 Hydrological modeling using Effective Rainfall routed by the Muskingum method (ERM)
M. Baymani-Nezhad and D. Han

ABSTRACT
This paper introduces a new rainfall runoff model called ERM (Effective Rainfall routed by Muskingum method), which has been developed based on the popular IHACRES model. The IHACRES model consists of two main components to transfer rainfall to effective rainfall and then to streamflow. The second component of the IHACRES model is a linear unit hydrograph which has been replaced by the classic and well-known Muskingum method in the ERM model. With the effective rainfall by the first component of the IHACRES model, the Muskingum method is used to estimate the quick flow and slow flow separately. Two different sets of input data (temperature or evapotranspiration, rainfall and observed streamflow) and genetic algorithm (GA) as an optimization scheme have been selected to compare the performance of IHACRES and ERM models in calibration and validation. By testing the models in three different catchments, it is found that the ERM model has better performance over the IHACRES model across all three catchments in both calibration and validation. Further studies are needed to apply the ERM on a wide range of catchments to find its strengths and weaknesses.

Key words | ERM, hydrological modeling, IHACRES, lumped rainfall runoff model, Muskingum routing method

INTRODUCTION
Rainfall-runoff models are used widely by hydrologists around the world and are considered as the main part of flood forecasting systems. Accurate flood forecasting is important in urban studies and still remains one of the unsolved problems in operational hydrology (Garrote & Bras 1995). Depending on the model type, streamflow is simulated using different series of data, such as rainfall, temperature, evaporation, soil type data, etc. Generally, they are divided into three main categories, as follows. (1) Lumped model: the catchment and hydrometeorological variables are treated as a whole without the consideration on their spatial variations (e.g. average rainfall is used instead of spatially varied rainfall, etc.). The main advantages of lumped models are simplicity which provides a good opportunity for users to carry out relatively quick and easy hydrological simulations. Therefore, lumped models are considered as practical models to implement in real-time flood forecasting systems for which the time factor is important. A major limitation about lumped models is related to their inability to consider the internal variations of hydrological process (Singh & Fiorentino 1996). Hence, the catchment size becomes an important factor and selecting small or mid-size catchment may lead to more feasible simulations by lumped models. During the last decades different types of lumped hydrological models have been developed by different researchers and a number of important models include SRM (Snowmelt Runoff Model) by Martinec (1973), Xianjiang model by Zhao et al. (1980), IHACRES by Jakeman et al. (1990), Stanford Watershed model (Crawford & Linsley 1966), the Sacramento model (Burnash et al. 1973), the Tank model (Sugawara et al. 1976) and HEC-1 (Hydrological Engineering Center 1981). (2) Fully-distributed model: the first concepts of distributed model were introduced by Freeze & Harlan (1969). In this type of modeling, the catchment is divided into small grids with individual hydrometeorological inputs. Therefore, selecting smaller...
grids may lead to a high resolution simulation of the catchment. Distributed models are quite complex and need a wide range of input data and are commonly used to simulate streamflow in large catchments where diversity of catchment characteristics, such as land cover, soil type and rainfall, is high. A series of popular distributed models has been developed in the past decades such as THALES (Grayson et al. 1992a, b), MIKE-SHE (Refsgaard & Storm 1995), IHDM (Beven et al. 1987) and TOPMODEL (Beven et al. 1995). Distributed models consider more details of hydrological process in comparison with other types of models (Refsgaard 1996).

(3) Semi-distributed model: a model between the lumped and fully-distributed models which divides the catchment into a number of small areas as sub-catchments (Wang et al. 2006) with each one simulated by using a lumped approach. Based on catchment characteristics, the number of sub-catchments is varied and is selected by considering catchment area, soil types and vegetation distribution. Among these three types of models, the lumped model has the simplest structure and is easy to use by operators. In this study, it has been attempted to prepare an accurate and simple rainfall runoff model to be used in a real-time flood forecasting model. In particular, the IHACRES, a popular rainfall-runoff model, in the current study is modified to increase its ability and flexibility in terms of streamflow simulation. The IHACRES model is a lumped parameter, hybrid conceptual-metric model and was investigated by Jakeman et al. (1998) and Jakeman & Hornberger (1993). The first PC version of the IHACRES model was developed by Littlewood et al. (1997) and then the model was revised by Croke et al. (2005) to increase its efficiency and better user interfaces for practical application. The new version of the IHACRES model contains a new loss module introduced by Ye et al. (1997) for converting total rainfall to effective rainfall. Moreover, the new version of the model employs a grid search scheme to calibrate the model parameters. The grid search calibrates the model parameters using an upper bound, a lower bound and a step value assigned to each parameter. The IHACRES model has been widely used in the hydrological community for over 20 years (Oudin et al. 2005; Post & Jakeman 1999; Kokkonen et al. 2001; Schreider et al. 2002; Dye & Croke 2003; Croke & Jakeman 2004; Croke et al. 2005; McIntyre & Al-Qurashi 2009; Pollard & Han 2012). However, despite its usefulness and popularity, there is still room to improve the model. One major shortcoming with the IHACRES model is its inflexibility of the routing module to cope with different catchment response times. In addition, the grid search method used in the model software may trap model parameters into the local optima which will be lead to reduced model performance.

