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AN ASSESSMENT OF ECOSYSTEM SERVICES: WATER FLOW REGULATION AND HYDROELECTRIC POWER PRODUCTION

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Abstract. Forest ecosystems in the watersheds of the Yangtze river regulate water flow in the rivers. The value of water flow regulation by ecosystems is usually not realized in situ but may transfer spatially through rivers to another spot out of watersheds where conditions are suitable to realize it. To take into account the transfer of value of biological resources spatially, we developed a process-based simulation model to estimate the capacity of water flow regulation by terrestrial ecosystems, taking into account such major processes as canopy interception, litter absorption, and soil/ground water conservation.

In this study we combined models and a GIS-embodied spatial database to assess the capacity and benefits of water flow regulation by ecosystems in Xingshan County, Hubei Province, China. The capacity of water flow regulation differs substantially among the 90 types of vegetation–soil–slope complexes in the watersheds. The simulation model estimates that in a wet season the watershed can retain $\sim 868.07 \times 10^6$ m^3 water, which may result in a decrease of water flow by ~ 111.63 m^3/s in the Yangtze River. The model also estimates that in a dry season the watershed can discharge $\sim 80.74 \times 10^6$ m^3 water, resulting in an increase of water flow by ~ 10.38 m^3/s. As the result of water flow regulation, the Gezhouba hydroelectric power plant increases its electricity production by up to 40.37×10^6 kWh in a year and generates an additional economic value of $\sim 5.05 \times 10^6$ RMB/yr (1 US$ = 8.3 RMB, Chinese currency). This value is 0.42 times the annual income from forestry in the county in 1994 and may reach 2.2 times the annual income from forestry when Three Gorges Hydroelectric Power Plant runs. We also proposed a model of economic compensation for the region.

Key words: assessment, ecosystem services; economic compensation; ecosystem service; GIS; simulation models; water regulation; watershed; Yangtze River.

INTRODUCTION

Ecosystem services provide multiple benefits for human societies. For example, a forest ecosystem may provide timber, fruits, and other forest products, which represent direct use values of forest ecosystems (Balick and Mendelsohn 1992, Pearce and Moran 1994). A forest ecosystem also provides other ecosystem services (e.g., water conservation, carbon sequestration, erosion and flood control, and recreation), which are generally characterized as indirect use values of forest ecosystems (Tobias and Mendelsohn 1991, Chopra 1993, Smith 1993). Many ecosystem services are of a public goods nature and serve human societies without passing through the monetary economy at all. Thus, in many cases people are not even aware of those ecosystem services. To better recognize the multiple benefits of biological resources, a number of studies (McNeely 1993, Cacha 1994, Groot 1994, Hyde and Kanel 1994, Lacy and Lockwood 1994, Kramer and Munasinghe 1994, White et al. 1997) have conducted economic and ecological assessments of biological resources. Peters et al. (1989) assessed the economic value of a tropical Amazon rainforest in Brazil and proposed a strategy to use rainforests in the region. Pearce and Moran (1994) discussed the methods of economic evaluation of different biological resources and their interpretations, and estimated the economic values of tropical forests, wetlands, rangelands, and marine systems worldwide. Gren et al. (1995) calculated the economic value of Danube floodplains. Further, Costanza et al. (1997) evaluated the world's ecosystem services and natural capital.

Forest ecosystems in watersheds regulate water flows in streams and rivers (Hewlett 1982). It is important to recognize that water flow regulation by forest ecosystems in local watersheds may provide substantial economic values to human societies and activities downstream. As shown in Fig. 1, the use values of water flow regulation by forest ecosystems in the upper stretches of a river transfer spatially by a river to a city, hydroelectric plant, and farmlands that possess some suitable conditions, respectively, where the use values of water flow regulation can be realized and economic benefits are detained.

Because of the spatial separation between the source

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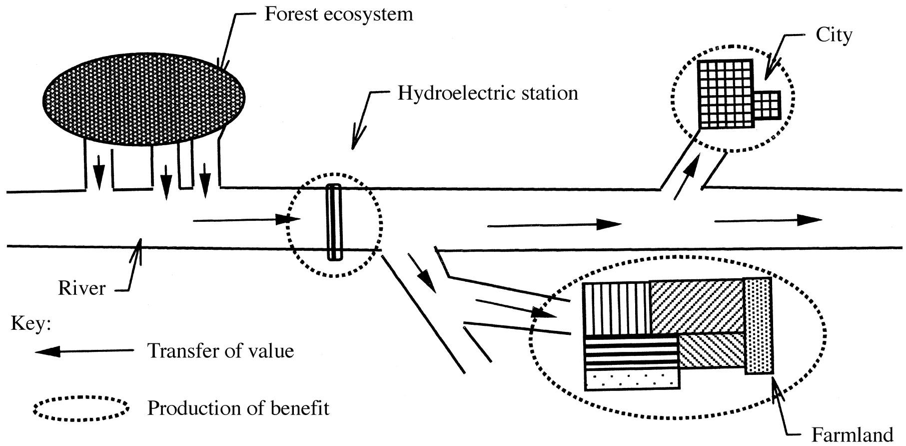

FIG. 1. Transfer of value of biological resources over space.

ecosystem services and the realization of their benefits due to the transfer of values of biological resources spatially, appropriation failure arises (Pearce and Moran 1994). For example, a forest ecosystem can help to sustain basic biogeochemical cycles on which human survival depends and can also yield benefits to people in other regions. Thus, a forest ecosystem contributes globally and externally. However, if the owner or caretaker of the biological resource receives no financial or other compensation for their contributions to these global external benefits, they will have no incentive to safeguard the biological resources.

Ecological compensation can provide a way to solve the problem of appropriation failure, by which the owner or caretaker of the biological resources can receive financial compensation from the regions that gain benefits from the biological resources (Perman et al. 1997). The use value of water flow regulation by forest ecosystems is a good example of transfer of values spatially and thus the problem of appropriation failure and the issue of ecological compensation are relevant. However, it is important to ascertain correctly the party that derives benefits from the resources, the party that supplies them, and the value of the benefits.

