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Simulation and scenario analysis of soil erosion in the Miyun Reservoir watershed

BAOLIN SU, HAIFENG JIA, JIANPING WANG, YUAN'AN HU & SHENGTONG CHENG

Department of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China

sbl@tsinghua.edu.cn

Abstract The Soil and Water Assessment Tool (SWAT) was applied to the Miyun Reservoir watershed to simulate soil erosion. Two tributaries within this watershed, the Chao and Bai rivers, were simulated separately and hydrological and soil erosion processes were calibrated and validated using observed data from downstream gauging stations. Data analyses and simulation results indicate that soil erosion in both sub-watersheds predominantly occurs during flood seasons, and soil erosion is closely correlated with the spatial distribution of rainfall. Although the Bai sub-watershed has a larger drainage area than the Chao sub-watershed, the former contributes less sediment to the Miyun Reservoir than the latter because two upstream reservoirs (Yunzhou and Baihepu) intercept upstream sediment. Several rainfall scenarios were set up to simulate the influence of changing rainfall patterns; as a result, key areas of soil erosion were identified.

Key words Miyun Reservoir; scenario analysis; soil erosion; SWAT model

INTRODUCTION

The Miyun Reservoir is an important drinking water resource for Beijing, the capital of China. Although the local government has adopted strict regulations for controlling point-source pollution during the past 10 years, serious nonpoint-source pollution, associated with soil erosion in the watershed, remains a problem. Some studies on the Miyun Reservoir have indicated that soil erosion is the key process associated with nutrient transport within the drainage area, which in turn could lead to reservoir eutrophication (Wang *et al.*, 2002, 2003a,b). Hence, to control nonpoint-source pollution in the Miyun Reservoir watershed, and to prevent eutrophication in the reservoir, a clear understanding of local soil erosion processes is necessary. Therefore, the objectives of this study are: (a) to determine the distribution of soil erosion using the SWAT model; and (b) using scenario analysis, to identify areas where high sediment yields are likely.

STUDY AREA

The Miyun Reservoir is located in Miyun County, about 100 km from the centre of Beijing (Fig. 1). It is the largest reservoir on the Chao and Bai rivers, and has a maximum capacity of 4375×106 m^3 and a maximum surface area of 188 km^2.

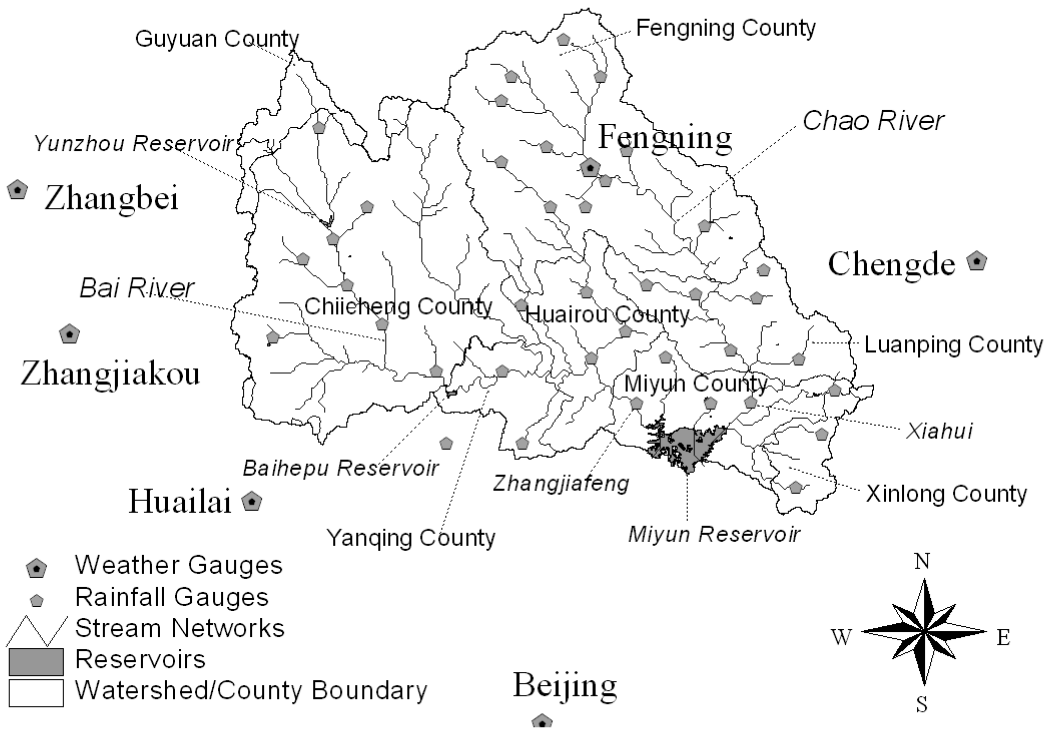

Fig. 1 The study area—the Miyun Reservoir watershed.

