Ecological Indicators 81 (2017) 159–170

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Evaluating regional water security through a freshwater ecosystem service flow model: A case study in Beijing-Tianjian-Hebei region, China

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ARTICLE INFO

Keywords:
Freshwater ecosystem service
Freshwater service provision
Freshwater service consumption
Spatial flow
Freshwater security
Beijing–Tianjin–Hebei

ABSTRACT

Freshwater ecosystem service is essential to human's survival and development. Many studies have documented the spatial differences in the supply and demand of ecosystem services and proposed the concept of ecosystem services flows. However, few studies characterize freshwater ecosystem service flow quantitatively. Therefore, our paper aims to quantify the effects of freshwater ecosystem service flow on downstream areas. We developed a freshwater ecosystem service flow model and applied it in the Beijing–Tianjin–Hebei (BTH) region, China, for the year of 2000, 2005, and 2010. We assessed the regional water security with an improved freshwater security index by integrating freshwater service provision, consumption and flow; and found that most areas of the BTH region (69.2%) were affected by upstream freshwater flows. The areas achieving water security in the region also expanded to 66.9%, 66.1%, and 71.3%, which were 6.4%, 6.8% and 5.7% increments compared to no-flow situation, in 2000, 2005 and 2010, respectively. Setting quota for human water consumption is suggested to further improve water security. These results highlight the need to fully understand the connections between distant freshwater ecosystem service provision and local freshwater ecosystem service consumption. This approach may also help managers to choose more sustainable strategies for critical freshwater resource management across different regions.

1. Introduction

Freshwater is widely regarded as the most essential natural resource in the support of human well-being (Hassan et al., 2005; UNESCO, 2009), and the supply of clean water has the highest value among all provisioning ecosystem services (Boithias et al., 2013; Costanza et al., 1997); therefore, it is particularly important to investigate the spatial and temporal patterns of regional freshwater security. Due to population growth, economic development, land-use intensification, a projected warming and drying climate, an increasing likelihood of persistent drought conditions, and poor environmental stewardship (Vörösmarty et al., 2010; Wilson et al., 2016), freshwater scarcity issues continue to gain urgency in science and policy circles (Green et al., 2015). However, most freshwater has no price in the market and is seldom accounted for in decision making; freshwater provision services are largely invisible and ignored (Jansson et al., 1999). Given these circumstances, a method connecting both the natural and human perspective is needed to set priorities for freshwater source management.

Ecosystem services is the benefits human obtain from nature (Costanza et al., 1997). Research into ecosystem services generates knowledge that influences policies, institutions, and technologies with regard to conservation and sustainable human development (Posner et al., 2016). Ecosystem services are thus suitable for freshwater security assessment. Recent studies have focused on mapping the supply and demand of ecosystem services (Boithias et al., 2013; Burkhard et al., 2012; Notte et al., 2012) and investigating whether the demand for ecosystem services are satisfied (Anton et al., 2010; Kroll et al., 2012). However, most studies make only a rough estimate of static freshwater provision service or value (Eigenbrod et al., 2010), ignoring the complex and multi-scale dynamics of freshwater service in the supply, flow, and use processes (Bagstad et al., 2013; Villa et al., 2014), and are therefore ultimately ineffective in supporting accurate decision-making. Some scholars, noticing the spatial mismatch between ecosystem services supply and demand (Brauman et al., 2007; Hein et al., 2006; Kroll et al., 2012), put forward the concept of ecosystem services flows to deal with this problem (Bagstad et al., 2013; Johnson et al., 2012; Seppelt et al., 2011).

Ecosystem services flows research establishes a spatiotemporal connection between supply and demand, and an understanding about when and where the benefits are enjoyed (Bagstad et al., 2012; Serna-

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http://dx.doi.org/10.1016/j.ecolind.2017.05.034
Received 12 February 2017; Received in revised form 10 May 2017; Accepted 11 May 2017
Available online 06 June 2017

Chavez et al., 2014; Wendland et al., 2010). Current research on ecosystem services flows, however, is rare and conceptual (Bastian et al., 2012; Serna-Chavez et al., 2014; Silvestri and Kershaw, 2010; Syrbe and Walz, 2012). The quantity and spatial features of ecosystem services flows are characterized according to broad categories defined by the spatial relations between provisioning and benefiting areas; however, no exact paths of ecosystem services flows are given (Costanza, 2008; Fisher et al., 2009; Palomo et al., 2013).

Although the Service Path Attribution Networks (SPANs) in the Artificial Intelligence for Ecosystem Services (ARIES) model were designed to simulate ecosystem services flows (Bagstad et al., 2011, 2013; Villa et al., 2009), ARIES was only tested in case studies based in southeast Arizona, southern California, and western Washington. In addition, ARIES requires online access and is currently not useful for external users (Bagstad et al., 2012), limiting its application in other locations. A simple and portable model is needed.

Depending on the UN Standard (UN, 2013), water resources in BTH region are absolute scarcity. The BTH region is experiencing the most severe resource pressure in China due to the rapid economic development and a growing population, restricting the region's sustainable development. Previous water resource researches on the BTH have been mainly undertaken at watershed or administrative scale (Gao et al., 2014). However, there remains no research evaluating the regional water security in BTH at the pixel scale. In fact, research indict that freshwater supply and demand are dependent on the considered spatial and temporal extensions (Syrbe and Walz, 2012). Hence, evaluating the freshwater security at finer spatial scale is needed for sustainable policies and management.

