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A framework of freshwater services flow model into assessment on water security and quantification of transboundary flow: A case study in northeast China

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ABSTRACT

Ecosystem service flow dynamics which establish the linkage between human and nature is essential in an ecosystem service assessment. This study constructed an ecosystem service flow model of freshwater flow then utilized it to assess the water-related ecosystem services in northeast China. We included the provision, consumption, and spatial flow of freshwater services in an index to assess the water security condition and quantified the services trans-boundary flow from the northeast forest belt (NFB) in northeast China. Our results showed that large areas (50.54%, 55.10% and 52.90%, respectively) of northeast China received upstream freshwater service in three years. The water security condition of northeast China deteriorated from 2005 to 2015 with the change of water security index considering water flow (WSI_{flow}), mainly influenced by precipitation and agriculture water consumption. Approximately 4.16 billion m^3 of freshwater service were delivered from NFB to surrounding regions demonstrating the importance of NFB in terms of ecosystem service provision. In addition, 73 key watersheds (4.71% of total area) within NFB that significantly affect the trans-boundary flow were further identified. We suggested that local government should advocate develop water-saving agriculture and livestock water quotas. Moreover, priorities should be given to protect the key watersheds within NFB in order to maintain the supply of freshwater service. This study provided a framework for exploring suitable strategies for managing water resources and laid a foundation for promoting the ecological compensation in the future.

1. Introduction

Water is widely regarded as the most essential natural resource in supporting human well-being, and the supply of freshwater is arguably one of the most essential provisioning ecosystem services (Costanza et al., 1997; Jansson et al., 1999; Li et al., 2017; D'Odorico et al., 2018). However, with rapid socioeconomic development, population growth and intense climate change, there is an increasing demand for freshwater (Khan and Zhao, 2019; Alimohammadi et al., 2020; He et al., 2020; Baggio et al., 2021). Consequently, water scarcity due to the imbalance between provision and consumption has occurred in many regions across the world (Mayer, 2001; Bangash et al., 2013; Huang and Ma, 2013; Boithias et al., 2014; Grafton et al., 2019). In general, water scarcity is determined by the balance between water availability on the supply side and water consumption on the demand side, which is influenced by various human and natural factors (Boithias et al., 2014; Zhang et al., 2021). The freshwater scarcity issue poses a threat to water security and consequently to the sustainability of human society across various spatial scales (e.g., international (Mekonnen and Hoekstra, 2016), national (Schyns and Hoekstra, 2014), regional (Feng et al., 2012), and local (Hoekstra, 2016)). As such the issue has gained urgency in scientific and political circles (Green et al., 2015). In that context,

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understanding the spatiotemporal dynamics of regional water supply and demand becomes necessary.

Spatial flow of freshwater service establishes the connection between water supply and demand, and affects the outcome of regional water security pattern (Li et al., 2017; Qin et al., 2019). However, current studies on water security assessment of freshwater service which include spatial flow have been rare, e.g., with only freshwater supply and demand included (Bastian et al., 2012; Serna-Chavez et al., 2014; Qin et al., 2019). On the provision side, most of the relevant assessments employ the ecosystem service assessment model or hydrological model to evaluate the service provision. Typical models such as the specialized Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Sharp et al., 2014), Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Veettil and Mishra, 2018) and SOURCE model (Hong Hanh et al., 2019) are usually incorporated into the assessment of freshwater provision. On the demand side, data on the consumption of freshwater services, e.g., agriculture, industry, livestock, and domestic water uses, are often collected by the government all agencies at different administrative levels (Boithias et al., 2014; Qin et al., 2019). However, studies based on static models using governmental average consumption data usually ignore the complex flow process of ecosystem service which will lead to a great deviation between the estimated and the real water security condition in the studied regions and finally encourage inefficient and irrational polices on the conservation of water resource and the maintain of water security (Qin et al., 2019). Therefore, a dynamic flow model, which quantifies the amount and characterizes the feature of such passive biophysical flow process of freshwater services, is in great demand.

A reasonable estimation of distant spatial flow of ecosystem services across geographic boundary would improve our understanding of the relationship between natural and socio-economic systems (Bagstad et al., 2013; Zhang et al., 2021). However, studies on quantifying distant flow of ecosystem services and applying them to ecological assessment is still in its infancy. This arguably is attributed to the semantic inconsistency (Bagstad et al., 2013) and the lack of a clearly-defined spatial boundary to study the interregional flow of ecosystem services (Koellner et al., 2019). Note that the quantifications of distant ecosystem service flow have made some progresses in different types of ecosystem services, such as biophysical flow (Watson et al., 2016; Lopez-Hoffman et al., 2017; Drakou et al., 2018; Hausmann et al., 2018). With respect to interregional flow of provisioning services, biophysical flows of traded goods has been a common approach as it is based on statistical data (Kleemann et al., 2020). Only a few very recent studies concentrating on the complex flow process of ecosystem services from one region to another region. For instance, Wang et al. (2020) incorporated the network theory and its network modelling into the visually mapping and the analysis into the process of evaluating freshwater flow in a Yanhe watershed within Loess Plateau. Vrebos et al. (2015) quantified the ecosystem services flow for data-scarce areas by scoring the land cover type. Xu et al. (2019a) detailed a flow path of freshwater services from upstream watersheds to downstream watersheds in a Lake Basin. Among these studies, Service Path Attribution (SPAN) model in the Artificial Intelligence for Ecosystem Services (ARIES) model (Bagstad et al., 2011), which is designed to characterize the ecosystem service flow, is now gaining attention with many scholars (Fang et al., 2015; Li et al., 2017; Qin et al., 2019). It provides a spatial framework for quantifying the flow and extracting its exact path (Johnson et al., 2012; Bagstad et al., 2013, 2014), making more comprehensive analysis on interregional flow of ecosystem services possible. Moreover, the spatial extent at which the interregional freshwater flow is assessed is relatively small, with usually only dozens of watersheds being considered. Hence studies of interregional flow of ecosystem services are really in need to answer the water security issues at large scales.

Northeast China is a base for production of crop, timber, and other industrial materials. Hence water security of the region is essential to the economic development and the stability of the whole country. Furthermore, in coping with the increasingly severe ecological issues, a national ecological security strategy named the “Two Barriers and Three Belts” strategy was established by the Chinese government according to its “13th Five-Year plan” (Wang et al., 2016b, 2019). “Northeast Forest Belt” (NFB), an important part of the ecological strategy, is a preliminary delineation that includes mainly forest land and grassland within northeast China (Yin et al., 2019). The huge demand for water resources and the general distinction between human society and natural ecosystems by policy make northeast China an appropriate research area, in terms of distant freshwater service flow and further assessment on water security condition. However, to our knowledge, relevant research is rarely done in northeast China. Thus, in this study, we attempt to evaluate the water security pattern and quantify the distant transboundary spatial flow of freshwater service in northeast China. The main objectives of this study are (1) to identify and map the provision, flow path and the consumption for freshwater services in northeast China; (2) to evaluate the water security condition and its main driving factors in northeast China; (3) to quantify the interregional flow of freshwater services coming from policy-related NFB to other regions.

