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Ecosystem function for water retention and forest ecosystem conservation in a watershed of the Yangtze River

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Abstract. The ecosystem function for water retention in a watershed of the Yangtze River was discussed in this study. The watershed was divided into 90 types of vegetation–soil–slope complex. A GIS-embodied spatial database was used to explore the relationships between the capacity of water retention by a complex and its types of vegetation, soil and slope. Furthermore, the capacity of water retention of every complex was estimated statistically by using estimation models. The spatial distribution of various capacity of water retention in the watershed was demarcated on a map based on the attributions and the locations of complexes. In addition, we evaluated integrally the situation of water retention in the watershed based on the estimation for the complexes from which it was distinctly recognized that the serious situation mainly results from the poor capacity of water retention of vegetation. The variation-location effect describes the phenomenon in which an identical variation of a factor may produce different effects on overall situation, when this variation occurs in a different spatial location. According to the variation-location effect on the expansion of forestland, a strategy 'spatial pattern-based forestland extension' was proposed to conserve forest ecosystem and improve the situation of water retention in the watershed.

Key words: conservation, ecosystem function, forest, spatial pattern, the Yangtze River, water retention, watershed

Introduction

Ecosystem services such as climate regulation, water regulation, water supply provide a major contribution to human society and accrue directly to humans without passing through the money economy (Costanza et al. 1997). To better recognize the multiple benefits of ecosystem services, a number of studies (McNeely 1993; Cacha 1994; Groot 1994; Hyde and Kanel 1994; Kramer and Munasinghe 1994; Lacy and Lockwood 1994) have conducted the economic and ecological assessments of ecosystem services. Peters et al. (1989) assessed the economic value of a tropical Amazon rainforest in Brazil and proposed a strategy to use rainforests in this region. Pearce and Moran (1994) discussed the methods of economic valuation used in 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. In addition, Costanza et al. (1997) evaluated the world's ecosystem services and natural capital. Recently, Guo et al. (2000) assessed the ecosystem service for forest ecosystems regulating water flow to increase the output of a hydroelectric power. These researches have shown that ecosystem services are of great importance to human society.

Ecosystem services represent the benefits human populations derive, directly or indirectly, from ecosystem functions. Ecosystem functions refer variously to the habitat, biological or system properties or processes of ecosystems. In some cases a single ecosystem service may be the product of two or more ecosystem functions whereas in other cases a single ecosystem function contributes to two or more ecosystem services. Therefore, the valuation of ecosystem service should always be based on the estimation of the capacity of ecosystem function. Here we primarily concentrated on the estimation of the ecosystem function relating to water retention – the absorption and storage of rainwater. This contributes to two types of ecosystem service, i.e., water supply and water regulation (Costanza et al. 1997; Guo et al. 2000). In the upper and middle stretches of the Yangtze River, water retention is a chief function of terrestrial ecosystems (MOF 1992; MOF 1995; Li et al. 1999). These ecosystems retain rainwater in wet seasons to decrease flood in the river and supply water in dry seasons to supplement the flow. However, this kind of ecosystem function is usually ignored because of lack of understanding. A striking illustration is that the area of forest ecosystem, providing the largest capacity of water retention in this basin, is being progressively reduced. Inappropriate exploitation and strong economic pressures have resulted in ecologically sensitive natural forests being harvested but not well regenerated. Land conversion was also a common phenomenon. These factors have led to decrease the capacity of water retention of the Yangtze River basin. The loss caused by the catastrophic flood in1998 was shocking. It was reported that the regular life of about 24 million people suffered from that flood and that 2000 persons died as a consequence. The area of farmland affected by this flood reached 2.2 million ha (PDN 1998). Scientists have repeatedly stressed the connection between the recent rapid loss of tree cover in the southern provinces and the reduced capacity of water retention, increased erosion, and more destructive floods in the Yangtze River (Wang 1993). To improve the situation, Chinese government has planned to establish protective forest system to conserve water and soil in the whole of the Yangtze River basin (Albers and Grinspoon 1997). The scale of this project makes it one of the largest afforestation undertakings in the developing world (World Bank 1992; Mather 1993). However, massive campaigns of afforestation in degraded areas were not very effective until the last decade (Yin 1998).

In this study, we have discussed the ecosystem function for water retention in a watershed of the Yangtze River. The watershed is located in the Xingshan County of Hubei Province, China (110°25′–111°06′ E, 31°03′–31°34′ N). It has an area of about 231 600 ha and forestlands of 107 000 ha (about 46.2% of the total country).

In the watershed, the Xiangxi River and the Liangtai River collect 62 relatively large streams and flow into the Yangtze River. They produce flow about 211 million m^3 mean a year. Thus, the capacity of water retention by the terrestrial ecosystems in this watershed influence directly the amounts of water flow of the Xiangxi River and the Liangtai River, and both rivers, in turn, influence the water flow of the Yangtze River. Based on analyses we proposed a strategy for conserving forests to improve the ecosystem function for water retention in the watershed. This study can provide useful information for conservation, management and sustainable use of ecosystem resources in the whole of the Yangtze River basin and other regions faced with similar problems.

