Modelling Ecosystem Water Supply Services across the Lancang River Basin

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Abstract: Ecosystem services related to water supply are now a hot topic in ecology and hydrology. Here, water supply service in the Lancang River basin was evaluated using the newly developed model InVEST. We found the mean annual water supply in Lancang River basin is approximately $7.24E+10$ m$^3$ y$^{-1}$ with 23.87\% from main stream and 76.13\% from the tributaries. There is an increasing trend downstream. Grasslands and forests contribute 71.66\% of the total water. A comparison of water supply capacity per unit area for ecosystems of different composition indicates that there is a decreasing trend from broad-leaved forest, mixed coniferous and broad-leaved forest, bamboo forest, coniferous forest, shrub forest and grassland. Two-thirds of the total water is provided by an area covering 40\% of the total basin area. This study provides guidelines for the efficient management of water resources in the Lancang River basin.

Key words: water supply service; InVEST model; ecosystem services; hotspot; Lancang River

1 Introduction

The ecosystem service of water supply refers to the function of vegetation to retain moisture and regulate runoff through redistributing precipitation (Li et al. 2010). Water supply services are affected by vegetation type, climatic change, soil properties, topography and geomorphology. Services show spatial and temporal heterogeneity because of the hydrologic cycle and water balance. It remains unclear how controlling factors affect water supply services at different spatial and temporal scales and this makes it difficult to evaluate water supply services at regional scales and to convert between different scales (Wang et al. 2010). The current evaluation methods for water supply services include soil water storage, water balance, precipitation storage and annual runoff (Zhang et al. 2009). Among them, the water balance method is the most efficient and has been widely applied (Lu et al. 2004; Zhang et al. 2008).

The InVEST model (Integrate Valuation of Ecosystem Services and Tradeoffs) is an ecosystem service appraisal tool developed in 2007 by Stanford University, the World Wide Fund for Nature and The Nature Conservancy. It has been widely used across many regions such as Hawaii (Goldstein et al. 2010), Indonesia (Barano et al. 2010), Colombia (Goldman et al. 2010) and China (Zhou et al. 2010; Bai et al. 2011). The water yield module is a large spatio-temporal scale model developed on the basis of water balance principles. Taking advantage of this model, we evaluated water supply services at a regional scale in the Lancang River Basin. The aims of this study were: (i) define the spatial distribution of water supply service and the water supply service of the sub-watersheds; (ii) define water supply services of selected typical ecosystems; and (iii) identify hotspots of water supply service where the water supply capacity is more than $5000$ m$^3$ ha$^{-1}$ y$^{-1}$ in the basin.

2 Study area

The Lancang River originates on the Qinghai-Tibet Plateau and is a famous transboundary river running throughout six countries. In China, the length of the main stream of the Lancang River is 2160 km with a drainage area of 164 000 km$^2$. Annual runoff is $7.65E+08$ m$^3$, representing 14.5\%
of the total river basin. The upper reach extends from the headwaters to Changdu, the middle reach from Changdu to Gongguoqiao, and the lower reach from Gongguoqiao to the Nana River estuary. Most of the major tributaries are located in upstream and downstream reaches (He et al. 2000, 2007). The Lancang River Basin (21°–34°N, 94°–102°E, Fig. 1) experiences large regional differences in climate as it flows from north to south. Temperature and precipitation increase from north to south, and decrease with increasing elevation. The diversity of physiographic settings results in a variety of soil types and ecosystems (Qiu 1996; Wang et al. 2007).

3 Method and data resource

3.1 Method
This study evaluates the water supply services of vegetation in the Lancang River Basin at a regional scale. Runoff can be used to estimate water supply services based on the principle of water balance (Li 2008; Egoh et al. 2008; Nie 2009, 2010), and was calculated by the water yield component in InVEST as follows (Tallis et al. 2011):

\[
Y_{jx} = (1 - \frac{AET_{ij}}{P_x}) \cdot P_x
\]

where \(Y_{jx}\) is annual water yield on pixel \(x\) with ecosystem \(j\); \(AET_{ij}\) is annual actual evapotranspiration on pixel \(x\) with ecosystem \(j\); \(P_x\) is annual precipitation on pixel \(x\); \(AET_{ij}/P_x\) is an approximation of the Budyko curve developed by Zhang et al. (2001); \(\omega_x\) is a non-physical parameter to characterize the natural climatic-soil; \(R_{ij}\) is the dimensionless Budyko Dryness index on pixel \(x\) with ecosystem \(j\), defined as the ratio of potential evapotranspiration to precipitation (Budyko 1974); \(Z\) is a seasonality coefficient that represents the seasonal rainfall distribution and rainfall depths ranging from 1 to 10 (Zhang et al. 2001); \(AWC_x\) is the volumetric (mm) plant available water content; \(K_{ij}\) is the plant (vegetation) evapotranspiration coefficient associated with the ecosystem \(j\) on pixel \(x\); \(ETo_x\) is the reference evapotranspiration from pixel \(x\).

