Postprint: Analysis of Water and Sediment Variation Patterns and Their Differences in the Wei River and Jing River Basins

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Date: 2021-04-13T00:00:00+00:00

Abstract

Based on measured hydrological data from 1956–2016, water conservancy and soil conservation statistics, TerraClimate annual mean temperature, and Landsat surface reflectance datasets for the Wei River and Jing River basins, this study analyzed the interannual variation patterns of hydrological elements, air temperature, and vegetation coverage in the basins. Using mathematical statistical methods such as the double mass curve method, cumulative anomaly method, ordered clustering method, Lee-Heghinan method, and rank-sum test method, the abrupt change years of annual runoff and annual sediment load in the basins were identified, and the water and sediment reduction effects of precipitation and human activities were analyzed. The results show that: (1) Annual precipitation, runoff, sediment load, and sediment concentration in both the Wei River and Jing River basins exhibit significant decreasing trends, with precipitation and runoff in the Wei River basin decreasing more than those in the Jing River basin, while sediment in the Jing River basin decreasing more than that in the Wei River basin. (2) The impact of human activities on runoff and sediment in both basins is greater than that of precipitation, and the Jing River basin is more significantly affected by human activities than the Wei River basin. (3) The water-sediment characteristics differ significantly between the two basins: the annual runoff, annual runoff depth, and runoff coefficient of the Wei River are 2.0–2.4 times those of the Jing River basin, while the annual sediment load, annual sediment transport modulus, and mean annual sediment concentration of the Wei River are only 1/2–1/5 of those in the Jing River basin. The main reasons for the significant differences in water-sediment characteristics between these two adjacent basins are differences in climatic conditions such as air temperature and precipitation, variations in underlying surface conditions such as vegetation coverage, and the impacts of human activities including water conservancy and soil conservation measures and the degree of water resources development and utilization.

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Full Text

Runoff and Sediment Variation Rules and Differences in the Wei River and Jing River Basins

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Abstract

Based on measured hydrological data, water conservancy and soil conservation statistics, TerraClimate surface reflectance dataset from 1956–2016 in the Wei River and Jing River Basins, this study analyzed the historical variation patterns of hydrological elements, temperature, and vegetation coverage. Using mathematical statistical methods including double mass curve method, cumulative anomaly method, ordered clustering method, Lee-Heghinan method, and rank sum test method, the abrupt years of annual runoff and sediment load changes were identified, and the effects of precipitation and human activities on runoff and sediment reduction were analyzed. The results show that: (1) Precipitation, runoff, sediment load, and sediment concentration in both basins showed significant decreasing trends. Precipitation and runoff in the Wei River Basin decreased more than in the Jing River Basin, while sediment in the Jing River Basin decreased more than in the Wei River Basin. (2) The impact of human activities on sediment load was greater than that of precipitation in both basins, and the Jing River Basin was more significantly affected by human activities than the Wei River Basin. (3) The hydrological characteristics differed significantly between the two basins. The annual runoff, runoff depth, and runoff coefficient of the Wei River Basin were 2.0–2.4 times those of the Jing River Basin, while the annual sediment load, sediment transport modulus, and average sediment concentration of the Wei River Basin were only 1/2–1/5 of those of the Jing River Basin. The main reasons for these large differences between the two adjacent basins are differences in climate conditions (temperature and precipitation), differences in underlying surface conditions such as vegetation coverage, and the influence of human activities such as water conservancy measures and water resource development and utilization.

Keywords: runoff; sediment; reduction effect of runoff and sediment; Wei River Basin; Jing River Basin

1. Introduction

In 2019, ecological protection and high-quality development of the Yellow River Basin became a national strategic issue, with the central government identifying watershed management as the key to solving Yellow River problems. With the implementation of regional soil and water conservation measures, significant changes have occurred in runoff and sediment in some Yellow River tributaries. Previous studies have shown that water and sediment in the Yellow River Basin are decreasing, primarily due to human activities and climate change. Xu Ruirui et al. analyzed water and sediment variation characteristics and driving factors in different reaches of the Wei River Basin using hydrological data from 10 stations from 1960–2009, finding that runoff in most reaches showed significant decreasing trends, with farmland-to-forest conversion, silt dam construction, and reservoir retention being the main causes. As the largest tributary of the Yellow River, the Wei River has experienced significant changes in spatiotemporal distribution of water and soil resources over recent decades, with soil erosion effectively controlled and river water environment 明显改善. However, problems such as regional water shortage, increasing water use conflicts, and deterioration of local ecological environments persist. Therefore, analyzing water and sediment variation patterns in the Wei River Basin under climate change and human activities is crucial for optimizing regional water resource allocation, adjusting soil erosion control patterns, and promoting ecological protection of the Yellow River Basin.

