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Adaptation of Cascade Hydropower Station Scheduling on A Headwater Stream of the Yangtze River under Changing Climate Conditions

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Academic Editor: Franco Salerno
Received: 25 February 2017; Accepted: 18 April 2017; Published: 22 April 2017

Abstract: Cascade hydropower stations are effective in water resource utilization, regional water allocation, and flood risk management. Under changing climate conditions, water resources would experience complex temporal and spatial changes, which may lead to various issues relating to flood control and water resource management, and challenge the existing optimal scheduling of cascade hydropower stations. It is thus important to conduct a study on cascade hydropower station scheduling under changing climate conditions. In this study, the Jinsha River rainfall–discharge statistical model is developed based on the statistical relationship between meteorological and runoff indicators. Validation results indicate that the developed model is capable of generating satisfactory simulation results and thus can be used for future Jinsha River runoff projection under climate change. Meanwhile, the Providing Regional Climates for Impacts Studies (PRECIS) is run to project future rainfall in the Jinsha River basin under two General Circulation Models (ECHAM5 and HadAM3P), two scenarios (A1B and B2), and four periods (1961–1990, 1991–2020, 2021–2050, and 2051–2099). The regional climate modeling data are analyzed and then fed into the Jinsha hydrological model to analyze the trends of future discharge at Xiangjiaba Hydro Station. Adaptive scheduling strategies for cascade hydropower stations are discussed based on the future inflow trend analysis and current flood scheduling mode. It is suggested that cascade hydropower stations could be operated at flood limited water level (FLWL) during 2021–2099. In addition, the impoundment of cascade hydropower stations should be properly delayed during the post-flood season in response to the possible occurrence of increased and extended inflow in wet seasons.

Keywords: climate change; adaptation; hydropower; flood; water resources

1. Introduction

Hydropower developments on the Yangtze River and its headwater streams have drawn significant attention in China and globally. Among major headwater streams, the Jinsha River with its abundant runoff has become the largest hydropower base in the basin and in all of China. Key hydropower stations at the Wudongde, Baihetan, Xiluodu, and Xiangjiaba stations of the Jinsha River compose cascade hydropower stations [1]. Cascade hydropower stations are effective to enhance water resource utilization, optimize regional water allocation, and mitigate flood risk through comprehensive scheduling. However, the changing climate has shown significant impacts on flood frequency in the Jinsha River [2], which challenges the scheduling of the cascade hydropower stations [3,4]. In the past, a variety of studies have been carried out on the optimal scheduling of cascade hydropower stations [5–7]. These studies can generally be grouped into two categories. One is mainly to maximize the economic benefits of cascade hydropower stations, while the other is focused on developing site-specific cascade station operation rules from a flood control perspective.

The previous research emphasized the maximization of economic benefits focused on the development of techniques or the establishment of management rules and applying them to water resources management and planning [8]. For example, Wang et al. (2015) [1] established rules for long-term scheduling of large cascade hydropower stations on the Jinsha River, and revealed that the joint operation of cascade hydropower stations could effectively increase total power production in wet seasons. Mu et al. (2015) [9] established three operating rules for instructing the operation of the Three Gorges and Gezhouba cascade hydropower stations in the flood season, aiming to maximize total hydropower production. Jiang et al. (2014) [10] presented a method for optimizing cascade hydropower stations graphs. Li et al. (2014) [11] applied a parallel dynamic programming algorithm for optimization of a five-reservoir system in China. Overall, these studies highlighted power generation maximization but failed to take into account flood control linked to climate change. According to the Yangtze Conservation and Development Report, the flood hazards of the Yangtze River correlate to a large extent with climate change [12]. Specifically, water resources would experience complex temporal and spatial changes under a changing climate. These changes in tendency and extent would vary from one place to another, leading to a series of devastating flood hazards in different reaches of the Yangtze River basin.

Previous research on flood control mostly focused on developing site-specific flood control rules to support decision-making dealing with extreme floods [13]. For instance, Lund and Guzman (1999) [14] developed a rule that could help improve the fullness storage rate without increasing the flood risk. Wei and Hsu (2009) [15] established tree-based optimal operation release rules for handling real-time flood control of a multi-purpose multi-reservoir system. Chou and Wu (2014) [16] explored stage-wise optimizing release rules and applied them to a reservoir flood control operation. Chaleeraktrakoon and Chinsomboon (2014) [17] developed dynamic flood control level curves for a dam with limited reservoir capacity to cope with flooding.

Overall, the previous studies mostly focused either on maximizing hydropower production or mitigating flood risk. However, they failed to fully address the relationships between climatic factors and runoff of the Jinsha River for comprehensive, long-term flood scheduling. Therefore, the objective of this study is to propose an adaptation strategy for cascade hydropower station scheduling on the Jinsha River (a headwater stream of the Yangtze River) under changing climatic conditions. The objective will be achieved through integrating climate change factors into a hydrological model. Specifically, a Jinsha River rainfall–discharge statistical model is first developed based on the statistical relationship between meteorological and runoff indicators. In the meantime, high-resolution future precipitation distribution (1960–2099) over Jinsha watershed is simulated using PRECIS (Providing Regional Climates for Impacts Studies), a regional climate modeling tool, given its proven performance at reproducing climate change in China and globally. The obtained regional climate modeling data are then fed into the Jinsha hydrological model to analyze the trends of future discharge at the Xiangjiaba Hydro Station, the most downstream station of four cascade hydropower stations on the Jinsha River.

Finally, climate change's impacts on the hydrological frequency of the Jinsha River are analyzed and a scheduling adaptation strategy for cascade hydropower stations' operation under climate change is proposed.

2. Rainfall Discharge Modeling over the Jinsha River Basin

The current techniques available for hydrological forecasting can be classified into two categories: process-driven models and data-driven models [18]. The process-driven models mainly take the internal physical mechanisms of hydrological processes into account, and usually need a large amount of data for calibration and validation. In previous studies, a number of process-based hydrological models were adopted for studying climate change studies in this region. For example, Wang et al. (2015) [19] proposed a rainfall–runoff process-based distributed hydrological model to explore the evolution of spatiotemporal variations of water resources from 1999 to 2099 associated with discussions on implications and uncertainties in the upstream Yangtze River region. Birkinshaw et al. (2017) [20] developed Shetran, a process-based, distributed hydrological model, to simulate discharge in the Yangtze River below the Three Gorges Dam at Yichang and examine the effect of climate change on river discharge for 2041–2070. Long et al. (2015) [21] adopted a global hydrological model (PCR-GLOBWB) for simulating total water storage changes in the Yangtze River basin. Lai et al. (2013) [22] developed a new Coupled Hydrodynamic Analysis Model aiming to simulate the water system in the middle reaches of the Yangtze River. Long et al. (2015) adopted a global hydrological model to simulate water storage changes for the Yangtze River basin. Chen et al. (2017) [23] mainly assessed changes of river discharge under global warming of 1.5 °C and 2 °C in the upper reaches of the Yangtze River Basin based on three distributed or semi-distributed hydrological models. Meng et al. (2016) [24] presented a rainfall-process hydrological model, which integrated the variable infiltration capacity model with artificial neural networks (ANNs) and applied it to Jinsha River basin for rainfall–runoff simulation.

Overall, most of the previous process-based hydrology models were developed for the study of discharge change with a focus on the Yangtze River. There are few process-base hydrological models developed and applied to Jinsha River basin. The Jinsha River process-based hydrological model developed by Meng et al. (2016) [24] did not take into account climate change impacts in a long-term discharge simulation. Although physical process-based hydrological models had advantages in directly addressing the relationship between climate change and water discharge dynamically, thus would provide more accurate information for decision support in a long-term perspective, accurate information requires a huge amount of high-quality data to simulate various hydrological processes. In fact, there were insufficient data available for supporting a high-quality process model development in the Jinsha River [25,26], the upper- most reaches of the Yangtze River. In addition, from a long-term perspective, the underlying surface conditions in the basin would be significantly changed. Such changes will affect the performance of process-based models in making future projections as they were developed based on past or current terrain and surface conditions.

The data-driven models adopt black-box methods, which do not ponder complicated physical hydrological processes, instead mathematically discerning the relationship between inputs and outputs. Linear regression models, as one kind of data-driven model based on observed time series (TS), have been widely used in water resources management to forecast streamflow forecasting in the past several decades. The linear regression models have also been applied to the upper-most reaches of the Jinsha River to predict the runoff at Batang station and analyze climate change's impacts on runoff (Xiong et al. (2013) [27]). Such a study indicated that multivariate linear regression model is suitable for Jinsha River discharge projection due to the lower demands for quantitative data and simpler formulation. To address the issue that the daily precipitation observation is earlier than the daily discharge observation downstream of Jinsha River, the time difference will be calculated by dividing the distance between meteorological stations and Xiangjiaba hydropower station by the average stream flow velocity. Accordingly, the developed multivariate linear regression-model-based rainfall discharge model for the Jinsha River will also be improved with the consideration of the process of runoff generation.

