Incorporating social and environmental factors into a regional soil erosion system analysis

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Abstract In the upper Changjiang and middle Huanghe the rate of soil erosion depends on climate and hydrometeorological conditions, the physical-chemical properties of the soil, topography and geomorphology, vegetation cover and human activity. In large basins, such factors as the position of the main area of heavy rain, the manner in which rainstorms move across the basin, localised intense rainfalls and the number of storms on a given day, all affect soil detachment and transport and the sediment delivered to the main river. In Sichuan, the dumping of over 33 Mt/yr of industrial waste into the Changjiang adds to pollutant levels, sediment loads and flooding.

INTRODUCTION

Soil erosion is a biophysical outcome of the integration of forces of soil detachment and transport with forces of resistance and deposition. The process is therefore the interaction of two sub-systems: an erosional dynamic system (rainfall, gravity, wind and frost action) and a land surface condition system (geology, geomorphology, soil, vegetation, cropping systems and management). This paper uses data from areas of severe soil erosion in China to analyse the factors involved in the assessment of regional soil erosion systems. Since 1984, varied construction activities have increased areas of severe soil erosion in Chongqing city by about 67 km^2/yr, with sediment yields rising by 1.5 Mt/yr.

FACTORS AFFECTING SOIL EROSION

Soil erosion is a complex dynamic process involving three sub-systems: land environment, erosion dynamics and human activity. These subsystems reflect the geology, geomorphology, climate and agricultural land use in a given region. For a region, the process of soil erosion may be said to be:

$$Se(t) \cong \begin{bmatrix} Gg(t) \\ Cm(t) \\ Ap(t) \end{bmatrix} \quad (1)$$

$$Se(ti) \cong [Gg(ti) \cap Cm(ti) \cap Ap(ti)/ti] \tag{2}$$

Soil erosion amount in the time period $t_1 - t_2$ $Se(T)$:

$$Se(T) = \int_{t_1}^{t_2} Gg(t) \cap Cm(t) \cap Ap(t)\, \mathrm{d}t \tag{3}$$

where: $Se(t)$: net result of soil erosion processes in a region; $Gg(t)$: geologic and geomorphic processes; $Cm(t)$: climate and hydrometeorological processes; $Ap(t)$: agricultural production; and $Se(ti)$: the erosion at time t_i.

Results from the upper Changjiang and middle Huanghe (Gu & Douglas, 1989; Zhao *et al.*, 1989; Gu & Ai, 1987) have shown that the rate of soil erosion depends on the physical-chemical properties of the soil, climatic conditions and weather, topography and geomorphology, vegetation cover and human activity, as equations (1), (2) and (3) imply.

Table 1 The relationship of soil type and erosion in Wufengdi watershed, inner Mongolia.

Soil	slope angle	Ks value mm s-1	erosive rain mm	runoff depth mm	runoff coe. %	sediment yield t ha-1
wind blown sand	9	3.0-3.5	190.6	15.0	7.86	4.31
soil type:						
loess	9	2.1-2.8	190.6	41.7	21.90	21.19
sand and silt	9	0.6-1.2	190.6	64.8	34.00	42.72

V: vegetation

Table 2 The relation of erosion and rock property and soil quality in Chongqing, China.

place	area ha	rock	soil	geomorphology	slope degree	land use	erosion t/ha
Tianjia	0.015	J2S	light soil	middle hilly	5	W-SP	2.4
Qianjin	0.019	J3S	middle soil	middle hilly	3	W-SP	7.2
Qianjin	0.027	J3S	M-L soil	middle hilly	8	W-SP	7.4

W:wheat
SP: sweet potato
M-L: middle and light

Geologic and soil factors

Surficial geologic and soil conditions directly influence soil erodibility. The properties and degree of weathering of earth surface materials affect permeability, cohesion and resistance to erosion. Data from north and south China (Zhao *et al.*, 1989; Wohlke *et al.*, 1988; Gu & Ai, 1987) show the variability of erosion with soil type. In inner Mongolia, under uniform slope, vegetation and rainfall conditions, soil permeabilities 3 to 5 times greater in one soil than another cause runoff 4.3 times greater and sediment yield 10 times greater (Table 1). In Chongqing, in the upper Changjiang basin, different soils under uniform slope and cultivation, have threefold differences in sediment yield (Table 2).