Methods

Spatial analysis for the watershed

The watershed in Xingshan County is very heterogeneous in vegetation, soil and slope. Experimental results have indicated that the capacity of water retention by terrestrial ecosystems is closely related to vegetation, soil and slope (Lee 1980; Hewlett 1982; Ma 1993). Therefore, we have developed a spatial database for exploring the relationships between various types of vegetation–soil–slope complexes and their capacities for water retention (Carver et al. 1995; Cowen et al. 1995; Eade and Moran 1996; Mallawaarachchi et al. 1996; Bradshaw and Moller 1998; Swetnam et al. 1998).

The spatial database of vegetation, soil and topography for the watershed 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, dense forest, opened forest, shrub, grass, orchard and crop. We digitized the soil map at the scale of 1:50 000. There are five types of soils: yellow brown soil, yellow soil, lime soil, purple soil and rice soil. 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: less than 15°, between 15 and 25° and more than 25°. Each type of vegetation, soil or slope has a special capacity of water retention, which results in spatial heterogeneity in the capacity of water retention in the watershed. Table 1 lists the types of vegetation, soil and slope in Xingshan County as well as their codes.

The digital maps of vegetation, soil and slope for Xingshan County are embodied within a geographical information system (GIS), using the ARC/INFO software (ESRI 1994). We used these maps to produce a set of special subject maps featuring specific ecological factors in the watershed and which were overlaid by key geographic layers, i.e., vegetation (six types), soil (five types) and slope (three categories)

Table 1. Types of vegetation, soil and slope in Xingshan County.

Name	Type	Code	Area (km^2)
Vegetation	Dense forest (canopy >0.3)	DFE	58.59
	Opened forest (canopy ≤0.3) mixed with bushes and grasses	OFE	895.15
	Shrubs	SHR	999.88
	Grasses	GRA	265.99
	Orchard	ORC	54.83
	Crop agricultural field	CRP	41.57
Soil	Yellow brown	YBS	1045.91
	Yellow	YLS	138.25
	Lime	LMS	844.30
	Purple	PPS	163.78
	Rice	RCS	123.76
Slope angle	More than 25°	$SA > 25°$	363.85
	Between 15° and 25°	$SA = 15–25°$	1520.73
	Less than 15°	$SA < 15°$	431.42

and integrated to subdivide the watershed into a number of vegetation–soil–slope complexes.

Assessment for the ecosystem function of water retention

The capacity of water retention by a complex is an integration of the capacities of vegetation, soil and slope (Ma 1993). Since each type of vegetation, soil or slope has a specific capacity, we can estimate the capacity of water retention by a complex according to these three variables. To understand the capacities of water retention of the three factors, we implemented *in situ* serial surveys and field experiments at 30 sites in the watershed in some rain events, and we also surveyed the integrated capacities of water retention of vegetation–soil–slope complexes in these sites (Guo et al. 2000). In the watershed DFE, YBS and SA $< 15°$ (see Table 1) have respectively the largest capacity of water retention among vegetation, soil and slope. In comparison with them, we used the data obtained *in situ* to estimate the relative efficiency of different type vegetation, soil, and slope in water retention (see Table 2). For example, shrub (SHR) can retain about 57% (0.57) of the amount of water retained by dense forest (DFE) under same conditions of soil and slope. Then, the relationship between the capacity of water retention by a complex and the relative efficiencies of vegetation, soil and slope can be found expression in the below formula based on observations.

$$WH_i = 0.0048 w_e \left(\frac{v_j}{0.491} + \frac{s_k}{0.518} + \frac{p_l}{0.662} \right) \tag{1}$$

where WH_i is the capacity of water retention by the ith type complex (mm). w is the capacity of water retention by the complex DFE–YBS–SA $< 15°$, which has the

Table 2. The comparison of water retention capacity of different types of vegetation, soils and slopes in a unit of area.

Type	Symbol	Coefficient of capacity
DFE	v_1	1.00
OFE	v_2	0.71
SHR	v_3	0.57
GRA	v_4	0.35
ORC	v_5	0.11
CRP	v_6	0.07
YBS	s_1	1.00
YLS	s_2	0.98
LMS	s_3	0.81
PPS	s_4	0.78
RCS	s_5	0.05
SA < 15°	p_1	1.00
SA = 15–25°	p_2	0.57
SA > 25°	p_3	0.31

largest capacity of water retention in the watershed. Hence, for a type of complex, the model has v_j, ($j = 1$ or $2 \ldots$ or 6), s_k ($k = 1$ or $2 \ldots$ or 5), and p_l ($l = 1$ or 2 or 3) (see Table 2). Then, the amount of water retained by a type of complex per year is:

