Assessing changes in water flow regulation in Chongqing region, China

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Received: 19 March 2014 / Accepted: 10 December 2014 / Published online: 17 May 2015
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Abstract Water flow regulation is an important ecosystem service that significantly impacts on ecological quality and social benefits. With the aim of improving our understanding of ecosystems and proposing strategies for optimizing ecosystem services, a geographic information system (GIS)-based approach was designed to estimate and map regulated water flow in the Chongqing region of China. In this study, we applied the integrated valuation of environmental services and tradeoffs (InVEST) model and mathematical simulations to estimate the provision of the regulated water flow across space and time in 2000, 2005, and 2010. The results indicated that this ecosystem service had improved by 2.07 % from 2000 to 2010 as a result of human activities (such as vegetation restoration) and climatic interaction. Places with positive changes mainly occurred in high mountain areas, whereas places with negative changes were mainly distributed in resettlement areas along the Yangtze River. The type of ecosystem in areas with high mountains and steep slopes was a relatively minor contributor to the total service, but this ecosystem had the higher water flow regulation

capacity. Moreover, with the increase in altitude and slope, the percentage contribution of forest increased significantly from 2000 to 2010; by contrast, the percentage contribution of cropland decreased rapidly. As for the impacts, the spatial variation of water flow regulation in the Chongqing region had a significant relation with climate and human activities at the regional scale. These results provided specific information that could be used to strengthen necessary public awareness about the protection and restoration of ecosystems.

Keywords Water flow regulation · GIS · Human activities · Climatic interaction · Ecosystem services

Introduction

Ecosystem services are crucial to the functioning of life on Earth (Daily 1997; Costanza et al. 1997; Guo et al. 2001; Bai et al. 2011). Water flow regulation, one of the most important ecosystem services, involves the influence of natural systems on the regulation of hydrological flow on the surface of the Earth, and is a function of the storage and retention components of the water flow (Hewlett 1982; De Groot et al. 2002). According to records, the total annual precipitation on Earth is approximately 1.19×10^4 billion m^3 . Most of the rainfall is absorbed primarily by soil, and is either then taken up by vegetation or percolates into the groundwater. However, without the regulation of this ecological system, the rain would fall directly on bare ground, reducing soil water uptake and increasing surface runoff, leading to the loss of soil and nutrients (Hillel 1991).

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Over the past decades, much progress has been made in understanding how ecosystems supply water. The “water conservation” ecosystem service provides vital information for regional ecosystem management and sustainable development, and various approaches and methods for ecosystem service evaluation have been developed extensively from case studies representing diverse spatial scales and sites (Miao et al. 2010; Zhang et al. 2010, 2011; Chen et al. 2011; Miao et al. 2011; Wang et al. 2014). However, there are few studies on the service of water flow regulation, and less attention has focused on the complicated spatial heterogeneity influenced by climate, vegetation, soil texture, terrain, and human activities, especially in the hilly areas with heterogeneous natural resources and geographic features.

Chongqing region, one of the most important ecological zones in China, is located on the upper reaches of the Three Gorges Reservoir Area (TGRA), the site of the largest dam project in the world (Zhang et al. 2009). The status of the ecosystem functions in Chongqing has direct impacts on the TGRA. Recently, rapid population growth and urban development in this region have increased the demand for food, housing, and factories (Hunter et al. 2003; Semwal et al. 2004), which have led to complex changes in ecosystem types. In addition, global changes in climate (Miao et al. 2014) have also highlighted the role of ecosystems in water flow regulation and climate change mitigation and adaption. However, there have been few studies on the quantitative estimates of the water-flow regulation and its spatial distribution characteristics.

The aim of this study was to use a new combined method including integrated valuation of environmental services and tradeoffs (InVEST) and mathematical simulations to map the water flow regulation. Moreover, we undertook a detailed analysis of the spatial and temporal variation of ecosystem services in Chongqing region and their driving forces.