Given the importance of the Wei River Basin, researchers have conducted numerous studies on water and sediment changes in the Wei and Jing River Basins. Wu Xiaohong et al. analyzed long-term water and sediment variation patterns and attribution in the Jing River using measured data from Zhangjiashan Station. Zheng Peilong et al. studied water and sediment variation in the Jing River Basin from 1960–2012. While these studies focused on individual basins, systematic comparative analysis of water and sediment differences between the two basins remains limited. Therefore, this study uses the latest long-term measured hydrological data to analyze variation patterns of hydrological elements, precipitation and human activity effects on runoff and sediment reduction, and differences in water-sediment characteristics between the Wei River (above Xianyang Hydrological Station before Jing River confluence) and Jing River Basins.

2. Study Area and Methods

2.1 Study Area

The Wei River originates from Niaoshu Mountain in Weiyuan County, Gansu Province, flowing through the Guanzhong Plain in Gansu and Shaanxi Provinces before joining the Yellow River at Tongguan County, Shaanxi Province. The river has a total length of 818 km and a basin area of 1.35×10^{5} km^{2}. Xianyang Hydrological Station is the control station on the main Wei River stream before the Jing River confluence, located 211.1 km from the Yellow River estuary, with a drainage area of 46,827 km^{2}, accounting for 43.4% of the entire Wei River Basin. The multi-year average runoff is 38.08×10^{8} m^{3}, multi-year average sediment load is 0.217×10^{8} t, and multi-year average sediment concentration is 0.586 kg$\cdot$m^{-3}.

The Jing River originates from Liupan Mountain in Ningxia, flows through

Gansu Province, and joins the Wei River in Gaoling District, Shaanxi Province. The basin area is 45,421 km^2, accounting for 36.2% of the Wei River Basin area. Zhangjiashan Hydrological Station is the basin outlet control station, located 483 km from the Wei River estuary, with a drainage area of 43,216 km^2. The multi-year average runoff is 15.66$×10^{8}$ m^3, multi-year average sediment load is 2.064$×10^{8}$ t, and multi-year average sediment concentration is 132.0 $kg \cdot m^{-3}$. The study area includes the Wei River main stream above Xianyang Station and the Jing River area above Zhangjiashan Station [Figure 1: see original paper].

2.2 Data Sources

Data used in this analysis include: (1) measured runoff and sediment data from representative rainfall stations in the basins (Xianyang Station on the Wei River and Zhangjiashan Station on the Jing River); (2) statistical data on water resource development and soil and water conservation measures from the 2016 water resources census; (3) TerraClimate annual average temperature data; and (4) Landsat surface reflectance dataset.

Hydrological data on precipitation, runoff, and sediment were measured by the Yellow River Conservancy Commission and Gansu Provincial Hydrology Department, compiled according to national standards, with complete and reliable data; abnormal values were corrected using water conservancy statistics. Temperature and surface reflectance data were obtained from Google Earth Engine platform. Temperature data were derived from the TerraClimate dataset, which combines WorldClim climatological data with CRU Ts 4.0 and JRA-55 reanalysis data. Landsat surface reflectance data include atmospheric correction products from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI/TIRS sensors, providing near-infrared and infrared bands for vegetation index calculation, plus auxiliary information on clouds, cloud shadows, snow, ice, and water bodies.

2.3 Research Methods

Double mass curve method was used to analyze turning points in long-term runoff and sediment load changes, with cumulative anomaly method, ordered clustering method, Lee-Heghinan method, and rank sum test method for verification. The time series was divided into baseline and treatment periods. Using the pre-turning period as baseline, correlation formulas between annual runoff and precipitation, and annual sediment load and precipitation were established. Post-turning annual precipitation values were input into these formulas to calculate natural runoff and sediment loads under baseline conditions. Differences between calculated and measured values represented human activity effects. The percentage reduction in measured values during treatment period relative to baseline period attributed to human activities was calculated as human activity effect, with precipitation effect being the remainder. Fractional vegetation coverage was calculated from Landsat near-infrared and infrared bands using Google Earth Engine platform for the growing season (June–September) maximum NDVI, based on pure vegetation and pure bare soil pixel values [Figure 2: see original paper].

