Stochastic Time Series Analysis of Stream Flow Data of the River Niger at Lokoja, Kogi State, Nigeria.

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Abstract

This paper is produced to improve the management and operation system of the River Niger at Lokoja - Nigeria. It is important to determine the hydrological system of River Niger, which is the major water sources of the annual flood in the area. Lokoja has been experiencing the problem of flooding every wet season from April to October of the year. It experienced the highest flood in 2022. In this study, a Modified Thomas Fiering Model (MTFM) is used. This method is a stochastic method that is employed for generating and predicting a synthetic flow in hydrology. It is used to generate a synthetic river flow in Lokoja, Kogi State, Nigeria. The procedure for stochastic or statistical method is applied on the data obtained at the Lokoja gauging station, Nigeria. The study utilized the monthly flows data (discharge in m^3/s) from the year 2000 to year 2019. After estimating the model parameters (mean, standard deviation, maximum, minimum, coefficient of variation, skweness and kutrosis), the synthetic time series of monthly flows were simulated. The results showed that the Modified Thomas Fiering model is appropriate and can be applied to forecast monthly flow for planning, design and operation of hydrological infrastructure. Hence in the presence of large dataset, future forecasting of the river flow can be done to create awareness on it, to allow adequate preparation in mitigating the future effects of flooding in the study area.

Keywords: Stochastic, Thomas Fiering Model, Stream flow, Time series, Synthesis

1. Introduction

In Water Engineering, Time Series Models are often used to determine the design capacity of Reservoir (Danielle et al, 2021 & Loucks et al, 2005). Presently, it is undebatable that the climate change increases the average air and water bodies' temperature (Odjugo, 2009 & Razmi et al, 2017), and increases the average sea water level all over the world (Merrifield et al, 2014, Sathish & Khadar, 2017). Climate change leads to change in hydrological cycle which results in increase in temperature, rate of evapotranspiration, and intensities of rainfall having the possibility of natural hazard (Calanca et al, 2006). These devastating impacts require the conducts of such studies, to forecast the level of future impacts and suggest an adaptive or mitigation measures that can improve the situation.

Lack of data or its inadequacy has been identified as a suitable method to enhance historical hydrological series data (Dornblut, 2009). The time series analysis of discharge data in the statistical domain has a wide area of specialization and vital application in hydrological investigation (Calanca et al, 2006). Recently, new techniques of analysing and managing the changes in the river flow regime have been developed (Gao et al, 2018 & Naderi, 2022). The time series analysis is employed for building mathematical model to calculate statistics from River flow data by using Thomas Fiering model. Similarly, Valencia Schaake (VS) and Thomas Fiering methods were used to generate monthly stream-flow of Pedi-Muda reservoir in Malaysia and their performances were better only that the two methods have the problem of overestimation and underestimation (Tukimat & Harun, 2021). That is why modified Thomas Fiering method is developed to take care of the flaws in Thomas fiering model. This study applied and verified the performance of time series analysis based on Modified Thomas Fiering model for the monthly discharge of River Niger at Lokoja gauging station. River Niger is one of the rivers that limited attempt have been made to test applicability of time series model. Lokoja in Kogi State suffers from the problem of flooding due to its location at the confluence of the country's major rivers (Niger-Benue Rivers). Lokoja flooding has caused huge yearly losses in terms of damage and disruption to economic livelihoods, businesses, infrastructure, services and public health (Jimoh & Salami, 2020). The contribution of this study is to generate and simulate the monthly hydrological flow series with the use of Modified Thomas Fiering model in order to predict the future flooding in the area to avert loss of lives, farm produce and functional failure of the Abuja-Lokoja road due to flooding.

2. Research Methodology

2.1 Study Area

Nigeria, republic in western Africa, with a coast along the Atlantic Ocean on the Gulf of Guinea. Most of Nigeria consists of a low plateau cut by rivers, especially the Niger and its largest tributary, the Benue. By topography, Nigeria's largest physical region is formed by mostly level valleys of the Niger and Benue rivers. The Niger enters the country from the northwest, the Benue from the northeast; they form a confluence at the city of ***Lokoja*** in the south central region and continue south, before emptying into the Atlantic Ocean (see Figure 1).