2.1. Overview of the Study Region and Data Collection

The Yangtze River Basin can be divided into three physiographic regions from upstream to downstream: Qinghai-Tibet Plateau, Mid-basin Mountains, and Eastern Plains region [28]. The selected region for this study is located in the upper Yangtze River reaches, namely Jinsha River and Yalong River (the largest tributary of Jinsha River). Jinsha River crosses the Qinghai-Tibet plateau, the Yunnan-Guizhou plateau and the western edge of Sichuan Basin, with longitude ranging from 90°23′ to 104°37′ and latitude from 24°28′ to 35°46′. The Jinsha River watershed covers an area of 326×10^3 km^2, and its elevation ranges from 320 m to 6574 m [25]. The climate is quite different between the northern and southern regions. The northern area has a typical continental climate, whereas most of the southern area is characterized by monsoons. Under unfavorable climate conditions, the vegetation in Jinsha Basin generally shows poor growth, especially in dry and hot valley areas. The average annual rainfall in the Jinsha River basin is 750 mm, which mostly occurs from May to October. The annual runoff of the river is stable, which accounts for 34.7% of the upper reaches of the Yangtze River [29].

Cascade hydropower stations are all located downstream of Jinsha River. The missions of the cascade hydropower stations are flood control and electricity generation. The existing 14 weather stations are distributed along the Jinsha River, including Batang, Shigu, Jinjiangjie, Panzhihua, Tongzilin, Yajiang, Ganzi, Longjie, Wudongde, Huatan, Baihetan, Xiluodu, Pinshan, and Xiangjiaba. The Xiangjiaba hydrological station is located at the end of Jinsha River and thus is selected as the study station (Figure 1). Daily rainfall data from 14 meteorological stations from 2000 to 2014 were collected from the Climate Data Center, National Meteorological Information Center, China. Rainfall observation starts at 20:00 (Beijing time) and ends at 20:00 the next day. The corresponding data of Xiangjiaba discharge are exported from the Yangtze River Water Level Information Management System [30].

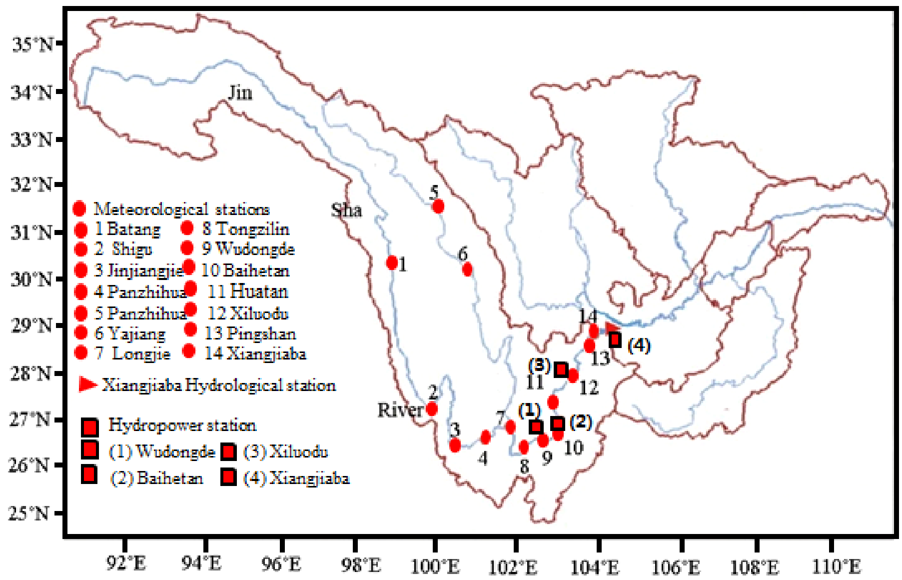

Figure 1. Selected meteorological and hydrological stations on the Jinsha River.

2.2. Weather Stations' Rainfall Collinearity Inspection

Linear regression analysis is used to examine the relationship between rainfall and discharge in the upper Jinsha River basin and identify whether rainfall variables are independent. Rainfall data from 14 meteorological stations need to be examined through collinearity inspection. If a perfect or exact relationship exists among the 14 meteorological stations, collinearity inflates the variability of parameter estimates, which may lead to a lack of statistical significance of individual predictor variables even though the overall model may be significant.

Typical diagnostic indexes like eigenvalue, conditional index, and variance proportion can be used to analyze collinearity among rainfall variables using the Statistical Package for Social Sciences (SPSS) [31]. According to the rule of eigenvalues, if values are near zero, collinearity exists among these linear dependent variables. Condition index is the square root of the ratio of the largest eigenvalue to the corresponding eigenvalue. When the conditional index value exceeds 15, there may be collinearity among those explanation variables. It becomes more significant when the conditional index values are greater than 30. Variance proportion refers to the proportion of variance of each estimate that can be accounted for by each component. When variance components are more than 50% and condition indexes have a larger value, collinearity exists between these variables. Therefore, based on daily rainfall data for June, July, and August (the flood seasons), 14 meteorological stations, located along the Jinsha River (Figure 1) were selected to derive eigenvalues using SPSS. As illustrated in Table 1, the condition index does not exceed 15 and the variance proportion index is not more than 50%. Obviously, no collinearity is shown among the rainfall variables observed from the rainfall stations upstream of Xiangjiaba.

2.3. Rainfall–Discharge Multivariate Linear Regression Modeling

The collinearity inspection indicates that each rainfall data is an independent variable. Therefore, these rainfall variables can be used for multivariate linear regression analysis and modeling with SPSS software. Given the confluence process, observed rainfall at the meteorological stations will take time to be reflected at hydrological stations. The daily rainfall observation would be earlier than the daily discharge observation downstream of Xiangjiaba hydrological station. The period can be calculated by dividing the distance between meteorological stations and Xiangjiaba hydropower station by the average stream flow velocity. In this study, after a preliminary collinearity inspection analysis of rainfall upstream of Jinsha River basin, a statistical analysis was conducted with discharge at Xiangjiaba between independent variable and dependent variable. The rainfall observations at a series of meteorological stations, such as Batang, Shigu, Jinjiangjie, Panzhihua, Tongzilin, Yajiang, Ganzi, Longjie, Wudongde, Huatan, Baihetan, Xiluodu, Pinshan, and Xiangjiaba, were selected as independent input variable with detailed locations shown in Figure 1. Meanwhile, the observed discharges at Xiangjiaba were selected as dependent variables to reflect the rainfall intensity in the upstream reaches. The improved statistical rainfall–discharge model was developed as follows:

$$Y_t = b_0 + \sum_{K=1}^{14} b_k \times X_{k,t-dk}, \tag{1}$$

where Y_t stands for the mean discharge (m^3/s) at Xiangjiaba hydrologic station on date t; b_0 is a constant term that reflects the stable inflow from glacial meltwater; b_k is the actual rainfall–runoff generation coefficient and reflects the correlation between the mean discharge at Xiangjiaba hydrologic station and rainfall at each upstream meteorological station; $X_{k,t-dk}$ is the precipitation at meteorological station k (k = 1 ... 14, representing the meteorological stations of Batang, Shigu, Jinjiangjie, Panzhihua, Tongzilin, Yajiang, Ganzi, Longjie, Wudongde, Huatan, Baihetan, Xiluodu, Pinshan, and Xiangjiaba, respectively) on date $t-dk$ (*t minus dk*), while the symbol of *dk* reflects the time lag before being observed at the Xiangjiaba hydrologic station, determined by the speed of runoff and the distance between meteorological station k and the hydrological station. To assess the statistical relationship between independent variables X and predictive variable Y, the F-test was used to test the significance of the regression equation. The determination coefficient R^2 was employed to assess the accuracy of the simulation. Statistical correlation will be considered significant when R^2 is larger than 0.7.

Table 1. Collinearity inspection by eigenvalue and conditional index.