2. Materials and methods

2.1. Study area

The study region is located in northeast China (38°43′-53°23′N, 118°50′-135°05′E), which covers Liaoning, Jilin, and Heilongjiang provinces, and the eastern area of Inner Mongolia Autonomous Region (Fig. 1). It encompasses 1.24×10^6 km^2 (approximately 97.6% of the land area within study region), ranges in elevation from 264 to 2509 m, and is partitioned into 3550 watersheds with an average area size of 100 km^2. With respect to climate, the region is in the high latitude East Asia monsoon zone, changing from warm temperate to cool temperate from east to west, with an annual mean temperature from 11.5 °C to −4 °C and an annual precipitation from 1100 mm to 250 mm (Tan et al., 2007).

NFB is a part of the administrative region of the whole northeast China, covering partial areas in Liaoning, Jilin and Heilongjiang provinces and Inner Mongolia Autonomous Region. It is located across Greater Khingan mountain, Xiaoxing’an mountain, and Changbai mountain range (Fig. 1). Land uses within NFB shows diverse composition and spatial patterns across the landscape. Woodlands dominate in regions including Greater Khingan mountain, Xiaoxing’an mountain and Changbai mountain range, while cultivated land and residential land are mainly distributed in the outside plain areas including Songneng plain, Liaohe plain, and Sanjiang plain.

In northeast China, with the rapid economy development, the imbalance between freshwater provision and consumption occurs causing water shortages happening. With the importance of northeast China in term of ecological significance and its current and future water consumption, a comprehensive study of the spatial flow of ecosystem services is important and urgent.

2.2. Data source

Nine different datasets were used in this research. (1) The land use and land cover dataset in 2005, 2010 and 2015 was obtained from the Resources and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) (Song et al., 2021). (2) The Digital Elevation Model data was provided by the Resources and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) (Xia et al., 2018). (3) The soil organic matter dataset was obtained from the second national soil data survey collection, and then interpolated using Inverse Distance Weighted (IDW) method (Wu et al., 2017). (4) The soil texture dataset was obtained from the Resources and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) (Wu et al., 2017). (5) the Vector data of the main roads network that characterizes the basic

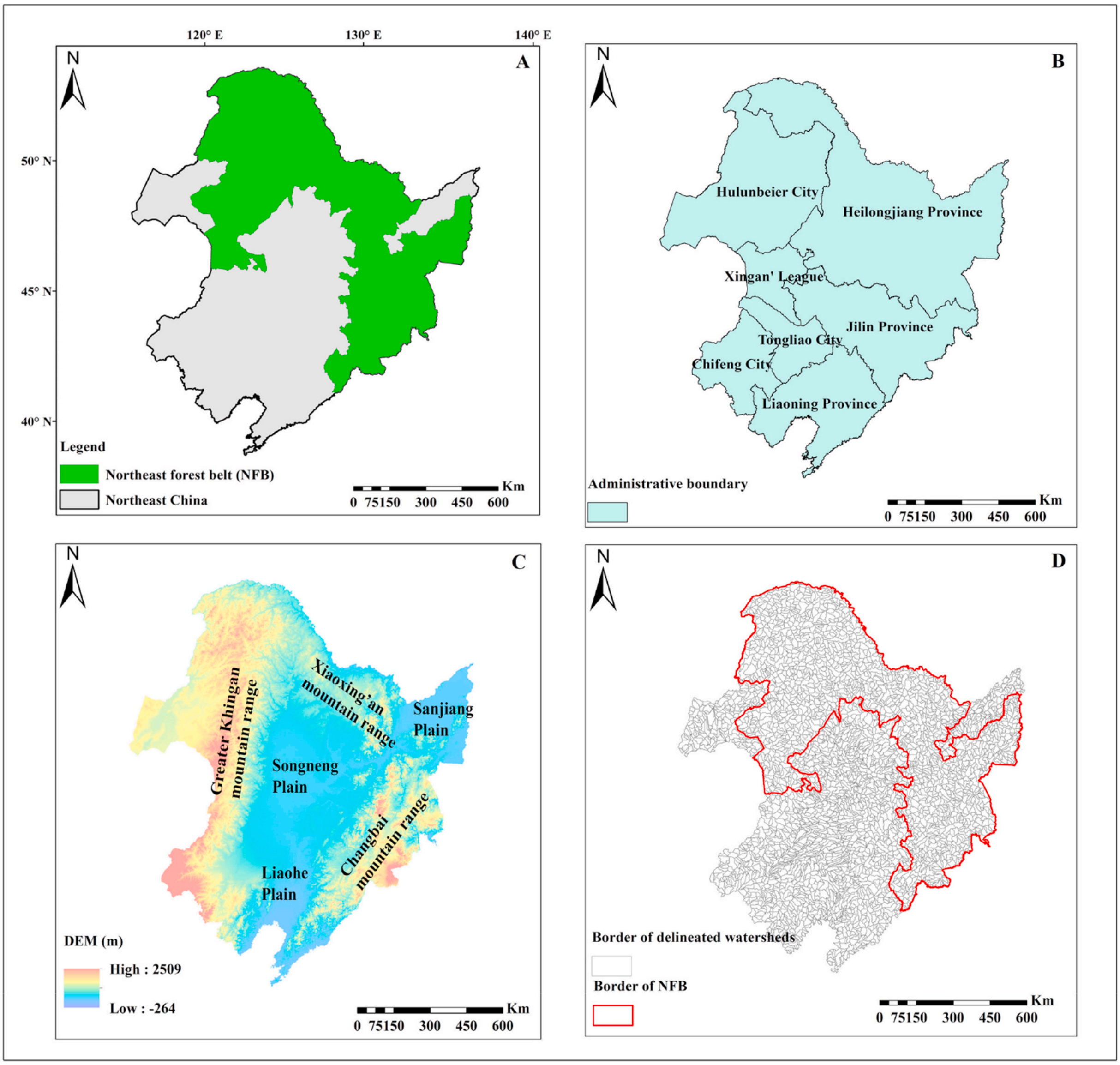


Fig. 1. The study area. (A. Geographical location. B. Administrative border. C. Subregion by landform. D. Subwatershed delineated by DEM.)

geographic information was derived from the National Basic Geographic Information System of China (http://nfgis.nsdi.gov.cn) (Dai et al., 2019). (6) The meteorological dataset was provided by the National Meteorological Information Center (http://data.cma.cn/), and then used interpolated using Inverse Distance Weighted (IDW) method (Wu et al., 2017). (7) The annual streamflow data was downloaded from the global consistent streamflow dataset named "FLO1K" (Barbarossa et al., 2018). (8) The statistical data were collected from local Water Resources Bulletin and Regional Statistical Yearbook, China's Economic and Social Development Database (http://data.cnki.net/YearData/Analysis) (Fu et al., 2020). (9) The livestock data in northeast China, including pig, sheep, chicken, and cattle, was collected from the global livestock distribution maps (Gilbert et al., 2018) and Regional Statistical Yearbook, China's Economic and Social Development Database (http://data.cnki.net/YearData/Analysis) (Fu et al., 2020). All the spatial data used in our research were unified to be 1 km resolution.

