

Modeling the Influence of Meteorological Variables on Runoff in a Tropical Watershed

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Abstract

Proper understanding of the historical annual runoff characteristics with respect to climate impacts is essential for effective planning as well as the management of water resources in river basins. In this study, the climate-flood model which connects the runoff and climate was developed for Adada River Nigeria. Thirty years records of climatic and runoff data were used to develop a multiple linear regression model. The coefficient of determination was evaluated for the developed model, and the hypothesis was equally tested with the aid of t-test and one-way analysis of variance. The multiple regression analysis indicated that the climate-flood model was statistically significant ($p < 0.05$) in predicting the annual runoff. The results also show that the climatic variables accounted for 66.1% of runoff variation due to the undisturbed gauging basin of the river. The wind speed and the duration of sunlight were not statistically significant predictors of runoff in the area. These results, obtained signify that climate has a major impact on runoff and it could help in understanding the availability of water within the catchment area.

Keywords: Climate; Multiple Regression Model; Runoff; Flood.

1. Introduction

An increasing concern throughout the world is the issue of climate change arising from global warming. Climate is the combination of the weather conditions of a specific location over a long period of time. Several findings indicate that potential climate variability would lead to heavy precipitation. This could contribute to more floods, especially as a channel adapts to the different stream flow conditions [1].

Flooding primarily results from heavy precipitation, in which the natural waterways lack the ability to transport excess water [2]. It could also be caused by other occurrences, especially in coastal regions emanating from heavy rainfall, which are associated with a tsunami or a tidal surge [3]. Flooding is among the most dreaded environmental issues in recent times. In several regions across the globe, floods pose significant challenges to the financial sector, citizens as well as the environment [4]. World Bank reported that floods caused financial damages amounting to over US\$ 1.6 trillion worldwide within the periods ranging from 1980-2017, in which over 225,000 people died [5]. Due to urban growth as well as climate change, such losses are likely to rise in the twenty-first century [2]. In Nigeria, flooding is the most recurrent hazard [6]. Thus, millions of Nigerian citizens have been affected by flooding, causing financial losses worth billions of USD [5]. The major detrimental effects of flooding in Nigeria encompass deaths, physical damages, prevalent infections and diseases, social unrest, deprivation, food shortages and

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financial losses which are primarily caused by farmland destruction, social-urban infrastructural disruption as well as economic interference in the distribution of power and telecommunications [7, 8]. An increase in the rate of annual flooding which occurs mostly in majority of the states in Nigeria, especially during the rainy seasons is due to increased precipitation related to climate change [9]. The statistics on the occurrence of natural disasters indicate that the wind storms and floods are the greatest causes of natural disaster recorded globally in the century.

Prediction techniques are important for planning, design, as well as monitoring of water resources framework [10]. In order to determine the flood risk intensity, geographic streamflow predictions and flood models are most often used [11]. The determination of the effect of climate on runoff is a very laborious task, which requires an extensive field investigation. This is because it helps in the description of hydrological processes which is of much importance in the design of hydraulic structures. Moreover, the intricacies involved in measuring these hydrological parameters increases with the geographical locations, and they could be temporal [12]. The regression model is among the most effective as well as the simplest statistical models used in streamflow forecasting, which is derived from the limited runoff and climate data of the gauged drainage basin [13].

In most cases, the data are lacking on the site, and the relationship between the parameters is obtained with the aid of a gauged basin having similar hydrological characteristics which are transferred to the site in focus. In the design of water scheme for irrigation or domestic uses, the annual or monthly yield with or without storage is needed. Jarboe and Haan [14] in their research considered the four-parameter model developed by Haan [15] involving the effects of the fraction of seepage turning to runoff, the maximum conceivable infiltration rate, maximum moisture-holding capacity of the soil and the maximum conceivable seepage rate used in the prediction of the water yields emanating from ungauged watersheds using a multiple linear regression model. They reported 6.5% error of prediction after comparing between the observed and the simulated runoff. Magette et al. [16] adopted Jones [17] method in fitting a portion of six parameters obtained in the Kentucky watershed model. They used 15 watershed properties and they obtained a convincing multiple regression model. Xu et al. [18] obtained a relationship existing between the land use and water balance model over a monthly period for the Swedish catchment area. They used regression analysis to determine the model variables within the catchment area. Their result showed less than 1% average error of prediction, with a 20 % maximum error in a catchment area.

