J. Resour. Ecol. 2018 9(4) 416-425
DOI: 10.5814/j.issn.1674-764x.2018.04.009
www.jorae.cn

Eco-compensati on in Guanting Reservoir Watershed Based on Spatiotemporal Variations of Water Yield and Purification Services

WEN Yihui[1], LIU Guihuan[1,*], WU Rui[1,2,3]

1. Chinese Academy for Environment Planning, Beijing 100012, China;
2. School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China;
3.Urban Planning & Design Institute of Shenzhen, Shenzhen, Guangdong 518000, China

Abstract: Guanting Reservoir (GR) is one of the most important water sources for Beijing and neighboring regions. Due to water pollution, it was withdrawn from the system to supply Beijing drinking water; however, after a thorough treatment process, GR was made a reserve water source since 2007. To develop a comprehensive and quantitative analysis of water yield and purification services in the GR watershed, this study selected two time periods: the period when GR was withdrawn from the system supplying local drinking water and the period that it has been designated a reserve water source. The InVEST model was used to evaluate the quantities of water yields, and total nitrogen and total phosphorus outputs from 1995 to 2010 Additionally, the spatiotemporal variations of water yield services and water quality purification services in the GR watershed were analyzed. The results showed that water yield services in the GR watershed first weakened and then became stronger, but weakened overall during the years 1995 to 2010. Water yield capacity in the basin decreased from 1.89×109 m^3 in 1995 to 1.43×109 m^3 in 2010 (a drop of 24.0% in total). Water quality purification services also showed the same tendency. Total nitrogen output decreased from 4028.7 t in 1995 to 3611.4 t in 2010, while total phosphorus decreased from 379.7 t in 1995 to 354.0 t in 2010. Nitrogen and phosphorus purification services were enhanced by 10.4% and 6.8%, respectively. Changes in the climate and land use were the main factors which lead to the changes in the water yield service in the GR watershed. Policies intended to protect water resource have matched the varying trends of water quality purification services during different periods. On one hand, the research results provide a foundation to identify key fields for eco-compensation in the Guanting Reservoir basin. On another hand, the ecosystem service value will increase on the basis of eco-compensation criteria through setting the scenarios of returning farmland to forest and ecological protection. This method directly reflects increases in ecosystem service values that have occurred since measures to protect the ecological environment have been implemented. This method is more persuasive and feasible than using eco-compensation criteria based on regional ecosystem service values determined by land use/ coverage type. It can provide a new way to assess eco-compensation in the Guanting Reservoir basin and other regions.

Key words: GR watershed; InVEST model; spatiotemporal variations; water quality purification; water yield

1 Introduction

Ecosystem services refers to natural environmental conditions and utilities formed and maintained by the ecosystem, and ecological processes on which human survival is based. Ecosystem service has extreme values and at times values that cannot be measured, and is closely related to human well-being (Jansson *et al*., 2000; Xie *et al*., 2015). Both water

---

Received: 2017-08-21 **Accepted:** 2018-01-15
Foundation: National Natural Science Foundation of China (51379084); National Key R&D Plan (2016YFC0503405)
***Corresponding author:** LIU Guihuan, E-mail: liugh@caep.org.cn

Citation: WEN Yihui, LIU Guihuan, WU Rui. 2018. Eco-compensation in Guanting Reservoir Watershed based on Spatiotemporal Variations of Water Yield and Purification Services. *Journal of Resources and Ecology*, 9(4): 416–425.

yield and purification are very important services that must be considered in the study of water basin ecosystems. These services have a direct impact on changes of water quantity and quality. As a result, water yields and purification services have become a hot research topics (Li, 2006; Costanza *et al.*, 1997; Li *et al.*, 2010) in the fields of hydrology and watershed management. Evaluations of ecosystem services were previously based on land use types combined with a factor analysis method (Hu *et al.*, 2002; Zhang *et al.*, 2001; Ma *et al.*, 2015). However the results of such evaluations are simple, not dynamic, and lack a spatial concept. In recent years, with the development of technologies such as GIS and RS, some researchers have begun taking advantage of modeling tools and this has led to breakthroughs that solve such problems. The InVEST model (Zhou *et al.*, 2010) is a mature, often used method, especially in developed countries. The searches focus on utilizing multiple InVEST modules to conduct a comprehensive assessment of ecosystem services, and then make use of the evaluation results for planning and management. For example, Nelson *et al.* (Nelson *et al.*, 2009; Eric *et al.*, 2001; Leh *et al.*, 2013) used the InVEST model to research land use changes in the Willamette River basin and Garner and Ivory Coast in West Africa, and evaluated the ecosystem service variation caused by land use. Goldstein *et al.* used multiple InVEST modules to evaluate ecosystem services on the Hawaiian island of Oahu and in the Sierra Nevada Mountains of California, and then used the research results to select local decision-making programs and plans for water resources protection. Use of the InVEST model began relatively late in China, and at present it is used mainly to assess a single ecosystem service or integrated services in one region. For example, Zhang and Pan Tao *et al.* (Zhang *et al.*, 2001; Pan, *et al.*, 2013) evaluated water yields in the Xitiaoxi watershed and Three-River-Source region, while Bai Yang *et al.* (Bai *et al.*, 2013) applied six InVEST modules, including ones for biodiversity, water conservation and water purification, to evaluate and analyze the spatial distribution characteristics of ecosystem services in the Baiyangdian watershed. The InVEST model is an effective tool to evaluate natural capital and undertake spatial analyses, and can provide reference information for the formulation of management decisions.

Although Guanting Reservoir is of great significance to the safety of drinking water in Beijing and surrounding areas, to date there has been no research on water yields and purification services in this region. Studies of the reservoir have focused mainly on pollution in the water and surrounding soil, and changes to water quality in the reservoir (Zhou *et al.*, 2005; Allen *et al.*, 1998). There has been no research on water quantity and quality from the perspective of ecosystem services. In order to fully understand and give full play to the ecosystem service functions of Guanting Reservoir watershed (GR watershed) and actively safeguard the ecological security of the water resources, it is essential to carry out research on spatiotemporal variations and the factors that drive regional water yields and purification services.