Currently, the Miyun Reservoir is the most important drinking water source for Beijing. Water from the reservoir is predominantly for municipal use in Beijing, but some water was earmarked for vegetable agriculture in the suburbs near Beijing. However, agricultural supply has ceased as a result of a water shortage in Beijing.

The area surrounding the reservoir is predominantly mountainous highlands. The Miyun Reservoir watershed (Fig. 1) mainly consists of the Chao and Bai sub-watersheds, which have a catchment area of 15 505 km^2. The Chao River originates in Fengning County, Hebei Province, and streams through Luanping County into Miyun County. The Bai River originates in Guyuan County, Hebei Province, and streams through Chicheng County, Hebei Province, as well as through Yanqing and Huairou Counties (Beijing) before reaching Miyun County. The Yunzhou and Baihepu Reservoirs are located on the Bai River; they have a maximum capacity of 114 and 91 × 10^6 m^3, and catchment areas of 1170 and 4040 km^2, respectively.

MATERIALS AND METHODS

The SWAT model

The Soil and Water Assessment Tool (SWAT) was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land-use, and management conditions, over long periods of time. It is a physically-based, nonpoint-source simulation model that can be used to evaluate long-term hydrological processes, soil erosion, and nonpoint-source pollution.

The SWAT model is a watershed model integrated from the Simulator for Water Resources in Rural Basins (SWRRB) and Routing Outputs to Outlet (ROTO) models, which includes two major parts: (a) a hydrology and water quality simulation component for evaluating hydrology, soil erosion, nutrients, and pesticides; and (b) a channel routing component (ROTO) (Neitsch *et al*., 2001a).

Using SWAT, the whole watershed is divided into sub-basins based on digital elevation and hydrological response units (HRUs). The latter are land areas within each sub-basin that are grouped according to unique combinations of land cover, soil type and management practices that have been determined from land-use and soil maps. SWAT simulates runoff, soil erosion, nutrient and pesticide loads at the outlet of each sub-basin based on various data inputs, such as land-use, soil type, weather and rainfall data; the results from each sub-basin are then routed to the outlet(s) of the entire watershed. Relative to its precursor (SWRRB), SWAT allows simulations of very extensive areas, while retaining all the features that made SWRRB such a valuable simulation model (Neitsch *et al*., 2001a).

Digital elevation model (DEM)

A digital elevation model, (DEM) based on 1:250 000 maps, was used for the delineation of stream networks and the division of the watershed into sub-basins. Other parameters necessary for running SWAT, such as watershed boundaries, the catchment areas of each sub-basin, and the average slope lengths and gradients of each sub-basin and reach, were extracted from the DEM. In this study, the whole watershed was divided into 138 sub-basins and 746 HRUs.

Land-use data

Nonpoint-source pollution, including soil erosion, is highly correlated with land use, as are such model parameters as the SCS curve number (CN) and the USLE cover and management factor (C). A 1:100 000 land-use map (Fig. 8(a)) was used in this study. The watershed has good vegetative cover; 49% is forests, shrub woods, and sparse woods, 27% is pasture with different cover percentages, and 21% are agricultural dry lands.

Soil data

The SWAT model requires data on soil distribution and physical/chemical properties to generate a soil database (Neitsch *et al*., 2002b). For this purpose, a 1:1 000 000 soil database which includes soil distribution and profile data was used. Soil classes consist of eluvial cinnamon soil (28%), brown soil (26%), cinnamonized soil (18%), calcic cinnamon soil (12%), fluvo-aquic soil (4%), skeletol soil (3%), castanozems (3%) and cinnamon soil (3%); these account for about 97% of the total area.

Climate data

The climatic variables required by SWAT consist of daily precipitation, maximum/-minimum air temperature, solar radiation, wind speed and relative humidity. The model permits entry of these variables either from existing datasets, or it can be simulated by a weather generator using average monthly values for the period of concern.

A long-term series of data (1971–2000) was collected from six weather stations surrounding the study area; these sites included Zhangbei (114°42′E, 41°09′N), Fengning (116°38′E, 41°13′N), Zhangjiakou (114°53’E, 40°47′N), Huailai (115°30′E, 40°24′N), Chengde (117°56′E, 40°58′N) and Beijing (116°17′E, 39°56′N) (Fig. 1). Site-specific data were: (a) monthly averages for maximum/minimum air temperature and standard deviations, precipitation and standard deviations, number of wet days, solar radiation, wind speed, and dew point air temperature; (b) a skew coefficient for daily precipitation during a month; (c) the probability of a wet day following a dry day during a month; and (d) the probability of a wet day following a wet day during a month.

