

Postprint: Runoff Evolution Patterns in Response to Precipitation and Soil and Water Conservation Measures Intensity in Semi-arid Regions

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Abstract

To investigate the evolution patterns of precipitation, soil and water conservation measure intensity, and runoff under varying temporal periods and soil and water conservation conditions, the Thiessen polygon method, Morlet wavelet analysis, and regression analysis were employed to construct a multivariate efficacy function, conducting a study on the evolution of precipitation, measure intensity, and runoff in Anding District, Dingxi City, Gansu Province over the past 60 years. The results indicate that annual runoff from 1957 to 2016 exhibited a decreasing trend, reaching an extremely significant level ($P < 0.001$). At time scales of 22–24 years, 8 years, and 4 years, annual precipitation and runoff exhibited distinct oscillation periods, with average periods of approximately 15 years, 5 years, and 3 years, respectively. The intensity of soil and water conservation measures, including terraced fields, afforestation, grass planting, and enclosure, increased year by year, reaching $36.14 \text{ hm}^2 \cdot \text{km}^{-2}$, $25.26 \text{ hm}^2 \cdot \text{km}^{-2}$, $11.56 \text{ hm}^2 \cdot \text{km}^{-2}$, and $3.22 \text{ hm}^2 \cdot \text{km}^{-2}$, respectively. As the period lengthened (3 years, 5 years, 15 years), the impact of equivalent precipitation on runoff yield increased, while the impact of equivalent soil and water conservation measure intensity on runoff yield decreased. The combination of precipitation and measure intensity explained 57.46% ~ 85.80% of the total variance in runoff modulus. The influence of precipitation on runoff modulus was approximately 40% lower, while the influence of measure intensity was approximately 60% higher, indicating that measure intensity had a greater impact on runoff than precipitation. The reduction in runoff over the past 60 years was primarily caused by the increasing implementation of soil and water conservation measures.

Full Text

Precipitation and Soil and Water Conservation Measures Intensity-Runoff Evolution Law in Semi-Arid Areas

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Abstract

The evolution law and causal analysis of runoff under changing environments, particularly the quantitative assessment of precipitation and soil and water conservation measures' impacts on runoff, remain critical research topics in hydrology and water resources. This study investigates the evolution patterns of precipitation, conservation measures intensity, and runoff across different periods in Anding District, Dingxi City, Gansu Province. Using the Thiessen polygon method, wavelet analysis, and regression analysis, we constructed a multivariate efficacy function to analyze 60 years of data. Results show that annual runoff exhibited a significant decreasing trend from 1957 to 2016, reaching an extremely significant level ($P < 0.001$). Both annual precipitation and runoff displayed distinct oscillation periods at time scales of approximately 22–24 years, 8 years, and 4 years, with average periods of about 15 years, 5 years, and 3 years, respectively. The intensity of soil and water conservation measures—including terracing, afforestation, grass planting, and enclosure—increased progressively over time, reaching 25.26 hm², 11.56 hm², 3.22 hm², and 36.14 hm², respectively. As the analysis period lengthened, the impact of equivalent precipitation amounts on runoff generation increased, while the effect of equivalent measure intensity decreased. The combined influence of precipitation and measure intensity explained 57.46%–85.80% of the total variance in runoff modulus, with measure intensity exhibiting approximately 60% greater influence than precipitation. The continuous decline in runoff was primarily attributed to the increasing intensity of soil and water conservation measures. These findings provide scientific support for rational land use adjustment and ecological conservation planning in semi-arid regions.

Keywords: evolution law; precipitation; soil and water conservation measures

intensity; runoff; semi-arid area

1 Study Area Overview

Anding District is located in the central-southern part of Gansu Province within the Zuli River basin, spanning 104°12'48" E -105°01'06" E and 35°17'54" N -36°02'40" N. The total land area is 3,638.71 km², with soil erosion affecting 1,573.65 km² (43.25% of the total area). The region experiences a temperate continental climate characterized by marked seasonal variations and significant temperature differences. Precipitation is scarce and concentrated, with an annual average of 415.6 mm and an average evaporation rate of [Figure 1: see original paper]. The district faces severe challenges including drought, serious soil erosion, and fragile ecological conditions, making it one of the impoverished counties in Gansu Province. Water and gravitational erosion constitute the primary soil loss types. By the end of 2016, terraced fields covered 9.21×10^4 hm² (76.18% of sloping land), afforestation measured 13.17×10^4 hm², and grass planting accounted for 4.21×10^4 hm².

