekouzhen.

Parameters. The main parameters in DYRM are as follows. K_{zus} is the saturated hydraulic conductivity of the surface layer (m/s). $K_{u\text{-}ds}$ is the saturated vertical hydraulic conductivity between the surface soil and under layer soil (m/s). K_{hu} and K_{hd} are the horizontal penetration parameters of the surface layer and under layer soil (m/s), respectively. θ_{us} and θ_{ds} are the saturated water contents of the surface layer and under layer soil (m^3/m^3), respectively. θ_{uf} and θ_{df} are the field water capacities of the surface layer and under layer soil (m^3/m^3), respectively. *LAI* is the leaf area index (m^2/m^2), which can be transformed from the normalized vegetation index acquired by remote sensing data. I_0 is the river closure index of vegetation canopy (m), which is related to the vegetation types. As calibrating and verifying the distributed parameters for such a large basin is difficult, the parameters were firstly calibrated and validated in the Chabagou watershed, were modified according to application in the Wuding River, and were finally applied in the whole CSSA (more details in Wang et al., 2007; Wang and Li, 2009).

3.2. 1D Model for Hyper-Concentrated Flows

The 1D unsteady model for hyper-concentrated sediment-laden flows can be used to simulate the flood propagation of hyper-concentrated sediment-laden flows in complex sections, such as the secondary-perched reach in the Middle and Lower Yellow River (He, 2008).

(1) Governing Equations

The governing equations for the 1D unsteady hyper-concentrated sediment-laden flow revised from the St. Venant equation are as follows (Wu and Wang, 2007):

$$\frac{\partial(\rho A)}{\partial t}+\frac{\partial(\rho Q)}{\partial x}+\rho\frac{\partial A_0}{\partial t}=\rho_l q_l \tag{1}$$

$$\frac{\partial}{\partial t}(\rho Q)+\frac{\partial}{\partial x}\left(\alpha_m\frac{\rho Q^2}{A}\right)+\rho gA\frac{\partial z_s}{\partial x}+\frac{1}{2}gAh_p\frac{\partial\rho}{\partial x}+\rho g\frac{n^2Q|Q|}{AR^{4/3}} =\rho_l q_l(u_l\cos\phi-V) \tag{2}$$

$$\frac{\partial(AS_k)}{\partial t}+\frac{\partial(S_kQ)}{\partial x}=\alpha B\omega_{s,k}(S_{*,k}-S_k)+S_{l,k}q_l \tag{3}$$

$$(1-p)\frac{\partial A_0}{\partial t}+\sum_k\alpha B\omega_{s,k}(S_{*,k}-S_k)=0 \tag{4}$$

where t = time; x = distance; Z = bed elevation; z_s = water surface elevation; Q = discharge; A = cross section area; A_0 = bed deformation area α_m = momentum correction coefficient; g = gravitational acceleration; p = porosity of bed material; ρ = $\rho_w(1 - S_v) + \rho_s S_v$, with ρ = density of water-sediment mixture, ρ_w, ρ_s = densities of water and sediment, respectively, and S_v =

$\sum S_k$ = volumetric suspended sediment concentration, in which S_k = volumetric suspended sediment concentration for *kth*-sized sediment group; $S_{*,k}$ = suspended sediment transport capacity for *kth*-sized sediment group; R = hydraulic radius; h_p = flow depth at the centroid of the cross section and can be calculated as $Ah_p = \int_0^h h_y B(y)dy$, in which *B(y)* = width of cross section at *y* distance from the bed, and h_y = local flow depth at a certain location *y*; u_l = velocity of lateral inflow; *V* = averaged flow velocity in the main channel; ρ_l = density of lateral inflow; q_l = lateral inflow discharge per unit channel length, ($q_l > 0$: inflow, $q_l < 0$: outflow); S_l = suspended sediment concentration of the lateral inflow; $\omega_{s,k}$ = settling velocity for *k*th-sized sediment group; ϕ = angle between lateral inflow and main flow; and *n* = Manning's roughness coefficient.

Manning's roughness coefficient should be specified empirically. According to Zhang et al. (2002), Manning's coefficient is approximately 0.035 ~ 0.04 on the floodplain of the Yellow River. In the main channel, the model back calculated it based on the observed stage hydrograph at the individual hydrology stations. The roughness coefficient was linearly interpolated at the sections between two adjacent hydrology stations.

The coefficient α is defined as the ratio between the reference concentration near the riverbed and the depth-averaged concentration in the equilibrium condition. This model treats this recovery coefficient as a calibrated parameter.