Dimension	Eigenvalue	Conditional Index	Variance Proportion														
			Constant	Batang	Shigu	Jinjiangjie	Panzhihua	Tongzilin	Yajiang	Ganzi	Longjie	Wudongde	Huatan	Baihetan	Xiluodu	Pingshan	Xiangjiaba
1	2.91	1.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.01	0.01	0.02	0.01	0.01
2	1.93	1.23	0.00	0.00	0.03	0.04	0.00	0.02	0.00	0.00	0.00	0.02	0.06	0.03	0.00	0.00	0.00
3	1.67	1.32	0.00	0.00	0.05	0.05	0.01	0.01	0.01	0.06	0.03	0.02	0.02	0.05	0.00	0.00	0.00
4	1.25	1.53	0.00	0.07	0.01	0.00	0.04	0.16	0.05	0.01	0.15	0.01	0.00	0.00	0.01	0.00	0.00
5	1.18	1.57	0.00	0.08	0.03	0.01	0.06	0.04	0.13	0.25	0.01	0.00	0.00	0.00	0.01	0.00	0.00
6	1.03	1.69	0.00	0.01	0.00	0.01	0.56	0.00	0.19	0.00	0.01	0.04	0.01	0.00	0.01	0.00	0.00
7	1.00	1.71	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.92	1.78	0.00	0.18	0.05	0.00	0.02	0.17	0.08	0.08	0.00	0.03	0.00	0.02	0.05	0.00	0.00
9	0.81	1.90	0.00	0.02	0.00	0.12	0.02	0.03	0.07	0.05	0.28	0.03	0.01	0.01	0.06	0.00	0.00
10	0.69	2.05	0.00	0.23	0.00	0.00	0.11	0.01	0.01	0.00	0.02	0.27	0.01	0.20	0.03	0.00	0.01
11	0.65	2.12	0.00	0.17	0.01	0.01	0.14	0.04	0.41	0.40	0.03	0.04	0.01	0.00	0.00	0.00	0.00
12	0.41	2.67	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.05	0.48	0.33	0.00	0.16	0.01	0.04
13	0.29	3.19	0.00	0.05	0.22	0.39	0.00	0.11	0.02	0.04	0.02	0.01	0.11	0.35	0.29	0.00	0.01
14	0.23	3.53	0.00	0.10	0.34	0.19	0.00	0.28	0.00	0.06	0.09	0.02	0.36	0.25	0.11	0.00	0.06
15	0.04	8.54	0.00	0.08	0.26	0.16	0.03	0.11	0.00	0.01	0.29	0.01	0.08	0.07	0.25	0.98	0.88

There are many different strategies for selection of variables in a regression model, including forward selection, backward selection, and step-wise selection. Stepwise regression is a combination of forward and backward selection methods. Every time a variable is added, all candidate variables in the model will be checked to see if their significance level has been reduced below a specified tolerance level. If a non-significant variable is found, it will be removed from the model. Step-wise regression requires two significant levels: one for adding variables and one for removing variables. The cutoff probability for adding variables should be smaller than the cutoff probability for removing variables so that the forward and backward selection procedure will not get stuck in an infinite loop. All these steps can be accomplished through SPSS software.

Through a step-wise method, shown in Table 2, it is indicated that the rainfall at Wudongde station would be accepted first, followed by rainfall at Xiangjiaba, Longjie, Jinjiangjie, Shigu, Ganzi, Bangtang, Huatan, Pingshan, Xiangjiaba, Tongzilin, Xiluodu, and Panzhihua stations. The above sieving sequence is mainly determined by the rainfall at each meteorological station in the multiple linear regression models' contributions to the downstream runoff at Xiangjiaba hydrological station.

Table 2. Rainfall variables of June, selected through a step-wise method.

Number	Input Variable	Remove Variable	Step-Wise Method
1	Wudongde	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
2	Longjie	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
3	Jinjiangjie	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
4	Shigu	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
5	Ganzi	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
6	Batang	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
7	Huatan	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
8	Pingshan	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
9	Xiangjiaba	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
10	Tongzilin	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
11	Xiluodu	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
12	Panzhihua	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
13	Baihetan	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)
14	Yajiang	-	Step (criterion: F-to-enter probability $\leq$ 0.050; F-to-remove probability $\geq$ 0.1)

Through an F-test for rainfall–discharge regression model for June (Table 3), 13 rainfall variables are added to a model with a correlation coefficient of 0.717 and F less than 0.05. This means that the rainfall data can explain 71.7% of the flow at Xiangjiaba Station, indicating a statistically significant relationship with the discharge at Xiangjiaba Station. The T-test (Table 4) shows that the results of Baihetan rainfall between upstream rainfall variables and downstream discharge is 0.018 higher than 0.05, indicating that the rainfall at Baihetan Station does not exert a significant effect on the flow at Xiangjiaba Station. Thus, the variable $X_{11,\,t}$ can be excluded. Finally, the rainfall–discharge statistical model for June is formulated as follows:

$$
\begin{aligned}
Q_{June,\,t} &= 2983.378 + 120.279\,X_{1,\,t-7} - 133.664\,X_{2,\,t-6} + 108.082\,X_{3,\,t-3} - 32.282\,X_{4,\,t-2} \\
&\quad -48.243X_{5,\,t-2} + 23.760X_{6,\,t-4} + 73.090X_{7,\,t-5} + 93.203X_{8,\,t-3} + 22.005X_{9,\,t-1} \\
&\quad +46.549X_{10,\,t-1} + 40.802X_{12,\,t} - 254.881X_{13,\,t} + 161.600X_{14,\,t}
\end{aligned}
\quad . \qquad (2)
$$

Similarly, all the rainfall variables are added into the rainfall–discharge models for July and August, with the determination correlation coefficients hitting a maximum of 0.724 and 0.745 respectively. Different from the above statistical model for June, models for July and August show that all rainfall variables have passed the T-test, indicating an obvious effect of the upstream rainfall (mm/d) on the downstream runoff (m^3/s). The Jinsha River rainfall–discharge statistical models for July and August are formulated as follows:

$$\begin{aligned} Q_{July,t} &= 5809.456 - 26.897X_{1,t-7} + 71.656X_{2,t-6} + 89.609X_{3,t-3} + 63.204X_{4,t-2} \\ &+ 33.183X_{5,t-2} + 41.21X_{6,t-4} - 35.453X_{7,t-5} + 26.509X_{8,t-3} + 28.282X_{9,t-1} \\ &+ 34.461X_{10,t-1} - 22.262X_{11,t} + 36.575X_{12,t} + 33.263X_{13,t} - 33.058X_{14,t} \end{aligned} \tag{3}$$

$$\begin{aligned} Q_{August,t} &= 5338.339 + 150.121X_{1,t-7} + 51.132X_{2,t-6} + 94.487X_{3,t-3} + 41.111X_{4,t-2} \\ &+ 49.356X_{5,t-2} + 33.169X_{6,t-4} + 56.208X_{7,t-5} - 52.334X_{8,t-3} + 39.558X_{9,t-1} \\ &- 34.519X_{10,t-1} + 34.406X_{11,t} - 32.511X_{12,t} - 41.160X_{13,t} + 68.677X_{14,t} \end{aligned}. \tag{4}$$

Table 3. F-test for June rainfall and runoff statistical model.

Model	*R*	*R* Square	Adjusted *R*	Standard Estimate Error	Sig. F	Correlation Coefficient
1	0.845	0.714	0.682	677.738	0.007	0.717

Table 4. T-test and regression coefficient.

Variables	B	Standard Error	T	Sig. T
constant	2983.378	121.262	24.603	0.000
Batang	120.279	17.003	7.074	0.000
Shigu	−133.664	12.197	−10.959	0.000
Jinjiangjie	108.082	11.307	9.558	0.000
Panzhihua	−32.282	8.664	−3.726	0.000
Tongzilin	−48.243	8.945	−5.393	0.000
Yajiang	23.760	8.695	2.733	0.007
Ganzi	73.090	10.971	6.662	0.000
Longjie	93.203	8.154	11.430	0.000
Wudongde	22.005	5.321	4.136	0.000
Huatan	46.549	7.164	6.498	0.000
Baihetan	−16.696	6.984	−2.391	0.018
Xiluodu	40.802	9.581	4.259	0.000
Pingshan	−254.881	31.724	−8.034	0.000
Xiangjia	161.600	25.342	6.377	0.000

2.4. Validation of Jinsha Rainfall–Discharge Statistical Model

Generally, the statistical forecasting models are validated through hold-out cross method for temporal sequence of the data that have not been used in model parameter inference. This method is to compare the simulated data generated by the model with the observed data. In this study, the average discharge at Xiangjiaba and upstream rainfall data for June, July, and August 2015 and 2016 are not adopted for model parameter inference, and are thus suitable for the cross-validation of Jinsha River rainfall–discharge statistical model. The average daily discharge data at Xiangjiaba hydrological station in 2015 and 2016 were obtained from the Yangtze River Water Level Query System [30] and the corresponding daily rainfall data as rainfall–discharge model input were provided by the China Meteorological Data Sharing Service System [32]. Subsequently, discharge data at Xiangjiaba Station, through the rainfall–runoff statistical model, were compared with on-site observations to assess the overall performance of the rainfall–flow multiple linear regression model (Figures 2 and 3). As presented in Figures 2 and 3, the simulated discharge at Xiangjiaba Station for 2015 and 2016, given by Equations (2)–(4), generally matched the upstream flow trend of observed discharge. According to the hydrological forecasting standard error, absolute relative error between the simulated upstream streamflow of Xiangjiaba and the observed data is generally below 20% and the simulated upstream streamflow trends are in good agreement with the observed discharge. Hence, simulation discharge results are capable of generating satisfactory simulation results and can be used for future Jinsha River runoff projection under climate change.

