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Assessing the damming effects on runoff using a multiple linear regression model: A case study of the Manwan Dam on the Lancang River

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Abstract

The Lancang River in Yunnan Province, with a length of 1170 km and a 1780-m drop from northwest to southeast, is the most controversial river in southwest China because 14 cascade hydropower stations have been planned on the main waterway. The Manwan Dam, the first of the 14 dams, began operating in 1993, and the associated downstream runoff may have been affected by its construction. To assess this impact, we first investigated the relationships between monthly runoff observed from the Gajiu station and meteorological data obtained from four meteorological gauging stations with a time-lag of 0-3 months over the pre-dam period (1957-2000). Second, we established and validated a multiple linear regression equation employing monthly meteorological and hydrological data during the pre-dam period. Finally, we simulated the monthly runoff after dam construction (1993-2000) using the established equations and assessed the impact of dam construction on runoff by comparing the observed actual monthly runoff with the simulated monthly runoff. Our results suggested a very high hydro-meteorological correlation for the pre-dam period, which opened up the possibility of runoff forecasting. Further, the multiple linear regression equation displayed good simulation performance as coefficient of determination (R^2) and the Nash-Suttcliffe coefficient (NS) reached 0.84 and 0.82 respectively. By comparing the observed and the predicted monthly runoff, we found that construction of the Manwan Dam caused a visible disturbance on monthly runoff that, with the disturbance value, displayed a multi-peak fluctuation of up-down variation in the annual hydrologic regime circle.

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Key words: dam construction; multiple linear regression; runoff simulation; Manwan Dam; Lancang River

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1. Introduction

Approximately 70% of the world's rivers are regulated by dams, which can provide great socioeconomic benefits for human development [1]. However, construction of dams results in serious negative consequences for the environment [2], such as reduced river connectivity [3, 4], altered hydrologic processes [5, 6], changes in riverbed and bank morphology [7, 8], degeneration of water quality [1, 9], and changes in the composition, function, and structure of river ecosystems [10, 11]. Among these factors, the hydrologic regime is recognized one of the most sensitive because it is the primary driving force of the structure and function of river ecosystems [10-3]. Therefore, many researchers have studied dam-induced hydrologic changes in various river basins [5, 11, 14, 15]. However, much of this work was conducted by comparing observed hydrologic data during the pre- and post-impact periods to assess the effect of dam construction on hydrologic change; there is lack of simulations for the natural hydrologic regime to evaluate the hydrologic alterations induced by dam construction. Additionally, there is a significant correlation between hydrologic regimes and climate. Indeed, changes in hydrologic regimes are often hypothesized to be forceful indicators of climate change because climate change can alter the hydrologic cycles of a river system by changing the magnitude, duration, frequency, timing, predictability, and variability of the flow events of hydrologic processes [15-18]. Therefore, it is essential to include climate change when assessing the hydrologic alterations caused by dam construction. Several methods have been used to investigate the relationship between hydrologic alterations and climate change [17-20], and previous results demonstrate that meteorological data can be effectively used to predict hydrology.

In the present study, we examined the Lancang River Basin in Yunnan Province, southwest China, where 14 dams have been planned on the main river and close correlations were detected between runoff variations and meteorological variables [21, 22]. Consequently, the aims of this study were to investigate the relationships between monthly hydrological and meteorological data, establish a prediction model based on the relationship between monthly runoff and meteorological variables, and assess the disturbance value of dam construction on monthly runoff.

2. Method

2.1. Study area and data collection

The Lancang River is 1170-km long from northwest to southeast, with a drop of 1780 m along its length [23]. As the largest international river in Asia, it is strongly influenced by both the southwest monsoon and westerly circulation [24], which result in significant seasonal divisions of climate [25]. However, its unique geographical features and plentiful hydraulic resources endow this region with great potential for cascade hydropower development [26-28]. Since the 1980s, four dams (including the Manwan, Dachaoshan, Jinghong, and Xiaowan Dam) have been constructed and begun operating. The Manwan Dam, which was the first multimillion kilowatt hydropower station in Yunnan Province [29], is located upstream of the town of Manwan, which is located on the border between Yun and Jingdong County in the upper Lancang River Basin in Yunnan Province [29]. Since it was first put into operation in 1993, hydrologic alteration downstream from the dam may have occurred, and while several groups have conducted studies of hydrologic change [25, 27, 30-35], there is still a lack of simulative analysis that considers the meteorological variation that is related to the hydrologic alterations. Therefore, in the present study, monthly runoff, precipitation, air temperature, and relative humidity data during the 1957-2000 period were analyzed. Runoff data were observed at the Gajiu hydrologic station located 2 km downstream from the Manwan Dam, and their characteristics were controlled directly by dam operation.

