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COMPARISON OF AUTOMATIC CALIBRATION TECHNIQUES FOR SIMULATING STREAMFLOW IN TROPICAL CATCHMENT

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Abstract: Efficacy of hydrological model strongly depends on model calibration. A number of methods has been developed and employed for optimization of hydrological model so that model can replicate the observed streamflow accurately. A study has been carried out in this paper to find the best parameter optimization method for the calibration of a daily rainfall-runoff model for streamflow simulation of a tropical catchment. For the purpose, seven well known parameter optimization methods namely, Uniform Random Search, Pattern Search, Multi Start Pattern Search, Rosenbrock Method, Multi Start Rosenbrock Search, Genetic Algorithm and Suffled Complex Evaluation are used for the calibration of a conceptual hydrological model known as SIMHYD. Performance of the methods is evaluated by using Nash-Sutcliff coefficient and correlation coefficient. The result indicates that evolutionary algorithm based optimization techniques can optimize the model parameters more accurately for precise calibration of model and reliable prediction of daily streamflow in a tropical catchment.

Keywords: *Rainfall-runoff modeling, optimization techniques, SIMHYD model, tropical catchment*

1.0 Introduction

Streamflow simulation is essential for water resources planning and management, flood forecasting, reservoir operation, hydraulic structure designing and climate change impacts assessment. Generally, hydrological models are used for the simulation of streamflow. The accuracy of hydrological models in simulating streamflow depends both on the structure of the model and definition of relevant parameters. Hydrological models usually have a large number of parameters because of their conceptual nature which cannot be measured directly (Franchini and Galeati, 1997). Therefore, model parameters are defined by using calibration, which is a process of changing parameter values until a satisfactory agreement between simulated and observed catchment hydrological behavior is obtained (Sorooshian and Gupta, 1995). Basically two approaches are used for the calibration of hydrological models namely, manual parameter fitting using trial and error and automatic fitting using an optimization algorithm. Manual method is very tedious and time consuming. Therefore, automatic optimization of model parameters is widely used nowadays for model calibration. Numerous optimization techniques have been developed so far for automatic optimization of model parameters including Uniform Random Search, Pattern Search, Multi Start Pattern Search, Rosenbrock Method, Multi Start Rosenbrock Search, Genetic Algorithm, Suffled Complex Evaluation, etc. (Wang, 1991; Franchini and Galeati, 1997; Cheng *et al*., 2005; Liong *et al*., 2005; Xu *et al*., 2013). This study intends to find the best parameter optimization method for the calibration of a daily rainfall-runoff model SIMHYD in simulating stream flow of a tropical catchment.

SIMHYD is a lumped conceptual daily rainfall-runoff model which has been employed widely across the world for rainfall-runoff modeling, simulation of future water availability in the context of climate change, flood frequency analysis, etc. (Mishra *et al*., 2009; Chiew *et al*., 2010; Vaze *et al*., 2011; Potter and Chiew, 2011; Bennett *et al*., 2012; Kamal and Massah Bavani, 2012; Fu *et al*., 2013; Liang *et al*., 2013; Zhan *et al*., 2013; Li *et al*., 2014). Mishra *et al* (2009) used SIMHYD for hydrologic simulation-aided regional flood frequency analysis. Chiew *et al*. (2009) used SIMHYD for comparing runoff from rainfall obtained through different downscaling methods. Vaze *et al*. (2011) studied the impact of climate change on water availability in the Macquarie-Castlereagh river basin in Australia using SIMHYD. Potter and Chiew used SIMHYD for investigating the changes in climate characteristics causing the recent very low runoff in the southern Murray-Darling basin of Australia. Bennett *et al*. (2012) made high-resolution projections of surface water availability for Tasmania of Australia using SIMHYD. Kamal and Massah Bavani (2012) compared future uncertainty of AOGCM-TAR and AOGCM-AR4 models in the projection of runoff using SIMHYD. Fu *et al*. (2013) employed SIMHYD for runoff modeling with statistically downscaled daily rainfall series. Liang *et al*. (2013) studied the impacts of climate variability and human activity on streamflow in the Middle Yellow River using SIMHYD. Zhan *et al*. (2013) conducted similar study with SIMHYD in Bai River basin of northern China. Li *et al*. (2014) predicted runoff of ungauged catchments in southeast Tibetan plateau using SIMHYD. All the studied revealed the efficacy of SIMHYD in rainfall-runoff modeling, simulation of future water availability in the context of climate change and flood frequency analysis. Therefore, SIMHYD is used in the present study for assessing the performance of various parameter optimization techniques in simulating runoff from runoff.

