Water and Sediment Variation Characteristics and Their Influencing Factors in the Huangfuchuan Basin (Postprint)

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Abstract

Based on long-term monitoring data of precipitation, runoff, and sediment discharge in the Huangfuchuan Basin from 1954 to 2018, this study investigated the periodic evolution characteristics of water and sediment in the Huangfuchuan Basin using methods such as linear trend analysis, Mann-Kendall test, and cumulative anomaly method, and quantitatively evaluated the contribution rates of precipitation change and human activities to runoff and sediment discharge variations in the Huangfuchuan Basin using hydrological analysis methods. The results indicate that precipitation in the Huangfuchuan Basin shows an insignificant decreasing trend over time, while runoff and sediment discharge exhibit significant decreasing trends, with the decreasing trend in runoff being greater than that in sediment discharge. Both runoff and sediment discharge underwent an abrupt change from abundant to scarce in 1986. Using 1954–1986 as the baseline period, the impacts of human activities on runoff and sediment discharge in the Huangfuchuan Basin during 1987–2018 were 83.04% and 75.24%, respectively, while the impacts of precipitation change were 16.96% and 24.76%, respectively. Sediment discharge decreased significantly around the abrupt change year, with the contribution rate of runoff generation capacity to sediment discharge variation exceeding 85%. Precipitation change and human activities are the influencing factors causing water and sediment reduction in the Huangfuchuan Basin, among which the intensifying human activities within the basin are the primary factor driving the reduction in runoff and sediment discharge, while precipitation reduction caused by climate change is a secondary factor.

Full Text

Abstract

Based on long-term monitoring data of precipitation, runoff, and sediment discharge in the Huangfuchuan basin from 1954 to 2018, this study investigated the periodic evolution characteristics of water and sediment using linear trend analysis, Mann-Kendall tests, and cumulative anomaly methods. The hydrological analysis method was applied to quantitatively evaluate the contribution rates of precipitation change and human activities to runoff and sediment transport variations. The results indicate that precipitation showed a non-significant decreasing trend over time, while runoff and sediment transport exhibited significant decreasing trends, with runoff decreasing more rapidly than sediment transport. An abrupt shift from abundant to dry conditions occurred in 1986 for both runoff and sediment transport. Using 1954–1986 as the baseline period, human activities contributed 83.04% to runoff reduction and 75.24% to sediment transport reduction during 1987–2018, while precipitation change contributed 16.96% and 24.76%, respectively. Reduced runoff capacity contributed over 85% to sediment transport changes. Both precipitation change and human activities influence water and sediment reduction in the Huangfuchuan basin, with intensifying human activities as the primary driver and climate-induced precipitation reduction as a secondary factor.

Keywords: Huangfuchuan basin; precipitation; human activities; runoff; sediment transport

1 Study Area and Methods

1.1 Study Area Overview

The Huangfuchuan basin (39°12 –39°54 N, 110°18 –112°12 E) is located in the middle reaches of the Yellow River between Hekou Town and Longmen, on the right bank upstream section. As a first-order tributary of the Yellow River, it originates from Zhungeer Banner in eastern Ordos, Inner Mongolia, flows through the transition zone of the Loess Plateau and Inner Mongolia grasslands, and empties into the Yellow River at Batu Ping in Fugu County, Shaanxi Province. The basin covers a total area of 3,246 km^2, with 1351 km^2 of primary tributaries and a main stream (Nalin River) length of 137 km. The climate is temperate continental monsoon, with an average annual temperature of 9.1°C and precipitation of 350–450 mm. Precipitation is concentrated from June to September, accounting for over 70% of the annual total, and shows a decreasing gradient from southeast to northwest. The basin is characterized by crisscrossing gullies, severe soil erosion, and a landscape of narrow ridges and dense gullies with fragmented terrain. Soil erosion is dominated by water erosion, combined with wind and gravitational erosion. The Loess thickness increases from northwest to southeast, with loose soil structure that is highly susceptible to weathering and erosion during high-intensity storms. The current vegetation consists mainly of grassland, farmland, shrubland, and arbor forest, with most natural forests and shrub grasslands having been replaced by artificial vegetation.

