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Evaluating the performance of a hydrological model on River Kaduna discharge

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Abstract
The ability of a rainfall-runoff, recharge-discharge model to simulate and predict the hydrology of River Kaduna as a basis for a sustainable water resources management strategy was cried out and the model performance was evaluated by simulating the discharges of the river under climate change and observed conditions. Results obtained yield correlation coefficient for 2,5,10, 20 50 and 100 year ARI as R^2=0.9999, R^2=0.9019, R^2=0.9072, R^2=0.9999, R^2=0.7168 and R^2=0.9103. Based on the data confirmation, the hydrognomon model evaluation performance yield coefficient close to 1.0. The model can be a reliable tool to predict flood levels, flow rates as well as for design purpose.
Keywords: Hydrological, Discharge, River basins, Correlation coefficient, Simulation, Flows, Model

I. Introduction

Hydrological computations and analysis required to establish design criteria and to make forecast by hydrologist and for water resources management decisions require data. Hydrological data on water levels, discharges, flows and rainfall which are usually time series need to be collected, stored and processed. The monitoring of river discharges according to [1] is ideally suited to detect and monitor changes resulting from climate change. Hydrological models as observed by [2] have been widely used to assess stream discharges by climate change although concern might arise on the accuracies of the model prediction under changed condition. Rainfall-runoff models according to [3] are the common tools for river discharge estimation in ungauged basins which is largely dependent on observed river discharge data for calibration. The use of observed river discharge data for calibration restrict the application of rainfall-runoff model, but [4] observed that due to the chaotic nature of flow in natural open channels, and the physical processes and the unknown in river basin variables, the parameters used in studying the behavior of a river basin cannot be measured directly and hydrological models needs to be calibrated with observed river discharge data and then applied to simulate the hydrology of a river basin.

In fitting probability distribution functions to discharge variability of river Kaduna, [4] performed a frequency analysis by fitting probability distribution function of Normal. Log-Normal and Log Pearson type III and Gumbel to the discharge variability of river Kaduna. From the measure of discrepancy it was observed that all the four distribution functions were accurate and acceptable at, $\alpha = 1\%$, $\alpha = 5\%$ and $\alpha = 10\%$ level of significance. This study is therefore aimed at reducing uncertainty in river discharge predictions as a specific objectives for the scientific initiative of Predictions in Ungauged Basins (PUB)[5]which is launched by the International Association of Hydrological Science (IAHS).

II. Methodology

2.1 Conceptual Background/Framework

The oldest statistical tools in hydrology are the regression and correlation analysis. It is used to fill missing data, to extend short records, to establish relationship between two or more hydrological variables, and to investigate the dependence between two successive values of hydrological data series. When only two variables are related the analysis is simple regression or correlation. When three or more variables are involved the analysis is multiple regression or correlation.

The most often used simple regression and correlation is linear one which a special case of curvilinear regression and correlation. The straight-line regression for variable *y* versus variable *x* is defined by a straight line which gives the best estimate of *y* for a given value of *x*. The straight regression line is generally fitted analytically by the method of least squares of the departures from the line. The regression equations are:

$$y - \bar{y} = R_{y/x}\left(x - \bar{x}\right)$$
$$x - \bar{x} = R_{x/y}\left(y - \bar{y}\right) \quad (1)$$

where *x* and *y* are the arithmetic means of the series, *Rx/y* and *Ry/x* are the regression coefficients. These two lines are crossing at the point with coordinates *x* and *y*. The regression coefficients are obtained by the expressions:

$$R_{y/x} = r\frac{\sigma_y}{\sigma_x}$$
$$R_{x/y} = r\frac{\sigma_x}{\sigma_y} \quad (2)$$

where *r* is a correlation coefficient, and *x* σand *y* σare the standard deviations of the series *x* and *y*, respectively. The correlation coefficient is statistical parameters which measures the degree of association of linearly dependent variables and is computed from the expression:

$$r = \frac{\sum_{i=1}^{i=n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{i=n}(x_i - \bar{x})^2 \sum_{i=1}^{i=n}(y_i - \bar{y})^2}} = \frac{\sum_{i=1}^{i=n}(\Delta x \Delta y)}{\sqrt{\sum_{i=1}^{i=n}(\Delta x)^2 \sum_{i=1}^{i=n}(\Delta y)^2}} \quad (3)$$