Figure 1: Map of Nigeria showing the study area

Lokoja is located between latitude 7º 45' N, 7º 51'N of the equator and longitude 6º 41' E 6º 45'E of the Greenwich Meridian. It is bounded in the west by the River Niger at an altitude of 45-125 metres above sea level. Lokoja (Kogi State) is almost predominantly underlain by high grade metamorphic and igneous rocks of Precambrian age generally trending NN-E-SS-W, these rocks comprise of gneiss, migmatite, granites and schist belt outcrops along the eastern margin of the area. The study area is grouped to be within the guinea savannah belt, even though what we really have now is derived savannah, only resistant vegetation still remains dominant due to anthropogenic activities of bush clearing, burning and lumbering (Jimoh and Salami, 2020). Most of the area consists of secondary regrowth. The climate is described as the tropical wet and dry climate of the Koppen's classification. It is characterized by wet and dry season. The wet season begins in May and ends in October, with an average annual rainfall of about 1000mm and a relative humidity at 60%. An average maximum day time temperature of 37.9 0C, is recorded between December and April.

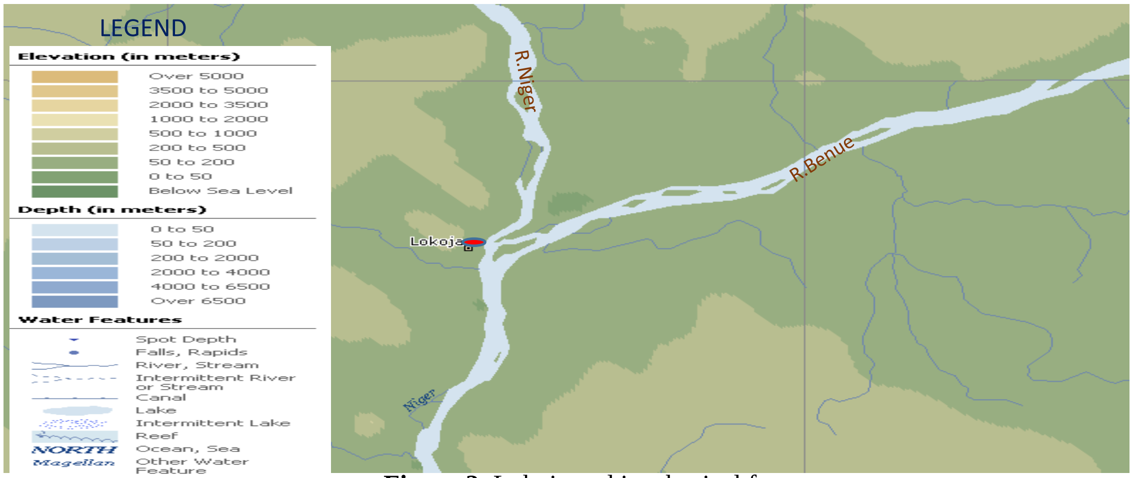

Figure 2: Lokoja and its physical features

3 Collection of Data

All the relevant discharges from Lokoja gauging station which were available from the past were collected from 2000 to 2019. The collected information formed the sample space for the random variable under consideration.

3.1 Time Series Model

3.1.1 Modified Thomas Fiering (MTFM) model

The Modified Thomas Fiering Model (MTFM) in its original form was employed for the synthetic or artificial generation of monthly discharge data (Arslan, 2014 & Fiering, 1962). After a brief analysis to historical record of River Niger and estimating the behaviour of river, the transform of Thomas Fiering model (TFM) was executed by extracting the persistency from the river characteristics and the serial autocorrelation between the random residuals of the observed data. In this study, the MTFM depended on the autoregressive approach with application of Wilson Hilferty transformation of independent random number. This model presents a set of 12 regression equations and best represented by the following equations:

$$q_{i,j+1} = \bar{q}_{j+1} + \delta_j . q\left(q_{i,j} - \bar{q}_j\right) + \sigma_{j+1} . \sqrt{1 - r_{1,j}{}^2} . \xi_{i,j+1} \qquad \text{(i)}$$

Where, $q_{i,j+1,}$ $q_{i,j}$ are monthly discharge in the j^{th} month of the i^{th} year and the i-step respectively, counting from the start of the generated series, $\bar{q}_{j+1,}\bar{q}_j$ are selective mean monthly discharge from the observe time series during $j+1$ and j respectively, where j ranges from January to December (i.e. 1 - 12 months) and C_j is the regression line slope for the estimation of j+1 month from the j month, C_j is given by the equation (ii) as:

$$C_j = r_{1,j} \frac{\sigma_{j+1}}{\sigma_j} \qquad \text{(ii)}$$

Where, $\delta_{j+1,}\delta_j$ are variance of monthly values during j+1 and j months from the observed data, $r1, j$ is the lag-1 autocorrelation coefficient between the monthly flow and $\xi i, j+1$ is independent random variable with a normal distribution, zero mean and unit variance. The mean, variance and lag-1 autocorrelation can be calculated from the given data set as follows:

$$\bar{q}_j = \frac{1}{n}\sum_{i=1}^{n} q_{i,j} \qquad \text{(iii)}$$

$$\delta^2 = \frac{1}{n}\sum_{i=1}^{n}\left(q_{i,j} - \bar{q}_j\right) \quad \text{(iv)}$$

$$r_{1,j} = \frac{\sum_{i=1}^{n}\left[\left(q_{i,j} - \bar{q}_j\right)\left(q_{i,j+1} - \bar{q}_{j+1}\right)\right]}{n\sigma_j\sigma_{j+1}} \quad \text{(v)}$$

The principle of computation is described by the following system; the values of mean, standard deviation and lag-1 correlation are considered, where $q_{i,\,jan,} = \bar{q}_{jan}$ defines the beginning of data generation. Then, the following equations are valid:

$$q_{2004,Feb} = \bar{q}_{Feb} + r_{1,Jan}\frac{\sigma_{Feb}}{\sigma_{Jan}}.\left(q_{2004,Jan} - \bar{q}_{Jan}\right) + \sigma_{Feb}.\sqrt{1 - r^2{}_{1,Jan}}.\xi_{2004,Feb} \quad \text{(vi)}$$

The value obtained from the Equation (vi), ($q_{2004,Feb}$) is applied to generate flow rate for the month of March i.e. ($q_{2004,Mar}$). Similarly, the estimated value for the month of December in the year under consideration ($q_{2004,Dec}$) can be used to generate the flow rate of January for the next year ($q_{2005,Jan}$).

$$q_{2005,Jan} = \bar{q}_{Jan} + r_{1,Dec}\frac{\sigma_{Jan}}{\sigma_{Dec}}.\left(q_{2004,Dec} - \bar{q}_{Dec}\right) + \sigma_{Jan}.\sqrt{1 - r^2{}_{1,Dec}}.\xi_{2004,Jan} \quad \text{(vii)}$$

The values of ξ was obtained with the aid of Excel random number generators tool.

4 Results and Discussion

The essential descriptive statistical characteristics of the discharge historical time series of River Niger at Lokoja are given in Table 1.

Table 1: Basic statistical characteristics of synthetic monthly flow time series for River Niger in Lokoja, Kogi State, Nigeria in 2004.

2004	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
¯Q		2418.5	2536.2	2361.1	2295.4	2684.8	4184.4	6522.7	10353	15390	11898	5639.4
δ		266.72	225.06	202.63	228.63	187.03	434.83	1023.4	1524	661.71	2556.5	496.73
Max		2889	3240	2915	2700	2949	4790	8422	13703	16098	15292	6724
Min		1989	2164	1937	1979	2290	2902	4790	8694	14102	7175	4835
CV		0.1103	0.0887	0.0858	0.0996	0.0697	0.1039	0.1569	0.1472	0.0430	0.2149	0.0881
Skewness		-0.2119	0.94957	0.89452	0.61384	-0.4071	-1.46	0.25502	0.78127	-0.6691	-0.5007	0.46973
Kurtosis		-1.1088	2.3349	1.8787	-0.9025	-0.5561	2.7171	-0.5183	-0.6269	-1.1837	-1.1798	-0.4125

After the estimation of the parameters of the MTFM, the series of historical monthly flow for 8 years were generated. These series were compared with the recorded monthly flow of River Niger for the hydrological period of 8 years (2004-2011), with the use of basic statistical characteristics like mean, standard deviation, maximum, minimum, coefficient of variation, skewness and kurtosis from 2004 to 2011 as shown in Table 1. The MTFM was used to predict the monthly flow of River Niger from 2004 to 2011. Thirty Six (36) parameters were computed (i.e. 12 means ($\bar{q}$), standard deviations (σ) and Lag-1 autocorrelation coefficients ($r1$)). The regression coefficient (C_j) between the months are computed as shown in Table 2.

Table 2: Comprises of the estimated values of the MTFM of River Niger.

2004	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\bar{Q}$		2418.5	2536.2	2361.1	2295.4	2684.8	4184.4	6522.7	10353	15390	11898	5639.4
δj		266.72	225.06	202.63	228.63	187.03	434.83	1023.4	1524	661.71	2556.5	496.73
r1,j		0	9.68E-30	-7.1E-30	1.35E-29	-1.9E-29	-4E-30	3.39E-30	-7.9E-30	1.88E-29	-3.5E-29	4.8E-30
Cj		0	7.84E-30	-9.1E-30	9.06E-30	-1E-28	-2.2E-29	7.53E-30	-1.5E-30	2.8E-28	-1.3E-30	6.72E-30

Figure 3 shows the comparison between observed and simulated monthly flow series of River Niger from 2004 to 2011.