Comparison of parameter optimization techniques for calibrating hydrological models has been studied by various researchers (Wang, 1991; Franchini and Galeati, 1997; Cheng *et al*., 2005; Liong *et al*., 2005; Xu *et al*., 2013). Franchini and Galeati (1997) compared several genetic algorithm schemes for the calibration of conceptual rainfall-runoff models. Xu *et al*. (2013) compared three global optimization algorithms for calibration of hydrological model parameters. It has been observed that performance of different parameter optimization methods depends on data set and hydro-climatic setting. Therefore, it is necessary to understand the suitable parameter optimization technique for a tropical catchment for better simulation of rainfall-runoff as well as to water resources planning and management, flood forecasting, reservoir operation, climate change impact assessment, etc.

The objective of the present study is to evaluate the performance of various automatic parameter optimization methods for the calibration of daily rainfall-runoff model in simulating streamflow of a tropical catchment. In the present study, performance of seven well-known generic parameter optimization methods namely, Uniform Random Search, Pattern Search, Multi Start Pattern Search, Rosenbrock Method, Multi Start Rosenbrock Search, Genetic Algorithm and Suffled Complex Evaluation are assessed. Thirty-year rainfall, temperature and streamflow data for a catchment located in east coast of Peninsular Malaysia is used for this purpose. Performance of parameter optimization methods is evaluated by using Nash-Sutcliff coefficient and correlation coefficient.

2.0 Methodology

2.1 The Rainfall-Runoff Model Structure

A conceptual hydrological model known as SIMHYD is used in the present study for evaluating the performances of various parameter optimization methods in hydrological model calibration. SIMHYD is a lumped conceptual daily rainfall-runoff model which has seven parameters (Chiew *et al*., 2002). This model has been used successfully across the world for various applications, including the estimation of runoff (Peel *et al*., 2000), understand the climate change impact on runoff (Chiew and McMahon, 2002), and various regional studies (Chiew and Siriwardena, 2005; Mishra *et al*., 2009; Chiew *et al*., 2010; Vaze *et al*., 2011; Potter and Chiew, 2011; Bennett *et al*., 2012; Kamal and Massah Bavani, 2012; Fu *et al*., 2013; Liang *et al*., 2013; Zhan *et al*., 2013; Li *et al*., 2014). SIMHYD simulates daily runoff using daily precipitation and potential evapotranspiration (PET) as input. The basic structure of the SIMHYD model can be found in Chiew *et al*. (2002). A short descript of hydrological modeling technique by SIMHYD is give below.

The daily catchment average rainfall and potential evapotranspiration (PET) are the input of SIMHYD. The concept of SIMHYD is that daily rainfall first fills the interception store, which is emptied each day by evaporation. The excess rainfall is then subjected to an infiltration function that determines the infiltration capacity. The excess rainfall that exceeds the infiltration capacity becomes infiltration excess runoff. Moisture that infiltrates is subjected to a soil moisture function that diverts the water to the stream, groundwater recharge and soil moisture store. Interflow is estimated as a linear function of the soil wetness (Chiew *et al*., 2002). The equation used to simulate interflow therefore attempts to mimic both the interflow and saturation excess runoff processes. Groundwater recharge is then estimated, also as a linear function of the soil wetness. The remaining moisture flows into the soil moisture store. Evapotranspiration from the soil moisture store is estimated as a linear function of the soil wetness, but cannot exceed the atmospherically controlled rate of areal potential evapotranspiration. The soil moisture store has a finite capacity and overflows into the groundwater store. Baseflow from the groundwater store is simulated as a linear recession from the store. The model therefore estimates runoff generation from three sources - infiltration excess runoff, interflow, saturation excess runoff and baseflow (Chiew *et al*., 2002).