This study uses the GR watershed as the study area and applies the InVEST model to evaluate water yields and purification services in the region, while paying attention at the same time to the influence of policy factors on water quality variations in the Guanting Reservoir. Time periods selected for the study are the period that water from Guanting Reservoir was withdrawn from the Beijing drinking-water system and the period that followed when GR was designated a backup water source for Beijing. Data from the years 1995, 2000 and 2010 are used by the InVEST model to analyze the spatiotemporal variations of water yields and purification services, and explore the factors driving the GR watershed during this time. The study provides a scientific basis and a reference for use in efforts to improve water resources management and enhance the water environment of the Guanting Reservoir.

2 Data and methodology

2.1 Study area

Guanting Reservoir is located in the Huailai County of Zhangjiakou City, Hebei Province and Yanqing County of Beijing City. It has been one of the most important sources of water sources for Beijing since it was built in 1954. However, in the middle of 1980s, Guanting Reservoir suffered from serious organic pollution, and its water quality worsened (Yang *et al.*, 2006). In May 1997, Guanting Reservoir was withdrawn from the Beijing drinking-water system. Withdrawal of the reservoir created supply pressure and, in 2003, the Beijing municipal government began a comprehensive treatment program for Guanting Reservoir in order to bring the supply of water resources in line with demand. In October 2007, Guanting Reservoir became a backup water source for Beijing City. The GR watershed is composed of the Sanggan River, the Yang River and the Guishui River, which together have total flowing area of 46768 km^2. This study area covers a total area of 34151 km^2, including the Guishui River basin in Yanqing County, Beijing City, the Yongding River basin in Mentougou District and the Yang River basin (including the Qingshui River) and Sanggan River basin (including Huliu River) in Zhangjiakou City, Hebei Province. The study area accounts for 3/4 of the total area of the GR watershed. This is main area affecting typical water quantity and quality variations in the Guanting Reservoir. The study area is a temperate, semi-arid region located between the Mongolian plateau and North China Plain. It has a continental monsoon climate characterized by short summers and long winters, and dry and windy weather with average annual precipitation of 400~600 mm, Precipitation varies seasonally, with most rainfall concentrated in the months June to September.

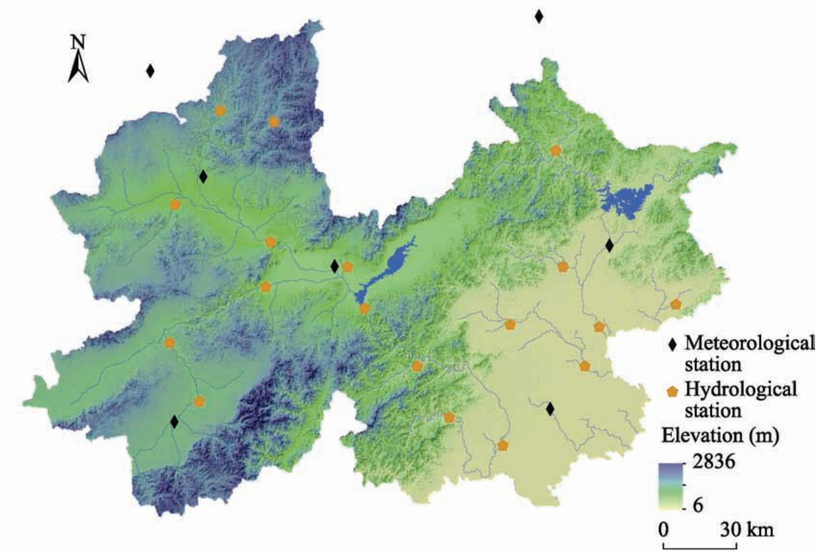

Fig.1 Location of meteorological stations and hydrological stations in study area

2.2 Data sources and processing

The InVEST model used data on land use, DEM, meteorological records, annual potential evaporation, soil depth, water content available to plants, basin and sub-basin boundaries, tables of biophysical properties and records of nitrogen-phosphorus output loads. Land use data was sourced from the Data Center for Resources and Environmental Sciences, CAS; data for the years 1995, 2000 and 2010 were selected, and the land use raster data with a resolution of 30 m in the study area was obtained by means of edge-fitting, conversion, cutting, etc. DEM data was generated by means of interpolation, cutting and filling from GDEMV2 digital elevation data with high resolution of 30 m which was sourced from http://www.gscloud.cn. Meteorological data was sourced from http://data.cma.gov.cn, and in order to avoid the possibility of single-year data being unrepresentative, average meteorological data for three multi-year periods (1993–1997, 1998–2002 and 2008–2012) were selected. After that, Kriging interpolation was conducted on precipitation data from 25 meteorological stations and hydrological stations in the study area and surrounding areas, and then grid maps with resolution of 30m were generated for the related years. Annual potential evaporation was worked out by means of Hargreaves Formula with the corrected coefficient for North China (Zhao *et al*., 2004):

$$ET_0 = 0.001 \times R_a \times (T_{\max} - T_{\min})^{0.66} \times \left(\frac{T_{\max} + T_{\min}}{2} + 34.5 \right) \quad (1)$$

Where: ET_0: potential evaporation in mm/d; $T_{\max}$ and $T_{\min}$ represent the mean daily maximum temperature and mean daily minimum temperature, respectively, in °C; R_a is the top solar atmosphere radiation in mm/d, which was sourced from NASA website (https://eosweb.larc.nasa.gov/sse/RETScreen), with divided the solar radiation data from meteorological stations and hydrological stations by 50% (Zhang *et al*., 2013).

After annual potential evaporation precipitation was calculated from data from 25 meteorological stations and hydrological stations, Kriging interpolation was conducted and then grid maps with resolution of 30m were generated for the related years. The soil depth and water content available in soil for planting were sourced from the China soil data set of the Cold & Arid Region Scientific Data Center (http://westdc.westgis.ac.cn/data/611f7d50-b419-4d14-b4dd-4a944b141175), and obtained through the rasterization of the attributed space. Data on water content available in soil for planting was obtained using calculations with nonlinear fitting from the soil AWC estimation model of ZHOU *et al.* (Liu *et al*., 2011). The basin and sub-basin boundaries were obtained with the Arc-SWAT tool through a small watershed division treatment specific to DEM data for the study area; the generated sub-basin was taken as an output unit of the statistical results of the modelling. Biophysics attributes and data for TN and TP output loads were obtained by estimating, with reference to the InVEST User Guide and relevant literature on the study area (Wang *et al*., 2003; Wang *et al*., 2004; Zhang *et al*., 2001); the TN and TP output parameters in this study are shown in Table 1.