3.2 Data
Precipitation (P) from 35 meteorological stations during 1960–2005 was retrieved from the Meteorological Center of China Meteorological Administration. The mean annual value is interpolated in ArcGIS v9.3 by Kriging. Reference evapotranspiration (ETo) is calculated by the modified FAO Penman-Monteith method (FAO 1998a). The evapotranspiration coefficient (K) followed FAO (1998b) and Tallis et al. (2011). The coefficient (Z) proposed by Zhang was considered to be 3, at which the results will have the least error (He 1995; Qiu 1996).

Ecosystem types (ET) and sub-types are derived from land use maps, vegetation maps and grass maps (Table 1). The land use maps (1:100 000) were provided by Data Sharing Infrastructure of Earth System Science, vegetation maps (1:1 000 000) were provided by the Institute of Botany (Chinese Academy of Sciences), and grass maps (1:1 000 000) were provided by the Institute of Geographic Sciences and Natural Resources Research (Chinese Academy of Sciences).

The DEM data was downloaded from the Earth Resources Observation and Science Center (EROS) (http://eros.usgs.gov/Find_Data/Products_and_Data_Available/gtopo30/hydro) and the division of watershed and sub-watersheds were operated in ArcSWAT.

Soil depth was obtained from the soil properties database of China, compiled by the Data Center of
Resources and Environmental Science (Chinese Academy of Sciences). Plant available water content (AWC) was provided by Zhou (2003), and maximum root depth was obtained from Canadell et al. (1996).

4 Results

4.1 Distribution of water supply services

The distribution of water supply in the Lancang River basin is shown in Fig. 2. Annual water supply in the whole river basin is 7.24E+10 m$^3$: 9.85E+09 m$^3$ from the upper river basin (13.60%), 1.18E+10 m$^3$ from the middle river basin (16.26%), and 5.08E+10 m$^3$ from the lower river basin (70.15%). Here, we define water supply capacity as the annual water supply per unit area. The water supply capacity in the three different reaches is 1856.69, 3199.82 and 6967.72 m$^3$ ha$^{-1}$ y$^{-1}$, respectively, increasing from upstream to downstream.

Annual water supply was also calculated for first order tributaries with an area larger than 1000 km$^2$. The main stream produces 1.73E+10 m$^3$ y$^{-1}$ with a contribution of 23.87%, while the tributaries supply 5.50E+10 m$^3$ y$^{-1}$ with a contribution of 76.13% (Fig. 3). The annual water supply in the Buyuan River was the highest among tributaries (7.46E+09 m$^3$ y$^{-1}$, 10.32%), followed by the Weiyuan River (8.11%) and the Heihui River (7.84%). Water supply capacity in the Buyuan River is also the highest among tributaries, with a value of 9459.70 m$^3$ ha$^{-1}$ y$^{-1}$. The water supply capacity of the Nanlei and Hei Rivers is 8933.67 and 8793.96 m$^3$ ha$^{-1}$ y$^{-1}$, respectively.