2.2 Approaches to Calibration

Hydrological model SIMHYD can be calibrated manually or using automatic techniques. The automatic calibration methods used by SIMHYD allow the user to select several optimization algorithms for parameter optimization. In the present study seven automated techniques of parameter optimization are used for the calibration of SIMHYD in simulating streamflow of a tropical catchment. Brief description of each optimization method is discussed below.

Uniform Random Search

Uniform random search optimization method divides each parameter space into a specified number of intervals between the minimum and maximum bounds. The optimization starts by randomly selecting a parameter. Then it runs the model and assesses the objective function. The process is repeated for a specified number of times and the best objective function value is taken as the optimum solution.

Pattern Search

Pattern search is a numerical optimization method which handles optimization problems with nonlinear, linear, and bound constraints. However, this method is often trapped to local optima rather than finding the global optimums, especially when the models are strongly non-linear. Consequently, the pattern search method often does not provide better optimization of model parameters which in turn affect the overall model performance. The problem of local trapping is often tried to overcome by using a multi-start on the search. However, the process is often time consuming and cumbersome.

Multi Start Pattern Search

Multi-start pattern search optimization method divides the parameter values into a specified number of increments between the specified bounds and then carried out a pattern search for these possible starting points until the global optimum is reached. Therefore, this method is more efficient than simple pattern search method.

Rosenbrock Method
Unlike pattern search method, the Rosenbrock method returns at each step a point at least as good as the previous one in the parameter space. Therefore, it is more capable than pattern search method in sense of better use of the local information from the response curve surrounding the point in the parameter space, and an adaptive step size (Rosenbrock, 1960).

Multi Start Rosenbrock Search
In multi start Rosenbrock search algorithm, the parameter values are divided into a specified number of increments between the specified bounds. For each of these possible starting points a Rosenbrock search is carried out to find the global optimum. The initial sampling of the parameter space provides the potential for locating the global optimum without being biased by pre-specified starting points.

Genetic Algorithm
Genetic algorithms (Holland, 1975; Goldberg, 1989) are probabilistic global search algorithms based upon the mechanics of natural selection and natural genetics. This algorithm searches among a population of points and works with a coding of the parameter set. The points are chosen initially at random in the search space and the objective function values are calculated at all points and compared. From these points few points are selected points and subsequently used to generate a new point in a certain random manner. The process is repeated until the generated points are expected to be concentrated in the vicinity of the optima.

Suffled Complex Evaluation
The shuffled complex evolution method is also a kind of probabilistic global search method. The method is based on a synthesis of four concepts namely, combination of deterministic and probabilistic approaches, systematic evolution of a complex of points spanning the parameter space in the direction of global improvement, competitive evolution, and complex shuffling.

2.3 Evaluation of Parameter Optimization Methods

Nash-Sutcliffe efficiency (Nash & Sutcliffe, 1970) and correlation coefficient are used to assess the relative efficiency of different optimization methods in calibrating hydrological model. For this purpose, SIMHYD model is calibrated with each optimization method for obtaining the best performance over the calibration period. The relative efficiencies of the different optimization methods are determined on the basis of their performances during model verification.

2.4 Study Area

The upper Dungun river basin located in the east coast of peninsular Malaysia is used as study area in the present study. Location of upper part of Dungun River basin is shown in the map of peninsular Malaysia in Figure 1. Dungun River is the main river in Dungun district which comprises a catchment area of 1858 km2. The river length of approximately 110 km, flowing through four mukims from Pasir Raja and flowing to Kuala Jengai, Jerangau and finally to Kuala Dungun (Chia, 2004; Barzani *et al*., 2007). The Dungun River is the second largest river in Terengganu ranging from 50 meters to 300 meters in width. The upper part of the catchment is mountainous and rugged whilst the lower catchment consists of vast flat coastal flood plains of about 2 to 4 m elevation above the mean sea level. Flood is common phenomena in Dungun basin during the northeast monsoon. In the present study, runoff of only the upper part of the basin is simulated.

