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Study on the Spatial–Temporal Variations and Driving Factors of Water Yield in the Yiluo River Basin

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Abstract: Water yield (WY) is an significant characteristic that reflects ecosystem services. In order to realize high-quality development, it is vital to explore the spatial and temporal (ST) distribution of WY and its driving factors in the Yiluo River Basin (YLRB) to uphold ecological stability and advance long-term sustainable growth. This paper quantifies WY in the YLRB from 2010 to 2020 using the WY model in the InVEST toolkit. Exploring ST characteristics and driving factors at both the raster and sub-watershed levels, results indicate that the overall WY (average water depth) of the YLRB in 2010, 2015, and 2020 was 26.93×10^8 m^3 (136.50 mm), 22.86×10^8 m^3 (113.38 mm), and 26.81×10^8 m^3 (137.61 mm), respectively. The spatial pattern of watershed WY remains consistent across various periods, illustrating spatial variation in the depth of low WY in the central and western regions and high WY depth in the eastern region. At the sub-watershed level, the Luo River (LR) Basin has the highest contribution (69%) to the WY of the entire basin and served as the principal WY region of the YLRB. Conversely, the Yiluo River section, formed after the confluence of the Yi River (YR) and the LR, has the lowest WY contribution (7%) in the entire watershed. Distinct variations exist in the WY capacity among various land use (LU) types. Construction land (CSL) and unused land (UL) exhibited the highest WY capacity (315.16 mm and 241.47 mm), whereas water area (WA) had the lowest (0.01 mm). WY was significantly positively correlated with slope, precipitation, actual evapotranspiration, percentage of cultivated land, and NDVI. It showed a significant negative correlation with altitude, WA, and population density. This study helps promote the research and development of watershed ecosystem services. It also provides scientific support resolving conflicts between watershed protection and economic development and promoting harmony in the YLRB.

Keywords: InVEST model; water yield; spatial–temporal variations; driving factors; the Yiluo River Basin

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Citation: Cao, Y.; Zhang, X.; Wei, H.; Pan, L.; Sun, Y. Study on the Spatial–Temporal Variations and Driving Factors of Water Yield in the Yiluo River Basin. *Water* **2024**, *16*, 223. https://doi.org/10.3390/w16020223

Academic Editor: Carmen Teodosiu

Received: 8 December 2023
Revised: 2 January 2024
Accepted: 7 January 2024
Published: 9 January 2024

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1. Introduction

Amidst global climate change, the depletion of surface water sources and decline in water quality pose significant challenges. Consequently, the spatial quantification and visual assessment of regional water yield (WY) have become focal points in contemporary ecological research and related fields [1–4]. The WY service of the basin shows considerable spatial and temporal (ST) differences, and its fluctuations influence the plant cover, climate, and soil regime directly. This service is a crucial index for assessing the quality of the basin ecosystem. In addition, it is vital for industries, agriculture, fisheries, human consumption, and recreational activities [5–8]. The spatial allocation of WY services intricately links with the sustenance of human life and the fostering of sustainable societal and economic development, as well as the safeguarding of the environment [5]. Therefore, analyzing the factors influencing variations in WY and investigating the ST patterns associated with these changes holds substantial practical and guiding significance. This research is crucial for optimizing the management of water resources and enhancing the sustainability of ecosystems [5,9].

Traditional methods for evaluating WY services typically rely on collecting actual observational data from small watersheds. Soil water storage capacity, water balance, annual runoff, and underground runoff growth are used to estimate WY by these methods. However, these approaches could lead to significant inaccuracies when applied over extensive spatial expanses, considering the restricted quantity of monitoring stations and the suboptimal state of observation equipment. Applications of geospatial technology, including GIS and remote sensing, in ecology and hydrology fields have involved the utilization of various models to simulate and assess the WY of watersheds. This study uses the MIKESHE, TOPMODEL, SWAT, and InVEST models [10–12]. The WY module takes into account spatial differences in land use (LU) types, soil permeability, and topography [10]. Factors such as runoff affect the quantitative estimation of WY for various LU types, using rasters as units [2,13]. The model has some advantages, such as adjustable parameter calibration, powerful spatial representation of evaluation outcomes, and the ability to achieve a trade-off between ST and multiple objectives [14], and it is widely used in various countries and regions. For example, Leh et al. [15] utilized the InVEST model for evaluating WY in Côte d'Ivoire, West Africa, while Marquès et al. [16] utilized the same model to evaluate WY in the Francois River Basin in northeastern Spain. Redhead et al. [17] also employed the InVEST model to assess WY in various rivers across the United Kingdom. They achieved favorable results in their applications. In addition, the WY module was used by Chinese scholars to evaluate WY and its ST patterns in different regions scientifically. These regions included the Loess Plateau [18], Hainan Island [19], Xiangjiang River Basin [20], Shaanxi Province [21], Yellow River Basin [22,23], Ebinur Lake Basin [24], and Hengduan Mountains [25]. These studies have yielded positive results in their applications.

At present, WY is impacted by pivotal factors linked to climate change and shifts in LU [26]. At the macro scale, precipitation and evapotranspiration in the basin are influenced by climate change, which affects WY [27,28]. Additionally, the subsurface of a watershed is altered by LU change, which impacts WY indirectly [29,30]. The effects of climate change and shifts in LU on watershed WY have been examined by some studies. Climate change significantly affects WY in the Missouri River Basin, as confirmed by Stone et al. [31] in their study. Additionally, Zhang et al. [32] and Li et al. [33] examined the impact of LU changes on WY and concluded that different LU patterns had varying effects on WY. China's water resources are progressively influenced by global climate change [34].