[Figure 1: see original paper] Geographical location and observation site distribution map of Anding District

2 Data and Methods

2.1 Data Collection

Precipitation and runoff data were obtained from the Gansu Provincial Bureau of Hydrology and Water Resources. The study area includes rainfall observation stations at Neiguanying, Hongtu, Qinggang, Xihe, and surrounding stations at Qinglan, Quantou, and Houtouwan (1957-2016). The Thiessen polygon method was used to determine average precipitation. The hydrological observation station was originally located at Chankou but was relocated to Donghe and Xihe stations in Dingxi City after 1971. Consequently, runoff data for 1957-1970 originated from Chankou station, while data from 1971 onward were derived from Donghe and Xihe stations using area-weighted averaging. Soil and water conservation measures data were primarily sourced from the Gansu Provincial Water Resources Statistical Yearbook and Soil and Water Conservation Annual Reports (1957-2016), supplemented by second national land survey data and annual updates (2009-2016), forestry department forest inventory data (1999-2016), and Grain for Green project data (2000-2016).

2.2 Methods

2.2.1 Thiessen Polygon Method The Thiessen polygon method is widely applied in precipitation data processing. Based on observational data and polygon areas, weighted averages are calculated to determine areal precipitation.

2.2.2 Wavelet Analysis Wavelet analysis is an effective time-frequency analysis method for studying periodic variations in hydrological time series. The key to applying wavelet analysis lies in selecting an appropriate mother wavelet function. This study employed the Morlet wavelet to generate wavelet coefficient contour maps and wavelet variance diagrams, revealing multi-timescale periodic characteristics of annual precipitation and runoff series.

2.2.3 Regression Analysis SPSS 20.0 was used for regression analysis between independent and dependent variables. Multiple regression analysis was performed between soil and water conservation measures and runoff modulus to determine the influence magnitude of various factors. Based on the power function $Y = aX^b$, a multivariate efficacy function was constructed. When $b > 0$, the function increases monotonically; when $b < 0$, the function decreases monotonically, with two asymptotes approaching zero as the independent variable increases or decreases.

3 Results and Analysis

3.1 Precipitation Variation Characteristics

3.1.1 Interannual Precipitation Variation Annual precipitation showed no significant increasing or decreasing trend from 1957 to 2016, averaging 415.6 mm. Maximum annual precipitation reached 715.6 mm (1967), while the minimum was 268.4 mm (1991). Flood season precipitation accounted for over 70% of annual totals, indicating concentrated rainfall distribution.

3.1.2 Precipitation Periodic Variation The wavelet coefficient real part contour map [Figure 3: see original paper] reveals precipitation periodicity at multiple timescales. Throughout the analysis period, periodic variations were evident at 22-24-year, 8-year, and 4-year scales. The 22-24-year scale exhibited the strongest energy and most pronounced oscillations, while the 8-year scale showed weaker energy but clear periodicity. The wavelet variance diagram [Figure 4: see original paper] identified three major peaks corresponding to 22-year, 8-year, and 4-year scales, with the 22-year period showing the strongest amplitude as the primary cycle, followed by the 8-year and 4-year periods as secondary and tertiary cycles, respectively.

Based on these results, the average periodicities were approximately 15 years at the 22-year scale, 5 years at the 8-year scale, and 3 years at the 4-year scale. Positive wavelet coefficients indicate wet periods, while negative values represent dry periods.

3.2 Runoff Modulus Variation Characteristics

3.2.1 Interannual Runoff Modulus Variation Annual runoff modulus averaged $1.198 \times 10^4 \text{ m}^3 \cdot \text{km}^{-2}$, with a maximum of $4.522 \times 10^4 \text{ m}^3 \cdot \text{km}^{-2}$ in 1967 (corresponding to maximum precipitation) and a minimum of $0.056 \times 10^4 \text{ m}^3 \cdot$

km^{-2} in 2016. Flood season runoff modulus accounted for over 70% of annual totals in most years [Figure 5: see original paper].

3.2.2 Runoff Periodic Variation The runoff wavelet analysis [Figure 6: see original paper] revealed periodicities at 22-24-year, 8-year, and 4-year scales, similar to precipitation. The wavelet variance diagram [Figure 7: see original paper] showed three major peaks at 22-year, 8-year, and 4-year scales, with the 22-year period as the primary cycle. At the 22-year scale, runoff exhibited an average periodicity of approximately 15 years with 4 wet-dry alternations, with amplitude decreasing after 2000. At the 8-year scale, the average period was about 5 years with 12 alternations, showing an initial amplitude increase followed by decrease. At the 4-year scale, the average period was approximately 3 years with 20 alternations, also displaying an initial increase then decrease in amplitude.

3.3 Soil and Water Conservation Measures Intensity Change

From 1957 to 2016, soil and water conservation measures primarily included terracing, afforestation, grass planting, and enclosure management. By the end of 2016, measure intensities reached 25.26 hm^2 , 11.56 hm^2 , 3.22 hm^2 , and 36.14 hm^2 , respectively [Figure 8: see original paper]. Measure intensity increased annually with implementation duration, with terracing and afforestation showing distinct stage characteristics. Terracing exhibited the highest average intensity at 14.25 hm^2 , followed by afforestation (10.05 hm^2) and grass planting (5.05 hm^2). The average annual growth rate was highest for terracing ($0.61 \text{ hm}^2 \cdot \text{a}^{-1}$), followed by afforestation ($0.57 \text{ hm}^2 \cdot \text{a}^{-1}$).