Climatic and hydrologic factors

The Universal Soil-Loss Equation recognises the role of rainfall amount, form, intensity and erosivity in producing runoff and splash erosion. However in large basins, such factors as the position of the main rainfall area, the way in which rainstorms move across the basin, localised intense rainfalls and the number of storms on a given day, can all affect soil detachment and transport and the sediment delivered to the main river.

In the 156 142 km^2 Jialinjiang basin, upper Changjiang, two storm events in which rain fell over the same general area and produced the same runoff (Table 3(a)) caused sediment yields differing by 1.9 times because rainfall intensities were 2.6 times greater in one storm. When the area of rainfall is not identical, sediment yields differ by as much as 5.3 times (Table 3(b)). In large basins, the area of maximum rainfall intensity has a major effect on sediment delivery. In this basin, differences in rainfall intensities and numbers of storms, despite giving the same monthly runoff, cause wide variations in sediment yield (Table 3(c)).

Topographic and geomorphic factors

Topography and geomorphology directly affect rainfall, runoff, rate of water erosion and intensity of wind erosion. Slope angle is the dominant parameter reflecting topography and geomorphology. Under otherwise uniform conditions and varying slopes below 40 degrees, soil erosion increases as slope increases (Tables 4 and 5).

Erosion plot data show that at a constant slope angle, length of slope affects soil erosion. But the effect of length of slope is more complex than that of slope angle because the relationship between length of slope and slope angle is disturbed and restricted by local environmental conditions and rainfall intensity. In wet regions or during heavy rainfalls, the longer the slope, the more water accumulates and higher is the erosivity and transporting capacity of the flow. In arid or low rainfall regions, the longer the slope, the greater the infiltration of water, and the smaller the surface runoff and soil erosion.

Table 3(a) Comparing rainfall with runoff and sediment under different rainfall intensity.

station	area km2	runoff event time	runoff Gm3	rainfall intensity mm/day	sediment Mt
Beipei	156142	2/8-11/8/84	6.78	26.8	6830
Beipei	156142	1/9-10/9/78	6.88	10.1	3630

Table 3(b) Comparing rainfall, runoff and sediment under different position of main rainfall area.

station	runoff event time	rainfall mm	runoff B m3	position main rain area	sediment Mt
Beipei	2/8-11/8/84	80.5	6.78	high erosion potential	68.3
Beipei	19/9-28/9/78	79.6	6.68	low erosion potential	12.9

Table 3(c) Comparing rainfall, runoff and sediment under different rainfall, rainfall intensity and rain day.

Time	month runoff Bm3	month sediment Mt	month rain mm	average rain intensity mm/day	>= 30mm days	>= 50mm days	Max. storm mm
July, 1981	11.6	29.3	102.5	9.3	1	0	48.0
July, 1966	12.1	178.0	218.7	10.9	4	2	92.6
Aug., 1983	9.77	18.6	126.4	11.5	0	0	23.8
July 1978	10.1	80.9	124.3	12.4	2	1	71.7
Sep., 1968	30.4	25.9	139.1	10.7	3	0	49.0
Aug., 1984	30.3	236.0	151.9	13.8	4	2	61.6

Data from the Tanjiaba station on the Jialinjiang, with a basin area of 9538 km2

Vegetation cover

The relationship between vegetation and soil erosion is readily apparent. In south China water erosion predominates (Table 6), but in north China wind erosion is more frequent (Table 7). Despite this difference in process, the same rule applies: as

Table 4 Variation of runoff and sediment yield with slope in the upper Changjiang basin.

slope	Yulin Yufeng			Xulin Shannin		Jiangjin
	P	R	erosion	R	erosion	erosion
angle	mm	m3 ha-1	t ha-1	m3 ha-1	t ha-1	t ha-1
5	642.5	1930.5	37.1	631.6	7.2	13.1
10	642.5	1682.3	51.2	813.3	68.7	19.2
15	642.5	2569.4	87.5	1031.6	92.7	39.3
20	642.5	2153.1	116.3	1133.9	109.5	57.9
25	642.5	1892.7	159.0	1760.0	148.3	77.7

observated data.
P: rainfall
R: runoff

Table 5 Comparison of slope and sediment yield in the Huangpuchuan basin, inner Mongolia.