To assess the economic value of water flow regulation by a forest ecosystem requires accurate calculation of its water flow regulation capacity. Quantitative analysis of the capacity of water flow regulation by forest ecosystems has been done by the means of simulation modeling and/or statistics modeling (Xu 1988, Noest 1994, Wen and Liu 1995). In many cases, there is large heterogeneity across a landscape. The differences in vegetation types, soil, and slope may result in the difference in the function of water flow regulation. By analyzing these differences spatially through a geographical information system (GIS), understanding can be improved greatly. GIS offers appropriate tools to combine spatial data, field survey data, and models within one graphic environment. The research benefit of a GIS approach has been illustrated by many successful ecological studies (Coleman et al. 1994, Carver et al. 1995, Cowen et al. 1995, Mallawaarachchi et al. 1996, Bradshaw and Muller 1998, Swetnam et al. 1998), but seldom for ecological valuation (Eade and Moran 1996).

In this study we quantitatively assessed the capacity and economic values of water flow regulation by forest ecosystems in Xingshan County (110°25′ E–111°06′ E, 31°03′ N–31°34′ N) of western Hubei Province in Central China. The objectives of this study were threefold: (1) to develop an integrated approach of evaluating ecosystem service for water flow regulation, using simulation models and a GIS; (2) to estimate the economic value of water flow regulation by forest ecosystems for increasing the output of the Gezhouba hydroelectric power plant; and (3) to discuss the marginal social benefit and marginal social cost for this program and provide a model for the economic compensation of land owners. This study will provide important information for conservation and sustainable use of forest ecosystems in the region.

WATERSHED CHARACTERIZATION AND SPATIAL ANALYSIS

Xingshan County has an area of 2316 km^2. The Xiangxi River and the Liangtai River in Xingshan County collect water from 62 relatively large streams and flow into the upper Yangtze River right before the Three Gorges Dam that is currently under construction. Forest ecosystems in the watersheds regulate water flow of the Xiangxi and Liangtai Rivers, which in turn directly affect water flow of the Yangtze River.

Watersheds in Xingshan County are very heterogeneous in vegetation, soil, and slope. Experimental results have indicated that the capacity of water flow regulation by forest ecosystems is closely related to vegetation, soil, and slope (Lee 1980). Therefore, we have developed a spatial database for exploring the relationships between various types of vegetation–soil–

TABLE 1. Vegetation types in Xingshan County, Hubei Province, China.

No.	Vegetation type	Dominant species	Area (km^2)	Percentage of total	Code
1	Evergreen–deciduous broadleaf mixed forests	*Quercus variabilis, Quercus serrata* var. *brevipetiolata, Cyclobalanopsis glauca*	50.58	2.2	MIX
2	Conifer forests	*Pinus henryi, Pinus armandii, Pinus massoniana*	855.15	36.9	CON
3	Shrubs	*Loropetalum chinense, Vaccinium racteatum, Rhododendron simsii*	989.88	42.7	SHR
4	Grasses	*Imperata cylindrica* var. *major, Saccharumarundinaceum, Cynodon clactylon*	265.99	11.5	GRA
5	Orchard	Tangerines	43.93	1.9	ORC
6	Crop agricultural fields	Maize, potato	31.48	1.4	CRP

slope complexes and their capacities for water flow regulation.

The spatial database of vegetation, soil, and topography for Xingshan County is organized at the scale of 1:50 000. The vegetation map was developed through visual interpretation of Landsat TM image on 15 September 1995 together with an extensive field survey in Xingshan County in 1997. Six vegetation types are used in this study (Table 1). We digitized the soil map at the scale of 1:50 000. There are five types of soils: yellow brown soil (YBS), yellow soil (YLS), lime soil (LMS), purple soil (PPS), and rice soil (RCS). We also digitized the topographical maps at the scale of 1:50 000. The slope is divided into three categories according to its degree value: $<15°$, 15°–25°, and $>25°$. Fig. 2 shows the maps of vegetation, soil, and slope of Xingshan County.

The above digital maps of vegetation, soil, and slope for Xingshan County are embodied within a geographical information system (GIS), using ARC/INFO software (Environmental System Research Institute, Redlands, California, USA). We overlaid the maps of vegetation (six types), soil (five types), and slope (three categories), which yielded ninety categories of vegetation–soil–slope complexes and 6184 polygons, respectively. A polygon is represented by one of the six vegetation types, one of the five soil types, and one of the three slope categories. Table 2 lists the areas of ninety categories of vegetation–soil–slope complex in Xingshan County. We used these maps to produce a set of special subject maps featuring specific ecological factors in Xingshan County.

DESCRIPTION OF THE QUANTITATIVE ASSESSMENT MODELS

In this study, the method of valuation includes the following three steps: (1) to identify the way of transfer of use value of the biological resource in question and the location where the use value is realized; (2) to analyze the process by which the use value produces a certain benefit and determine quantitatively the contribution of the resource to the production of benefit; and (3) to assess the benefit by determining its market price, using conventional market approaches or surrogate market approaches. Then the price of the benefit is taken as the economic value of this kind of service provided by the biological resource.

We have developed a simplified assessment model that takes into account two such sets of processes: (1) water flow regulation by terrestrial ecosystems in watersheds; and (2) hydroelectricity production and marketing (Fig. 3). The model first calculates the capacity of water flow regulation by various ecosystems in watersheds, and then estimates its economic benefits for hydroelectricity production and market value. The following text is a brief description of the assessment model.

The model for water flow regulation by terrestrial ecosystems

Forest ecosystems regulate water flow through canopy interception, litter absorption, storage in soils and underground, and groundwater discharge (Lee 1980, Hewlett 1982, Ma 1993; also Fig. 3). In a rain event, the vegetation canopy intercepts part of the rainfall. The proportion of rain intercepted by the vegetation canopy is related to the leaf area index (LAI) and rainfall intensity. The rate of canopy interception in a rain event is defined as follows:

$$dC/dt = \mathrm{LAI} \times dl/dt = \mathrm{LAI} \times \alpha\rho[(l_0 - l)/l_0]^{\beta} \quad (1)$$

where C is the amount of rain intercepted by a unit area of canopy of a tree (mm) and l is that intercepted by a unit area of leaf (mm). See Table 3 for definitions of, α, ρ, l_0, and β.