(2) Initial and Boundary Conditions

The boundary conditions for flow simulation are the flow hydrograph at the upstream boundary and stage hydrograph at the downstream boundary, lateral inflow, and water diversion. The boundary conditions for the sediment transport model are measured sediment concentrations at the upstream boundary. The mathematical formulae are as follows:

$$Q_1 = Q_1(t) \text{ and } S_{v(1)} = S_{v(1)}(t) \tag{5}$$

(upstream boundary condition)

$$z_{s(2)} = z_{s(2)}(t) \tag{6}$$

(downstream boundary condition)

where Q_1 and $S_{v(1)}$ are the flow discharge and sediment concentration at the upstream boundary, respectively; and $z_{s(2)}$ is the water surface elevation at the downstream boundary. Initial conditions, including water surface elevations, sediment concentrations, discharge, and geometric data, were obtained from a field survey.

(3) Numerical Scheme

The four-point-finite-difference Preissmann scheme was applied to discretize Equations (1) and (2) (Sturm 2002). The weighting factor for the temporal derivative, θ, is 0.65, and the weighting factor for the spatial derivative, φ, is 0.5, satisfying the requirement of the numerical stability suggested by Venutelli (2002). The resulting linear equations were solved using the double-sweep algorithm. Equation (3) was solved for suspended sediment concentration. The method of Ju and Lin (1995), and Holly and Preissmann's (1977) two-point fourth-order scheme were adopted to solve Equation (3).

3.3. Simulation and Evaluation

During the loosely coupled simulation, DYRM and 1D model were calibrated separately by observed data. The simulated results of DYRM were used as the upstream boundary condition of the 1D model (Figure 2).

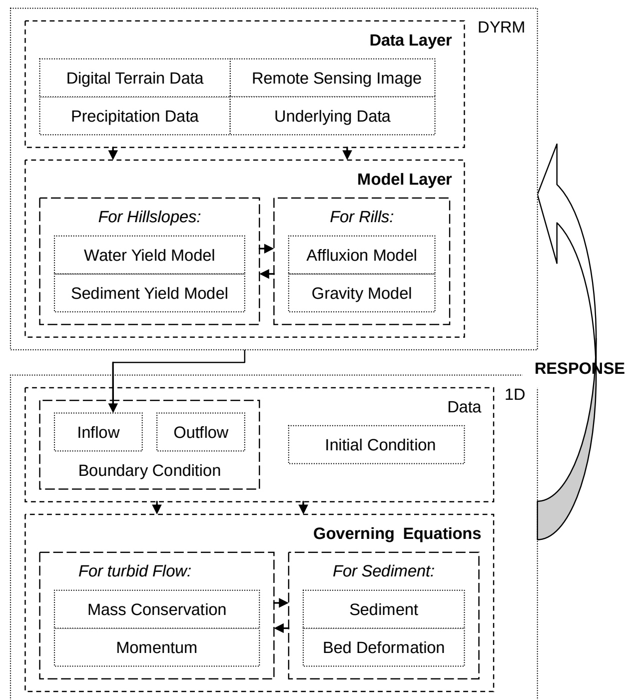

Figure 2. Sketch map of linking simulation.

The performance was evaluated using PBIAS, NS statistics of the residuals, and PD defined respectively as:

$$PBIAS = \frac{\sum_{t=1}^{N}\left(q_t^{sim} - q_t^{obs}\right)}{\sum_{t=1}^{N} q_t^{obs}} \times 100\% \tag{7}$$

$$NS = 1 - \frac{\sum_{t=1}^{N}\left(q_t^{sim} - q_t^{obs}\right)^2}{\sum_{t=1}^{N}\left(q_t^{obs} - q^{mean}\right)^2} \tag{8}$$