Wufengdigou		Wubujingou	
slope angle	sediment yield t ha-1	slope angle	sediment yield t ha-1
9	10.281	9	12.079
12	11.087	17	59.699
15	22.766	19	101.278
30-50	100-300		

Table 6 Runoff and erosion under different vegetation cover in Jianyang county of Sichuan Province.

place	cover (%)	runoff m3 ha-1	erosion T ha-1	surface lowering (mm)
waste slope	20	411	2.25	0.166
bush	90	132	0.45	0.033

Table 7 The relation of grass cover and soil erosion in Wufengdi watershed, inner Mongolia.

grass cover (%)	< 1	24	28	49	67	72
erosion (t ha-1)	9.246	5.142	3.650	1.750	0.732	0.466

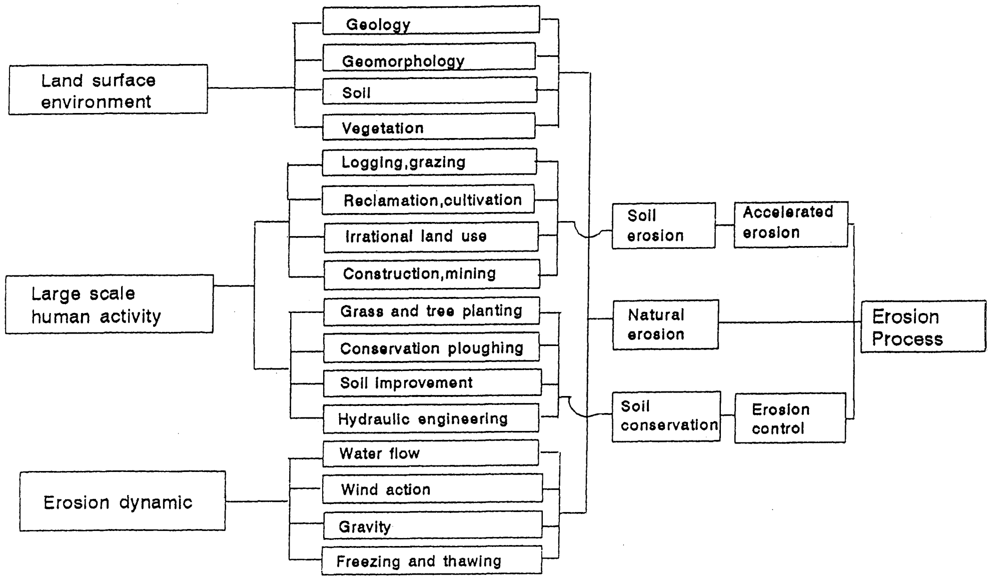

Fig. 1 Soil erosion and control system.

vegetation increases, erosion of the land surface decreases. Not only do natural forests and grasses have the function of decreasing erosion on the land surface, but man-made vegetation, like crops in fields, performs the same function. In inner Mongolia and Helongjiang, the *C* value (the index of reflecting vegetation cover in the USLE) varies not only with the crop cover, but also with the type and growing period of individual crops (Table 8).

Agricultural land use

Human activity affects soil erosion mainly by agricultural and construction activities. The effects may be either positive or negative. The positive effects are expressed by

Table 8 *C* value in Keshan county of Helongjiang Province, China.

Crop	grown periods				
	seeding	seedling	ripe	harvest	average
Corn	0.49	0.31	0.16	0.28	0.31
Sorghum	0.50	0.54	0.67	0.25	0.49
Millet	0.41	0.50	0.48	0.25	0.41
Bean	0.88	0.43	0.09	0.16	0.39
average	0.57	0.45	0.35	0.24	0.40