Prior research has contributed positively to the ecological development and preservation of resources in the Yiluo River Basin (YLRB). As an illustration, Hou et al. [35] investigated how historical alterations in LU and land cover influence the value of ecosystem services. Li et al. [36] analyzed the ST features of reference evapotranspiration and the factors influencing it in the YLRB. Liu et al. [37] explored annual precipitation and flow trends in the YLRB from 1960 to 2006. Analyzing LU and land cover, including flow, flow direction, and internal driving factors in the YLRB from 1990 to 2020, Huang Yu et al. [38] examined ST characteristics. Using satellite data, Hou et al. [39] determined the contribution of different driving factors to the alterations in natural runoff in the YLRB. Ling et al. [40] discussed the relevance between actual evapotranspiration and climate, vegetation, and other driving factors. Applying the InVEST model, Fan et al. [41] quantified the correlation between water supply and demand in the YLRB. Hou et al. [42] examined the past and future dynamics and factors influencing the WY in the YLRB. These studies mainly focused on changes in vegetation cover, evapotranspiration, runoff, landscape pattern evolution, and environmental impact assessment before and after ecological construction in representative regions. However, research on the connection between WY and climate change and shifts in LU in the YLRB is still relatively limited. Moreover, the impact of socioeconomic factors on WY has been rarely studied. In conclusion, it is crucial to research ST variations of WY in the YLRB, as well as driving factors.

As one of the Yellow River's ten primary tributaries, the Yiluo River is the biggest branch downstream of the Sanmenxia. It plays a crucial role in the flood control system, the allocation of water resources, and overseeing water and sediment dynamics in the lower reaches of the Yellow River. Owing to shifts in climate urban expansion, the YLRB has witnessed transformative shifts in WY and patterns of water utilization, profoundly impacting the region's water availability. In response to these multifaceted changes, the InVEST model is a robust tool for quantifying the WY service of the basin. Beyond mere quantification, the investigation delves into the spatial–temporal variations in WY at both the intricate raster and sub-watershed scales. Correlation analysis, encompassing socioeconomic factors, is intricately woven into methodology to unravel the complex web of influences on the spatial–temporal dynamics of WY. The research is poised not only to unravel the current state of WY in the YLRB but to decipher the factors that propel these spatial–temporal variations. Ultimately, the findings will offer scientific assessment and decision guidance for the creation of an ecological civilization in water sources, and the enhancement of high-quality development in the Yellow River Basin.

2. Materials and Methods

2.1. Study Area

Flowing between 33°34′–34°54′ N and 109°44′–113°08′ E, the Yiluo River contributes as a feeder to the middle segment of the Yellow River. Stretching across 974 km, it passes through 21 counties and cities within Shaanxi and Henan (Figure 1). The main branches, the Yi River (YR) at 265 km and the Luo River (LR) at 447 km, contribute to the overall length. Heishiguan Station, responsible for monitoring the basin's outflow, encompasses 1.86 km^2. The basin receives an average annual rainfall of around 700 mm, and the precipitation distribution exhibits variations across different seasons. The annual water evaporation in the basin varies between 800 and 1000 mm. The basin, which has an average elevation ranging from 58 to 2659 m, exhibits a distinct ecological and environmental gradient. The upper reaches consist of hilly and mountainous areas, primarily covered in forest and grassland, while the lower reaches are predominantly loess alluvial plains. Functioning as a crucial grain production base, the basin has experienced a significant reduction in water resource availability due to the impact of climate patterns and human activities in recent years. This has led to a water shortage crisis. In addition, the ecological environment has become increasingly complex and fragile.

2.2. Data Source and Processing

Table 1 presents the vegetation evapotranspiration coefficient and maximum root depth for each land use, essential inputs for the InVEST model. These values were derived from research findings by others [43–45], the FAO crop reference value [46], and parameters recommended by the InVEST model. Additional data sources and treatments are detailed in Table 2.

Table 1. Biophysical parameters of land use (LU) types in the InVEST model.

LU Type	LU Type Code	Maximum Root Depth	Vegetation Evapotranspiration Coefficient
Cultivated land (CL)	1	2100	0.65
Forest land (FL)	2	5200	1.00
Grassland (GL)	3	2300	0.65
Water area (WA)	4	100	1.00
Construction land (CSL)	5	100	0.30
Unused land (UL)	6	100	0.50