Meteorological data were provided by the Yunnan Weather Bureau from four surrounding National Reference Meteorological Stations (i.e., the Deqin, Weixi, Dali, and Baoshan stations). In addition, the amount of precipitation (in mm), average air temperature (in °C), and relative humidity (in %) at the four meteorological stations were respectively used to represent the precipitation, temperature, and relative humidity variables when investigating the correlation between runoff and meteorological variables and establishing the multiple regression equation.

2.2. Method

In this study, a stepwise multiple regression model was applied. First, correlations between monthly runoff and meteorological variables, with a time-lag of 0-3 months, were analyzed. Second, a stepwise multiple regression equation was established using monthly runoff and meteorological data during the 1958-1987 time period, and then, the established model was validated using an independent period of 5 years before dam construction (1988-1992). The model performance was evaluated through the coefficient of determination (R^2) [36] and the Nash-Suttcliffe coefficient (NS) [37]. Third, based on the relationship between monthly runoff and meteorological variables, as well as the established and validated multiple regression equation, the monthly precipitation, air temperature, and relative humidity data during the post-dam period (1993-2000) were prepared as the function of a time-lag of 0-3 months for predicting the monthly runoff after dam construction. Ultimately, after predicting the monthly runoff, the disturbance value of dam construction on monthly runoff was calculated using the following formula [38]:

$$D_{\mathrm{j}} = \frac{1}{n}\sum_{i=1}^{n}(P_{ij} - O_{ij}) \quad (1)$$

where P and O are the predicted and observed monthly runoff, respectively, for the month j of year i, and n is the number of years. In addition, the data were analyzed using SPSS version 17 for Windows.

3. Results

3.1. Variation in monthly runoff

Fig.1 illustrates the variations of annual runoff over 12 months. We found that the monthly runoff displayed an up-down variation throughout the period of 1957-1992, with the largest runoff value observed in August (70.3×10^8 m^3) and the least runoff value observed in February (9.4×10^8 m^3). Nearly half (45.4%) of the annual runoff was concentrated in the summer season (June-August), while the runoff in the winter season (December-February) contributed only 9.2%. Moreover, monthly runoff displayed high inter-annual variability, especially in August.

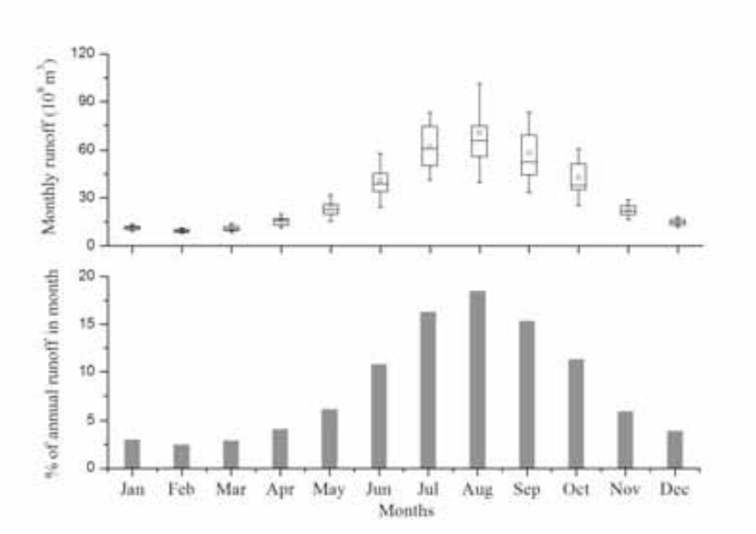

Fig. 1 Magnitude and distribution (as a percentage of the annual total) of mean monthly runoff during the pre-dam period for the Gajiu station downstream of Manwan Dam