The sign of *r* depends on the sum of the cross products Δ*x*Δ*y* and it varies from +1 to −1. If the correlationcoefficient is zero, the variables *x* and y are linearly independent. A positive value of *r* means that *y*increases with increase of *x*. A negative value of *r* means that *y* decreases with increase of *x*. The standarddeviations of the regression lines *y* versus *x* and *x* versus *y* are defined:

$$S_y = \sigma_y\sqrt{1-r^2}$$
$$S_x = \sigma_x\sqrt{1-r^2} \quad (4)$$

The greater *Sy* and *Sx* are, the wider is the spread of the points around the regression line and the less accurate are the values determined from the regression lines. The standard deviation of the correlation coefficient is obtained:

$$S_r = \pm\frac{1-r^2}{\sqrt{N}} \quad (5)$$

2.2 The study area

This study is focused on River Kaduna which takes its source from Sherri Hill in Plateau State. River Kaduna flows north-west towards the Kaduna metropolis and thereafter takes a south west direction turn at Mureji. River Kaduna covers a total distance of 540km from source to mouth [6]. The drainage basin for this study is approximately 18,277.83 km$^{2.}$ Kaduna State which occupies a central position in the Northern geographical region of Nigeria lies within the Northern Savana Zone of Nigeria with an absolute location of latitude 9^{0}30’N and latitude 11^{0}45’N; longitude 7^{0}E and 8^{0}30’E. It covers a total land mass of 2,896,000km$^{2.}$ The topography is that of undulating plateau, as shown in Figures 1.