$$PD = \frac{(q^{sim} - q^{obs})}{q^{obs}} \times 100\% \tag{9}$$

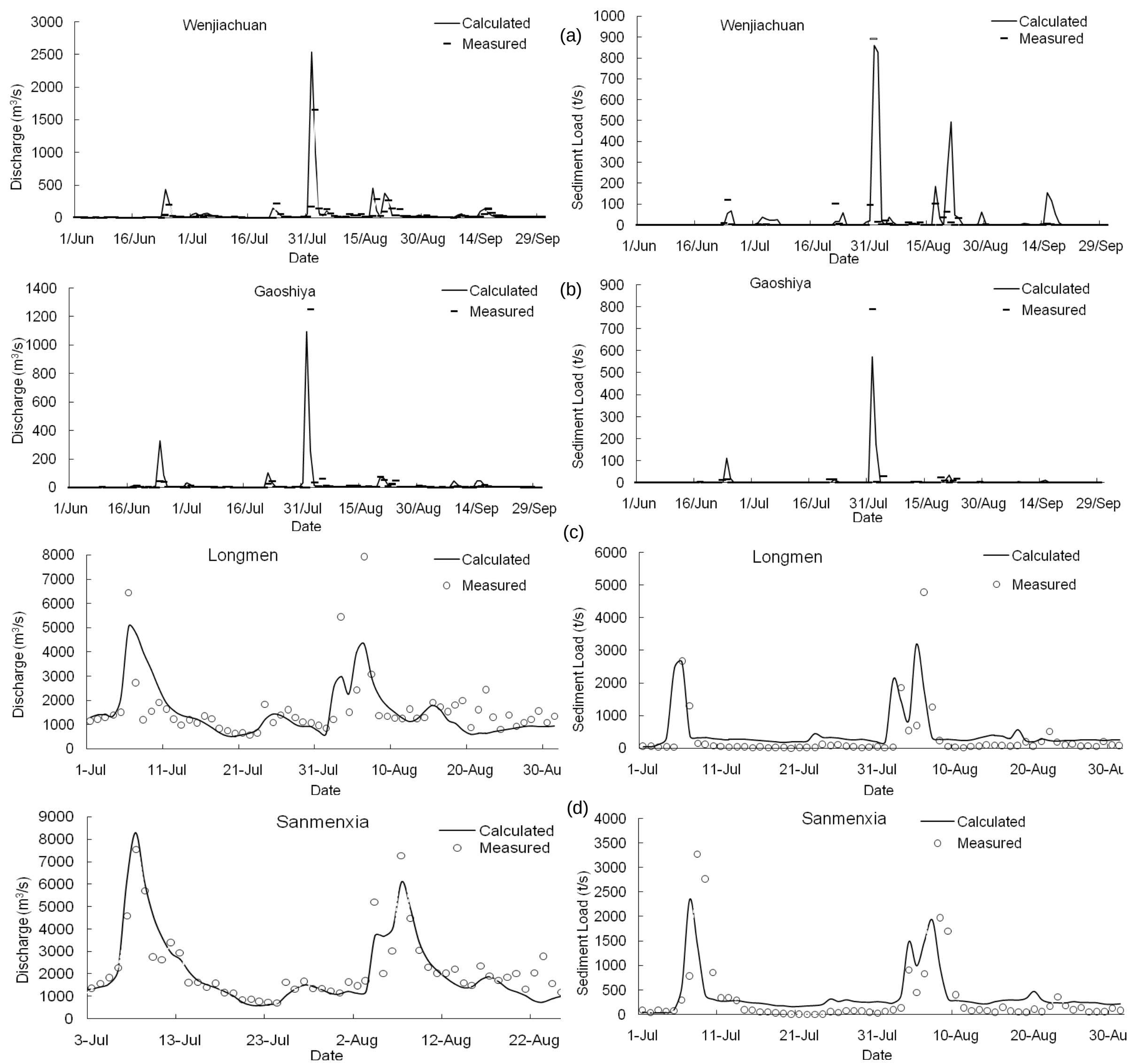

Figure 3. Comparison of the simulated and observed discharge and sediment loads: (a) Wenjiachuan Hydrology Station (Kuye River), (b) Gaoshiya Hydrology Station (Gushan River), (c) Longmen Hydrology Station (CSSA), (d) Sanmenxia Hydrology Station (Longmen-Sanmenxia Reach).

where q^{mean} is the mean observed daily flow; q^{sim} and q^{obs} are the simulated and observed daily flow, respectively; and subscript t represents day. PBIAS measures the tendency of the simulated flows to be larger or smaller than their observed counterparts. The optimal value is 0.0, with the positive values indicating a tendency toward overestimation and the negative values indicating a tendency toward underestimation. NS measures the fraction of the variance of the observed flows explained by the model in terms of the relative magnitude of the residual variance ("noise") to the variance of the flows ("information"). The optimal value is 1.0, and the values should be larger than 0.0 to indicate "minimally acceptable" performance. NS can be used to evaluate the degree of conformity. PD measures the difference of the total amount and peak values between the simulated and observed.