3.2. Correlations between monthly runoff and meteorological variables

The correlations between monthly runoff and meteorological variables with time-lags from 0-3 months (Lag0, Lag1, Lag2, and Lag3) for the pre-dam period were determined (see Fig. 2). For the study area, the correlation between monthly runoff and precipitation was highly variable for all time-lags, and it decreased with an increase in time-lag that varied from 0.75-0.19 for a time-lag from 0-3 months. In general, runoff was positively and highly correlated with precipitation. The values of the runoff-temperature correlation for the pre-dam period demonstrate that the monthly runoff was well correlated with monthly temperature, and no consistent change in correlation was found with a decrease in time-lag (0.74, 0.83, 0.7, and 0.41, respectively). The highest correlation between monthly runoff and temperature was obtained with a 1-month time-lag. In other words, monthly runoff in a particular month displayed the greatest correlation (0.83) with the temperature of the preceding month. The correlation between monthly runoff and relative humidity demonstrated the same variation as the runoff-precipitation relationship, which decreased with an increase in time-lag that varied from 0.86-0.04. However, there was a greater difference among the time-lags. Indeed, the correlation value for a 0-month time-lag is 0.86, which is the highest value between monthly runoff and meteorological variables, indicating that monthly runoff was significantly related to the relative humidity of the same month. In addition, monthly runoff was significantly correlated with meteorological variables ($P \leq 0.01$), with the exception of the correlation between monthly runoff and relative humidity over a 3-month time-lag ($P \geq 0.05$). In conclusion, good correlations were found between runoff and meteorological variables with a time-lag of 0-3 months for the pre-dam period, indicating the important role of meteorological variables in producing runoff in the study area and implicating the possibility for runoff forecasting.

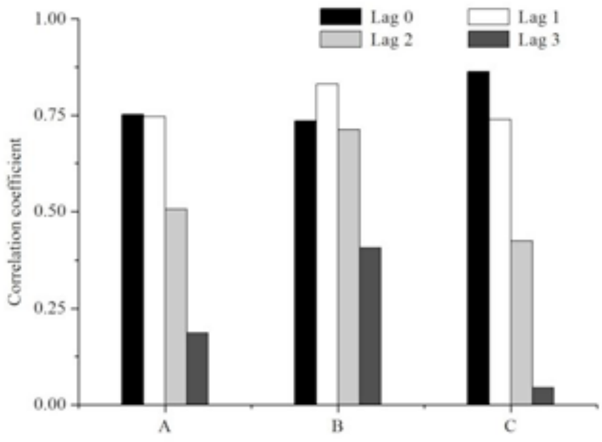

Fig. 2 Correlations between monthly runoff and precipitation (A), monthly runoff and temperature (B), and monthly runoff and relative humidity (C) as a function of time-lag (0-3 months) during the pre-dam period for the study area

3.3. Regression relationship and its efficiency for forecasting runoff

The significant positive relationships established above between runoff and meteorological variables opened up the possibility of a variety of strategies for runoff forecasting. Therefore, a stepwise regression technique was employed to identify important variables for predicting runoff in the study area. The regression equation was developed by considering the possible meteorological variables, which may significantly influence the monthly runoff. Monthly runoff observed from the Gajiu station was used as the dependent variable, and 12 independent variables (i.e., precipitation (P_i, P_{i-1}, P_{i-2}, and P_{i-3}), temperature (T_i, T_{i-1}, T_{i-2}, and T_{i-3}), and relative humidity (H_i, H_{i-1}, H_{i-2}, and H_{i-3})) were used as independent variables. The resulting regression equation and the corresponding values of correlation for the period of 1958-1987 are presented in Table 1. It should be noted that some of the variables that had insignificant relationships with runoff were dropped in the regression equation. The high value of R^2 =0.82 indicates that monthly runoff was well represented by the regression equation.

Table 1 Regression equation developed for the Gajiu station using a stepwise regression approach.

Period	Multiple regression equation	R^2
1958-1987	$Q_i = -695287.223 + 4136.999H_i + 19.587P_{i-1} + 26.732P_i + 4905.025H_{i-3} + 1586.743T_I + 620.105T_{i-3} - 8.567P_{i-3}$	0.818

Moreover, to assess the model adequacy, an independent period of 5 years before dam construction (1988-1992) was used for validation, and two methods (R^2 and NS) were applied. Then, the predicted monthly runoff values of the stepwise regression equation for the validation period were compared with the observed values (Fig. 3). The validation results revealed that the predicted values consistently match well with the observed values for runoff in all years. The R^2 and NS values are 0.84 and 0.82, respectively, for monthly data during the validation period. These reasonably high R^2 and NS values indicate "good" performance [39, 40] by the stepwise regression equation in runoff simulation in this study.