$$W_i = \mu W H_i A_i \tag{2}$$

where W_i is the amount of water retained by the ith type complex (m^3 yr^{-1}). A_i is the total area of this type complex in the watershed (ha). Clearly rainfall is not well-distributed in the watershed and not identical in each rainfall. Thus, to estimate the amount of water retained by a complex in a rain season statistically, we used a parameter, i.e., the equivalent value of raining μ, which relates to the rainfall and the times of raining in a rain season per year. To determine it, the precipitation intensity (mm h^{-1}) 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–September) using weather data during the 5-year-period from 1991 to 1995, and estimated the proportions of these types of precipitation intensity in the seasonal precipitation. Then, their equivalent values for standard precipitation intensity were calculated. Adding them up, the equivalent value of rain in a wet reason was obtained. If there are n types of complex in the watershed, then the total amount of water retained by all types of complex in the watershed, W_{total}, can be calculated by the followed equation:

$$W_{\text{total}} = \sum_{i}^{n} W_i \tag{3}$$

At any polygon (a patch of land), the characteristics (e.g., vegetation, soil and slope) of a complex at this polygon determine the ‘strengths’ of ecosystem functions.

A polygon has a special complex type, and a complex has a special capacity of water retention. Then the locations of polygons can show the locations of complexes, in turn, the locations of the capacities of water retention estimated by Equations (1) and (2). Therefore, we can determine the spatial distribution of the capacities of water retention based on the attributions (complex types) and the locations of polygons.

Just like a complex, the capacity of water retention by a watershed also depends on the conditions of vegetation, soil and slope. Optimal vegetation coverage rate for water retention CR is an index for evaluating the condition of vegetation.

$$\mathrm{CR} = \frac{PA_\mathrm{f}}{W_\mathrm{c}A_\mathrm{t}} \times 100\% \tag{4}$$

where P is the maximum daily rainfall of many years mean ($\mathrm{m}^3\ \mathrm{ha}^{-1}$). A_f is the area of study region except town, village, farmland and water body (ha) and A_t is the total area of this region (ha). W_c is the capacity of water retention by this region ($\mathrm{m}^3\ \mathrm{ha}^{-1}$).

Variation-location effect on forest ecosystem conservation

In a complex, the change of vegetation can result in a variance in the function of water retention. For example, according to survey the complex GRA–RCS–SA $> 25°$ has a water retention capacity of 2.64 mm, while GRA–YBS–SA $< 15°$ 18.43 mm. If the type of vegetation is changed into DFE in both complexes, their capacities for water retention will be increased to 15.71 and 109.81 mm, respectively. The mean rainfall of a rain for the watershed is 25.58 mm and the maximum daily rainfall of many years mean is 86.4 mm. Then the increase from 2.64 to 15.71 mm provides 100% 'effective increment' of the capacity of water retention for the former complex. While the increase from 18.43 to 109.81 mm adds some redundant capacities for the latter complex, because 109.81 mm is over the maximum rainfall by about 27%. The identical changes of vegetation type in both complexes produce different effects on the capacity of water retention of the watershed because both changes occur in different spatial locations that have different physical attributes, or the types of soil and slope. That is to say, the identical variation of a factor, qualitative or quantitative, when it occurs in different spatial location, may produce different effects on overall situation. We called this phenomenon as 'variation-location effect'. Then, in the ith type of complex, when vegetation that holds a relative capacity of water retention v_l is replaced by another that holds the relative capacity v_m, the variation-location effect may occur in the variance of the capacity of water retention of this complex. We can use an index W_{S_i} to evaluate this variation-location effect.

$$W_{S_i} = \frac{(v_\mathrm{m} - v_\mathrm{l}) \sum_j^k \lambda_j\, rw_j}{kWH_i} \tag{5}$$

where k is the number of all kinds of precipitation (divided by intensity). λ_j is the weight coefficient for the jth kind rain. rw_j is the precipitation intensity in the jth kind rain. A larger index indicates that, when vegetation type is changed, a larger variation-location effect will occur in the variance of the capacity of water retention in the complex. In other words, this complex can yield larger effective increment for the capacity of water retention by the change of vegetation type. In this study, we improved the capacity of water retention of the watershed in question by regulating the spatial pattern of vegetation based on the variation-location effect shown by this index.

Results and discussion

Characteristics of the watershed

The watershed was divided into 90 categories of vegetation–soil–slope complexes by GIS tool, yielding 6184 polygons. A polygon is represented by one of the six vegetation types, one of the five soil types and one of the three slope categories. The areas of all types of complex were also obtained by this means (see Table 3). Each of the polygons represents a unique combination of physical and biological attributes, or soil, slope, and vegetation. This illustrates the relationships between the types of vegetation, soil and slope, and the capacity of water retention by a complex. The spatial situation of water retention can also be demarcated on a map based on the spatial patterns of these polygons.

The capacities of water retention in the watershed

In this study, the estimation was twofold: (1) for the capacities of water retention by the 90 types of vegetation–soil–slope complexes, and (2) for the capacity of water

Table 3. Areas (km^2) of 90 types of vegetation–soil–slope complex.