Study area

The study area (Chongqing region) is located between 105°11′–110°11′ E and 28°10′–32°13′ N, covering the lower section of the upper reaches of the Yangtze River (Fig. 1). It covers a total area of 82,400 km² with a total population of 20.1 million. It has complicated geographic conditions with lower land in the west and higher land in the east; 75.8 % of the region is mountainous, 6.0 %

of the region is plains and 18.2 % is hilly, with a variety of ecosystem types, including forest, shrubland, grassland, cropland, river, urbanization, and bare soil. The dominant soil types are purple soil, yellow soil, and paddy soil. The Chongqing region has a subtropical monsoon climate and, for most of the year, it experiences humid conditions with an annual mean temperature of 17–19 °C and mean minimum and maximum temperatures of 4–8 °C in January and 26–29 °C in July, respectively. The mean annual precipitation is approximately 1100 mm. Rainfall is variable in amount and timing, in that 85 % of the annual rainfalls occurs mainly during summer (6–9 months).

Methodology and data collection

Model description

Ecosystems such as forests, shrubland, grassland, and so on, impact the timing and magnitude of water flow and water runoff (Guo et al. 2000). These changes can alter hydrological cycles, affecting patterns of evapotranspiration, infiltration, and water retention. Here, we used InVEST including a two-step process to analyze the water flow regulation of ecosystem services. First, the application of a water yield model calculates the average annual water yield (annual average runoff) in each mapped grid cell based on climate data, geomorphological information and land-cover characteristics. The model does not incorporate subsurface or groundwater flow, but assumes that all precipitation becomes surface water runoff without any loss to evapotranspiration. In the second step, water flow regulation is the difference between potential (without the vegetation cover) and actual water yield (under the current ecosystem pattern). The water yield model is based on the Budyko curve (Budyko 1974) and average annual precipitation. Annual water yield for each pixel on the ecosystem was defined as follows:

$$Y_w = \left(1 - \frac{1 + w_x \times R_{xj}}{1 + w_x \times R_{xj} + \frac{1}{R_{xj}}} \right) \times P_x$$

where Y_w is the annual water yield for each pixel; P_x is the annual precipitation in the pixel; R_{xj} is the ratio of potential evapotranspiration to precipitation, which is

Fig. 1 Location of the study area of Chongqing

the dimensionless Budyko Dryness index on pixel x with ecosystem j ; and W_x is a modified dimensionless ratio of plant-accessible water storage to expected precipitation during the year.

As defined by Zhang et al. 2001, W_x is a nonphysical parameter used to characterize natural climatic-soil properties. W_x and R_{xj} can be calculated as follows:

$$W_x = Z \times \frac{AWC_x}{P_x}$$

$$R_{xj} = \frac{k_{xj}ET_{0x}}{P_x}$$

where AWC_x is the plant-available water content (mm). The soil texture and effective soil depth define AWC_x , which establishes the amount of water that can be held and released in the soil for use by a plant, estimated as the product of the difference between field capacity and wilting point and the minimum soil depth and root depth. Z is a seasonality factor that represents the seasonal rainfall distribution and rainfall depths ranging from 1 to 10 (Zhang et al. 2001); k_{xj} is the vegetation

evapotranspiration coefficient associated with the ecosystem j on pixel x ; and ET_{0x} is the reference evapotranspiration from pixel x , and is computed with reference to the Hargreaves equation (Hargreaves et al. 1985; Hargreaves 1994). After repeated validation, when the Z value is 3.0, the water yield is similar to natural runoff.

Based on the above water yield results, the water flow regulation is expressed as:

$$WFR = Y_0 - Y_v$$

where WFR is the water flow regulation, which is a consequence of vegetation cover; Y_0 is the potential water yield without vegetation cover; and Y_v is the actual water yield under the current ecosystem conditions.