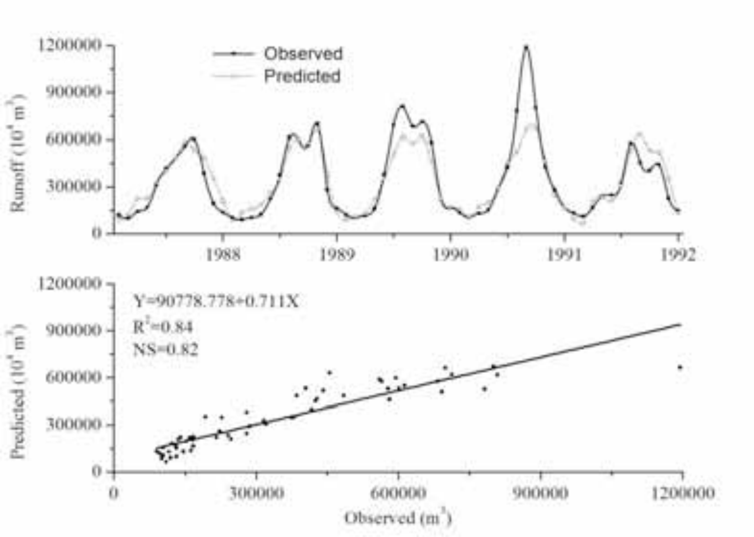

Fig. 3 Observed and predicted runoff at the Gajiu station and their correlations for the validation period of 1988-1992.

3.4. Runoff forecasting and assessing

Using the validated stepwise regression model, we further predicted the monthly runoff during the post-dam period of 1993-2000. A comparison between the observed and predicted monthly runoff for the period of 1993-2000 is given in Fig. 4. These results indicated that both the observed and predicted runoff mainly distributed in the summer season. However, there were changes of months the extreme values. For example, the largest observed values in 1994-1997 were delayed 1-2 months than predicted due to the operation of the Manwan Dam, while the extreme occurred 1 month early in 2000 and there was no change in 1993 and 1998. The lowest observed values in 1993, 1996, 1997, and 1999 all occurred in February, but they were predicted to occur in March in 1993 and in January in 1996, 1997, and 1999. There was no change in the lowest monthly runoff in 1995, 1998, and 2000 between the observed and predicted values.

Monthly variations in the observed and predicted runoff during 1993-2000 were different (Fig. 5). Depending on whether or not a change in magnitude occurred between the observed and predicted monthly runoff, we distinguished three types of months for the Gajiu station. First, some months were characterized by an increase in the observed compared to the predicted average runoff: January, July, August, and December. The actual runoff in January and July was statistically significantly different from the predicted data. Second, some months were characterized by a decrease in the observed compared to the predicted average runoff (i.e., March, April, June, October, and November), though there was no significant decrease between the observed and predicted data. Finally, there was no change between observed and predicted values in three months: February, May, and September. In addition, the average largest runoff occurred in August in both the observed and predicted data, but the least runoff occurred in January in the predicted data and in February in the observed data. The results of disturbance value analysis indicated that the largest disturbance of the Manwan Dam on runoff at the Gajiu station was observed in July, while observed the least disturbance occurred in February. Compared to the predicted runoff, the observed runoff, which is directly controlled by dam operation, displayed a visible increase in January, July, August, and December (3.7, 10.7, 3.1, and 2.1 × 10^8 m^3/year, respectively), and there was a visible decrease in March, April, June, October, and November (2.4, 2.2, 1.5, 5.5, and 5.0 × 10^8 m^3/year, respectively). In general, the disturbance effect of the Manwan Dam on monthly runoff was visible, which displayed a multi-peak fluctuation of up-down variation in the annual hydrologic regime circle, indicating the adjusting effect of dam operation. These data also reflect the efficiency of Manwan Dam at accomplishing one of its goals, i.e., it was designed to reduce the flood peak in the wet season and increase the water yield in the dry season.

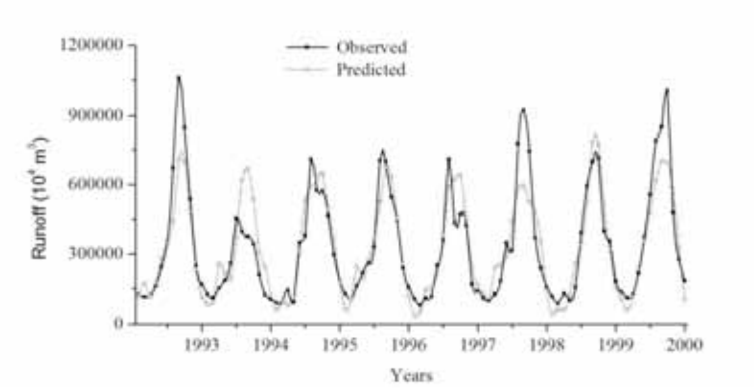

Fig. 4 Time series (1993-2000) of observed and predicted monthly runoff for the Gajiu station