This study attempted to evaluate the regional freshwater security pattern jointly affected by the upstream and local freshwater provision services through the freshwater ecosystem service flow model. First, the water provision service was modeled with InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), an annual water yield model (Tallis et al., 2013). The water consumption service was calculated using the quota method. Second, by using a simplified water flow model, the spatial flow of freshwater ecosystem service was simulated. Finally, the water security pattern in static and flowing scenarios was compared with an improved freshwater security index. The main objectives of this paper are: (1) to identify where the freshwater ecosystem service is generated and consumed in space, and delve into the reasons for distribution of high provision and consumption; (2) to quantify the spatial flow of freshwater resources in different regions, especially among 13 cities in the BTH region; (3) to evaluate the regional water security using an improved freshwater security index; and (4) to characterize the beneficial effect on the downstream regions derived from upstream freshwater provision service.

2. Materials and methods

2.1. Study areas

The BTH (Beijing-Tianjin-Hebei) region (35°03′–42°40′, 113°27′–119°50′) is located in North China, the second largest traditional agricultural area in the country. The BTH region, covering 214,900 km^2, accounts for 2.2% of the total area of China, but generated over 10% of the total national GDP in 2010 (–2011). The average annual precipitation is 538 mm, and the average amount of water resources consumed per capita is 345 m^3 in Beijing City, 279 m^3 in Tianjin City, and 307 m^3 in Hebei Province, less than 1/7 of the Chinese national average. The elevation of the region decreases from the northwest to the southeast, with altitudes ranging from 2841 to −2 m (Fig. 1). The spatial heterogeneity of land use/cover in the BTH region is significant. In moving from southeast to northwest, ecosystems transition from coastal beaches to coastal wetland, farmland, city, thickets, forests, forest steppe, and meadow. The western high mountain areas provide an important ecological barrier, the region in the southeastern plains are the main grain-producing areas, and densely-populated, large cities such as Beijing and Tianjin are the main ecosystem services consumption areas. In the BTH region, the supply and the consumption of ecosystem services occur in different spatial positions. The BTH region is an ideal place to analyze the spatial flow of ecosystem services considering its obvious spatial gradient.

2.2. Data source and processing

The land use and land cover (LULC), population, and Gross Domestic Product (GDP) data sets for 2000, 2005, and 2010 (1 km resolution grids) were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn). Root restricting layer depth was obtained from a recent 1:1,000,000 scale soil map of China, provided by the Institute of Soil Science, Chinese Academy of Sciences (Fischer et al., 2008). Plant available water content (PAWC) was calculated referring the Zhou et al. (2005)'s experience equation, using raster grids obtained from polygon shape files of weight average soil texture (% clay, % sand, % silt) and organic carbon content (% OC). The meteorological data (2474 sites) including air temperature, precipitation, relative humidity, wind speed, and sunshine time were collected from China's National Meteorological Information Center (NMIC, 2012). The annual reference evapotranspiration was estimated using the Penman-Monteith formula (Allen et al., 1998). The boundaries of the BTH region were obtained from the China Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn/). Digital elevation model (DEM) data were provided by the Cold and Arid Regions Sciences Data Center at Lanzhou (http://westdc.westgis.ac.cn). These DEM data, with an accuracy of 1000 m, were used to calculate water flow directions with ArcGIS software. The landscape was classified into six categories including croplands, forest, grasslands, water bodies, urban areas, and unused land. All data except the soil map, DEM, and boundaries were obtained for the years 2000, 2005, and 2010. The value of resolutions ranged from 30 m to 1 km, and all data were resampled to a resolution of 1 km. Because the aim of this effort was to evaluate water security, we did not apply monetary values to the freshwater service.

2.3. Quantification of freshwater ecosystem service provision

The provision of freshwater ecosystem services was estimated by the freshwater yield algorithm, a sub-module of the InVEST model, developed by Stanford University (Tallis et al., 2013). The water yield model uses a basic hydrologic model that subtracts evapotranspiration from combined infiltration and runoff, without differentiating between surface, subsurface, and base flow. In InVEST, the water yield model is based on the Budyko curve (Budyko, 1974) and annual precipitation. Annual water yield for each pixel (Y_{xj}) on the landscape (indexed by x = 1, 2,...X) was defined as follows:

$$Y_{xj} = (1 - AET_{xj}/P_x) \times P_x \tag{1}$$

Where AET_{xj} is the annual actual evapotranspiration on pixel x with $LULU_j$, and P_x is the annual precipitation on pixel x. AET_{xj}/P_x represents an approximation of the Budyko curve estimated by Zhang et al. (2001) as follows:

$$AET_{xj}/P_x = (1 + \omega_x R_{xj}) \Big/ \left[1 + \omega_x R_{xj} + \left(\frac{1}{R_{xj}}\right)\right] \tag{2}$$

where R_{xj} represents the dimensionless Budyko dryness on pixel x with land use type j, and ω_x is defined as the plant available water coefficient on pixel x. All the input data included the annual precipitation, annual potential evapotranspiration, soil depth, plant available water content, land use and land cover, and root depth.

2.4. Quantification of freshwater ecosystem service consumption

We estimated the freshwater ecosystem service consumption as the