Data

Annual precipitation data from 38 meteorological stations during the period 1970–2010 were obtained from the Chinese National Meteorological Information Center/China Meteorological Administration (NMIC/CMA). The average annual precipitation raster value (Fig. 2a) was generated by the application of the kriging

interpolation method in ArcGIS v9.3, which has been widely used in regionalizing various variables at different scales (Piao et al. 2001; Zhu et al. 2006). Average annual reference evapotranspiration (ET_0) (Fig. 2b) was obtained using the modified Hargreaves equation, which can generate good results when information is uncertain (Droogers and Allen 2002). This process was completed in interactive data language (IDL) which is a programming language used for data analysis. The soil depth data (Fig. 2c) at a scale of 1:250,000 were acquired from the Institute of Soil Science at the Chinese Academy of Sciences (CAS). Plant-available water content (PAWC) is defined as the difference between the fraction of volumetric field capacity and the permanent wilting point. We used Zhou's method (Zhou et al. 2005) to estimate PAWC (Fig. 2d). Given the large geographic extent of the research area and the complexity of the land surface, it was difficult to meet the accuracy requirements of a maximum likelihood classification (MLC) method alone, which is acknowledged to be one of the most efficient parametric methods for image classification. Therefore, a decision rule-based classification

method proposed by Chen and Wang 2010 was adopted. The information on distribution of ecosystem type in 2010 was generated and interpreted based on Landsat MSS and TM satellite remote sensing with an overall accuracy of approximately 82.6 % (Fig. 2e). Each two adjacent temporal images were overlaid in the geographic information system (GIS) software, and the changes in ecosystem were then identified and digitized by visual interpretation, with the help of the sample database. In this way, information on ecosystem changes for three periods (2000, 2005, and 2010) was extracted. The watershed and subwatersheds (Fig. 2f) were generated by using ArcSWAT and the required shapefile formats based on a SRTM digital elevation model data, which were obtained from the International scientific data service platform. Maximum root depth was obtained from Canadell et al. 1996 and the evapotranspiration coefficient table (K_c) was estimated based on Allen et al. 1998 and the InVEST user guide.

Moreover, other data, including temperature, carbon dioxide (CO_2) concentration, gross domestic product proportion (GDP), GDP1 proportion (agricultural

Fig. 2 **a** Average annual precipitation; **b** average annual potential evapotranspiration; **c** soil depth; **d** plant-available water content; **e** ecosystem types; and **f** watershed and subwatersheds

GDP), GDP2 proportion (industrial GDP), GDP3 proportion (service industry GDP) and population density, were also collected. The annual temperature from 2000 to 2010 was generated using the Kriging interpolation method. In addition, the annual CO₂ concentration data were obtained from the global carbon dioxide concentration model (Guo et al. 2012). In addition, GDP, GDP1, GDP2, GDP3 and population density were collected from statistical yearbooks and the government sector.

Data analyses

To determine the reasons for changes in water flow regulation during the research period (2000–2010), trend analyses, correlation, and regression analyses were applied. The least-squares linear regression method, which is one of the commonly used methods in trend analysis (Eklundh and Olsson 2003; Stockli and Vidale 2004; Beck et al. 2011), was applied as follows:

$$y = a + b \times t + \varepsilon \quad (1)$$

where y represents dependent variables, t is year, a and b are fitted variables (b is the slope as a proxy of trend and a is the intercept), and ε is the residual error.

For the purpose of exploring the relations among factors including climate, human disturbance, and the variation of water flow regulation, Pearson correlation analyses were applied. We also used a stepwise regression between variation of water flow regulation and impacts (climate and human activities, represented by the temperature, CO₂ concentration, GDP density and population density, respectively) to reveal their relative contribution in influencing the variational characteristics of water flow regulation. Given that variables such as precipitation, evapotranspiration, and ecosystem type can be highly autocorrelated with water flow regulation, such variables were not considered. All statistical analyses mentioned above were performed at the county level. The analyses were implemented using SPSS 17.0, and SigmaPlot 11.0.