2.3. *The provision of freshwater service*

2.3.1. *InVEST model*

In this study, the amount of water yield was used as the freshwater provision service value and was calculated using the InVEST model (Qin et al., 2019). InVEST model is based on the Budyko curve (Budyko, 1974) and annual average precipitation with the equation as follows:

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

where Y_{xj} is the annual water yield of the research area on pixel x with land use/land cover (LULC) j at grid scale, AET_{xj} is the annual average evapotranspiration on pixel x with LULC j. P_x is the annual precipitation on pixel x. AET_{xj}/P_x, which is the evapotranspiration partition of the water balance, represents an appropriation of the Budyko curve proposed by Zhang et al. (2001):

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x + R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \tag{2}$$

where R_{xj} represents the dimensionless Budyko dryness on pixel x with LULC j and ω_x represents the ratio of plant accessible water storage to expected precipitation during the year (Budyko, 1974).

$$R_{xj} = \frac{k_c(l_x) ET_{0_x}}{P_x} \tag{3}$$

where ET_{0x} is the reference evapotranspiration on pixel x. k_c (l_x) represents the plant evapotranspiration coefficient for LULC j on pixel x.

$$\omega_x = Z\frac{AWC_x}{P_x} + 1.25 \tag{4}$$

where AWC_x is the volumetric plant available water content (in mm) on pixel x. Z factor is an empirical constant that is positively correlated with N, the number of rain events per year.

2.3.2. *Model calibration*

The simulated annual average water yield was compared to the observed data which were obtained from the global streamflow dataset FLO1K (Barbarossa et al., 2018). The annual simulated water yield at each watershed was the sum of water yield of all the grids within each sub-watershed. The annual observed data of water yield at each sub-watershed were extracted at the output point of each sub-watershed. Seasonality constant (Z) (Cong et al., 2020) was calibrated and manually changed within the referenced range of literature-related data, in order to obtain an optimized output (Sharp et al., 2014). The Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) and R^2 value (Song et al., 2011) were further computed to quantify the model accuracy.

2.4. *The consumption of freshwater service*

We estimated the anthropogenic demand based on freshwater consumption (Boithias et al., 2014). In northeast China, the water consumption can be characterized into four types: agricultural, industrial, livestock, and residential water consumption. The water consumption value on each pixel is calculated using the following equation:

$$WC_{ant} = WC_{agr} + WC_{ind} + WC_{liv} + WC_{res} \tag{5}$$

$$WC_{agr} = S_{agr} \times P_{agr} \tag{6}$$

$$WC_{ind} = G_{ind} \times P_{ind} \tag{7}$$

$$WC_{liv} = D_{chiken} \times P_{chicken} + D_{cattle} \times P_{cattle} + D_{goat} \times P_{goat} + D_{pig} \times P_{pig} \tag{8}$$

$$WC_{res} = D_{res} \times P_{res} \tag{9}$$

where WC_{ant} represent anthropogenic demand for freshwater. WC_{agr}, WC_{ind}, WC_{liv} and WC_{res} represent the water demand by agriculture, industry, livestock and residents, respectively. S_{agr} is the area of cropland on each pixel. P_{agr} is the annual average irrigation water consumption per hectare. G_{ind} denotes the gross industrial production on each pixel. P_{ind} denotes the annual average industrial water consumption per ten thousand GDP. $D_{chicken}$, D_{cattle}, D_{goat}, D_{pig} refer to the spatial distribution of the four main livestock (chicken, cattle, goat and pig, respectively) in northeast China. $P_{chicken}$, P_{cattle}, P_{goat} and P_{pig} refer to the annual average water consumption by chicken, cattle, goat and pig, respectively (Table 1). D_{res} is the population of residents on each pixel. P_{res} is the annual average water consumption by residents. P_{agr}, P_{ind} and P_{res} differed at a province or municipality level (Table 2).

2.5. *Routing the freshwater flow*

The dynamic freshwater services flow algorithm was based on the assumption that the remaining freshwater (if existed) all moves into its downstream grid after meeting the demands of local grids. In northeast China, the freshwater flow was quantitively simulated through four matrices with the same rows and columns representing 4 variables over the same geographic extent: water provision, water consumption, water flow direction and designated boundary (Fig. 2). Water provision referred to the total amount of water provided by each corresponding cell within a certain period (one year for this study). The water consumption indicates the water resources consumed by human society in each corresponding cell within one year. The static freshwater surplus was noted as the difference between provision and consumption. The geographical boundary of 3550 sub-watersheds were delineated based on the Digital Elevation Model. We further accumulated the static freshwater surplus along the flow direction in each sub-watershed, which captured the freshwater flow from upstream to downstream areas after satisfying the local demand. The process of freshwater services flow spatially were simulated in R 3.5.2 (https://www.rstudio.com/).

Table 1
Average daily water consumption for cattle, goat, pig and chicken.

Livestock	Water consumption	unit
Cattle	40.4	l/head/day
Goat	3	l/head/day
Pig	12	l/head/day
Chicken	400	l/1000head/day

It is important to point out that the water resources utilized by human activities includes both surface water and ground water (Ma et al., 2016). As reliable data of ground water sources in northeast China are not available, only surface water was considered in this research. Our dynamic algorithm which involves the main three steps is obviously different from the previous static ones.

2.6. *Calculation of water security index based on flow model*

Water security index (WSI), which is the ratio of freshwater service provision and consumption, is to serve as the metric linking ecosystem services and human demand. WSI is used in then study to represent the water scarcity condition. To compare the conventional static and dynamic water flow model, we calculate the WSI both with and without considering the amount of freshwater services coming from upstream. Both WSI results are then logarithmically transformed to facilitate their visualization and mutual comparison. Their calculation are as follows:

$$WSI_{static} = \log_{10}\left(\frac{S}{D}\right) \tag{10}$$

$$WSI_{flow} = \log_{10}\left(\frac{S+F}{D}\right) \tag{11}$$

where WSI_{static} and WSI_{flow} represent the static and dynamic water scarcity index respectively. Here, S is the amount of freshwater provision within a year at each pixel. D denotes the amount of freshwater consumed by human activities within a year at each pixel. F is the amount of freshwater coming from upstream for each pixel within a year (if surplus exists). Hence, the interpretations of WSI are as follows: WSI value greater than 1 means the freshwater resources are pretty sufficient; WSI value greater than 0 and less than 1 means the supply surpasses the demand slightly; WSI value great than -1 and less than 0 denotes the supply does not quite meet the demand; WSI value less than -1 denotes the supply is far from meeting the demand.

