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AUTO-CALIBRATION OF DAILY AND HOURLY TANK MODEL'S PARAMETERS USING GENETIC ALGORITHM

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Abstract: The only calibration method for Hydrologic Tank model in early days is using trial-and-error. This method required much time and effort for obtaining better results since a large number of parameters need to be calibrated. Therefore, various Global Optimization Methods (GOMs) have been applied to optimize Tank model parameters automatically. In this study, genetic algorithm was introduced to auto-calibrate daily and hourly Tank model parameters. The selected study area is Bedup Basin, Samarahan, Sarawak, Malaysia. Input data used for both daily and hourly model calibration are rainfall and runoff only. The accuracy of the simulation results are measured using Coefficient of Correlation (R) and Nash-Sutcliffe Coefficient (E^2). The robustness of the model parameters obtained are further analyzed by boxplots analysis. Peak errors are also evaluated for hourly runoff simulation. Results show that GA method is able to obtain optimal values for ten parameters fast and accurate within a multidimensional parameter space that could provide the best fit between the observed and simulated runoff.

Keywords: *Hydrological Tank model, Global Optimization Methods (GOMs), Genetic Algorithm (GA), Rainfall-runoff model.*

1.0 Introduction

Hydrological Tank model was introduced by Sugawara and Funiyuki in 1956. This model assumed the watershed as a series of storage vessels and the data required for model calibration are only rainfall and runoff. Tank model has proven its remarkable ability in rainfall-runoff simulations and verifications due to its simplified model frame, reasonable function in runoff response and ability to provide good simulation results.

However, the major work in applying this hydrological model is fitting the model parameters. In early days, the most common procedure for searching the model parameters is through trial-and-error procedure. This manual calibration process is really tedious and time consuming owing to the large numbers of model parameters involved

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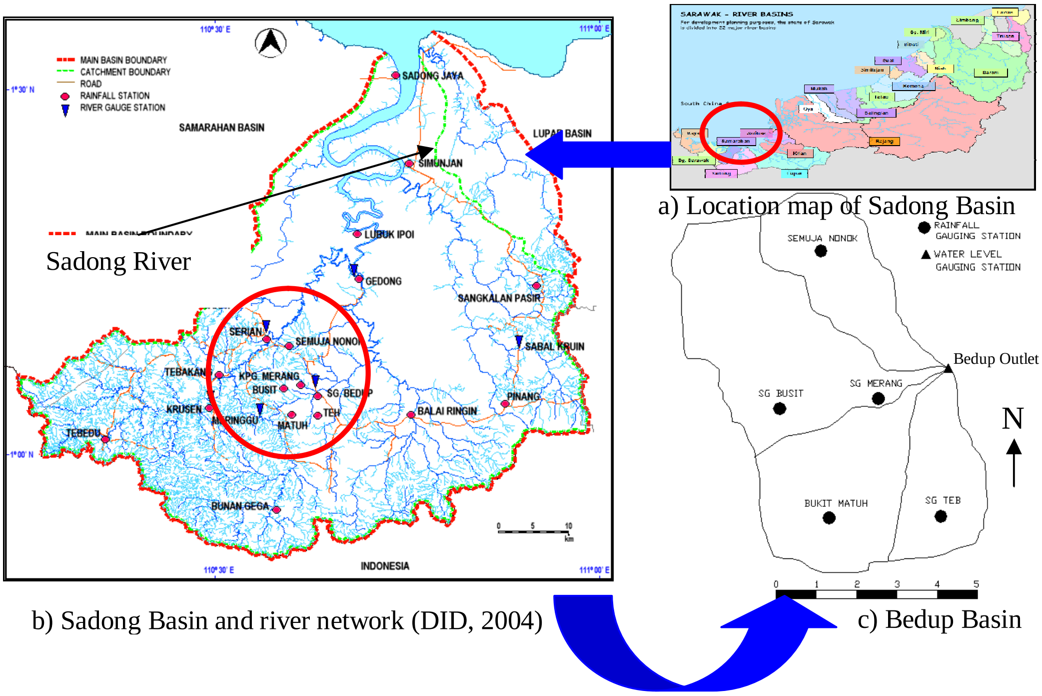
in the four-layered Tank model. Sometimes, the simulation results may be uncertainty due to the subjective factors involved. Therefore, this study has been performed to determine a more efficient automatic calibration procedure.

According to Chen *et al.* (2005), the study of optimizing Tank model parameters was started about three decades ago. Numerous global optimization methods (GOMs) were adopted. GOMs including genetic algorithms (GA), simulated annealing (SA), shuffle complex evolution (SCE), TABU, adaptive random search, multistart powel method have been successfully employed in model calibration (Wang (1991); Sorooshian *et al.* (1993); Cooper *et al.* (1997); Yapo *et. al.* (1996); Kuezera (1997); Kuok *et al.* (2007; 2008; 2009; 2010; 2011). All these GOMs algorithms are able to navigate numerous local optima present in the response surface of the conceptual rainfall-runoff model calibration problem. However, the most suitable GOM for optimizing Tank model parameters in tropical region still required further investigation. This study investigates the performance of GA for calibrating daily and hourly Hydrologic Tank model for Bedup Basin, Sarawak, Malaysia. The programming language used for model development is Microsoft Visual Basic.