1.2 Data Sources

Considering data continuity and completeness, and based on the distribution of hydrological stations in the basin, this study analyzed water and sediment periodic variation characteristics using runoff and sediment data from 1954–2018. Runoff and sediment data for 1954–2010 were obtained from the Yellow River Basin Hydrological Yearbook, while data for 2011–2018 came from the Yellow River Sediment Bulletin. Although there are seven rainfall stations in the Huangfuchuan basin, some data were missing. Therefore, precipitation data for 1954–2018 were generated using inverse distance weighting of data from seven rainfall stations to discuss the impact of climate change on basin water and sediment. According to relevant research, temperature in the Loess Plateau shows no significant correlation with runoff or sediment volume, so only precipitation factors were considered in the climate change analysis. Human activities affect runoff and sediment transport in various ways, but these activities are difficult to statistically quantify on an annual basis. The numerical impact of human activities on water and sediment changes is hard to collect, and inconsistent statistical standards across different decades have led to data inaccuracies. Therefore, this study only discusses the contribution rate of human activities to water and sediment changes in the Huangfuchuan basin.

1.3 Methods

1.3.1 Stage Changes in Runoff and Sediment Transport Simple linear regression analysis and cumulative anomaly methods were used to systematically analyze long-term stage differences in runoff and sediment transport in the Huangfuchuan basin. For a specific time series Xi with length n, the cumulative anomaly value Xt can be calculated as follows:

$$Xt = \sum_{i=1}^{t} (Xi - \bar{X})$$

where Xt is the cumulative anomaly value, Xi represents the observation value, and $\bar{X}$ is the mean value. Cumulative anomaly values primarily detect potential mutation points in observations and identify temporal trends. When the observation value is positive, it indicates that the value at the mutation point is above the average; conversely, a negative value indicates it is below the average.

1.3.2 Sediment Attribution Diagnostic Analysis Sediment attribution diagnostic analysis was used to determine the contribution of precipitation, runoff generation capacity, and sediment generation capacity to the proportional change rate of sediment transport in the Huangfuchuan basin, thereby assessing the influence of each factor on sediment transport changes. The specific calculation formulas are as follows:

Let P be the average precipitation in the Huangfuchuan basin, f be the runoff generation capacity (ratio of runoff to precipitation), s be the sediment generation capacity (ratio of sediment transport to runoff), F be the runoff volume, and S be the sediment transport volume. The proportional change rate of X is defined as r(X), and the proportional change rate of sediment transport S is r(S).

2 Results and Analysis

2.1 Interannual Variation Characteristics of Precipitation

The average annual precipitation in the basin was 419.78 mm, with a coefficient of variation of 0.25–0.37, indicating moderate-scale variation. The maximum precipitation was 715 mm in 1967, and the minimum was 211.3 mm in 1965. Precipitation in the Huangfuchuan basin showed a gradual decreasing trend across decades in the 20th century, with a gradual increase only emerging in the 21st century. The coefficient of variation ranged from 6.76 to 21, with an average of 14.13, also indicating moderate-scale variation. The precipitation extreme value ratio ranged from 2.31 to 6.76, with a mean of 4.44. The rate of precipitation decrease was 0.71 $\mathrm{mm \cdot a^{-1}}$ ($P > 0.05$), which did not reach significance, indicating a non-significant decreasing trend in precipitation from 1954 to 2018.

2.2 Interannual Variation Characteristics of Runoff and Sediment Transport

2.2.1 Runoff Interannual Variation Characteristics The average annual runoff in the Huangfuchuan basin was 1.23×10^8 $\mathrm{m^3}$, with a coefficient of variation of 0.56–1.01, indicating moderate-scale variation. The runoff extreme value ratio ranged from 14.13 to 44.04, with an average of 0.63. The rate of runoff change was -3.62×10^6 $\mathrm{m^3 \cdot a^{-1}}$ ($P < 0.05$), reaching a significant level and indicating a significant decreasing trend in runoff from 1954 to 2018.

2.2.2 Sediment Transport Interannual Variation Characteristics The average annual sediment transport in the Huangfuchuan basin was 5.83×10^6 t, with a coefficient of variation of 0.63–1.39, indicating moderate-scale variation. The sediment transport extreme value ratio ranged from 1.17×10^{-1} to 1.01, with an average of 0.36. The rate of sediment transport change was -1.17×10^5 $\mathrm{t \cdot a^{-1}}$ ($P < 0.05$), reaching a significant level and indicating a significant decreasing trend in sediment transport from 1954 to 2018.

Both runoff and sediment transport trend test Z-values were negative, passing the 0.05 significance test, indicating significant decreasing trends. The runoff trend test Z-value was -5.83, while the sediment transport trend test Z-value was -4.76, indicating that the decreasing trend in runoff was greater than that in sediment transport. The Sen's slope values were also negative, confirming that both runoff and sediment transport in the Huangfuchuan basin showed downward trends, with runoff decreasing more rapidly than sediment transport.