Results and discussion

Ecosystem change monitoring

The dominant ecosystem type in the study area was cropland, and forest was the second major ecosystem

type, which occupied around 36.34 % of the study area in 2000 and 38.91 % in 2010 (Fig. 3). Obvious ecosystem changes could be observed during the research period. The area under forest increased by 2.58 %, and shrub and grassland increased by 0.11 and 0.56 %, respectively, during the 11-year period. Cropland decreased significantly by approximately 3.30 %. Meanwhile, urbanized areas and bodies of water increased slightly (0.21 and 0.04 %, respectively).

There were changes in ecosystem type across the entire study area, with an uneven distribution (Fig. 4). Most changes occurred in the mountain areas of north-eastern and central Chongqing. Cropland represented the main type of change, including a gain and loss accounting for 31.91 % of the total changes from 2000 to 2010. Moreover, the changes in forest were mainly distributed in northeastern mountain areas, which accounted for 21.87 % of the total change. The change trends of different ecosystem types were not the same (Fig. 4). The net changes in area of each ecosystem were positive in forest, shrub, grassland, built-up and water bodies, but negative in cropland and bare land.

Specifically, the area of forest increased by 2122 km², from 30,016 km² in 2000 to 32,138 km² in 2010. Forests (gradient >25°) in mountainous areas showed more significant changes, whereas forests (gradient <25°) showed little change. From 2000 to 2010, the area of forest (gradient >25°) increased rapidly, with the 1196 km² of forests being converted from other types of ecosystem, at a rate of approximately 100 km²/year. Meanwhile, the area of cropland decreased by 2824 km², from 35,057 km² in 2000 to 32,333 km² in 2010. Cropland (gradient >25°) in mountainous areas showed little change, whereas cropland (gradient <25°) showed more severe changes. From 2000 to 2010, the area under crops (gradient <25°) decreased rapidly, with 2,018 km² of cropland being converted to other types of ecosystem, at the rate of approximately 200 km²/year.

Changes, such as the increase in forest and decrease in cropland, showed that evolution in ecosystem patterns was mainly driven by human activity, especially ecological restoration projects, such as forest engineering, greenbelt construction projects, grain-to-green projects and natural forest protection projects. Especially in areas with steep slopes and at high altitude, where serious soil erosion risks remain, projects included tree planting, aerial planting, returning farmland to forest and grassland, closing

Fig. 3 Area of each ecosystem type in 2000, 2005, and 2010

hillsides to facilitate afforestation and other measures to protect the existing forest resources, and these have been strictly implemented strictly and are taking effect (National Development and Reform Commission NDRC 2005). The distribution of croplands in the areas with gentle slopes and low altitude, coupled with dense population and greater human disturbance, declined rapidly. This is probably the result of a growing population, urbanization, and the development of economy in this area. Specifically, forest engineering projects have accelerated the development of the regional economy, which usually leads to the rapid increase in nursery base areas (i.e., a transition from cropland to shrub and forest) (National Development and Reform Commission NDRC 2005).

Estimation of changes in water flow regulation

Validation of water yield

In this study, the distribution of water yield (watershed) was modeled using the InVEST model. To verify the reliability of the model, we validated the model results based on observed data collected from hydrometric stations in the study area from 2000 to 2010. Significant correlations were found between our simulated results and observation-based data (water yield: $r=0.860$, $p<0.05$, $n=11$). These indicated that the InVEST model is applicable to the modeling of water yield across the study area.