An attempt is made in this study to develop a new model based on the IHACRES model with a more flexible routing module. The new model is termed ERM (hydrological modeling using Effective Rainfall routed by Muskingum method). To compare the performance of the new model with the original IHACRES model, both models are calibrated by the genetic algorithm (GA) to estimate a series of global model parameters. In the following sections, the IHACRES and ERM models are introduced and the performance of the ERM is evaluated versus the IHACRES model in three different catchments used as case studies.

MODELS

This section describes the structure of IHACRES and ERM and the relevant equations. Schematic flowcharts of the models are drawn to show the sequence of converting total rainfall to the streamflow.

IHACRES

The generic structure of the IHACRES model (Figure 1) consists of two main modules: (1) a non-linear loss module which converts total rainfall to effective rainfall using temperature or evapotranspiration data; and (2) a second module which transfers the effective rainfall to the streamflow by a linear transfer function (to represent unit-hydrograph).

For the non-linear module to convert rainfall to effective rainfall, rainfall and temperature data are required. The effective rainfall $u$ is calculated by the following equation:

$$u_{k} = [c \phi_{k} - l]^{p} r_{k}$$

where $k$ is time, $r_{k}$ is total rainfall mm, $c, l$ and $p$ are parameters (mass balance, soil moisture index threshold and power on soil moisture, respectively), $\phi_{k}$ is soil moisture
The effective rainfall, \( u_k \), as assessed through Equations (1)–(3), is then converted in streamflow by a linear unit hydrograph. Based on the model structure, the effective rainfall can be routed by a single routing component or two components normally connected in parallel. The best routing scheme is selected according to the catchment condition. In most of the studies carried out about the catchment modeling have recommended applying the IHACRES model with two routing components connected in parallel, except for semi-arid areas which can be simulated by one routing component properly (Ye et al. 1997). The slow and quick routing components are described by the following equations:

\[
\begin{align*}
Q_k &= Q_k^{(\text{quick})} + Q_k^{(\text{slow})} \\
Q_k^{(\text{quick})} &= -\alpha_q Q_k^{(\text{quick})}_{k-1} + \beta_q u_k \\
Q_k^{(\text{slow})} &= -\alpha_s Q_k^{(\text{slow})}_{k-1} + \beta_s u_k
\end{align*}
\]

where \( Q_k^{(\text{quick})} \) and \( Q_k^{(\text{slow})} \) are quick and slow flows, respectively, \( \alpha_q \) and \( \beta_q \) are recession rate and peak response for quick flow and \( \alpha_s \) and \( \beta_s \) are for slow flow, respectively. The relation between the routed slow and quick flow volumes can be defined by a portion of total flow for the two components (Equation (7)).

\[
V_q = 1 - V_s = \frac{\beta_q}{1 + \alpha_q} = 1 - \frac{\beta_s}{1 + \alpha_s}
\]

where \( V_q \) is the portion of the quick flow to the total flow and \( V_s \) in the portion of slow flow. Also, Dynamic Response Characteristics (DRCs) for the quick and slow flows are calculated by the following equations:

\[
\begin{align*}
\tau_q &= -\Delta/\ln (-\alpha_q) \\
\tau_s &= -\Delta/\ln (-\alpha_s)
\end{align*}
\]

where \( \Delta \) is the time step, \( \tau_q \) and \( \tau_s \) are the recession time constants for quick and slow flows, respectively.

\section{ERM}

Similarly to the IHACRES model, the ERM model consists of one non-linear module for effective rainfall assessment and one module for streamflow estimation. The first module of the ERM model has the same mechanism as the IHACRES, but the discrepancy is observed in the second module to route effective rainfall to streamflow. A schematic structure of the ERM model is demonstrated in Figure 2.