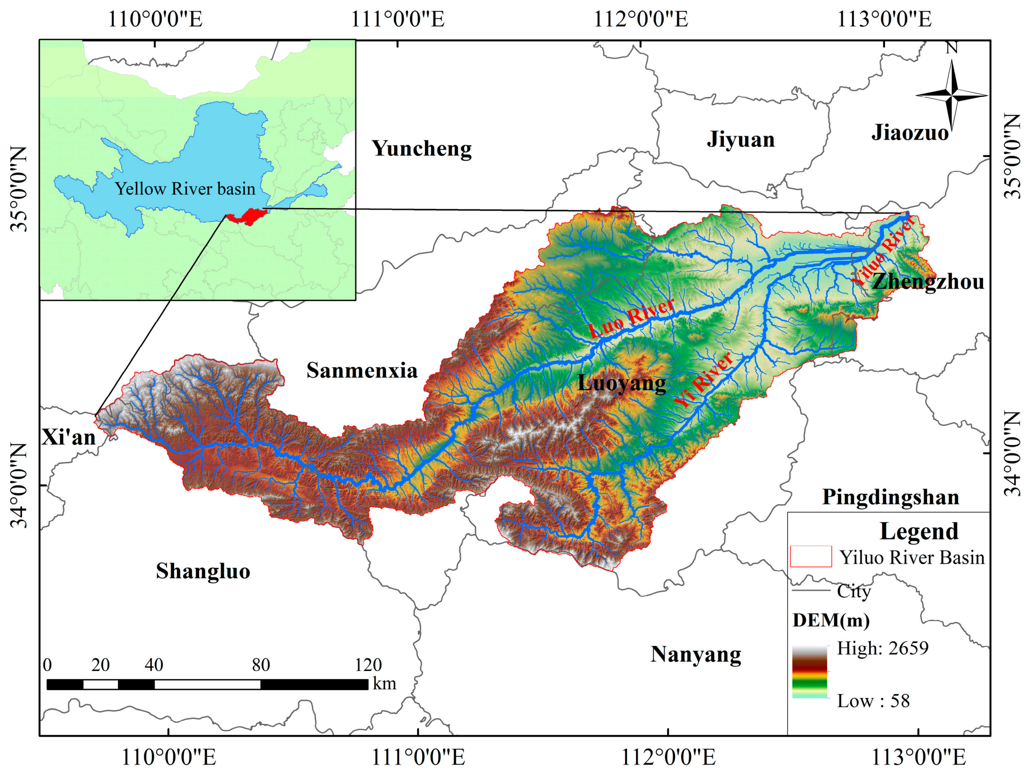

Figure 1. Geographical overview of the Yiluo River Basin (YLRB).

Table 2. Datasets and sources.

Datasets	Data	Source
LU datasets	LU	https://zenodo.org/records/5816591 (accessed on 3 September 2023) [47,48]
Meteorological datasets	Average annual precipitation Average annual temperature potential evapotranspiration	http://www.geodata.cn (accessed on 5 September 2023) [49,50]
Soil datasets	Sand, silt, clay, OM	HWSD v1.1 [51]
Vector datasets	DEM (Digital elevation model) Watershed and sub-watershed	http://www.resdc.cn/ (accessed on 1 September 2023)
NDVI datasets	Normalized Difference Vegetation Index	http://www.resdc.cn/ (accessed on 16 September 2023) [43]
Social and economic data	Population density GDP Proportions of secondary and tertiary industry	People's government of the counties and districts in the YLRB, previous years' statistical yearbooks [38]

The Zhang parameter [49] is a seasonal constant that characterizes the distribution of precipitation. The value ranges from 1 to 30. After conducting multiple simulations, it was found that when the Zhang parameter is 2.8, the estimated WY of the YLRB in 2010, 2015, and 2020 is closest to the measured multiyear average runoff. The measured runoff data is derived from the comprehensive planning of the YLRB, the Yellow River Water Resources Bulletin, and relevant research findings.

2.3. InVEST Model

This study utilized version 3.12.0 of the InVEST model (Integrated Valuation of Ecosystem Services and Trade-offs), specifically its "Water Yield" sub-module, to simulate the ST variations of WY in the basin. The study adheres to the water balance principle within the basin for the application of this module. It is believed that precipitation in the basin is primarily lost or retained on the surface through three mechanisms: runoff, evapotranspiration, and changes in water storage within the basin. It is generally believed that, over a period of several years, the amount of water storage change in a naturally closed basin is negligible. Therefore, runoff in the basin is characterized by the difference between precipitation and evapotranspiration. Following this principle, the "Water Yield" module computes the WY value at the raster level by subtracting evapotranspiration from precipitation on a raster scale. The calculation follows the subsequent formula:

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

where Y_{xj} represents the WY of raster unit x for LU type j, AET_{xj} is the annual actual evapotranspiration of LU type j for raster unit x, and P_x represents the annual precipitation for raster unit x. The AET_{xj}/P_x ratio relies on the Budyko curve established by Zhang et al. [49]. The formula for calculating this ratio is as follows:

$$\frac{AET_x}{P_x} = \frac{1 + \omega_x + R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \quad (2)$$

$$\omega_x = Z\frac{PAWC_x}{P_x} \quad (3)$$

$$R_{xj} = \frac{k_{xj} \times ET_0}{P_x} \quad (4)$$

where R_{xj} represents the Budyko dryness index of raster unit x for LU type j, ω_x denotes the ratio of corrected annual available water to expected precipitation, and Z represents the Zhang parameter [52]. The plant evapotranspiration coefficient is denoted as k_{xj}, and $PAWC_x$ refers to the plant available water content.

The PAWC can be determined using soil texture and soil organic matter content [50] as follows:

$$\begin{aligned} PAWC = 54.509 - 0.132 sand\% - 0.003(sand\%)^2 - 0.055 silt\% - 0.006(silt\%)^2 \\ -0.738 clay\% + 0.007(clay\%)^2 - 2.688 OM\% + 0.501(OM\%)^2 \end{aligned} \quad (5)$$

where *sand*, *silt*, *clay*, and *OM* represent the soil sand content, soil silt content, soil clay content, and soil organic matter content (%), respectively.

2.4. Study Framework

In this paper, a quantitative assessment of WY in the YLRB from 2010 to 2020 was conducted at two scales: raster and sub-watershed. The study also analyzed the ST distribution of WY and its driving factors in the YLRB. The research framework (Figure 2) was constructed as follows: (1) The study utilized meteorological, LU, and soil data, alongside basin and raster data specific to the study area. The InVEST model's WY module was applied for assessing WY in the YLRB for the years 2010, 2015, and 2020. The assessment was then verified using multiyear runoff data from the comprehensive planning of the YLRB. (2) Based on this, the study aimed to clarify the ST variation characteristics of WY in the YLRB from four perspectives: temporal variation characteristics, spatial variation characteristics, WY comparison at the sub-watershed scale, and the dispersion of WY across various LU types. (3) The principal factors driving the ST variation of WY were determined by analyzing the correlation between WY and terrain, climate, LU, and socioeconomic factors. (4) Based on the distribution patterns of WY, we suggested appropriate measures and recommendations.