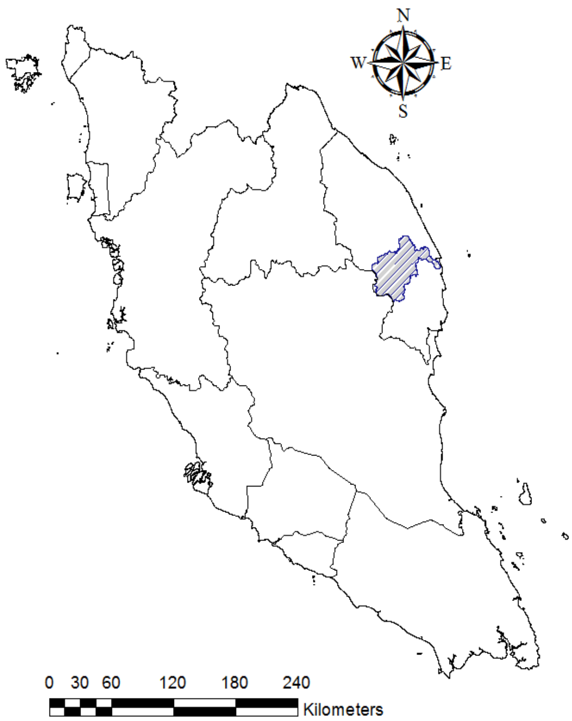

Figure 1: Location of upper part of Dungun catchment in Peninsular Malaysia.

Major floods recorded in the study area are the flood of Dec 2003, Dec 2004, Dec 2005, Feb 2006 and Nov 2009 (DID 2004; Norhayati *et al*., 2008; Hafiz *et al*., 2013). High rainfall intensity and the properties of the river regime are among the factor of Dungun flood (DID 2009; Norhayati *et al*., 2008; Hafiz *et al*., 2013). Details map of the upper part of Dungun River basin used in the present study is shown in Figure 2. The map shows the river network and the location of rainfall and river flow gauge stations.

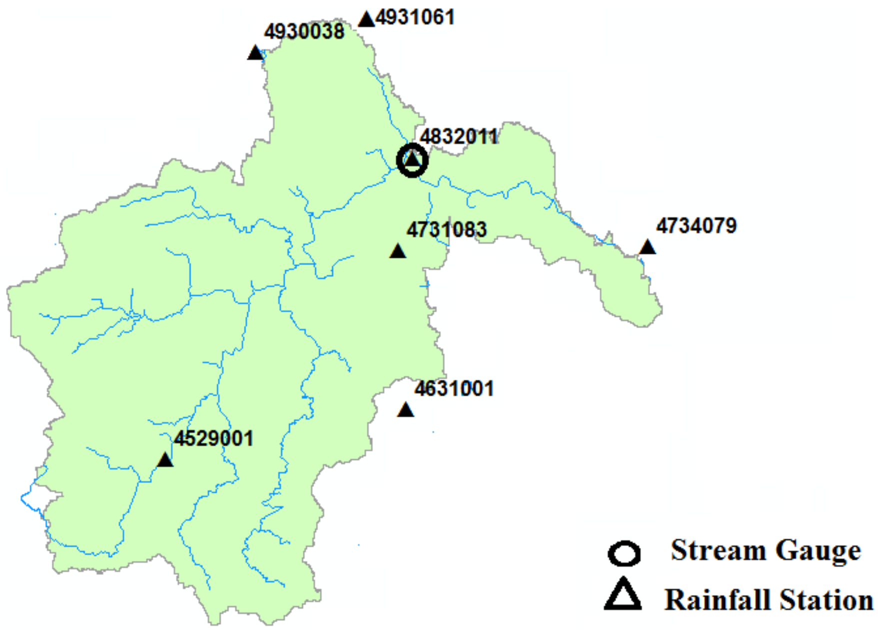

Figure 2: The upper Dungun River catchment with river network and location of rainfall and river gauges