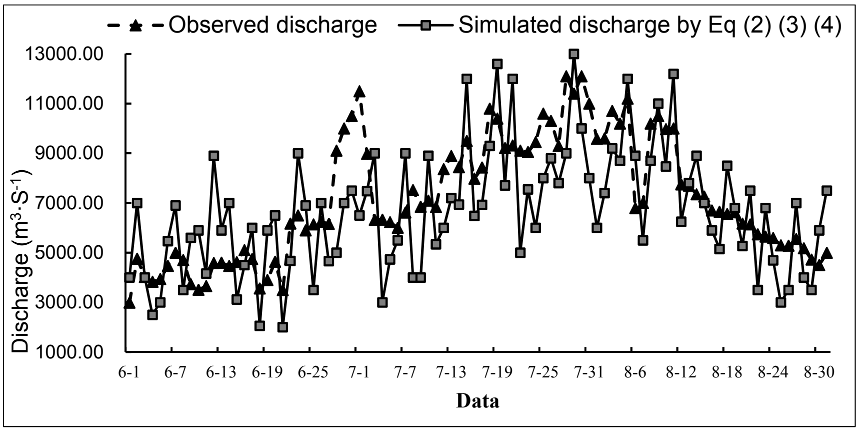

Figure 2. Simulated and observed results of average daily Jinsha River discharge during flood season in 2015.

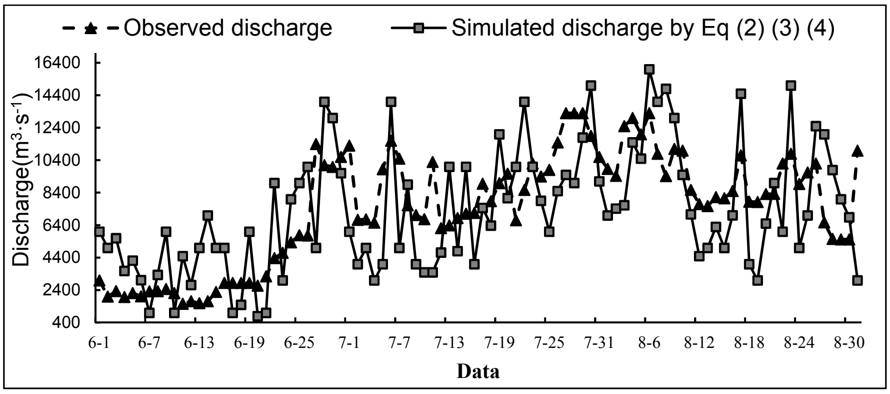

Figure 3. Simulated and observed results of average daily Jinsha River discharge during flood season in 2016.

Meanwhile, there are some deviations between the simulated and observed discharge in 2015 and 2016. At the beginning of the rainy season (June) in 2015 and 2016, the simulated discharge series of Jinsha River is mostly higher than the observed discharge series. However, the simulated discharge values in July 2015 and 2016 are generally below the observed discharge values. As for the late rainy season (August) in 2015 and 2016, the simulated discharge oscillated around the observed discharge values. These deviations are mainly due to the following reasons. Firstly, the rainfall data collected at weather station points could hardly reflect the actual rainfall precipitation in the control area of the point. Secondly, the difference between simulated and observed discharge could exist due to atmospheric acyclic and unstable disturbances, which will affect the accuracy of rainfall measurement and further affect the simulation. Moreover, the deviation between simulation and observation is likely to be amplified due to the operation of upstream hydropower stations, according to the literature (e.g., Djebou (2015) [33]). According to Xiong et al. (2013) [27], from a long-term perspective, the annual streamflow of Jinsha River is more likely influenced by climatic variability; while from a short-term perspective, the simulated discharge is mainly influenced by human activities. In addition, according to Wang et al. (2011) [34], human activities like water diversion, water and soil conservation measures, and dam construction would be also mainly responsible for the drastic decline in river discharge since the 1950s in the Yangtze River basin.

In order to improve the accuracy of discharge simulation, there are some potential measures that could be taken. For example, more weather stations should be set to obtain more precipitation data over the Jinsha River basin. It could also be helpful to investigate the underlying surface conditions (such as different types of soils, land use, and management conditions) and further refine the hydrologic model parameters to improve the projection accuracy.

3. Inflow Trend Analysis of Jinsha River under Climate Change

3.1. Climate Change Simulation over Jinsha River Basin

Generally, it is widely accepted that assessment of the impact of climate change on future precipitation scenarios is critical for water resources planning and development [35,36]. Through the above statistical rainfall analysis, it is indicated that climatic factors, particular rainfall, do greatly affect the Jinsha River's upstream inflow water discharge. Therefore, in order to get a better understanding of climate change's impacts on the flood scheduling of Jinsha River cascade hydropower stations and develop solid adaptive strategies, it is important to carry out long-term climate change simulation over Jinsha River basin. PRECIS (Providing Regional Climates for Impacts Studies) is adopted in this research to generate high-resolution future climate data at a regional level, given its proven performance at reproducing climate change in China and globally.

To address the uncertainty related to emission levels in regional climate modeling, three scenarios, A2, B2, and A1B, are normally adopted. The emissions level of the A1B scenario is medium. B2 describes an emissions scenario aiming toward economic, social, and environmental sustainability that is more reasonable than A2, which is aiming at intensive economic development and thus is unreasonable, particularly after the Paris Agreement came into effect. Therefore, the A2 scenario is excluded from this study. The A1B scenario simulation, covering 1960 to 2099, is based on a global model ECHAM5, while the B2 scenario is mainly focused on simulating the climate change of 2070–2099 based on the HADAM3P global model. Considering that the main flooding of the Jinsha River mostly occurred in the month from May to October, this study has given emphasis to analyzing climate change's impact on rainfall and Jinsha River runoff under the A1B and B2 scenarios from May to October.

Figures 4–6 show the variance of Jinsha River's average rainfall, from May to October, between the simulation periods (2010–2040, 2040–2070, and 2070–2099) and the historical periods (1960–1990 and 1980–2010) under A1B and B2 scenarios. The figures illustrate the rainfall intensity or future rainfall change trends, in which dark blue indicates that the region would experience increasing rainfall intensity and light yellow denotes a shortage of rainfall during the whole simulation period in the region. In a comparison of average rainfall in May in 2010–2040, 2040–2070, and 2070–2099 and the average rainfall in 1960–1990, the results (Figure 4) indicate that the precipitation in May shows an increasing trend under the A1B scenario. However, in a comparison of average rainfall in May in 2010–2099 and the historical period of 1980–2010, the simulation results indicate that Jinsha River's rainfall will have a slight decrement in the period 2010–2099. The precipitation in June for 2010–2040 would decrease compared with 1980–2010 but be higher than in 1960–1990. However, during 2040–2070 and 2070–2099, the average rainfall over the Jinsha River basin shows an increasing trend. Similarly, the variations of Jinsha River's rainfall from July to October (Figures 4 and 5) indicate that rainfall in future simulation periods are likely to experience a significant increase compared to 1980–2010. Under the B2 scenario, the variations in Jinsha River's rainfall from May to October (Figure 6) indicate that rainfall in future simulation periods, compared to 1980–2010, are likely to experience a significant decrease.

