APPLICATION OF TWO RAINFALL - RUNOFF MODELS TO KELANTAN CATCHMENT

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ABSTRACT

Rainfall-runoff models can be used for forecasting flow from catchments. Flow forecasting from a catchment has great use for proper water resources development and operational management. Countless models have been produced in different parts of the world to simulate this transformation of rainfall over the catchment into outflow from the catchment. However, there is no unique model which can universally be accepted and used for all catchments. Moreover, there is no catchment which can also be fitted to all models. Therefore, it is necessary to find a model or models for a catchment which can most simulate the rainfall - runoff transformation. Simple Linear Model (SLM) and Soil Moisture Accounting and Routing (SMAR) Model have been applied to Kelantan Catchment data. The model efficiency criterion (R^2) and the index of volumetric fittings (IVF) have been used as criteria for evaluation of the performance of the models. For this catchment, it has been found that the revised SMAR model has better performance than the SLM in terms of efficiencies, both in the calibration and verification periods

INTRODUCTION

Flow forecasting is one of the most important aspects of hydrology that has great use for proper water resources development and operational management In operational management, flow forecasting can mainly be used for flood control or river regulation for the benefit of protecting lives and properties during high flows, and regulation of reservoirs during low flows Usually, flow at a particular river section in a catchment under consideration can be forecast from rainfall over that catchment Therefore, the relationship between rainfall and runoff must be determined for the catchment that may even be used in real-time flow forecasting.

For this reason, different researches have been conducted on rainfall-runoff transformation in different parts of the world, and countless models have been produced to simulate this transformation

A model is a representation of reality, and it can never be a complete representation Therefore, all models seek to simplify the complexity of the real world by selectively exaggerating the fundamental aspects of system at the expense of incidental detail Depending on the extent to which models try to represent the reality, rainfall-runoff model structures are classified into three types These are:

1) Physically based distributed models, or white box models, which are based on complex physical theory.
2) Black box models, which contain no physically based transfer function to relate input to output
3) Conceptual models, or grey box models, which occupy an intermediate position between the physically based distributed models and empirical black box models.

Physically Based Models: Physically based model is a model that is based on our understanding of the physics of the hydrological processes which control catchment response. Physically based models are necessarily distributed, thus called physically based distributed models, because the equations on which they are defined generally involve one or more space co-ordinates [1].

The well known physically based distributed model is the SHE model (System Hydrological European Model) [20] It has been developed jointly by hydrologists in Denmark, France and Britain. The other distributed models are the Institute of Hydrology Distributed Model (IHDM) and the Agricultural Research Service Small Watershed Model (SWAN) [1].

Black Box Models: The empirical black box models simply attempt to identify a relationship between rainfall input and stream flow output without attempting to describe any of the internal mechanism whereby this transformation takes place This approach is frequently referred to as the system approach, as it relies heavily on techniques of system theory. The rational formula developed from Mulvaney's work was one of the first 'event' models relating storm runoff to rainfall [20]

The first well known development of system approach to the problem of streamflow forecasting is to be found in the work of Sherman [21] in which the concept of unit hydrograph for a catchment was postulated. Later this concept was further refined by Clark [3] who introduced the concept of the instantaneous unit hydrograph. The subsequent evaluation of the instantaneous unit hydrograph provided the basis for the storm response models of Nash [12] and Dooge [5].

Examples of black box models in the hydrological context include the unit hydrograph method, the constrained linear systems model [16], the linear perturbation model [13] and the simple linear model.

Conceptual Models: Conceptual models, unlike black box models, generally attempt to simulate the important hydrological components of the catchment response, e.g. interception, infiltration, groundwater flow, evapotranspiration, surface water flow, etc., and also unlike physically based models, they can never try to completely represent the system. Blackie and Eeles [2] state that when the natural system is as complex, large and imperfectly understood as a catchment it is unlikely that a complete representation of every process occurring at every point in the system can never be achieved; and therefore, the aim must be to identify the major processes contributing to the response that is of particular interest, to quantify or simulate these processes as accurately as possible, to compare the results with those observed in the real system and to progressively refine the representation until the best possible results are achieved within the constraints of time, computing power and the modeller's own ability and experience.

Conceptual models of both elaborate ones in which attempts are made to simulate the effects of most of the known physical phenomena through representation of the relevant processes by a number of parameters, and simplified abstract systems described by a relatively fewer parameters have been widely applied and tested on real catchment data [9]. But the superiority of either approach has not yet been proved by the results obtained in such studies.

Standford Watershed model, TANK model, O'Donnel model, NAM model [4], Xinanjiang model [23], PDM model [10, 11], and SMAR model [6, 7, 18] are some examples of conceptual models.

No matter what type of model is used, there is no unique model which can universally be accepted and used for all catchments. Moreover, there is no catchment which can also be fitted to all models. Therefore, it is necessary to find a model or models for a catchment which can most simulate the rainfall - runoff transformation.

In this study, two river flow forecasting models, Simple Linear Model (SLM) and Soil Moisture Accounting and Routing (SMAR) model, have been applied to catchment data. The catchment under consideration is the Kelantan river basin, which is one of the Malaysian river basins. A brief catchment description, data used and its preliminary analysis and models used are first presented. Then, the results obtained have been analysed and discussed, and conclusion of the work has been made.