2.0 Study Area

The selected study area is Sungai Bedup Basin, located approximately 80km from Kuching City, Sarawak, Malaysia. It is non-tidal influence river basin, located at upper stream of Batang Sadong. The basin area is approximately about 47.5km^2 and the elevation varies from 8m to 686m above mean sea level (JUPEM, 1975). Vegetation cover is mainly of shrubs, low plant and forest. The development and land use changes are not really significant in this rural watershed for the past 30 years. Sungai Bedup's basin has a dendritic type channel system. Maximum stream length for the basin is approximately 10km, which is measured from the most remote area point of the stream to the basin outlet.

The locality plan of Sungai Bedup Basin was presented in Figure 1. Figure 1a shows the location of Sadong Basin. Main boundary of the Sadong Basin, rainfall and river stage gauging stations within Sadong Basin, are shown in Figure 1b. The Bedup basin is upstream of Batang Sadong, where it is a non-tidal influence river basin. Figure 1c shows the 5 rainfall gauging stations available in Sungai Bedup Basin, namely, Bukit Matuh (BM), Semuja Nonok (SN), Sungai Busit (SB), Sungai Merang (SM) and Sungai Teb (ST), and one river stage gauging station at Sungai Bedup located at the outlet of the basin.



a) Location map of Sadong Basin

b) Sadong Basin and river network (DID, 2004)

c) Bedup Basin

Figure 1: Locality map of Bedup Basin, Sub-basin of Sadong Basin, Sarawak

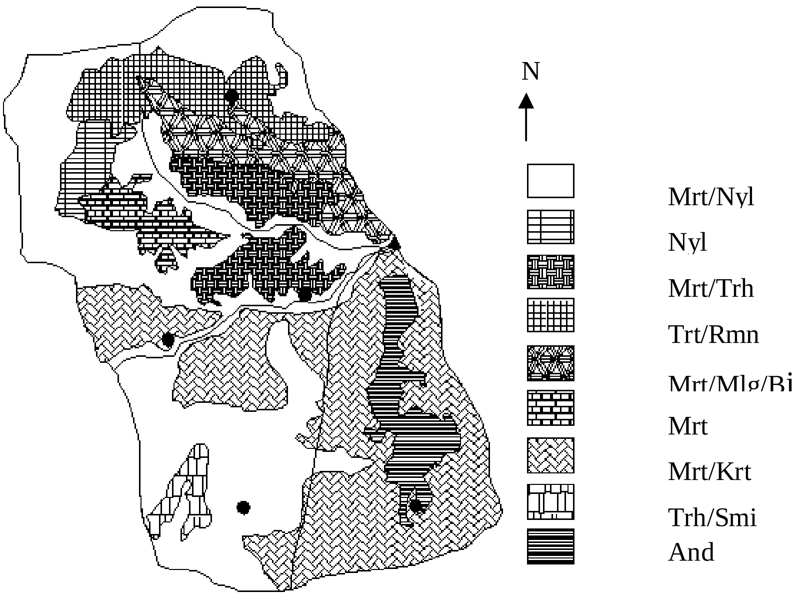


Figure 2: Soil Map of Bedup Basin, Sarawak (DOA, 1975)

Soil map of Bedup Basin was presented in Figure 2. In general, Bedup Basin was mostly covered with clayey soils, that were symbolized with *Mrt, Mlg, Trt, Krt, Bjt* and *And*. Clayey soil has low infiltration rate (minimum infiltration rate of 0.04 inches/hr), where the most of the precipitation fails to infiltrate and runs over the soil surface and thus produce surface runoff. *Nyl, Trh, Sml* are the coarse loamy soil available in Bedup Basin. This group of soils has higher infiltration rate (minimum infiltration rate of 1.02 inches/hr) and therefore has moderately low runoff potential.

The input data used are daily rainfall data from the 5 rainfall stations. Data series used for model calibration and verification are daily and hourly rainfall and runoff from year 1990 to year 2003 that obtained from Thiessen Polygon Analysis. The area weighted precipitation for BM, SN, SB, SM, ST are found to be 0.17, 0.16, 0.17, 0.18 and 0.32 respectively. The average areal daily and hourly rainfall data for that time step is then fed into the Tank model. The calibrated Tank model will then carry out computations to simulate the daily discharges for Bedup Outlet. Observed runoff data are converted from water level data through a rating curve given by Equation 1 (DID, 2004).

$$Q=9.19(H)^{1.9} \qquad \text{Eq. (1)}$$

where Q is the discharge (m^3/s) and H is the stage discharge (m). These observed runoff data were used to compare the model runoff.

3.0 Genetic Algorithm (GA) Method

Genetic algorithm was originally developed by Holland (1975). GA starts with an initial set of random solutions called population. Each individual in the population is called a chromosome, a string of symbols representing a solution to a problem at hand. The chromosome evolves through successive iterations, called generations. During each generation, the chromosomes are evaluated by fitness function. The chromosomes will then pass through three main processes in GA namely selection, crossover and mutation. For creating the new generation, parent chromosomes are selected according to their fitness where the fitter chromosomes have higher probabilities of being selected. Then, crossover and mutation occurred to produce new offspring. The process is then repeated until the stop condition is satisfied. After several generations, the algorithms converge to the best chromosome, which represents the optimal or the suboptimal solution to the problem. The general structure of GA approach is shown in Figure 3 and the details of GA algorithm can refer to Gen and Cheng (1997).