Precipitation data

A daily rainfall time-series data set (1995–2002) was collected from 39 gauges which are approximately evenly distributed throughout the study area to ensure an accurate representation of rainfall distribution (Fig. 1).

Reservoir outflow data

In addition to the foregoing, daily outflows of the Yunzhou and Baihepu reservoirs, from 1995 to 2002, also were collected as inputs for the SWAT model.

SIMULATION RESULTS

Hydrological process

The SWAT model provides two methods for estimating surface runoff: the SCS curve number (CN) procedure and the Green and Ampt infiltration method (Neitsch *et al.*, 2001a). In this study, the SCS method was used to simulate surface runoff. The observed discharges at two hydrological gauges, Xiahui in the Chao sub-watershed, and Zhangjiafeng in the Bai sub-watershed, were used to calibrate hydrological parameters including CN values for different land-use classes, soil available water capacity, a soil evaporation compensation factor, a base flow factor, channel hydraulic conductivity, and concentration time. The initial calibration was performed using average annual conditions; a second calibration was then performed, using monthly values, to fine-tune the model. The annual and monthly observed data for 1995–1996, 1997–1999 and 2000–2002 were used to set up, calibrate and validate the model (Figs 2 and 3).

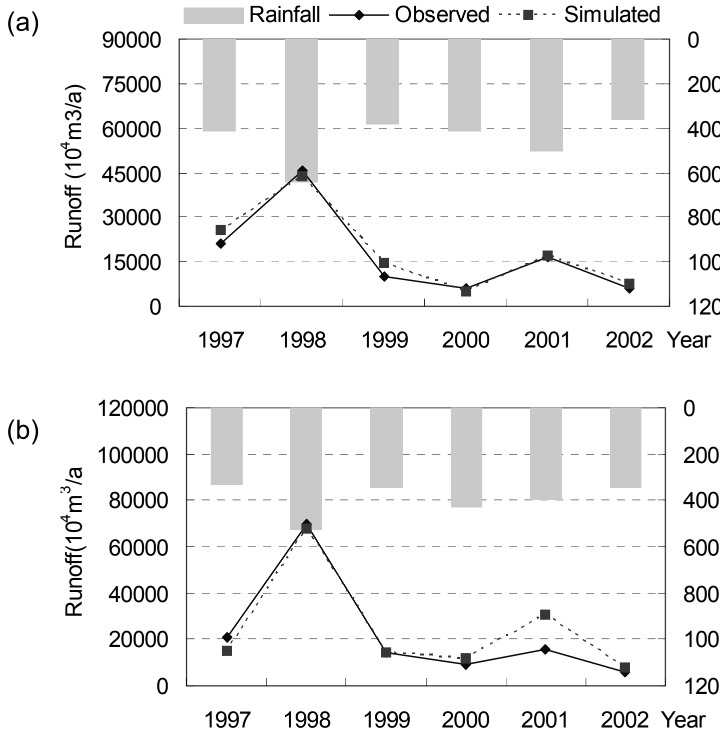

Fig. 2 Annual hydrological calibration and validation: (a) Xiahui, (b) Zhangjiafeng.