Distribution of water flow regulation

Recently, an ecological restoration program was launched in the Chongqing region, and a large number of crop fields have been converted to forests, shrubs, and grasslands. Meanwhile, urban expansion caused by growth of the human population and development of the economy took over large areas of farmland, and the construction of the Three Gorges Dam led to an increase in area under water. These complicated changes in ecosystem might significantly impact ecosystem structure and services. In this study, we applied the InVEST model and mathematical functions to predict the provision of water flow regulation in 2000, 2005, and 2010. The spatial distribution and dynamic changes from 2000 to 2010 of water flow regulation are shown in Fig. 5. The potential and actual annual water yield in 2010 were calculated to be $8.53 \times 10^{10} \text{ m}^3$ and $5.08 \times 10^{10} \text{ m}^3$, respectively. Thus, the total amount of water flow regulation was $3.45 \times 10^{10} \text{ m}^3$, with a mean capacity of $4145.76 \text{ m}^3 \text{ ha}^{-1}$. Water flow regulation displayed great heterogeneity in terms of its spatial distribution, with mountainous area generally performing better than flat agricultural areas and developed urban areas. Obvious changes could be observed during the research period. The total amount of water flow regulation increased significantly by approximately 2.07 % (the total amount of water flow regulation was $3.38 \times 10^{10} \text{ m}^3$ in 2000). Figure 5c shows the spatial patterns of change in water flow regulation in the study area during the research period. The places with a positive change mainly

Fig. 4 Map of ecosystem changes from 2000 to 2010 and histogram of net change in area of each cover type (*flow-in* gain in that other types changed to the highlighted type;

flow-out loss in that the highlighted type changed to other types; net change: the difference between area loss and gain)

occurred in the high mountain areas in central Chongqing, where the dominant ecosystem category is forest. The places with negative change were mainly distributed in the resettlement areas along the Yangtze River. Decreases in water regulation services were primarily the result of rapid urbanization. Large areas of agricultural land in the peripheral zones surrounding the urban centers were acquisitioned by local governmental departments and developers for urban expansion. Other areas with negative change also appeared in eastern

Chongqing, close to the reservoir region. This reduction in water flow regulation was the result of a combination of land inundation, rural resettlement, and urban relocation. According to the official reports, the water level of TGRA was 135 m in June 2003. With the continuous increase in height of the water in the dam, approximately 1.13 million inhabitations will be resettled. Therefore, construction of Three Gorges Dam not only caused a rapid expansion in water body area and built-up areas, but also influenced water flow regulation in the

Fig. 5 **a** Spatial distribution of water flow regulation in 2000 and **b** 2010 **c** Change in water flow regulation from 2000 to 2010

surrounding regions because of the large amount of resettlement and population migration.

Influence of topography

The spatial distribution of the water flow regulation in mountainous areas is significantly affected by topography. The topographic effect can be defined simply as the difference in the amount of water flow regulation at different altitudes and slope positions. In view of the agricultural and urban ecosystems being mainly distributed in low altitude regions in Chongqing, four zones

can be defined. These are hilly (elevation below 500 m), low mountain (elevation range 500–800 m), middle mountain (elevation range 800–1,200 m), and high mountain zones (elevation above 1,200 m). In addition, the slope angle was divided into four categories: flat slope (less than 5°), gentle slope (between 5° and 15°), slanting slope (between 15° and 25°), and steep slope (more than 25°).

Comparisons among altitudes (Fig. 6a) showed that ecosystems located in a high mountain zone displayed the highest water flow regulation capacity, followed by those located at middle mountain zones. With regard to

Fig. 6 Amount of water flow regulation at (a) different altitudes and (b) on different slope angles in 2000, 2005, and 2010

quantity, ecosystems in the hilly and low mountain zones regulated more water flow than others, with those in the hilly zone regulating the most (approximately 36.09 % of the total). Although the ecosystem located at the high mountain zone was a relatively minor contributor to the total service, this ecosystem had the highest water flow regulation capacity. In general, the water flow regulation capacity at low mountain, middle mountain, and high mountain zones gradually increased from 2000 to 2010. Specifically, with the increase in altitude, the rate of capacity (the amount of increase accounting for the proportion of capacity in 2000) increased steadily, by 0.97 % in low mountain, 1.64 % in middle mountain, and 2.52 % in high mountain zones. Unlike the distributed structure of water flow regulation with altitude, the amount of the water regulation in the slope zones showed no obvious trend (Fig. 6b). Ecosystem located on gentle slopes provided the largest proportion of the total amount of service (approximately 33.46 % of the total), followed by ecosystems located on slanting slopes.