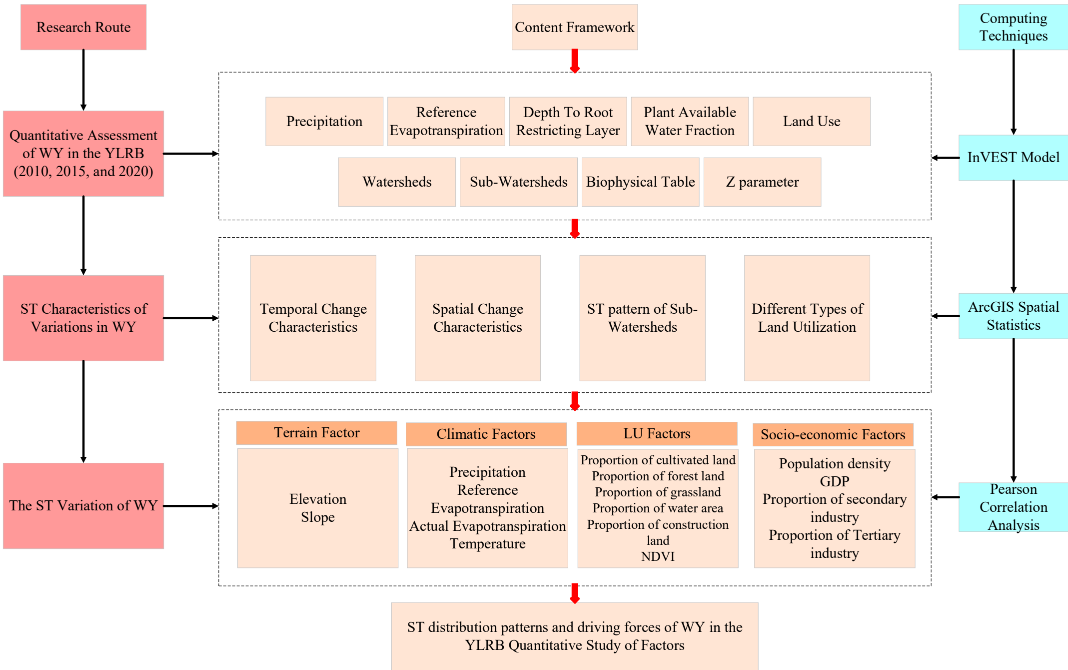

Figure 2. Research framework of ST variations and driving factors of WY in the YLRB.

3. Results

3.1. Temporal Variation Characteristics of WY in the YLRB

The total WY (average water depth) of the YLRB in 2010, 2015, and 2020 was 26.93×10^8 m^3 (136.50 mm), 22.86×10^8 m^3 (113.38 mm), and 26.81×10^8 m^3 (137.61 mm), respectively. (Table 3). The WY of the YLRB exhibited a pattern of initially decreasing and then increasing from 2010 to 2020. The decrease from 2010 to 2015 was approximately 15.11%, and the increase from 2015 to 2020 was approximately 14.73%. The WY of the YLRB was highest in 2010 and lowest in 2015. Compared with WY in 2010, WY in the YLRB in 2020 did not change significantly. The standard deviation of WY in the YLRB from 2010 to 2020 demonstrated an initial decline followed by an ascent. This indicates that the spatial heterogeneity of WY services in the YLRB also increased gradually during this period.

Table 3. The total amount and the mean value of WY services in the YLRB from 2010 to 2020.

	2010	**2015**	**2020**
Total WY (m^3)	26.93×10^8	22.86×10^8	26.81×10^8
Average WY depth (mm)	136.50	113.38	137.61
Standard deviation	84.06	79.59	88.89

3.2. Spatial Variation Characteristics of WY in the YLRB

Figure 3 illustrates water depth's spatial distribution in the YLRB for 2010, 2015, and 2020 under the actual scenario. From a spatial distribution perspective, water depth exhibits minimal variation across different periods, maintaining a consistent overall pattern. Low water depth characterizes the central and western regions, contrasting with elevation in the eastern region. In 2010, high WY was primarily concentrated in the southeastern (eastern Luoyang) and the uppermost part of the basin. In 2015, the WY in the western region (west of Sanmenxia) was significantly lower than that in 2010. In 2020, WY in the western region slightly increased, while the eastern region (eastern Luoyang) experienced a significant increase in WY. The eastern region emerged as the area with the highest WY. By 2020, the spatial differentiation of WY in the northwest, central, and northeast regions became more pronounced. This pattern closely correlates with precipitation distribution and LU types in the YLRB. Areas experiencing abundant precipitation and low evapotranspiration, such as construction land (CSL) and grassland (GL), exhibit a high potential for WY. Conversely, regions with low precipitation and high evapotranspiration, such as forests and bodies of water, exhibit a limited WY capacity [51]. Evapotranspiration is more pronounced in the upper stretches of the YLRB in contrast to the lower stretches [40]. This difference may be attributed to the prevalence of woodland vegetation in the higher regions.