2.3 Model principles and verification

2.3.1 Principles of the model

The InVEST water yield module is an estimation method based on the water balance method, while the water yield of a grid unit refers to precipitation minus actual evapotranspiration, and the more the water yield per unit area is, the stronger the water yield service will be. Actual evapotran spiration is worked out according to the algorithm proposed by ZHANG *et al.* on the basis of the Budyko coupled water-energy balance hypothesis (Zhang *et al*., 2011). The main algorithm of this model is as follows:

Table 1 Output parameters of nitrogen and phosphorus

Land use/coverage type	TN load ($kg·ha^{-1}·a^{-1}$)	TP load ($kg·ha^{-1}·a^{-1}$)	TN, TP Common interception efficiency
Broadleaf forest	2.38	0.15	0.84
Coniferous forest	4.38	0.35	0.78
Mixed broad leaf-conifer forest	3.38	0.25	0.81
Shrubbery	4.85	0.43	0.65
Shrubby grassland	5.56	0.51	0.53
Grassland	6.26	0.68	0.48
Water	0	0	0
Farmland	22.8	1.25	0.4
Dry land	20.2	2.06	0.27
Garden plot	9.01	1.31	0.35
Towns	5.51	0.25	0.01
Country side	17.35	0.97	0.01
Land for transportation	1.8	0.13	0.01
Bare land	0.001	0.001	0.05

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \tag{2}$$

Where: Y_{xj} is the annual water yield of the land coverage type j in Grid x in mm; AET_{xj} is the actual evapotranspiration of the land coverage type j in Grid x in mm; and P_x is the precipitation of Grid x in mm.

The InVEST water purification module is used to assess water purification services provided by vegetation and soil in the ecosystem, based on the notion that vegetation and soil can remove or reduce nutrient pollutants in runoff by means of storage or conversion to achieve water purification. This model ignores other sources of pollution and only focuses on the TN and TP in non-point source pollution; the higher the output is, the lower water purification service will be. The calculation uses the formula below:

$$ALV_x = HSS_x \times pol_x \tag{3}$$

Where: ALV_x is an adjusted output of Grid x; HSS_x is hydrological sensitivity score of Grid x; and pol_x is an output coefficient of Grid x. After the output of nutrients (TN, TP) is obtained, the nutrient-maintaining (interception) amount can be worked out according to the pollutant removal efficiency of the land use and coverage types.

2.3.2 Model Checking

Model checking is to compare results generated by the model with the measured data to determine the most suitable model for the study area. As the data on section runoff cannot accurately reflect the natural runoff and the study area does not include the entire basin (Liang *et al.*, 2011), it is difficult to use section data for checking. However, the calculated results from the water yield module includes surface water and groundwater, so the average runoff depth and the corresponding model-assessed values are employed for checking. When the seasonal factor is assumed to be 4.22 after repeated adjustments of seasonal factors, the model evaluation results most closely matched the measured value with an error of 0.05%. The depth of water yield is 55.16 mm and water yield is $18.85\times10^8 m^3$ in the GR watershed.

3 Spatiotemporal variations of water yields

3.1 Spatiotemporal variations of water yield

The three maps in Fig. 2 show water yields per unit area in 44 sub-basins of the GR watershed in 1995, 2000 and 2010. Overall, water service for the GR watershed first showed a decrease and then an increase. The entire watershed had the strongest water yield service in 1995 with a specific water yield of 550.17 $m^3·ha^{-1}·a^{-1}$, annual water yield of $18.85\times 10^8 m^3$, and annual water yield depth of 55.16 mm. The weakest water yield service occurred in 2000 with a specific water yield of 203.54 m^3 $m^3·ha^{-1}·a^{-1}$, annual water yield of $7.59\times10^8 m^3$, and annual water yield depth of 22.35 mm. Compared with service in 2000, water service in 2010 increased to some extent with a specific water yield of 408.37 $m^3·ha^{-1}·a^{-1}$, annual water yield of $14.33\times10^8 m^3$, and annual water yield depth of 40.77 mm.

In any given year, the spatial distribution of water yield per unit area is not evenly in the GR watershed; however, for different years, water yield per unit area is consistently distributed throughout the entire watershed and water yield per unit area in downstream areas is significantly greater than that in the upstream areas. According to the statistical

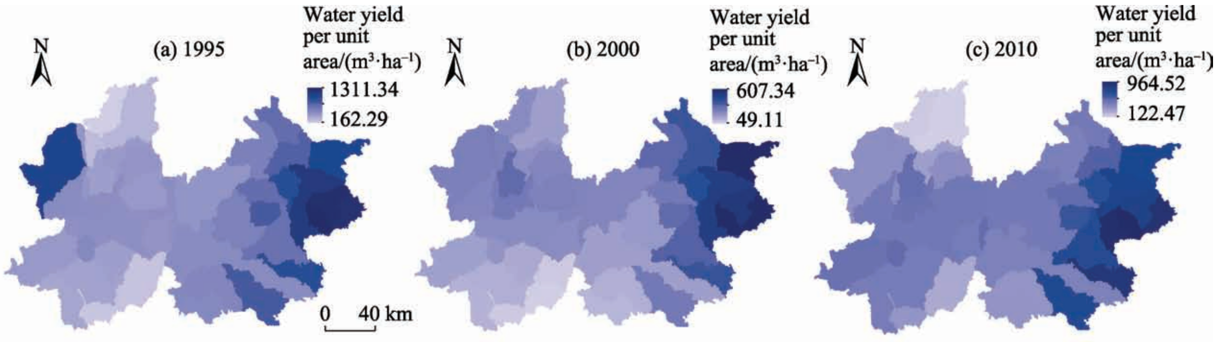

Fig.2 Water yields per unit area of the GR watershed in 1995, 2000 and 2010

Table 2 Water yield capacity and water yield per unit area of the main districts in the basin

Region	Water yield capacity ($10^8 m^3$)			Water yield per unit area ($m^3 \cdot ha^{-1} \cdot a^{-1}$)		
	1995	2000	2010	1995	2000	2010
Beijing	11.68	4.92	8.77	660.32	281.53	497.55
Zhangjiakou	7.17	2.67	5.56	404.53	158.21	322.56
GR watershed	18.85	7.59	14.33	550.17	203.54	408.37

analysis presented in Table 2, there is quite a difference in water yields per unit area between the six districts and five counties of Zhangjiakou City and Beijing City. The Zhangjiakou yields in 1995, 2000 and 2010 were 38.6%, 45.7% and 36.6%, respectively, and lower than those in Beijing for the same years.