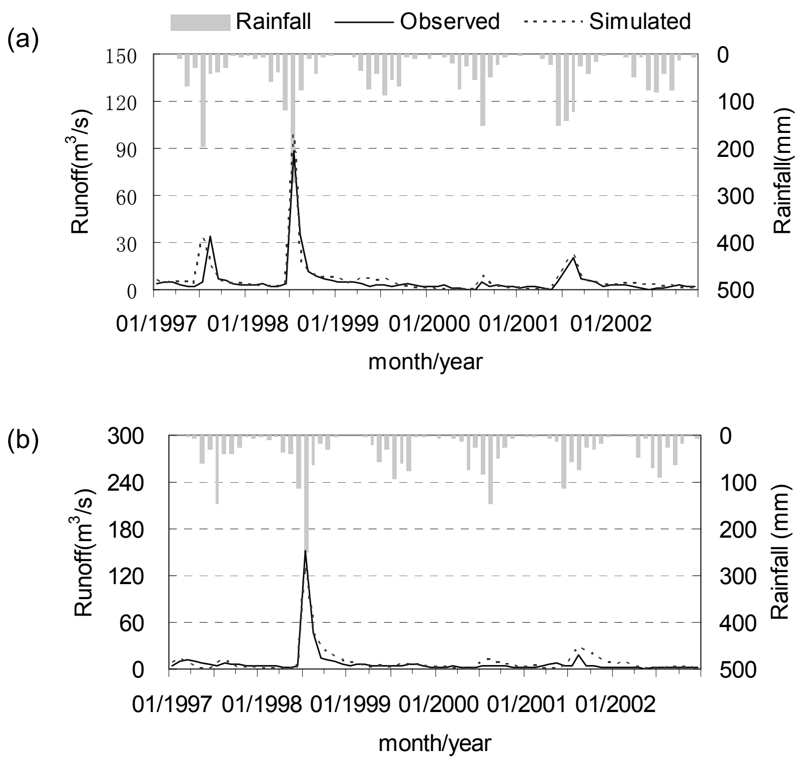

Fig. 3 Monthly hydrological calibration and validation: (a) Xiahui, (b) Zhangjiafeng.

Calibration (1997–1999) and validation (2000–2002) results, using both annual averages and monthly values, showed good agreement between observed and simulated values, with the exception of overestimated discharge peaks at the Zhangjiafeng station on the Bai River for 2001. The most likely cause of this discrepancy was a lack of local rainfall data that was replaced, for this period, with data from a neighbouring region.

Soil erosion

The SWAT model simulates soil erosion using the Modified Universal Soil Loss Equation (MUSLE). There are two sources of sediment in these simulations: (a) loadings from the HRUs/sub-basins; and (b) channel degradation/deposition. A variety of calibration parameters are required for these simulations (Neitsch *et al.*, 2001a,b). Depending on calibrated and validated hydrological parameters, calibration and validation of soil erosion parameters can be conducted. As with the hydrological process modelling described above, initial calibration was performed using annual averages, and fine tuning was performed using monthly values (Figs 4 and 5). There was good agreement between the observed and simulated values for both annual and monthly soil erosion, especially for peak loads. Daily sediment loads observed from 16 July to 10 August 1997 at the Xiahui Stationwere also used to evaluate the model. The comparison indicated that the simulated sediment loads could match the observed ones; albeit, the simulated peak occurred 1 day ahead of the observed one because the simulated daily hydrograph was 1 day ahead of the observed one (Fig. 6).

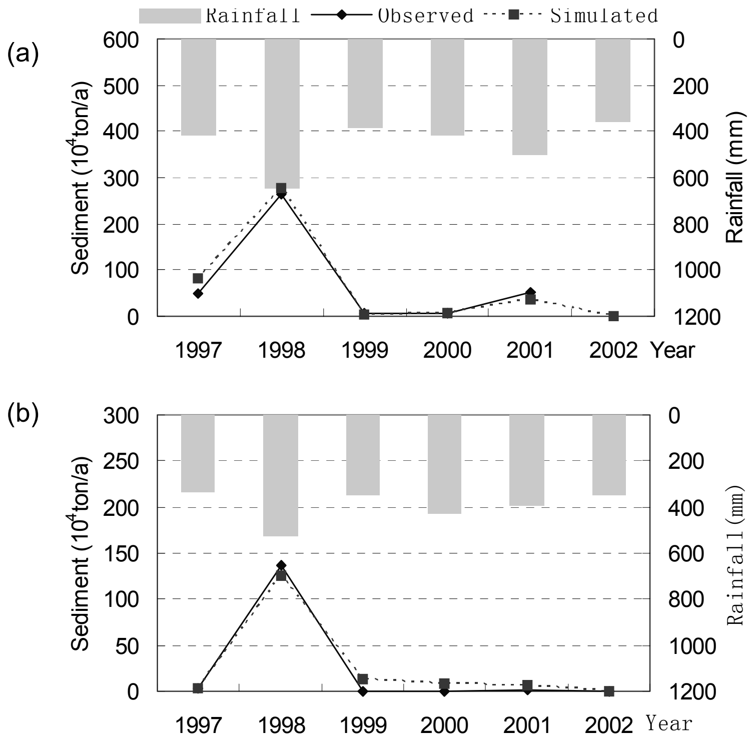

Fig. 4 Annual sediment calibration and validation:(a) Xiahui, (b) Zhangjiafeng.