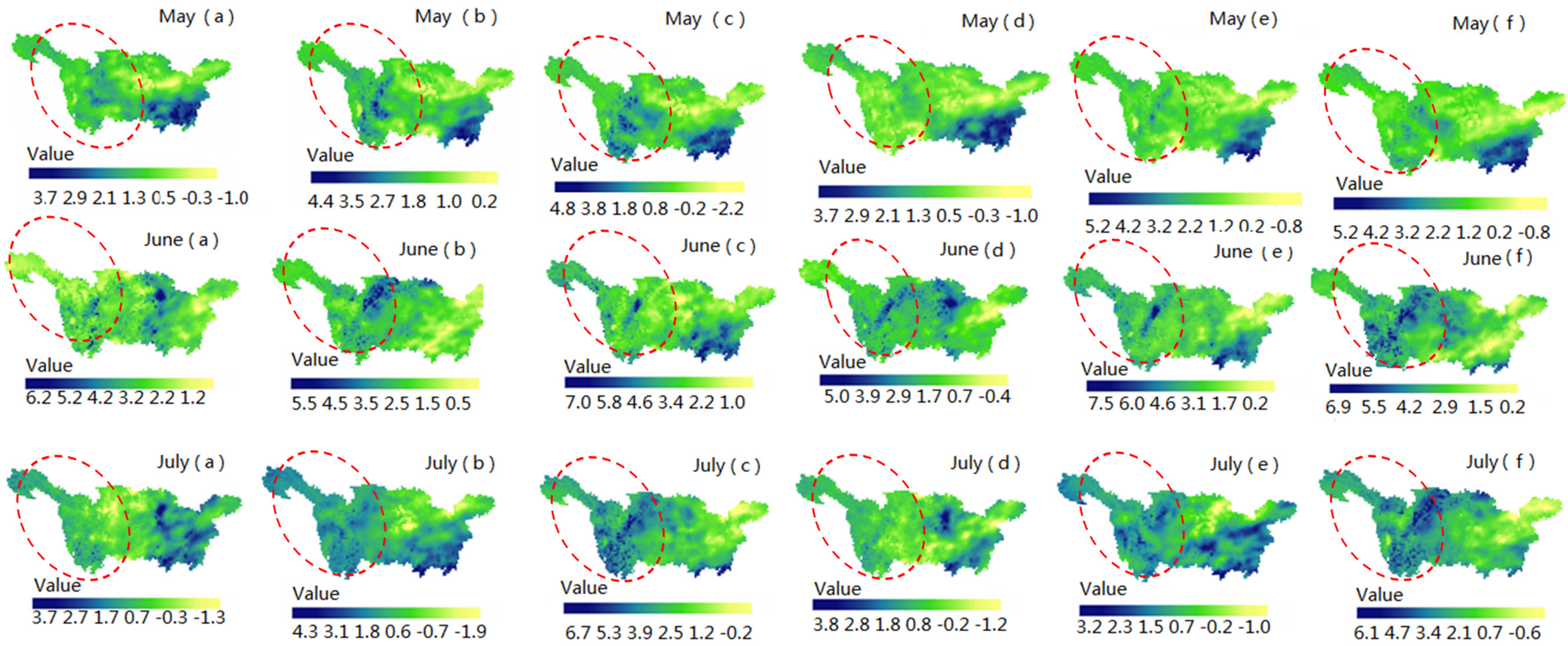

Figure 4. Rainfall distribution over the Jinsha River basin under A1B from May to July in different periods: (**a**) 2010–2040 rainfall compared with 1960–1990; (**b**) 2040–2070 rainfall compared with 1960–1990; (**c**) 2070–2099 rainfall compared with 1960–1990; (**d**) 2010–2040 rainfall compared with 1980–2010; (**e**) 2040–2070 rainfall compared with 1960–1990; (**f**) 2070–2099 rainfall compared with 1980–2010.

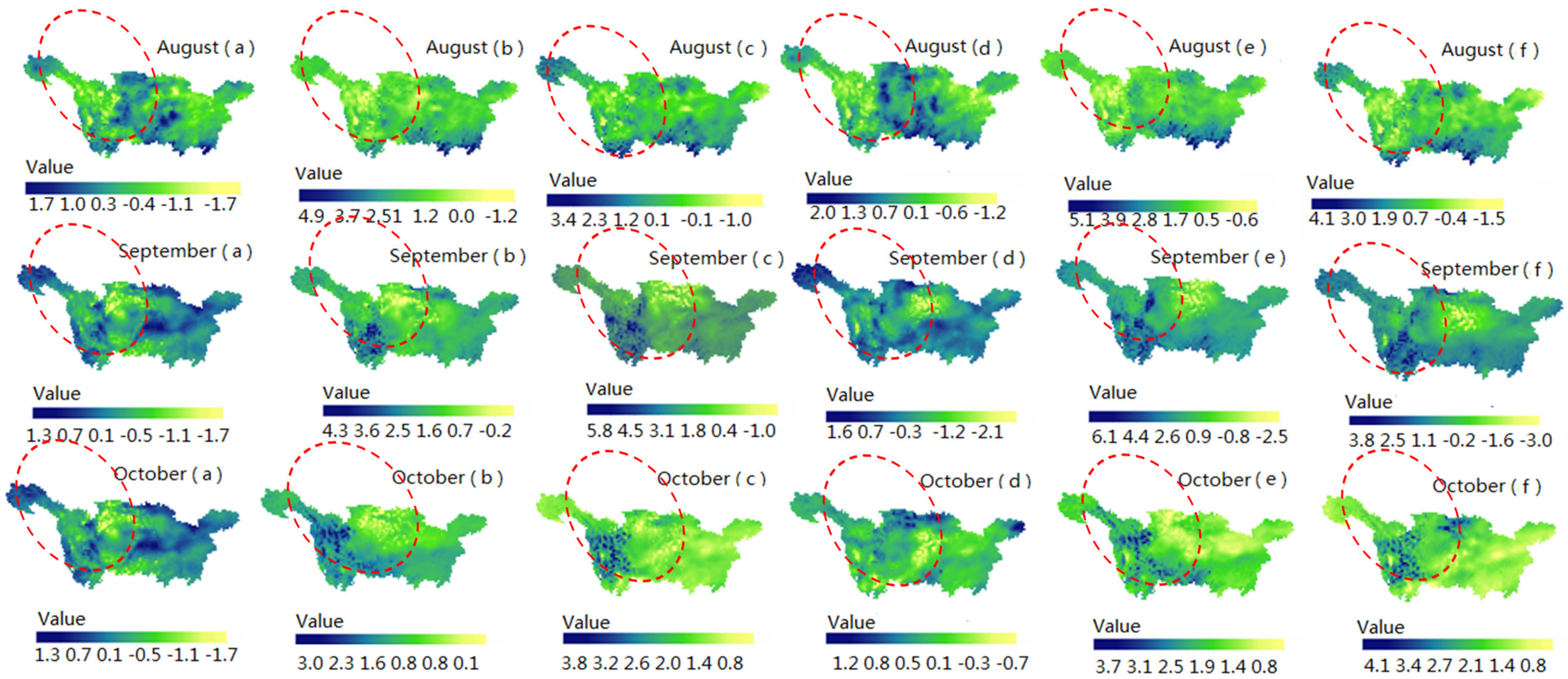

Figure 5. Rainfall distribution over Jinsha River basin under A1B from August to October during different periods: (**a**) 2010–2040 rainfall compared with 1960–1990; (**b**) 2040–2070 rainfall compared with 1960–1990; (**c**) 2070–2099 rainfall compared with 1980–2010; (**d**) 2010–2040 rainfall compared with 1980–2010; (**e**) 2040–2070 rainfall compared with 1960–1990; (**f**) 2070–2099 rainfall compared with 1980–2010.

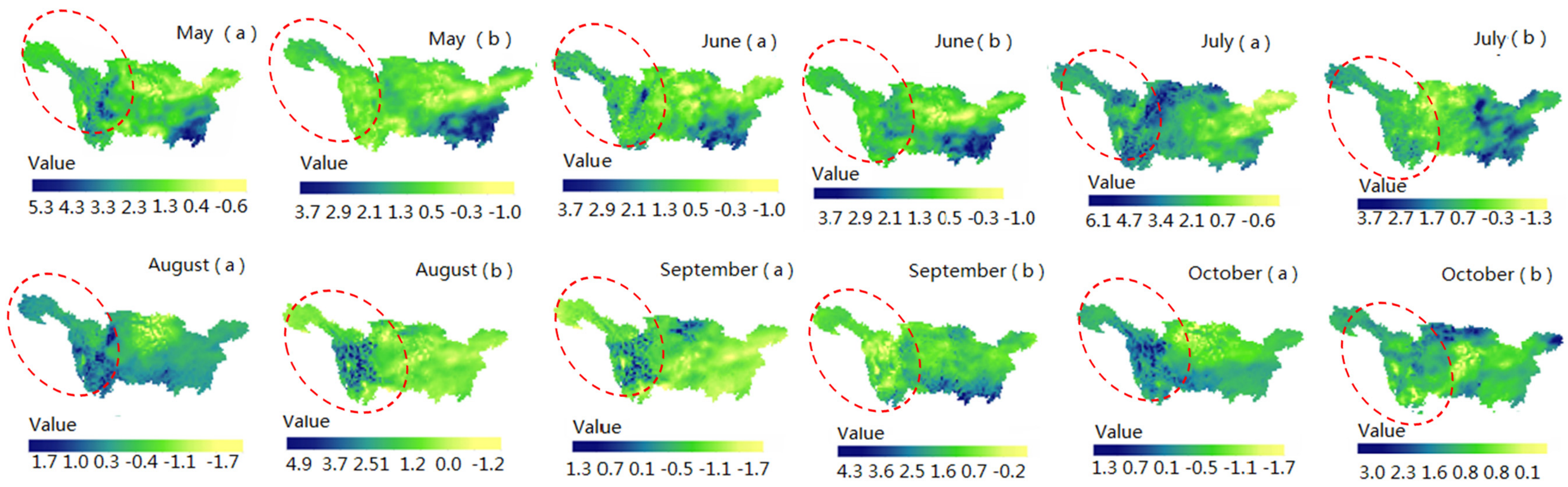

Figure 6. Rainfall distribution over Jinsha River basin under B2 from May to October in different periods: (**a**) 2070–2099 rainfall compared with 1960–1990; (**b**) 2070–2099 rainfall compared with 1980–2010.