Water yield variations between Beijing and Zhangjiakou were great from 1995 to 2010. The variations between Beijing and Zhangjiakou were –57.9% and –62.8% from 1995 to 2010, and 78.3% and 108.2% from 2000 to 2010. The amplitude of variations was relatively larger in Zhangjiakou, but the water yield in Beijing showed a higher drop rate as a whole.

3.2 Spatiotemporal variations of water yield services

From 1995 to 2000, water yields for most regions in the GR watershed decreased with areas that had declining water yields accounting for 84.5% of total area of the watershed. The amplitude of water yield decrease was greater in downstream areas more than in upstream areas. Water yields increased in 7.6% of the watershed's total area and remained constant in 7.9% of watershed, mostly in the area around central Beijing. From 2000 to 2010, the water yields in most regions of the GR watershed increased, with areas that had increases accounting for 88.2% of total area of the watershed. Areas where the amplitude of increase was large were concentrated mainly in downstream areas of the watershed. Water yields in 9.0% of the total watershed area decreased and they remained constant in 2.8% of the total watershed area (see Fig. 3).

4 Analysis of factors driving water yield services

The InVEST water yield module was developed on the basis of the water balance method, with results obviously affected by precipitation and actual evapotranspiration. Precipitation is an important variable of climate change, while actual evapotranspiration is affected by climate and the type of surface coverage. Because it has an influence on precipitation and evaporation capacity, climate change affects water yields, and because land use determines the type of surface coverage, it also affect water yields (Li *et al.*, 2006; Hu *et al.*, 2011). This study uses scenario analysis to assess the impact of climate change and land use changes on water services in the GR watershed, and identifies the reasons for spatiotemporal variations of regional water services. The study uses two scenarios. One scenario assumes that weather conditions remain the same as in 1995, and the other assumes that land use status remains constant at the same level as in 1995. Each of the scenarios is used to evaluate water yields for the GR watershed in the years 1995, 2000 and 2010.

Using the unchanged climate scenario, the evaluation results show water yield trending steadily downward (see Fig. 4). The result based on this scenario is significantly different than the actual situation in 2000, suggesting that the actual situation in that year was produced by changes in regional land use types. From 1995 to 2000, woodland and water areas in the GR watershed declined by 19 974 ha and 4739 ha, respectively, and this change led directly to a sharp decline in runoff water yield services. We can conclude that land use changes are an important cause of water service changes.

The evaluation result for water yields in the unchanged land use scenario is similar to the actual situation (see Fig. 4). An analysis of climate change (precipitation and temperature) from 1995 to 2010 indicates that temperature change was essentially flat, while precipitation presents an inverted parabola trend (see Fig. 5). These trends are consistent

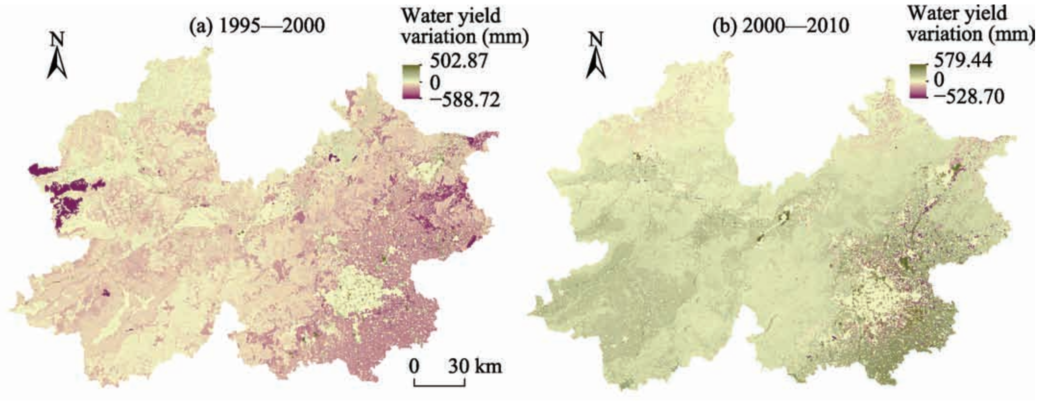

Fig.3 Changes of water yield capacity in the GR watershed during 1995–2010

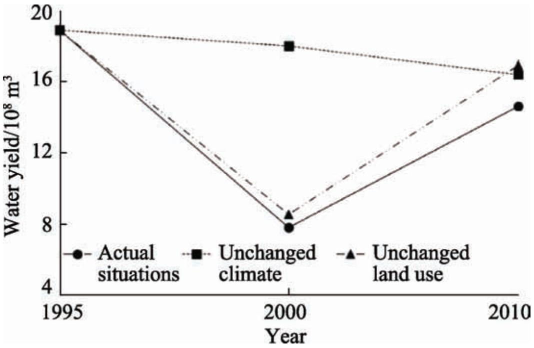

Fig.4 Changes of water yields under different scenarios

with variations of water yields shown by the unchanged land use scenario, suggesting that climate is an important cause of water service changes.

From a spatial perspective, precipitation in Zhangjiakou is generally less than that in Beijing, and generally has the same spatial distribution as water yields (see Fig. 2). From 1995 to 2000 the decline and from 2000 to 2010 the increases of precipitation in Beijing were significantly greater than those in Zhangjiakou. These changes correspond to the changes of water yields in the GR watershed during the same time periods (see Fig. 3); that is, the decline and increase of water yields in Beijing were higher than those in Zhangjiakou during the two periods. This provides further confirmation that climate change (precipitation) is an important cause of changes in water yield.

5 Spatiotemporal variations of water purification services

5.1 Spatial differentiation of TN and TP outputs

There is spatial differentiation of TN and TP outputs per unit area distributed through each of the sub-watersheds. Maximum TN and TP outputs per unit area were 2.55 and 0.24 kg·ha^{-1}, respectively, both of which occurred in 1995. Minimum TN and TP outputs per unit area are 0.27 and 0.03 kg·ha^{-1}, respectively. The minimum TN output per unit area occurred in 2010, while the minimum TP output per unit area occurred in 1995, and presented consistent trends in 1995, 2000 and 2010 (see Fig. 6).

