Postprint: Impacts of Production-Living-Ecological Space Reconstruction and Precipitation Change on Water Yield Services in the Shanxi Yellow River Basin

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Abstract

The Yellow River Basin in Shanxi Province is a crucial energy and chemical industry base in China, which has been confronting severe challenges of soil erosion and water scarcity in recent years. Investigating the water yield service in this region can provide decision-making support for the high-quality development of energy and chemical industrial zones within the Yellow River Basin. This study employs the InVEST model and scenario simulation method to analyze the impacts of "production-living-ecological" space restructuring and precipitation variation on watershed water yield services from 2000 to 2020. The results reveal that the "production-living-ecological" space in the Shanxi Yellow River Basin exhibits an overall spatial pattern of ecological > production > living, with a slight decrease in ecological space area, significant reduction in agricultural production land, and notable increases in industrial and mining production, urban living, and rural living land areas. The average water yield in the basin was 89.57 mm in 2000 and 138.01 mm in 2020, demonstrating an upward trend during 2000–2020. Scenario-based analyses indicate that precipitation change contributed 80.4% to the variation in water yield, while "production-living-ecological" space change contributed 19.6%.

Full Text

Abstract

The Yellow River Basin in Shanxi Province is an important energy and chemical industry base in China that has faced severe soil erosion and water shortage issues in recent years. Studying water yield services in this region can provide decision-making support for the high-quality development of energy and chemical industrial zones in the Yellow River Basin. Based on the InVEST model and scenario simulation method, this paper analyzes the impacts of "production-living-ecology" space transformation and precipitation changes on watershed water yield services from 2000 to 2020. The results show that the "production-living-ecology" space in the Yellow River Basin of Shanxi Province follows an overall pattern of ecology > production > living. Ecological space area decreased slightly, agricultural production land contracted significantly, while industrial/mining production land and urban/rural living land areas increased substantially. The average water yield in the Yellow River Basin of Shanxi was 89.57 mm in 2000 and 138.01 mm in 2020, indicating an increase in water yield over this period. Scenario analysis reveals that precipitation change contributed 80.4% to water yield variation, while "production-living-ecology" space change contributed 19.6%.

Keywords: production-living-ecology space; water yield service; Yellow River Basin; Shanxi

Introduction

Ecosystem services refer to the benefits that humans obtain from ecosystems and represent a hot topic in ecology and related disciplines [1]. Water yield service is a crucial ecosystem service with both provisioning and regulating functions, primarily indicating the capacity of precipitation to effectively convert into surface runoff, soil water, and groundwater. As a bridge connecting natural ecosystems and socio-economic systems in watersheds, water yield service plays a vital role in watershed water cycling, sediment export, and numerous other ecological functions, as well as in human survival and development [2]. With the expansion of human water demand and the emergence of water pollution and waste, water shortage has become prominent in some regions [3], limiting sustainable economic and social development. In this context, studying ecosystem water yield services is significant for industrial and mining production, social life, agricultural irrigation, and water resource management and development.

Current research on water yield services mainly focuses on regional water yield quantity, water conservation capacity, spatial-temporal patterns of water resource supply and demand, trade-off and synergy relationships, hydrological process simulation, water ecological footprint, and service spatial flow [4-6]. Wei et al. [7] conducted a temporal and spatial analysis of water yield in the upper Shule River basin; Wang et al. [8] examined the trade-offs between water conservation and other services in the Loess Plateau ecosystem; Zhang [9] simulated hydrological processes and ecological water demand in the Jinghe River basin; and Jia et al. [10] studied the temporal and spatial variation characteristics and driving factors of water resources ecological footprint in Shanxi Province. These studies have thoroughly explored water yield services from various perspectives, demonstrating that water yield service is influenced by the combined effects of climate change and land cover change. Climate change affects water yield by altering regional precipitation, temperature, and evapotranspiration

[11]. For instance, Dai et al. [12] used the InVEST model to evaluate water yield services and concluded that climate is the main cause of spatial differences in water yield services. Land use change may affect water volume, nutrient concentration, and sediment load by changing infiltration and evapotranspiration rates. Bao et al. [13] found that land use changes under the Grain for Green Program significantly impacted water conservation in the Loess Plateau of northern Shaanxi. Shirmohammadi et al. [14] simulated future climate and land use changes and assessed their impacts on water yield in a semi-arid forest watershed in Iran. These studies all indicate that water yield services are affected by both factors, but quantitative assessment of the impacts of climate change and land use/cover change on water yield services remains insufficient.

