Evaluation and Combined Analysis of Runoff Abundance and Deficiency in the Hotan River, Xinjiang: A Postprint

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Abstract

Based on annual and monthly runoff data from 1960 to 2016 at the Tongguziluoke and Uluwati hydrological stations, the mean-standard deviation method and fuzzy set pair analysis method were respectively employed to evaluate the wetness-dryness categories of the two major tributaries of the Hotan River. Building upon this, the fuzzy set pair method and Copula function method were optimized to calculate the combined wetness-dryness probabilities of the runoff from the two source streams, while simultaneously analyzing the complementary advantages and disadvantages between the two tributaries. The results indicate that the fuzzy set pair method, by considering the intra-annual runoff contribution, yields more objective evaluation results; the Yulongkashi River has the highest proportion of dry years, necessitating enhanced water resource utilization during dry periods; the Karakashi River has the highest proportion of normal flow years, indicating stable annual water availability in the Karakashi River. The wetness-dryness probabilities derived from statistical methods and Copula functions exhibit discrepancies related to data usage, classification methods, and the elevation of the source regions. Both methods demonstrate that asynchronous wetness-dryness probabilities are greater than synchronous wetness-dryness probabilities, indicating good complementarity between the two tributaries. This result can more clearly describe the runoff wetness-dryness status and combination characteristics of the Hotan River, providing a reference and decision-making basis for water resources regulation in the Hotan River basin.

Full Text

Abstract

Based on annual and monthly runoff data from the Tongguziluoke and Wuluwati hydrological stations, this study employs both the mean-standard deviation method and fuzzy set pair analysis to evaluate the wetness-dryness categories of the two major tributaries of the Hotan River. Building upon this evaluation, the fuzzy set pair method and Copula function are used to calculate the combined probability of synchronous-asynchronous runoff encounters, while analyzing the complementary characteristics between tributaries. Results demonstrate that the fuzzy set pair method yields more objective evaluations by considering intra-annual runoff contributions. The Yulong Kashi River exhibits the highest proportion of dry years, indicating the need to improve water resource utilization during low-flow periods. The Karakashi River shows the highest proportion of normal years, reflecting its consistently stable runoff. Differences exist between the wetness-dryness probabilities derived from statistical methods and Copula functions, which are related to data usage, classification approaches, and source region elevations. Both methods consistently show that asynchronous encounter probabilities exceed synchronous encounter probabilities, indicating good complementarity between the two tributaries. These findings provide a clearer description of runoff wetness-dryness conditions and combination characteristics in the Hotan River, offering valuable references and decision-making support for water resources management in the basin.

Keywords: fuzzy set pair method; Copula function; mean-standard deviation method; synchronous-asynchronous combination; Hotan River; Xinjiang

1 Study Area Overview

The Hotan River basin is located in southwestern Xinjiang, between the southern margin of the Tarim Basin and the northern foothills of the Kunlun Mountains, with geographical coordinates of 34°52 ~40°28 N and 77°25 ~81°43 E, covering a drainage area of approximately 48,870 km^2. Influenced by the obstruction of the Kunlun Mountains and Pamir Plateau, warm-moist airflow from the Indian Ocean struggles to enter the region, resulting in a continental climate characterized by aridity, low precipitation, high temperatures, and high potential evaporation. The Hotan River main channel is formed by the confluence of the Yulong Kashi River (Yulong River) and the Karakashi River (Kara River) [Figure 1: see original paper], flowing through the Taklamakan Desert before joining the Tarim River as one of its three sources. The Hotan River not only undertakes the task of water conveyance to the Tarim River but also maintains the ecological environment of surrounding areas. With continuous infrastructure development and economic investment in southern Xinjiang, the population and cultivated land area in the Hotan River basin have rapidly increased. Ecological water use has been squeezed by domestic and productive water demands, threatening ecological stability. Without rational water allocation, the basin faces risks of land desertification and ecological imbalance.

2 Data and Methods

Traditional analyses often use the mean-standard deviation method to classify runoff wetness-dryness categories. This method relies on annual runoff data for classification but neglects differences in intra-annual runoff contributions to the annual total, while also failing to address the fuzziness of wetness-dryness boundaries, potentially leading to biased results. To address these limitations, this study incorporates fuzzy concepts and weight calculations into set pair analysis, employing fuzzy set pair analysis for scientific classification of runoff wetness-dryness. Research on runoff variation patterns typically relies on statistical methods requiring extensive data to ensure accuracy. This study uses fuzzy set pair analysis to determine runoff wetness-dryness categories and calculates variation probabilities using statistical methods based on these results. Copula functions are employed to construct a wetness-dryness combination model for comparison with statistical method results, aiming to explore runoff variation patterns and provide theoretical references for wetness-dryness combination probability research.

Research data consist of monthly runoff measurements from the Tongguziluoke and Wuluwati hydrological stations.