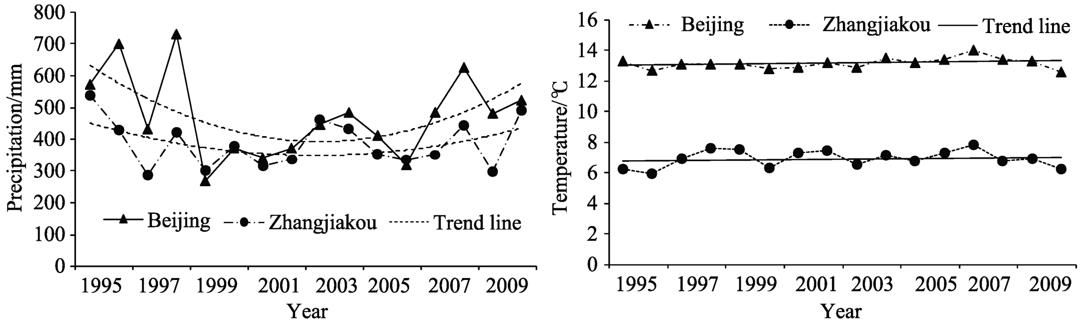

Fig.5 Changes of precipitation and temperature during 1995–2010

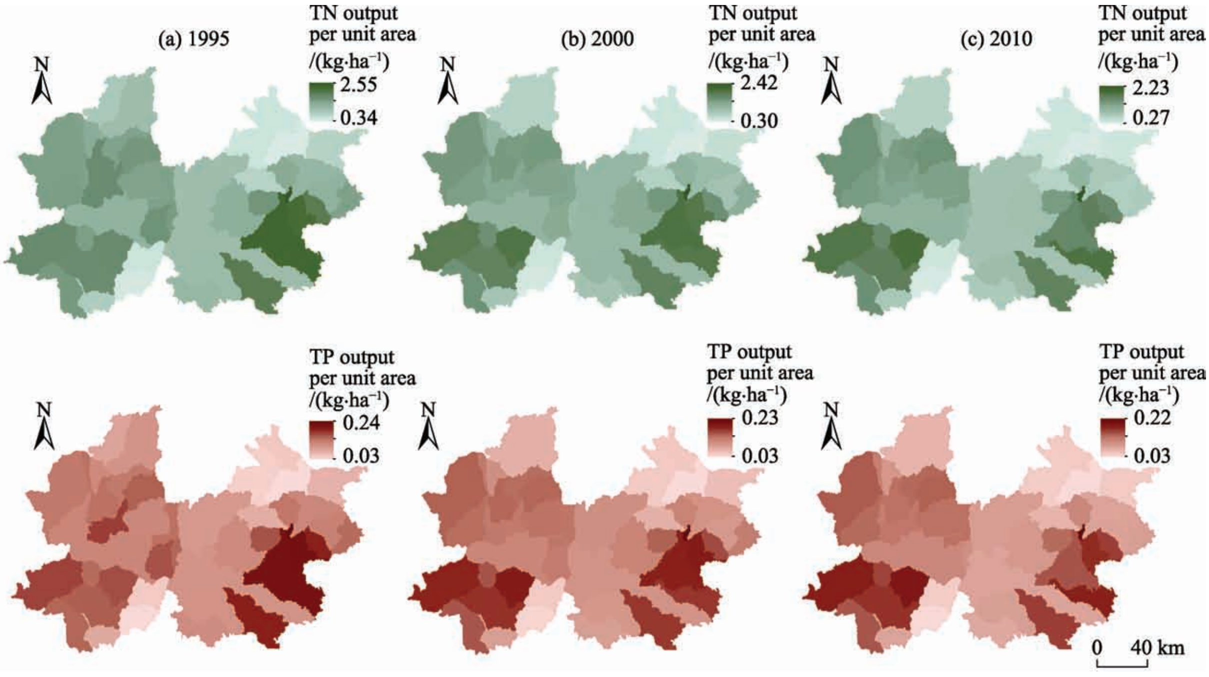

Fig.6 TN and TP outputs for the GR watershed in 1995, 2000 and 2010

From a spatial perspective, sub-basins with higher TN and TP outputs per unit area are mainly distributed in locations that generally have lower vegetation coverage in the southeast of Beijing and the southwest of Zhangjiakou. The sub-basins with lower TN and TP outputs per unit area are mainly distributed in the north of Beijing and southeast of Zhangjiakou in locations that generally have higher vegetation coverage.

From a temporal perspective, TN and TP outputs in many areas remained basically unchanged during different years. From 1995 to 2000, the areas with unchanged TN output accounted for 81.5% of the total area of the watershed and those with unchanged TP output accounted for 90.3% of total watershed area. From 2000 to 2010 areas with unchanged TN output accounted for 86.9% of total area and those with unchanged TP output accounted for 95.2% (Table 3). The areas with changed TN and TP outputs were distributed randomly throughout the watershed in the different study years; they were not concentrated.

5.2 Variations of water purification services

From 1995 to 2010, TN and TP outputs in the GR watershed first increased and then decreased. TN output increased 2.7% and TP output increased 5.8% from 1995 to 2000, while TN output declined 12.7% and TP output declined 11.9% from 2000 to 2010. Overall, during the 15 years considered in this study, TN output dropped by 10.4% and TP output decreased by 6.8% in the GR watershed.

TN and TP outputs both declined in Beijing and Zhangjiakou during the years 1995 to 2010, but the degree of decline was significantly greater in Beijing than in Zhangjiakou. TN output dropped by 18.2% and TP output by 17.7% in Beijing from 1995 to 2010, while TN output decreased by 3.0% and TP output increased by 3.8% in Zhangjiakou over the 15 years (see Table 4).

In general, water purification services in the GR watershed present a trend of gradual improvement from 1995 to 2010. TN accounted for a 10.4% enhancement and TP for a 6.8% enhancement over the 15 years. The nitrogen and phosphorus purification services in Beijing both had a certain degree of enhancement. In Zhangjiakou, the nitrogen purification service was enhanced slightly while the phosphorus purification became slightly weaker.