The rate of water absorbed by litter is defined by the following equation:

$$dL/dt = \sigma(\rho - C_t)[(L_0 - L)/L_0]^{\tau} \quad (2)$$

where L is the amount of water contained by litter (mm) and $\rho - C_t$ is the rainfall falling through the canopy, which varies with the amount of rain intercepted by the canopy. Therefore, the rate of water absorbed by litter increases with the amount of litter and rainfall

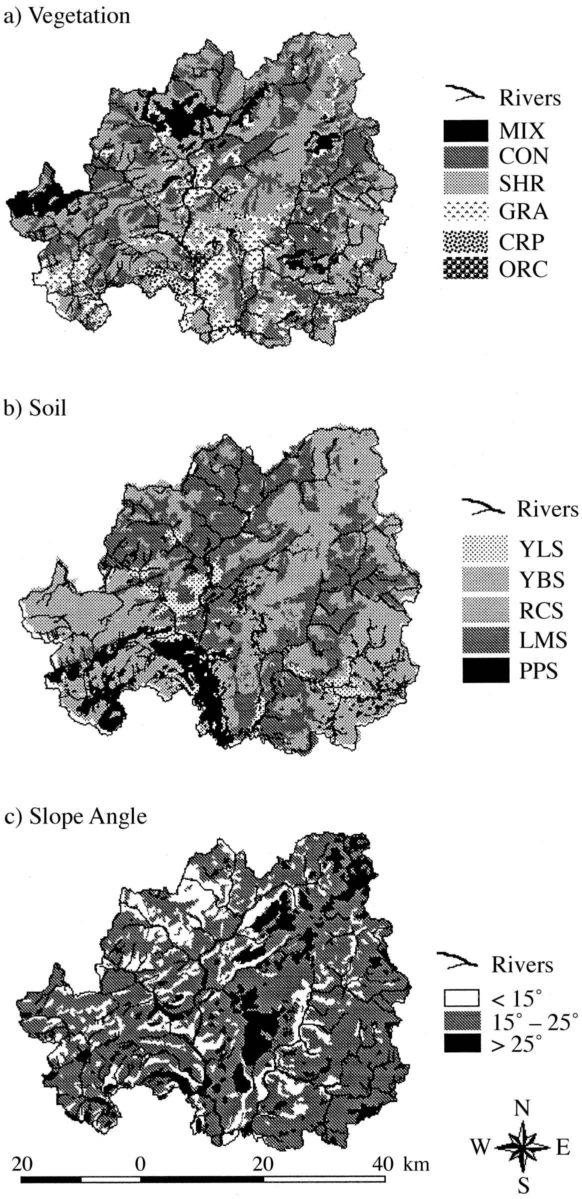

FIG. 2. The spatial distribution of vegetation, soils, and slope in Xingshan County, Hubei Province, China.

falling through the canopy, but decreases as the amount of water in litter approaches the water absorption saturation value of litter. See Table 3 for definitions of σ, C_t, L_0, and τ.

Soil water storage and underground water storage have similar effects on water flow regulation and these two processes are linked with each other temporally and spatially. To simplify the description of complex water dynamics in soils and underground, we combined the soil water component and the underground water component into one state variable: ground water (G in Fig. 3). Thus, soil water storage in soils and underground water storage are combined together into one state variable, i.e., ground water storage (G). Similarly, the releases of water in soils and underground are also considered as a unity, i.e., ground water discharge. The rate of accumulation of ground water is described as follows:

$$dG/dt = [\delta_1(U_t - U_c)]/(1 + \delta_2 G) \qquad (3)$$

where G is the amount of conservation of underground water (mm) and $U_t - U_c$ indicates the fluctuation of the pressure head of ground water with time. See Table 3 for definitions of δ_1, U_t, U_c, and δ_2.

In the dry season, underground water replenishes the flows of rivers based on the balance mechanism of amount of underground water. According to the earlier work of Ma (1993), the rate of ground water discharge is estimated by the following equation:

$$dR/dt = r_0 e^{-(t/Kg_t)} \qquad (4)$$

where R is the rate of ground water discharge (mm/min). (See Table 3 for definitions of r_0, K, and g_t.) The amount of ground water discharge during a period of $\triangle t$, is given by

$$R = \int_t^{t+\Delta t} r_0 e^{-(t/Kg_t)}\, dt = Kg_t r_0 e^{-(t/Kg_t)}[1 - e^{-(\Delta t/Kg_t)}]. \qquad (5)$$

Thus, the capacity of water flow regulation by terrestrial ecosystems in rain events (wet season) or dry period (dry season), W_{rain} and W_{dry}, respectively, can be expressed by the following equations:

$$W_{rain} = C + L + G \qquad (6)$$

$$W_{dry} = R. \qquad (7)$$

The capacity of water flow regulation by terrestrial ecosystem in a year, W_{yr}, can be expressed by following equation:

$$W_{yr} = \mu(W_{rain} + W_{dry}) \qquad (8)$$

where μ is an equivalent value of raining which relates to the precipitation intensity in a rain season. A more complete explanation of the calculation of μ is given in the next paragraph.

There are 17 parameters in the above eight equations that together describe water dynamics from vegetation canopy interception to ground water discharge in the watersheds (Table 3). First, we carried out the parameterization of models, using the field data observed in the vegetation–soil–slope complex MIX + YBS + slope angle < 15° (Table 3). The following data sets were used for the initialization of these equations: (1) monthly precipitation data of the Xingshan meteorological station from 1991 to 1995; (2) field measurements of water content in soil and litter from 30 sites and water flows of Xiangxi River and Liangtai River from 12 spots in both the wet and the dry season; (3) monthly water flow of Yangtze River at Yichang hy-

TABLE 2. The areas (km²) of the 90 vegetation–soil–slope complexes in the watersheds of the Xingshan County, Hubei Province, China.