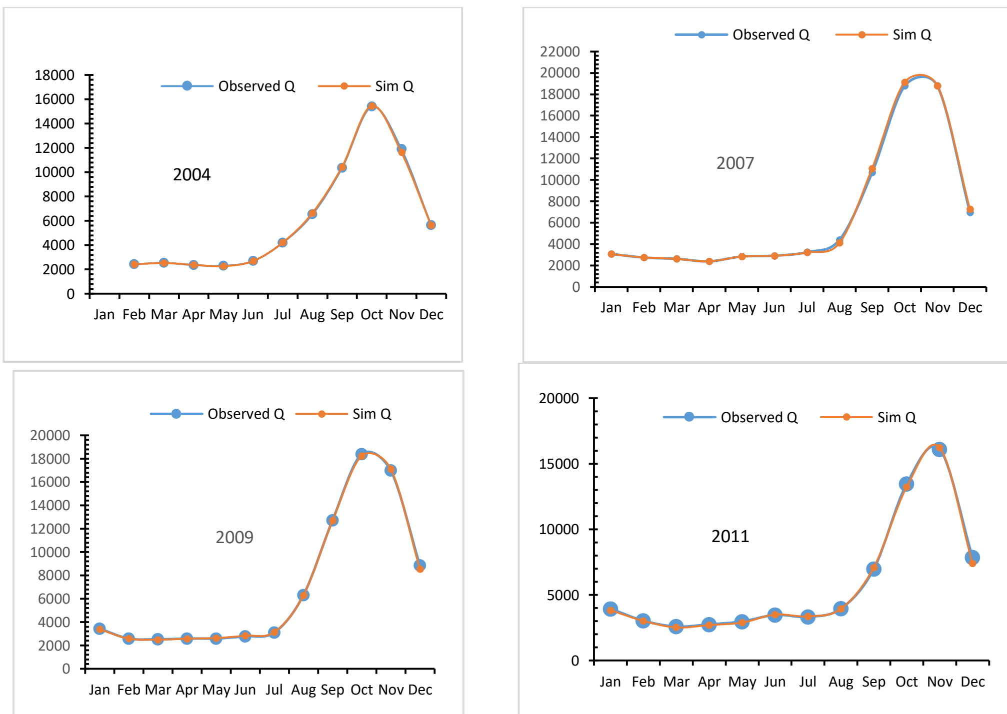

Figure 3: Comparison between observed and simulated monthly discharges (Q in m^3/s) of River Niger from 2004 to 2011.

To check the performance of the Thomas Fiering model, means, standard deviations, maximum, minimum and coefficient of variation of monthly flow in observed series were considered. In Figure 3, it is observed that the trend is similar for all the simulated and observed flow from 2004 to 2011. This is due to seasonal variability in rainfall that occurs every year. Figure 4 shows the Maximum estimated for the observed and simulated monthly flow time series of River Niger.