3. Results

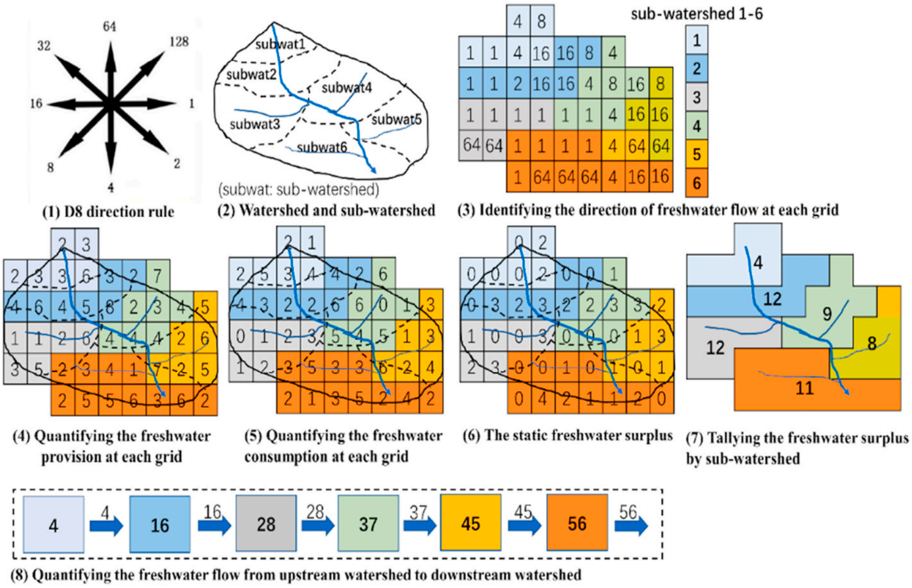
3.1. *The provision and consumption of freshwater service*

When Z equaled to 19.79, the normalized square of error between simulated and observed value equaled to 4437.8 across the whole 3138 watersheds (watersheds containing nodata were removed during calibration). The freshwater service provision was further predicted by InVEST model with Nash-Sutcliffe efficiency coefficient (NSE) of 0.57 and R^2 of 0.80 respectively during calibration, indicating good performance of InVEST model.

The freshwater service provision in northeast China showed

Table 2
Average annual water consumption for agriculture, residents, and industry in different provinces or municipalities in 2005, 2010 and 2015.

	2005			2010			2015		
	Agr (m^3/hectare)	Dom (m^3/person)	Ind (m^3/10^4GDP)	Agr (m^3/hectare)	Dom (m^3/person)	Ind (m3/10^4GDP)	Agr (m^3/hecture)	Dom (m^3/person)	Ind (m^3/10^4GDP)
Heilongjiang	7113	40.39	186.59	6421	55.31	102.22	5479	42.52	49.68
Jilin	3937	35.86	118.86	4522	42.99	59.11	4676	46.56	32.99
Liaoning	5497	51.45	53.22	5554	51.06	24.07	4736	57.00	16.40
Hulunbeier	3176	25.91	164.80	2632	38.98	69.22	1802	42.28	41.35
Xing'an League	3970	28.75	225.27	3304	25.46	100.36	3180	29.39	44.22
Tongliao	4580	27.14	135.76	3393	44.31	32.93	3157	45.50	26.14
Chifeng	4015	22.53	95.20	2714	46.53	37.36	2910	42.33	22.88



(1) D8 direction rule

(2) Watershed and sub-watershed

(3) Identifying the direction of freshwater flow at each grid

(4) Quantifying the freshwater provision at each grid

(5) Quantifying the freshwater consumption at each grid

(6) The static freshwater surplus

(7) Tallying the freshwater surplus by sub-watershed

(8) Quantifying the freshwater flow from upstream watershed to downstream watershed

Fig. 2. Schematic of the water flow algorithm.

significant spatial variations as well as substantial year-to-year changes (Fig. 3a). The average annual provision values of each grid in 2005, 2010 and 2015 were 16.3 $\times 10^4$ m^3, 20.7$\times 10^4$ m^3, 16.1 $\times 10^4$ m^3, respectively. In all three years, provision of freshwater service in the mountainous areas of eastern Liaoning province was the highest, followed by those in a portion of the Xiaoxing 'an mountain range. On the other hand, the provision in the west of the study region was always the lowest. Correlation analysis showed a strong positive association between water provision and precipitation in 2005($r = 0.796$), 2010($r = 0.762$) and 2015 ($r = 0.643$).

The consumption for freshwater service showed a similar spatial pattern with moderate year-to-year variation (Fig. 3b). The average annual consumption for freshwater services in 2005, 2010 and 2015 were 9.4 $\times 10^4$ m^3, 8.5$\times 10^4$ m^3, 9.5 $\times 10^4$ m^3, respectively. In three years, areas with high freshwater consumption were mainly located in two regions – the Sanjiang plain near the northeastern edge and the Northeast plain in the middle and southern area of the study region.

3.2. Flow pattern of freshwater provision service

The natural flow of freshwater services in the year 2005, 2010 and 2015, were shown in Fig. 4a and b, respectively. In general, large area (50.54%, 55.10% and 52.90%, respectively) of the whole northeast China received the freshwater services from their upstream areas which provided the surplus service after consumption to the downstream areas. They were mainly located in the northeast forest belt region as well as the south and southwest areas of the study region. However, fragmentation was also obvious in the middle and northeast of the study region. In particular in 2010, no-surplus areas existed in not only the whole northeast plain, but also some mountainous areas that were located within the northeast forest belt region. It suggests no downstream water flow in these areas due to the failure of water provision meeting the demand of water consumption.

3.3. Pattern of water security condition in northeast China

The water security index in three years were calculated with and without taking into account the upstream effects to evaluate the water security condition in northeast China and their temporal and spatial patterns were shown in Fig. 5a and b, respectively. The index was classified into four categories based on its values (<-1, −1–0, 0–1 and > 1) with a higher value representing a more secure condition. The average value of WSI_{flow} in 2005, 2010, and 2015 were 3.41, 3.32, and 3.17, respectively. In these three years, WSI_{flow} exhibited a similar overall spatial pattern, in which the values within northeast forest belt were higher than these outside the northeast forest belt were, along with some local differences of the unsecure areas. For example, the Songnen plain was always under the unsecure condition of freshwater services with $-1 < WSI_{flow} < 0$ in all three years. Meanwhile, freshwater condition in Liaohe plain became worse gradually with the water secure level changing from high ($WSI_{flow} > 1$) to low ($-1 < WSI_{flow} < 0$) over three years. Especially in 2005 and 2010, WSI_{flow} of some small areas, including areas near southern edge of northeast forest belt and in the west of Hulunbeier plateau had very low values of WSI_{flow} (i.e., WSI_{flow}