CATCHMENT DESCRIPTION

Kelantan river basin (Fig. 1), which is found in Malaysia, is a humid, temperate catchment. Having tropical climatic conditions it receives its precipitation mainly through monsoon rain. The drainage area of the river up to the gauging station under consideration, Jambatan Guillemard, is 11900 Km2. The maximum length and width of the catchment are about 153Km and 140 Km respectively. About 95% of the catchment is steep mountainous region rising to heights of 2135 m above mean sea level, while the remainder of the catchment is undulating lands. The mountainous areas of the catchment are under virgin jungle while rubber and some rice are planted in the lowlands. The eastern and western portions, consisting of mountainous ranges, have a granitic soil cover consisting of a mixture of fine sand to coarse sand and clay. A fine sandy loam soil is found in the extreme east and west of the southern half. The remaining portion comprising almost one-third of the catchment is cloaked by a variable soil cover. The alluvium, along the Sungai Kelantan, consists of fine sandy clay loam and thin layers of gravel.

DATA AND ITS PRELIMINARY ANALYSIS

The daily discharge, rainfall and pan evaporation data of six years, from 1st January 1989 to 31st December 1994, are used. The discharge data are determined by rating curve from the telemetric water level at Jambatan Guillemard gauging station. For rainfall recording, there are six telemetric rainfall stations in the catchment. The mean rainfall over the catchment is determined by Thiessen polygon. There is no evaporation data in the catchment, but the data used are taken from a station near to the border of catchment.

The missing data for both the rainfall and discharge are filled by their seasonal means, while the missing

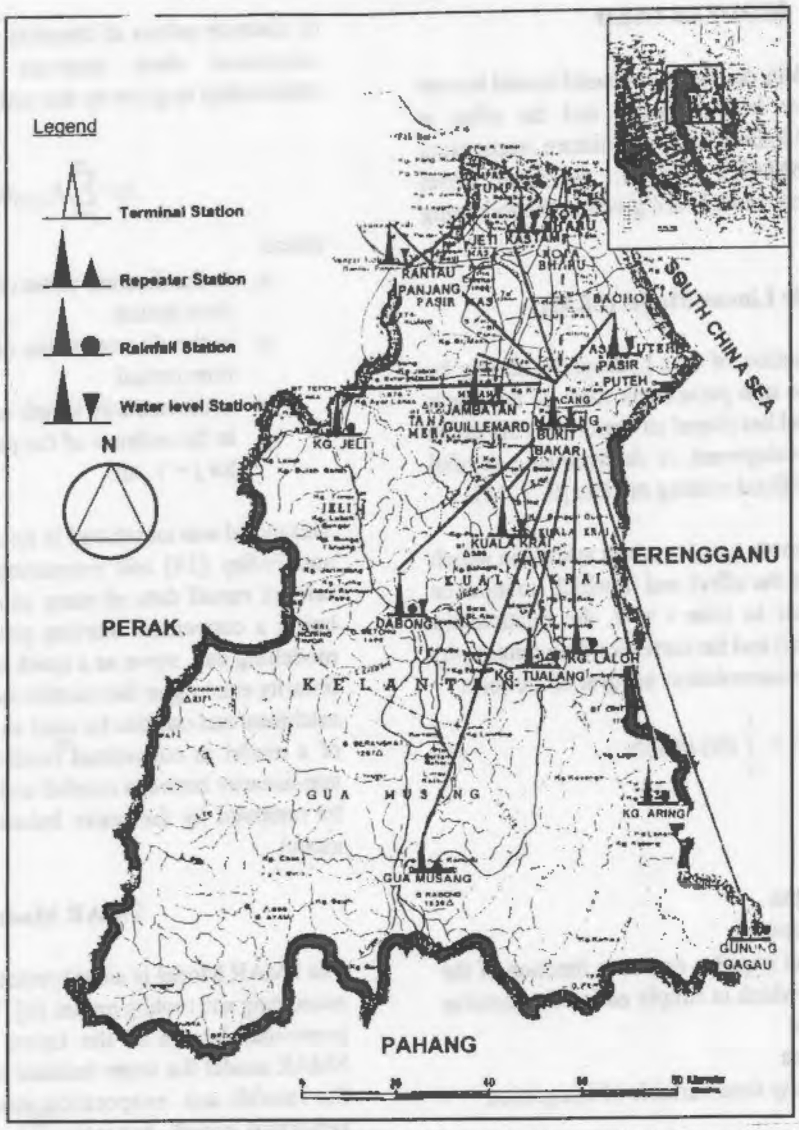


Figure 1 Location of the Kelantan river basin and its telemetric station network

evaporation data are filled by linear interpolation. The locations of telemetric water level station and rainfall stations are shown in Fig. 1.

The length of the calibration and the verification periods for the catchment are chosen to be four and two years, respectively. The Mean values of the rainfall, evaporation and discharge data for the calibration period (C) and the verification period (V) are then determined and given in Table 1.