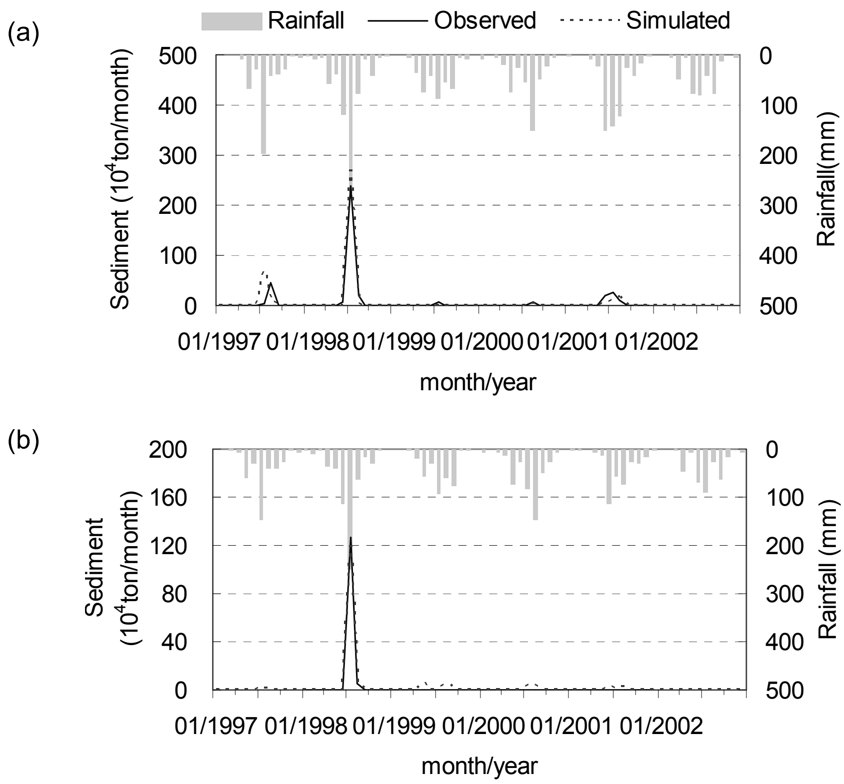

Fig. 5 Monthly sediment calibration and validation: (a) Xiahui, and (b) Zhangjiafeng.

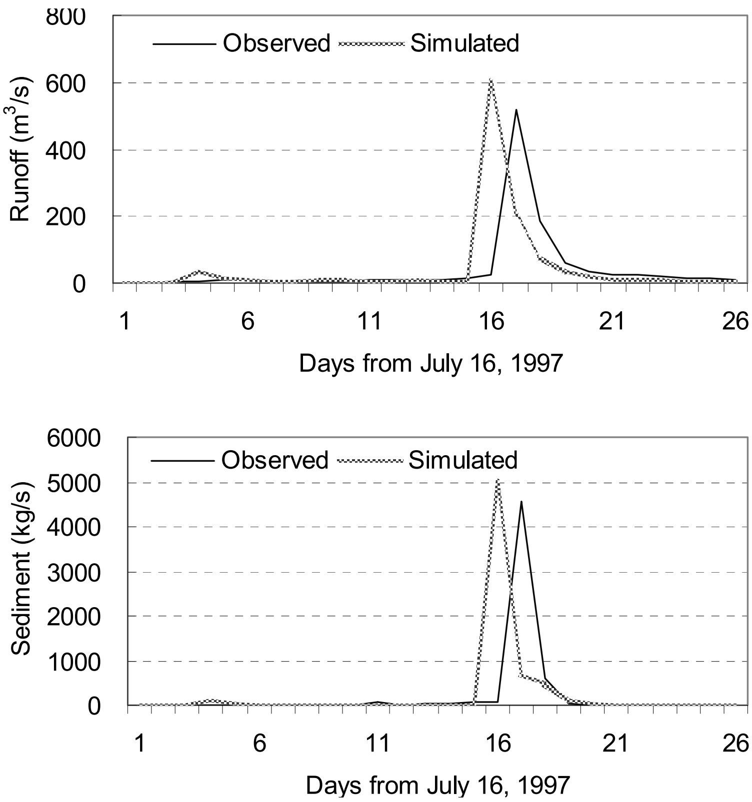

Fig. 6 Daily hydrological and sediment calibrations at the Xiahui station.

DISCUSSION

Temporal distribution

The Miyun Reservoir watershed is semiarid; in recent years (1995–2002) 350–650 mm and 330–570 mm of annual rainfall fell in the Chao and Bai sub-watersheds, respectively. Owing to the influence of a temperate continental monsoon, rainfall displays seasonal variations and mainly occurs from June to September (the flood season). For example, about 65–83 and 69–85% of annual rainfall occurred in the flood season in the Chao and Bai sub-watersheds, respectively. Soil erosion also mainly occurs during the flood season; hence, this is the period when maximum nonpoint-source inputs occur. The simulated results for soil erosion in both sub-watersheds match actual observations (Fig. 5); they also match a simulated monthly hydrograph (Fig. 3). Soil erosion during the flood season could account for more than 95% of the annual sediment yield during most of the years simulated (Table 1) except 1999, which was a dry year, with annual rainfall <370 mm.