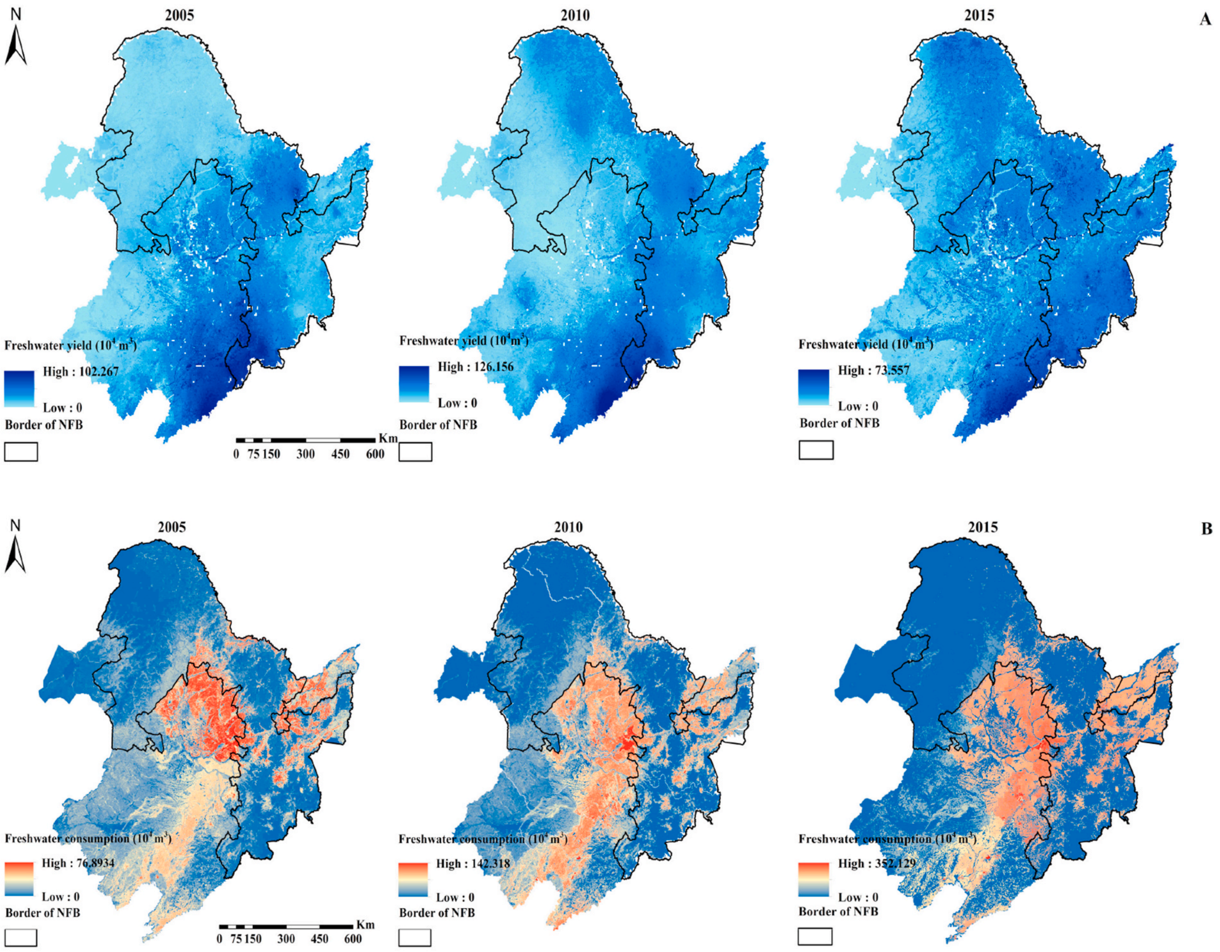


Fig. 3. The provision and consumption of freshwater service in northeast China in 2005, 2010 and 2015. (A. Freshwater provision. B. Freshwater consumption.)

< -1) which indicates the freshwater services at these areas were severely insecure.

The overall spatial distribution of WSI_{static} without considering the upstream effect was different compared to that of WSI_{flow} in these three years (Fig. 5a, b and 5c). Although the average value of WSI_{static} in northeast forest belt was still higher overall, the areas with different levels of water secure condition changed dramatically both within and outside the northeast forest belt. The areas in which WSI values increased for at least one level from static to dynamic status within northeast forest belt was 143.66×10^3, 106.38×10^3, 48.55×10^3 km^2, respectively, while the areas of the same situation but outside the northeast forest belt are 125.27×10^3, 149.14×10^3, 115.86×10^3 km^2, respectively (Table S1). It indicates an enhancement of the water security condition due to the flow of freshwater service from upstream.

3.4. Flow of freshwater service from NFB to other regions

The Strahler order stream and the connecting watersheds that connect the provision systems of freshwater services within NFB to the receiving systems outside the NFB and the spatial flow pattern of freshwater service were shown in Fig. 6a. There were 6923 streams, which were divided into 6 levels and 151 connecting watersheds in the whole study region. Overall, freshwater services (what remained after consumed locally) flowed from watersheds within NFB to those outside the NFB along different levels of channels. Specifically, services in Greater Khingan mountain range, Xiaoxing'an mountain range and Changbai mountain range flowed to connecting watersheds near the boundary of NFB along the low levels of channels (mainly 1st, 2nd and 3rd level), then flowed from connecting watersheds outside NFB along higher levels of channels (mainly 4th, 5th and 6th level) to Plain areas like Songnen Plain, Liaohe Plain and Sanjiang Plain, mainly for agricultural, industrial, livestock and domestic uses.

The amount of surplus freshwater services flowing from NFB to other areas in 2015 was quantified and shown in Fig. 6a and Table S2. In total, approximately 4.16 billion cubic meters of freshwater services flowed from provision systems in NFB to receiving systems outside NFB through different levels of stream system. The amount of freshwater provision coming from Greater Khingan mountain range is more than those from Xiaoxing'an mountain range and Changbai mountain range. In order to improve the protection efficiency under limited conditions, key watersheds that significantly affect the service provision were further identified (Fig. 6b). In total, 689 upstream watersheds were located in the upper reach of these connecting watersheds with a total area of 23.9×10^4 km^2, among which the water provision level of 73 watersheds is higher than 3. The total area of these key watersheds is 3.16×10^4 km^2, accounting for approximately 4.74% of the total area of NFB. They are mainly located in Greater Khingan mountain range and Xiaoxing'an mountain range, urging the importance of the protection towards ecosystems within these regions.

4. Discussion

By analyzing the flow of freshwater service with a comprehensive model, our study has provided valuable insights on the relationship between freshwater service provision and consumption in northeast China. Results of the regional flow of freshwater services emphasize the importance of the Northeast forest belt with regard to the provision of freshwater service to the receiving systems outside the northeast forest