Table 1: General Catchment and Data Information, and the Mean Values of the Data

Catchment Name	Catchment Area (km^2)	Country	Test Period	Total No. of days	Mean Rainfall (mm/day)	Mean discharge (mm/day)	Mean Evaporation (mm/day)
Kelantan	11900	Malaysia	C	1461	6.65	3.16	3.81
			V	730	8.42	4.18	3.60

MODELS USED

Two types of models, one is system based model known as Simple Linear Model (SLM) and the other is conceptual model known as Soil Moisture Accounting and Routing (SMAR) model , are used. Brief description of these models are given in the following sections.

Simple Linear Model (SLM)

Since the introduction of unit hydrograph theory by Sherman [21], the non parametric form of the linear time invariant model has played an important role in the history of the development of deterministic rainfall runoff models and flood routing models [6, 9, 14].

For a continuous linear time invariant system in which the cause precedes the effect and in which no input or output occurs prior to time $t = 0$, the relationship between the input $x(t)$ and the corresponding output $y(t)$ is expressed by the convolution integral of the form

$$y(t) = \int_0^t x(t)\, h(t)\, d\tau \qquad (1)$$

where,

$x(t)$ - is the input
$y(t)$ - is the output
$h(t)$ - is the unit impulse response function of the system, which is simply called the impulse response
t - is the time
τ - is a dummy time variable of integration

When the input $x(t)$ represents the effective rainfall of a catchment and $y(t)$ is the storm runoff (i.e., the total river flow less the base flow) at the outlet of the catchment, the unit impulse response function is conceptually identical with the instantaneous unit hydrograph of the catchment. If a time invariant linear relationship between the total rainfall and total runoff of a catchment is required instead of that between the effective rainfall and storm runoff, then Eq. (1) results in the continuous form of the non-parametric Simple Linear Model (SLM).

As rainfall and runoff data are most often obtained in discrete form, either in terms of average intensity in equal intervals of time or in terms of sampled values at regular intervals, it is convenient for practical application to express Eq. (1) in summation form. Thus, when the input function is expressed in the form of discrete pulses of duration T or mean values over successive short intervals T, the input-output relationship is given by the convolution summation

$$y_i = \sum_{j=1}^{m} x_{i-j+1} h_j \qquad (2)$$

where

x_i is the discrete value of the rainfall at the i-th time period
y_i is the discrete value of the runoff at the i-th time period
m is the memory length of the system
h_j is the ordinate of the pulse response function for $j = 1...m$.

This model was introduced in its discrete form by Nash and Folley [14] and extensively tested on the daily rainfall runoff data of many catchment, [8]. A SLM, being a convenient starting point for rainfall runoff modelling can serve as a quick check on the extent of linearity existing in the rainfall-runoff relationship of a catchment and can also be used as a routing component of a model in conceptual rainfall runoff models, for non-linearity between rainfall and runoff is assumed to be removed by the water balance component of the model.

SMAR Model

The SMAR Model is an abbreviation for soil moisture accounting and routing model [6]. This model has been previously known as the layers model [18]. In the SMAR model the water balance component, in which the rainfall and evaporation interact to produce the generated runoff, behaves as a stack of horizontal layers, each of which contains a certain amount of water at the field capacity. The general structure of the SMAR Model is shown in Fig. 2. In this model, evaporation from the first layer takes place at a potential rate on the exhaustion of the first layer it occurs from the second layer at the potential rate multiplied by a parameter C, whose value is less than unity. Evaporation from the third layer, on the exhaustion of the second layer, occurs at the remaining potential multiplied by C^2 and so on. Thus a constant potential evaporation applied to the basin reduces the soil moisture storage in an exponential manner.

The total storage capacity is represented by a parameter Z which would be optimized. Evaporation ceases when the total storage in the layer is exhausted. The potential evaporation over the catchment is estimated by multiplying the estimated pan evaporation by a parameter T, where T is a parameter to be optimized. When the rainfall exceeds the potential evaporation a fraction H' of the excess contributes to the generated runoff and of the remainder any thing exceeding a threshold value or the maximum infiltration capacity Y also contributes to the generated runoff. H' is taken as a function of the available soil moisture content in the top five layers, and is defined as

$$H' = (S/S_c)H \qquad (3)$$

where

S is the average available soil moisture over the catchment (i.e., actual moisture content in the first five layers)

S_c is the average soil moisture capacity of the first five layers over the catchment taken as 125 mm of water.

H is a parameter to be optimized.

The remaining rainfall stores in each layer to the field capacity from the first layers downwards until the rainfall is exhausted, or all the layers are at the field capacity. Any remaining surplus then contributes to the generated runoff. From the above, one can see that the runoff in the SMAR model is generated by three different components. The components being the direct run off $r_1 = Hx$, the runoff in excess of infiltration, $r_2=(1-H)x-Y$, and the moisture in excess of soil capacity, r_3. The total volume of generated runoff is then given by the sum of these three components. The water balance part of the SMAR model, thus, consists of five parameters that should be determined by model calibration.

By introducing an extra parameter to account for the substantial groundwater component in wet and seasonal catchments, the original SMAR model was revised by Liang [9]. In the revised SMAR model (Fig. 2), the generated runoff component, r_3, i.e., runoff in excess of soil moisture storage, is divided into two parts by a parameter G, where G is the groundwater runoff coefficient, making one part of the flow groundwater and the other part of the flow an inter-flow. The inter flow part is added to the surface runoff. The two parts, i.e., the groundwater part and the added surface water are then routed through different storage systems.