The Muskingum method has been applied in hydrology studies widely as a river routing module so that users are...
familiar with its equations and the parameter meanings (Gill 1978; Perumal 1994; Kshirsagar et al. 1995; Mohan 1997; Birkhead & James 1998; Kim et al. 2001; Samani & Jebelifard 2003; Das 2007; Chu & Chang 2009). Also, the capability of Muskingum parameters in responding to the hydrological changes (i.e. its \( K \) parameter for the travel time) provides a good opportunity for the model to be used in real-time model updating, which has been important in terms of real-time flood forecasting. Hence, implementation of the Muskingum method instead of the linear-unit hydrograph may lead to increased model performance and accuracy. It should be noted that the Muskingum method is used in this study to transfer the effective rainfall to streamflow at the river outlet. This is different to the original Muskingum method which is used to route an upstream hydrograph to downstream hydrograph in a river channel without lateral inflow. The basic Muskingum equation is expressed as Equation (10):

\[
S = K[I + (1 - X)O]
\]  

where \( S \) is storage volume, \( I \) is the inflow, \( O \) is outflow, \( K \) and \( X \) are storage constant and weighting factor, respectively. The Muskingum model for flow simulation can be expressed by Equation (11):

\[
Q_{j+1} = C_1 u_{j+1} + C_2 u_j + C_3 Q_j
\]

where

\[
C_1 = \frac{\Delta t - 2KX}{2K(1 - X) + \Delta t}, \quad C_2 = \frac{\Delta t + 2KX}{2K(1 - X) + \Delta t},
\]

\[
C_3 = \frac{2K(1 - X) - \Delta t}{2K(1 - X) + \Delta t}
\]

\( Q_j \) is the streamflow at the basin outlet, \( u_j \) is effective rainfall, \( \Delta t \) is time interval, \( C_1, C_2, C_3 \) are the Muskingum coefficients. Equation (11) is used in the ERM model to convert the effective rainfall to the streamflow. The sequence of ERM model can be summarized in the flowchart shown in Figure 3 which is used in the modeling process. Similar to the IHACRES model, the routing part of the ERM model can be implemented in two components connected in parallel to route quick and slow flows. The Muskingum parameters are calibrated for slow flow (\( K_s \) and \( X_s \)) and quick flow (\( K_q \) and \( X_q \)) separately and two streamflows are generated (quick streamflow and slow streamflow). Then the total streamflow is calculated by Equation (4).

### CALIBRATION METHODS

The ERM and IHACRES models are implemented in MATLAB because it is a comprehensive programming language with an efficient optimization toolbox for model calibration. To start the model simulation, three sets of calibration data: rainfall, temperature (or evapotranspiration) and observed streamflow are loaded in the program to calibrate the model parameters. The GA is used to calibrate both the ERM and IHACRES models so that a fair comparison will be made between two models in terms of model calibration and validation. In the following sections, the calibration schemes are described briefly.

#### Grid search optimization scheme

The latest version of the IHACRES model consists of a calibration scheme which generates a grid network by
using parameter ranges specified to each parameter. Also, to generate the points of network a step value must be assigned to each parameter to divide the parameter range to small values. Obviously, it is clear that selecting the small step values will lead to more parameters checks. The main concern is to select proper parameter range and step values which is a tricky job, especially when there is no full recognition about the catchment characteristics. On the other hand, during the calibration process by the grid search scheme, it has been observed that the calibration process is very time consuming and the running time could be up to several hours to achieve a relatively feasible combination of parameters. Also, the possibility of missing the best parameters which may be out of the step value is high. To overcome this issue, after implementation of the IHACRES model by the MATLAB, the model is calibrated by the GA scheme. The GA provides a good means to evaluate more parameter combinations and avoid local optima. During the IHACRES calibration, seven parameters are involved in the calibration process ($\tau_w$, $f$, $t_r$, $l$, $c$, $p$, $\tau_s$, $V_s$) directly and the rest of the parameters ($\alpha_s$, $\beta_s$, $\alpha_q$, $\beta_q$, $V_q$) are estimated using Equations (7)–(9). The IHACRES parameters and their calibration ranges are listed in Table 1.

GA optimization scheme

As mentioned before, the IHACRES model uses a grid search method to estimate the model parameters and the process is time consuming and less accurate, because finding the best ranges for calibrating the model parameters is tricky. GA is a global optimization scheme based on the Darwin evolution theory which has been inspired by natural evolution such as inheritance, mutation, selection and crossover. The concept of GA was presented for the first time by Holland (1975) and its algorithm was developed by DeJong (1975) for use in optimization problems. The GA optimizer has included a number of concepts such as cross over,
mutation and fitness function that construct the optimization process and during this process, optimizer applies the mutation and crossover functions to produce new individuals at every generation.