Since the concept of land use change was proposed, research methods and theories have continuously developed [15]. Among them, research on "production-living-ecology" space transformation based on land function perspectives represents a new direction for comprehensive studies [16]. This approach primarily achieves transformation among production, ecological, and living space types [17]. The 18th National Congress of the Communist Party of China proposed constructing "production-living-ecology" space with "intensive and efficient production space, livable and moderate living space, and beautiful ecological space" [18], which aligns with the internationally recognized "three pillars" concept of sustainable development [19]. This spatial classification method creates new pathways for studying land function transformation and its impacts on natural ecosystems from the perspective of structural and functional changes in "production-living-ecology" space. Su et al. [20] conducted multi-scenario simulation predictions for ecological space in the Fen River basin; Si [21] studied the transformation of "production-living-ecology" land use and its eco-environmental effects in the Central Plains urban agglomeration; Hua et al. [22] examined changes in "production-living-ecology" land and ecosystem service values in Yuanzhou District of Guyuan City; Gou et al. [23] studied the ecosystem service value effects of land use transformation in the Three Gorges Reservoir Area from a "production-living-ecology" perspective; and Wang [24] conducted research on optimizing "production-living-ecology" spatial patterns based on ecosystem service values. These studies have focused on "production-living-ecology" land prediction, transformation, or the impact of "production-living-ecology" space on ecosystem service values, but insufficient attention has been paid to studying how "production-living-ecology" spatial reconstruction affects changes in ecosystem service quality. Researching the impact of land use change on ecosystem services from the "production-living-ecology" space perspective can provide references for regional spatial planning.

The Yellow River Basin has a complex geographical environment and fragile ecological conditions, making it sensitive to human activities and climate change [25]. In recent years, due to its important ecological role, the Yellow River Basin has attracted national attention [26]. As a major energy and chemical industry base in China, the Yellow River Basin in Shanxi Province has long faced water shortage as a limiting factor for development, along with ecological environment deterioration and other issues. Studying the current status of water yield services and the impacts of precipitation changes and "production-living-ecology" space transformation can provide an important theoretical basis for scientific planning and management of land spatial resources and maintaining stable water supply functions in this watershed. This paper uses the InVEST model to analyze the temporal and spatial variation characteristics of water yield in the Yellow River Basin of Shanxi, and explores the impacts of "production-living-ecology" space transformation and precipitation changes on water yield services, aiming to provide theoretical references for formulating ecological protection policies in the Yellow River Basin of Shanxi.

1 Study Area Overview

The Yellow River enters Shanxi at Laoniuwan, flows through the province along its western and southern sides, and exits at Nianpangou. The Yellow River Basin in Shanxi is located in western and southern Shanxi (34°59 ~40°29 N, 110°24 ~113°54 E), covering more than half of the province' s area (Fig. 1) [Figure 1: see original paper]. The total area is 97,138 km^2. The terrain shows obvious undulating changes, with various landforms including mountains, hills, and basins. The topography decreases from northeast to southwest, with mountains and hills dominating the northeast and basins in the southwest. The basin has a continental climate with distinct seasons and concurrent rainfall and heat. Influenced by latitudinal differences and terrain conditions, the temperature gradually increases from north to south and from mountains to basins. Located in the eastern Loess Plateau, the basin' s soil is mainly composed of loess and sandy soil, with poor fertility that is highly susceptible to erosion during heavy rainstorms. Severe soil erosion, poor ecological conditions, and water shortage are major limiting factors for ecological protection and high-quality development in this region.

2 Data and Methods

2.1 Data Sources and Processing

Land use data for the Yellow River Basin in Shanxi for 2000 and 2020 were obtained from the Resources and Environmental Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), with classification accuracy exceeding 90% for each land use type. DEM data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn/); meteorological data were sourced from the National Meteorological Science Data Center (http://data.cma.cn); and soil data were obtained from the Cold and Arid Regions Science Data Center of the Chinese Academy of Sciences (http://www.ncdc.ac.cn/portal/). The data were extracted, interpolated, and clipped using ArcGIS to obtain the required datasets.