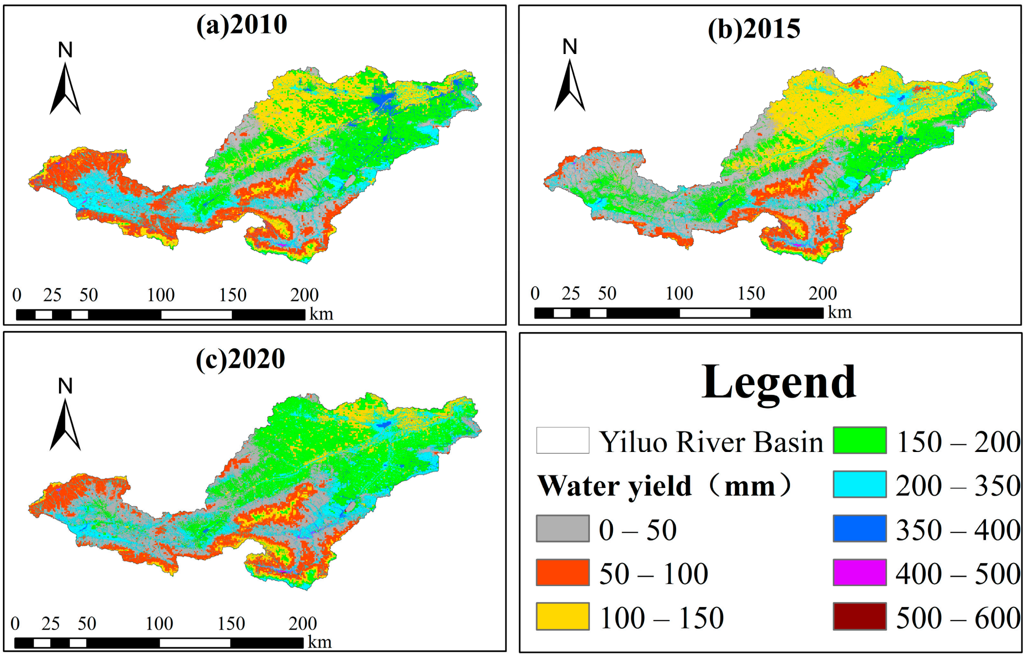

Figure 3. Spatial distribution of water depth in the YLRB in 2010 (**a**), 2015 (**b**), and 2020 (**c**).

Figure 4 depicts spatial variations in WY depth in the YLRB during three time periods: 2010 to 2015, 2015 to 2020, and 2010 to 2020, based on the actual scenario. From 2010 to 2015, WY exhibited a declining trend in the majority of YLRB areas, constituting around 91% of the entire basin area. Only the WY in the stretch between the upper YR and the Luhun Reservoir increased by approximately 0~20 mm, and the depth of WY in other areas showed a trend, reaching 20 mm. The decrease in the upper basin is approximately −80~−30 mm, while the reduction in the middle and lower basin is around −30~0 mm. From 2015 to 2020, the WY depth in the YLRB primarily increased, with the expanded area representing about 95% of the entire basin. The expanded region is mainly concentrated in the entire YLRB and the lower reaches of the LR, indicating an increase of approximately 0~20 mm and 20~70 mm, respectively. The regions that have undergone a reduction are primarily the YR and the main course of the LR, displaying a decrease of about −30~0 mm. In general, from 2010 to 2020, the WY depth of the YLRB mainly increased. The expanded region comprised over 60% of the overall area, predominantly concentrated in the middle stretches of the LR and the upper reaches of the YR. The diminished region is primarily concentrated in the upper stretches of the LR and the Yiluo River section, with the reduction being approximately −30~0 mm.

3.3. ST Pattern of WY at the Sub-Watershed Scale

The watershed stands as the fundamental unit for WY formation and water resource management. Although expressing WY at the raster scale can offer more detailed spatial differences, there is insufficient scientific support for implementing water resource policies and effective water resource management. Expanding on earlier investigations, this study conducted an analysis of the ST variation pattern of the average WY depth at the scale of the Yiluo River sub-watershed, encompassing the YR, LR, and Yiluo River sections.

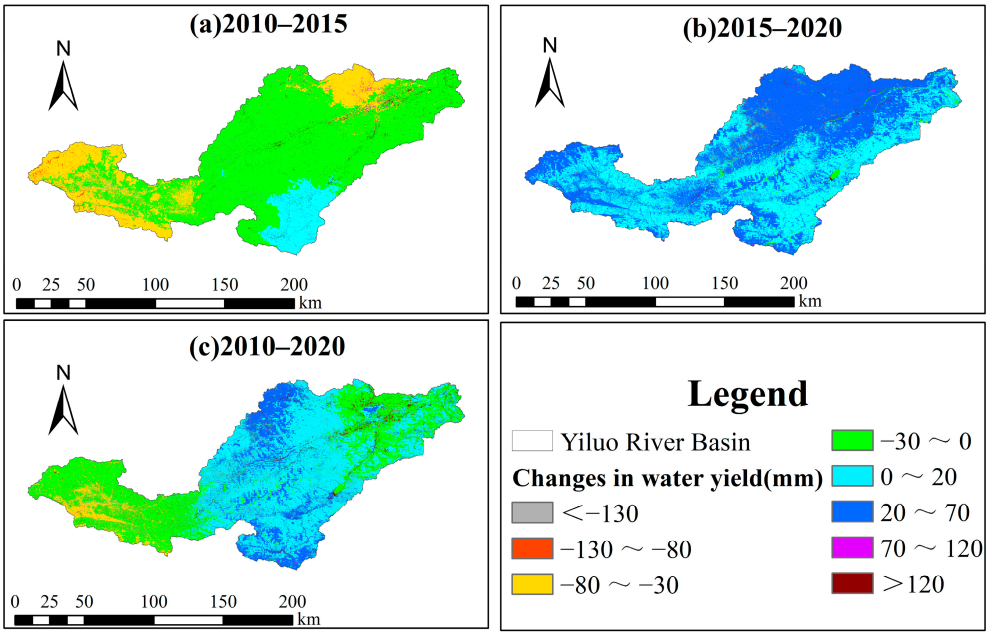

Figure 4. Spatial variations in WY depth in the YLRB over three different time periods: 2010 to 2015 (**a**), 2015 to 2020 (**b**), and 2010 to 2020 (**c**).

From a sub-watershed perspective, the WY of the YLRB varies greatly, ranging from 1 to 19 × 10^8 m^3. In 2010, 2015, and 2020, the average WY depth of the YR Basin was 143.05 mm, 135.62 mm, and 152.14 mm, respectively. The total WY for those years was 6.00 × 10^8 m^3, 5.68 × 10^8 m^3, and 6.36 × 10^8 m^3, respectively. The average water depths in the LR Basin are 125.70 mm, 94.90 mm, and 122.06 mm, with corresponding WY of 19.04 × 10^8 m^3, 15.46 × 10^8 m^3, and 18.47 × 10^8 m^3, respectively. The average WY depth of the Yiluo River section was 177.37 mm, 161.28 mm, and 186.27 mm, and the WY was 1.89 × 10^8 m^3, 1.72 × 10^8 m^3, and 1.99 × 10^8 m^3, respectively (Table 4).