Meanwhile, the precipitation in three simulation periods in the future (2010–2040, 2040–2070, and 2070–2099) indicates that the whole Jinsha River basin is likely to undergo a marked increase from 2010 to 2070 in May, July, September and October rainfall compared to historical rainfall (1960–1990 and 1980–2010). The precipitation would decrease in 2040–2070 but increase in June and August compared to historical rainfall (1960–1990 and 1980–2010). Moreover, the rainfall displays spatial diversity over Jinsha River basin in the whole simulation (1960–2099). For example, the difference in precipitation between May and July is not very distinct upstream of the Jinsha River basin. The upper reaches of Jinsha River are short of rainfall; nevertheless, downstream of Jinsha River rainfall has an increasing trend. In June, September, and October, total precipitation is generally growing in most areas of Jinsha River. In early August, there is an obvious precipitation increment upstream of Jinsha River, and a decrease downstream of Jinsha River in mid-to-late August. Generally, from the simulated precipitation in the Jinsha River basin under the A1B scenario, during 1960–2099, there first emerges an increasing trend in 2010–2070 compared to the historical periods (1960–1990 and 1980–2010). However, this trend may slow down after 2070. In addition, the above trends are mostly average rainfall trend and it is difficult to guarantee the possibility that the runoff will increase in a certain period or in a certain section of Jinsha River. Under climate change conditions, water resources may undergo some changes of spatial diversity and temporal difference. Therefore, it is desirable to combine these simulations with a rainfall–discharge model to analyze Jinsha River's future inflow trends and develop appropriate strategies for flood control of the four hydropower stations, under climate change conditions.

3.2. Inflow Trend Analysis of Jinsha River

The above statistical rainfall analysis indicates that climatic factors (particularly precipitation) have a significant effect on upstream runoff at Jinsha River and may lead to changes in the flood control scheduling of cascade hydropower stations.

The Xiangjiaba hydrological station located downstream of Jinsha River is selected for annual discharge analysis. Firstly, high-resolution (25 km) daily average rainfall data (1960–2099) upstream of the Jinsha River basin are obtained through the PRECIS modeling simulation under scenario A1B. The simulated precipitation data are used to drive the Jinsha River rainfall–discharge model and obtain the average annual discharge at Xiangjiaba hydrological station (1961 to 2099).

Figure 7 presents the results of average annual discharge at Xiangjiaba hydrological station. Through inter-annual discharge (Xiangjiaba) inspection for May under scenario A1B, the results indicate that the discharge basically fluctuates around a mean value of 3000 m^3/s. Specifically, the inflow begins with a slow decreasing tendency at the first stage (1961–2020) and then gradually increases after 2020, with the oscillation amplitude of inter-annual discharge decreasing before 2020 but increasing after 2020. Similarly, the upstream inflows of Jinsha River from June to October (Figure 7) generally show significantly increasing trends. Over the simulation period (1961–2099), the discharge at Xiangjiaba varies around 7500–8000, 8000–8400, 7900–8000, and 7000–8000 m^3/s in July to October, respectively. Under climate change conditions, the occurrence of peak discharge in the non-flood season (September and October) would likely increase. Overall, as illustrated in Figure 7, the discharge curve shows a larger oscillatory variation around 2050 and 2081–2099. Results also vary in different months. For example, the discharge originally shows increasing trends in July and August, ranging from 7500 to 8000 m^3/s and reaching a maximum of 8500 m^3/s at the end of July.

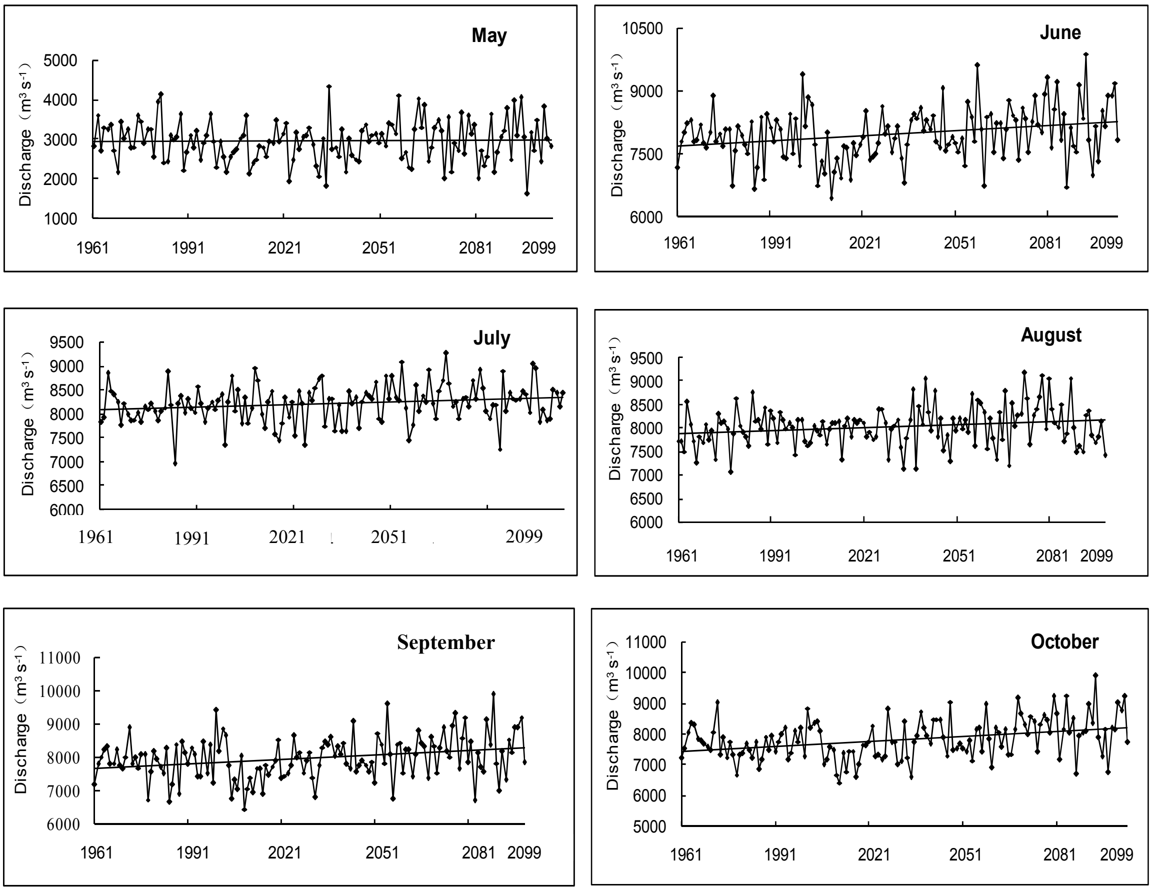

Figure 7. Simulation of discharge for Jinsha River from May to October (1961–2099) under scenario A1B.

The most striking feature of Jinsha River discharge under B2 (Figure 8) during 2071–2099 is that Jinsha River will undergo varying degrees of downward trend in the wet season (from May to October). Specifically, the average Jinsha River discharge in early May 2071 is 4000 (m^3/s), then sharply inclines to 3000 (m^3/s) in 2099. Similar to the simulation results under A1B, Jinsha discharge keeps creeping up from June to August and then falling in September and October. Meanwhile, it is noticeable that Jinsha discharge is lower during the same simulation period under the A1B scenario than under the B2 scenario. Compared to the B2 scenario, the A1B scenario is closer to the real level of greenhouse emissions predicted for the future. Therefore, the prediction of future Jinsha River inflow under A1B is more reasonable.