In addition, the water flow regulation capacity located on slanting slopes and steep slopes gradually increased from 2000 to 2010. Specifically, with the increase in slope angle, the rate of capacity increased rapidly, by 0.81 % on slanting slopes and 4.38 % on steep slopes. These areas (high altitudes and larger slope) with environmental conditions encouraging good vegetation growth (e.g., rainfall, temperature, sunlight, topography, soil nutrients, soil moisture content and less human disturbance) were conducive to the growth of

vegetation, and enhancing evapotranspiration. Therefore, improvement in the capacity of water flow regulation at higher altitude and with larger slope values should be the main focus of future management in the study area.

To estimate the change in water flow regulation accurately, it would be necessary to measure the service provision of each ecosystem type. Therefore, observation of changes in the size and percentage contribution of ecosystem categories must be treated with caution. It is clear that, with the increase in altitude and slope, the percentage contribution of forest increased significantly, and the percentage contribution of cropland, by contrast, decreased rapidly (Fig. 7). In 2000, the forest category in the entire area provided the largest fraction of water flow regulation, with a percentage contribution of 43.96 %; by 2005, the total contribution of this category was estimated to have increased by approximately 45.63 %, and by approximately 47.80 % by 2010. Specifically, positive changes were mainly focused on high mountain and steep slope areas, with a 5.52 and 8.80 % net change, respectively. By contrast, the cropland category decreased substantially in the total study area, from 41.14 % in 2000, to 40.21 % in 2005, and to 37.10 % in 2010. Unlike the positive changes, the negative changes were mainly focused on middle mountain and steep slope areas, with a 4.96 and 6.12 % net change, respectively. The sizeable decrease in the contribution of cropland and the concomitant increase in the size of the contribution of the forest category are consistent with the widespread and rapid planting of forests

Fig. 7 **a** Size and percentage of the contribution of each ecosystem category in the altitude zones and the total study area **b** Size and percentage of the contribution of each ecosystem category in the slope zones and the total study area

in the region and the implementation of some environmental management policies, as *h* described in the section “Ecosystem change monitoring”. The contribution of the shrub category was estimated to have fluctuated from 12.66 % in 2000, to 11.95 % in 2005, and to 12.61 % in 2010. In addition, the contributions of grassland, barren land, urbanized areas, and water body areas were small.

Water flow regulation in Chongqing region was unevenly distributed spatially, because of the vast territory and enormous differences in environmental conditions. Ecosystems located in areas at altitudes of 500–1200 m and slopes of 5–25 demonstrated excellent water flow regulation, thus deserving careful protection in the future.

Influence of climate change and human activities

The spatial variation characteristics of water flow regulation are formed by interactions between influencing factors (temperature, CO₂ concentration, GDP density, and population density). The partial correlation between water flow regulation and temperature or CO₂ concentration was positively correlated and statistically significant ($r=0.461$, $p<0.039$ and $r=0.450$, $p<0.009$, respectively). By contrast, water flow regulation was negatively correlated with GDP density and population density ($r=-0.399$, $p<0.022$ and $r=-0.348$, $p<0.047$, respectively). This correlation could also be observed from the scatter plot based on the unit of county (Fig. 8). Stepwise regression indicated that the CO₂

Fig. 8 Relation between water flow regulation and driving factors: **a** temperature, **b** CO₂ concentration, **c** GDP density, and **d** population density from 2000 to 2010. Each *dot* represents a county. The *line* represents the fitted curve