2.1 Mean-Standard Deviation Method

Based on annual-scale runoff data, this method divides wetness-dryness into five categories using the following intervals: $[x+k_{1s},+\infty)$, $[x+k_{2s},x+k_{1s})$, $[x+k_{3s},x+k_{2s})$, $[x+k_{4s},x+k_{3s})$, and $(-\infty,x+k_{4s}]$, where the empirical coefficients are $k_1=-0.9$, $k_2=-0.3$, $k_3=0.3$, and $k_4=0.9$, with x and s representing the mean and standard deviation of annual average flow, respectively.

2.2 Fuzzy Set Pair Method

Using monthly runoff data as a foundation, this method constructs fuzzy set pair equations to determine wetness-dryness grades for the Yulong and Kara rivers. First, the mean-standard deviation method is applied to establish interval ranges for five classification grades. Since the classification standard follows a "smaller-is-better"constraint, a left-skewed function is adopted for fuzzification to establish the connection degree formula:

$$\mu_{A_i-x_{i,j}}=\begin{cases}1 & x_{i,j}\le x_{i,j}^1\\ \frac{x_{i,j}^2-x_{i,j}}{x_{i,j}^2-x_{i,j}^1} & x_{i,j}^1<x_{i,j}<x_{i,j}^2\\ 0 & x_{i,j}\ge x_{i,j}^2\end{cases}$$

where I represents the differential uncertainty component coefficient, empirically valued as $I_1=-0.5$, $I_3=0.5$, with connection numbers ranging $[-1,1]$, and J

as the opposition coefficient.

The entropy weight method is used to determine intra-annual runoff contribution ratios, with results substituted into the set pair equation to obtain the comprehensive connection degree formula:

$$\mu_{A-B} = \sum_{j=1}^{n} \lambda_j a_j + \sum_{j=1}^{n} \lambda_j b_j I + \sum_{j=1}^{n} \lambda_j c_j J$$

where a, b, and c are connection degree components; n is the number of study object indicators; λ_j is the weight value corresponding to the jth indicator; and μ_{A-B} represents the set connection degree.

To avoid subjective interference in coefficient selection, a confidence criterion is applied to determine sample classification levels:

$$f_i = \sum_{j=1}^{n} \lambda_j a_j, \quad h_k = \sum_{j=1}^{n} \lambda_j a_j, \quad \alpha \in [0.5, 0.7]$$

where f_i is the sample' s connection degree to the kth evaluation standard, h_k is the sample belonging to the kth level, and α is the confidence level.

2.3 Copula Function Joint Distribution

Copula functions connect marginal distributions of multiple variables to form multidimensional joint models. Assuming univariate marginal distributions $F_1(x_1)$ and $F_2(x_2)$, the corresponding two-dimensional joint distribution $F(x_1, x_2)$ can be expressed as:

$$F(x_1, x_2) = C(F_1(x_1), F_2(x_2))$$

where u and v represent univariate marginal distributions.

Modeling proceeds through: (1) fitting and optimizing single-variable marginal distribution functions (Weibull, Gamma, Generalized Extreme Value, Exponential, and Normal distributions) using AIC and RMSE criteria; (2) calculating Kendall' s rank correlation coefficient τ and parameter θ for Copula function parameter estimation; and (3) fitting Copula functions (Gumbel, Frank, Gaussian, Clayton) to two-dimensional cumulative empirical frequencies and evaluating goodness-of-fit. Based on wetness-dryness classification frequencies, runoff is divided into wet, normal, and dry periods using $P_f = 62.5\%$ and 37.5% as threshold frequencies.

3 Results

3.1.1 Wetness-Dryness Classification Based on Mean-Standard Deviation Method

Classification results using the mean-standard deviation method are presented in Table 1.

3.1.2 Wetness-Dryness Classification Based on Fuzzy Set Pair Method

Monthly runoff samples x_i $(i = 1, 2, \dots, 57)$ were established for both rivers, with critical values determined for different indicators. Taking Yulong River' s January 1962 runoff as an example, the sample $x_{1962,1} = 7.600$ falls between critical values S_j, yielding a connection degree component b of 0.27756 indicating dry year membership, while component a of 0.48061 indicates extreme dry year membership.

Entropy weights were calculated: Yulong River monthly weights λ_j and Kara River monthly weights λ_j $(j = 1, 2, \dots, 12)$. Substituting weights, connection degree components, and differential uncertainty coefficients into the comprehensive formula yields classification possibilities. With confidence level $\alpha = 0.6$, Yulong River shows 10 wet years and 26 dry years, while Kara River shows 9 wet years, 18 normal years, and 26 dry years. Both rivers exhibit more dry years than wet years, consistent with arid region characteristics, emphasizing the need to focus on water resource utilization during dry years in the Yulong River basin while the Kara River demonstrates relatively stable runoff.