2.5 Data and Sources

Daily values of precipitation, air temperature and potential evaporation are used as the input of the model. Precipitation data recoded at seven stations, shown in Figure 2 are used in the present study. The data are collected from Department of Irrigation and Drainage (DID), Malaysia. Air temperature data collected at a station located in Kuala Terengganu have been used. The data is collected from Malaysian Meteorological Department. The Potential evaporation has been estimated from daily temperature based on Hargreaves equation (Hargreaves and Samani, 1985).

Digital elevation model (DEM) data are used for the demarcation of catchment boundary. For this purpose 90m resolution ASTER DEM freely available in United States Geological Survey (USGS) website is used. Hydro tool, a GIS based catchment boundary derivation tool is used in the present study to derive catchment boundary from DEM. Data. Average catchment daily values of precipitation, air temperature and potential evapotranspiration are spatially interpolated by Theisson methods. Catchment average values were then found by intercepting the Theissan polygon catchment boundary in a geographical information system. To calibrate and verify a catchment model, daily runoff data were used. Pre-processed daily rainfall, evaporation and discharge data are divided to two parts for calibration and evaluation processes. In the present study, the model is calibrated with two-thirds of the data and the remaining data is used for verification.

Daily rainfall, evapotranspiration and river discharge data used in the present study for model calibration and validation are shown in Figure 3. The upper graph of the figure shows the average rainfall time series over the study area. It can be seen from figure that rainfall in the study area varies with season. The area receives highest rainfall during northeast monsoon and lowest rainfall during June and July. The middle graph of the Figure 3 shows the time series of evapotranspiration of the study area. The graph shows that evapotranspiration of the study area does not vary much with season in the study area. This is due to more or less similar temperature in the study area over the whole year. The lower graph of the figure is the time series of river discharge. The river discharge follows the similar pattern of rainfall in the study area.

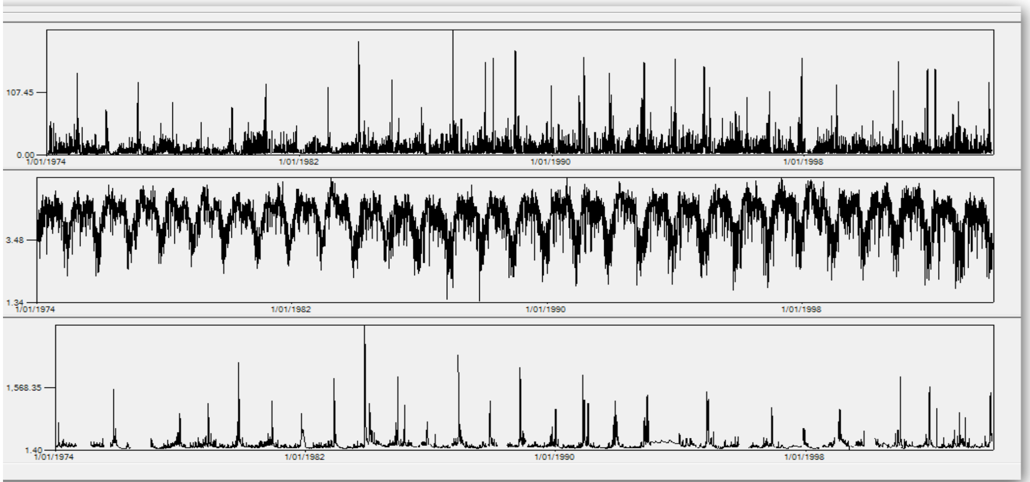

Figure 3: The daily rainfall, evapotranspiration and river discharge input data for SIMHYD