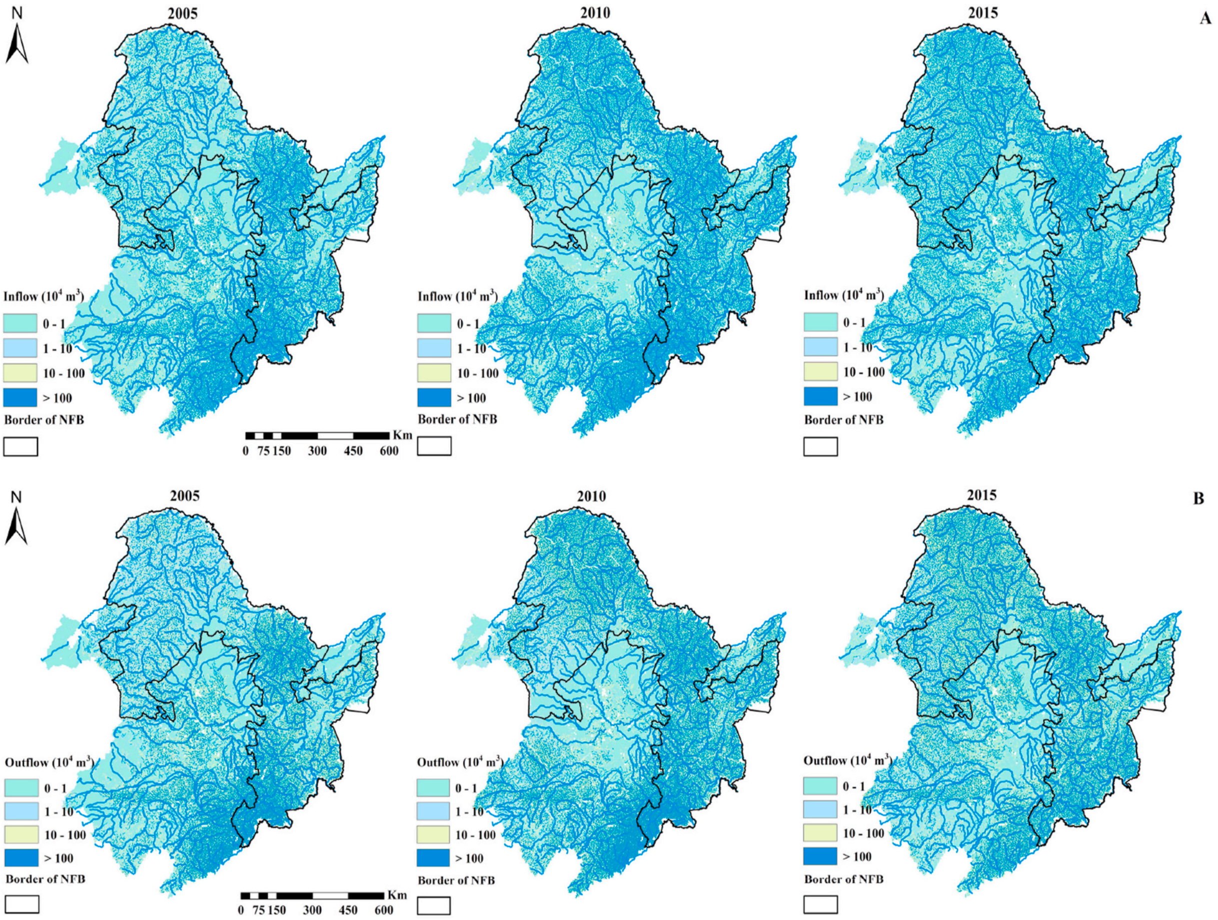


Fig. 4. The spatial flow of freshwater services in northeast China in 2005, 2010 and 2015. (A. inflow. B. outflow).

belt.

4.1. The analysis for supply-demand relationship of freshwater services

We have found a clear spatial misalliance between ecosystem services and consumption in northeast China. On one hand, the provision of freshwater services varies greatly both in terms of space and time. On the other hand, the consumption for services exhibits a similar spatial pattern over the three years of 2005, 2010, and 2015. Note that this spatiotemporally mismatch between provision and consumption is consistent with some previous studies on ecosystem services assessment (Burkhard et al., 2012; Boithias et al., 2014). For provision, the uneven distribution of freshwater services in northeast China may be attributed to varying climatic factors such as precipitation, whereas the consumption for services is mainly determined by the structure of water resources utilization, which to large extent results from water use policy. Therefore, we suggest that more attention should be paid to water-related policies, for it could rather easily manage and control human activities compared to intervening the provision of water resources in northeast China. This aspect has been suggested by other scholars in other study regions (Curran and de Sherbinin, 2004; Boithias et al., 2014; Li et al., 2017). Unlike some other provisioning services, freshwater services are not confined in the same area where it is created. Thus, the quantification of freshwater services flow is an important part, when considering the service provision and consumption relationships (Koellner et al., 2018). as such the flow model used in this study was able to quantify the freshwater services receiving from upstream areas (inflow) and delivering to the downstream areas (outflow) given freshwater service provision and consumption records. The result shows that most areas, except for substantial plain areas in northeast China, receive freshwater services from upstream areas and deliver them to their downstream areas in all three distinctive years. This result demonstrates the typical flowing characteristics of freshwater service. Our result is similar to a case study conducted in Beijing–Tianjin–Hebei Region which quantify the freshwater services flowing from mountainous areas to plain areas in north China (Li et al., 2017).

Having an appropriate metric of water security condition that reflects a more realistic supply and demand relationship is essential. Previous studies often used the ratio of supply to actual demand for ecosystem service to reflect their relationship on a static state. Such static measure on water security condition overlooked the spatial flow of ecosystem services. As a consequence, such static measures have limitations when applied to large study areas (Zhang et al., 2021). In that context, the metric used to represent the water security condition, WSI which is the ratio of maximal potential provisioning to actual use of freshwater services (Vorosmarty et al., 2000; Boithias et al., 2014), is arguably more suitable. With respect to other studies which used static models (Anand et al., 2018; Meisch et al., 2019), the main difference of employing a dynamic model mainly lies in understanding and obtaining the maximal potential provision of the services, within a certain space and time. Conceptually, this value is comprised of two parts: local provision and local surplus flowing from upstream areas, thus representing a more realistic condition as the effect of benefits from upstream areas is considered. In our study, WSI_{flow} confirms that water security condition has an overall regularity with some local differences among three different years (Fig. 5b). Notably, the water security condition in the plain areas at lower altitude is lower than that those in mountainous areas, implying a less sustainable provision-consumption relationship in these areas (Li et al., 2017). This can be attributed to the differences of provision as well as that of water utilization structure between plain