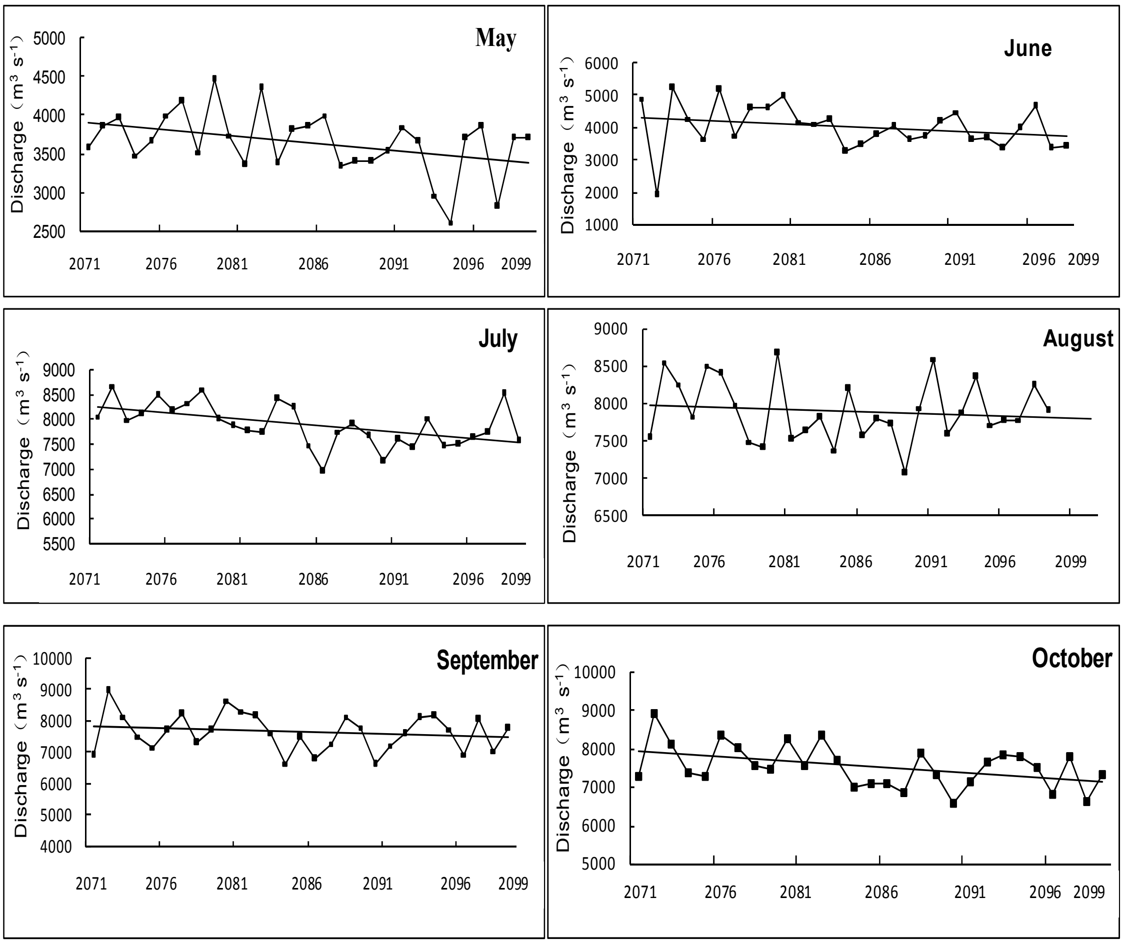

Figure 8. Simulation results of Jinsha River discharge from May to October in 1961–2099 under scenario B2.

3.3. Hydrological Frequency Analysis for Jinsha River

To get a better understanding of the flood risk to cascade hydropower stations under climate change conditions, it is important to conduct hydrological frequency analysis. In most cases, recurrence interval is widely adopted by policy makers or researchers to estimate likely severity. This indicator reflects the probability that an event of any given magnitude will happen in any given year.

The hydrological frequency analysis of this study is mainly based on the discharge results from the above rainfall–discharge model under scenario A1B. These results are then applied to a hydrological frequency curve analysis. As shown in Table 5, in May and August, the designed flood discharge standard with respect to recurrence intervals of 100 years and 50 years would decrease significantly in 1991–2020 and then rise from 2021 to 2099. Jinsha River inflow discharge with respect to a 100-year return period and a 50-year return period in May correspond to 4187 and 4052 m^3/s from 1961 to 1990, decreasing to 3888 and 3748 m^3/s during 1991–2020, rising in 2021–2050, and reaching 4603 and 4386 m^3/s in 2051–2099. The designed flood discharge for August, under the two hydrological frequency conditions in 1961–1990, corresponds to 8896 and 8773 m^3/s and then would fall to 8599 and 8525 m^3/s, respectively, in 1991–2020 before gradually rising in 2021–2099 and finally reaching a maximum of 9389 and 9224 m^3/s. Therefore, drought is likely to occur in May between 1991 and 2020. The inflow discharge in Jinsha River would likely decrease in August between 1991 and 2020 under climate change conditions. However, in June, July, and October, the flood discharge with varying levels of hydrological frequency may increase during four periods (1961–1990, 1991–2020, 2021–2050, and 2051–2099), indicating that the probability of flooding events being affected by climate change may also increase. In September, the discharge with respect to two levels of recurrence (intervals of 100 years and 50 years) also shows great inter-annual variation. For example, the recurrence interval of a 100-year return period during 1960–1991 is 9060 m^3/s and then may rapidly rise to 9515 m^3/s in 1991–2020. The recurrence interval of 100 years in 2021–2050 is basically close to that in 1960–1991, and may then increase up to 9936 m^3/s. It is obvious that the potential flood risk would increase in September of 1991–2020 and 2051–2099, implying that the flood seasons of Jinsha River may be delayed to September.

Table 5. Jinsha River hydrological frequency analysis from May to October.

Recurrence intervals	1961–1990	1991–2020	2021–2050	2051–2099
May				
100-year return period	4187	3888	4117	4603
50-year return period	4052	3748	3952	4387
June				
100-year return period	5313	5509	5829	6161
50-year return period	5167	5338	5648	5981
July				
100-year return period	9054	9066	9152	9403
50-year return period	8926	8951	9040	9254
August				
100-year return period	8896	8599	9140	9389
50-year return period	8773	8525	9000	9224
September				
100-year return period	9060	9515	9161	9936
50-year return period	8908	9267	8992	9721
October				
100-year return period	8907	9045	9485	9848
50-year return period	8721	8864	9223	9636

The above variation implies that the underlying occurrence of extreme discharge intensity and frequency likelihood may greatly increase in wet seasons (from June to October). The possibility of extreme drought frequency events may increase in May and June. For example, in May of 1991–2020 and June of 1960–2020, the discharge in Jinsha River with a 100-year return period risk is less than that in other simulation periods (e.g., 1960–1990 and 2021–2099). This also implies that the upper reaches of Jinsha River may be short of rainfall in this period. Consequently, it is likely to delay the arrival of the conventionally recognized flood season (May and June) in 1991–2020. It is also worth noticing that the generally recognized post-flood inflow discharge, with the decreasing hydrological frequency, would conversely increase significantly and be more obvious in September and October. Under this circumstance, an increase of runoff in the flood season could occur under future climate scenarios, indicating a high possibility of flooding events in the Jinsha River basin in the future.

4. Adaptation of Cascade Hydropower Stations' Scheduling on Jinsha River under Changing Climate Conditions

According to China's current Flood Control Act, the flood-limiting water level (FLWL) for cascade hydropower stations is a key parameter of flood control guidelines [37–39]. Under these flood control guidelines, before the flood season (June) of each year, the preserved flood control capacity for cascade hydropower stations should be determined in order to reserve sufficient detention capacity for forecasted inflow volume, which is based on the trade-off between flood prevention and water resource use [40,41]. During the flood season (i.e., July and August) the cascade hydropower stations are operated below FLWL in order to reserve adequate reservoir storage for flood prevention. In the recession of flood season (i.e., September and October), cascade hydropower stations reserve water to increase power production. Although the above conventional flood-control operation modes are easy to implement, flood utilization rate is low as excessive water is released from hydropower stations in the pre-flood and post-flood seasons. Frequently, hydropower stations may fail to reserve enough water to maintain normal operating levels in dry years [42]. Due to the fact that the current FLWLs are mostly derived from the maximum discharge value of annual data, they may neglect the seasonal dynamics of flood and climate change factors, leading to non-optimal decision-making, unrealistic expectations, danger, and even failure.