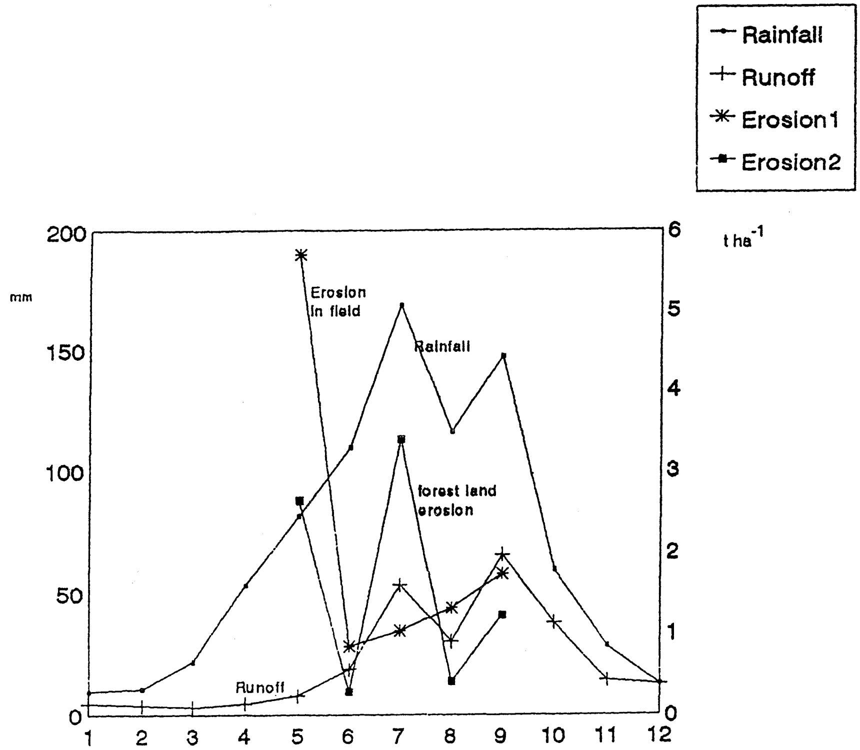

Fig. 2 Soil erosion over a year in Yanting, Jialinjiang basin.

such actions as cultivation on steep slopes, logging of forests, excessive grazing, and mining which aggravate soil erosion. The negative effects, which reduce erosion, are field improvements, planting of grasses and trees, establishment of engineering structures to trap sediment, and water and soil conservation measures.

In areas of severe water loss and soil erosion, periods of bare soil or reduced crop cover during a year would affect soil erosion. Soil erosion in the Yangting

Table 9 The effect of urban and rural activities on soil erosion in 11 counties of Sichuan Province.

items	number	new erosion area (km2)	annual erosion amount (Mt)
Mining	3947	374.62	16.5
Construction	15022	363.48	5.53
made stone	66423	377.03	5.98
road building	23944(km)	734.72	26.78
logging	35406	565.82	5.59
other	94259	438.72	14.58
total		2854.39	74.97

experimental watershed in the Jialinjiang basin, shows two peaks (Fig. 2), the first peak in May accounting for 58% of the annual total, the second peak in July to September corresponding to seasonal rainfall and runoff peaks. In May, rainfall only accounts for 13% of the total wet season rainfall, runoff is only 3% of the total seasonal runoff, but sediment yield is 58% of the total for the year. The reason is that after harvesting, crops are sown in late spring, crop cover is very low, most fields are bare, soil is dry and loose, then soil is scoured easily by flow.

Urban and rural construction activities

Human activities, such the building of houses, road construction, quarrying, dam construction, cuttings and embankments, tree felling and waste disposal, change land surface features and vegetation cover. Waste material from these engineering works often causes problems such as debris flow and severe soil erosion. In Sichuan, over 33 Mt/yr of industrial waste is dumped into rivers causing not only pollution, but aggravating flooding. In 11 Sichuan counties, human activity from 1984 to 1986, including mining, quarrying, logging and road construction, increased the area of severe erosion by 2854.39 km^2, accounting for 1.64% of the total area of these counties, or a total sediment yield of 74.97 Mt/yr (Table 9).

COMPREHENSIVE ASSESSMENT OF SOIL EROSION

Data from Chongqing are used to illustrate a correlation method of analysing soil erosion.

(a) Using seven variables (j_1, ..., j_7) comprising the parameters geomorphological type, slope, ruggedness, altitude, surface materials condition and land use as and relating the dependent variable erosion intensity for a statistical sample of 38 sites (i_1, ..., i_{38}) in the hills northwest of Chongqing City, the following calculation was made for each site:

$$Xij = \sum_{k=1}^{M} S_k P_k \quad (i = 1,2,3...38; j = 1,2,..7) \qquad (4)$$

where S_k represents the percentage of the total site area occupied by each class (k grade) (e.g. each of seven slope categories) of each variable at each site; and P_k represents an assigned numerical value allocated to each class of each variable at each site (e.g. 0 to 5° slope has an assigned value of 1, a 5° to 10° slope a value of 2 ...). The assigned values would be decided by experts based on field experience and observations.