Routing Components of the SMAR Model

The lumped generated surface runoff and groundwater flow produced by revised SMAR model at the end of each time interval are diffused to river basin flow by flow routing models. The most commonly used procedure in hydrology to provide the attenuation and diffusive effects of the catchment is by routing through linear time-invariant storage systems, Eq. (1).

The volume of surface runoff, r_1 and r_2 and part of the groundwater, $(1-G)r_3$ generated by the revised SMAR model is routed through a parametric linear system having the gamma distribution as its unit impulse response.

Instead of assuming an arbitrary non-parametric functional form for a unit hydrograph, Gamma function model was proposed by Nash [12]. The impulse response function of this system is given by

$$h(t) = \frac{1}{K\,\Gamma(n)} \left(\frac{t}{K}\right)^{n-1} \exp\left(-\frac{t}{K}\right) \qquad (4)$$

where,

n is the number of equal linear reservoir in the cascade

K is a real positive value corresponding to the system storage coefficient

$\Gamma(n)$ is the gamma function of n and is given by the following improper integral.

$$\Gamma(n) = \int_0^\infty e^{-x}\, x^{n-1}\, dx \qquad (5)$$

Thus the system corresponds exactly to a series of n equal linear reservoirs each of its storage S equal to the product of K and y, where y is the output from the storage. That is,

$$S = Ky \qquad (6)$$

The unit step response function of the gamma function model, or S-curve, is given by

$$S(t) = \int_0^t h(\tau)d\tau = \frac{1}{K\,\Gamma(n)} \int_0^t e^{-\frac{\tau}{K}} (\frac{\tau}{K} \qquad (7)$$

When the input is expressed as a series of pulses (blocks of uniform intensity over short duration T) and the output is expressed as ordinates at the intervals T, the corresponding unit pulse response of the gamma function model is given by

$$h(T,t) = \frac{1}{T}[S(t)-S(t-T)] = \frac{1}{T}\int_{t-T}^{t} h(\tau)d \qquad (8)$$

where T is the duration of the pulse.

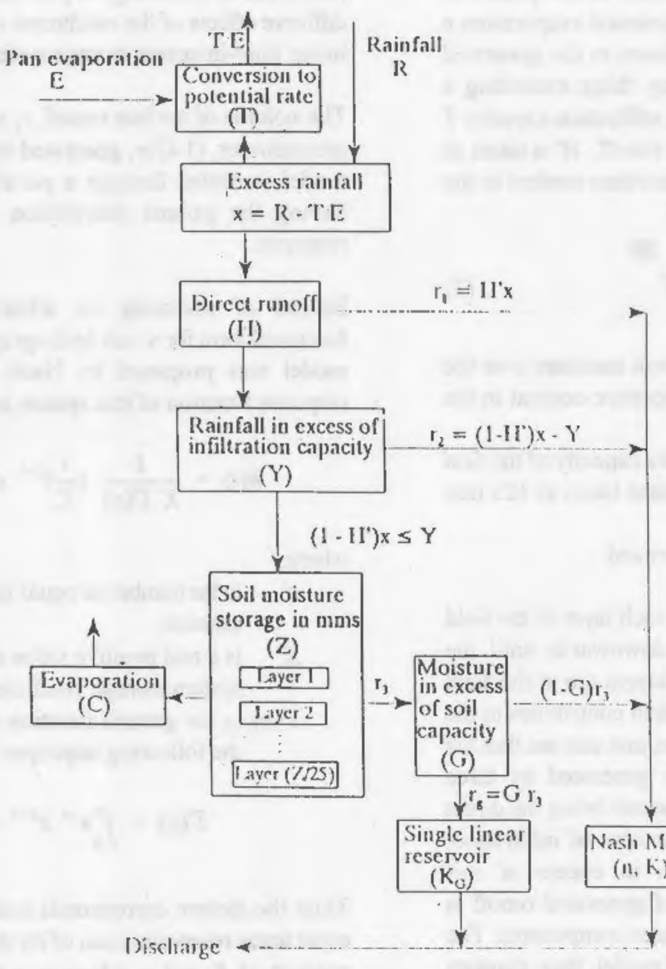


Figure 2 Schematic diagram of the revised SMAR model

When both the input and the output data are expressed in blocks of duration T, i.e., averaged over T, the corresponding pulse response is also expressed in blocks and is obtained by the following integral.

$$h_j = \frac{1}{T}\int_{(j-1)T}^{jT} h(T,t)dt \qquad (9)$$

This integration can be obtained numerically when required, and the relationship between the input and the output in this case is given by the convolution summation as given in Eq. (2).

The portion of the generated volume of groundwater Gr_3 is routed through a single linear reservoir which is a special case of routing through the gamma function model corresponding to n=1. Therefore, with an introduction of additional storage coefficient of the single linear reservoir, KG, the routing of this groundwater component can be explicitly determined from continuity and reservoir equations.

APPLICATION AND RESULTS OF THE MODELS

The Simple Linear Model (SLM) and Soil Moisture Accounting and Routing Model (SMAR) have been applied to Kelantan Catchment. The total length of the data is split into two periods, calibration period for estimating the appropriate model parameters and the verification period for testing the model. The lengths of the calibration and verification periods for the catchment are from 1989 to 1992 and from 1993 to 1994, respectively.