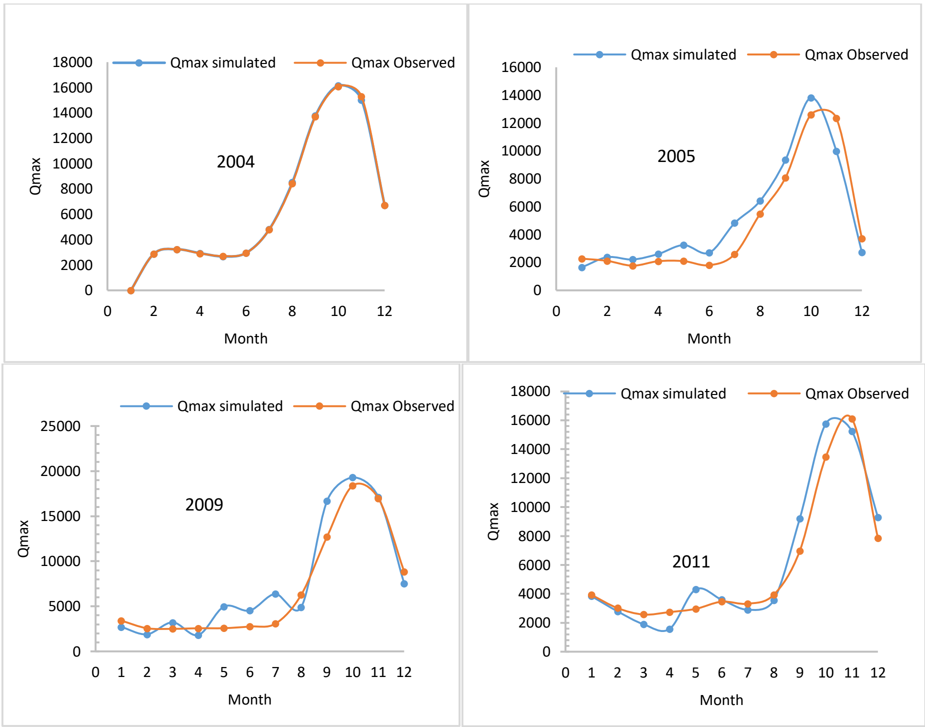

Figure 4: Maximum estimated for the observed and simulated monthly flow time series of River Niger.

In Figure 4, there is a good agreement between the observed and predicted discharge during the wet seasons and the model prediction of the discharge during the dry season appears slightly inconsistent around the observed value. Figure 5 depicts the graph of minimum discharge for observed and simulated flow.

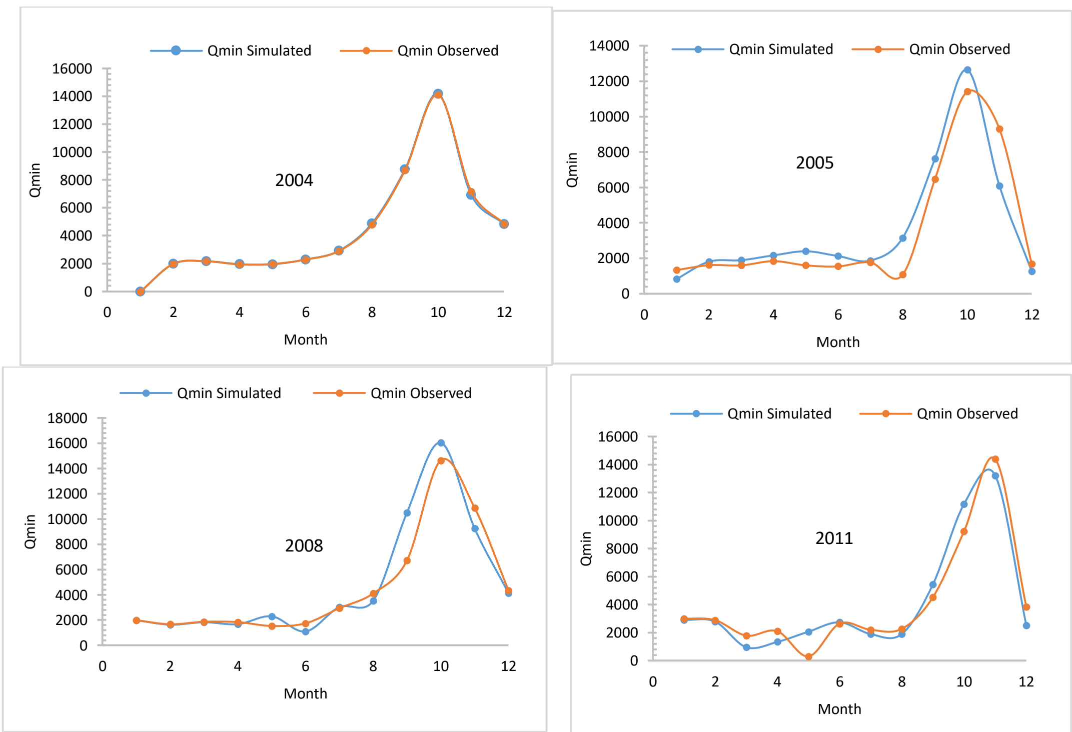

Figure 5: Selected Minimum estimated for the observed and simulated monthly flow time series

In Figure 5, there is a good agreement between the observed and predicted discharge and the model predict well during the dry season with a slight difference in the wet season. Figure 6 exhibits the graph of standard deviation for both simulated and observed flow.