When classifying "production-living-ecology" space, land natural attributes served as the primary reference. Following existing classification schemes [27], the basic land data were divided into 3 primary categories and 8 secondary categories (Table 1) .

2.2.1 Land Use Transfer Matrix

The land use transfer matrix uses matrix methods to describe the conversion area of each land use type from the beginning to the end of the study period [28], providing the theoretical foundation for studying land use change directions and quantitative classifications. It can also reveal specific changes in land function transfers. The calculation formula is as follows:

where S, a, b, and n represent land area, land use type at the beginning of the study, land use type at the end of the study, and the number of land use types, respectively.

2.2.2 Water Yield Model

Water yield per unit area refers to the volume of water produced per unit area within a certain time period in a given region, playing a significant role in climate regulation and water resource supply [29]. Early water yield assessments primarily focused on quantitative and statistical analyses. With the continuous development of multi-factor comprehensive analysis models, the InVEST model has achieved spatial expression of water yield and is most widely applied [30]. The InVEST water yield module estimates water supply capacity based on the Budyko water-heat coupling balance [31], with the calculation formula:

where: the annual water yield per grid cell x (Y(x)) is calculated from annual precipitation (P(x)) and actual evapotranspiration (AET(x)); PET(x) is potential evapotranspiration; and ω(x) is a non-physical parameter representing natural climate-vegetation characteristics.

2.2.3 Scenario Simulation Method

The scenario simulation method was used to simulate the impacts of precipitation changes and "production-living-ecology" space changes on water yield in the Yellow River Basin of Shanxi from 2000 to 2020 (Table 2) . The simulation included: Scenario 1, where precipitation in 2020 remained unchanged from 2000 and only "production-living-ecology" space changed, to study the impact of spatial transformation on water yield compared to the 2000 baseline; and Scenario 2, where "production-living-ecology" space in 2020 remained unchanged from 2000 and only precipitation changed, to study the impact of precipitation changes on water yield compared to the 2000 baseline.

The contribution of precipitation and "production-living-ecology" space changes to watershed water yield variation was quantified using the following formulas [32]:

where Wl and Wp represent the contribution rates of "production-living-ecology" space transformation and precipitation change to water yield variation in the study area, respectively; and ΔWl and ΔWp represent water yield changes under these two scenarios.

3 Results and Analysis

3.1 Characteristics of "Production-Living-Ecology" Space Land Use Transition

Based on the "production-living-ecology" space classification scheme, the spatial distribution of land use in the Yellow River Basin of Shanxi was obtained for 2000 and 2020 (Fig. 2) [Figure 2: see original paper]. Spatially, ecological space was the dominant land use type, followed by production space, with living space accounting for only a small portion of the watershed. Among secondary categories, forest ecological land, grassland ecological land, and agricultural production land were most widely distributed. Forest ecological land was mainly distributed in the Lüliang Mountains in central Shanxi, the Taiyue Mountains in central-eastern Shanxi, and the Zhongtiao Mountains in southern Shanxi. Grassland ecological land was primarily located in the western part of the basin. Water ecological land was sporadically distributed in the Taiyuan, Linfen, and Yuncheng basins. Production space was mainly distributed in the Taiyuan, Linfen, and Yuncheng basins. The distribution of living space was roughly consistent with production space, as human production and living activities are closely interdependent, resulting in similar spatial patterns of their land use types.

In terms of area changes, both ecological and production spaces decreased slightly, with ecological space decreasing by 2.67% and production space by 0.97% compared to 2000. Living space showed an opposite trend, with urban and rural living land increasing by 110.5% and 49.3%, respectively. The two types of land in production space showed opposite change directions: agricultural production land decreased, while industrial/mining production land increased by 65.9%. The main sources of growth for both were transfers from agricultural production land, which contributed 64.1% to industrial/mining production land and 26.1% to urban living land.

