Surface Water Resources Prediction in Danjiangkou Basin Based on ESP Concept and Distributed Hydrological Model

Ruifang Yuan[1,*], Yunxiang Lan[1], Junliang Shen[1]

[1]PowerChina Huadong Engineering Corporation Limited, Hangzhou, 311122, China

*Corresponding author's: yuan_rf@hdec.com

Abstract. The prediction of surface water resources quantity in the Danjiangkou Basin is of great significance. However, the accuracy of mid- to long-term hydrological forecasts is slightly lower compared to short-term forecasts. In order to enhance the reliability of mid- to long-term forecasts and predict water resources quantity, this paper proposes a forecasting and prediction system based on the concept of Extended Streamflow Prediction (ESP) and distributed hydrological models. In this paper, a prediction and forecasting system for the annual surface water resources quantity in the Danjiangkou Basin is proposed based on the Extended Streamflow Prediction (ESP) concept and a distributed hydrological model. Using the distributed hydrological model Wetspa, flood inflows into the Danjiangkou Reservoir are forecasted. The period from 2006 to 2012 is used for calibration, while the period from 2013 to 2016 is for validation. The Nash efficiency coefficients for monthly average runoff during the calibration and validation periods are 0.97 and 0.95, respectively, indicating good predictive performance. Building upon this, assuming precipitation for 2017 can be forecasted by a rainfall prediction model, the rainfall process is derived using ESP, and the runoff process at the basin outlet is obtained through the established Wetspa model. Consequently, the predicted surface water resources quantity for the control basin of Danjiangkou in 2017 is calculated to be 454.48 billion m3, while the computed quantity is 403.95 billion m3, resulting in a relative error of 12.51%. The results demonstrate that the prediction of surface water resources quantity in the Danjiangkou Basin based on the ESP concept and distributed hydrological model can provide valuable insights for the water diversion scheme of the Danjiangkou Reservoir.

Keywords: Prediction of Water Resources,ESP, Wetspa Model.

1 Introduction

The Danjiangkou Basin, located in the upper reaches of the Han River, encompasses counties and cities including Hanzhong, Ankang, and Shangluo in Shaanxi Province, Nanyang in Henan Province, and Shiyan in Hubei Province, totaling 43 counties

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(cities). It covers a drainage area of 95,220 km^2 with a population of approximately 15 million [1]. The region falls under the East Asian subtropical monsoon climate, characterized by distinct seasons, with an average annual precipitation ranging from 700 to 1100 mm [2]. As the source of water for the Middle Route of the South-to-North Water Diversion Project, the water resources of the Danjiangkou Reservoir not only impact flood control and drought resistance efforts in the region and downstream areas but are also closely related to the livelihoods, production, and development of more than 20 large and medium-sized cities in four provinces and municipalities including Henan, Hebei, Beijing, and Tianjin[3]. Moreover, China's water resources exhibit uneven temporal and spatial distributions[4]. Therefore, predicting the quantity of surface water resources in the Danjiangkou Basin is of utmost importance for ensuring the harmonious and stable economic and social development of cities along the water diversion project. To predict the water resources quantity in the Danjiangkou Basin, this paper first establishes a model for forecasting flood inflows into the Danjiangkou Basin based on the Wetspa model, followed by calibration and validation. Building upon this, assuming precipitation can be forecasted by a rainfall prediction model, the rainfall process is derived using ESP. Subsequently, the runoff process at the basin outlet is obtained through the established Wetspa model, enabling the prediction of surface water resources quantity.