Code	Soil type†	Slope angle	Area (km²), by vegetation type‡					
			MIX	CON	SHR	GRA	ORC	CRP
T_{01}	YBS	< 15°	2.406	58.165	44.527	8.193	0.390	0.266
T_{02}	YBS	15°–25°	16.35	275.59	347.21	73.39	8.260	6.989
T_{03}	YBS	> 25°	0.694	48.010	91.601	22.93	9.290	0.748
T_{04}	YLS	< 15°	0.282	6.140	8.395	2.768	0.187	0.719
T_{05}	YLS	15°–25°	0.917	24.355	35.395	15.47	3.460	3.845
T_{06}	YLS	> 25°	0.073	3.270	4.063	3.934	3.698	1.279
T_{07}	LMS	> 15°	9.487	122.83	80.802	23.54	0.400	0.769
T_{08}	LMS	15°–25°	16.48	247.28	220.38	55.49	3.405	4.090
T_{09}	LMS	> 25°	2.307	16.847	26.612	12.37	1.495	0.624
T_{10}	PPS	< 15°	0.890	9.860	12.376	5.345	0.703	0.907
T_{11}	PPS	15°–25°	0.211	20.703	51.541	22.32	2.700	5.071
T_{12}	PPS	> 25°	0	2.547	8.487	6.027	2.734	2.352
T_{13}	RCS	< 15°	0.090	1.926	30.097	1.316	0.063	0.124
T_{14}	RCS	15°–25°	0.328	14.139	19.822	8.245	2.896	2.309
T_{15}	RCS	> 25°	0.065	3.488	8.576	4.648	4.244	1.387

† YBS, yellow brown soil; YLS, yellow soil; LMS, lime soil; PPS, purple soil; RCS, rice soil.

‡ MIX, evergreen–deciduous broadleaf mixed forests; CON, conifer forests; SHR, shrubs; GRA, grasses; ORC, orchard; CRP, crop agricultural fields.

drometric station and monthly electricity output of GHPP from 1991 to 1995. In order to determine the equivalent value of raining μ (see Eq. 8), the precipitation intensity (mm/h) was divided into four types: <2.5, ≥2.5 and <8, ≥8 and <16, and ≥16. We first calculated the mean values of rainfall and rain duration in the wet season (June to September) using weather data during the 5-yr period from 1991 to 1995, and estimated the proportions of those types of precipitation intensity in the seasonal precipitation. Then, their equivalent values for standard precipitation intensity were calculated. By adding them up, the equivalent value of rain in a wet reason was obtained.

The capacity of water flow regulation by forest ecosystems varies significantly with different types of vegetation, soil, and slope. In comparison with MIX + YBS + slope angle < 15°, we used data from in situ surveys and field experiments to determine the relative efficiency of different types of vegetation, soil, and slope in water flow regulation (Table 4). For example, lime soil (LS) can regulate about 81% (0.81) of the amount of water regulated by yellowish brown soil (YBS) in the same unit of area. Table 4 lists the coefficients of capacity in water flow regulation for the other five vegetation types, three soil types, and two slopes, using the capacity of water flow regulation by MIX + YBS + slope angle < 15° to be the standard.

Thus, the actual capacities of water flow regulation by each type of the ninety complexes (vegetation–soil–slope, as described in *Watershed characterization and spatial analysis*) in the watersheds is determined by the equation

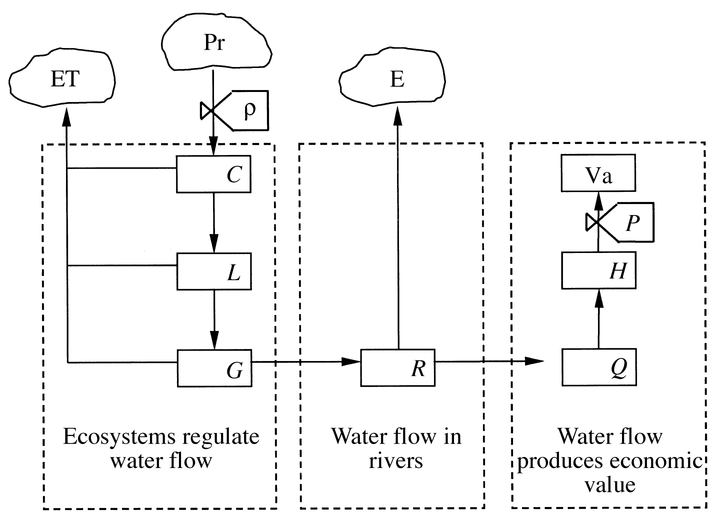

FIG. 3. The flow diagram of the assessment models: Pr is precipitation; ρ is the intensity of rainfall; C is the amount of rain intercepted by the canopy; L is the amount of water contained by litter; G is the amount of underground water; R is the rate of groundwater discharge; Q is the flow of the river; H is the output of the hydroelectric station; P is the price of a unit of electric power; and Va is the value of water regulation of the ecosystem. ET is the evapotranspiration of water and E is the evaporation of water. See *Methods* for units.

TABLE 3. The description of the parameters in the simulation models.

Parameter	Description	Units	Value
l_0	the saturated amount of rain intercepted by a unit area of leaf	mm	0.11
LAI	leaf area index		6.205
ρ	the intensity of rainfall	mm/min	0.15
L_0	the saturation value of rainwater contained by litter	mm	5.92
U_c	the maximum amount of water contained in unit area of ground when permeation ends	mm	0.6
r_0	the initial value of underground water	mm	5.88
g_t	the amount of underground water conserved per unit time	mm	147.01
σ	the coefficient of accumulation of litter		2.064
K	the coefficient of release of underground water		0.65
α	the coefficient of leaf interception		0.005
β	the coefficient of water carrying capacity of leaf		0.907
δ_1	the coefficient of pressure head of ground water		0.131
δ_2	the coefficient of underground water capacity		−0.025
τ	the coefficient of water carrying capacity of litter		0.032
μ	an equivalent value of raining, which relates to the rainfall and the times of raining in a rain season		61
C_t	the rate of water interception of canopy	mm/mm	dC/dt
U_t	the fluctuation of amount of water on a unit area of ground with time	mm	$(\rho - C_t - L_t)t$

$$W_{yr}(p_i) = \varepsilon_l \delta_j \eta_k \mu (W_{rain} + W_{dry}) \quad (9)$$

where $W_{yr}(p_i)$ is the amount of water flow regulation of the ith type of complex in a year. Hence, for a type of complex, the model has ε_l ($l = 1, 2, \ldots, 6$), δ_j ($j = 1, 2, \ldots, 5$), and η_k ($k = 1, 2$, or 3).