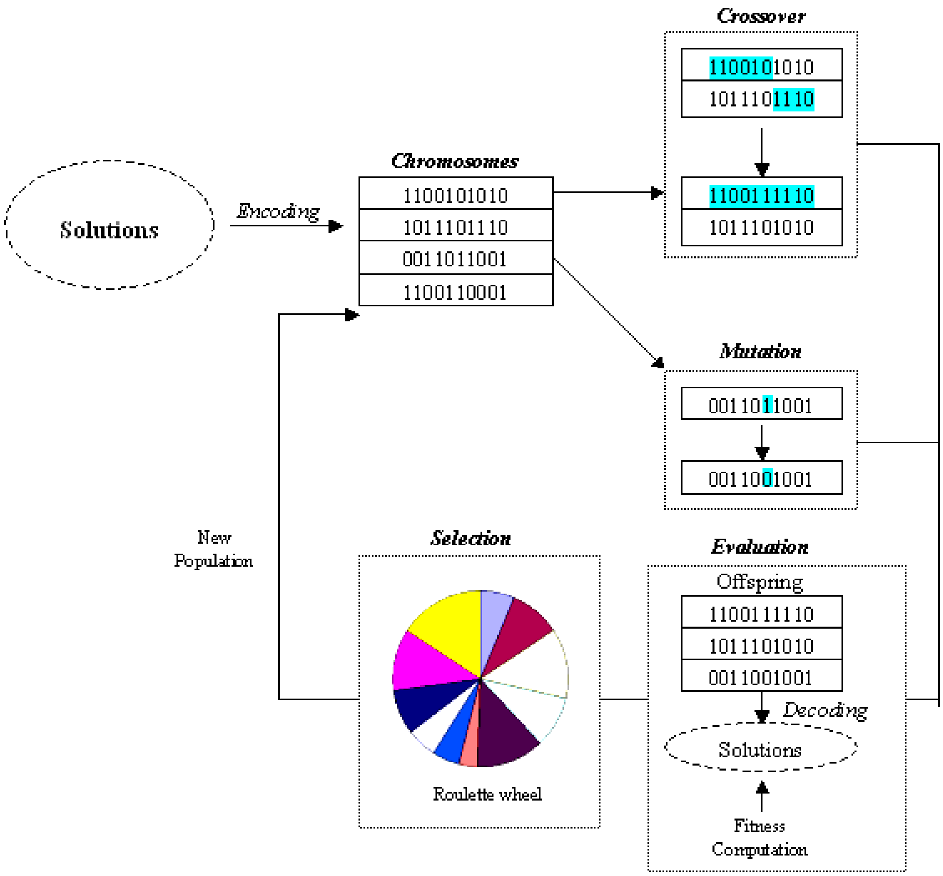


Figure 3: The general structure of GA (Gen and Cheng, 1997)

4.0 Tank Model Parameters

Since Tank model developed in 1956, it has been adopted by many water resources development or management agencies all over the world. This is owing to Tank model is not only simple and easily understood, but also able to indicate accurately the response for surface runoff (Kawasaki, 2003).

The response of surface runoff system is explained by vertically connected plural tanks. The proposed Tank model consists of four storage vessels (4-Tank) that lay vertically. This storage type Tank model is based on hypothesis that both discharge and infiltration are functions of amount of water stored in the ground. Each tank has one or more outlets on its side and bottom. According to Kawasaki (2003), the side flow from the first tank (located upper-most) indicates flood or a high surface flow. The side flow from the second and third tanks means a normal river flow and side flow from the forth tank (located bottom) is a base flow. The water infiltrating from the lowest tank recharges the groundwater. The schematic of the Tank model used in this study was presented in Figure 4.

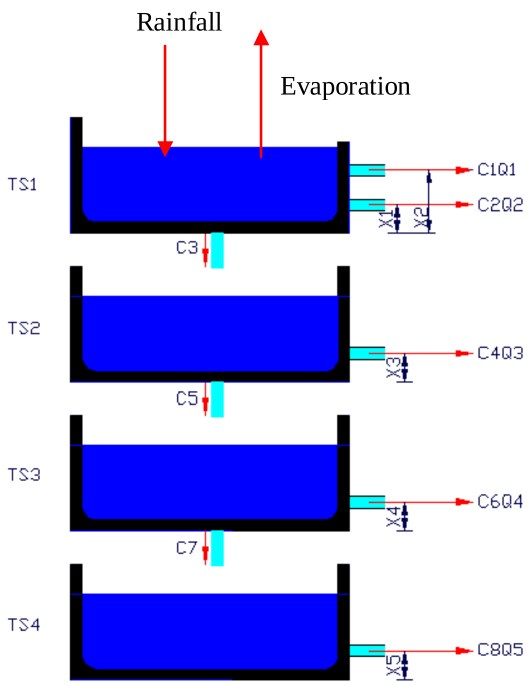


Figure 4: Schematic of Tank model used in this study

Parameters of Tank models are side outlet coefficients (C1, C2, C4, C6 and C8), bottom outlet coefficient (C3, C5 and C7), height of side outlets (X1, X2, X3, X4 and X5) and initial storages in tanks (TS1, TS2, TS3 and TS4). The coefficient calibrated automatically are C1, C2, C3, C4, C5, C6, C7, C8, X1, X2, X3, X4 and X5. Prior to calibration, parameters X3, X4 and X5 were found have little impact to model output. Therefore, these parameters were set to zero (0). The descriptions of calibrated 10 parameters are tabulated in Table 1.