A comparative analysis between the regression and deterministic models is required in determining the maximum flow of flood frequencies in rural ungauged watersheds. A study to compare the results obtained from the regression and deterministic models involving the volume of storm-runoff-storm in Colorado showed that no model is superior to the other with respect to a specific basin [19]. Asati and Rathore [20] developed a multiple linear regression equation which relates the runoff and rainfall as output and input variables respectively. Thus, they failed to compare the performance of the models and to consider the type of the process involved. The climate - flood model is very important in predicting the change in climate and flood pattern. It is also very useful in the description of the catchment responses to the variation in land use together with the climate for actual flood prediction.

So many rivers in developing countries like Nigeria have experienced collapse of the hydraulic structures at the inlet or outlet of the tributary channel and gauging stations. Among them is Adada River, Nigeria. Most of them today, are either non-performing (performing optimally low) or totally collapsed. Critical evaluations of these hydraulic structures showed that: they were either poorly designed or constructed, or there was application of wrong or faulty data and statistics at the design stage. The in-depth study of empirical modelling of flood at Adada River in Enugu state of Nigeria, using climatic or meteorological data has not been carried out and its need is increasingly necessary for effective hydraulic design. This article presents a holistic approach in the formulation of a climate - flood model, model calibration, model verification and the significance of the model for prediction of runoff for the small tropical watershed of Adada River.

2. Method

2.1. Study Area

The study area is Adada River in Uzo Uwani Local Government Area. Also one is among the Local Government areas in Enugu State, Nigeria, which is notable for her agrarian practice particularly in rice production. It is bounded to the north by Benue, to the east by Ezeagu and Udi, to the south by Kogi and to the west by Anambra State [21]. Adada River is situated between latitude $6^{\circ} 25' - 6^{\circ} 45' N$ and $7^{\circ} 00' E - 7^{\circ} 23' E$ (Figure 1). The River is a major tributary of River Niger. The study area has two apparent climatic seasons; such are: the rainy and dry seasons. The rainy season starts in April and stops in September whereas the dry season starts in October and stops in March [22]. These seasons are brought about by the north-south changes between the damp Atlantic air and the dry mainland air [23]. The anthropogenic activities have intensified in the river over the years after the construction of a standard bridge at Nkpologu. The river serves as the major source of water supply for the villagers as well as the surrounding towns, and it is readily available throughout the year. Commercial tanker drivers collect water for sale to the natives and towns within Nsukka area especially during the dry season. Apart from normal cultivation along the river's course during the

farming season, the water is used for irrigation by many communities along its length for dry season farming.

2.2. Method of Data Collection

The data on monthly rainfall, maximum temperature, minimum temperature, sunshine, evaporation, humidity, wind velocity, cloud cover, atmospheric pressure, soil temperature and solar radiation for Enugu was obtained from the Nigerian Meteorological Agency (NIMET) located at Lagos, Nigeria. The data spanned between 1983 and 2004 (30 years). The maximum monthly runoffs of Adada River basin were collated from the available discharge records to form a time series of maximum annual runoff as shown in Table 1. The flowchart of research methodology is shown in Figure 2.