3.0 Results and Discussion

Nine parameters are required to optimize for accurate simulation of streamflow by using SIMHYD. The parameters are listed in Table 1. To evaluate the performance of various optimization methods discussed in methodology section, SIMHYD model was calibrated and validated with those optimization methods. The daily rainfall and river discharge data for the period of January 1, 1974 to December 31, 1994 was used for calibration and the daily river discharge data for the period of January 1, 1995 to December 31, 2003 was used for validation of the model. The estimated parameters sets using different optimization methods are presented in table 1. All these values were estimated within a defined upper and lower bounds. The reliability of the model parameters produced by each optimization method was judged by comparing performances of the model with observed data. The performance of the models was measured using Nash-Sutcliff coefficient (E) (Nash and Sutcliffe 1970) and correlation coefficient (r) during both calibration and verification.

Table 1: Optimized values of SIMHYD parameters using different optimization method

	Optimization Method						
Parameteres	GA	MPS	URS	MSRS	RM	SCE-UA	PS
Baseflow Coefficient	0.133	0.145	0.593	0.021	0.166	0.294	0.094
Impervious Threshold	3.902	0.061	2.211	1.360	0.002	1.623	0.123
Infiltration Coefficient	352.941	387.647	163.556	259.537	271.806	275.821	275.821
Infiltration Shape	0.196	0.405	1.635	2.546	0.034	0.000	0.000
Interflow Coefficient	0.008	0.012	0.930	0.619	0.099	0.544	0.144
Pervious Fraction	0.988	0.977	0.896	0.500	1.000	1.000	1.000
Rainfall Interception Store Capacity	0.059	0.093	0.048	1.394	0.000	0.023	0.023
Recharge Coefficient	0.647	0.967	0.993	0.942	1.000	0.554	0.954
Soil Moisture Store Capacity	110.584	52.348	406.019	266.934	174.847	3.936	3.936

The Nash-Sutcliff coefficient (E) and correlation coefficient during model calibration and validation using different optimization methods are given in Table 2. The table indicates that higher calibration efficiencies are resulted when Genetic algorithm (GA), multi-start pattern search MPS), Rosenbrock method (RM) and pattern search (PS) optimization were used. The Nash-Sutcliff coefficients during model validation were found as high as 0.645 for those methods. The correlation coefficients were also found as high as 0.8. Performance of those methods during model calibration was also found very well. On the other hand, performance of Uniform random search (MSRS), multi-start Rosenbrock search (MSRS) and shuffled complex evaluation (SCE-UA) methods was found very poor during both calibration and validation periods. This indicates that genetic algorithm (GA), multi-start pattern search MPS), Rosenbrock method (RM) and pattern search (PS) perform better compared to other methods. Among all the methods, genetic algorithm based optimization method is found to perform best in term of Nash-Sutcliffe coefficient and correlation coefficient. The Nash-Sutcliffe coefficient and correlation coefficient values obtain using genetic algorithm optimization method in SIMHYD were 0.66 and 0.83, respectively. This means that genetic algorithm optimization method increases the model performance higher than any other optimization methods under study.

The results collaborate with the finding of other studies. Wang (1991) showed that the Genetic Algorithm (GA) is a robust and efficient method for the calibration of hydrological conceptual models. Cheng *et al*. (2005) also reported the efficacy of GA in calibration of rainfall-runoff models.

Table 2: Comparison of performance of SIMHYD during calibration and validation with different optimization methods

Optimisation Method		Calibration		Verification	
		Nash-Sutcliffe (E)	correlation	Nash-Sutcliffe (E)	correlation
Genetic algorithm	(GA)	0.636	0.809	0.663	0.831
Multi start pattern search	(MPS)	0.64	0.807	0.662	0.822
Uniform random search	(URS)	-0.321	0.472	-0.45	0.414
Multi start Rosenbrock search	(MSRS)	-0.359	0.426	-0.497	0.364
Rosenbrock method	(RM)	0.624	0.798	0.645	0.814
Shuffled complex evolution	(SCE-UA)	0.422	0.729	0.394	0.712
Pattern search	(PS)	0.613	0.783	0.642	0.806

The scatter plot of observed and simulated river discharge obtained by using SIMHYD with Genetic Algorithm optimization method is shown in Figure 4. The plot shows that most of the points are aligned along the line bisecting the plot. This indicates good agreement between simulated and observed discharge. Detail analysis of the plot shows number of points below the bisect line is more compared to the number above the line. This means a bit underestimation of the river discharge by the model.