Table 4. The average WY variation of the Yi River (YR), Luo River (LR), and Yiluo River section in 2010, 2015, and 2020.

Sub-Watershed	Year	2010	2015	2020
YR	Average WY depth (mm) WY (billion m^3)	143.05 6.00	135.62 5.68	152.14 6.36
LR	Average WY depth (mm) WY (billion m^3)	125.7 19.04	94.9 15.46	122.06 18.47
Yiluo River section	Average WY depth (mm) WY (billion m^3)	177.37 1.89	161.28 1.72	186.27 1.99

From 2010 to 2020, the LR Basin had the highest contribution to the total WY of the entire basin, averaging approximately 69%. The area serves as the main water catchment for the YLRB. On the other hand, the Yiluo River section had the lowest contribution, averaging approximately 7%. This can be attributed to the smaller size of this specific area within the basin. The average contribution rate from the YR to the overall WY of the entire basin is approximately 24%. From 2010 to 2020, the WY of the three basins initially exhibited a decline, followed by an upward trend. This pattern aligned with the overall change in total WY in 2015. The WY in the LR decreased by 3%, while the YR witnessed a 6% increase, and the Yiluo River section experienced a 5% increase in WY.

3.4. Changes in WY Depth and WY of Different LU Types

Figure 5 illustrates the distribution of LU at the YLRB for the 2010, 2015, and 2020 actual scenarios. The total WY exhibits notable variations across different LU types, influenced by the average WY capacity per unit area and the distribution area. Cultivated land (CL) and forest land (FL) comprised the largest proportion of the study area, with GL and CSL following. The extent of water area (WA) and unused land (UL) is relatively limited, as illustrated in Table 5. Between 2010 and 2020, the extent of FL, CSL, and WA saw varied increases. Among these changes, the extent of FL increased by 583.3 km^2, representing the most substantial growth, with the proportion rising by 3.1%. The extent of CSL saw an increase of 289.5 km^2, with the proportion growing by 1.5%. The increase in WA and proportion is minimal. Between 2010 and 2020, the extent of CL and GL experienced varied decreases. Among them, the extent of CL consistently decreased in area to 364.0 km^2, or by 1.9% in proportion. The area of the GL decreased to 514.4 km^2, a decrease of 2.7%. The UL did not change significantly. Based on the data above, we can deduce that the project of converting farmland back to forest in the study area achieved remarkable results from 2010 to 2020. The extent of CL markedly decreased, whereas the area of FL witnessed a significant increase.

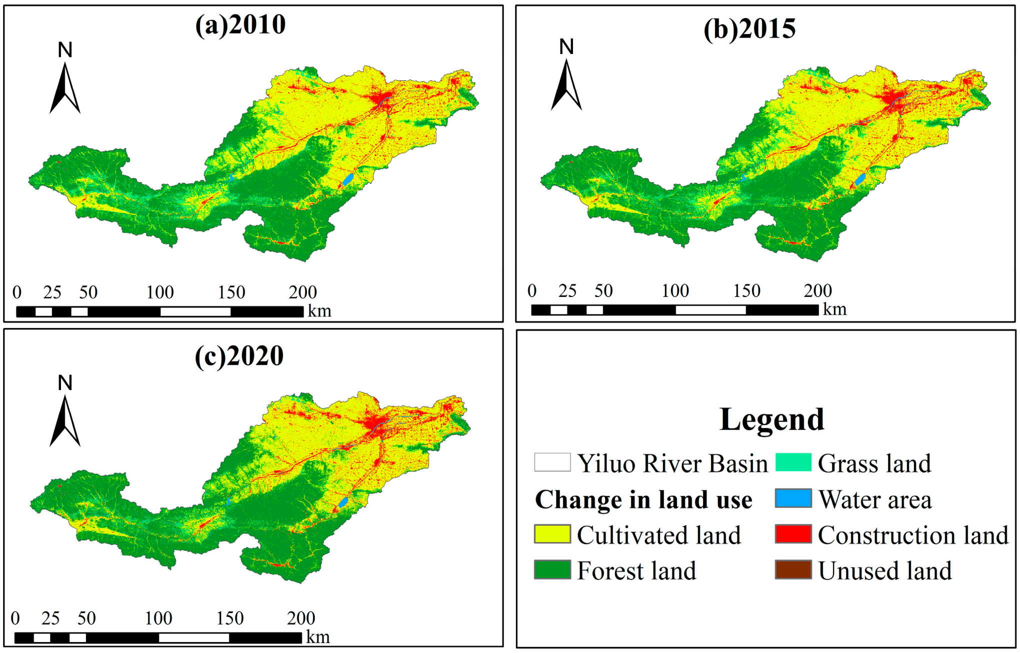

Figure 5. LU in the YLRB in 2010 (**a**), 2015 (**b**), and 2020 (**c**).

Table 5. The LU changes in different years.

LU Type	2010		2015		2020		2010–2015 Change Value		2015–2020 Change Value		2010–2020 Change Value	
	Area km^2	Proportion %	Area km^2	Proportion %	Area km^2	Proportion %	Area km^2	Proportion %	Area km^2	Proportion %	Area km^2	Proportion %
CL	8439.8	44.9	8116.8	43.2	8075.8	43.0	−323.0	−1.7	−41.0	0.2	−364.0	−1.9
FL	7994.3	42.6	8253.1	44.0	8577.6	45.7	258.8	1.4	324.5	1.7	583.3	3.1
GL	1181.3	6.3	1040.1	5.5	666.9	3.6	−141.2	−0.8	−373.2	−2.0	−514.4	−2.7
WA	91.4	0.5	98.8	0.5	96.8	0.5	7.4	0	−2.0	0	5.4	0
CSL	1072.2	5.7	1270.1	6.8	1361.8	7.2	197.9	1.1	91.6	0.5	289.5	1.5
UL	0.5	0	0.6	0	0.6	0	0.1	0	0.1	1.5	0.2	0