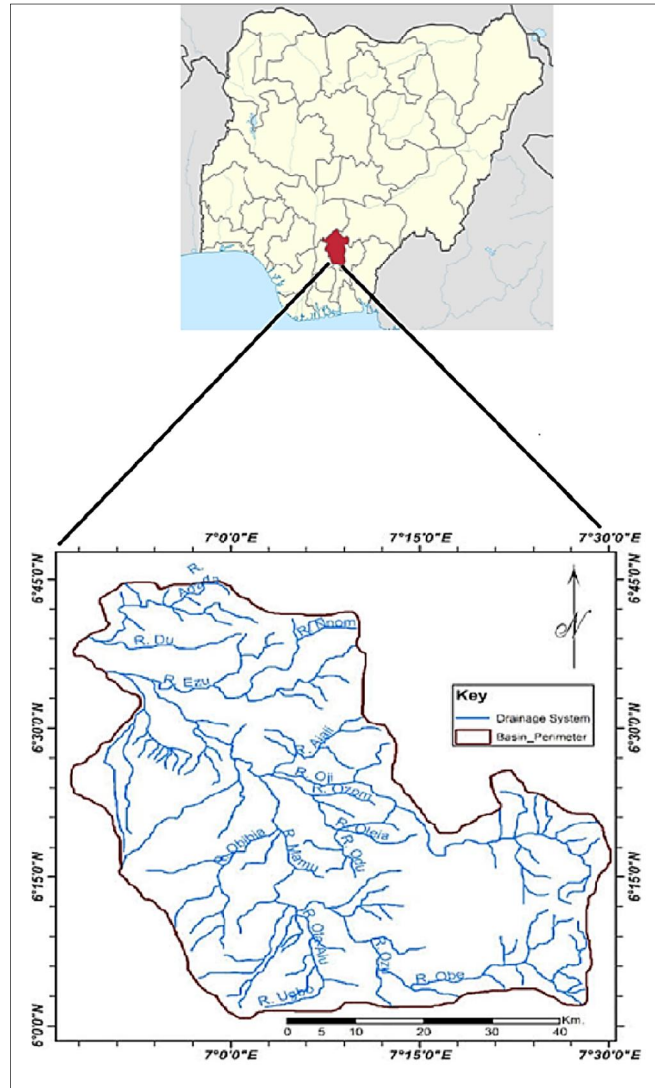


Figure 1. Map of Enugu State in Nigeria showing Adada River

2.3. Formulation of Climate-Flood Model

The variables which were used for the development of the empirical model include: annual average of rainfall depth (I, mm), maximum and minimum Air Temperatures (T, °C), Sunshine (S, hours), Evaporation (E, mm), Humidity (H), Wind Speed (W, km/hr), Soil Temperature (T_s, °C), Cloud Cover (%), Solar Radiation (R), Atmospheric Pressure (P) and runoff (Q, m³/s), for Adada river basin located in Enugu. Climate-Flood Model was formulated with the discharge at the gauging station as a function of climate variables as follows:

$$Q = \alpha_0 * I^{\alpha_1} * S^{\alpha_2} * T^{\alpha_3} * E^{\alpha_4} * H^{\alpha_5} * W^{\alpha_6} * R^{\alpha_7} * T_s^{\alpha_8} \tag{1}$$

The values of input variables of the climate-flood model of River Adada given in Table 1 were substituted into Equation 1.

Table 1. Input Variables for Flood Model of Adada River, Enugu

Year	Evaporation (E)	Sunshine Hours (S)	Radiation (R)	Rainfall (I)	Atmospheric Temperature (T-Ave)	Wind Speed (W)	Humidity (H)	Soil Temp (Ts)	Discharge (Q)
1980	3.30	5.28	12.00	166.20	27.20	4.60	73.80	26.80	50.28
1981	3.44	5.58	12.69	142.00	27.25	5.40	74.70	26.70	42.51
1982	3.35	5.28	12.23	130.50	27.40	5.40	73.20	26.70	46.95
1983	3.48	5.15	12.22	75.80	27.15	6.75	74.00	27.50	46.71
1984	3.45	5.50	12.88	148.50	27.15	5.75	68.00	26.80	57.13
1985	3.36	5.28	12.53	160.80	27.90	5.33	71.80	26.40	50.53
1986	3.30	5.43	12.63	120.80	27.60	6.25	74.20	26.80	45.67
1987	3.52	5.75	13.50	120.90	26.90	6.00	73.60	27.40	47.86
1988	3.37	5.23	13.13	121.70	27.60	6.20	73.60	27.20	47.99
1989	3.49	5.79	13.49	136.90	31.70	6.00	69.20	26.70	50.15
1990	3.38	5.16	13.08	171.30	31.80	6.00	73.80	27.10	50.15
1991	3.24	5.33	12.78	165.40	31.90	5.50	74.70	26.60	56.75
1992	3.41	5.94	12.60	142.10	31.90	5.40	73.20	26.40	51.95
1993	3.39	5.59	12.76	130.40	32.10	5.71	74.00	26.60	50.35
1994	3.37	5.28	12.65	122.20	26.90	5.50	68.00	26.60	51.25
1995	3.38	5.58	12.89	180.60	27.60	5.10	71.80	26.70	48.95
1996	3.34	5.27	12.53	159.90	31.50	5.50	74.20	26.50	49.82
1997	3.33	5.15	12.75	188.20	31.60	5.40	73.60	26.60	49.23
1998	3.45	5.51	12.74	125.00	32.30	5.30	73.60	27.10	52.80
1999	3.32	5.28	12.44	137.20	31.60	4.10	69.20	27.10	55.23
2000	3.42	5.43	12.95	168.90	31.90	5.90	73.80	26.90	51.38
2001	3.41	5.75	12.54	139.70	31.80	5.60	75.50	27.00	52.51
2002	3.38	5.23	12.68	143.30	31.80	5.70	72.00	27.00	53.38
2003	3.41	5.79	12.30	157.50	32.00	5.30	74.70	27.30	53.93