2 Data Collection and Analysis

2.1 Basic Data

This study collected 25 years of inflow runoff data from the Danjiangkou Reservoir spanning from 1993 to 2017. The inflow runoff data were deduced based on the outflow discharge and reservoir storage variation using the water balance equation, sourced from the Hydrology Bureau of the Changjiang River Commission. Additionally, rainfall data from 1993 to 2017 were obtained from nine meteorological stations within the Danjiangkou control basin, including stations in Hanzhong, Foping, Shiquan, Ankang, Zhen'an, Shangzhou, Yunxi, Yunxian, and Xixia. These data were acquired from the China Meteorological Data Service Center. To calculate the natural runoff, it was necessary to restore the measured runoff. The restoration calculation required data on the consumption of water for industrial, agricultural, and domestic purposes, as well as for urban public and ecological environmental consumption, obtained from the water resources bulletin of Shaanxi Province. Storage variation data were collected from the reservoirs upstream, including Shiquan Reservoir, Xihe Reservoir, Ankang Reservoir, and Shu River, spanning from 2000 to 2017. The modeling of water resources quantity prediction required data such as Digital Elevation Model (DEM), soil type, and land use data, which were sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences.

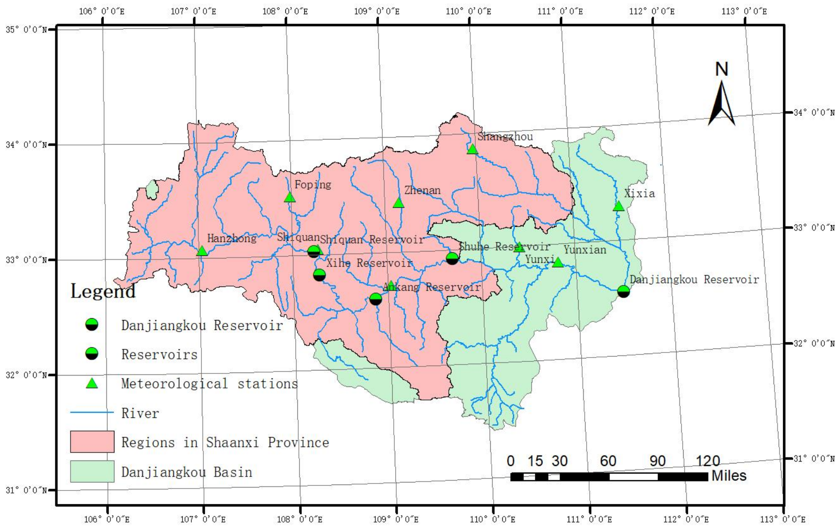


Fig. 1. Location and Distribution of Stations in the Danjiangkou Control Basin.

2.2 Representativeness Analysis of Data

The data used to calculate the quantity of surface water resources in this paper are all from authoritative official websites within the industry, thus ensuring their reliability. This study spans a lengthy series of 25 years, providing a certain level of representativeness regarding the rainfall-runoff situation in the basin. Therefore, this paper focuses on elucidating the consistency of the data, specifically analyzing the consistency of annual runoff sequences.

Precipitation is the main source of river runoff and is closely related to changes in runoff volume. The spatial and temporal distribution of precipitation affects the spatial and temporal distribution of runoff, and their correlation can be expressed using correlation coefficients. The correlation coefficient is a statistical indicator used to reflect the degree of closeness between two variables, where $0.7 \leq |r| < 1$ indicates a high degree of correlation between two variables [5]. Its formula is as follows:

$$r = \frac{(x_i - x)(y_i - y)}{\sqrt{(x_i - x)^2 \quad (y_i - y)^2}} \tag{1}$$

Where: r represents the correlation coefficient; x denotes the annual precipitation in millimeters (mm); y represents the annual runoff volume in billion cubic meters (bcm).

Using rainfall data from 1993 to 2017 and inflow runoff data from the Danjiangkou Reservoir, the correlation coefficient between precipitation and runoff was calculated. The annual precipitation value was obtained as the arithmetic mean of annual precipitation at meteorological stations within the Danjiangkou control basin, while the annual runoff volume was calculated from daily measured runoff data. Substituting these values into Equation (1), the correlation coefficient was computed as 0.74, indicating a high degree of correlation between rainfall and runoff, and good consistency between the two, as shown in the results depicted in the figure.