3. Results

3.1 Historical Changes in Hydrological Elements

Annual precipitation, runoff, sediment load, and sediment concentration in both basins showed decreasing trends from 1956–2016. Multi-year average precipitation was 609.2 mm in the Wei River Basin and 531.6 mm in the Jing River Basin, decreasing at 1.41 mm $\cdot$ a^{-1} and 0.85 mm $\cdot$ a^{-1}, respectively. Multi-year average runoff was 38.08×10^{8} m^3 and 15.66×10^{8} m^3, decreasing at 0.711×10^{8} $m^3 \cdot a^{-1}$ and 0.042×10^{8} $m^3 \cdot a^{-1}$. Multi-year average sediment load was 0.217×10^{8} t and 2.064×10^{8} t, decreasing at 0.037×10^{8} $t \cdot a^{-1}$ and 0.217×10^{8} $t \cdot a^{-1}$. Multi-year average sediment concentration was 0.586 $kg \cdot m^{-3}$ and 132.0 $kg \cdot m^{-3}$, decreasing at 0.905 $kg \cdot m^{-3} \cdot a^{-1}$ and 25.0 $kg \cdot m^{-3} \cdot a^{-1}$. Precipitation and runoff decreased more in the Wei River Basin than in the Jing River Basin (about 2–3 times), while sediment decreased more in the Jing River Basin (1.1–1.5 times). Vegetation coverage increased faster in the Jing River Basin, with annual increases of 0.79% $\cdot$ a^{-1} and 0.71% $\cdot$ a^{-1} for Jing and Wei River Basins, respectively [Figure 3: see original paper].

3.2 Analysis of Turning Points in Water-Sediment Relationships

Double mass curves of annual runoff versus precipitation and annual sediment load versus precipitation were plotted [Figure 4: see original paper]. The slope represents runoff and sediment yield per unit precipitation. For Xianyang Station on the Wei River, the runoff-precipitation double mass curve showed obvious turning points in 1970 and 1994, while the sediment load-precipitation curve showed two consecutive turning points after 1973. For Zhangjiashan Station on the Jing River, both runoff-precipitation and sediment load-precipitation double mass curves showed turning points in 1997, with sediment load showing a major change in 1973. These turning points indicate consistent underlying surface conditions before the turning years. The continuous decrease in water and sediment after these years, with more significant sediment reduction, resulted from human activities including water conservancy projects (silt dams and terraces) and vegetation measures (afforestation, grass planting, and closure for natural regeneration) implemented vigorously in the 1970s–1990s in the Wei River Basin, while Jing River Basin measures increased significantly only after the late 1990s [Figure 5: see original paper].

Statistical tests (Lee-Heghinan method, rank sum test) confirmed significant jump trends at turning points (statistics above confidence levels). Final determined turning years were 1970 and 1994 for runoff, and 1973 and 1994 for sediment load at Xianyang Station; 1997 for both runoff and sediment load at Zhangjiashan Station . The inconsistency in turning years between basins reflects different implementation intensities of soil and water conservation measures.

3.3 Water-Sediment Relationships and Reduction Effects

Correlation curves between annual runoff/precipitation and annual sediment load/precipitation before and after turning years [Figure 6: see original paper] enabled quantification of reduction effects. At Xianyang Station, measured annual runoff decreased from 60.16×10^{8} m^3 in baseline period (1956-1970) to 38.67×10^{8} m^3 (1971-1994) and 22.38×10^{8} m^3 (1995-2016). Human activity effects accounted for 74.7% and 67.1% of runoff reduction, while precipitation effects accounted for 25.3% and 32.9%. Annual sediment load decreased from 1.937×10^{8} t in baseline period (1956-1973) to 0.865×10^{8} t (1974-1994) and 0.233×10^{8} t (1995-2016), with human activity effects of 71.7% and 64.4%, and precipitation effects of 28.3% and 35.6%.

At Zhangjiashan Station, measured annual runoff decreased from 17.43×10^{8} m^3 (1956-1997) to 10.36×10^{8} m^3 (1998-2016), with human activity and precipitation effects of 94.2% and 5.8%, respectively. Annual sediment load decreased from 2.556×10^{8} t to 0.975×10^{8} t, with human activity and precipitation effects of 72.6% and 27.4% . Human activity effects on sediment reduction far exceeded precipitation effects in both basins, playing a dominant role.