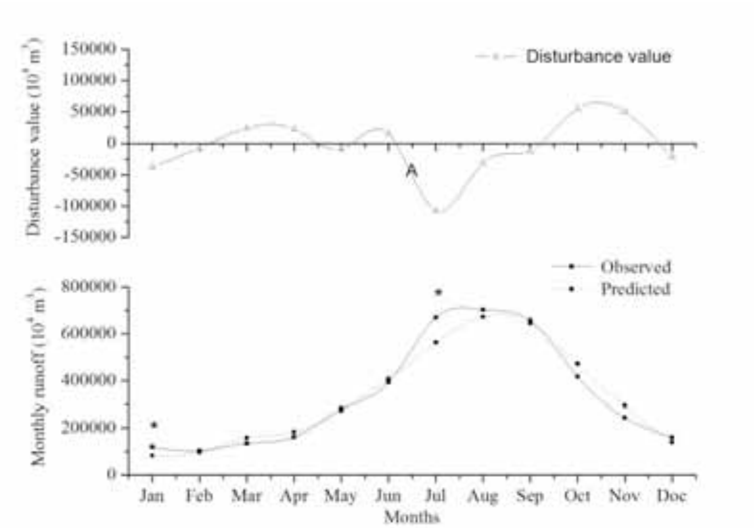

Fig. 5 Comparison between the observed and predicted monthly runoff after dam construction and the disturbance value of dam construction on monthly runoff. * indicates a significant difference at the P = 0.05 level

4. Conclusions and discussions

Using a stepwise multiple regression model, we predicted the monthly runoff during 1993-2000 (i.e., after construction of the Manwan Dam) and assessed the changes in runoff at the Gajiu station using the disturbance value. The following conclusions can be drawn from our analyses:

- The monthly runoff displayed an up-down variation throughout the period of 1957-1992 (i.e., before dam construction), with the largest runoff value observed in August and the least observed in February;
- The monthly runoff was closely related to the meteorological variables ($P \leq 0.01$) with the exception of the correlation between monthly runoff and relative humidity over a 3-month time-lag ($P \geq 0.05$), indicating the important role of meteorological variables in producing runoff in the study area and allowing the possibility of runoff forecasting;
- According to the significant positive relationships established between runoff and meteorological variables, we established a regression equation for runoff forecasting within the study area. The validation results demonstrated that the R^2 and NS values reached 0.84 and 0.8, respectively, for monthly data during 1988-1992, indicating the good performance of the established regression equation for runoff simulation in this study; and
- By comparing the observed and predicted monthly runoff during the post-dam period, the disturbance value of dam construction on monthly runoff was determined, and it displayed a multi-peak fluctuation of up-down variation in the annual hydrologic regime circle, indicating that the disturbance effect of the Manwan Dam on monthly runoff was obvious.

However, in the present study, uncertainty is inevitable in the results of monthly runoff forecasting, which is related to the assessment results of the damming effect on runoff. Like other regression models, the stepwise regression equation we established only considers the meteorological variables with their time-lags, without considering other important factors. Guo et al. [41] demonstrated that the climate effect is dominant in annual runoff in the Poyang Lake Basin. However land-cover change may have a moderate impact on annual runoff because variation in vegetation can influence evapotranspiration, and increased forest cover can reduce wet season runoff and increase it in the dry season, ultimately reducing drought severity in the dry season and flood potentials in the wet season [41, 42]. In addition, additional groups have developed runoff forecasting models using hydrologic data with other meteorological variables, such as vapor pressure [43], solar radiation [44], shortwave incoming and net radiation, and absorptivity and wind speed [45]. Therefore, it is necessary to determine the suitable variables for runoff forecasting. Furthermore, while the stepwise regression model has been commonly used to forecast runoff, it is a stochastic model and is not free of error [46]. The outcomes of this study indicate that the established regression equation is not suitable to forecast peak flow values (Fig. 3). Consequently, future work will compare the efficiency of stochastic models (e.g., the stepwise regression model [18, 19] and ANN models [46]) and process-based models (e.g., SWAT [41, 46, 47] and WEEP [36]) for accurate runoff forecasting.

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