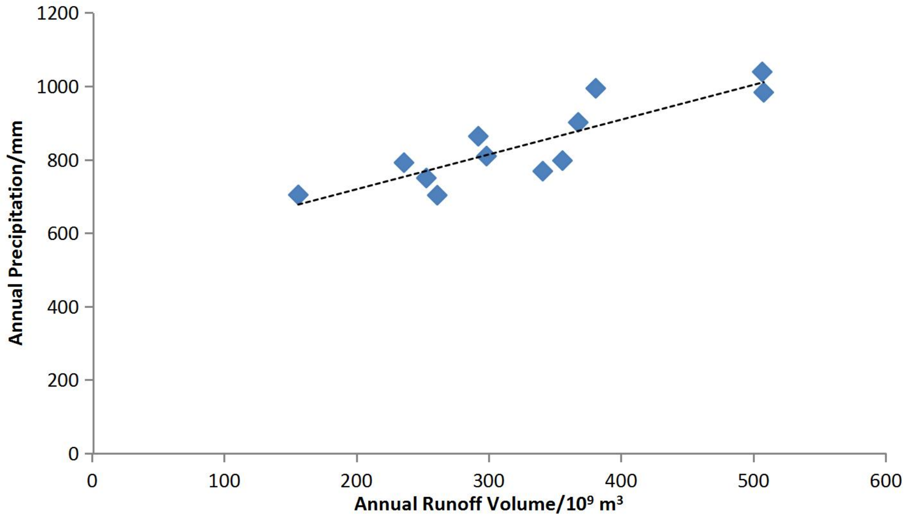


Fig. 2. Danjingkou Rainfall-Runoff Double Accumulative Curve

2.3 Single Station Runoff Analysis Calculation

For the prediction of surface water resources quantity in the Danjiangkou basin, the first step is to conduct restoration calculations for the runoff at the station based on the water balance equation. In this paper, in accordance with the characteristics of the Danjiangkou basin, the restoration calculations primarily focus on the following items [6]:

$$W_{\text{natural}} = W_{\text{measured}} + W_{\text{agricultural}} + W_{\text{industrial}} + W_{\text{domestic}} + W_{\text{ecological}} \pm W_{\text{storage}} \quad (2)$$

Where: W_{natural} — represents the restored natural runoff after restoration; W_{measured}—denotes the measured runoff; $W_{\text{agricultura}}$—represents agricultural irrigation consumption; $W_{\text{industrial}}$— denotes industrial water consumption; W_{domestic}—represents domestic water consumption; $W_{\text{ecological}}$ — denotes urban public and ecological environmental water consumption; W_{storage}— represents reservoir storage variation (decrease as negative, increase as positive).

The catchment area of the Danjiangkou basin is 95,220 km^2. According to the collected data, 62,263 km^2 are located within the territory of Shaanxi Province. Therefore, this paper intends to use the agricultural irrigation consumption, industrial water consumption, domestic water consumption, and urban public and ecological environmental water consumption provided in the water resources bulletin of Shaanxi Province, adjusted according to the proportion of surface water in the water supply, to calculate the corresponding restoration items for the Danjiangkou basin using area conversion coefficients. The conversion formula is as follows:

$$W_{\text{djk agricultural}} = W_{djk\,\cap\text{Shaanxi agricultural}} \cdot \frac{S_{djk}}{S_{djk\,\cap\text{Shaanxi}}} = W_{\text{Shaanxi agricultural}} \cdot \frac{S_{djk\,\cap\text{Shaanxi}}}{S_{\text{Shaanxi}}} \cdot \frac{S_{djk}}{S_{djk\,\cap\text{Shaanxi}}} = W_{\text{Shaanxi agricultural}} \cdot \frac{S_{djk}}{S_{\text{Shaanxi}}} \quad (3)$$