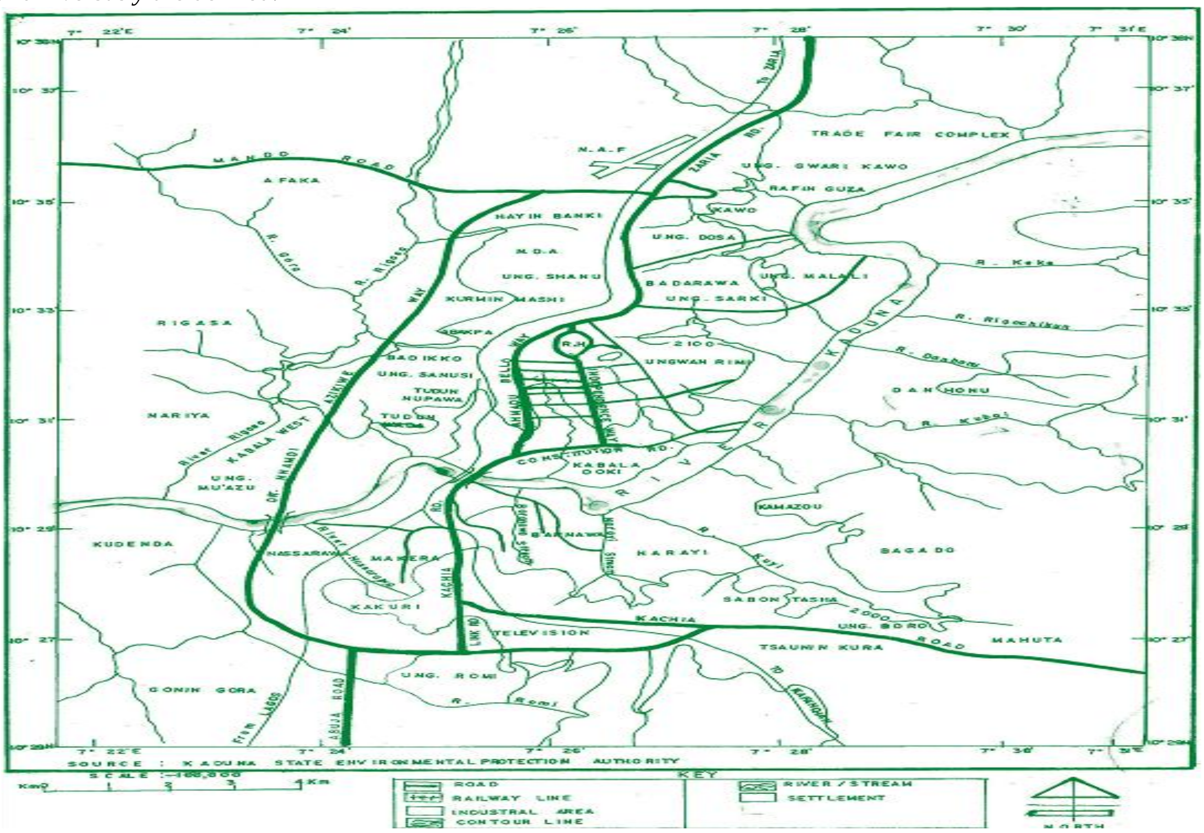


Fig 1 River Kaduna and Tributries

2.3 Rainfall-Runoff model

The rainfall-runoff model termed Hydrognomon is a free software tool used for the analysis and processing of hydrological data. It is open source software available on the hydrognomon web [7]. The model was employed to calibrate, validate the process parameters and used to simulate the flood discharge of River Kaduna under observed and climate change conditions.

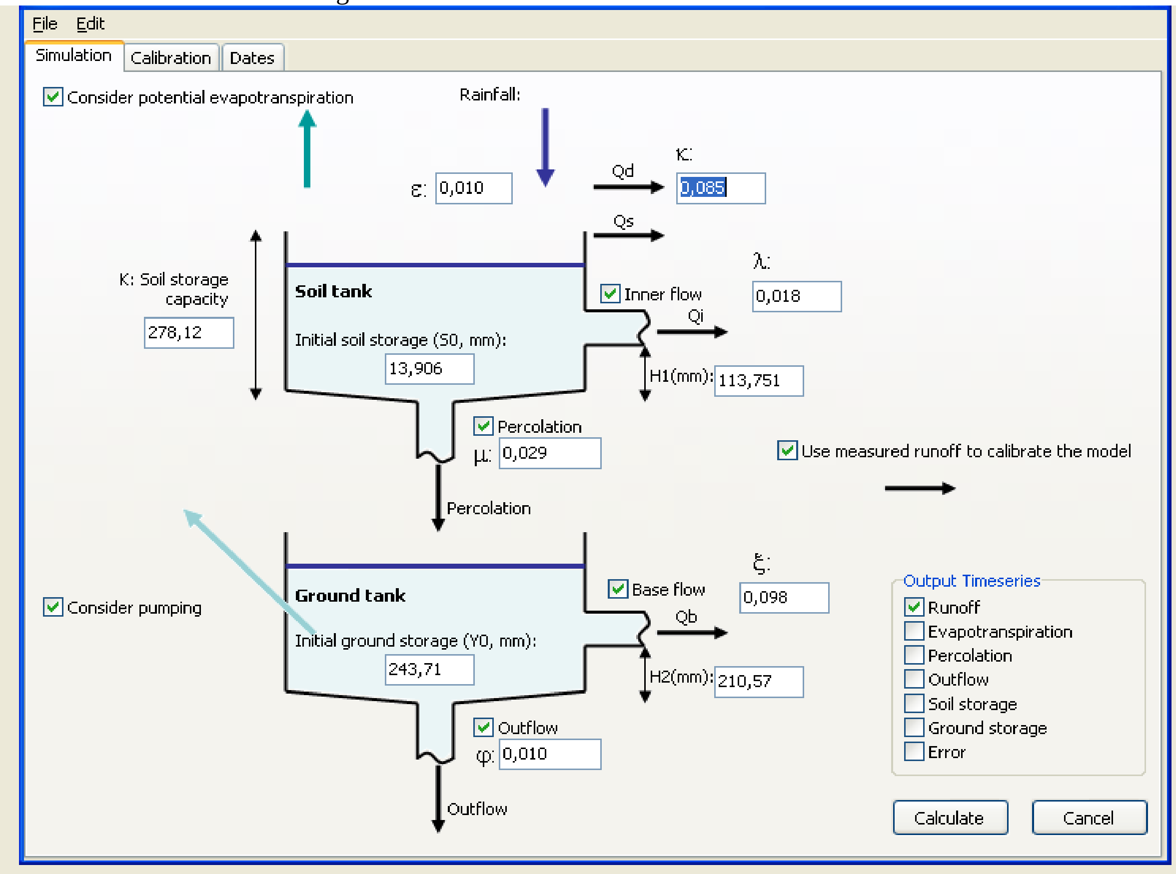


Fig: 2 Structure of the simulation module [8]