2.3 Stage Variation Characteristics of Runoff and Sediment Transport

The cumulative anomaly curves for runoff and sediment transport in the Huangfuchuan basin showed distinct stage characteristics. Both cumulative anomaly values reached their maximum in 1986, indicating that runoff and sediment transport underwent a mutation in 1986. Based on this mutation year, the runoff and sediment transport can be divided into two stages: 1954–1986 and 1987–2018. The average annual runoff was 1.84×10^8 m^3 before the mutation and 0.66×10^8 m^3 after, representing a decrease of 64.1%. The average annual sediment transport was 1.833×10^7 t before the mutation and 5.83×10^6 t after, representing a decrease of 68.2%. According to the intersection point of the UF and UB curves, the mutation for both runoff and sediment transport occurred in 1986, consistent with the cumulative anomaly test results.

2.4 Impacts of Precipitation Change and Human Activities on Water and Sediment Variation

Using 1986 as the breakpoint, the precipitation, runoff, and sediment transport data were divided into two periods. Substituting post-mutation precipitation data into the regression equation established by the double mass curve yielded correlation equations for the impacts of precipitation change and human activities on water and sediment variation, with correlation coefficients reaching significance levels above 0.01 ($P < 0.01$). Using 1954–1986 as the baseline period, human activities contributed 83.04% to runoff variation and 75.24% to sediment transport variation in the Huangfuchuan basin during 1987–2018, while precipitation change contributed 16.96% and 24.76%, respectively. Both the precipitation-runoff and precipitation-sediment double mass curves showed inflection points, with post-mutation curve slopes smaller than pre-mutation slopes. Before the mutation, the cumulative runoff variation amplitude was greater than that of cumulative sediment transport, and the cumulative runoff curve slope was greater than the cumulative sediment transport curve slope. This occurred because increased precipitation enhanced river flow, substantially improving water delivery capacity more than sediment transport capacity. After the mutation, the cumulative runoff variation amplitude was smaller than that of sediment transport, and the cumulative sediment transport curve slope was greater than the cumulative runoff curve slope, primarily because reduced runoff decreased sediment transport capacity, causing substantial sediment deposition.

While precipitation in the Huangfuchuan basin from 1954 to 2018 showed a non-significant decreasing trend ($P > 0.05$), water and sediment changes showed significant decreasing trends ($P < 0.05$), indicating that intensifying human activities in the basin are the main factor driving runoff and sediment reduction, with precipitation reduction caused by climate change being a secondary factor.

Sediment attribution diagnostic analysis was applied to calculate the proportional change rates of sediment characteristic factors (S, P, f, s) in different periods using formulas (5) and (6), thereby determining each factor's contribution to sediment transport changes. As shown in Table 5, sediment transport in the Huangfuchuan basin generally decreased from 1954 to 2018, with a proportional change rate of -0.49% $\cdot$ a^{-1}. The runoff factor f contributed 0.54% $\cdot$ a^{-1}, the sediment factor s contributed 0.36% $\cdot$ a^{-1}, while precipitation factor P showed an opposite trend, contributing -0.41% $\cdot$ a^{-1} to the proportional change rate. Both runoff and sediment transport mutations began in 1986, dividing the sediment transport changes into two periods: 1954–1986 and 1987–2018. From 1954 to 1986, the proportional change rate was -0.17% $\cdot$ a^{-1}, with factor f contributing 0.19% $\cdot$ a^{-1}, factor s contributing 0.11% $\cdot$ a^{-1}, and factor P contributing -0.13% $\cdot$ a^{-1}. From 1987 to 2018, the proportional change rate was -0.81% $\cdot$ a^{-1}, showing a significant decreasing trend, with factor f contributing 0.89% $\cdot$ a^{-1}, factor s contributing 0.61% $\cdot$ a^{-1}, and factor P contributing -0.69% $\cdot$ a^{-1}. Analysis of both periods reveals that the runoff factor f plays a decisive role in the proportional change rate of sediment transport in the Huangfuchuan basin, the sediment factor s contributes relatively less, and the precipitation factor P even plays an opposite role.