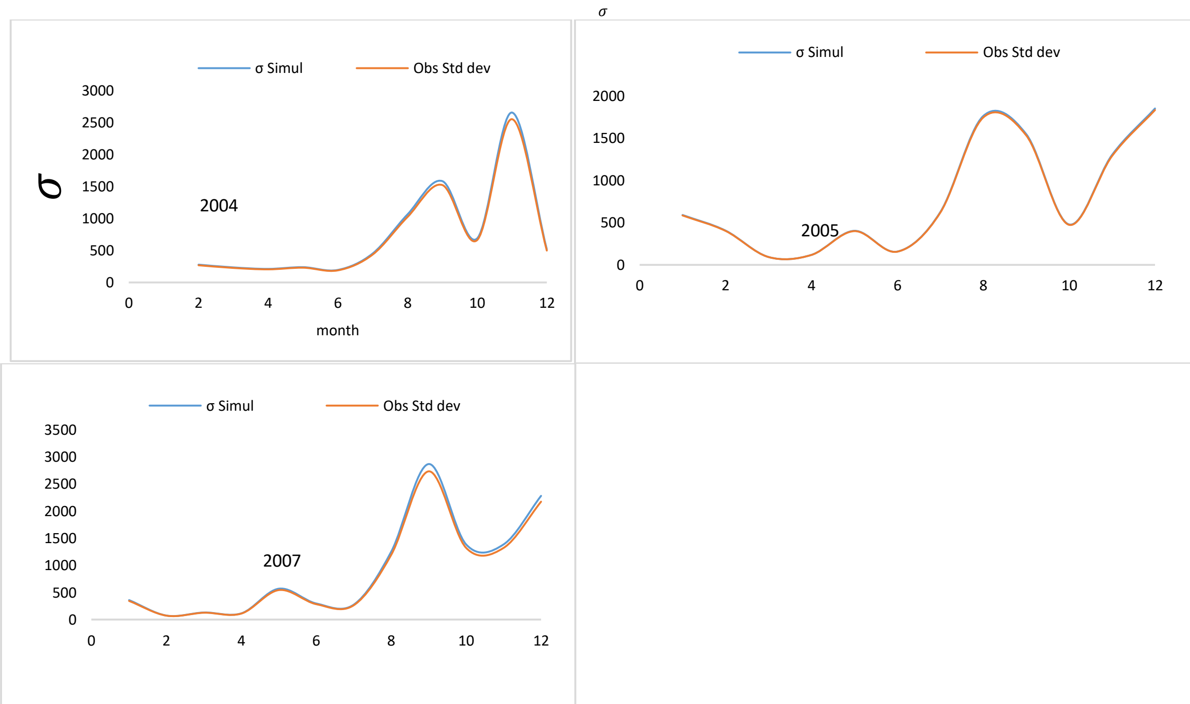

Figure 6: Selected Standard deviation estimated (σ) for the observed and simulated monthly flow time series

Figure 6 shows the comparison between the computed standard deviation of the observed flow data with simulated values using MTFM, there is a good agreement between the standard deviation of the observed and simulated discharges. Hence, the MTFM yields a very good prediction of the observed dataset. Figure 7 shows the coefficient of variation of the observed and simulated flow from 2004 to 2011.