Therefore, the amount of water flow column regulated by all complexes averaged over many years, AWP, is given by

$$AWP = \sum_{i}^{90} W_{yr}(p_i) \times A_i \quad (10)$$

where A_i is the area of the ith type of complex.

The mathematical integrations of the dynamic differential equation require initial states of water in the ecosystems. All of initial states were set to typically observed values by the experimental sites within the watersheds. The initial conditions for water interception by canopy, water absorption by litter, and underground water storage were observed before a rain in June.

TABLE 4. The comparison of the capacity among water conservation of different types of vegetation, soils, and slopes in a unit of area.

Type	Symbol	Coefficient of capacity
MIX	ε_1	1.00
CON	ε_2	0.71
SHR	ε_3	0.57
GRA	ε_4	0.35
ORC	ε_5	0.11
CRP	ε_6	0.07
YBS	δ_1	1.00
YLS	δ_2	0.98
LMS	δ_3	0.81
PPS	δ_4	0.78
RCS	δ_5	0.05
SA <15°	η_1	1.00
SA 15°–25°	η_2	0.57
SA >25°	η_3	0.31

The model for hydroelectricity production and marketing value

At present, the Gezhouba Hydroelectric Power Plant (GHPP) in the Yangtze River is the largest hydroelectric power plant in China and is the only hydroelectric power plant downstream of the confluence of the Xiangxi and Liangtai Rivers (~100 km away). The mean annual electricity output of the GHPP is 15.7 billion kWh, supplying electricity to people in Eastern and Central China. It is obviously important for the development of the country to raise the efficiency of the GHPP.

The amount of electricity generated by a hydroelectric power plant depends upon three main factors: (1) the total amount of water flow per year; (2) the temporal distribution of the water flow; and (3) the water level difference (water head) in the dam (Chengdu Prospecting And Designing Institute of the Power Industry Ministry of China 1981). Fig. 4 shows the relationship between water flow and power generation at the GHPP. When the water flow entering the reservoir is <17 900 m^3/s, all of the water is used by the generators to produce electricity and electricity production increases as water flow rises. When the water flow is between 16 400 and 20 000 m^3/s, the generators run at full power. If water flow continues to increase and reaches more than 20 000 m^3/s, part of it will have to be discharged by sluice gates, and consequently, the water level is raised downstream, resulting in a smaller water level difference (water head) in the dam. This results in a decrease of electricity production as water flow increases. When water flow reaches over 65 000 m^3/s, the water level difference in the dam is <8.3 m, and the generators are not able to run. Therefore, under the condition that

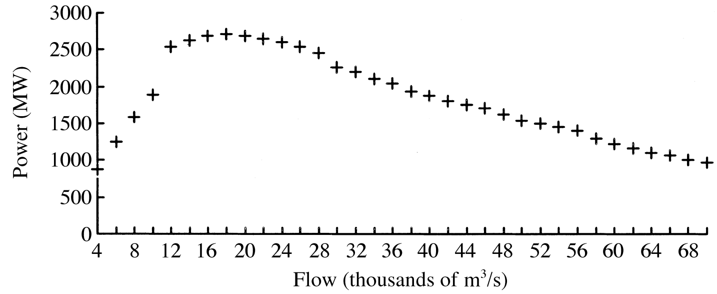

FIG. 4. The relationship between water flow in the Yangtze River and power generation at the Gezhouba Hydroelectric Power Plant.

water flow is either too high or too low, electricity production of a hydroelectric power plant would be reduced.

The relationship between water flow of the Yangtze River and hydroelectricity generated at the GHPP is described as follows:

$$dH/dQ = \begin{cases} -4.7 \times 10^{-6}Q^2 + 0.2398Q & Q \leq 18\,000 \\ -0.039Q + 3498.33 & Q > 18\,000 \end{cases} \quad (11)$$

where H is the output of GHPP (kWh) and Q is the flow of the Yangtze River (m^3/s).

The analysis of variance gave F statistics (regression mean squares divided by residual mean squares) $F_{1,6} = 655.474$ and $F_{1,7} = 704.591$, respectively. The two F values are well above the critical values, 5.99 and 5.59 respectively, at the 0.05 significance level, indicating that the regression analyses were statistically significant.

The above two regression models show that electricity output of the GHPP fluctuates with the change of water flow of the Yangtze River. The large fluctuation of electricity output of the GHPP has negative impacts on the income of the GHPP and the economy in Middle and Eastern China where most of its electricity is consumed. Terrestrial ecosystems in the watersheds along the Yangtze River, however, can regulate water flow of the Yangtze River, increasing water flow in the dry season and decreasing water flow in the wet season. A relatively smaller fluctuation in water flow of the Yangtze River would raise electricity production of the GHPP. The economic value of increased electricity output of the GHPP due to water flow regulation by terrestrial ecosystems in the watersheds is estimated by the following equation:

$$\text{Va} = H \times P \quad (12)$$

where Va is the value of output of GHPP (RMB: Chinese currency) and P is the price of a unit of electric power (RMB/kWh).

The model for economic compensation

We assume that for the ith patch of land, the amount of water flow regulation in a unit of area by the jth type of vegetation is V_j, the kth type of soil, So_k, and the lth type of slope, Sl_l, respectively ($j = 1, 2, 3, 4, 5, 6$; $k = 1, 2, 3, 4, 5$; $l = 1, 2, 3$), and its area is A_i. Then the economic compensation gained by the landowner of this patch of land, CP_i, can be estimated as follows:

$$\text{CP}_i = (V_j + \text{So}_k + \text{Sl}_l)A_iB \quad (13)$$

where B is landowner's benefit gained from a unit of water flow by generating electricity. It is a part of the profit of generating electricity. Here, the profit is the value of a unit of water flow by generating electricity, or Va/AWP, minus the cost of a hydraulic power plant's using a unit of water flow to generate electricity. The values of V_j, So_k, and Sl_l can be calculated by Eqs. 1–9. However, B is based upon the distribution of profit between the hydraulic power plant and landowner.