The two indices used for model efficiency are the Nash and Sutcliffe [15] model efficiency criterion (R_2) and the index of volumetric fit (IVF).

The most commonly used objective function in hydrology for model parameters estimation is the sum of squares of the errors. This criterion has been proposed by Nash and Sutcliffe [15]. The sum of squares of differences, F between the observed and the estimated discharges is given by

$$F = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad (10)$$

Where n is the total number of flow data in the period considered, calibration or verification periods, y_i is the observed flow, $\hat{y}_i$ is the simulated flow, and F is the index of disagreement which reflects the extent to which a model is successful in reproducing the observed discharge.

Instead of the sum of squares of errors, the residual variance in calibration or in verification, which is usually referred to as the mean square error (MSE), is usually used. The mean square error, MSE in calibration period is defined as

$$(MSE)_c = \frac{1}{n_c} \sum_{i=1}^{n_c} (y_i - \hat{y}_i)^2 \qquad (11)$$

Where n_c is the total number of flow data in the calibration period. The mean square error $(MSE)_v$ in the verification period can also be determined when n_c is replaced by n_v, where v is the total number of discharge data in the verification period.

Nash and Sutcliffe [15] have provided the R^2 efficiency criterion. The efficiency criterion is established by normalising the MSE to obtain a dimensionless quantity. Defining the initial variance, F_o as

$$F_o = \frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y}_c)^2 \qquad (12)$$

where F_o is the mean square error of flow estimates obtained by no-model, and the no model forecast for all time is given by

$$\bar{y}_c = \frac{1}{n_c} \sum_{i=1}^{n_c} y_i \qquad (13)$$

Then the criterion of model efficiency can be expressed as

$$R^2 = 1 - \frac{MSE}{F_o}. \qquad (14)$$

Where MSE can be (MSE)c in calibration period and $(MSE)_v$ in verification period to obtain the values of the model efficiency, R^2 for the calibration and verification periods, respectively

In most rainfall runoff models, since the interest is to find good estimates of output, it is also of interest to find whether the volume of the estimated flows of a model agree with the observed flow volumes in a test period or not. The method used to compare these volumes is the Index of Volumetric Fit, (IVF), which is defined as the ratio between the sum of estimated flows and the sum of observed flows. That is

$$IVF = \frac{\sum_{i=1}^{n} \hat{y}_i}{\sum_{i=1}^{n} y_i} \qquad (15)$$

Where n is the nomber of data point in that period.

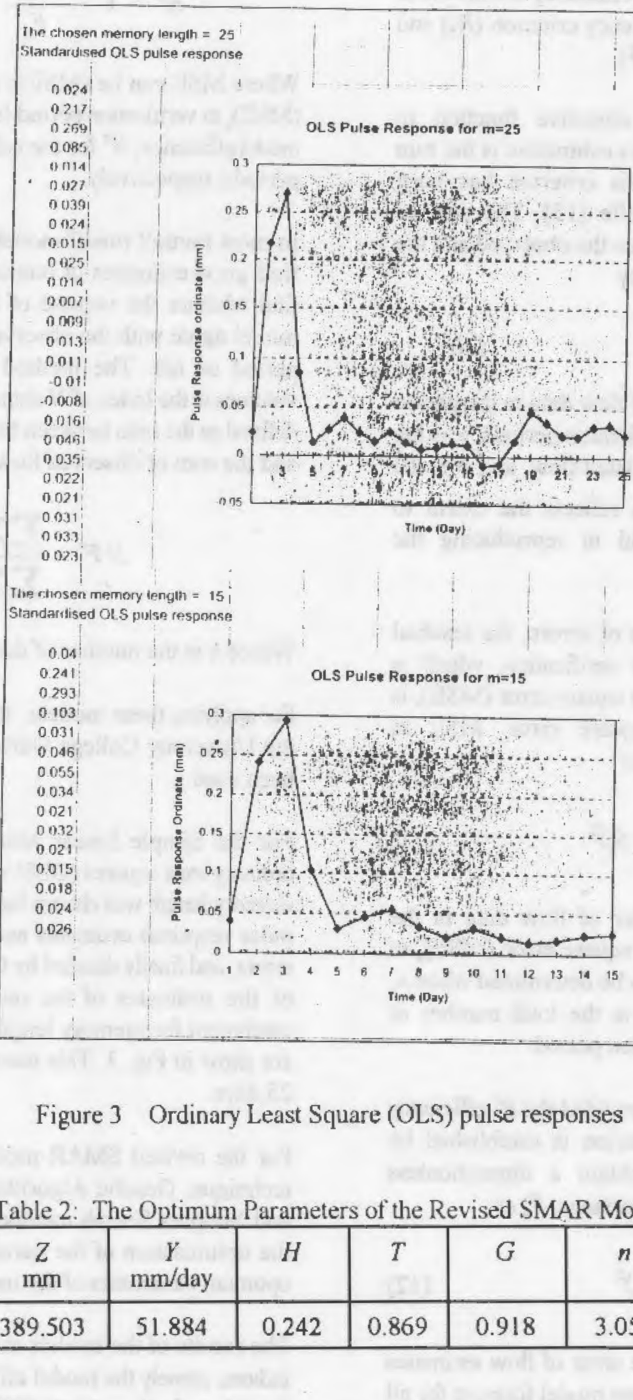
For applying these models, the WINDOW versions of the University College Galway, UCG, software have been used.