Spatial distribution

The MUSLE incorporates surface runoff volume Q_{surf} (mm ha^{-1}) and peak runoff rate q_{peak} (m^3 s^{-1}), for the modeled area, according to the following equation: $(Q_{surf}\, q_{peak})^{0.56}$. The results from the application of the model indicate that soil erosion is closely correlated with the spatial distribution of rainfall and subsequent surface runoff (e.g. for 1998, Fig. 7).

Influences of reservoirs

The simulation results also indicate that, although the Bai sub-watershed has a larger catchment area (9200 km^2) than the Chao sub-watershed (6300 km^2), the Bai River contributes less sediment to the Miyun Reservoir than the Chao River (Figs 4 and 5; Table 1). Apparently, this is the result of the presence of two major reservoirs

Table 1 Simulated runoff volumes and sediment yields.

Year	Chao River sub-watershed:				Bai River sub-watershed:			
	Runoff volume		Sediment yield		Runoff volume		Sediment yield	
	Whole year (10^4 m^3)	Flood season (%)	Whole year (10^4 t)	Flood season (%)	Whole year (10^4 m^3)	Flood season (%)	Whole year (10^4 t)	Flood season (%)
1997	49172	62.2	352.40	99.6	19215	49.3	43.78	99.2
1998	61771	74.6	360.20	99.2	72562	81.2	160.00	99.9
1999	19923	37.4	4.14	85.9	14687	30.1	13.72	49.2
2000	10886	71.3	53.54	99.8	12316	63.4	7.84	97.9
2001	33141	75.0	144.60	99.1	32029	60.9	6.48	98.6
2002	12793	34.1	1.84	92.7	7863	12.4	0.68	96.2