GA is a population based method and the number of population (individual) is a random generation of a series of possible answers based on a fitness function. The method explores among the population to derive the best offspring (answer) using probabilistic transition rules (Wang 1997). Since this process always operates on the whole population, the GA may be considered as a global optimizer (Franchini & Galeati 1997). During the last decades, GA has been considered widely in different studies to estimate the key parameters of hydrological models (Wang 1991; Franchini & Galeati 1997; Nadiritu & Daniell 2002; Cheng et al. 2002; Khu & Madsen 2005). In most of the studies it has been confirmed that GA is capable of being used as an efficient method to estimate a series of global model parameters with a reliable streamflow simulation and reduced model parameter uncertainties. Also, by the implementation of the GA model, the chances of trapping into the local answers are reduced. Basically, during the rainfall-runoff modeling, it has been attempted to reduce the difference between the observed and simulated streamflow and the comparison between two streamflow hydrographs is evaluated by a coefficient of performance. The coefficient shows the similarity of model runoff and measured runoff and depending on the coefficient range, it should be increased to achieve an acceptable level. To start the parameter optimization, GA needs an upper range and lower range for each parameter. Unlike the calibration scheme implemented in the Java version of the IHACRES, the GA algorithm does not require the parameter steps. Therefore, it will lead to more accurate estimation of the parameters which are sensitive in some cases and should be calibrated properly.

Two main factors affect the GA optimization running time: defining the size of population (parameter combination), and the number of generations during an optimization process. These factors should be selected to achieve a feasible answer based on the objective function and, also, possibly reducing the running time.

The model proposed in the current study (ERM) applies the GA optimizer to derive the model parameters based on an objective function. By putting the model performance as an objective function, GA tries to find the best combination of parameters that can satisfy the simulation criteria and also increase the model performance. Basically, the optimization algorithm is started by defining the number of involved parameters and their upper and lower range for each parameter. Other optimization elements, such as crossover and mutation values, could be configured with the program defaults.

In addition to the parameters in the non-linear module, the Muskingum routing parameters for slow and quick flows are estimated by the GA optimization. In 1997, Mohan proved that GA is an efficient optimizer on estimating the Muskingum parameters and avoids the subjectivity and computation time associated with the traditional estimation methods. The ERM parameters with their ranges used in the calibration process are listed in Table 2.

### MODEL PERFORMANCE EVALUATION

To assess model performance, there are several potential coefficients available, such as coefficient of determination ($R^2$), Root Mean Square Error (RMSE), Index of agreement (d), Mean Absolute Error (MAE), etc. Basically, the main reasons for hydrological model evaluation can be categorized into three groups: (1) to provide a quantitative estimate of model’s ability to reproduce catchment behavior; (2) to provide a means for evaluating improvements to the modeling approach through adjustment of model parameter values; and (3) to compare the current modeling results with the historic

### Table 2

<table>
<thead>
<tr>
<th>ERM parameter</th>
<th>Calibration range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>0–1</td>
</tr>
<tr>
<td>$\tau_w$</td>
<td>0–500</td>
</tr>
<tr>
<td>$f$</td>
<td>0–20</td>
</tr>
<tr>
<td>$t_r$</td>
<td>0–30</td>
</tr>
<tr>
<td>$l$</td>
<td>0–400</td>
</tr>
<tr>
<td>$p$</td>
<td>0–2</td>
</tr>
<tr>
<td>$K_s$</td>
<td>0–30</td>
</tr>
<tr>
<td>$X_s$</td>
<td>0–0.5</td>
</tr>
<tr>
<td>$K_q$</td>
<td>0–30</td>
</tr>
<tr>
<td>$X_q$</td>
<td>0–0.5</td>
</tr>
</tbody>
</table>
modeling results (Krause et al. 2005). In this study, the ERM and IHACRES models apply RMSE and \( R^2 \) coefficients to compare different sets of parameter combinations, as shown in Equations (12) and (13). In terms of model calibration, the GA algorithm uses the \( R^2 \) value as an objective function to derive the best parameter combination.

The \( R^2 \) and RMSE are the most popular indices in hydrological modeling and represent numerical comparisons between simulated and observed streamflows, as in the following equations:

\[
R^2 = 1 - \frac{\sum_{i=1}^{N} (Q_o - Q_m)^2}{\sum_{i=1}^{N} (Q_o - \bar{Q}_o)^2}
\]  
(12)

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Q_o - Q_m)^2}
\]  
(13)

where \( Q_o \) and \( Q_m \) are the observed streamflow and modeled streamflow respectively, \( \bar{Q}_o \) is the average of the observed streamflow and \( N \) is number of data records.