Between 2000 and 2020, the average WY depth for each LU type, arranged from largest to smallest, was as follows: CSL (315.16 mm), UL (241.47 mm), GL (199.73 mm), CL (168.78 mm), FL (54.44 mm), and WA (0.01 mm). This is consistent with many previous studies [52]. Due to variations in evapotranspiration, soil composition, water retention capacity of litter, and canopy interception among various LU types, significant variations exist in WY capacity [53,54]. The WY from various LU types inversely correlates with the evapotranspiration by vegetation on that land. Among them, CSL generally has the least amount of vegetation [54]. It lacks vegetation to intercept precipitation, resulting in lower evapotranspiration compared with other types of land. The WY capacity is higher as a result. On the other hand, WA has a high evapotranspiration capacity that is significantly greater than that of terrestrial vegetation. Consequently, the WY capacity of WA is low. CL and FL can intercept a portion of precipitation, infiltrate the soil, and generate runoff. The average WY capacity of grassland surpasses that of other ecosystems. The evapotranspiration capacity of WA is significantly higher than that of vegetation. Consequently, WA has the lowest WY.

3.5. Analysis of the Driving Factors Influencing the ST Variation of WY

To elucidate the spatial distribution pattern of WY and discern the factors driving temporal changes in the YLRB, we selected 16 factors for analysis. These factors include terrain factors (altitude, slope), climate factors (precipitation, potential evapotranspiration, actual evapotranspiration, temperature), LU factors (LU factors, including the proportion of CL, FL, GL, WA, CSL, and NDVI), and socioeconomic factors, (population density, GDP, proportions of secondary and tertiary industry). We conducted a Pearson correlation analysis of these factors (Figure 6). From a spatial pattern perspective, similar to previous research [55], there is a pronounced negative correlation between WY and altitude in terrain factors. Precipitation and vegetation types vary significantly with altitude, which in turn can indirectly impact WY capacity. It is worth noting that WY is positively correlated with slope. Among climatic factors, similar to previous studies [56,57], WY has a significant positive correlation with precipitation and actual evapotranspiration, but no significant correlation with potential evapotranspiration and temperature. Among LU factors, WY exhibited positive correlations with the proportion of CL and NDVI, and negative correlations with the proportion of WA. However, it was not significantly correlated with the proportion of FL, GL, or CSL. The WY in this investigation is computed as the disparity between precipitation and evapotranspiration. Compared with CL, FL has a greater capacity for litter water retention and canopy interception [53,58]. Among socioeconomic factors, a significant negative correlation existed between WY and population density. Nevertheless, GDP, the proportion of secondary industry, and the proportion of tertiary industry showed no significant correlation [52].

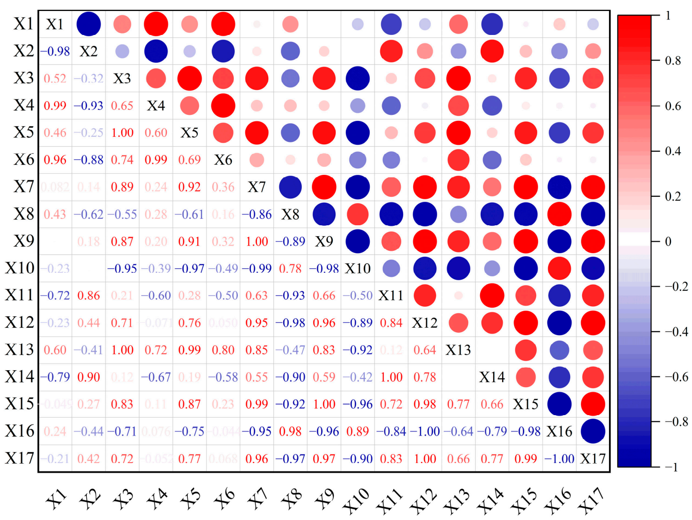

Figure 6. Correlation analysis between WY and driving factors. Notes: X1: WY, X2: Elevation, X3: Slope, X4: Precipitation, X5: Reference evapotranspiration, X6: Actual evapotranspiration, X7: Temperature, X8–X12: Proportion of CL, FL, GL, WA and CSL, X13: NDVI X14: Population density, X15: GDP, X16: Proportion of secondary industry, X17: Proportion of tertiary industry.

4. Discussion

WY is a crucial ecological indicator with a direct impact on the sustainable development of socioeconomic and ecological systems [34]. This study focuses on exploring and analyzing ST patterns as well as drivers of WY in the YLRB. The findings revealed a modest decline in WY of the YLRB from 2010 to 2020. Notably, there was a significant decrease from 2010 to 2015, directly attributable to a decline in precipitation during this period. The precipitation in the entire basin decreased by an average of 23.12 mm during this period. Zhao Lixia et al. [59] and Li Hongxia [60] believe that the annual precipitation in the YLRB has generally shown a negligible downward trend since the 21st century. According to Yang Jie et al. [61], precipitation was a major factor affecting WY in the Yellow River Basin, with little impact from LU change. Zhu Chunxia et al. [62] conducted research on the ecosystem services of the Yellow River Basin and determined that climate and geographical factors significantly drive WY and soil conservation services. The two factors that have the highest explanatory power are annual precipitation and slope. Zhu et al. [63] focused their research on the WY coefficient of the YLRB. They found that the spatial distribution of the WY coefficient was strongly linked to precipitation characteristics, followed by LU type and vegetation coverage. Therefore, the overall WY in the YLRB demonstrated a negligible downward trend.