RESULTS

The capacities of water flow regulation by various ecosystems in watersheds

Fig. 5 shows a set of comparisons between observed and modeled rain interception by the vegetation canopy, water absorption by litter, and underground water storage during a rain event for the MIX + YBS + slope angle < 15° ecosystem type. The standard errors between the model and the data are 0.0016, 0.0348 and 0.062, respectively. According to the coefficients of capacity in Table 4, the amounts of water flow regulation by various types of vegetation, soil, and slope in a rain event were estimated. Fig. 6 shows some comparisons between the observed and modeled water flow regulation by the ecosystem types CON + YBS + slope angle > 25°, SHR + YLS + slope angle 15°–25°, ORC + LMS + slope angle 15°–25°, and CRP + RCS + slope angle 15°–25°. The simulation results agree reasonably well with the observation data; standard errors are 0.0085, 0.0368, 0.0087, and 0.0584, respectively (Fig. 6).

We estimated the capacity of water flow regulation by the MIX + YBS + slope angle < 15° by Eqs. 1–5 in a typical rain event, i.e., $t = 60$ min and $\rho = 0.15$ mm/min. During the rainy period, the amount of rain intercepted by the canopy, the amount of water absorbed by litter, and the amount of water stored in soil/underground were 0.68 mm, 5.65 mm, and 13.56 mm,

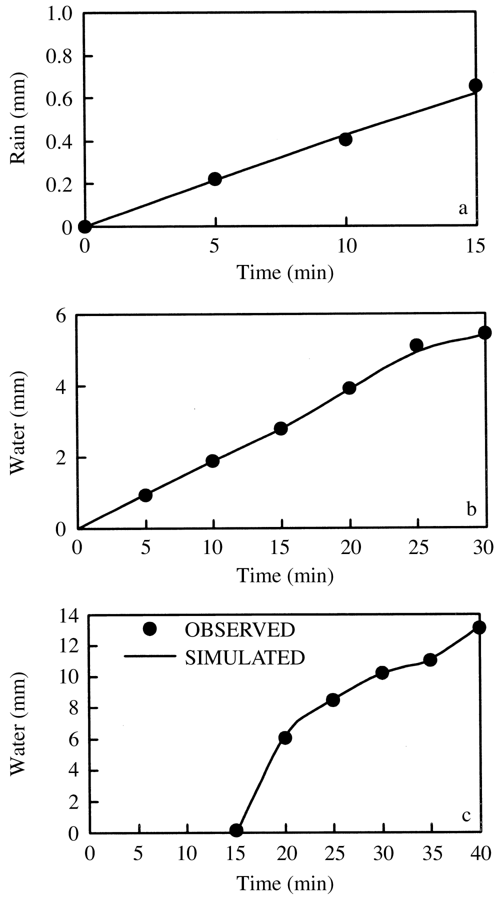

FIG. 5. The comparison between the observed and simulated capacity of water flow regulation during a rainfall event by the MIX + YBS + slope angle < 15° complex in Xingshan County (see Table 2 for reference): (a) rain interception by forest canopy, (b) water absorption by litter, and (c) underground water storage.

respectively. Ground water discharge during the dry period was 1.58 mm. Thus, the yearly integrated capacity of water flow regulation by the MIX + YBS + slope angle $< 15°$ ecosystem type was 1326.23 mm, as estimated by Eqs. 6–8 with $\mu = 61$.

The capacities of the other ecosystem types in Xingshan County were also determined by Eq. 9 using the coefficients of capacity in Table 4. For example, the yearly integrated capacity of water flow regulation by the twentieth ecosystem type (CON + YLS + slope angle 15°–25°) is: $W_{yr}(p_{20}) = 0.71 \times 0.98 \times 0.57 \times 1326.23 = 525.99$ mm. Fig. 7 compares the simulated capacity of water flow regulation by each of ninety types of ecosystems in the watershed.

Furthermore, the total amounts of water flow regulation by all ecosystems in the whole watershed in a dry season (December to April) and in a wet season (June to September) were calculated using Eq. 10. In the dry season the watersheds in Xingshan County released 80.74×10^6 m^3 water and resulted in a river water flow increased by 10.38 m^3/s (Table 5).

Economic evaluation of water flow regulation by terrestrial ecosystems

Benefit of water flow regulation.—The electricity generated by a hydroelectric power plant is affected by the temporal distribution of river water flow. Zhang and Zhang (1994) made a statistical analysis for a time series of daily mean river water flow measurements during the 109-yr period from 1882 to 1990 at the Yichang hydrology station near the GHPP. Their result showed that the annual power output of the GHPP does not depend on the total amount of river water flow in a year, but depends on how well the river water flow is distributed throughout the year (also see Fig. 4). Fig. 8 shows the monthly dynamics of river water flow over a year in the Xiangxi River and the Yangtze River. The ecosystems in the watershed of the Xiangxi River regulate the water flow of the Xiangxi River and, in turn, contribute to water flow regulation of the Yangtze River. The net result is a more even distribution of river water flow within the year, which may improve the efficiency of the GHPP.

According to Eq. 11, an increase of water flow by 1 m^3/s in the dry season can result in an increase of electricity production by 887.256 kW at the GHPP, while a decrease of water flow by 1 m^3/s in the wet season can also increase electricity production by 39.001 kW at the GHPP. Using the amounts of water flow increase and decrease in the dry and wet seasons listed in Table 5, the increases of power output by the

TABLE 5. The total water flow regulation by all 90 types of vegetation–soil–slope complexes in the watersheds of Xingshan County over the dry and wet season, as well as its economic value.