4. Application

The year 1977 was a typical year with a large amount of sediment yield and high sediment concentration. The annual sediment yield over CSSA in 1977 reached an amount of 2.17 $\times 10^9$ t, and the annual runoff yield was only 8.14×10^9 m^3. The maximum concentration of 911 kg/m^3 occurred on September 7, 1977, and the averaged suspended sediment concentration was about 36.8 kg/m^3 (data from the Sanmenxia station from 1919 ~ 1960). Thus, DYRM and 1D model were linked to simulate the fluvial process in 1977.

The hydrological performance of the simulated results at the controlling stations of the eight main tributaries (i.e., Huangfu River, Gushan River, Kuye River, Tuwei River, Jialu River,

Table 1. Main Parameters of the Underlying Surface

Parameter	Value	Note
K_{zus}	18 mm/hr	Measured + Adjustment
$K_{u\text{-}ds}$	8 mm/hr	Calculated + Adjustment
K_{hu}	290 mm/hr	Calculated + Adjustment
K_{hd}	30 mm/hr	Calculated
θ_{us}	0.55	Measured
θ_{uf}	0.10	Measured
θ_{ds}	0.52	Measured
θ_{df}	0.18	Measured
LAI	0.10~0.86	Remote Sensing
I_0	3.6 mm	Calculated

Sanchuan River, Wuding River, and Qingjian River) in CSSA and at the three hydrology stations (i.e., Longmen, Tongguan, and Sanmenxia) in the Longmen–Sanmenxia reach was evaluated by PBIAS, NS, and PD. Table 1 shows the calibrated parameters. Table 2 summarizes the simulated results of discharge and sediment load. Figure 3 presents the selected hydrographs.

The NS of the eight main tributaries was not acceptable. Only the hydrographs of the sediment load in Jialu River and discharge in Wuding River indicated "minimally acceptable" performance. However, the NS of Longmen, Tongguan, and Sanmenxia was better than that of the eight main tributaries, and the values tended to be the optimal value the longer the distance from CSSA. In the Longmen–Sanmenxia reach, the average NS for flow and sediment load was 0.66 and 0.38, respectively. The NS of the eight main tributaries indicated a necessity for the further improvement of DYRM.

In the discharge hydrographs, Gushan River had a tendency toward underestimation and accordingly an underestimated peak discharge. The other seven tributaries had a tendency toward overestimation; however, Sanchuan River and Qingjian River had underestimated peak discharges. The discharge in the Longmen–Sanmenxia reach had a tendency toward underestimation. In sum, the discharge hydrographs of most of the tributaries were overestimated, whereas the discharge hydrograph in the main channel was underestimated.

In the hydrographs of the sediment load, only Huangfu River and Kuye River had a tendency toward overestimation; however, the peak discharge in Kuye River was underestimated. The peak discharge of Huangfu River, Tuwei River, and Wuding River was overestimated. In sum, the sediment load of most of tributaries and the main channel was underestimated.

The magnitude of the simulated sediment load had the same order as measured, and the simulated daily sediment load matched the trend of the field processes. Thus, in the hydrographs of the discharge and sediment load, the simulation exhibited the trend of measured hydrographs very well, including the high discharge and low discharge parts. The inconsistency in the simulated water and sediment in the tributaries and main channel indicates that more efforts are required to conduct better simulation, including the data input and processing, and DYRM and 1D model.

5. Summary and Discussion

The analysis of the relationship between sediment erosion in the sediment source area and sediment deposition in the channel can help understand better the whole river system, which may also provide good management decisions and help in projecting changes in hydrology caused by changes in land use. Thus, DYRM and 1D model were loosely coupled to simulate the whole sediment process from CSSA to the Longmen–Sanmenxia reach. The coupled models were applied to simulate rainfall-runoff, sediment erosion, and fluvial propagation of the sediment-laden flow in 1977. PBIAS, NS, and PD were used to evaluate the performance of the coupled simulation. Analysis indicates that these two models can be used to explore the interrelationship of sediment erosion in CSSA and deposition in the downstream main channel.

However, further improvement of these two models may provide better understanding of the interrelationship. The following could be the reasons for the discrepancies between the measured and simulated:

DEM and its extraction. Owing to the low resolution of DEM, the terrain slope used in the simulation is different from reality, as the extracted slopes have a larger slope, slower slope-gradient, and longer slope-length. Accordingly, some topographic information may deviate from the actual value. However, the precision of the digital terrain data, resolution of the digital drainage network being extracted, and time consumed during the simulation should be balanced when simulating a large watershed.

Submodels. The submodels require further improvement. For instance, landscape features of sandy areas may deviate from the model assumptions, and specific models should be constructed. Extended application of the V-assumption in gullies and the evolution model in larger catchments requires more demonstration. Moreover, the simulation of the hyper-concentrated flood in V cross sections is different from either low-concentrated flow or hyper-concentrated flow in the main channel. Thus, the submodel for flood routing needs more analysis.