3 Discussion

Precipitation is the primary source of runoff recharge and directly affects runoff magnitude, while runoff changes influence sediment transport, making precipitation one of the decisive factors affecting both. Meteorological data studies indicate that precipitation in the Huangfuchuan basin has a decreasing trend, with the climate developing toward warmer and drier conditions. Climate change-induced precipitation reduction significantly impacts runoff and sediment transport in the basin. From 1954 to 2018, precipitation in the Huangfuchuan basin showed a decreasing trend (Figure 2), and water and sediment showed the same trend (Figure 3), demonstrating that precipitation is an important factor. Zhao et al. [5] quantitatively evaluated the contribution rates of precipitation and human activities to water and sediment changes at the Huangfu hydrological station using hydrological analysis methods, finding that precipitation change contributed 25.8% to runoff variation, with similar impacts on sediment transport. Wan et al. [7] studied runoff and sediment transport in the Huangfuchuan basin from 1955 to 2013 using linear trend methods, calculating an average annual precipitation of 424 mm and identifying precipitation reduction as an important factor causing corresponding decreases in water and sediment. Hu et al. [8] explored the causes of runoff reduction in the Huangfuchuan basin using hydrological sensitivity analysis, finding that precipitation reduction contributed 24.76% to runoff variation when comparing the natural period (1954–1986) with the runoff change period (1987–2010). These related studies are consistent with our conclusions. However, while precipitation in the Huangfuchuan basin showed a non-significant decreasing trend ($P > 0.05$), water and sediment changes showed significant trends ($P < 0.05$), indicating that the declining trend in water and sediment is more pronounced than that in precipitation. This suggests that precipitation's influence on runoff and sediment generation capacity is weakening over time and is not the sole factor affecting water and sediment changes—other important factors are also involved.

Human activities refer to various practices that directly affect basin runoff and sediment transport or alter underlying surface conditions, including urbanization, soil and water conservation, water consumption, and hydraulic engineering construction [9]. Water and sediment changes in the Huangfuchuan basin are influenced by human activities such as the Grain for Green program, check dam construction, and soil and water conservation measures, which have markedly altered the underlying surface and increased disturbance to water and sediment, reducing river runoff and sediment transport. Since the 1980s, large-scale implementation of the Grain for Green program has converted extensive farmland to grassland and forest, serving soil and water conservation and windbreak functions. Additionally, the promotion of conservation tillage techniques such as no-tillage and reduced tillage has directly reduced soil erosion material sources. Optimized crop planting structures and densities have decreased bare soil area, effectively intercepting rainfall, reducing surface erosion, improving soil structure, increasing soil porosity, and enhancing permeability, thereby reducing surface runoff and sediment transport [10]. Mu et al. [11] quantitatively evaluated the contribution rates of precipitation and human activities to water and sediment changes at the Huangfu hydrological station, finding that human activities contributed 77.5% to runoff variation during the 1980s and 56.4% during the 1990s. Liu et al. [12] conducted mutation analysis on Huangfuchuan runoff, concluding that human activities became the dominant factor reducing runoff after the 1980s due to urbanization, increased built-up area, vegetation type changes, and ecological balance disruption. Zhao et al. [5] found that despite no significant precipitation reduction, the primary cause of sediment reduction in the Huangfuchuan basin was the numerous check dams that effectively stored water and trapped sediment. By 2012, the basin had constructed 1,833 check dams controlling the entire basin's runoff; after river flow was impounded, upstream water lost its capacity to scour downstream channels, achieving erosion reduction. These studies consistently demonstrate that climate change-induced precipitation reduction and human activities are influencing factors for reduced runoff and sediment transport in the Huangfuchuan basin, with intensifying human activities as the main driver and precipitation reduction as a secondary factor.

4 Conclusions

This study utilized long-term water and sediment monitoring data from 1954–2018 in the Huangfuchuan basin, employing linear trend analysis, Mann-Kendall tests, and cumulative anomaly methods to analyze water and sediment evolution characteristics. Hydrological analysis methods were applied to quantitatively assess the contribution rates of precipitation change and human activities to runoff and sediment transport variation, while sediment attribution diagnostic analysis determined the contributions of precipitation, runoff generation capacity, and sediment generation capacity to the proportional change rate of sediment transport. The main conclusions are:

1) Precipitation in the Huangfuchuan basin showed a non-significant decreasing trend, while runoff and sediment transport showed significant decreasing trends, with runoff decreasing more rapidly than sediment transport.

2) Precipitation change and human activities are influencing factors for water and sediment reduction in the Huangfuchuan basin, with intensifying human activities as the primary driver of runoff and sediment reduction, and climate-induced precipitation reduction as a secondary factor.

3) Sediment attribution diagnostic analysis for different stages indicates that the runoff generation factor f plays a decisive role in the proportional change rate of sediment transport in the Huangfuchuan basin, the sediment generation factor s contributes relatively less, and the precipitation factor p plays an opposite role.

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