To further analyze the reconstruction characteristics of "production-living-ecology" space, a land transfer matrix was constructed based on secondary categories (Table 3) . The results show that from 2000 to 2020, all four types of ecological space (forest, grassland, water, and other ecological land) decreased in area. Various ecological land types mainly converted to agricultural production land, with grassland ecological land being the most significant, transferring 3,362.66 km^2 to agricultural production land, accounting for 64.1% of ecological land transferred to agricultural production. Forest ecological land ranked second, with a cumulative transfer area of 1,367.12 km^2, accounting for 26.1% of ecological land transferred to agricultural production. Unlike the area changes in ecological and production spaces, living space overall showed an expansion trend. The main sources of urban and rural living land expansion were agricultural production land transfers, with agricultural land contributing 1,367.12 km^2 and 1,367.12 km^2 to urban and rural living land, respectively. Production space mainly transferred to grassland, forest ecological land, and rural living land, with transfer rates of 21.4%, 21.4%, and 19.4%, respectively. The area transferred to grassland and forest ecological land was higher than the area transferred from these types back to production space. Industrial/mining production land increased by 3.5 times, with its main sources being agricultural production land and forest/grassland ecological land, with transferred areas of 1,367.12 km^2 and 1,367.12 km^2, respectively.

3.2 Spatiotemporal Patterns of Water Yield

The InVEST model water yield module was used to estimate water supply capacity per unit area, yielding the spatial distribution of water yield in the study area (Fig. 3) [Figure 3: see original paper]. The average water yield in the Yellow River Basin of Shanxi was 89.57 mm in 2000 and 138.01 mm in 2020, representing an increase of more than 65.9%. The spatial patterns of water yield in the two periods also differed. High water yield areas in 2000 were concentrated in the southeastern and a small central-eastern portion of the study area, with sporadic distributions in the central Taiyuan urban agglomeration. Low-value areas were mainly concentrated in the central Taiyuan Basin and the southwestern Linfen and Yuncheng basins. Compared to 2000, the high-value area range expanded significantly in 2020, with the western Lüliang Mountains joining the original southeastern and central-eastern high-yield regions. Low-value areas remained concentrated in the southwestern Linfen and Yuncheng basins, but their extent decreased noticeably.

Different "production-living-ecology" spaces exhibited varying water yields (Table 4) . The average water yield of ecological space was 97.42 mm, with other ecological land having the highest yield at 179.17 mm. Production space had an average water yield of 120.77 mm, with industrial/mining production land showing the highest yield at 140.6 mm. Living space had the highest average water yield at 160.80 mm, with urban living land yielding 307.19 mm. From 2000 to 2020, all land use types in "production-living-ecology"space showed varying degrees of increase, with living space increasing most significantly (68.3%), followed by ecological space (44.3%) and production space (63.0%).

3.3 Impacts of Precipitation and "Production-Living-Ecology" Space Changes on Water Yield

Scenario 1: Precipitation unchanged, "production-living-ecology" space changed. The average water yield in 2020 was 98.57 mm, with an increase of only 9.57$×10^{6}$ m^3 compared to the actual water yield in the 2000 baseline year. The overall water yield change in the study area was minimal, with a spatial distribution basically consistent with 2000. Only the Taiyuan urban agglomeration and Linfen and Yuncheng basins showed slightly expanded high-yield areas due to urban expansion and industrial/mining production land expansion. All land use types in "production-living-ecology" space showed varying degrees of increase, with ecological and agricultural production land changes being minimal, industrial/mining production land increasing by 51.1%, and rural and urban living land increasing by 19.4% and 39.6%, respectively. Overall, when "production-living-ecology" space changed, the water yield of the study area showed little change.

Scenario 2: Precipitation changed, "production-living-ecology" space unchanged. The average water yield in 2020 was 126.53 mm, with an increase of 1.23$\times$10^{9}$ m^{3} compared to the actual water yield in the 2000 baseline year. The spatial distribution differed from 2000, with expanded high-yield areas showing significant changes throughout most of the study area except the northern and southern parts, and an overall significant increase in water yield. Examining each land use type, forest land water yield in ecological space increased the most (36.96 mm), followed by grassland. Both production and living spaces increased by more than 33.9%, with industrial/mining production (39.6%) and urban living (39.6%) showing the highest increase rates (Table 39) . This scenario simulation indicates that when precipitation changes, the water yield pattern of the study area changes significantly and shows strong spatial differentiation.