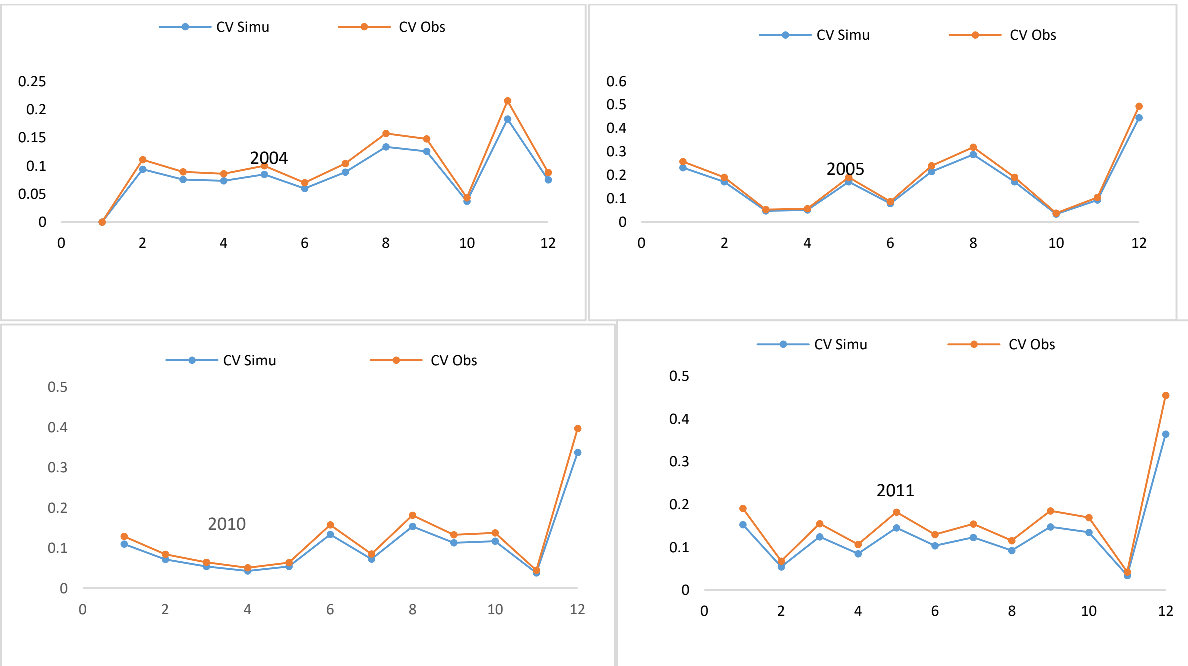

Figure 7: Coefficient of Variation (CV) estimated for the observed and simulated monthly flow time series

In Figure 7, the larger the coefficient of variation, the more the variability in discharge (that is, the seasonal variability between the flow in rainy season is higher than that of dry season), thus the model prediction is satisfactory, but slightly with under prediction. Figure 8 presents the skewness for the observed and simulated flow.

Figure 8: Selected Skewness estimated for the observed and simulated monthly flow time series of River Niger.

In Figure 8, the values of the skewness and kurtosis of the generated for the predicted and historical data were compared. The model considered well the values of the coefficient of skewness and kurtosis for monthly flow in the simulated series. However, a considerable difference was found in simulated and observed values in the year 2011. Thus, skewness and kurtosis showed a large disparity in the distribution of the discharges in the transition phase from dry to wet season. This shows that normal distribution is not the best distribution model for the time series analysis of stream flow. After the estimation of the parameters of the Modified Thomas Fiering model, the series of historical monthly flows for 20 years were generated. These series were compared with the recorded monthly flow of River Niger for the hydrological period of 8 years (2004 -2011), with the use of basic statistical characteristics like mean, standard deviation, maximum, minimum, coefficient of variation, skewness and kurtosis as shown in Table 3.

Table 3: Basic descriptive statistic of generated monthly discharge time series of River Niger for 20 years (2000 to 2019).

Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	2913.95	2582.738	2404.313	2299.313	2369.088	2581.575	3171.563	5221.538	9746.138	16090.88	16293.75	7068.5
σ	482.3725	408.1081	191.8049	144.7416	334.5388	293.26	398.6475	1102.808	1765.758	1582.346	1648.656	2394.541
Max	2913.95	2582.738	2404.313	2299.313	2369.088	2581.575	3171.563	5221.538	9746.138	16090.88	16293.75	7068.5
Min	1341	1614	1605	1718	298	1546	1772	1079	1298	9160	7175	1673
CV	0.175735	0.16417	0.077794	0.057345	0.142297	0.118016	0.132877	0.21551	0.18201	0.107512	0.091472	0.371246
Skewness	0.190212	1.366075	-0.18349	0.27965	0.334426	-0.02021	0.034945	0.124464	0.020083	-0.85074	-0.5277	0.716005
Kurtosis	-0.32705	6.516158	-0.20052	0.104251	5.47406	2.734613	0.673938	0.25217	1.08501	-0.06116	-0.00902	-0.20549

Figure 9 pose the Long-term mean Q, standard deviation (Q_σ), Q Maximum (Q Max), Q Mininmum (Q min), coefficient of variation (CV), skewness and kurtosis estimated for observed and simulated discharge (2001 - 2019).