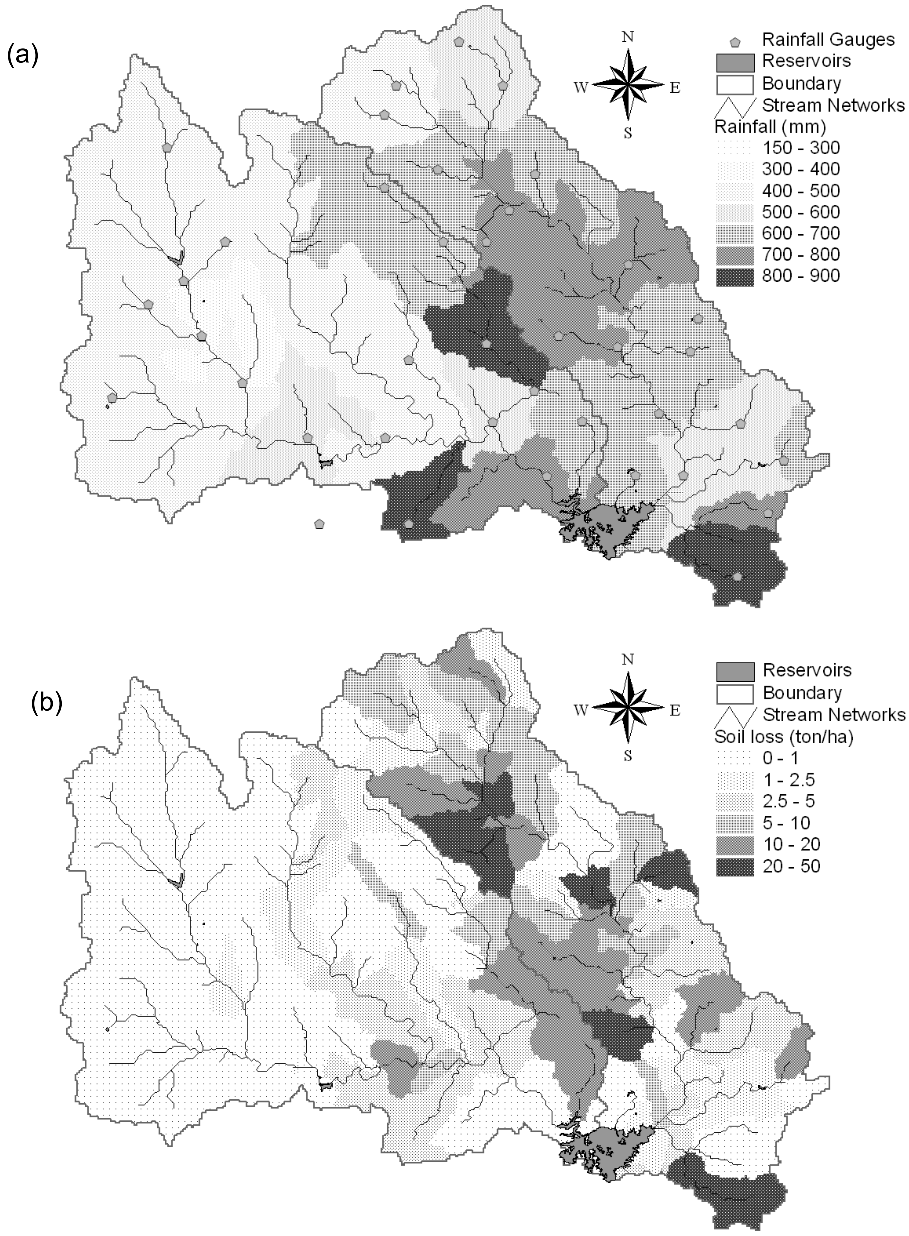

Fig. 7 (a) Rainfall distribution, and (b) soil loss distribution in 1998.

(Yunzhou and Baihepu) in the upstream area of the Bai sub-watershed. These reservoirs probably intercept substantial quantities of sediment before they can reach the Miyun impoundment.

SCENARIO ANALYSIS

As shown previously, the spatial distribution of soil erosion (sediment yield) is closely correlated with rainfall distribution and subsequent surface runoff. However, runoff is also a function of antecedent moisture conditions as well as rainfall energy. During

1998 (the year of the initial simulation) the distribution of both rainfall and antecedent moisture was extremely uneven. Hence, the 1998 results could not be used to identify areas with a high potential for soil erosion (i.e. the so-called key areas of soil erosion). To do so, it became necessary to simulate evenly spaced rainfall and similar antecedent moisture conditions as inputs for the SWAT model so that key areas of potential soil loss could be identified.

Scenario assumptions and simulations

Three different rainfall scenarios (wet, dry and normal) were simulated for six continuous years. To assure the same antecedent soil moisture conditions in the whole watershed for each scenario, rainfall inputs from 39 gauging stations collected during the first five years were replaced with areal-averaged daily rainfall from the same gauges for 1997, 1998, 1999, 2000 and 2001, respectively. The rainfall inputs for the sixth year were replaced with the areal-averaged daily rainfall for a wet year (1998, 610 mm), a dry year (1999, 360 mm), and a normal year (2000, 430 mm), respectively.

Using the same calibrated SWAT model described previously, soil erosion was then simulated under the three scenarios. The results for each scenario were normalized as the soil erosion index (*NSEI*, 0–1): where $NSEI = S/S_{max}$, where S is the simulated sediment yield from each sub-basin (t ha^{-1}); and S_{max} is the maximum sediment yield for each simulated scenario in the watershed.

Soil erosion can be graded at five different levels according to the *NSEI* value (Table 2). The key areas of soil erosion (above level 3) in the Chao River sub-watershed are predominantly located in both upstream and downstream areas. The latter are characterized by some small catchments near the outlet of the sub-watershed. Although there are some differences among simulation results for wet, dry, and normal years, the key areas of soil erosion (above level 3) in the Bai River sub-watershed predominantly are located in upstream areas in Chicheng County. Comparisons with land-use maps indicate that the key areas of soil erosion in both sub-watersheds are mainly croplands, whereas areas with normal or light soil erosion mainly are covered by forests and pastures (Fig. 8(a)).

CONCLUSIONS

The SWAT model was successfully applied to the Miyun Reservoir watershed to simulate soil erosion. Data analyses and simulation results indicate that soil erosion, in both of two sub-watersheds predominantly occurs during flood seasons (i.e. usually

Table 2 Soil erosion levels.

Level	NSEI	Soil erosion level
1	0.0–0.2	Slight
2	0.2–0.4	Ordinary
3	0.4–0.6	Moderate
4	0.6–0.8	Very serious
5	0.8–1.0	Extremely serious