For the Simple Linear Model (SLM), estimated by ordinary least squares (OLS) without any constraint, the memory length was chosen based on examination of the pulse response ordinates and corresponding standard errors, and finally decided by their efficiencies. The plot of the ordinates of the unit pulse response of the catchment for memory lengths of 25 days and 15 days are show in Fig. 3. This memory length is found to be 25 days

For the revised SMAR model, the sequential search technique, Genetic Algorithm [22], Rosenbrock [19] and Simplex Search methods [17], has been used for the optimisation of the parameters of the model. The optimum parameters of the model are given in Table 2.

The results of the models in terms of model efficiency indices, namely the model efficiency criterion (R^2) and the index of volumetric fit (IVF) for both the calibration and the verification periods are summarised and presented in Table 3.

Moreover, the plots of rainfall, and observed and estimated discharges obtained by the two models are presented as a graphical output of the models, See Fig. 4 to Fig. 15.



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The chosen memory length =  25
Standardised OLS pulse response

0.024
0.217
0.269
0.085
0.014
0.027
0.039
0.024
0.015
0.025
0.014
0.007
0.009
0.013
0.011
-0.01
-0.008
0.016
0.046
0.035
0.022
0.021
0.031
0.033
0.023
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```
The chosen memory length =  15
Standardised OLS pulse response