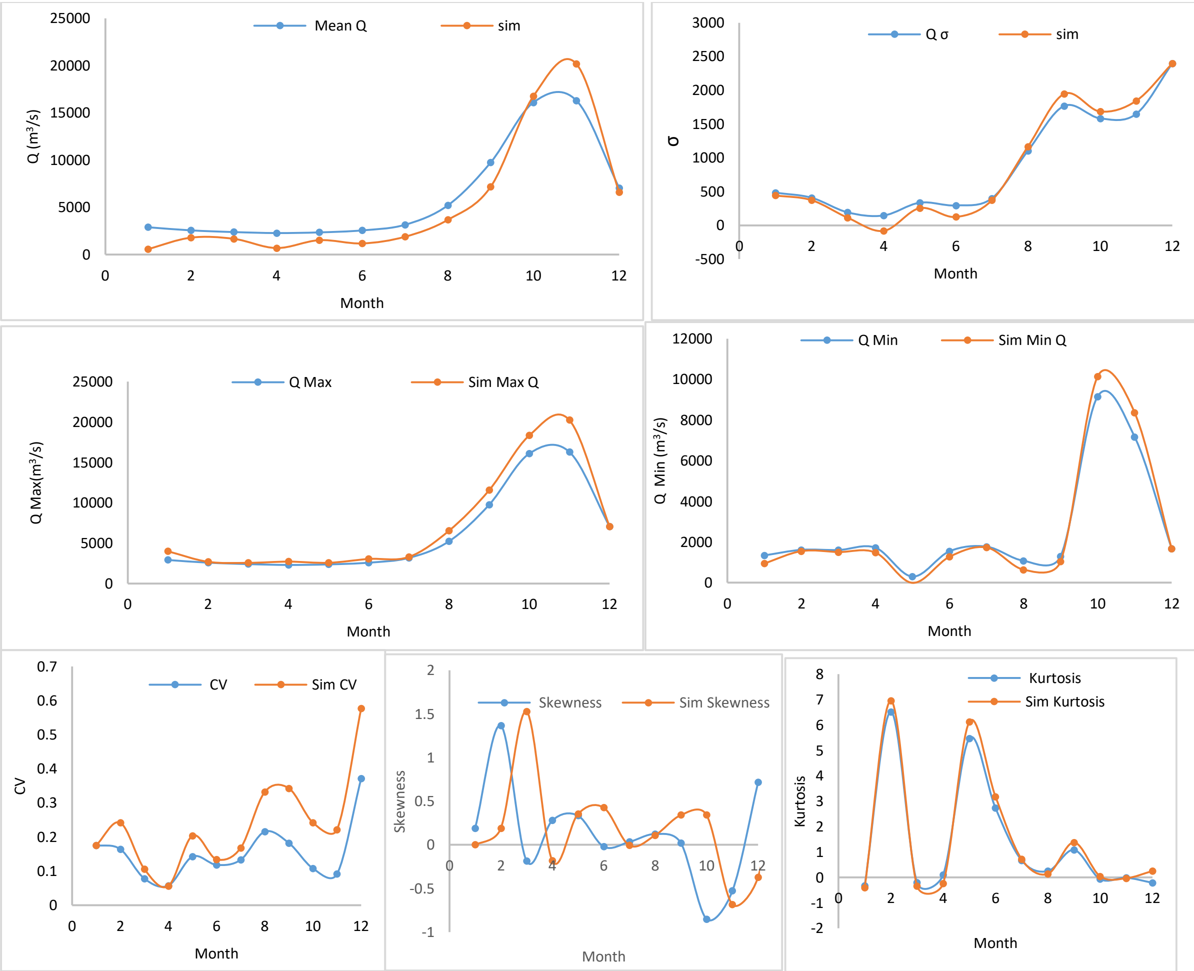

Figure 9: Long-term Q $_{mean}$, standard deviation (Q_{σ}), Q Maximum (Q $_{Max}$), Q Minimum (Q $_{min}$), coefficient of variation (CV), skewness and kurtosis estimated for observed and simulated discharge from 2000 to 2019 of River Niger at Lokoja, Kogi State, Nigeria.

Figure 9 demonstrates the results of basic descriptive statistic of the data and the forecasted value of Modified Thomas Fiering model for the twenty years (2000 to 2019) respectively. The results obtained is related with the observed data to justify the model's veracity. It is found that the mean Q, Q max, Q min and CV (observed and simulated) follow the same trend except at the peak values that is slightly over-predicted based on the assumption of Normal probability distribution model for the statistical analysis of the observed data. Furthermore, standard deviation for the observed and simulated flow follow the same trend all through the season. But skewness and kurtosis have large disparity in the observed and simulated data.

5 Conclusion

In this study, the performance assessment for Modified Thomas Fiering model was carried out, using the monthly discharge data from River Niger at Lokoja gauging station, Nigeria. The model was developed and applied to forecast the monthly inflow to River Niger, Nigeria. The performance of the model was evaluated by comparing values of basic statistical descriptive parameters including mean, standard deviation, maximum, minimum, coefficient of variation, skewness and kurtosis between observed and simulated monthly data values. Thus, general results of prediction showed that, Modified Thomas Fiering model is appropriate and can be applied to forecast monthly flow for planning, design and operation of hydrological infrastructure as supported by Tukimat & Harun, (2021). Thus, the Modified Thomas Fiering model can be used to generate and forecast discharge data for River Niger with least percentage of uncertainty. It is recommended that further studies should be done to consider the most appropriate probability distribution model for the study area.

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