Ecosystem services	Dry period	Rain period	All year
Water released (millions of m^3)	80.74		
Water retained (millions of m^3)		868.07	
Flow increased (m^3/s)	10.38		
Flow decreased (m^3/s)		111.63	
Increase in the output of Gezhouba power plant (millions of kWh)	27.42	12.96	40.37
Economic value of water flow regulation (millions of RMB/yr)			5.047

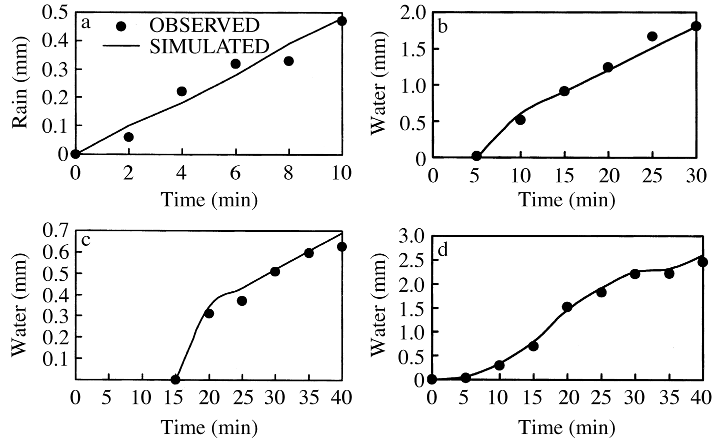

FIG. 6. The comparison between the observed and simulated capacities of water flow regulation during a rainfall event: (a) the amount of rain intercepted by the canopy of CON, (b) the amount of water contained by litter in SHR + YLS + slope angle 15°–25°, (c) the amount of water conserved by underground in ORC + LMS + slope angle 15°–25°, and (d) in CRP + RCS + slope angle 15°–25°.

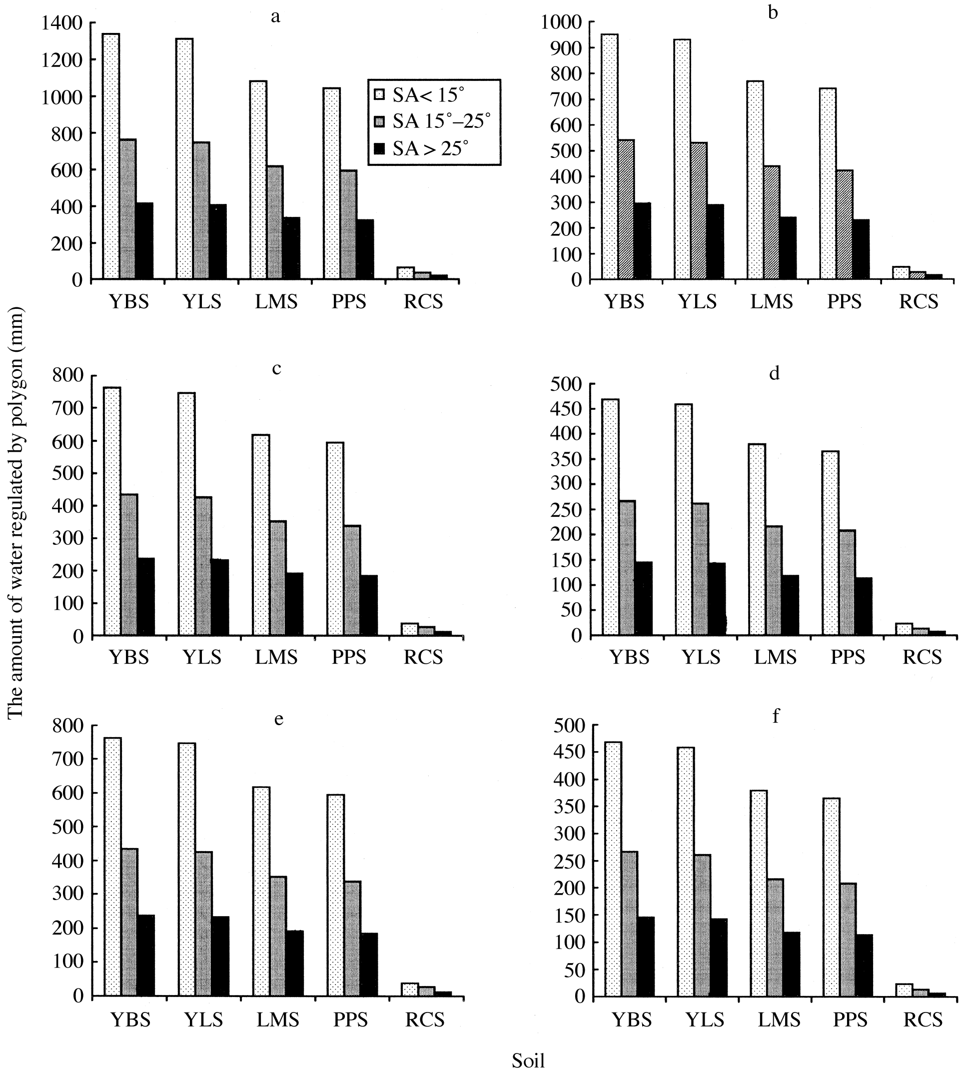

FIG. 7. The comparison among the simulated capacities of water flow regulation by all 90 types of vegetation–soil–slope complexes in Xingshan County (see Table 1 and 2 for reference), as grouped by vegetation types: (a) MIX, (b) CON, (c) SHR, (d) GRA, (e) ORC, and (f) CRP. SA = slope angle.

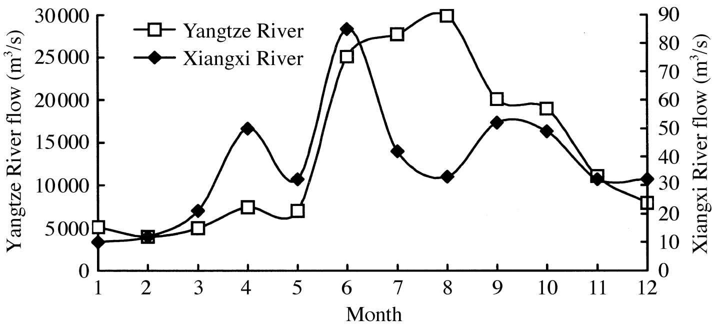

FIG. 8. A comparison between the monthly flows of Yangtze River and Xiangxi River in Xingshan County.

GHPP due to the water flow regulation by terrestrial ecosystems were calculated. The result, listed in Table 5, is a net increase in power output by about 40.37 million kWh due to water flow regulation by terrestrial ecosystems in Xingshan County.

Economic valuation of water flow regulation.—By the above analysis, clearly the ultimate effect of water flow regulation by terrestrial ecosystems is the increase in power output of a hydroelectric power plant. Because there is no exchange in the market for this benefit, we assessed the economic value of water flow regulation by terrestrial ecosystems in watersheds by evaluating the benefit resulted from the increase in the annual power output of the GHPP.