Where: $W_{\text{djk agricultural}}$ represents the surface water consumption of agriculture in the Danjiangkou basin; $W_{djk\,\cap\text{Shaanxi agricultural}}$ represents the surface water consumption of agriculture within the area of Shaanxi province in the Danjiangkou basin; $W_{\text{Shaanxi agricultural}}$ represents the surface water consumption of agriculture in Shaanxi province; S_{djk}、 $S_{djk\,\cap\text{Shaanxi}}$、 S_{Shaanxi} represent the areas of the Danjiangkou basin, the part of the Danjiangkou basin within Shaanxi, and the area of Shaanxi province respectively. The methods for calculating industrial, domestic, and urban public and ecological environmental surface water consumption are exactly the same. The calculation results are shown in the table below:

Table 1. The calculation results of water consumption(10^9 m^3).

Year	$W_{\text{djk agricultural}}$	$W_{\text{djk industrial}}$	$W_{djk\text{ domestic}}$	$W_{\text{djk ecologica}}$
2017	10.79	1.88	2.12	1.39
Average from 2000-2017	9.93	1.36	1.81	0.65

The reservoir storage variation mainly considers four large reservoirs in the Danjiangkou basin, namely Shiquan, Xihe, Ankang, and Shu River. The value of reservoir storage variation is the sum of the storage variations of these four reservoirs. The calculation results are shown in the table below:

Table 2. Reservoir storage variation calculation results($10^6 m^3$).

Year	Shiquan	Shuhe	Xihe	Ankang	Total
2017	87.1	0.48	8.49	599	695.07
Average from 2000-2017	2.65	3.76	3.14	11.54	21.09

3 Prediction of Surface Water Resources Quantity

This paper predicts the annual streamflow and water resources in the Danjiangkou Basin based on Extended Streamflow Prediction (ESP) and WETSPA model. The flowchart is as follows:

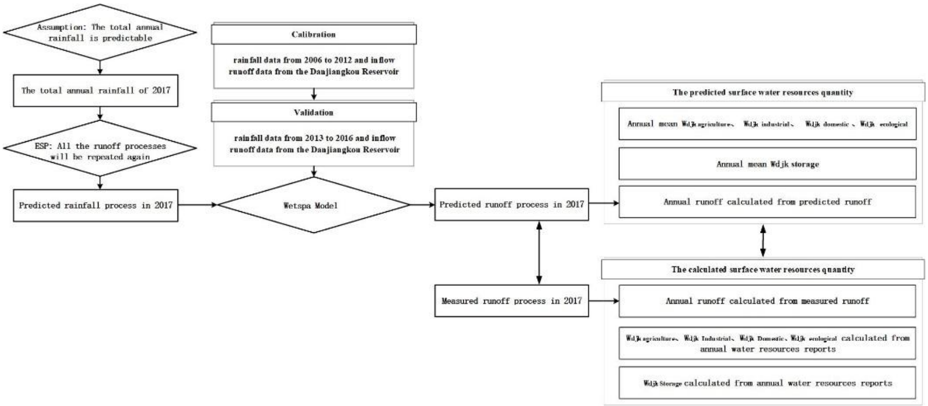


Fig. 3. Flowchart of this paper

3.1 Long-term Streamflow Forecast

Long-term streamflow forecast [7] (also known as extended streamflow prediction, ESP) is a hydrological ensemble forecasting method that originated in the 1970s and continued until the end of the 20th century. It primarily assumes that historical rainfall processes will repeat in the future. For all historical rainfall processes, the initial basin conditions for the forecast year's month and date are used to obtain the corresponding flow processes through the basin's rainfall-runoff model.