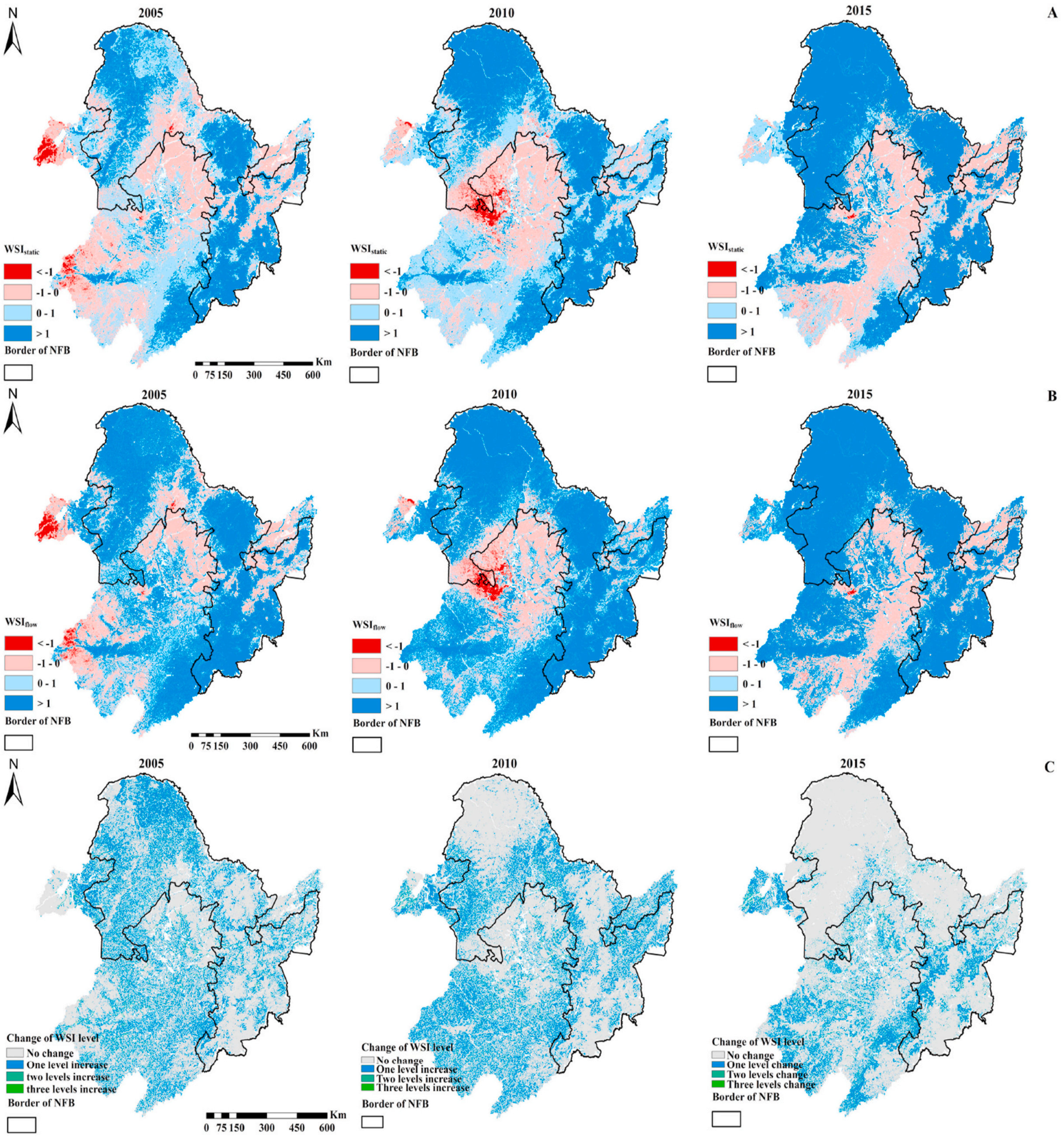


Fig. 5. A. The water security index without and B. with considering the water flow (WSI$_{static}$ and WSI$_{flow}$) in 2005, 2010 and 2015. C. The change of water security index (WSI) from conventional static model to dynamic flow model in 2005, 2010 and 2015.

areas, where populations are concentrated, and other areas, where natural or semi-natural ecosystems are located. Furthermore, extreme insecure conditions occur in some specific areas in 2005 and 2010 (Fig. 4b) indicating the inability for these areas to cope with potential climate-induced imbalance between provision and consumption. Our result urges the investigation on the water secure condition under different climate change scenarios in northeast China, and thus puts forward response plans supporting the implementation of policy on freshwater security.

4.2. Spatial analysis to identify driving factors of WSI

Regional water security is a complex issue involving freshwater services provision, flow and consumption. Furthermore, social, economic, climatic, and other factors can influence the spatial pattern of WSI, and identifying such factors can help provide a stronger support for the government decision makers in terms of improving the water security condition. Therefore, in our study, several key factors of regional water security index were selected and analyzed from the perspective of water provision, water consumption, social and economic dimension in northeast China across all three different years using geographic detector (Wang et al., 2010, 2016a; Zhang et al., 2021).

The influence of different factors was analyzed both within and outside the NFB respectively using *q* statistics, and the result is exhibited in Table 3. Within NFB, the explanatory power of agriculture water consumption and precipitation to sub-watershed WSI was much stronger than other influencing factors. This indicated that the spatial pattern of water security condition is mainly determined by climate on the supply side while agriculture on the demand side within NFB. From 2005 to 2015, The explanatory power of livestock water consumption to sub-

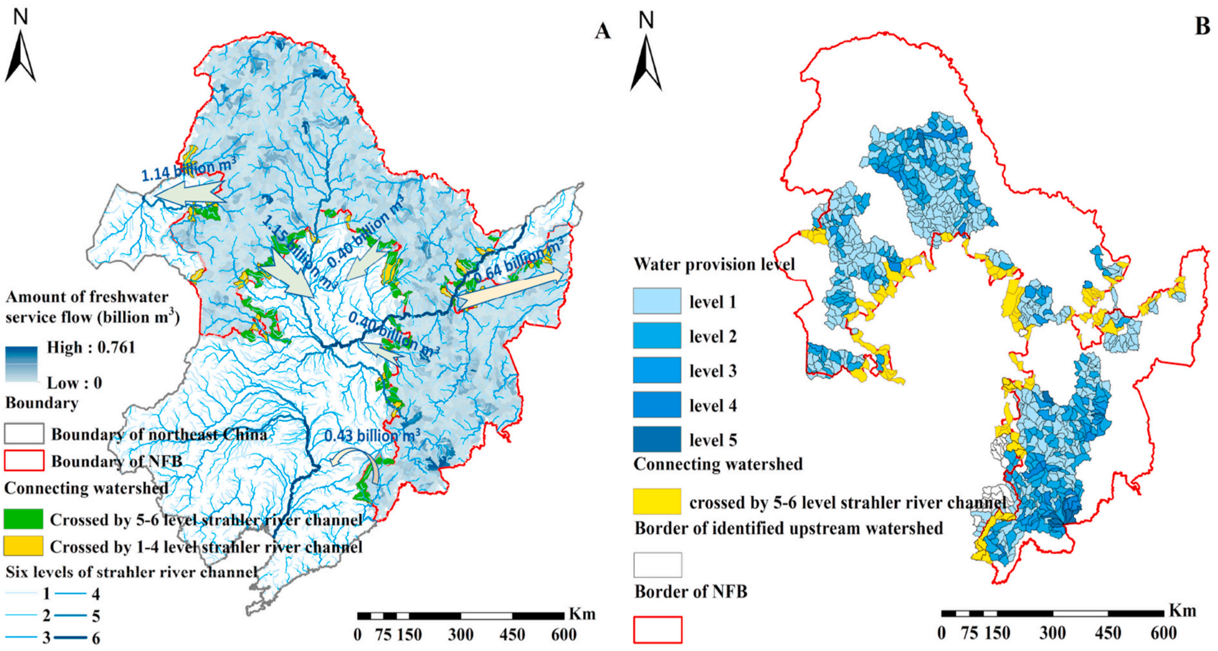


Fig. 6. A. The trans-boundary flow of freshwater services from NBF to other regions in 2015 and B. the position of the key upstream watersheds within NFB affecting the trans-boundary flow. (The green arrow shows the main direction of freshwater service flow from NFB to surrounding areas and its size indicates the amount of freshwater service that is transferred.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Risk factor detection results.