In this study, through the above inflow trend analysis for Jinsha River, it is revealed that future climate change may increase the likelihood of flooding in the Jinsha River basin. The varying upstream runoff under a changing climate also challenges the current scheduling of the downstream cascade hydropower stations. Ignoring climate change effects and runoff variation may lead to certain risks and negative consequences. In view of the variability of inflow processes and climate change factors in flood and non-flood seasons, adaptive impoundment scheduling approaches are presented here for the pre-flood, flood, and post-flood seasons to respond to the varying future upstream runoff in Jinsha River basin. Therefore, it is important to conduct assessment and adaptability analysis of climate change's effects on Jinsha River cascade hydropower station scheduling. The cascade hydropower stations are located downstream of Jinsha River (Figure 1). The main flood control parameters of these cascade hydropower stations are listed in Table 6. Specifically, the normal water storage level of the cascade hydropower stations is the highest water level under normal operating conditions; the dead water level is the minimum level that could meet normal power generation. Generally, the water level of hydropower stations would fluctuate between the dead water level and the normal water level in the pre-flood seasons; however, in the flood season the water level of cascade hydropower stations should be below the FLWL for preventing floods.

Table 6. Parameters of four cascade hydropower stations in the Jinsha River basin [43,44].

Parameter	Wudongde	Baihetan	Xiluodu	Xiangjiaba
Adjustment ability	Annual	Annual	Annual	Season
Regulating storage (billion m^3)	2.60	10.40	6.46	0.90
Installed capacity (MW)	8700	14,000	13,860	6400
Dead water level (m)	945	765	540	370
Flood limiting water level (m)	952	785	560	370
Normal storage water level (m)	975	825	600	380
Water level range (m)	[945, 975]	[765, 825]	[540, 600]	[370, 380]

The specific adaptive strategies are generated based on Jinsha River inflow runoff trend analysis in 1961–2099. According to the projected hydrological frequency result under the A1B scenario, flow upstream of Jinsha River in May of 1961–2020 shows a significant decreasing trend and extreme flood occurrences during 2021–2099 are increasing. The inflow trends before and after 2020 indicate that flood control strategies generated before 2020 may no longer be applicable under climate change. Accordingly, the specific flood control scheduling for these cascade hydropower stations before 2020 could be: the reservoirs' water level for these cascade hydropower in May would keep the normal reservoir water level at 975, 825, 600, and 380 m; however, taking climate change impacts into account, flood control operation with respect to lowering the hydropower reservoirs' water level could be postponed until late June. The cascade hydropower stations' water level should be ensured below the FLWL and higher than the dead water level in late May from 2021 to 2099. In addition, all the reservoirs' water levels should be adjusted within the water level range (the upper bound is the reservoir's normal storage water level; the lower bound is the reservoir's dead water level). The above adaptive flood control strategies developed in pre-flood seasons (May) could not only enhance flood control security for the cascade hydropower stations but also increase the power generation.

In flood seasons, from late June to the middle of July of 1961–2099, the hydrological frequency under the A1B scenario indicates that the occurrence of floods shows an increasing trend. Therefore, the reservoir water level should not exceed FLWL to offer adequate storage capacity for the likely increase in flooding. The main principle of flood scheduling for cascade hydropower stations should be to ensure that cascade hydropower stations are secure during a flood. The upstream cascade hydropower stations like Wudongde and Baihetan hydropower stations with large regulating storage can be involved to fulfill the tasks of reducing the peak discharge of Jinsha River, while Xiluodu hydropower station should be adopted for filling the valley and providing an emergency reserve. It is noted that the upstream inflow discharge of Jinsha River is likely to decrease in August from 1991 to 2020 and increase greatly from 2021 to 2099. However, as shown in Figure 6, the general inflow trend would also vary around 8000–8400 (m^3/s), which is higher than that in July with the inflow discharge varying around 7500-8000 (m^3/s) from 1991 to 2020. Therefore, these four cascade hydropower stations should also ensure that the water level of cascade hydropower stations in August remains below the FLWL during 1991–2020 and 2021–2099.

In the post-flood season (September and October), the previously developed flood scheduling strategies could be: cascade hydropower stations would mostly begin to reserve water up to the normal water level for hydropower generation. However, hydrological frequency analysis under the A1B scenario indicates that flood likelihood under climate change generally shows an increasing trend in September during 1961–2020 and 2051–2099 and a decreasing trend in 2021–2050; the inflow of Jinsha River would generally shows an increasing trend in October from 1961 to 2099. Therefore, the possibility of flooding shows an increasing trend (during 2051–2099). This implies that the flood seasons of Jinsha River may be delayed from August to September or even October. It thus will be secure for cascade hydropower stations to postpone reserving water to October. Therefore, the water level of these four cascade hydropower stations should also operate at FLWL to offer adequate regulating storage capacity to cope with extreme hydrological events in post-flood seasons (September and October) during 1961–2099. In late October, conflicts may exist in terms of water impoundment among cascade hydropower stations for different flood control assignments. The principles of impoundment strategy for the cascade hydropower stations should reflect both the urgency of flooding control assignment and the economic benefits of hydropower stations. For example, if there is no urgent flood control assignment for upstream cascade hydropower stations at Wudongde and Xiluodu, these hydropower stations with large installed capacity can be prioritized to impound water back to the normal water level. A hydropower station with less flood protection such as Baihetan cascade hydropower stations can be ranked in second place. A hydropower station with a small reservoir storage capacity for flood protection and ecology conservation such as Xiangjiaba can be ranked last to impound water.

Based on the above analysis, it is suggested that the current flood control and management mode of the Jinsha River should reflect the impacts of future climate change. As extreme hydrological events increase, it is desirable to advance the joint scheduling management of cascade stations to reduce the flooding risk caused by extreme hydrological events. It is suggested that cascade hydropower stations could postpone decreasing reservoirs' water level to improve the water utilization rate during the pre-flood season (May and June) before 2020 but should operate at the FLWL during 2021–2099. In addition, the impoundment of cascade hydropower stations should be properly delayed during the post-flood season in response to the possible occurrence of increased and extended inflow in the wet season.

5. Conclusions

This research focused on adaptive scheduling for cascade hydropower stations upstream of Yangtze River, namely Jinsha River, in response to a changing climate. An improved multivariate linear regression model with consideration of hydrological processes was developed for rainfall–discharge projection. Validation results indicated that the developed rainfall–discharge model was capable of generating satisfactory simulation results and can be used for future Jinsha River runoff projection under climate change. PRECIS, a reginal climate modeling tool, was run to project future rainfall in the

Jinsha River basin under multiple GCM models (ECHAM5 and HadAM3P), and multi-scenario (A1B and B2) and multi-period (1961–1990, 1991–2020, 2021–2050, and 2051–2099) conditions. The simulated precipitation data were used to drive the Jinsha River rainfall–discharge model and obtain the average annual discharge at Xiangjiaba hydrological station (1961–2099). The data were further applied to inflow trend and frequency analysis of Jinsha River. It was indicated that extreme hydrological events in terms of intensity and frequency of river discharge would significantly increase in both the flood season (July and August) and the post-flood season (September and October). Based on extreme hydrological frequency analysis and the current flood scheduling mode, adaptive flood scheduling strategies for cascade hydropower stations were generated. It was suggested that cascade hydropower stations could postpone decreasing reservoirs' water level to improve the water utilization rate during the pre-flood season (May and June) before 2020, while hydropower stations should operate below the FLWL in pre-flood seasons during 2021–2099. In addition, the impoundment of cascade hydropower stations should be properly delayed during the post-flood season in response to the possible occurrence of increased and extended inflow in the wet season.

Acknowledgments: This research is supported by the National Key Research and Development Program of China (Grant number: 2016YFA0601502) and the Nature Conservancy (TNC). The authors are grateful to the anonymous reviewers of this manuscript for their valuable suggestions and comments, which have greatly improved the paper.

Author Contributions: Ming Yang Zhai conducted rainfall-discharge modeling and result analysis, carried on climate change simulation and result analysis; Qian Guo Lin was the principal investigator of this project; designed and implemented this research, contribute idea and conducted climate change simulation and result analysis; Guo He Huang contributed idea to this research and provided guidance on climate change modeling; Le Zhu and Kai An contributed idea to this research, steered the research and provided guidance on adaptation of cascade hydropower stations scheduling on Jinsha River under changing climate conditions; Gong Chen Li was involved in rainfall-discharge modeling result analysis; Yue Fei Huang contributed to rainfall-discharge modeling result analysis and climate change impact analysis.

Conflicts of Interest: The authors declare no conflict of interest.

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