Table 1: The description of the 10 parameters for Tank model

No	Coeff	Identification	Description
1	C1	Side outlet coefficients No.1 for TS1	Surface runoff coefficient No.1
2	C2	Side outlet coefficients No.2 for TS1	Surface runoff coefficient No.2
3	C3	Bottom outlet coefficient from TS1 to TS2	Infiltration coefficient from surface tank to intermediate tank
4	C4	Side outlet coefficients for TS2	Intermediate runoff coefficient
5	C5	Bottom outlet coefficient from TS2 to TS3	Infiltration coefficient from intermediate tank to sub-base tank
6	C6	Side outlet coefficients for TS3	sub-base runoff coefficient
7	C7	Bottom outlet coefficient from TS3 to TS4	Infiltration coefficient from sub-base tank to base tank
8	C8	Side outlet coefficients for TS4	Base runoff coefficient
9	X1	Height of side outlets No.2 for TS1	Height of surface runoff No.2 from surface tank
10	X2	Height of side outlets No.1 for TS1	Height of surface runoff No.1 from surface tank

The total discharge, Q was calculated using Equation 2:

$$Q = C1Q1 + C2Q2 + C4Q3 + C6Q4 + C8Q5 \qquad \text{Eq. (2)}$$

5.0 Methodology

5.1 Calibration for Daily Runoff

Various sets of daily rainfall-runoff data were calibrated to find the best model configuration for simulating daily runoff at Sungai Bedup. Daily Tank model developed for simulating daily runoff is denoted as GA-Tank-D. GA algorithm will automatically select the best mutation rate ranged from 0.005 to 0.25. The parameters investigated by GA-Tank-D are:

a) Different length of calibration data ranging from 7, 9, 11, 13, 15 and 17 months, from 1st Jan 1998 to 31st May 1999
b) Relative fitness rate of 0.6, 0.7, 0.8 and 0.9
c) 0.5, 0.6, 0.7, 0.8 and 0.9 of crossover rate

The best length of calibration data for GA-Tank-D was found to be 17 months. The calibration process is further investigated with 6 different sets of daily rainfall-runoff data at secondary stage (as presented in Table 2). The aim is to find the best and most robust parameters set for simulating daily runoff at Sungai Bedup. Each set of parameters obtained will then validated with another 11 sets of daily rainfall-runoff data as tabulated in Table 3. Therefore, there are 66 repetitions for model calibrated with GA algorithms.

Table 2: Details of GA-Tank-D calibration data

Description	Date
GASetDA	1 Jan 1998 to 31 May 1999
GASetDB	1 Jan 1990 to 31 May 1990+1 Jul 1990 to 30 Jun 1991
GASetDC	1 Jan 1992 to 30 Jun 1998+1 Aug 1992 to 30 Jun 1993
GASetDD	1 Jan 2002 to 31 May 2003
GASetDE	1 Jan 2003 to 31 May 2004
GASetDF	1 Jan 2000 to 31 May 2001

Table 3: Validation data for daily runoff

Item	Period
1	1 Jan 1990 to 31 May 1990
2	1 Aug 1990 to 31 Dec 1990
3	1 Jan 1992, 1 Apr 1992 to 31 Jul 1992
4	1 Aug 1992 to 31 Dec 1992
5	1 Aug 1993 to 31 Dec 1993
6	1 Jan 2002 to 30 Jun 2002
7	1 Jul 2002 to 31 Dec 2002
8	1 Jan 2003 to 30 Jun 2003
9	1 Jul 2003 to 31 Dec 2003
10	1 Jan 2000 to 30 Jun 2000
11	1 Jul 2000 to 31 Dec 2000

5.2 Calibration for Hourly Runoff

In order to find the best configuration, hourly Tank model, denoted as GA-Tank-H was developed for simulating hourly runoff. GA-Tank-H will be calibrated with 11 sets of hourly rainfall-runoff data and further investigated with:

a) 0.5, 0.6, 0.7, 0.8 and 0.9 of relative fitness rate
b) Crossover rate of 0.1, 0.2, 0.3, 0.4 and 0.5

The optimal mutation rate ranged from 0.005 to 0.25 is automatically selected by GA algorithm. Each set of parameters obtained will then validated with other 11 storm hydrographs. Hence, there are 121 repetitions for the experiments calibrated GA-Tank-H. Table 4 presents 11 storm hydrographs for calibrating GA-Tank-H in searching the optimal tank model's parameters.

Table 4: Calibration data for GA-Tank-H

Description	Storm Date
GASetHA	1-7 Jan 99
GASetHB	5-8 Apr 99
GASetHC	5-8 Feb 99
GASetHD	8-12 Aug 98
GASetHE	9-12 Sep 98
GASetHF	15-18 Mac 99
GASetHG	20-24 Jan 99
GASetHH	26-31 Jan 99
GASetHI	16-20 Apr 03
GASetHJ	18-21 Jan 00
GASetHK	9-12 Oct 03

5.3 Objective Function

Objective function selected is ordinary least squares (OLS). According to Cooper *et al*. (1997), OLS always provide better approximations of the model parameters due to its algebraic formulations where each of these formulations consists of a summation of the least squares differences for every point in the flow series. Cooper *et al*. (2007) had used this objective function when extending his works by reducing the parameter search space using some suitable constraints to describe the interactions between the rainfall and runoff processes considered. The objective function will evaluate the performance of the GOMs in calibrating Tank model and it will ensure that the learning error is getting lesser with the increase of number iterations.