3.2 Wetspa Modeling and Accuracy Assessment

Principles of the Wetspa Model. The Wetspa (A Distributed Model for Water and Energy Transfer Between Soil, Plants and Atmosphere) model was proposed in 1996 by Wang and Batelaan from Belgium as a distributed physical hydrological model with a daily time step [8]. De Smedt, Liu Yongbo, and others subsequently made improvements to the model, which is based on the conceptualization of each grid cell as a fundamental unit. These grid cells are vertically generalized into five layers: the saturated zone, the vapor transport zone (unsaturated layer), the plant root zone, the plant canopy, and the atmosphere. These layers simulate water and energy balances [9]. The model simplifies downward movement of soil water into one-dimensional vertical flow, and groundwater flow convergence is computed using linear or nonlinear reservoir methods. The collection of runoff from grid cells, overland flow, and channel flow towards the basin outlet is simulated using the linear diffusion wave equation [10].

Calibration of Model Parameters and Accuracy Assessment. The model employs the Particle Swarm Optimization (PSO) algorithm to calibrate parameters, obtaining the optimal parameter combination as shown in the table below [11].

Table 3. Wetspa model parameter calibration results.

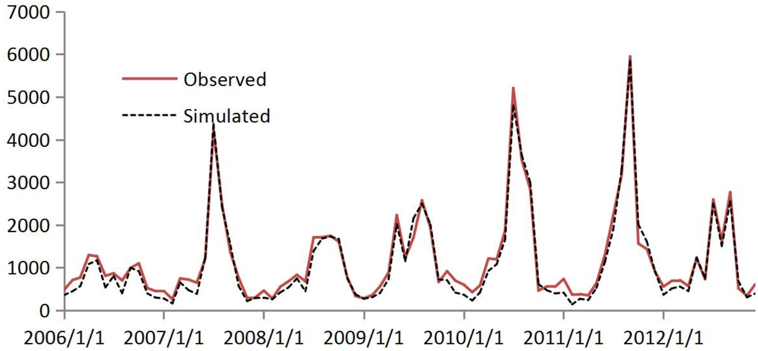
Number	Parameter	Meaning	Value
1	ki_sub	Shape index of the subsurface runoff	1.25
2	kg_tot	Shape index of the groundwater	0.03
3	T0	Snowmelt temperature	0.50
4	p_max	Maximum rainfall intensity	300.00
5	UnitSlopeM	Slope correction coefficient	5.15
6	ConductM	Permeability coefficient correction factor	7.75
7	PoreIndexM	Soil porosity correction coefficient	0.90
8	LaiMaxM	Leaf area index correction coefficient	1.00
9	DepressM	Fill depression correction coefficient	2.65
10	RootDpthM	Root depth correction coefficient	0.90
11	ItcmaxM	Field capacity correction coefficient	2.65
12	CH_S2	River slope correction coefficient	1.65
13	CH_L2	River length correction coefficient	1.25
14	CH_N2	Roughness coefficient correction factor	1.65
15	CH_K2	Hydraulic conductivity correction coefficient	1.65
16	Imp_M	Impervious surface correction coefficient	1.00
17	petm	Evaporation correction coefficient	0.75

According to the accuracy assessment criteria outlined in the "Specifications for Hydrological Information Forecasting," this paper evaluates the accuracy of the model simulation by computing the monthly average runoff process. Parameters such as runoff depth, Nash efficiency coefficient, and correlation coefficient are selected for this evaluation [12]. The permissible error for runoff depth is set at 20% of the measured runoff depth. The Nash efficiency coefficient is used as an indicator to characterize the fitting degree between the simulated and measured flow processes, with values closer to 1 indicating better simulation performance. The assessment results of the Wetspa model are presented in the table below.