Source: Anambra-Imo River Basin Development Authority (AIRBDA) [24]

2.4. Calibration

To ensure the feasibility of the assumptions of the multiple linear regression models, the logarithm to base 10 of both the left and right hand side of Equation 1 were taken to linearize the function as shown in Equation 2.

$$\log_{10} Q = \log_{10} \alpha_0 + \alpha_1 \log_{10} I + \alpha_2 \log_{10} S + \alpha_3 \log_{10} T + \alpha_4 \log_{10} E + \alpha_5 \log_{10} H + \alpha_6 \log_{10} W + \alpha_7 \log_{10} R + \alpha_8 \log_{10} T_s \tag{2}$$

The least squares estimates of the regression parameters were estimated using the Minitab statistical software.

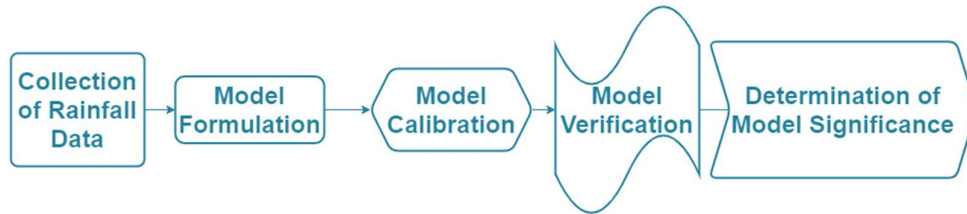


Figure 2. Flowchart of Research Methodology

After the coefficients were estimated, they were substituted back into Equation 1 and was used for prediction of the annual runoff using annual records climatic variables as predictors. The result was compared with the observed values of runoff in order to ascertain the model performance. It is noteworthy that Equation 1 yielded runoff produced by only climatic variables excluding other natural processes like groundwater as well as anthropogenic sources. The error measure employed in this study to make the evaluation of the model predictions is the coefficient of determination (R²) defined as follows:

$$R^2 = \left[\frac{\sum_{i=1}^n (Q_i - \bar{Q})(\hat{Q}_i - \bar{\hat{Q}})}{\sqrt{\sum_{i=1}^n (Q_i - \bar{Q})^2 (\hat{Q}_i - \bar{\hat{Q}})^2}} \right]^2 \tag{3}$$

Where; Q_i is the observed discharge, \hat{Q}_i is the simulated discharge, \bar{Q} is the mean of the observed discharges, $\bar{\hat{Q}}$ is the mean of the simulated discharges and n is the length of the observed/simulated series. The R^2 which ranged from 0 to 1, is a statistical measure of how well the regression line close to the observed data.

2.5. Significance Tests of Model

Two types of test on the parameters of the model, namely; individual test (t-test) and joint test (F-test) were conducted. F-test for Model was used to test whether any of the independent variables were linearly associated with Y. The T- test involved testing whether an explanatory variable has any influence on the dependent variable when the other explanatory variable is held constant. F-test for the significance of the entire climate-flood model was evaluated using the Minitab statistical software.