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Sub-ecosystem</th>
<th>Code</th>
<th>Area (m$^2$)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassland</td>
<td>High-cold meadow</td>
<td>HM</td>
<td>5.26E+10</td>
<td>32.08</td>
</tr>
<tr>
<td></td>
<td>Warm-temperate herbosa</td>
<td>WH</td>
<td>1.82E+9</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>Tropical herbosa</td>
<td>TJ</td>
<td>2.07E+10</td>
<td>12.63</td>
</tr>
<tr>
<td></td>
<td>Montane meadow</td>
<td>MM</td>
<td>5.37E+9</td>
<td>3.28</td>
</tr>
<tr>
<td>Desert</td>
<td>High-cold bare desert</td>
<td>HB</td>
<td>7.38E+9</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>High-cold sparse desert</td>
<td>HD</td>
<td>3.17E+9</td>
<td>1.93</td>
</tr>
<tr>
<td>Forest</td>
<td>Dry valley sparse scrub and grass</td>
<td>DS</td>
<td>6.25E+9</td>
<td>3.81</td>
</tr>
<tr>
<td></td>
<td>Alpine and subalpine shrub forest</td>
<td>AS</td>
<td>8.48E+9</td>
<td>5.17</td>
</tr>
<tr>
<td></td>
<td>Alpine and subalpine broad-leaved forest</td>
<td>AB</td>
<td>1.47E+9</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Alpine and subalpine mixed coniferous and broad-leaved forest</td>
<td>AM</td>
<td>7.44E+7</td>
<td>0.05</td>
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<tr>
<td></td>
<td>Alpine and subalpine coniferous forest</td>
<td>AN</td>
<td>8.09E+9</td>
<td>4.93</td>
</tr>
<tr>
<td></td>
<td>Tropical and subtropical bamboo forest</td>
<td>TB</td>
<td>3.15E+8</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Tropical forest and monsoon rain forest</td>
<td>TM</td>
<td>2.41E+9</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>Subtropical shrub forest</td>
<td>SS</td>
<td>4.94E+9</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td>Subtropical broad-leaved forest</td>
<td>SB</td>
<td>5.64E+9</td>
<td>3.44</td>
</tr>
<tr>
<td></td>
<td>Subtropical mixed coniferous and broad-leaved forest</td>
<td>SM</td>
<td>2.68E+9</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>Subtropical coniferous forest</td>
<td>SN</td>
<td>5.32E+9</td>
<td>3.24</td>
</tr>
<tr>
<td>Farmland</td>
<td>Dryland crops</td>
<td>DC</td>
<td>1.79E+10</td>
<td>10.93</td>
</tr>
<tr>
<td></td>
<td>Paddy field</td>
<td>PF</td>
<td>7.69E+9</td>
<td>4.69</td>
</tr>
<tr>
<td>Human settlement</td>
<td>Human settlement</td>
<td>HS</td>
<td>2.59E+8</td>
<td>0.16</td>
</tr>
<tr>
<td>Wetland</td>
<td>Wetland</td>
<td>WL</td>
<td>1.40E+9</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 1 Ecosystem types in the Lancang River basin.
4.2 Water supply services of typical ecosystems

The study area is dominated by grassland and forest ecosystems, accounting for 49.10% and 27.85% of the region. The water supply services for these two ecosystems are shown in Fig. 4.

The grassland ecosystem supplies 2.28E+10 m³ y⁻¹ (31.26%). The high-cold meadow widely occurs in the upper and middle river basins, which supplies 1.11E+10 m³ (15.40%), followed by tropical herbosa (13.17%) and montane meadow (2.10%); warm-temperate herbosa (3817.66 m³ y⁻¹) and alpine and subalpine coniferous and broad-leaved forest (4216.93 m³ ha⁻¹ y⁻¹). The forest ecosystem provides 2.89E+10 m³ (49.10%), in the subtropical coniferous forest is 4.20 E+09 m³ (6.57%), in the alpine and subalpine coniferous and broad-leaved forest (5.81%), in the alpine and subalpine coniferous forest (7.900.25 m³ ha⁻¹ y⁻¹), followed by subtropical broad-leaved forest (8416.42 m³ ha⁻¹ y⁻¹), subtropical coniferous forest (7900.25 m³ ha⁻¹ y⁻¹), and alpine and subalpine shrub forest (4216.93 m³ ha⁻¹ y⁻¹).

Water supply capacity in broad-leaved forest is 8319.98 m³ ha⁻¹ y⁻¹, 7868.94 m³ ha⁻¹ y⁻¹ in mixed coniferous and broad-leaved forest, 7622.29 m³ ha⁻¹ y⁻¹ in bamboo forest, 6117.10 m³ ha⁻¹ y⁻¹ in coniferous forest, 5159.15 m³ ha⁻¹ y⁻¹ in shrub forest, and 2836.77 m³ ha⁻¹ y⁻¹ in grasslands.