	Inside the NFB			Outside the NFB		
	2005	2010	2015	2005	2010	2015
Precipitation	0.1225	0.1359	0.0267	0.1775	0.1001	0.0109
Agriculture water consumption	0.1758	0.3057	0.3492	0.0078	0.0410	0.0217
Industrial water consumption	0.0017	0.0090	0.0060	0.0008	0.0175	0.0039
Domestic water consumption	0.0108	0.0006	0.0003	0.0013	0.0005	0.0031
Livestock water consumption	0.0108	0.0370	0.2901	0.0013	0.0638	0.0513
Population Density	0.0149	0.0002	0.0003	0.0040	0.0007	0.0018
GDP Density	0.0002	0.0003	0.0003	0.0049	0.0094	0.0013

watershed WSI increased significantly, showing that its influence increase obviously in recent years. Thus, for decision makers who regulate water resources, more attention should be put on livestock and related water consumption within NFB in the future, besides mere agriculture. Outside the NFB, the *q* statistic of different influencing factors is more even, especially in 2015. The explanatory power of precipitation and agriculture to sub-watershed WSI is still higher than other influencing factors, but such influence is gradually decreasing. It needs to be pointed out that the influence of livestock water consumption on sub-watershed WSI outside the NFB also increased gradually, with the *q* statistic value ranking increased from 2005 to 2010. In brief, climatic and agricultural factors were the two main determinants to the spatial pattern of regional WSI in northeast China, but their influence is decreasing outside the NFB, compared to that within NFB. Furthermore, the influence of Livestock water consumption increases gradually both within and outside the NFB in the recent years. These results are partly consistent with a previous published study, which showed that the agricultural use is the main determinant of regional WSI in Weihe river basin in China (Zhang et al., 2021).

At the regional scale, the regulation and policy making should be centered around the demand side, due to the difficulty to control the climate factors on the provision side (Boithias et al., 2014). Within NFB, government decision makers should focus on improving the agriculture and livestock water quotas. We suggest that land-use adjustment policies should be made and advanced especially near the boundary of NFB, and in particular the cropland should be conversed back to forestland or grassland gradually. Outside the NFB, a more comprehensive freshwater saving policy considering varying influencing factors should be put forward. given the decreasing trend of the agriculture influence on the demand side. Policies regarding land-use allocation for different freshwater usage should be made based on a more scientific trade-off analysis. Moreover, new water saving technology could be brought into realistic production of agricultural products and industrial products to improve the efficiency of freshwater use. For urban region where residents were densely concentrated, we also recommend adjusting water-pricing and thus managing the urban water quotas to resist the possible severe risk of water shortage occurring in the future.

4.3. The importance of quantifying the trans-boundary flow of ecosystem services

In a meta-coupled social-ecological system, trans-boundary ecosystem services flow has become more common and essential to the bond between human and society (Liu et al., 2016). Our result demonstrated the importance of NFB as a source of freshwater services provision (nature) to other receiving systems (human) for the whole northeast China and the necessity to implement national ecological protecting policy for ecosystems within NFB, from the perspective of ecosystem service provision. Many studies of trans-boundary ecosystem services flow have been conducted previously. For instance, Xu et al. (2019b) assessed the flow of virtual material and financial capital across different countries and analyzed the effect of such flow crossing administrative boundary. Kleemann et al. (2020) employed a conceptual framework and quantified the multi-ecosystem services flowing outside Germany (Kleemann et al., 2020). However, few has applied the quantification of the flow from the policy-related ecological security barrier to the surrounding regions. Taking China as an example, although many environmental policies (e.g., the nature reserve policy, the afforestation policy, and the zoning policy) have been enacted, rigorous target on environmental outcomes is still lacking (Bai et al., 2016). This leads to not being able to recognize the existence of such ecological security barrier. Therefore, quantification of ecosystem services flow from NFB can provide future support for coping with the freshwater issues in northeast China.

Besides the trans-boundary flow at the regional scale, our study also provided valuable information of freshwater services flow across hydrological watershed boundary based on the flow model, which is a progress compared to previous studies (Li et al., 2017; Liu et al., 2020). Information of the flow of freshwater services across upstream and downstream watersheds is a prerequisite for pricing the value of service flow, and thus it can promote local ecological compensation programs (Grizzetti et al., 2016). Ecological compensation is a term commonly used to describe the payments for ecosystem services in China. Relevant studies of ecological compensation have been conducted in some regions to cope with the conflicts between resources providers and users in northeast China. For example, a total amount of 3.2 million dollars of willingness-to-pay for the eco-compensation were estimated in the upper reach of Hun River Basin (Jiang et al., 2019). However, in many cases, the calculation of economic value usually lacks the support coming from upstream watershed, which produces inaccuracy. Therefore, our trans-boundary flow algorithm of freshwater service also can be applied on promoting local ecological compensation programs in northeast China.

4.4. Limitations and future study

While providing valuable information on freshwater provision, flow and consumption in the study area and having demonstrated the necessity to involve the freshwater flow into the water security assessment in northeast China, the study still has several limitations. First, we used a simple algorithm based on the Digital Elevation model for simulating passive spatial flow of freshwater services. This algorithm neglects the loss of water resources in the process of lateral transmission and only takes into account the natural flow of freshwater services that are not regulated by human infrastructure including dams and reservoirs. This might cause bias in the quantification of freshwater services flow. Second, for the demand, we collected and quantified the data related to the freshwater consumption at a relatively large spatial scale due to the limited data availability. This may lead to an inaccuracy of the provision and consumption relationship in some local regions.

5. Conclusion

A simplified dynamic model that incorporated the freshwater service flow was applicated on assessing the water security condition and further quantifying the freshwater transboundary flow at the watershed level in northeast China. Our study demonstrated the importance of NFB to northeast China as a source of ecosystem service provision. We found an increase in water security condition of northeast China due to the spatial flow of freshwater service in 2005, 2010 and 2015. Result of geographic detector analysis showed that climate and agriculture water consumption were the two determinants influencing the water security condition both within and outside the NFB, whereas such influence is decreasing outsider the NFB. In particular, the influence of livestock water consumption increasing gradually should be brought to public notice. Therefore, it is necessary to promote the policies of quotas for agriculture and livestock water consumption to avoid the risk of water shortage in northeast China. Furthermore, spatial pattern of freshwater services flow at the watershed level in the study region can be used to support local ecological compensation programs in the future.

Credit author contribution statement

Qi Zhu: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing. **Liem T. Tran:** Validation, Writing – review & editing. **Yan Wang:** Methodology, Software. **Lin Qi:** Methodology, Supervision. **Wangming Zhou:** Methodology, Supervision. **Li Zhou:** Funding acquisition. **Dapao Yu:** Supervision, Project administration, Funding acquisition. **Limin Dai:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.114318.

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