5.4 Performance Evaluation

The simulated results obtained are evaluated to determine the differences between observed and predicted values. The accuracy of model performance are measured by Coefficient of Correlation (R) and Nash-sutcliffe coefficient (E^2). According to Lauzon *et al*. (2000), the R and E^2 are measuring the overall differences between observed and estimated flow values. The formulas of these two coefficients are given in Table 5.

Table 5: Formulas for R and E^2

Concept	Name	Formula
Coefficient of Correlation	R	$\dfrac{\sum(obs-\overline{obs})(pred-\overline{pred})}{\sqrt{\sum(obs-\overline{obs})^2\sum(pred-\overline{pred})^2}}$
Nash-Sutcliffe Coefficient	E^2	$E^2=1-\dfrac{\sum_i^j(obs-pred)^2}{\sum_i^j(obs-\overline{obs})^2}$

Note : obs = observed value, pred = predicted value, $\overline{obs}$ *= mean observed values,* $\overline{pred}$ *= mean predicted values and j = number of values.*

The robustness of parameters investigated are determined using Boxplots. Five sample statistics represented by boxplots are the minimum, the lower quartile, the median, the upper quartile and the maximum, in a visual display. Each storm hydrograph simulated by optimal configuration of Tank model's parameters are evaluated for peak runoff. Error between simulated and observed peak generated by optimal configuration of GA-Tank-H approaches are compared for 11 validation data sets. The objective is to evaluate how successful the simulated runoff in approaching the observed peak. Error between observed peak and simulated peak was calculated using Equation 3:

$$Error=\left(\frac{simulated\_peak-observed\_peak}{observed\_peak}\right)x100\% \qquad \text{Eq. (3)}$$

6.0 Results and Discussion

6.1 Daily Runoff Simulation

The six optimal parameters sets obtained using GA calibration method is presented in Table 6. Results revealed that the best parameter set is obtained using GASetDA (1 Jan 1998 to 30 Nov 1998), where R and E^2 are yielded to 0.648 and 0.6216 respectively with the configuration of 17 months of calibration data, relative fitness rate of 0.8 and crossover rate of 0.8. Generally, the result obtained is accurate with little discrepancy between simulated and observed runoff. The simulated peak for GA-Tank-D is always slightly underestimated than the observed peak, as shown in Day 180 to Day 310, and Day 430 to Day 510 in Figure 5. In contrast, the simulation for low discharges is slightly higher than the observed data. This was presented in Figure 5 from Day 0 to Day 180, and from Day 310 to Day 430. Generally,

Table 6: Different parameters obtained using GA calibration methods

	C1	C2	X1	C3	X4	C4	C5	C6	C7	C8
GASet DA	0.000878	0.049575	7.59624	0.994551	7.01746	0.002293	0.279663	0.031167	0.422029	0.000034
GASet DB	0.000024	0.000865	14.0505	0.00564	17.45364	0.541959	0.000005	0.570193	0.170798	0.954784
GASet DC	0.118948	0.200654	8.73678	0.008243	14.96426	0.882902	0.000034	0.998694	0.217036	0.980312
GASet DD	0.000521	0.000425	8.71154	0.010274	19.76464	0.019755	0.000008	0.535999	0.715379	0.311154
GASet DE	0.117447	0.035935	8.0497	0.024473	8.52444	0.006937	0.000027	0.993934	0.986356	0.148457
GASet DF	0.034391	0.026399	14.79592	0.001359	5.5607	0.029772	0.000052	0.996077	0.413989	0.408236

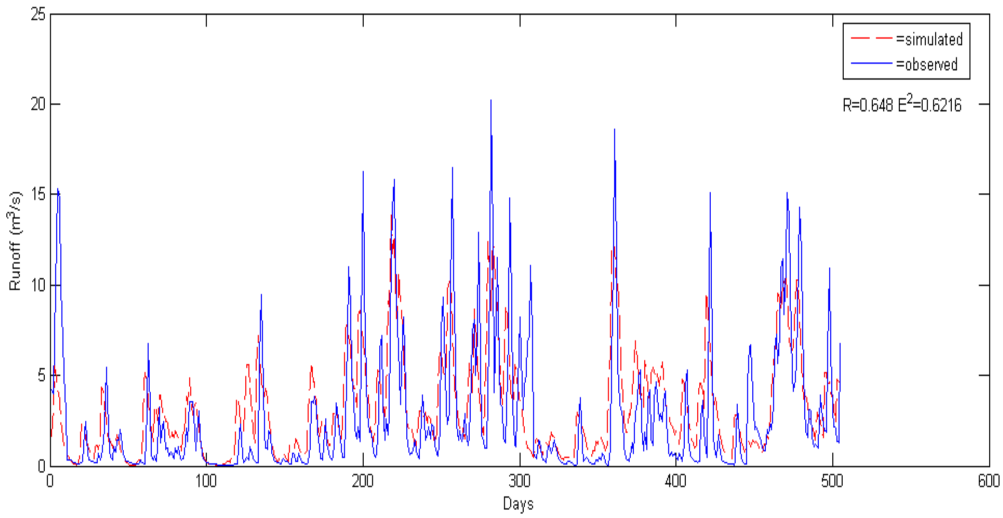
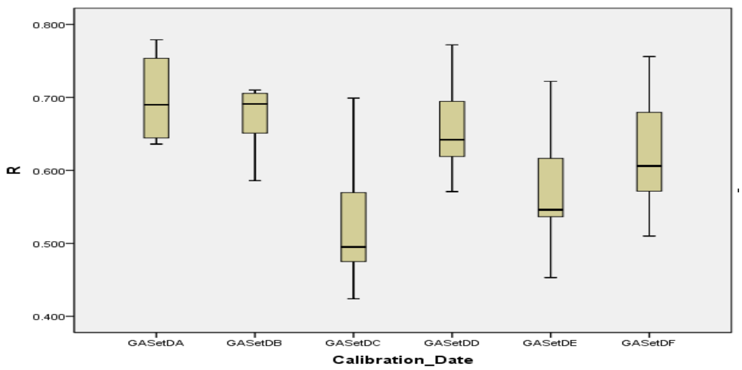