3. Results and Discussion

3.1. Climate-Flood Model

When the estimates of regression coefficients were substituted into Equation 1, the climate-flood model of Adada River was obtained as Equation 3.

$$Q = 10.22I^{0.12}S^{0.61}T^{0.47}E^{-1.65}H^{-1.78}W^{0.19}R^{-0.77}T_s^{2.8} \tag{3}$$

The non-linearity in the climate flood model as shown in Equation 3 is consistent with the findings of Zhang et al. [25] who reported non-linearity between the climate and runoff. The climate-flood model for River Adada in Enugu shown in Equation 3 indicates that climatic variables accounts for 64.73 % of the annual variation in runoff (Figure 2). The result obtained implies that climate change had an effect on runoff. This result is consistent with the findings of Akinnubi and Babatolu [26] in a similar research where the climatic variables accounted for 54.4% of the annual runoff variation in River Niger. The gauging station of River Adada is located at Umulokpa village in Enugu state which is remote from huge developmental activities. The river is undisturbed as it exists in its natural state. Thus, it is more likely to be influenced by only climatic factors. The little influence from non-climatic factors 36.27% may have been as a result of the agricultural activities along the river bank. Xu et al. [27] reported a similar finding in which 72.9% and 78.6% of natural and annual observed runoffs respectively decreased as a result of the climate change. Sun et al. [28] pointed out that the annual runoff as well as the meteorological variations could be as a result of the motion of the solar activity and celestial body. On the contrary, Conway [29] reported that climate change had no effect on Nile River runoff owing to the fact that the predicted rainfall trend could be uncertain in the catchment area.

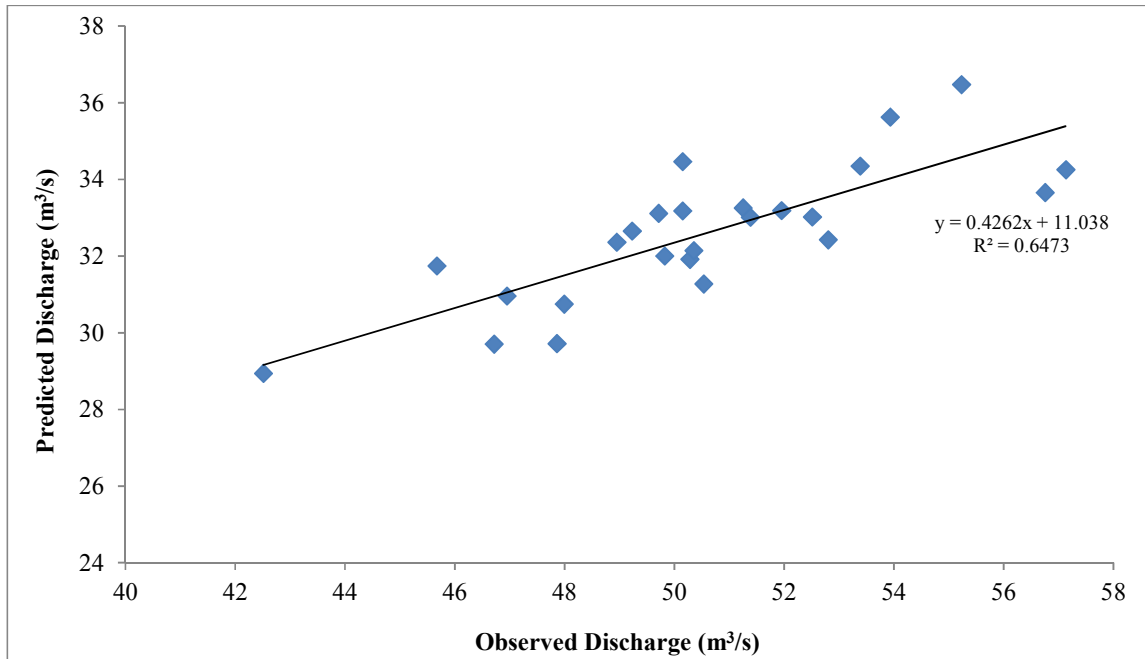


Figure 3. Validation of Flood Model of Discharge of Adada River

3.2. Results of Significance Tests of Model

The result of the significance of the entire climate-flood model is presented in Table 2. Table 2 shows that the multiple regression analysis indicates that the climate-flood model of River Adada was statistically significant in predicting annual runoff ($\text{sig} < 0.05$) with significant F value of 3.893. This result is in conformity with previous finding by Okpara et al. [27] in which the hydro-climatic variables were significant parameters in a study conducted for River Niger.