concentration, temperature and GDP density factors could explain all variance in water flow regulation, with the variance contribution reaching 32.72, 30.56 and 36.72 %, respectively. Stepwise regression further demonstrated that the variation of water flow regulation in Chongqing region during the research period were primarily controlled by CO₂ concentration, temperature and GDP density, whereas the effects of population density were relatively small at the regional scale. It is likely that the increasing CO₂ concentration and temperature in the atmosphere is conducive to the growth of vegetation, which will enhance evapotranspiration. It is generally assumed that vegetation growth in alpine regions is sensitive to temperature change (Angert et al. 2005; Zhou et al. 2001; Qin et al. 2014). Rising temperature increases the length of the growing season and increases soil water by melting snow and ice; thus, more days and more water are available for biomass growth. Human activities now comprise nearly one-third to one half of global ecosystem production (Vitousek et al. 1986) and, as development and population pressures continue to mount, these will exert significant pressure

on ecosystems. Census-based socioeconomic variables as a main indicator of human activities (e.g., population density and GDP) have shown significant positive effects on urban expansion (Seto et al. 2011; Wu and Zhang 2012), which can disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow (Foley et al. 2005). A negative partial correlation was found between water flow regulation and GDP or population density. These findings suggest that GDP and population density have a negative influence on the water flow regulation.

Conclusions

The ecosystem of the Chongqing region can provide water flow regulation that has significant eco-effects on the downstream TGRA. However, the lack of information on the magnitude of ecosystem service constitutes an obstacle to the understanding of the ecosystems in this region, making it difficult to propose strategies for optimizing ecosystem services.

Here, we applied the InVEST model and mathematical simulations to estimate the provision of water flow regulation across space and time in 2000, 2005, and 2010. The spatial patterns and impacts of water flow regulation, which are significant in ecosystem conservation and management, were also discussed using spatial analyses and statistical analyses. The results suggest that ecosystems regulated a huge amount of water flow in 2010, with a total of $3.45 \times 10^{10} \text{ m}^3$ of water being regulated annually in Chongqing region. Moreover, the total amount of water flow regulation increased significantly, by approximately 2.07 % from 2000 to 2010. This growth was partly correlated with extensive ecological restoration policies that resulted in a continuous increase in the area of forest (by 2.58 %) and a significant decrease in the area of cropland (by 3.30 %).

In addition, water flow regulation displayed great spatial heterogeneity, with mountainous areas generally performing better than flat agricultural area and developed urban areas. Specifically, ecosystems located in the areas with high altitudes and larger slope demonstrated excellent water flow regulation capacity, thus deserving careful protection and management in the future.

Furthermore, we also analyzed the spatial and time variation in water flow regulation during the research period in different locations (gradient and elevation) in Chongqing region. Locations with positive change in water flow regulation mainly occurred in high mountain areas, and places with negative change were mainly distributed in resettlement areas along the Yangtze River. Furthermore, with the increase in altitude and slope, the percentage contribution of forest increased remarkably; by contrast, the percentage contribution of cropland decreased rapidly. These results provide specific information that could strengthen necessary public awareness of the protection and restoration of ecosystems; this is particularly important given that the spatial variation in water flow regulation in the Chongqing region was significantly affected by climate and human activities at the regional scale.

The processes involved in water flow regulation are complicated. Although we discussed here the regional variations in water flow regulation at different elevations and slopes, the study has several drawbacks, and some parts of the study still need to be exploring further. For example, the spatial heterogeneity of precipitation in different time periods was neglected, the stand structure and growth of forest in regulating ecohydrological functions were also ignored, and some parameters (e.g.,

evaporation coefficient and root depth) were defined according to the results of previous studies. Furthermore, the calculated results of water flow regulation in this study were not the same as in real terms, but the potential maxima were based on the mathematical models. Nevertheless, it is expected that the simulation methods developed in this study will provide theoretical support for other researchers, and that an increased understanding of the topographic, climatic and anthropogenic impacts on water flow regulation will assist policy, design, assessment, and management in China and other parts of the world.

Acknowledgments This study was funded by National Key Basic Research Program of China (Grant 2009CB421105, 2006CB403402) and Special Foundation from State Key Laboratory of Urban and Regional Ecology. The authors gratefully thank editors and anonymous reviewers for their very helpful comments and constructive feedback.

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