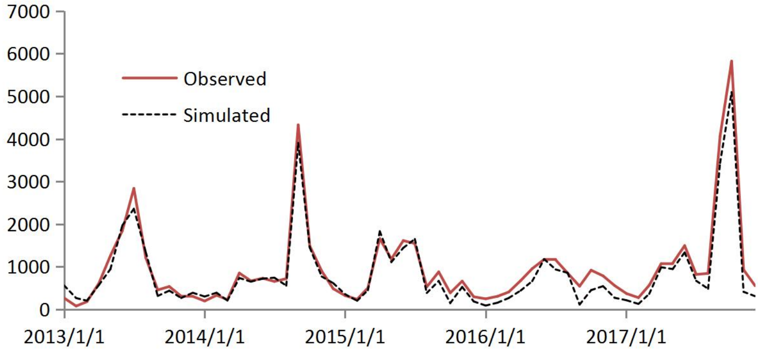
Table 4. Danjiangkou Station calibration and validation results.

Station	Calibration results			validation results		
	Runoff depth error	Nash	Correlation coefficient	Runoff depth error	Nash	Correlation coefficient
Danjiangkou Reservoir	8%	0.97	0.99	15%	0.95	0.98

This study utilized rainfall data from 2006 to 2012 and inflow runoff data from the Danjiangkou Reservoir for model calibration, while rainfall data from 2013 to 2016 were used for model validation. Figures 4(a) and 4(b) depict the simulated monthly average runoff and observed monthly average runoff processes during the calibration and validation periods, respectively.



(a) Danjiangkou 2006-2012 Parameter Calibration Results



(b) Danjiangkou 2013-2016 Parameter Validation Results

Fig. 4. Model Parameter Calibration and Validation Results

3.3 Prediction Results of Surface Water Resources Quantity

For the prediction of surface water resources quantity, the focus lies on the forecast of runoff volume. The key to forecasting runoff volume lies in predicting rainfall. With the continuous development of technology, significant progress has been made in rainfall forecasting. However, it has not yet become feasible to forecast daily rainfall processes for the entire year ahead. In this paper, it is assumed that the annual precipitation for 2017 can be obtained through rainfall prediction. Following the ESP concept, which suggests that all runoff processes will repeat, historical rainfall data are compared to derive the rainfall process. This process is then applied to a distributed hydrological model to obtain the runoff process at the basin outlet.

By comparing the annual precipitation, it is found that the actual annual average rainfall for the nine meteorological stations in 2017 was 994 mm, which is closest to the value of 983 mm in 2010. Therefore, the rainfall process for 2010 is selected as the input rainfall data for the Wetspa model simulation. The simulation results of the hydrological model are shown in Table 5:

Table 5. The calculation results of water consumption(Billion m^3).

	Runoff depth error	Nash	Correlation coefficient
2017	15.67%	0.84	0.92

From Table 5, it can be observed that the simulation of runoff using the rainfall data from 2010 yielded satisfactory results for the year 2017. Consequently, the calculation of water resources quantity continues. By adding the simulated annual runoff calculated from the model to the multi-year values of each restoration item and the average storage variation of the reservoirs, the predicted surface water resources quantity for the Danjiangkou control basin is determined to be 454.48 billion cubic meters. Similarly, by adding the annual runoff calculated from the measured station data to the values of each restoration item and the storage variation of the reservoirs calculated from sources such as the annual water resources report, the calculated surface water resources quantity is determined to be 403.95 billion cubic meters. The relative error between the two is 12.51%.

4 Conclusion

This paper proposes a predictive forecasting system for the annual surface water resources quantity in the Danjiangkou reservoir control basin based on the ESP concept and distributed hydrological model, validated using data from 2017. The predicted surface water resources quantity for the Danjiangkou control basin in 2017 is determined to be 454.48 billion cubic meters, while the calculated surface water resources quantity is 403.95 billion cubic meters. The relative error between the two is 12.51%. This indicates that the basin's surface water resources prediction based on the ESP concept and distributed hydrological model can provide valuable insights for water resource allocation in the Danjiangkou region. However, due to the limited data collected in this study, there is insufficient material for thorough validation of the results. It is recommended to gather more data for comprehensive verification of the conclusions.

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