0.04
0.241
0.293
0.103
0.031
0.046
0.055
0.034
0.021
0.032
0.021
0.015
0.018
0.024
0.026
```

Figure 3 Ordinary Least Square (OLS) pulse responses

Table 2: The Optimum Parameters of the Revised SMAR Model

Model	*C*	*Z* mm	*Y* mm/day	*H*	*T*	*G*	*n*	*Nk*	*KG*
SMAR2	0.43	389.503	51.884	0.242	0.869	0.918	3.053	1.891	73.974

Table 3: Model Efficiencies R^2 and IVF of the SLM and SMAR2 Models

Catchment	Model	Calibration Period		Verification Period	
		R^2 (%)	IVF	R^2 (%)	IVF
Kelantan	SLM	70.02	1.03	61.08	0.85
	SMAR2	84.14	1.00	83.79	1.02

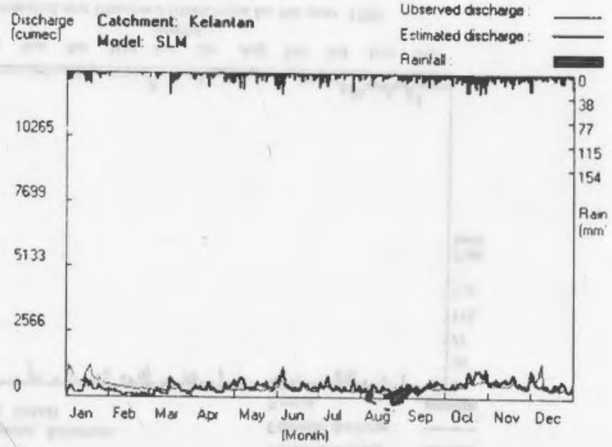


Figure 4 Rainfall and estimated and observed discharges for the year 1989

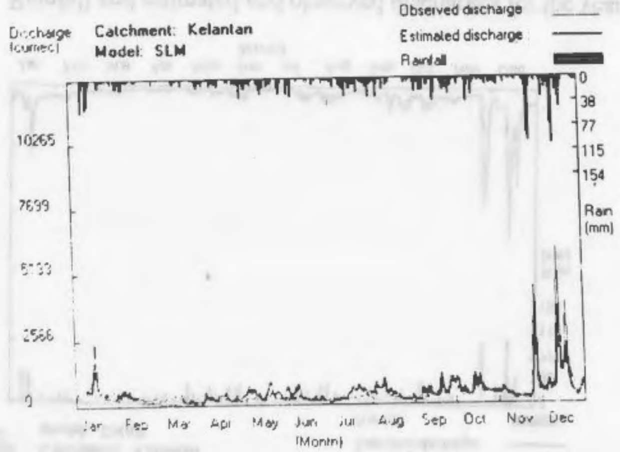


Figure 5 Rainfall and estimated and observed discharges for the year 1990

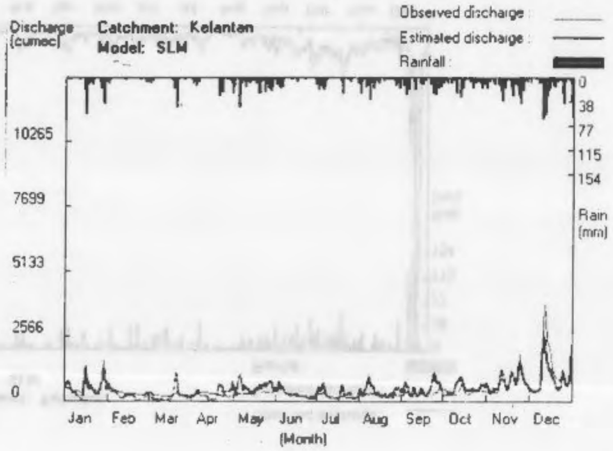


Figure 6 Rainfall and estimated and observed discharges for the year 1991

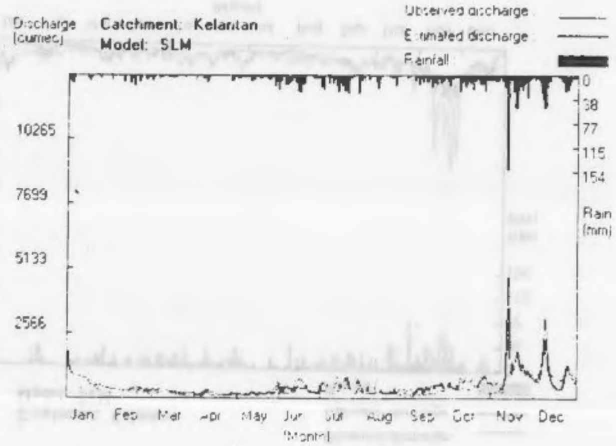


Figure 7 Rainfall and estimated and observed discharges for the year 1992

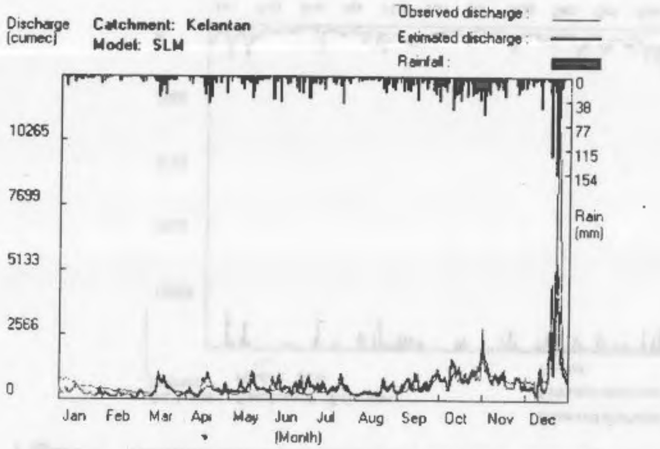


Figure 8 Rainfall and estimated and observed discharges for the year 1993

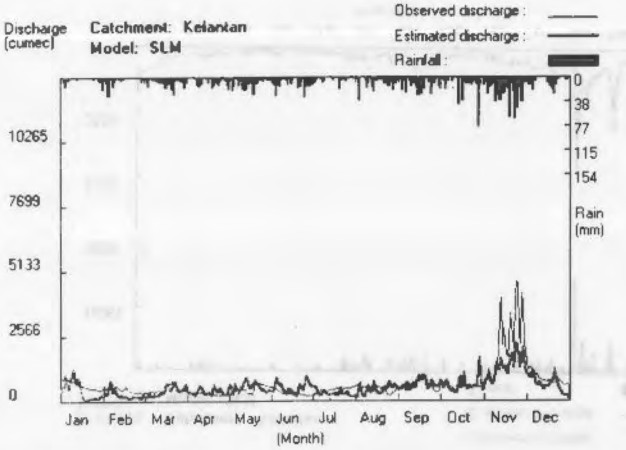
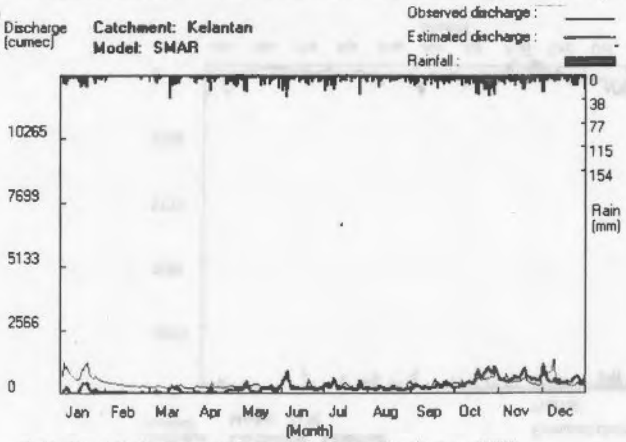


Figure 9 Rainfall and estimated and observed discharges for the year 1994



Rainfall and Estimated and Observed Discharges for the year 1989

Figure 10 Rainfall and estimated and observed discharges for the year 1989

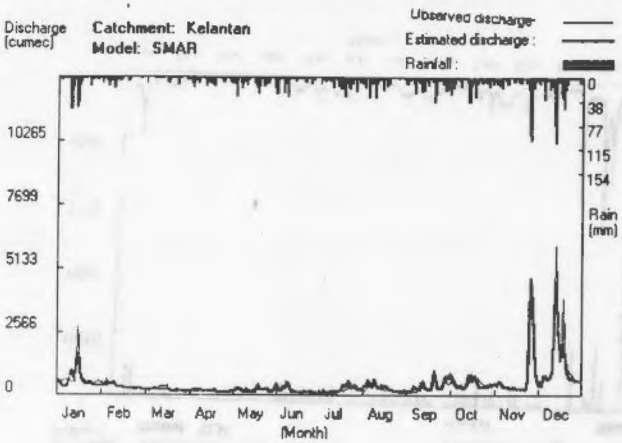


Figure 11 Rainfall and estimated and observed discharges for the year 1990

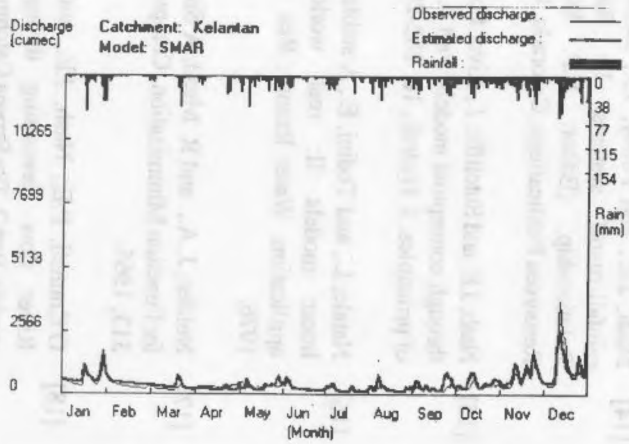