Code	Soil–slope	DFE	OFE	SHR	GRA	ORC	CRP
T_1	YBS–SA < 15°	2.406	58.165	44.527	8.193	0.390	0.266
T_2	YBS–SA = 15–25°	16.35	275.59	347.21	73.39	8.260	6.989
T_3	YBS–SA > 25°	0.694	48.010	91.601	22.93	9.290	0.748
T_4	YLS–SA < 15°	0.282	6.140	8.395	2.768	0.187	0.719
T_5	YLS–SA = 15–25°	0.917	24.355	35.395	15.47	3.460	3.845
T_6	YLS–SA > 25°	0.073	3.270	4.063	3.934	3.698	1.279
T_7	LMS–SA < 15°	9.487	122.83	80.802	23.54	0.400	0.769
T_8	LMS–SA = 15–25°	16.48	247.28	220.38	55.49	3.405	4.090
T_9	LMS–SA > 25°	2.307	16.847	26.612	12.37	1.495	0.624
T_{10}	PPS–SA < 15°	0.890	9.860	12.376	5.345	0.703	0.907
T_{11}	PPS–SA = 15–25°	0.211	20.703	51.541	22.32	2.700	5.071
T_{12}	PPS–SA > 25°	0	2.547	8.487	6.027	2.734	2.352
T_{13}	RCS–SA < 15°	0.090	1.926	30.097	1.316	0.063	0.124
T_{14}	RCS–SA = 15–25°	0.328	14.139	19.822	8.245	2.896	2.309
T_{15}	RCS–SA > 25°	0.065	3.488	8.576	4.648	4.244	1.387

retention of the whole of the watershed studied. The capacity of water retention by every complex type was estimated by using Equations (1) and (2). Furthermore, the capacity of water retention of the watershed was evaluated integrally based upon the estimations for all types of complexes.

The capacities of water retention by complexes and their spatial distributions

Here, we estimated statistically the capacity of water retention by every vegetation–soil–slope complex in the watershed by Equation (1) using the coefficients of capacity in Table 2 and w in Table 4 (see Figure 1). We surveyed *in situ* the actual capacity of water retention by 20 complexes in the watershed and compared them with those simulated by Equation (1). Figure 2 gives the comparison, which illustrates that the estimation results agree reasonably well with the observation data. The amount of water retained in every type complex was estimated by Equation (2) using its area

Table 4. Parameters used in the assessment models.

Parameter	Description	Value
w	Standard capacity of water retention (mm)	108.23
μ	Equivalent value of raining	61
λ_1	Weight coefficient for the first kind of raining	0.19
λ_2	Weight coefficient for the second kind of raining	0.31
$_3$	Weight coefficient for the third kind of raining	0.3
λ_4	Weight coefficient for the fourth kind of raining	0.2
rw_1	Precipitation intensity of the first kind of raining (mm min^{-1})	0.04
rw_2	Precipitation intensity of the second kind of raining (mm min^{-1})	0.12
rw_3	Precipitation intensity of the third kind of raining (mm min^{-1})	0.25
rw_4	Precipitation intensity of the fourth kind of raining (mm min^{-1})	0.33
n	Number of complexes	45
K	Number of type of precipitation intensity	4

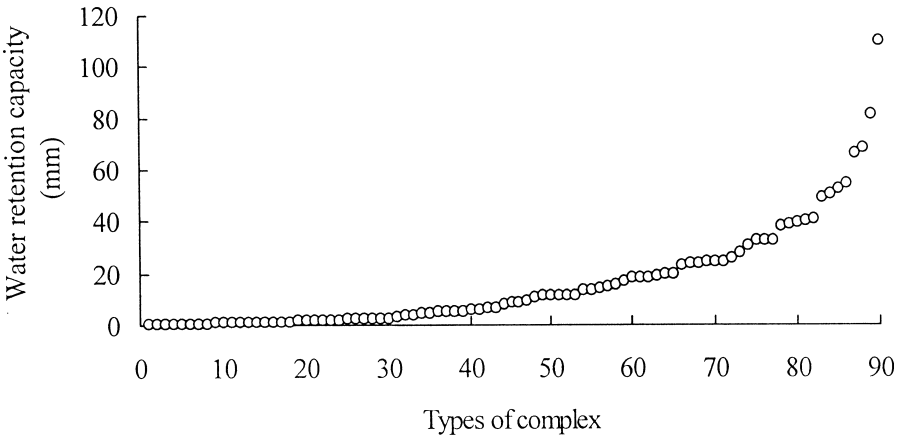

Figure 1. The saturated capacity of water retention by 90 types of complex.