3.1.3 Analysis of Classification Differences

Comparing both methods reveals that fuzzy set pair analysis considers intra-annual runoff contributions to annual totals, making results more objective. Yulong River, as a seasonal river with large flood season flows and small non-flood season flows, shows different classification outcomes. The mean-standard deviation method treats all time periods equally, amplifying extreme intra-annual conditions and potentially overestimating results. Calculations show Yulong River' s flood season weight as 51.6% and non-flood season as 49.4%, indicating that wetness-dryness classification depends on both runoff magnitude and intra-annual weight distribution. The fuzzy set pair method comprehensively and objectively reflects actual runoff conditions.

Representative year analysis (FIGURE:2) shows that for 1962 (a dry year), monthly runoff from January to March falls below critical value S_4, classifying as "dry" or "extremely dry," while July runoff exceeds S_1, classifying as "extremely wet." However, weighted calculations determine 1962 as a dry year overall, demonstrating how the method accounts for intra-annual distribution.

3.2.1 Wetness-Dryness Combination Probability Analysis Based on Fuzzy Set Pair Results

For combination probability analysis, "extremely wet" and "extremely dry" categories are merged into "wet" and "dry," respectively. Statistical analysis of monthly runoff data yields synchronous encounter probabilities of 35.83% (wet-wet: 15.51%, normal-normal: 2.77%, dry-dry: 17.54%) and asynchronous probabilities of 64.17%. The wet-dry combination probability is 5.54%, while dry-wet is 7.75%, indicating favorable complementarity between rivers, though the complementary probability is relatively low.

3.2.2 Wetness-Dryness Combination Probability Analysis Based on Copula Function

Copula functions use annual runoff data to construct joint distributions. Fitting tests (Table 5) show Yulong and Kara rivers follow Generalized Extreme Value distributions under AIC criteria. Two-dimensional joint frequencies are fitted using Gumbel, Frank, Gaussian, and Clayton Copulas, with Frank Copula showing the best performance (AIC = -192.63, RMSE = 0.0216). Kendall' s correlation coefficient $\tau = 0.6295$ yields Copula parameter $\theta = 8.354$.

Joint wetness-dryness combination probabilities (Table 6) show synchronous probability of 48.3% (wet-wet: 16.66%, normal-normal: 8.41%, dry-dry: 23.23%) and asynchronous probability of 51.7%. The most favorable complementary combination (wet-dry) has a probability of 18.48%. Both methods demonstrate asynchronous combination probabilities exceeding synchronous probabilities, confirming good complementarity between tributaries.

4 Discussion

Comparisons between statistical probabilities from fuzzy set pair results and Copula joint probabilities show overall consistency but with some differences: maximum synchronous probability difference of 14.09% and asynchronous difference of 12.47%. These discrepancies may arise from: (1) different data scales—Copula functions use annual data while fuzzy set pair analysis uses monthly data; (2) subjective judgment in frequency thresholds (62.5% and 37.5%) for Copula classification; and (3) limited hydrological sequence length (57 years) for statistical frequency calculation versus Copula' s ability to infer longer-term patterns from two-dimensional joint frequency trends.

Physical causation analysis reveals that different snow-glacier coverage areas and elevations between the West Kunlun Mountains (Yulong River source) and Karakoram Mountains (Kara River source) contribute to asynchronous probabilities. The Karakoram' s larger ice coverage and higher elevation (with 0°C isotherm around 3800-4000 m) cause delayed melting compared to the West Kunlun Mountains, creating asynchronous wetness-dryness patterns.

The Wuluwati Reservoir, constructed in 1998 on the Kara River outlet with a control area of 19,983 km^2 and beneficial storage of 2.24×10^{8} m^3, significantly reduces flood peaks and equalizes intra-annual runoff distribution. Reservoir pre-release operations decrease synchronous wetness-dryness probabilities between the two rivers. For short-term hydrological sequences, statistical methods better reflect recent basin conditions for water resource optimization, while Copula functions provide stronger support for hydraulic engineering design. The methods discussed offer improved research approaches for runoff wetness-dryness evaluation and combination analysis.

5 Conclusions

Runoff wetness-dryness variation patterns are fundamental for basin water resources planning and management. This study, based on mean-standard deviation method, fuzzy set pair analysis, and Copula functions, explores wetness-dryness combination probabilities in the Hotan River basin. Key conclusions include:

1) The mean-standard deviation method, based on annual runoff data without considering intra-annual variations, yields partial evaluation results. In contrast, fuzzy set pair analysis incorporates intra-annual runoff distribution and boundary fuzziness, constructing fuzzy connection degree equations using monthly runoff data from hydrological stations for more objective classification.

2) Fuzzy set pair analysis reveals that the Yulong Kashi River has a high proportion of dry years, necessitating improved water utilization during low-flow periods. The Karakashi River shows a high proportion of normal years, demonstrating consistently stable runoff.

3) Wetness-dryness combination analysis indicates that asynchronous combination probabilities exceed synchronous probabilities, showing good complementarity between rivers with low probability of extreme floods. These findings provide a solid foundation for basin water resources management.

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