3.4 Analysis of Differences in Hydrological Characteristics

Hydrological characteristics differed significantly between the two basins . The Wei River Basin' s annual runoff, runoff depth, and runoff coefficient were 2.0-2.4 times those of the Jing River Basin, while its annual sediment load, sediment transport modulus, and average sediment concentration were only 1/2-1/5 of the Jing River Basin' s values. Main reasons for these large differences include: (1) The Wei River Basin receives more precipitation (19.31% higher), generating greater runoff; (2) Higher temperature and vegetation coverage (1.2 times that of Jing River Basin) result in lighter soil erosion and lower sediment yield; (3) More extensive soil and water conservation measures in the Wei River Basin (terrace area of 85.46×10^{4} hm^2 vs. 28.19×10^{4} hm^2 in Jing River Basin by 2016) provide greater sediment retention; (4) Different water resource development levels (47.6% in Wei vs. 36.8% in Jing by 2016) contribute to more significant measured runoff reduction in the Wei River Basin; (5) Different rates of temperature increase ($0.023°C \cdot a^{-1}$ in Wei vs. $0.026°C \cdot a^{-1}$ in Jing) and vegetation coverage increase ($0.71\% \cdot a^{-1}$ in Wei vs. $0.79\% \cdot a^{-1}$ in Jing) contribute to greater sediment reduction in the Jing River Basin [Figure 7: see original paper].

4. Discussion

The Jing River joins the Wei River in Gaoling District, Xi' an, where distinct water quantity and quality characteristics create the famous "Jing-Wei distinct" phenomenon. Historically, many believed this resulted from the Wei River being more turbid than the Jing River. However, this study reveals that the Wei River Basin has greater annual runoff and runoff depth but only 1/2–1/5 the sediment load, transport modulus, and concentration of the Jing River Basin, showing the Wei is generally clearer. The historical misinterpretation may stem from different mineral compositions in upstream soils causing darker Wei River water color, but based on sediment concentration standards, the Jing River is indeed more turbid.

Comparisons with previous studies show consistency: Ran Dachuan et al. found human activity effects on runoff and sediment reduction in the Wei River Basin were 67.2% and 72.0% during 1970–1996, similar to this study' s results of 67.1% and 64.4% for 1995–2016, indicating stable human activity impacts. For the Jing River Basin, this study shows increased human activity effects (94.2% and 72.6% during 1998–2016) compared to earlier periods, reflecting intensified conservation measures.

The Wei River Basin' s runoff coefficient being 2.0–2.4 times that of the Jing River Basin aligns with the pattern that humid regions have higher runoff coefficients than arid regions. Adjacent to the Yangtze River Basin with tributaries originating from the Qinling Mountains, the Wei River Basin receives 19.31% more precipitation and has higher vegetation coverage, making it relatively more humid and producing more runoff from the same precipitation amount.

Given severe soil erosion and poor water quality in the Jing River Basin, particularly in the upper MaLian River area, intensified management is recommended, including increased terraces, silt dams, and vegetation measures. The Bailong River water transfer project should be accelerated to provide ecological water replenishment for both rivers, improving riverine ecological environments.

5. Conclusions

(1) From 1956–2016, multi-year average annual precipitation in the Wei and Jing River Basins was 609.2 mm and 531.6 mm, respectively; annual runoff was 38.08×10^{8} m^3 and 15.66×10^{8} m^3; annual sediment load was 0.217×10^{8} t and 2.064×10^{8} t; and annual average sediment concentration was 0.586 kg $\cdot$ m^{-3} and 132.0 kg $\cdot$ m^{-3}. While precipitation showed slow decreasing trends, runoff, sediment load, and sediment concentration decreased significantly. Although sediment decreased more in the Jing River Basin, it remains higher than in the Wei River Basin, confirming that the "Jing-Wei distinct" phenomenon is not caused by "Wei water being more turbid than Jing water."

(2) Human activity effects on sediment reduction exceeded precipitation ef-

fects in both basins, with the Jing River Basin more significantly affected. At Xianyang Station, human activity effects on runoff and sediment reduction were 74.7% and 71.7% (1971-1994) and 67.1% and 64.4% (1995-2016). At Zhangjiashan Station, human activity effects were 94.2% and 72.6% (1998-2016).

(3) The two basins showed significantly different hydrological characteristics. The Wei River Basin' s annual runoff, runoff depth, and runoff coefficient were 2.0-2.4 times those of the Jing River Basin, while its sediment load, transport modulus, and concentration were only 1/2-1/5 of the Jing River Basin' s values. These differences primarily result from different climate conditions (temperature and precipitation), underlying surface conditions (vegetation coverage), and human activities (soil conservation measures and water resource development).

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Note: Figure translations are in progress. See original paper for figures.