Table 3 Percentage of areas with changed TN and TP outputs

Variation trend	TN output (%)		TP output (%)	
	1995—2000	2000—2010	1995—2000	2000—2010
Decreased	9.0	7.1	4.6	3.0
Unchanged	81.5	86.9	90.3	95.2
Increased	9.5	6.0	5.1	1.8

Table 4 TN and TP outputs in the main areas in the watershed

Region	TN output (t)			TP output (t)		
	1995	2000	2010	1995	2000	2010
Beijing	1945.6	1960.4	1591.1	187.3	198.2	154.2
Zhangjiakou	2083.1	2177.5	2020.3	192.4	203.6	199.8
GR watershed	4028.7	4137.9	3611.4	379.7	401.8	354.0

5.3 Discussion factors influencing water purification service

The InVEST water purification module evaluates the interception effect of vegetation and soil on TN and TP. Both vegetation coverage and soil type are important factors affecting the water purification service. From a spatial perspective, the regions with weak water purification service are mainly distributed in plain areas of the Guanting Reservoir watershed (see Fig. 6). These areas generally have lower vegetation coverage, so their pollutant interception effects are weaker. The level of urbanization is much higher in these than elsewhere in the watershed, and frequent human activity results in increased emissions of pollutants, further weakening the water purification service.

Variations of vegetation coverage and pollutant emissions due to human activities impact water purification services, and this is reflected in the history of the Guanting Reservoir and related policy changes. From 1995 to 2000, the problem of eutrophication due to pollution, mostly from nitrogen and phosphorus, became increasingly pronounced in the Guanting Reservoir, with these two substances being the principal pollutants during this period (Liu *et al.*, 2001). This resulted in the Guanting Reservoir being withdrawn from the Beijing drinking water system in 1997; TN and TP outputs in the GR watershed both increased during this period. From 2000 to 2010, a series of government plans, such as *The Plan for Sustainable Utilization of Capital Water Resources in the Initial Period of the 21st Century (2000–2005)* and *The Plan to Prevent Water Pollution in the Haihe River Basin (2006–2010)*, were implemented. Water quality of the Guanting Reservoir was significantly improved, TN and TP outputs were significantly reduced, and water purification service were restored and improved to some extent. Water resources plans and policies improved the water environment of the GR watershed, and these can provide a solid basis and important reference for water resources management in the Guanting Reservoir.

From the perspective of the administrative divisions in the study area, water yield and purification services in Beijing were enhanced significantly more than those in the Zhangjiakou from 2000 to 2010. Zhangjiakou, which is upstream from Beijing, has taken many environment-friendly and pollution-control measures to protect Guanting Reservoir (Wang *et al.*, 2009). Future research could determine whether there is a link between water yield and purification services and environment-friendly and pollution-control measures, and provide a reference for the formulation of environmental policy for the GR watershed.

6 Use of different scenarios to assess changes of water yield and purification services

6.1 Scenarios

Based on data for land use and land coverage in 2010, as well as national policies and related researches, two scenarios were developed for changes to land use and coverage. These scenarios are used to discuss changes to water yield and purification services of the Guanting Reservoir watershed:

1) Returning farmland to forests: according to related policies, such as the *Circular of the State Council on Improving the Policy of Returning Farmland to Forest*, *Regulations on Returning Farmland to Forest*, and *Overall Plan on a New Round of Returning Farmland to Grassland*, all cultivated land with a slope greater than 25° within the study area is converted into broadleaf woodland on the basis of data for land use and coverage in 2010. The new data on land use and coverage forms the basis of the scenario for returning farmland to forest;

2) Ecological protection: using research on ecosystem services in riparian buffer zones as the theoretical basis, this scenario sets a riparian buffer zone to enhance water yield and purification services in the study area.

6.2 Use of the returning farmland to forest scenario to assess water yield and purification services

6.2.1 Use of the returning farmland to forest scenario to assess water yield services

Beginning with the assumption that climate and soil conditions remain the same as those in 2010, the water yield service in the study area is evaluated on the basis of data for land use and land coverage under the returning farmland to forest scenario. When this scenario is used, total water yield of Guanting Reservoir basin is $14.44\times10^8 \mathrm{m}^3$ and water yield depth is 42.27 mm. In terms of spatial distribution, water yields per unit area are high on both sides of Guanting Reservoir basin and lower in the middle. The maximum water yield per unit area is 948.42 $\mathrm{m}^3\cdot\mathrm{ha}^{-1}\cdot\mathrm{a}^{-1}$ and the minimum value is 189.71 $\mathrm{m}^3\cdot\mathrm{ha}^{-1}\cdot\mathrm{a}^{-1}$.

6.2.2 Use of the returning farmland to forest scenario to assess water purification services

When the returning farmland to forest scenario is used to evaluate water purification services in Guanting Reservoir basin, the results show that the TN output in the study area is 3432.3 tons and TP output is 338.7 tons. The minimum TN output per unit area is 0.25 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$ and the maximum TN output is 2.21 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$, while the minimum TP output value per unit area is 0.02 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$ and the maximum value is 0.22 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$. From a spatial perspective, TN and TP outputs per unit area were higher in the southwestern region of Zhangjiakou and southeastern area of Beijing. The vegetation coverage is low in these areas where the land use and land coverage types are mostly urban or cultivated.

6.3 Use of the ecological protection scenario to assess water yield and purification services

6.3.1 Use of the ecological protection scenario to assess water yield services

Beginning with the assumption that climate and soil conditions remain the same as those in 2010, the water yield service in the study area is evaluated on the basis of data on land use and land coverage under the ecological protection scenario. When this scenario is used, total water yield of the Guanting Reservoir basin is $14.58\times10^8 \mathrm{m}^3$ and water yield depth is 42.68 mm. Water yields per unit area are high in the eastern Guanting Reservoir basin area and lower the western and middle areas. The maximum water yield per unit area is 944.12 $\mathrm{m}^3\cdot\mathrm{ha}^{-1}\cdot\mathrm{a}^{-1}$ and the minimum value is 185.39 $\mathrm{m}^3\cdot\mathrm{ha}^{-1}\cdot\mathrm{a}^{-1}$.