The contribution rate of precipitation change to water yield variation was 80.4%, while that of "production-living-ecology"space change was only 19.6%, indicating that precipitation change has a greater impact on water yield than space change. However, transformations between different land use types in "production-living-ecology" space may lead to increases or decreases in water yield. For example, industrial/mining production land expansion increases water yield, while other conversions may decrease it, resulting in non-significant overall water yield changes.

4 Discussion

From 2000 to 2020, the Yellow River Basin in Shanxi showed a spatial pattern of slightly shrinking ecological space, expanding living space, contracting agricultural production land, and expanding industrial/mining production land, consistent with the findings of Chang et al. [33]. The conversion between agricultural production land and ecological land during the study period may be closely related to a series of ecological protection measures in the Yellow River Basin of Shanxi, such as the Grain for Green Program. Meanwhile, due to population growth and socio-economic development, construction land area expanded, the proportion of living space increased continuously, and agricultural production land and ecological space were encroached upon by industrial/mining production and living spaces, indicating that ecological space still faces the risk of continuous shrinkage. Therefore, ecological protection policies should be considered when formulating territorial spatial planning, with rational land use planning based on local natural resource distribution, geographical conditions, and economic development to achieve more rational "production-living-ecology" space layout.

According to water balance principles, precipitation and potential evapotranspiration are the two key factors determining water yield. Precipitation change is the main influencing factor of water yield variation, while "production-living-ecology" space change has a smaller impact, consistent with the findings of Yang et al. [34]. Precipitation is mainly affected by climate change, while potential evapotranspiration is influenced by both climate change and land use. Transformations between different spaces in "production-living-ecology" space may cause increases or decreases in overall water yield in the Yellow River Basin of Shanxi, resulting in non-significant overall changes. Water yield estimation for 2020 showed a significant increase during the study period, mainly due to significantly increased precipitation. Liu et al. [35] found that since the 21st century, evapotranspiration in the Yellow River Basin has shown a decreasing trend while precipitation has increased significantly, leading to increased actual water yield.

Although the InVEST model is widely used in ecosystem service evaluation, it does not consider topographic factors, resulting in certain uncertainties [36]. The ω parameter varies across regions [37], and precipitation and potential evapotranspiration data were obtained through interpolation of station data, which may produce errors with different interpolation methods. Moreover, when classifying "production-living-ecology" space, previous classification schemes were referenced, and the dominant functions of the same land type may differ due to different perspectives, potentially causing spatial overlap issues. Therefore, land use classification should be as detailed as possible [38] to enable more accurate measurement of various land functions. Different classification schemes yield different results, and the classification scheme for ecological land remains controversial and requires further research.

5 Conclusions

This paper classified "production-living-ecology" space based on land natural attributes, used land use transfer matrices to study the temporal and spatial variation characteristics of "production-living-ecology" space, applied the InVEST model to estimate water yield in the Yellow River Basin of Shanxi from 2000 to 2020, and evaluated the impacts of "production-living-ecology" space and precipitation changes on water yield services through different scenarios. The main conclusions are as follows:

1. From 2000 to 2020, the area distribution of "production-living-ecology" space in the Yellow River Basin of Shanxi showed: ecology > production > living. Ecological space was the dominant land type, followed by production space, with living space accounting for only a small portion of the watershed. Ecological space area decreased slightly, agricultural production land contracted significantly, while industrial/mining production land and urban/rural living land areas increased substantially. Various

ecological land types mainly converted to agricultural production land, with forest and grassland ecological land transferring to agricultural production land at higher rates than the reverse transfers, showing consistency with socio-economic development and macro policies.

2. The average water yield in the Yellow River Basin of Shanxi was 89.57 mm in 2000 and 138.01 mm in 2020. The spatial distribution of water yield differed between the two years, with high-value areas increasing and low-value areas decreasing. Different "production-living-ecology" spaces had different water yields, with living space having the highest average water yield.
3. In Scenario 1, the 2020 water yield was 98.57 mm, with minimal increase and non-significant spatial changes. In Scenario 2, the 2020 water yield was 126.53 mm, with significant changes and strong spatial differentiation. The contribution rate of precipitation change to water yield variation was 80.4%, while that of "production-living-ecology" space change was only 19.6%. However, conversions between different land use types in "production-living-ecology" space may lead to increases or decreases in water yield, resulting in non-significant overall water yield changes.

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