Figure 12 Rainfall and estimated and observed discharges for the year 1991

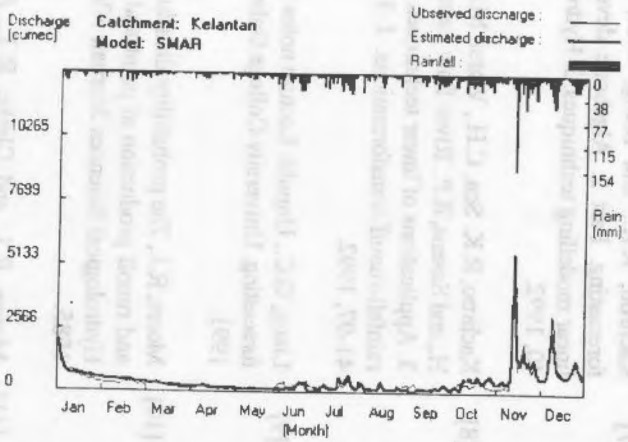


Figure 13 Rainfall and estimated and observed discharges for the year 1992

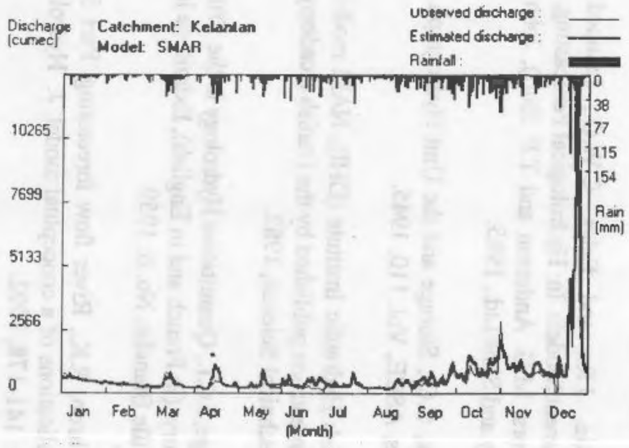


Figure 14 Rainfall and estimated and observed discharges for the year 1993

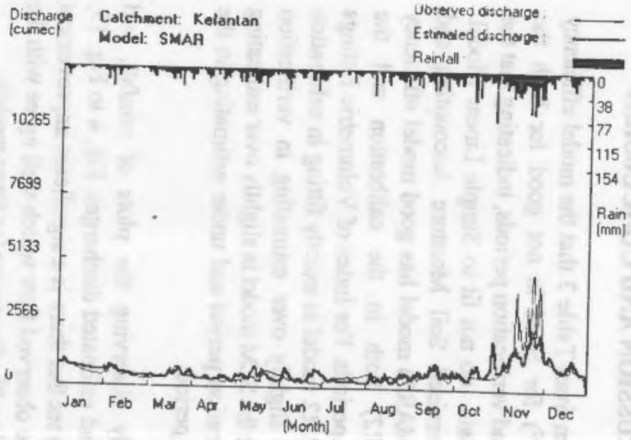


Figure 15 Rainfall and estimated and observed discharges for the year 1994

DISCUSSION AND CONCLUSION

It can be seen from Table 3 that the model efficiency criterion (R^2) for SLM is not good for both the calibration and verification periods, indicating that the catchment data do not fit to Simple Linear Model. While the revised Soil Moisture Accounting and Routing (SMAR2) model has good model efficiency criterion ($R2$) both in the calibration and the verification periods. For Index of Volumetric Fittings (IVF), SMAR2 model is exactly fitting in calibration period and slightly over estimating in verification period, while the SLM model is slightly over estimating in the calibration period and under estimating in the verification period.

By carefully observing the plots of rainfall, and observed and estimated discharges, Fig. 4 to Fig. 15, one can also see that there is a significant improvement in fitting the observed flow which well agree with the corresponding R^2 efficiencies for these models.

On the bases of the R^2 efficiencies, it can be concluded that SMAR2 model performs well in both the calibration and verification periods, and may be used for forecasting flow from the Kelantan Catchment.

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