4.3 Hotspot of water supply service

The study area was divided into four regions according to the water supply capacity of catchments (Table 2). The water supply index, defined as the ratio of the percent of water supply services to the percent of area, was used to characterize different regions (Fig. 5). Regions in the first class have a water supply capacity less than 2000 m³ ha⁻¹ y⁻¹, with a water supply index of 0.36. These regions are located in the upper and middle river basins. The water supply capacity in regions in the second class varies from 2000–5000 m³ ha⁻¹ y⁻¹ and the water supply index is 0.78, mainly in the Angqu River and Heihe River watersheds. Regions in the third class had a variable water supply capacity of 5000–8000 m³ ha⁻¹ y⁻¹ and water supply index of 1.45. These regions include Weiyuan River basin, Liusha River basin and Nana River basin. Regions in the fourth class are characterized by a water supply capacity of 8000 m³ ha⁻¹ y⁻¹ and a water supply index of 2.02, including the Buyuan River basin, Xiaohe River basin, Heihe River basin and Nanlei River basin.

The term “hotspot” was originally used for regions or sites of high species richness and has been widely applied to prioritize areas for biodiversity conservation (van

Table 2 Hotspot classes of water supply services in the Lancang River Basin.

<table>
<thead>
<tr>
<th>Class</th>
<th>Area (ha)</th>
<th>Water supply (%)</th>
<th>Water supply index</th>
<th>Water supply capacity (m³ ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.11E+6</td>
<td>31.39</td>
<td>11.2</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>4.62E+6</td>
<td>28.4</td>
<td>22.23</td>
<td>0.78</td>
</tr>
<tr>
<td>3</td>
<td>4.18E+6</td>
<td>25.66</td>
<td>37.21</td>
<td>1.45</td>
</tr>
<tr>
<td>4</td>
<td>2.37E+6</td>
<td>14.56</td>
<td>29.36</td>
<td>2.02</td>
</tr>
</tbody>
</table>
This study analyzed water supply service in the Lancang River Basin at a regional scale using the water yield module in InVEST. We conclude:

(1) An average volume of $7.24\times10^{10}$ m$^3$ y$^{-1}$ of water is supplied in the Lancang River basin, and increases from upstream to downstream. The contribution of the main stream and tributaries was 23.87% and 76.13%. The Buyuan River supplied the highest volume of water both in total and unit area.

(2) Approximately 72% of the total water was produced by grasslands and forest ecosystems. High cold meadows supplied the highest volume of water in grassland ecosystems and subtropical broad-leaved forest the highest in forest ecosystems. Water supply capacity per unit area in ecosystems with different composition and structure were compared, and the results showed a decreasing trend from broad-leaved forest, mixed coniferous and broad-leaved forest, bamboo forest, coniferous forest, shrub forest and grassland.

(3) The study area was divided into four regions according to water supply per unit area. The hotspot covers 40% of the total basin area and provides two thirds of the total water.

This study evaluated the water supply service using the InVEST model, and mapped water supply spatial distribution patterns. The hotspot which produced most water supply services has practical significance for water resources and ecosystem management. However, several factors such as topography and geomorphology were not taken into account and some parameters such as evaporation coefficient and the root depth were defined according to the results of previous studies. Hence, there are some uncertainties in some regions. Nevertheless, this study provides a useful initial exploration into the research of ecosystem services at regional scales.

Fig. 5 Hotspot distribution of water supply service in Lancang River Basin.

Jaarsveld et al. 1998). This study defines a hotspot as a river basin that has a water supply capacity of more than 5000 m$^3$ ha$^{-1}$ y$^{-1}$ and therefore a significant region for water supply services. Generally, hotspots occur in the lower river basin (Fig. 5).

5 Discussion

This study analyzed water supply service in the Lancang River Basin at a regional scale using the water yield module in InVEST. We conclude:

This study provided a useful initial exploration into the research of ecosystem services at regional scales.

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(in Chinese)

澜沧江流域生态系统水源涵养功能研究

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摘要：生态系统的水源涵养功能一直以来都是生态学和水文学研究的热点和难点问题。本文基于新开发的InVEST模型对澜沧江流域的水源涵养功能进行了研究，得出以下结果：（1）澜沧江流域年均供水7.24E+10 m³ y⁻¹，其中干流贡献率为23.87%，而支流贡献率为76.13%，从上游至下游呈明显递增趋势。（2）草地生态系统和森林生态系统的水源涵养量贡献率共计达71.66%；对不同组成结构生态系统类型的水源涵养能力进行比较，阔叶林>针阔混交林>竹林>针叶林>灌木林>草地。（3）澜沧江流域三分之二的水由占总面积40%的热点区域提供。研究为澜沧江流域水资源的有效管理提供一定依据。

关键词：水源涵养；InVEST模型；生态系统服务；热点；澜沧江