The price of electricity generated by the GHPP was 0.125 RMB per kWh in 1994 (Wang 1994). Thus, according to Eq. 12, the total annual economic value resulted from water flow regulation by ecosystems in Xingshan County was estimated to be about 5.047 million RMB (Table 5).

Marginal social benefit, marginal social cost, and economic compensation

Because of the limitation of capacity, the fixed amount of water provided will likely significantly increase the output of the hydraulic power plant, but surplus water exceeding this limitation will not bring benefits. Thus, we can draw the marginal social benefit (MSB) and marginal social cost (MSC) schedules for this kind of ecosystem service as shown in Fig. 9 (Seneca and Taussig 1984, Common 1996, Perman et al. 1997). In this study, we considered that the marginal social cost of a landowner mostly results from a decrease in timber sales. The MSC schedule indicates that the cost of water will rise with the increase of amount of water regulated, which corresponds to the assumption that if more forests are conserved, the amount of water regulated will increase but the price of timber will rise. Therefore, the loss of RMB of land-owner on a unit of land, resulted from the conservation of forest, will increase with the increment of amount of water regulated. The MSB schedule represents the benefit to the hydraulic power plant at each level of amount of water regulated, that is, the amount of the hydraulic power plant should pay for regulating one more unit of water at particular level of the amount of water. The downward slope of the MSB schedule reflects the diminution of marginal value of water (Seneca and Taussig 1984, Costanza 1991).

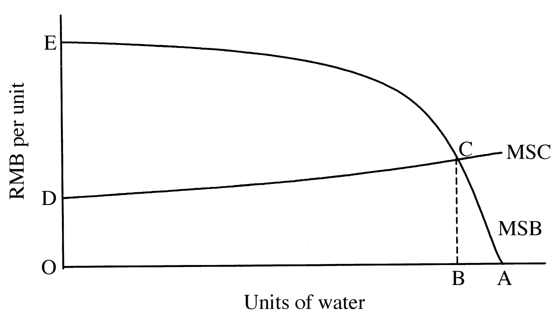

FIG. 9. The marginal social benefit (MSB) and marginal social cost (MSC) of water flow regulation by ecosystems to increase the output of a hydraulic power plant.

As shown in Fig. 9, the efficient amount of water is OB, because for any lesser level the additional benefit of one more unit of amount of water exceeds the additional cost per unit, and for any greater level the additional cost per unit exceeds the additional benefit per unit. Therefore, CB is just the landowner's benefit gained from a unit of water flow by generating electricity, or *B.* The value of EO and the curve EA can be determined by the Eqs. 1–11. The value of DO can be calculated by the price of timber. Then, we can calculate the value of *B*, and the economic compensation for the landowner of this stretch of land, CP_i, by Eq. 13.

DISCUSSION

In this paper we developed an integrated approach to assess ecosystem services based upon processes and benefits. The combination of the simulation model and the spatial database (vegetation, soil, and slope) embodied within a GIS provides quantitative and spatially explicit estimates of the capacities of water flow regulation in the watersheds. We also used the regression model to link water flow regulation and hydroelectricity production in the GHPP with their economic values. The assessment of ecosystem services is typically fraught with uncertainly and imprecision. However, if people hope that the assessment can provide a reliable basis for the compensation for ecosystem services and be received by the public, it should be more objective and accurate. Our approach, based upon processes and benefits, is a step toward this aim.

Water flow regulation is a major ecosystem service provided by the ecosystems in the watersheds of the Yangtze River. In this study we suggested that the function of ecosystems water flow regulation has indirect use value and holds economic value. Terrestrial ecosystems in Xingshan County regulate the water flow of the Yangtze River and thus increase the power output of the GHPP. The economic value of the ecosystem service of water flow regulation was calculated from the associated value of the increase in power output and was estimated to be 5.047×10^6 RMB/yr. In comparison, the annual income of forestry in Xingshan County was 1.204×10^7 RMB in 1994, all of which was generated from the direct use value of forests. With the completion and operation of the Three Gorges Project, the economic value of water flow regulation by ecosystems in the upper stretch of the Yangtze River will increase further. It was estimated that the average annual output of the Three Gorges Hydroelectric Power Plant will reach 84 billion kWh, which is 5.3 times that of the GHPP currently. Because both hydroelectric power plants were built on the Yangtze River and the distance between them is just 40 km, the more output shows that the Three Gorges Hydroelectric Power Plant can obtain larger benefit from water flow than the GHPP, and the output is in proportion to the benefit. Supposing that the benefit of water flow regulation by ecosystems on the Three Gorges Hydroelectric Power Plant will also be 5.3 times that of the GHPP, the economic value of water flow regulation by ecosystems in Xingshan County could reach 2.6765×10^7 RMB/yr, which is about 2.2 times of the annual income of direct forestry products of Xingshan County. Though an increase of the output of the GHPP is only part of the benefit resulting from water flow regulation by ecosystems, the results clearly illustrate that the indirect use values of ecosystem services are capable of producing more economic benefits than from the direct use values. Closer attention to the economic benefits of ecosystem services' indirect use values is warranted.

The GHPP is ~100 km away from Xingshan County. The use value of water flow regulation by ecosystems transfers from the watersheds in Xingshan County to the GHPP, along the Xiangxi River, Liangtai River, and the Yangtze River, resulting in an increase of hydroelectricity output of the GHPP. The electric power generated by the GHPP is, in turn, transported (by wires) to the lower stretch of the Yangtze River and other areas. The people who live in the region studied cannot gain this part of the benefit of water flow regulation by ecosystems, although they need to make an effort to conserve the ecosystems. In this situation, it is usually difficult to issue economic compensations, due to the difficulty in determining the amount of benefits and beneficiaries. In this paper, we explored the approach to provide the economic compensation to landowners, and developed the model for it based upon the situations of land use. To determine how to distribute the economic profit, we discussed the MSB and MSC of the program studied. The models of economic valuation developed in this paper provide a way to determine MSB and MSC because this set of models is based upon the analyses of process of realization of economic value. Thus, we can establish a system of sharing ecosystem services by that economic compensation model.

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