(b) Multiplying Sk area percentage of every grade in i sample by the assessmental value of the corresponding grade for every grade, and summing all the conceptualized values in i sample gives a characteristic value of assessment factors and sets up a matrix for correlation analysis:

$$X= \begin{bmatrix} x_{11} & x_{12} \ldots x_{1m} \\ x_{21} & x_{22} \ldots x_{2m} \\ \ldots\ldots\ldots \\ \ldots\ldots\ldots \\ x_{n1} & x_{n2} \ldots x_{nm} \end{bmatrix} \quad (5)$$

(c) The following steps eliminate differences of parameter values.

$$X'ij = \frac{Xik - Xk}{Dk} \quad (i = 1,2,\ldots,n;\ j = 1,2,\ldots,m) \quad (6)$$

where

$$Xk = \frac{1}{n}\sum_{k=1}^{n} Xik \quad (7)$$

$$Dk = \frac{\sum_{i=1}^{n} (Xik - Xk)^{-2}}{n-1} \quad (8)$$

(d) Coefficient of correlation matrix

$$rij = (\sum_{k=1}^{n} X'ki * X'kj)/n \quad (i,j = 1,2,\ldots,m) \quad (9)$$

giving a correlation matrix

$$R = \begin{bmatrix} r_{11} & r_{12} \ldots r_{1m} \\ r_{21} & r_{22} \ldots r_{2m} \\ \ldots\ldots\ldots \\ \ldots\ldots\ldots \\ r_{m1} & r_{m2} \ldots r_{mm} \end{bmatrix} \quad (10)$$

Table 10 Correlation matrix of environmental factors influencing erosion in Chongqing.

	2	3	4	5	6	7
1. Geomorph.. type	0.781	-0.046	0.088	0.717	0.618	0.520
2. Slope		-0.082	-0-160	0.612	-0.789	0.701
3. Surface materials			-0.004	-0.024	-0.070	-0.300
4. Height				0.221	-0.270	-0.287
5. Ruggedness					0.221	0.457
6. Land Use						0.796
7. Erosion Intensity						

(e) The data in Table 10 show that the largest coefficient of correlation between erosion intensity and the six factors in the matrix is that with land use, r_{76} (0.796), indicating the importance of human activities for soil erosion intensity in Chongqing city. Soil erosion intensity is also closely associated with slope, r_{72} (0.701); with good correlations with geomorphological type, r_{71} (0.520); and

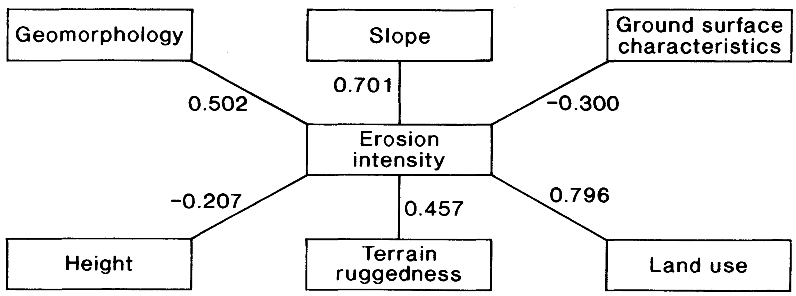

Fig. 3 Relationship between erosion intensity and environmental factors.

ruggedness, r_{75} (0.457). Thus people's activities clearly have a greater effect than natural factors on erosion processes on the present land surface in Chongqing (Fig. 3).

Overall, the factors promoting increased erosion include grazing, forest clearance, logging, mining, industrial and residential construction, and waste disposal, while those counteracting erosion include improvements to field boundaries, retention of water on site, detention ponds and other conservation measures. In areas subject to severe water losses and soil erosion, variations in crop cover through the year create specific opportunities for erosion which need to be modified by retention of organic matter, minimizing fallow periods and avoiding excessive cultivation of steep slopes. Detailed analysis of the way in which human activities intervene and different scales in the basin sediment problem is absolutely essential if an effective management plan is to be established.

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