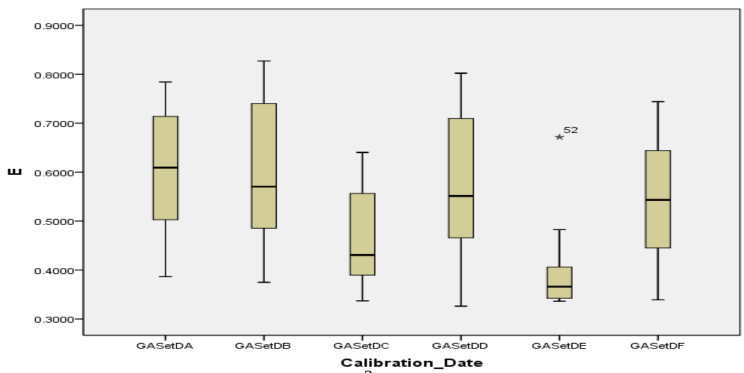
Figure 5: Optimal performance of GA-Tank-D with 17 months of calibration data, 0.8 relative fitness rate and crossover rate of 0.8

The optimal GA automatic calibration illustrated that seven parameters namely C2, X1, C3, X2, C5, C6 and C7 are dominant for runoff simulation. Three other parameters, C1, C4 and C8 that are 0.000878, 0.002293 and 0.000034 respectively, are found less sensitive to daily runoff generation. The values of infiltration coefficient C3, C5 and C7 are 0.994551, 0.279663 and 0.422029 respectively. This reflected that the infiltration rate from first to second tank is high. The infiltration rate will be reduced from second to third tank and third to forth tank.

To ensure the effectiveness and robustness of the GA algorithm in calibrating Tank model, each parameter sets obtained will then be validated with 11 independent sets of data to produce different flow series. Therefore, the experiments consisted of 66 repetitions. Boxplots is used to show the quartile distributions of R and E^2 performances for GA at different parameters set and different time frame as presented in Figure 6. The six different parameters sets are compared according to their robustness and accuracy, where the robust method was the one with little variability.



a) Boxplots of R for GA-Tank-D



b) Boxplots of E^2 for GA-Tank-D

Figure 6: Boxplots of GA-Tank-D for validating 11 data sets

Boxplots analysis revealed that GASetDA produced highest median with R=0.690 and E^2=0.6093 among the 6 calibration sets (refer Figure 6). Upper quartile of R=0.766 and E^2=0.7635 are obtained, while the lower quartile of R=0.644 and E^2=0.4872 are obtained for GASetDA. The maximum and minimum R recorded for GASetDA are 0.779 and 0.636 respectively. Where else, the maximum and minimum E^2 are found to be 0.7841 and 0.3864 respectively.

6.2 Hourly Runoff Simulation

Eleven sets of single storm event were calibrated using GA optimization method and the results are tabulated in Table 7. GASetHF is the best parameters set obtained using single storm on 15 to 18 Mac 1999, with the relative fitness rate of 0.8 and crossover rate of 0.1.

Table 7: Optimal parameters obtained using GA algorithm with different dataset

	C1	**C2**	**X1**	**C3**	**X4**	**C4**	**C5**	**C6**	**C7**	**C8**
GASetHA	0.041672	0.272144	0.000237	0.001655	0.03584	0.991883	0.056497	0.105158	18.42204	12.94972
GASetHB	0.906979	0.151178	0.006531	0.000106	0.056608	0.951583	0.053953	0.079236	1.47062	4.1253
GASetHC	0.003248	0.007562	0.014901	0.061953	0.063003	0.065483	0.731622	0.996964	1.81816	18.34346
GASetHD	0.68563	0.399342	0.002915	0.001956	0.060863	0.949345	0.07279	0.075697	10.24762	16.45502
GASetHE	0.654203	0.88805	0.001684	0.219454	0.17399	0.996961	0.027309	0.122059	2.69602	7.9581
GASetHF	0.198868	0.030931	0.005819	0.003186	0.054817	0.971401	0.15737	0.058961	10.82168	8.64644
GASetHG	0.024976	0.023563	0.000198	0.000692	0.029719	0.897316	0.083876	0.101906	12.71422	17.15306
GASetHH	0.635164	0.274036	0.002382	0.003704	0.074463	0.988949	0.047026	0.324104	6.16826	17.49068
GASetHI	0.499056	0.702753	0.006134	0.869972	0.111811	0.982054	0.012687	0.884571	15.62088	14.15532
GASetHJ	0.10761	0.205061	0.005846	0.016876	0.058136	0.974358	0.109147	0.067362	14.15238	3.0533
GASetHK	0.773552	0.4789	0.002694	0.017734	0.169918	0.981232	0.033574	0.07826	2.99306	12.14994

Figure 7 presents the best storm hydrograph calibrated by the optimal configuration of GA algorithm where the optimum R and E^2 values are obtained with high accuracy of 0.948 and 0.9051 respectively. However, it was observed that the simulated peak is slightly lower than the observed peak.