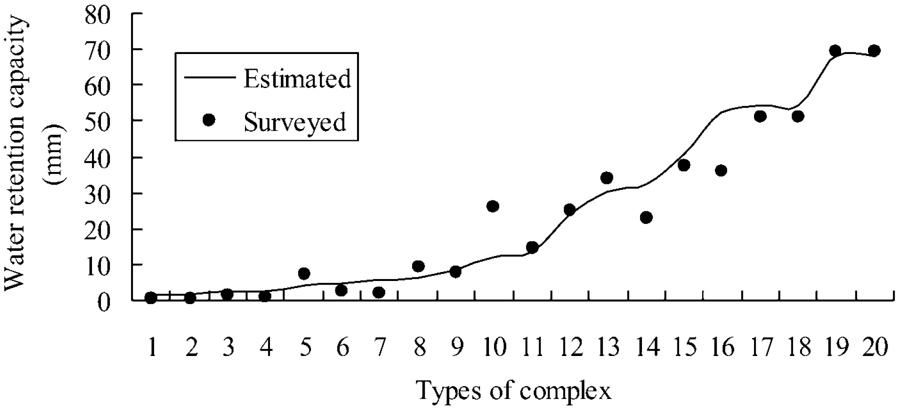

Figure 2. Comparison between the observed and the estimated capacity of water retention.

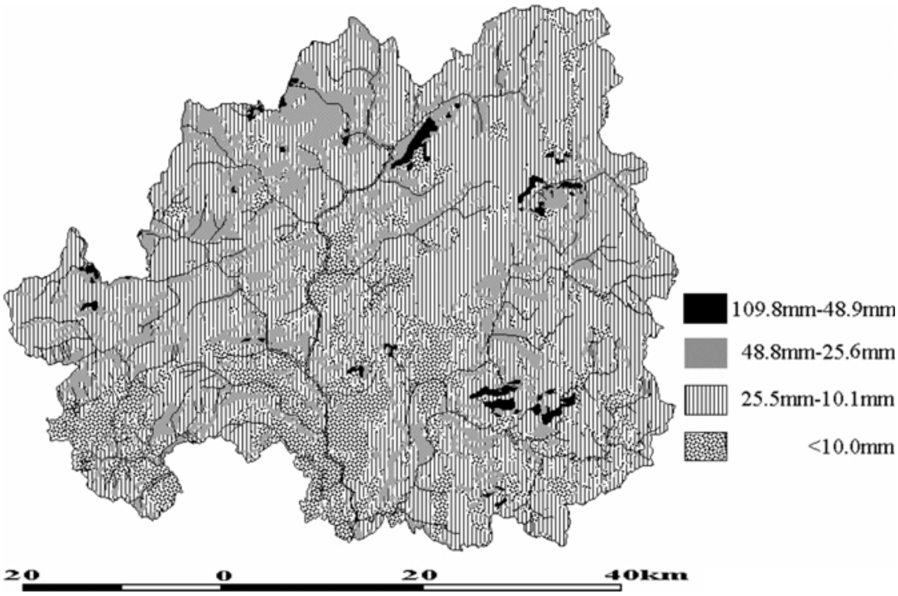

Figure 3. The spatial distributions of the capacities of water retention in the watershed.

in Table 3 and the value of the parameter, μ, in Table 4. Figure 3 shows the spatial distributions of various capacities of water retention in the watershed. According to Equation (3), the total amount of water retained in the watershed is approximately 71.1 million m^3 yr^{-1}.

The capacity of water retention of the watershed

The capacity of water retention by the watershed relies on those of the polygons. According to the above discussions, only a few polygons, occupying about 28.6% of the total area, hold the capacity of water retention more than the mean rainfall, or, 25.58 mm. However the capacity of the other polygons are below this value. This result shows that the integral situation of water retention by the watershed is quite serious.

We calculated the optimal vegetation coverage rate for water retention, and compared it with the current situation of vegetation coverage in the watershed. In Xingshan County, the maximum daily rainfall of many years mean is 864 $\mathrm{m}^3\,\mathrm{ha}^{-1}$ and the capacity of water retention by the forestland in the county is 1090 $\mathrm{m}^3\,\mathrm{ha}^{-1}$. The total area of the county and the area except town, village, farmland and water body are 2316 and 2219.6 km^2 respectively. Then the optimal forest coverage rate for water retention in the watershed should be 64.9% by Equation (4). But, at present, the actual forest coverage rate is only 39.1%, being 60.2% of the optimal, and the canopy densities of these forestlands are mostly below 0.3.

Furthermore, we compared the areas of the four types natural vegetation, DFE, OFE, SHR and GRA in the 15 types of soil–slope combination (T_1–T_{15} in Table 3), which are related to 60 types of vegetation–soil–slope complex. The area of DFE in every type of combination is the smallest among the four vegetation types, all being less than 10% (see Figure 4). The total area of DFE just occupies approximately 1.91% of the whole of the watershed, while OFE, SHR and GRA occupy 31.8, 48.89 and 17.7%, respectively. It indicates that the area of DFE is excessively small, whether the absolute area in the whole of the watershed or the relative area in every type of soil–slope combination.