Parameters. The drainage area of CSSA involves different landforms and soil types. The specific parameters for different soil types are calibrated separately. They only consider the spatial distribution of different soil types to a certain extent.

Rainfall data. The temporal resolution of rainfall data is an important factor in rainfall-runoff simulation. In DYRM, daily rainfall is downscaled into hourly (He et al., 2010; Wang et al., 2007), whereas the time step used in the simulation is 6 min. Thus, more effects are required to obtain a proper temporal series.

Projects. Hydraulic projects and their effects should also be included, such as water conservation projects for DYRM and the Sanmenxia Reservoir and Xiaolangdi Reservoir for the 1D model. The main reason is that projects will influence not only the amount but also the hydrographs of water and sediment.

Although further improvement is required to simulate the whole sediment process better, the linked simulation may give

Table 2. Comparison of the Simulated and Observed, 1977 (July 1 to August 31)

Hydrology Station	NS	PBIAS	Water amount ($\times 10^7$ m^3)			Peak discharge (m^3/s)		
			Measured	Calculated	PD(%)	Measured	Calculated	PD(%)
Huangfu River	-5.38	48.23	6.72	11.9	77.08	170	593	--
Gushan River	-0.44	-3.55	15.9	15	12.22	1250	1092	-12.64
Kuye River	-1.3	22.50	37.4	51	27.77	1650	2531	53.39
Tuwei River	--	125.93	9.04	3.02	-66.59	88.4	99.9	13.01
Jialu River	-1.34	41.07	3.34	5.55	40.3	76	135	77.63
Sanchuan River	-17.63	135.33	17.8	56.7	--	410	199	-51.46
Wuding River	0.83	--	63	72.3	16.08	1560	1600	2.56
Qingjian River	-6.16	51.01	22	40.2	82.73	719	238	-66.90
Longmen	0.46	-2.71	8.59×10^2	8.22×10^2	-4.31	6450	5059	-21.57
Tongguan	0.73	-8.37	1.14×10^3	0.99×10^3	-13.16	8920	6857.4	-23.12
Sanmenxia	0.79	-2.92	1.12×10^3	1.07×10^3	-4.46	7550	8283.5	9.72
Hydrology Station	NS	PBIAS	Sediment amount ($\times 10^6$ t)			Peak sediment discharge (t/s)		
			Measured	Calculated	PD (%)	Measured	Calculated	PD (%)
Huangfu River	-1.09	38.74	23.8	38.8	63.03	148	171	15.54
Gushan River	-0.02	-61.95	79.8	70.7	1.21	791	571	-27.81
Kuye River	-0.11	76.89	123	27.6	-77.56	890	858	-3.6
Tuwei River	-0.1	-61.33	18.3	21.1	15.30	572	573	0.17
Jialu River	0.52	-2.40	11.8	11.3	-4.2	42.2	41.2	-2.37
Sanchuan River	-0.06	-61.53	45	34.2	-24.00	161	144	-10.56
Wuding River	--	--	25.6	51.9	--	1150	1956	70.09
Qingjian River	-0.08	-61.90	114	191	67.54	489	109	-77.71
Longmen	0.25	-36.36	1.48×10^3	2.51×10^3	69.59	2660×10^3	2632.4×10^3	-1.05
Tongguan	0.47	-0.49	1.99×10^5	1.98×10^5	-0.5	3960×10^3	2053.4×10^3	-48.16
Sanmenxia	0.41	3.63	1.96×10^5	2.07×10^5	5.61	3280×10^3	2349.2×10^3	-28.38

a qualitative description. Human-induced modifications on river basins, especially modifications in upland regions, may cause strong geomorphic responses by sediment supply, transport, and deposition. The linked simulation has been used to address the interaction between the upper watershed and the downstream channel, e.g., influence of land-use change in the upland on the fluvial process (Li, 2010; He, 2008).

Acknowledgments. The authors are grateful for the research funding provided by the National Basic Research Program of China (Grant No. 2011CB403305), and the National Natural Science Foundation of China (Grant No. 51109198), Chinese Academy of Sciences. This is also funded by the National Science & Technology Pillar Program of China in the Eleventh Five-year Plan Period (Grant No. 2007BAC06B06), and the National Natural Science Foundation of China (Grant No. 50725930), State Key Laboratory of Hydroscience and Engineering at Tsinghua University.

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