[Figure 8: see original paper] Intensity of control measures and rate change

3.4 Relationship Between Precipitation, Measures Intensity and Runoff Modulus at Different Periods

3.4.1 Dynamic Variation Analysis Multiple regression models for different periods (3-year, 5-year, 15-year) all reached extremely significant levels ($P < 0.001$). As the period lengthened, correlation coefficients (r) and F-test values increased. The regression coefficient for precipitation (b_1) increased significantly, indicating that equivalent precipitation produced greater runoff over longer periods. Conversely, the regression coefficient for measures intensity (b_2) decreased significantly, showing that equivalent measure intensity reduced runoff modulus more effectively over longer periods.

TABLE:1 Regression equation of annual precipitation, intensity of measures and runoff modulus at different periods

3.4.2 Impact Factor Analysis Standard regression coefficients (absolute values) reflect the magnitude of influence. Precipitation's influence increased from 23.46% to 44.09% as the period lengthened, while measures intensity's

influence decreased from 71.34% to 61.15%. Nevertheless, measures intensity consistently exerted greater influence than precipitation, with its impact being approximately 60% higher. The combined factors explained 57.46%-85.80% of runoff modulus variance, indicating that measures intensity is the dominant factor controlling runoff change.

TABLE:2 Standard regression coefficient of annual precipitation, intensity of measures and runoff modulus at different periods

4 Discussion

4.1 Runoff Modulus-Precipitation Relationship

During the first decade, runoff responded strongly to precipitation changes with high trend synergy and good correlation. Over the subsequent 50 years, this response attenuated rapidly, with synergistic alienation indicating that runoff changes after 1986 were increasingly influenced by other factors, particularly after 2000. This attenuation is closely associated with implemented conservation measures including terracing, afforestation, grass planting, and enclosure. The study area established small-scale check dams starting in 1970 and large-scale gully engineering projects (25 dams) after 2000. Research in the Loess Plateau's Huangfuchuan watershed demonstrated that check dams can cause over 52.32% runoff reduction. Additionally, summer convective weather concentrates heavy rainfall in afternoons, with summer runoff increases having the greatest impact on annual totals. Regional differences and environmental complexity mean runoff is influenced by multiple factors including precipitation, snowmelt, slope measures, gully engineering, temperature, evapotranspiration, and groundwater fluctuations.

4.2 Runoff Modulus-Measures Intensity Relationship

From 1957-1970, when measures intensity was low, runoff showed weak response to measures changes with poor trend synergy. From 1971-2016, as measures intensity increased, runoff response strengthened. After 2000, the implementation of Grain for Green, slope-to-terrace conversion, and gully engineering caused sharp runoff declines. Soil and water conservation measures effectively intercepted surface runoff, consistent with findings from the Loess Hilly Region.

4.3 Period-Dependent Relationships

Analysis across different periods revealed that as the period lengthened, precipitation's regression and standard coefficients increased, indicating greater runoff generation from equivalent precipitation amounts. Conversely, measures intensity coefficients decreased, showing that interception capacity gradually diminished over longer periods, with reduced runoff reduction per unit area.

5 Conclusions

This study analyzed precipitation, soil and water conservation measures intensity, and runoff characteristics in Anding District from 1957–2016, yielding three main conclusions:

1. **Runoff and Precipitation Variation:** While annual precipitation showed no significant trend, it exhibited clear oscillation periods at 22–24-year, 8-year, and 4-year scales. Runoff modulus displayed a significant decreasing trend ($P < 0.001$) with similar periodicities. Both shared average periods of approximately 15 years, 5 years, and 3 years.
2. **Runoff and Measures Intensity:** Conservation measures intensity increased annually, reaching 36.14 hm^2 , 25.26 hm^2 , 11.56 hm^2 , and 3.22 hm^2 for enclosure, terracing, afforestation, and grass planting, respectively. As measures intensity increased, runoff modulus decreased correspondingly, confirming measures intensity as the primary factor influencing runoff.
3. **Combined Effects:** With period lengthening, equivalent precipitation increased runoff modulus while equivalent measures intensity decreased it. The combined factors explained 57.46%–85.80% of runoff variance, with measures intensity exerting approximately 60% greater influence than precipitation. Under relatively stable precipitation conditions, the continuous runoff decline was primarily caused by increasing conservation measures intensity.

These findings provide scientific support for rational land use planning and soil and water conservation deployment in semi-arid regions.

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