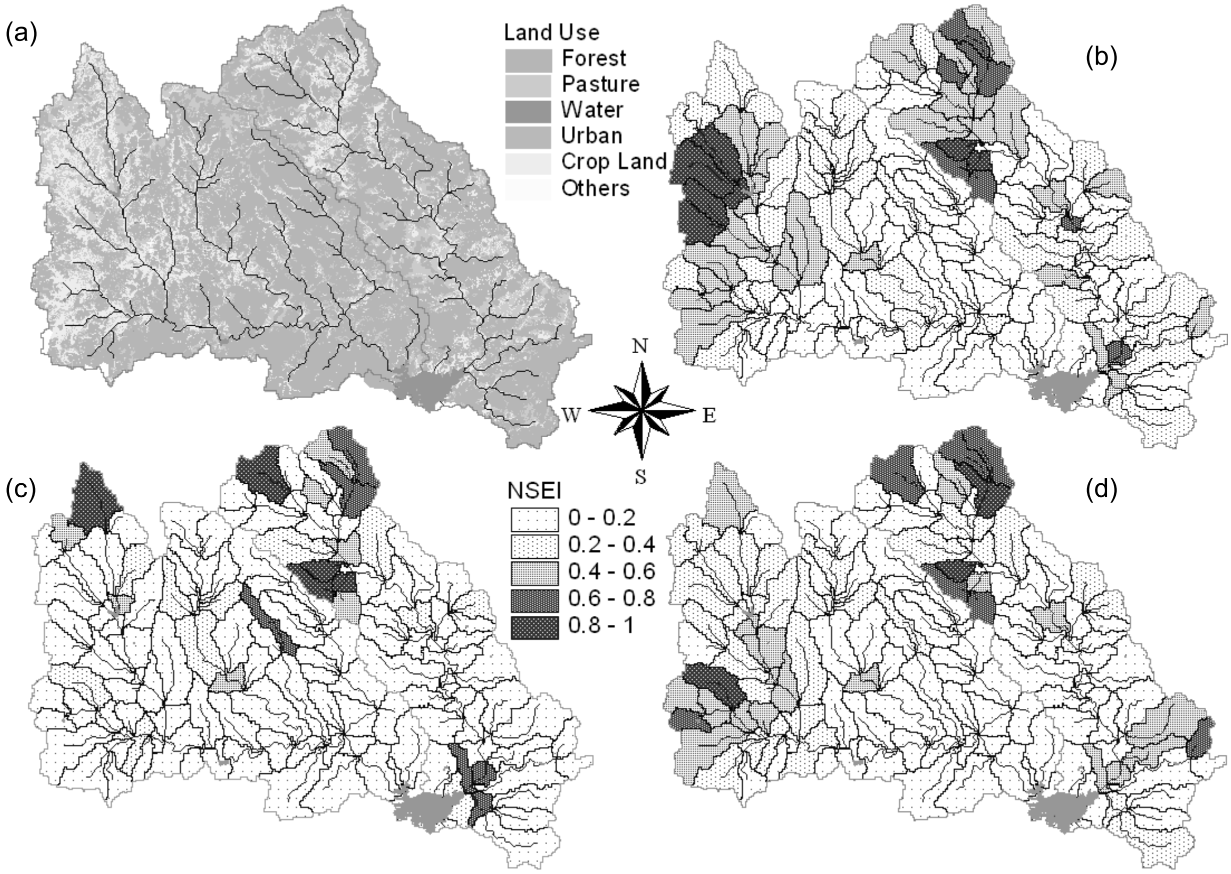

Fig. 8 Land-use distribution and soil erosion of different scenarios: (a) land-use map, (b) wet year, (c) dry year, and (d) normal year.

from June to September), which accounts for >70–80% of the annual rainfall. Soil erosion was closely correlated with the spatial distribution of rainfall and subsequent surface runoff. The results also showed that, although the Bai River sub-watershed has a larger catchment area than the Chao River sub-watershed, the Bai River contributed less sediment to the Miyun Reservoir because of the presence of two major upstream reservoirs that limited the downstream dispersion of sediment. Lastly, a variety of simulations indicate that agricultural areas have the highest sediment yields in the Miyun Reservoir watershed.

REFERENCES

Neitsch, S. L., Arnold, J. G., Kiniry, J. R. & Williams, J. R. (2001a) *Soil and Water Assessment Tool Theoretical Documentation (Version 2000)*. TWRI Report TR-192. Texas Water Resources Institute, College Station, Texas, USA.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R. & Williams, J. R. (2001b) *Soil and Water Assessment Tool User's Manual (Version 2000)*. Agricultural Research Service (Draft-April, 2001).

Wang Xiao-Yan, Wang Yi-Xun, Cai Xin-Guang, Xu Qian & Li Ting-Fang (2002) *Environmental Science & Technology* **25(**4), 1–3 (in Chinese).

Wang Xiao-Yan, Wang Yi-Xun, Wang Xiao-Feng, Wang Zhen-gang, Wang Qing-ping, Hu Qiu-ju & Cai Xin-guang (2003a) The character of nutrient loss and land use in a small watershed of Miyun Reservoir. *Res. Environ. Sci.* **16**(1), 30–33 (in Chinese).

Wang Xiao-Yan, Go Fang, Cai Xin-Guang & Hu Qiu-Ju (2003b) Non-point source pollution loading of Miyun Reservoir, Beijing. *Urban Environ. & Urban Ecol.* **16**(1), 31–33 (in Chinese).