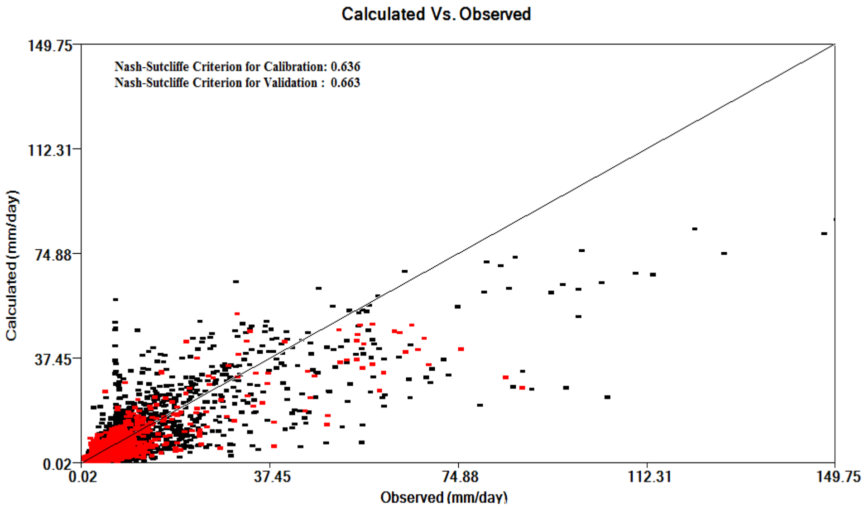

Figure 4: scatter plot comparing the modelled vs. Observed flows during validation of SIMHYD with Genetic Algorithm optimization method

This figure also shows little scatter for low flow values which mean better prediction by the model for low flow. However, the model performance found to deteriorate a bit for large events and most of the peaks were found to be underestimated. Figures 5 and 6 present observed and modeled runoffs during calibration and verification of SIMHYD using genetic algorithm optimization method. It can be seen from the figures that bias was minimal during low flow. It means that the model has a good potential to simulate low flow. However, the model found to underestimate almost all the peak flows. This indicates that the model may not be capable to simulate peak flows as well as the low flows. Overall, the figures show that the model has a good potential for estimating low and as usual flows and can therefore be quiet adequate for predicting runoff.