LU change influences actual evapotranspiration, as well as soil's physical and chemical properties and the water status of land surfaces. These changes in turn impact WY in the study area. For instance, observed restricted WY in forested land can be attributed to the presence of a more profound root system that effectively intercepts precipitation through robust transpiration. Additionally, forested land assumes a pivotal role in mitigating surface runoff by intercepting precipitation through forest canopy, absorbing precipitation in the litter layer, and storing and infiltrating precipitation in the soil layer. Consequently, an escalation in forested land area corresponds to a reduction in WY, consistent with the findings of precedent studies [64]. Furthermore, our investigation underscores that CL and GL manifest analogous impacts on precipitation, as observed in forested land. Nonetheless, the regulatory influence of CL on WY is comparatively subdued when juxtaposed with that of GL and forested land, owing to disparities in plant density and root depth. Specifically, this study identifies that the average WY depth of CL and GL in the YLRB surpasses that of forested land and CL. This phenomenon is principally ascribed to the prevalence of GL in the upper reaches of the Yiluo River, where the basin encounters the highest annual precipitation. Although GL facilitates the redistribution of precipitation through surface interception and absorption by the litter layer, its pervasive distribution and concentration in regions with elevated precipitation values contribute to an augmented average WY depth for GL across the entire basin. This substantial contribution of GL to the overall WY of the basin accentuates the imperative consideration of spatial distribution and inherent characteristics of diverse LU types when appraising water resource dynamics in the YLRB.

The InVEST model is extensively employed for ecosystem evaluation. However, the WY module does not account for complex terrain and is unable to illustrate the water balance process under intricate LU patterns and subsurface geography. Thus, the model has some uncertainty [25,65]. Going forward, there are plans to explore the integration of the SWAT model to utilize its ability to handle complex terrain to improve the accuracy of water quantity estimates. In addition, efforts can be made to utilize higher precision data to mitigate the effects of complex terrain on study results [66]. Moreover, the WY module of this study relies on data from the World Soil Database and existing literature on maximum root depth, clay, and sand content. This adjustment will not alter the overall WY pattern in the entire basin, but it may impact the precision of the model simulation. It is essential to improve the reliability of soil data in future research. To this end, cooperation with local professional research institutes can be actively sought to obtain more detailed and reliable soil data for the study area. Cooperating with a team of experts to carry out onsite investigations and validation work will undoubtedly lay a more solid foundation for simulating water production in future studies. This study estimated the annual WY of the

YLRB without considering variations in WY within and between years. Future research endeavors should recognize the importance of delving into intra-annual and interannual variations in WY, considering their potential implications for water resource management. Methodologies such as using hydrological models with higher temporal resolution could be explored to address this aspect and provide a more nuanced understanding of WY dynamics in response to climatic and LU changes over shorter time scales. Additionally, the selection of sub-watersheds only included the sections of the YR, LR, and Yiluo River section within the YLRB. This method partially masked the influence of spatial variations in LU change on WY. The Zhang parameter varies in different geographical environments. In this research, the Zhang parameter is determined without considering variations in climate types and rainfall frequencies across the Yiluo River. The unified Zhang parameter is being adopted. Although it closely approximates the actual WY of the basin after multiple simulations, further verification with a substantial amount of observed data is needed to determine its suitability for the entire YLRB. Despite these uncertainties, the study results can effectively portray the temporal changes and spatial distribution of WY, revealing the driving factors of ST variations, and contribute scientific insights to enhance the effective management, rational utilization, and conservation of water resources in the YLRB.

5. Conclusions

This study estimates and analyzes ST patterns of WY and its drivers in the YLRB from 2010 to 2020, using InVEST model's WY module. The study arrives at the following conclusions:

(1) The overall WY (average water depth) of the YLRB in 2010, 2015, and 2020 was 26.93×10^8 m^3 (136.50 mm), 22.86×10^8 m^3 (113.38 mm), and 26.81×10^8 m^3 (137.61 mm), respectively. The spatial pattern of watershed WY remains consistent across various periods, illustrating spatial variation in the depth of low WY in the central and western regions and high WY depth in the eastern region.

(2) At the sub-watershed scale, the YR Basin, the LR Basin, and the Yiluo River section account for 24%, 69%, and 7% of the total WY in the YLRB, respectively. From 2010 to 2020, the WY of the three basins initially decreased and then increased.

(3) Significant variations exist in WY capacity across diverse LU types. The land types with the highest WY capacity in the YLRB are developed land and undeveloped land. The average WY depth is 315.16 mm and 241.47 mm, respectively. The WA has the lowest WY capacity, with an average WY depth of 0.01 mm.

(4) WY was significantly positively correlated with slope, precipitation, actual evapotranspiration, percentage of CL, and NDVI. It showed a significant negative correlated with altitude, WA, and population density.

Author Contributions: Conceptualization, Y.C. and X.Z.; methodology, Y.C. and X.Z.; software, X.Z.; validation, X.Z.; formal analysis, X.Z.; investigation, H.W.; resources, H.W.; data curation, Y.S.; writing—original draft preparation, L.P.; writing—review and editing, L.P.; visualization, X.Z.; supervision, L.P.; project administration, L.P.; funding acquisition, L.P. All authors have read and agreed to the published version of the manuscript.

Funding: This publication is funded by the National Natural Science Foundation of China (No. 52209018, No. 51979107, No. 51909091) and the open subjects of Henan Key Laboratory of Ecological Environment Protection and Restoration of Yellow River Basin (No. LYBEPR202204) and Science and Technology Projects of Water Resources Department of Henan Province, China (GG202332 and GG202334).

Data Availability Statement: Data sharing not applicable. No new data were created or analyzed for this research, and therefore, data sharing is not applicable to this article.

Acknowledgments: The authors are grateful to the editors and anonymous reviewers for their insightful comments and helpful suggestions.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

WY	Water yield
ST	Spatial and temporal
YLRB	Yiluo River Basin
YR	Yi River
LR	Luo River
LU	Land use
CL	Cultivated land
FL	Forest land
GL	Grassland
WA	Water area
CSL	Construction land
UL	Unused land

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