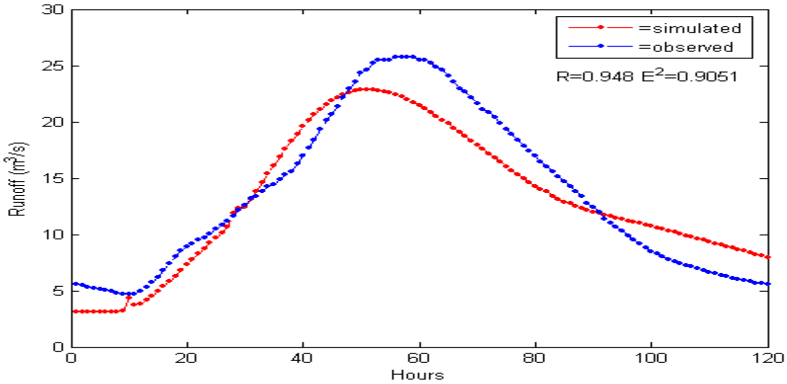


Figure 7: Comparison between observed and optimal simulated storm hydrograph using GA

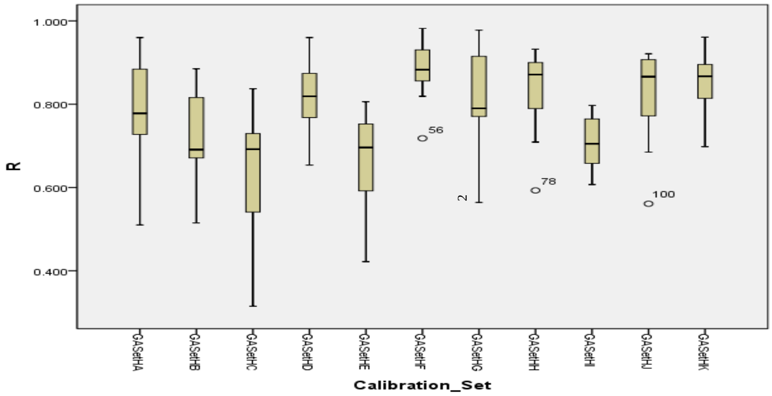
GASetHF demonstrated that all parameters are strongly affecting the hourly runoff generation except C1, C3, C4, C5 and C7. Infiltration coefficient C3, C5 and C7 are found to be 0.000237, 0.03584 and 0.056497 respectively. The small values of infiltration coefficient reflect that the infiltration rate for Bedup Basin, which is mostly covered by clayey soil is very little.

The simulated peak for optimal configuration GASetHF was compared with observed peak. Table 8 presents the comparison between observed and simulated peak flow, error (%) between observed and simulated peak flow for optimal configuration of GA algorithm when validating 11 storms hydrograph.

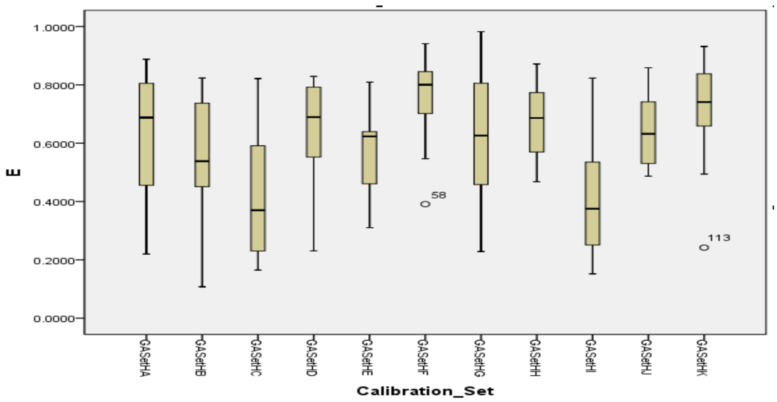
Table 8: Comparison between observed and simulated peak flow for GASetHF

Storms	**Observed Peak**	**Simulated Peak**	**Error (%)**
1998 Aug 8-12	25.75	30.64	18.97
1999 Jan 1-7	34.63	35.33	2.02
1999 Apr 5-8	18.37	14.08	23.39
1999 Feb 5-8	14.26	15.53	8.92
1998 Sep 9-12	40.40	44.98	11.34
1999Mac 15-18	13.20	13.18	0.14
1999 Jan 20-24	20.36	24.37	19.68
1999 Jan 26-31	28.37	28.97	2.11
2000 Apr 5-8	22.45	28.11	25.23
2000 Jan 18-21	22.18	16.41	26.03
2003 Oct 9-12	19.36	20.68	6.84
Average Error			**13.15**

It was found that average error (%) between simulated and observed peak for GASetHF, is 13.15%. These simulated peaks can be used as early warning flow forecaster to take necessary flood protection measures before a severe flood occurs.The accuracy was expressed as R and E^2 of the simulated flow series generated by the parameter set found in the search. The R and E^2 obtained are analyzed using boxplots (presented in Figure 8). The eleven optimized parameters sets were compared according to their robustness and accuracy, where the robust method was one which had little variability.



a) Boxplots of R for GA-Tank-H.



b) Boxplots of E^2 for GA-Tank-H.