Table 2. ANOVA of Climate-Flood Models for of Southeast Nigeria

ANOVA of Climate-Flood Model for Adada River, Enugu						
Model		Sum of Squares	df	Mean Square	F	Sig.
$Q = 10.22I^{0.12}S^{0.61}T^{0.47}E^{-1.65}H^{-1.78}W^{0.19}R^{-0.77}T_s^{2.8}$	Regression	0.013	8	0.002	3.0523.893	0.010
	Residual	0.007	16	0		
	Total	0.02	24			

At 0.05 level of significance ($p < 0.05$), the results of t-test and the corresponding level of significance of the independent input variables of the climate-flood models for River Adada are presented in Tables 3.

Table 3. Statistical Significance of Climatic Variables in Climate-Flood Model of Adada River

Variables	Coefficient	Std. Error	t-value	significance	Partial correlation
(Constant)	1.208	1.584	0.763	0.457	-
Evaporation	-1.654	0.853	-1.939	0.07	-0.436
Sunshine hours	0.605	0.319	1.895	0.076	0.428
Solar Radiation	-0.769	0.528	-1.456	0.165	-0.342
Rainfall	0.117	0.083	1.41	0.178	0.332
Average temperature	0.467	0.141	3.314	0.004	0.638
Wind speed	0.191	0.164	1.163	0.262	0.279
Relative humidity	-1.78	0.452	-3.934	0.001	-0.701
Soil temperature	2.804	1.22	2.299	0.035	0.498

The result of statistical significance showed that the soil temperature, relative humidity, and average temperature were significant predictors of annual runoff in Adada River (Table 3). Thus, the relative humidity, soil and average temperatures had major effects on annual runoff in the catchment area. The sunshine hour on the other hand, is not a significant predictor of annual runoff ($p > 0.05$). This implies that sunshine hour had no effect on runoff variation. It can be observed that a negative correlation existed between the annual relative humidity and annual runoff (correlation coefficient of -0.701). In other words, as the annual runoff decreased the relative humidity increased during the study period. The result further showed that the wind speed was not statistically significant to the model ($p > 0.05$). This shows that the wind speed had no effect on the variation of runoff. Moreover, a positive correlation was observed between annual soil temperature and annual runoff (correlation coefficient is 0.498). In other words, annual runoff generally increased with increased soil temperature in River Adada. In addition, a positive correlation was also observed between air temperature and runoff (correlation coefficient is 0.638). This means that as the air temperature increased, the annual runoff also increased. Furthermore, the study area showed -1.654 coefficient of mean evaporation which means a reduction in runoff by an average of 1.654 m^3/s for each 1 mm increase in evaporation. A coefficient of -0.769 was observed for solar radiation, which implies a reduction in runoff by 0.769 m^3/s for each 1 KW/m^2 rise in solar radiation. In the case of relative humidity, a coefficient of -1.78 was obtained which indicates that runoff decreased by 1.78 m^3/s as relative humidity increased by 1%. The sunshine hours, rainfall, average temperature, wind speed, and soil temperature showed positive coefficients which signify an increase in runoff for every rise in those parameters. This finding is in agreement with the result obtained by Suleiman and Ifabiy [28] in which an increase in rainfall brought about an increase in runoff at Shiroro Dam. This is because an increase in rainfall could lead to a subsequent increase in annual flow [29].

4. Conclusion

This study examined the connections between meteorological variables and runoff in Adada River in Enugu, Nigeria in the context of understanding the present susceptibility to meteorological variables and intense disasters, and also enhancing control strategies to cope with the worst-case scenarios as well as seizing opportunities which might emerge. The climate-flood model was formulated with the discharge at the gauging station as a function of climate

variables. The results of this study showed that the climatic variables accounted for 64.73% of the annual variation in runoff, whereas the non-climatic variables accounted for 33.27%. This indicates that the climate had an effect on runoff in the catchment area. The outcome is a detrimental effect on the surrounding environment as well as on the inhabitants of the region. The multiple regression analysis also indicates that the climate-flood model of River Adada was statistically significant in predicting annual runoff. The result of statistical significance equally indicated that soil temperature, relative humidity, and average temperature had major effects on annual runoff as evidenced by their statistical significance. Whereas, evaporation, sunshine hours, solar radiation, rainfall and wind speed had minor effects on annual runoff as they were not statistically significant. It can therefore be deduced from the results that the identification of factors controlling the variation of runoff could enhance the understanding of the long-term processes of climate-runoff.

5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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