Table 1 gives the areas of all types of soil and slope in the watershed. The area of YBS that has the largest capacity of water retention among the five types of soil accounts for 45.17% of the total, while the area of RCS that has the smallest capacity of water retention is just 4.64% of the total. In addition, the area of SA = 15–25°

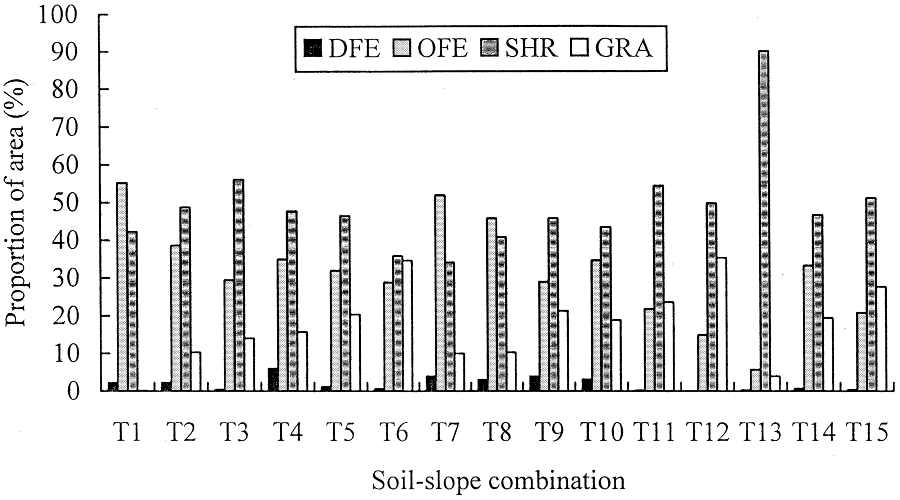

Figure 4. The proportions of area for four types vegetation, DFE, OFE, SHR and GRA in every soil–slope combination.

accounts for more than 60% of the total, and the area of SA $<$ 15° is about 1.2 times that of SA $>$ 25°. Thus the situations of soil and topography in the watershed are good for water retention. On the basis of the above discussion, we can distinctly recognize that such serious situation of water retention in the watershed mainly results from the poor capacity of water retention of vegetation.

The conservation of forest ecosystem and the improvement of water retention function

Obviously, in the watershed conserving or rehabilitating forest can greatly improve the condition of vegetation and in turn strengthen the ecosystem function for water retention. Thus, DFE will replace OFE, SHR and GRA at some areas by afforestation. Based on Equation (5) using the parameters in Table 4 we can yield a set of index (1–0.001) for evaluating the variation-location effect on afforestation in the 45 types of complex that embody OFE, SHR and GRA. These indexes increase with the decreases in the capacities of water retention by complexes. This indicates that a complex having a smaller index just yield a less effective increment of the capacity of water retention. Based on these indexes, we can determine which type of complex can obtain more effective increment of the capacity of water retention by afforestation. For example, if converting both complexes OFE–RCS–SA $>$ 25° and

Table 5. Waiting list of complexes for afforestation.

Sequence	Index	Types of complex	Area (ha)
1	1.000	GRA–RCS–SA > 25°	465
2	0.611	GRA–RCS–SA = 15–25°	825
3	0.462	GRA–PPS–SA > 25°	603
4	0.330	GRA–RCS–SA < 15°	132
5	0.323	SHR–RCS–SA > 25°	858
6	0.282	GRA–PPS–SA = 15–25°	2232
7	0.197	SHR–RCS–SA = 15–25°	1982
8	0.195	GRA–LMS–SA > 25°	1237
9	0.152	GRA–PPS–SA < 15°	535
10	0.149	SHR–PPS–SA > 25°	849
11	0.143	GRA–YLS–SA > 25°	393
12	0.119	GRA–LMS–SA = 15–25°	5549
13	0.106	SHR–RCS–SA < 15°	3009
14	0.092	GRA–YBS–SA > 25°	2293
15	0.091	SHR–PPS–SA = 15–25°	5154
16	0.087	GRA–YLS–SA = 15–25°	1547
17	0.064	GRA–LMS–SA < 15°	2354
18	0.063	SHR–LMS–SA > 25°	2661
19	0.056	GRA–YBS–SA = 15–25°	7339
20	0.049	SHR–PPS–SA < 15°	1238
21	0.047	GRA–LS–SA < 15°	277
22	0.046	SHR–YLS–SA > 25°	406
23	0.038	SHR–LMS–SA = 15–25°	22 038

GRA–RCS–SA > 25°, they having indexes 0.0031 and 1, into DFE–RCS–SA > 25° by afforestation, the effective increments of the capacity of water retention obtained by relevant polygons will respectively be 4.06 and 13.08 mm. This indicates that the latter complex, having a larger index, can obtain a more effective increment than the former by afforestation.