2. 3.2 Data used

Historical data used for calibration and validation consisted of daily raw values of rainfall for the periods (1975-2000 and 2001-2010) and average gauged height readings of the river for the said period were collected from Kaduna State Water Board, soil moisture index data at some selected points on the basis of land use along the river was also determined. The daily raw values of the data were converted (consolidated) to mean monthly values there enhancing the appraisal performance characteristics of the model. The double mass analysis technique was used to check and correct the consistency of the rainfall records for calibration and validation.

2.3.3 Calibration/Validation

Calibration of the hydrognomon model was carried out to obtain values of process parameters that optimized (minimized or maximized) the value of the objective function. The output parameters generated to establish the model are; Land use (soil moisture date), antecedent moisture (coefficient for inner flow, coefficient for base flow, coefficient for out flow, threshold for inner and out flow. Validation procedure was carried out after calibration to test the model performance using a different set of data which are outside the calibration period.

2.3.4 Simulation of flood discharge

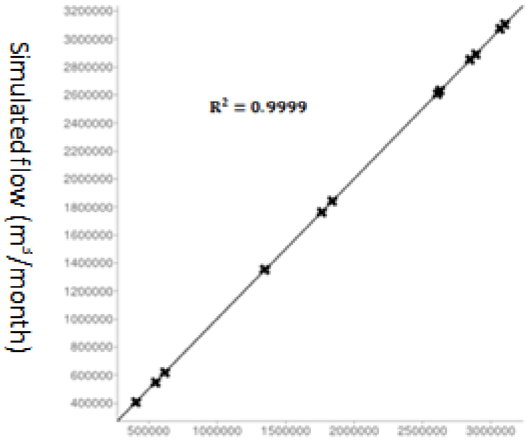
Prior to the simulation process, the weather forecast module of the hydrognomon model was applied to generate time series of rainfall and temperature for 2.5.10.20.50 and 100 years return periods and applied as forcing. The rational formular;

$$Q = CiA \qquad (6)$$

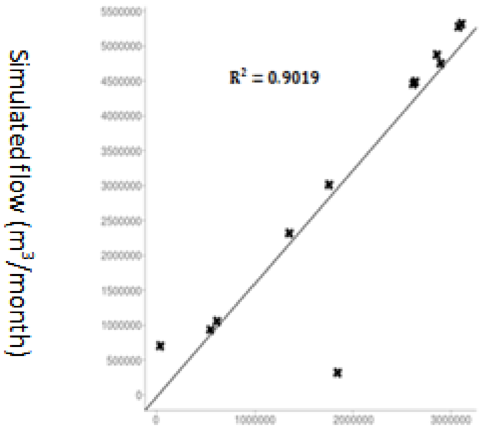
Where Q is the flood discharge (m^3/s), C is rainfall distribution coefficient. I is the rainfall (mm) and A drainage area of River Kaduna (km^2), was use to generate the hypothetical flood (observed condition). The discharge under climate change conditions was generated by setting the process parameters using rainfall and temperature as forcing. The correlation coefficient between the observed and simulated discharges was then establish as a basis of evaluating the performance of the model.