6.3.2 Use of the ecological protection scenario to assess water purification services

When the ecological protection scenario is used to evaluate water purification services in the Guanting Reservoir basin, the results show that TN output in the study area is 3320.1 tons and TP output is 327.2 tons. The minimum TN output per unit area is 0.25 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$ and maximum TN output is 2.07 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$, while the minimum TP output value per unit area is 0.02 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$ and maximum value is 0.21 $\mathrm{kg}\cdot\mathrm{ha}^{-1}$ (Fig. 4–Fig. 5). The TN and TP outputs per unit generated by the ecological protection scenario are almost the same as those generated by the returning farmland to forest scenario. Generally, regions with higher TN and TP output have lower vegetation coverage, and vice versa.

6.4 Ecological compensation standards

The market value method and cost method are used to calculate the increments of ecosystem service value. Under the returning farmland to forest scenario, water production in the river basin increased by 0.11×10^8 m^3, while the output of TN and TP decreased by 179.06 t and 15.28 t, respectively, and the total monetary value of water service and water purification services increased by CNY 57.903 million. Under the ecological protection scenario, water production increased by 0.25×10^8 m^3, and the output of TN and TP decreased by 291.26 t and 26.85 t, respectively. The increase in the monetary value of water ecosystem services under this scenario is CNY 121.554 million (Table 5).

Based on the amount of land subject to afforestation and the project for returning farmland to forest, the area of farmland returned to forest is 70 221.17 ha. The ecological compensation standard used for the returning farmland to forest scenario is CNY 824.58 ha^{-1}. Under the ecological protection scenario, the area of land actually converted to forest is 84 141.81 ha. The ecological compensation standard for ecological protection areas in this scenario is CNY 1444.64 ha^{-1}.

Table 5 Ecological Compensation Standards under Different Scenarios

Scenarioes	Ecosystem service change	Value of ecosystem service change	Market value	Value increase (million CNY)
Returning farmland to forest scenario	Increased water production	0.11×10^8 m^3	CNY 3.64 m^{-3}	4.004
	Decrease in TN output	179.06 t	CNY 35700 t^{-1}	6.39
	Decrease in TP output	15.28 t	CNY 750700 t^{-1}	11.47
	total	–	–	57.90
Ecological protection scenario	Increased water production	0.25×10^8 m^3	CNY 3.64 m^{-3}	91
	Decrease in TN output	291.26 t	CNY 35700 t^{-1}	10.40
	Decrease in TP output	26.85 t	CNY 750700 t^{-1}	20.15
	total	–	–	121.55

7 Conclusions and recommendations

This paper uses the InVEST model to evaluate water yield and purification services of the Guanting Reservoir basin from 1995 to 2010, and analyzes the factors driving changes to the two services. The findings of the study indicate that water yield and purification services for Guanting Reservoir have been enhanced as a result of the comprehensive effort to control pollution in the Guanting Reservoir. From the perspective of the spatial distribution of services, downstream areas gain more from pollution control than upstream areas, suggesting the importance of eco-compensation in the region. In term of the factors that most impact the services, with exception of climate conditions that are beyond human control, water yield and purification services in the basin can be improved by increasing forest coverage. This can be used as a basis to identify key fields of eco-compensation in the Guanting Reservoir basin.

This study uses the InVEST model in combination with data on land use, DEM, meteorological conditions and soil conditions to analyze water yield and purification services in the GR watershed in the years 1995, 2000 and 2010. The conclusions are as follows:

1) Water yield services in the GR watershed first decreased and then increased with annual water yields of 18.85×10^8 m^3, 7.59×10^8 m^3 and 14.33×10^8m^3 for 1995, 2000 and 2010, respectively. Overall there was a decrease of 24.0% during the 15-year period.

2) Water yields show significant spatial heterogeneity across the sub-basins in the GR watershed. Water yield services in Beijing at the lower reaches were evidently higher than those in Zhangjiakou at the upper reaches, and there was considerable variation of water yield services in Zhangjiakou.

3) Water purification services for the GR watershed first decreased and then increased. Annual TN output was 4028.7 t, 4137.9 t and 3611.4 t for the years 1995, 2000 and 2010, respectively; and annual TP output was 379.7 t, 401.8 t and 354.0 t for the years 1995, 2000 and 2010, respectively. Overall, TN output increased by 10.4% during the study years and TP output increased by 6.8%.

4) From 1995 to 2010, water purification services for Beijing were more significantly enhanced than those of Zhangjiakou. TN purification service was increased by 18.2% and TP purification service was increased by 17.7% in Beijing, while TN purification service in Zhangjiakou increased by 3.0% and TP purification service declined by 3.8%.

This study also developed two scenarios, a returning farmland to forest scenario and an ecological protection scenario, and used these to obtain increments of ecosystem service value. This method reflects recent increases in ecosystem service values that have resulted from efforts to protect the ecological environment. This method is more persuasive than eco-compensation criteria that use regional ecosystem service values based on land use and land coverage types. It offers a new approach to determine eco-compensation in the Guanting Reservoir basin and other regions.

References

Allen R G, Pereira L S, Raes D, *et al*. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. *FAO, Rome*, 300(9): D05109.

Bai Yang, Zhen Hua, ZhuangChangwei, *et al*. 2013. Ecosystem services valuation and its regulation in Baiyangdian Basin: based on InVEST-model. *ActaEcologicaSinica*, 33(3): 711–717.

Costanza R, d'Arge R, de Groot R, *et al*. 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387: 253–260.

Eric Haunreiter, Dick Cameron. 2001. Mapping Ecosystem Services in the Sierra Nevada, CA. *The Nature Conservancy, California Program*, 12(1): 16–32.

Hu Qingfang, Yang Dawen, Wang Yintang, *et al*. 2011. Global calibration of Hargreaves equation and its applicability in China. *Advances in Water Science*, 22(2): 160–167. (in Chinese).

Hu Xuetao, Chen Jilin, Zhang Tianzhu. 2002. A Study of Non-Point Source Pollution Source. *Environment Science*, 23(3): 124–128. (in Chinese)

Jansson N K, Levin S, Lubchenco J, *et al*. 2000. The value of nature and the nature of value. *Science*, 289(5478): 395–396.

Leh M D K, Matlock M D, Cummings E C, *et al*. 2013. Quantifying and mapping multiple ecosystem services change in West Africa. *Agriculture Ecosystems & Environment*, 165(1751): 6–18.