Figure 8: Boxplots of GA-Tank-H for validating 11 storms hydrograph

The median R obtained by GASetHF is 0.883. When E^2 is referred, median E^2 provided by GASetHF is 0.8003. However, the minimum E^2 value of 0.3911 was not considered in boxplots analysis. Besides, the upper quartile and lower quartile of R for GASetHF are found to be 0.9203 and 0.8352 respectively, where else 0.8264 and 0.7057 for E^2. Meanwhile, boxplots also presented that the maximum and minimum R recorded are 0.9725 and 0.8185 respectively. In contrast, 0.9111 and 0.5791 are the maximum and minimum values recorded for E^2. Besides, boxplots also revealed that GASetHF has smallest variability for both R and E^2 than other parameters set. Therefore, GASetHF is best parameters set in this study for hourly runoff simulation.

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7.0 Conclusion

These results revealed that GA method is able to calibrate the daily and hourly Tank models accurately. The study demonstrated that GA optimization search method has proved to be robust, efficient and effective in searching optimal Tank model parameters. By providing the best fit between observed and simulated flows, GA methods has proven its ability in searching the optimal parameters.

The methodology has been tested for rural catchment in humid region. Hydrologic Tank model clearly manage to demonstrate the ability to adapt to the respective lag time of each gauge through training, learning or calibration. Rainfall and runoff as inputs are sufficient to develop an accurate hourly rainfall-runoff model.

References

Chen, R.S., Pi, L.C., and Hsieh, C.C. (2005). A Study on Automatic Calibration of Parameters in Tank Model. *Journal of the American Water Resources Association (JAWRA).*

Cooper, V.A., V.T.V. Nguyen, and J.A. Nicell (1997). Evaluation of Global Optimization Methods for Conceptual Rainfall-Runoff Model Calibration. *Water Sci. Technol*, 36(5):53-60.

Cooper, V.A., V.T.V. Nguyen, and J.A. Nicell (2007). Calibration of Conceptual Rainfall Runoff Models using Global Optimisation Methods with Hydrologic Process-Based Parameter Constraints. *Journal of Hydrology*, Elsevier.

DID (2004). Hydrological Year Book Year 2004. Department of Drainage and Irrigation Sarawak, Malaysia.

DOA (1975). Jabatan Pertanian Malaysia. Scale 1:50,000

Gen, M.S. and Cheng, R.W. (1997). Genetic Algorithm And Engineering Design. John Willey and sons, inc.

Holland, J.H. (1975). Adaptation in Natural and Artificial Systems. University of Michigan Press, Ann Arbor.

JUPEM (1975). Jabatan Ukur dan Pemetaan Malaysia. Scale 1:50,000

Kawasaki, R. (2003). Application of Synthetic Tank Model Simulation on the Area with Poor Basic Hydrological Data Availability. *Japan Society of Shimanto Policy and Integrated River Management*, Vol 2-2, pp 18-19.

Kuczera, G. (1997). Efficient subspace probabilistic parameter optimisation for catchment models. *Wat. Resour. Res.,* 33(1), 177-185.

Kuok, K.K., Harun, S., and Shamsudin, S.M. (2007). Optimization of Tank Model's Parameters Using Global Optimization Methods (GOMs). *Proceeding of 2nd International Conference on Managing Rivers in the 21st Century: Solution Towards Sustainable River Basins (Rivers'07)*, 6th-8th June 2007, Kuching, Sarawak.

Kuok, K.K., Harun, S., Shamsudin, S.M., and Chiu, P.C. (2008). Tank Model's Parameters Optimization Using Particle Swarm Optimization (PSO) Technique and Shuffle Complex Evolution (SCE) Technique. *Proceeding of Curtin University of Technology Science and Engineering International Conference (CUTSE'08)*, 24th - 27th November 2008, Miri, Sarawak.

Kuok, K.K., Harun, S., Shamsudin, S.M., and Chiu, P.C. (2009). Optimization of Tank Model's Parameters Using Particle Swarm Optimization approach (PSO). *Proceeding of International Conference on Engineering and Education in the 21st Century (ICEE)*, 23rd - 25th Mac 2009, Kuching, Sarawak.

Kuok, K.K., Harun, S., and Shamsudin, S.M. (2010), Global Optimization Methods for Calibration and Optimization of the Hydrologic Tank Model's Parameters. *Canadian Journal on Civil Engineering*, Vol. 1, No. 1, Feb. 2010. AM Publishers

Kuok, K.K., Chiu, P.C., and Harun, S. (2011). Multiobjective Particle Swarm Optimization for optimizing Daily Tank Model's Parameters. *Proceeding of ASEAN Australian Engineering Congress, 25th -27th July 2011, Kuching.*

Lauzon, N., Rousselle, J., Birikundavyi, S., and Trung, H.T. (2000). Real-time Daily Flow Forecasting Using Black-box Models, Diffusion Processes and Neural Networks. *Can. J. Civ. Eng.* 27: 671-682.

Sorooshian, S., Q. Duan, and V.K. Gupta (1993). Calibration of Rainfall-Runoff Models: Global Optimization to the Sacramento Soil Moisture Accounting Model. *Water Resources Research* 29(4):1185-1194.

Sugawara M and Funiyuki M. (1956). A Method of Revision of the River Discharge by Means of a Rainfall Model. *Collection of Research Papers about Forecasting Hydrologic variables*: 14-18.

Yapo, P. O., Gupta, H. V., Sorooshian, S. (1996). Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data. *J. Hydrol.*, 181, 23-48.

Wang QJ.(1991). The Genetic Algorithm and Its Application to Calibrating Conceptual Rainfall-runoff Models. *Water Resources Research* 27(9): 2467-2471.