III. Results and Discussions

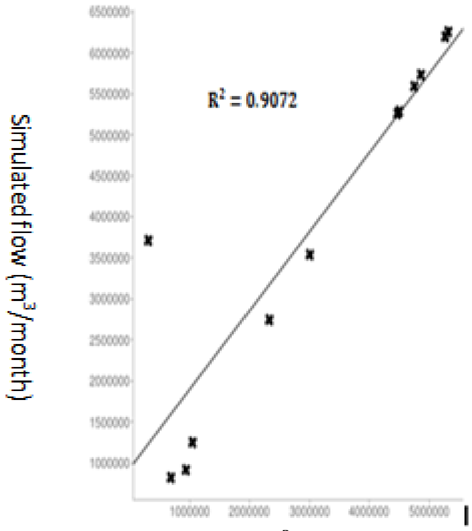
3.1 Results



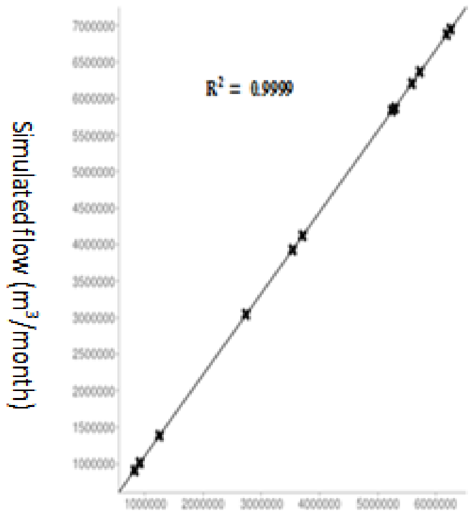
Observed flow (m^3/month)
Fig: 3 Simulated versus observed flow (2ARI)



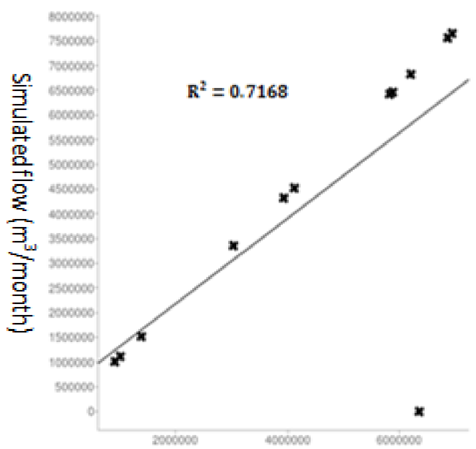
Observed flow (m^3/month)
Fig: 4 Simulated versus observed flow (5ARI)



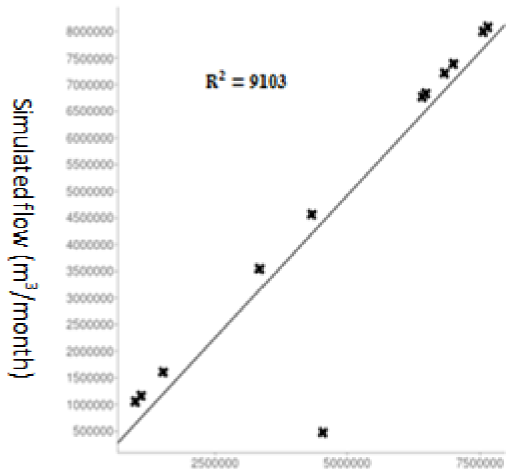
Observed flow (m^3/month)
Fig: 5 Simulated versus observed flow (10 ARI)



Observed flow (m^3/month)
Fig: 6 Simulated versus observed flow (20 ARI)



Observed flow (m^3/month)
Fig: 7 Simulated versus observed flow (50 ARI)



Observed flow (m^3/month)
Fig: 8 Simulated versus observed flow (100 ARI)

3.2 Discussions of result

The model was first calibrated and validated with historical records of rainfall. Judging from the high values of the objective functions of 0.993 and 0.994 for calibration and validation respectively, the performance of the model was considered satisfactory.

The model was then simulated with the calibrated parameters and the changes in the trends of the variability's of the flood discharges for 2.5.10.20.50 and 100 years return periods showed the following: For 2 year ARI, the simulated versus observed flows showed that all the points fall close to each other with a correlation coefficient R^2=0.9999. For 5 year ARI, the correlation coefficient was R^2=0.9019. For 10 year ARI, the simulated versus observed flow with few exceptions most of the points fall close to each other with a correlation coefficient of R^2=0.9072. For 20 year ARI, all the points fall close to each other with a correlation coefficient of R^2=0.9999. 50 year ARI the correlation coefficient was R^2=0.7168. and for 100 years ARI, the correlation coefficient was R^2=0.9103.

IV. Conclusion

Based on the results and data confirmation, hydrognomon model can be a reliable tool to model river flow. Evaluation performance yield coefficient close to 1.0. The hydrognomon model can be used to predict flood levels, flow rates as well as for design purposes.

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