According to the plan of establishing water and soil conservation forest system, the forestland will be increased by 2 million ha during 30–40 years in the whole of the Yangtze River basin, which is 53.19% of the area of existing forestland (MOF 1995). If it is in proportion to the whole of the basin, then the area of forestland increased in Xingshan County should be 57 000 ha. To obtain the maximum benefit of water retention from these forestlands, we suggest that the polygons used for

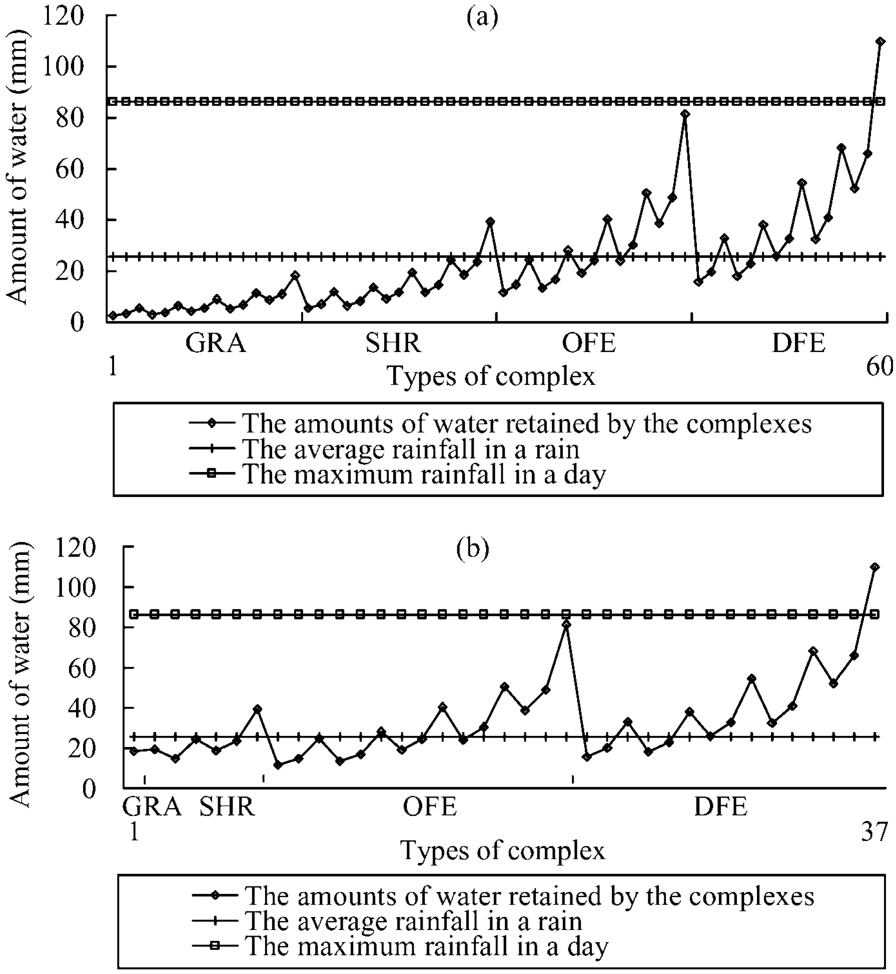

Figure 5. The capacities of water retention by various complexes in current status (a) and after improvement (b).

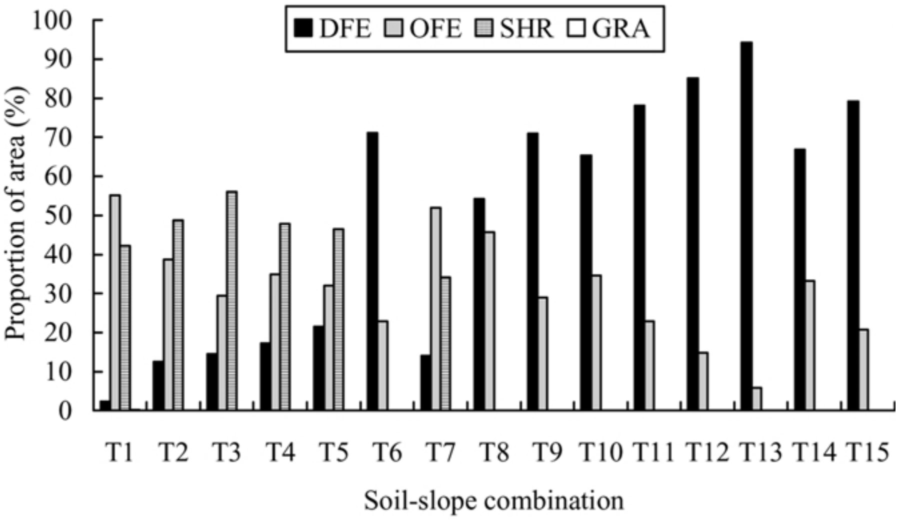

Figure 6. The proportions of area for four types vegetation, DFE, OFE, SHR and GRA in every soil–slope combination after improvement.