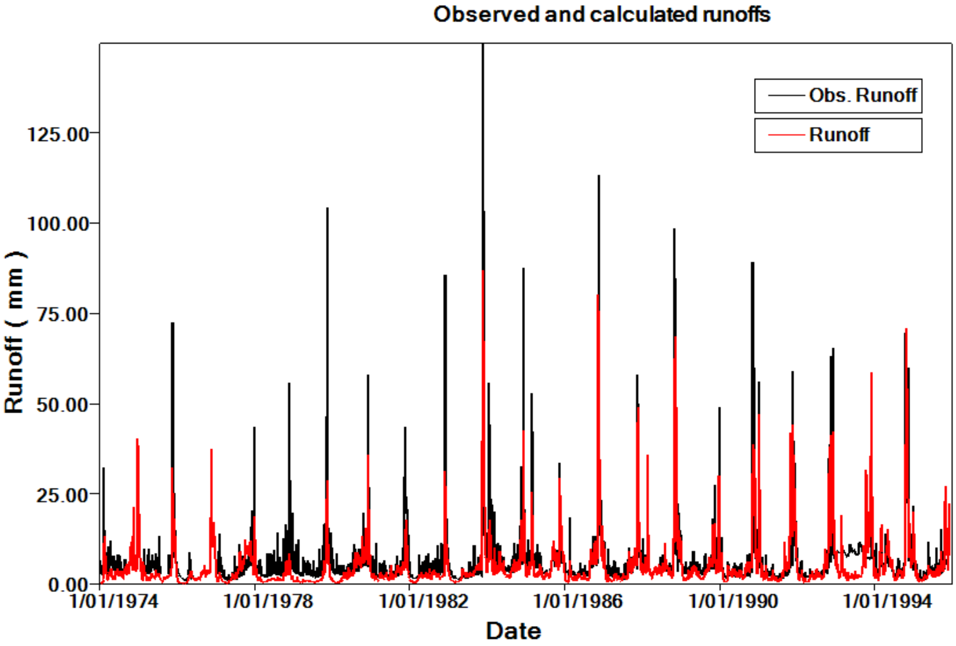

Figure 5: Observed and modeled runoffs during calibration (1974-1994) of SIMHYD using Genetic Algorithm optimization method

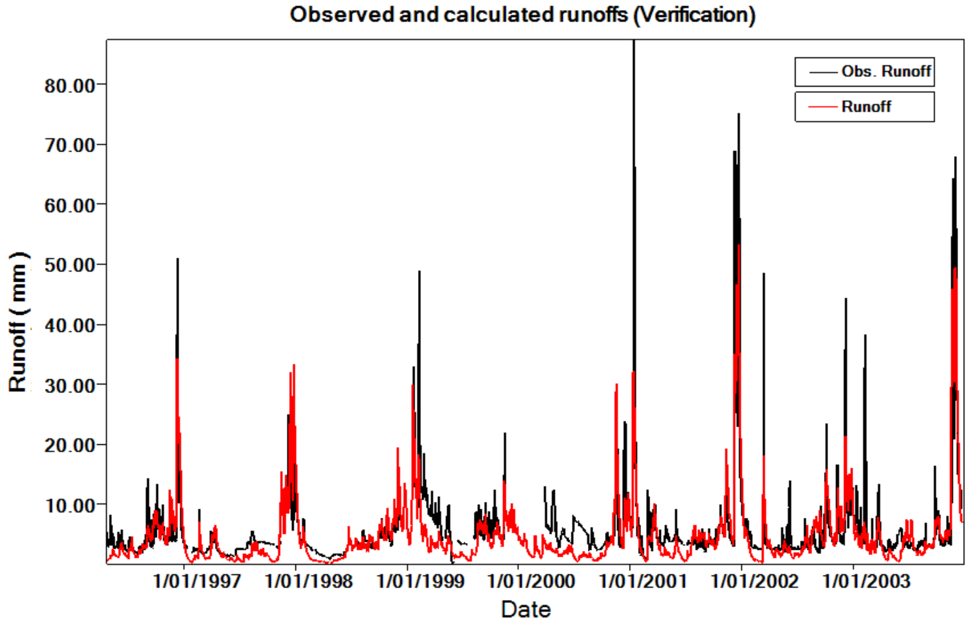

Figure 6: Observed and modeled runoffs during validation (1995-2003) of SIMHYD using Genetic Algorithm optimization method

4.0 Conclusion

Heavy rainfall throughout the year is the most common characteristics of tropical climate. Sudden peak in river flow induced by extreme rainfall is often noticed in tropical catchment which is very difficult to simulate accurately using hydrological model. Scarcity of data makes the situation more difficult. To overcome these challenges parameter intensive hydrological models are often used which needs to optimize the model parameters properly for getting precise output. In the present research, performance of various parameter optimization techniques are assessed for reliable calibration of a conceptual lumped hydrological model SIMHYD in a tropical catchment. The result indicates that evolutionary algorithm based optimization techniques can estimate the model parameters more accurately for precise calibration of model and reliable prediction of daily streamflow. It is expected that the study will help in better understanding of hydrological model simulation in tropical region for various hydrological applications.

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