Li Shimei, XieGaodi, Zhang Caixia, *et al*. 2010. Flow process of water conservation service of forest ecosystem. *Journal of Natural Resource*, 25(4): 585–593. (in Chinese)

Li Wenhua. 2006. Ecosystem services study is core of ecosystem evaluation. *Resource Science*, 28(4): 4–4. (in Chinese)

Liang Tao, Zhang Xiumei, Zhang Shen. 2011. The study of distribution of N, P and heavy metals in Guanting Reservoir and YongdingheRiver. *Progress in Geography*, 20(4): 341–346. (in Chinese)

Liu Guihuan, Wen Yihui, Zhang Huiyuan. 2010. A study on ecological compensation for the Guanting Reservoir based on ecosystem services. *Resource Science*, 32(5): 856–863. (in Chinese)

Liu Hangui. 2001. Full implementation of water resources planning and support the sustainable development of the capital. *Beijing Water Resources*, 5: 002. (in Chinese)

Liu Yaqiong, Yang Yulin, Li Fahu. 2011. Estimation of pollution loads from agricultural nonpoint sources in Beijing region based on export coefficient model approach. *Transactions of the CSAE*, 27(7): 7–12. (in Chinese)

Ma Liang, Jin Taotao, Wen Yihui, *et al*. 2015. The research progress of InVESTmodel. *Ecological Economy*, 31(10): 126–131. (in Chinese)

Nelson E, Mendoza G, Regetz J, *et al*. 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*, 7(1): 4–11.

Pan Tao, Wu Shaohong, Dai Erfu, *et al*. 2013. Spatiotemporal variation of water source supply service in Three Rivers Source Area of China based on InVESTmodel. *Chinese Journal of Applied Ecology*, 24(1): 183–189. (in Chinese)

Wang Dong, Zhang Jing. 2009. Interpretation of "*Water Pollution Prevention Planning of Haihe River Basin*": govern partition by partition and step by step to achieve major breakthroughs. *Environment Protection*, 13(4): 31–32. (in Chinese)

Wang Xiaoyan, Wang Yixun, Wang Xiaofeng, *et al*. 2003. The character of nutrient loss and land use in a small watershed of MiyunReservoir. *Research of Environmental Sciences*, 16(1): 30–33. (in Chinese)

Wang Xiaoyan, Wang Xiaofeng, Wang Qingping, et al. 2004. Loss ofnon-point source pollution from Shixia small watershed, Miyun Reservoir, Beijing. *Scientia Geographica Sinica*, 24(2): 2227-231. (in Chinese)

XieGaodi, Zhang Caixia, Zhang Changshun, *et al*. 2015. The value of ecosystem services of China. *Resource Science*, 37(9): 1740–1746. (in Chinese)

Yang Xiaoguang, Zhang Qiuping, XuChangyin, *et al*. 2006. Crop coefficient of aerobic rice in North China. *Transactions of the CSAE*, 22(2): 37–41. (in Chinese)

Zhang Keyang, Li Chunguang. 2011. The analysis on water resources actuality of Zhangjiakou. *Haihe Water Resources*, 12:10-11. (in Chinese)

Zhang L, Dawes W R, Walker G R. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water resources research*, 37(3): 701–708. (in Chinese)

Zhang Weiwei, Li Hong, Sun Danfeng, *et al*. 2013. Pollution loads variation of agricultural source in upstream of HuairouReservoir. *Transactions of the CSAE*, 29(24): 124–131. (in Chinese)

Zhang Zhiqiang, XuZhongmin, Cheng Guodong. 2001. Valuation of ecosystem services and natural capital. *Acta Ecologica Sinica*, 21(11):1918-1926. (in Chinese)

Zhao Yong, CaiHuanjie, Wang Jian, *et al*. 2004. Determination of the empirical coefficient of Hargreaves formula in computing crop evapo-transpiration. *Agricultural Research in the Arid Areas*, 22(4): 44–47. (in Chinese)

Zhou Bin, Yu Xinxiao, Chen Lihua, *et al*. 2010. Soil erosion simulation in mountain areas of Beijing based on InVEST model. *Research of Soil and Water Conservation*, 17(6): 9–13. (in Chinese)

Zhou W, Liu G, Pan J, *et al*. 2005. Distribution of available soil water capacity in China. *Journal of Geographical Sciences*, 15(1): 3–12. (in Chinese)

基于官厅水库流域产水和水质净化服务时空变化的生态补偿机制研究

文一惠[1]，刘桂环[1]，吴瑞[1,2,3]

1. 环境保护部环境规划院，北京 100012；
2. 北京林业大学水土保持学院，北京 100083；
3. 深圳市城市规划设计研究院有限公司，广东深圳 518000

摘　要：官厅水库（GR）是北京及其周边地区最重要的水源地之一，曾因水质污染严重而被迫退出北京市饮用水供应系统，经过全面治理后于 2007 年恢复成为北京市备用水源地。为了从整体上定量分析官厅水库流域生态系统的产水和水质净化服务，基于 InVEST 模型，选择官厅水库退出北京市饮用水供应系统和恢复成为北京市备用水源地为时间节点，定量评估 1995—2010 年官厅水库流域生态系统的产水量和 TN、TP 输出量，分析其产水服务和水质净化服务的时空变化。结果表明：1995 年至 2010 年，官厅水库的产水服务服务先减弱后增强，整体呈现减弱趋势，流域产水量从1995年的 1.89×10^9 m^3降至2010年的 1.43×10^9 m^3，产水服务减弱 24.0%，水质净化服务表现为先减弱后增强，但整体呈增强趋势。TN 产量从 1995 年的 4028.7 吨下降到 2010 年的 3611.4 吨，TP 从 1995 年的 379.7 吨下降到 2010 年的 354.0 吨。TN 和 TP 净化服务分别增加了 10.4％和 6.8％。研究显示，气候和土地利用的变化是导致官厅水库水利服务变化的主要因素，不同时期的水资源保护政策导向也与水质净化服务变化趋势相吻合。一方面，以上研究成果可以为确定官厅水库流域生态补偿的关键领域奠定基础，另一方面，通过设定退耕还林还草和生态保护的目标情景，在这个目标情景作为生态补偿标准的基础上，可以获得生态系统服务价值的增量。这种方法直接反映了自生态环境得到保护以来新增的生态系统服务价值，这与土地利用/覆盖类型视角下，基于区域生态系统服务价值的生态补偿标准相比，更具说服力和可行性，并且为官厅水库流域及其他地区的生态补偿提供了新的途径。

关键词：官厅水库流域；InVEST 模型；时空变化；水质净化；产水量