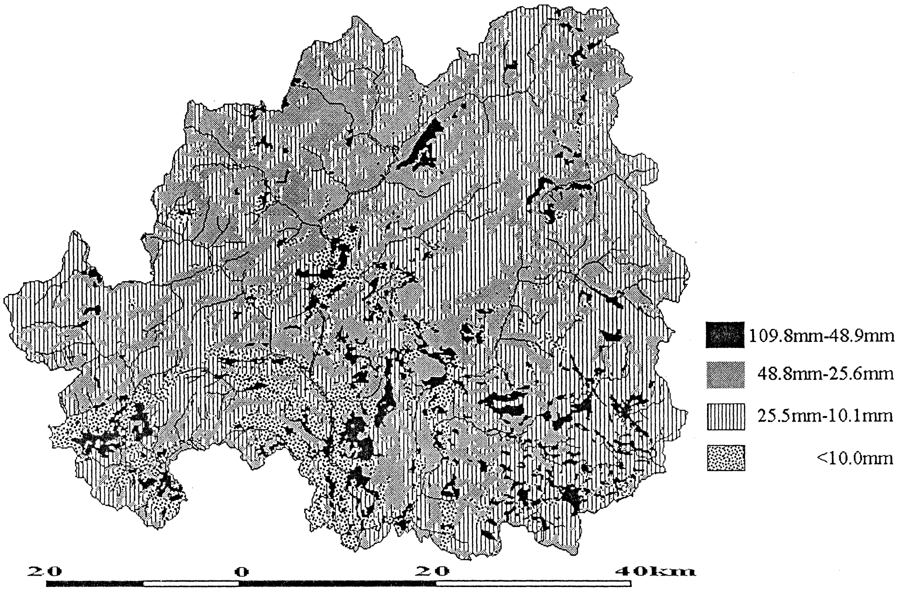

Figure 7. The spatial distribution of the capacities of water retention in the watershed after improvement.

establishing water and soil conservation forests should have larger indexes for the variation-location effect. In other words, we should give priorities to the polygons that can obtain larger effective increments of the capacity of water retention. By this means, the situation of water retention of the watershed can be improved to the maximum. We called this strategy an 'spatial pattern-based forestland extension', which gives special attention to the variation-location effect on the expansion of forestland. Using this strategy, a 'waiting list' for afforestation will be made by the 45 types of complexes that embody one of OFE, SHR and GRA. The complex that has the largest index among the waiting list will be selected out until the total area of the chosen complex reaches 57 000 ha. Table 5 gives these complexes that are chosen for afforestation, amounting to 23 types. The vegetation type in these complexes will be turned into DFE. Figure 5 compares the current situation with the improved one for the capacities of water retention by the complexes. Then the proportions of areas of DFE will be more than half in T_8–T_{15} (see Figure 6). The number of complex that holds the capacity of water retention more than 25.58 mm (the mean rainfall of a rain) will be increased by 75%. The mean capacity of water retention of the polygons that embody the four types natural vegetation will be increased by about 10 mm. As a result, the watershed in question will obtain the maximum effective increment of the capacity of water retention. Figure 7 shows the spatial distributions for these capacities in Xingshan County after improvement.

Conclusions

In this study, the watershed in question was divided into 90 types of vegetation–soil–slope complexes by GIS to form a 'digital ecosystem'. A complex is represented by one of 90 combinations of vegetation, soil and slope, which indicates its capacity of water retention. Therefore, the types of vegetation, soil and slope can be considered as the inputs of the model to estimate the capacity of water retention by a type complex. A data layer of the GIS correlates to a set of input of the estimation model. By this means, both were combined with each other. Therefore, we can estimate the capacity of water retention, complex by complex, based on the types of vegetation, soil and slope, and demarcate the spatial distributions of the capacities of water retention on a map.

The mean flow volume in the Xiangxi River is approximately 200 million $m^3\ yr^{-1}$. Based on the estimation in this study the total amount of water retained by the terrestrial ecosystems in the watershed is 71.1 million $m^3\ yr^{-1}$, which is 36.35% of the mean flow of volume of the Xiangxi River. This degree of water retention can bring marked economic benefits (Guo et al. 2001).

To improve the situation of water retention, people usually pay close attention on the extension of the area of forestland, but neglect the affection of the spatial pattern of forestland to this situation. This spatial pattern is always related to the combination of vegetation, soil and topography. The variation-location effect discussed in this study highlights this situation. According to this effect we can change the situation of water retention by regulating the combination of vegetation, soil and slope. The strategy 'spatial pattern-based forestland extension' is just based upon the variation-location effect. This study shows that the maximum benefit of water retention in the watershed can be obtained from the extension of forestland according to this strategy. Likewise, applying this strategy in the establishment of protective forest system in the Yangtze River basin, the situation of water retention in this basin can also be improved to the maximum, and people can derive more benefit from water and soil conservation. The variation-location effect is of universal significance and useful for ecosystem restoration, conservation and management.

The terrestrial ecosystems in the watershed studied are undergoing a great change, and, as one of consequences, the ecosystem function for water retention will be weakened (Yin 1998). The conservation and restoration of these ecosystems will be a critical problem people must face. Our research work will be an essential step to the restoration of the ecosystem functionality in the watershed.

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