**STUDY AREA AND DATA SETS**

The main objective of the current study is to explore the structure of the ERM model and to evaluate its performance versus the IHACRES model to confirm which model has a better performance in terms of model calibration and validation. Both models are used to simulate the streamflow of three catchments characterized by different aspects in: (1) catchment size; (2) catchment location; and (3) time interval of data records (rainfall, temperature and streamflow). The following paragraphs show a brief description of climate conditions and characteristics for the catchments selected for case studies.

**Brue catchment**

The Brue catchment (Figure 4) is located in Somerset, southwest England, with an area of 132 km\(^2\). It is a predominantly rural catchment of modest relief with spring-fed headwater rising in the Mendip Hills and Salisbury Plain. The data used in this study are obtained from the HYREX project (Hydrological Radar Experiment) which is a NERC (Natural Environment Research Council) special topic and the data have been recorded from 1993 to 2000. Two sets of data are selected to evaluate the Brue catchment in terms of calibration and validation. Rainfall, potential evaporation and streamflow are available as hourly records for this catchment. The rainfall and potential evaporation data are in millimeter (mm) and streamflow data in cumecs (m\(^3\)/s). Hence, 3,438 data records are selected for model calibration from 1:00, 19 September 1993 to 05:00, 9 February 1994. Also, 2,656 data records...
between 09:00, 12 September 1999 and 00:00, 1 January 2000 are arranged for the model validation period. The calibration and validation periods have been selected to cover vegetation growing and non-growing seasons to check the model performance under different weather conditions.

**Canning catchment**

The Canning river is a tributary of the Swan River (Figure 5) and is located in the southeast of Perth, Western Australia. A sub-catchment within the Canning catchment has been selected for the study. The sub-catchment is approximately 517 km², with a Mediterranean climate, 890 mm mean annual rainfall and 80% of the rainfall occurring between May and October. Three types of data (rainfall, potential evaporation and streamflow) have been recorded daily at the Scenic Drive station which is at the outlet of the sub-catchment from 1 January 1977 to 31 December 1987 (the data are available within the IHACRES software package). The daily rainfall and evaporation data are in

![Figure 5](image1.png) | The study area of the Canning catchment, southeast of Perth, Western Australia.

![Figure 6](image2.png) | The study area of the Namoi catchment, northeast of New South Wales, Australia.
millimeters (mm) and the streamflow data in millimeters per day (this unit is from the original data). The unit of mm/day for streamflow can be easily converted to the commonly used m³/s by multiplying with the catchment area and divided by the total number of seconds in a day. The calibration period is between 12:00, 22 March 1980 and 12:00, 19 March 1982, and the validation period starts from 12:00, 1 January 1977 to 12:00, 1 December 1978.

**Namoi catchment**

The Namoi (Figure 6) is an Australian catchment located in the northeast of New South Wales (NSW). The catchment area is approximately 42,000 km² and is located adjacent to the Liverpool plains. The mean annual rainfall recorded for the catchment is 633 mm varying from 1,300 mm in the east to 400 mm in the west and the highest average monthly rainfall has been recorded between December and February. Also, in terms of runoff modeling, it has been observed that the mean annual modeled runoff over the Namoi region for the past 112-year period is 24 mm and is relatively uniform through the year (CSIRO 2007). Three types of data are collected by the gauge 419,034 (Mooki river, Caroona) which covers 2,540 km² of the catchment area. The data are recorded from 24 May 1979 to 30 Jun 1998. The data set consists of rainfall in millimeters (mm) daily maximum temperature in Celsius (°C) and the streamflow in cumecs (m³/s) Two different sets of daily data are selected to use in the process of

Table 3 | Calibrated parameters of IHACRES obtained for the Brue, Canning and Namoi catchments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Brue</th>
<th>Canning</th>
<th>Namoi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>mm</td>
<td>0.0000517</td>
<td>0.0007523</td>
<td>0.005</td>
</tr>
<tr>
<td>$\tau_w$</td>
<td>hours-days</td>
<td>0.49 (h)</td>
<td>6.09 (d)</td>
<td>17.14 (d)</td>
</tr>
<tr>
<td>$f$</td>
<td>1/°C</td>
<td>0.78</td>
<td>8.05</td>
<td>0.50</td>
</tr>
<tr>
<td>$I$</td>
<td>°C</td>
<td>0.48</td>
<td>5.96</td>
<td>2.06</td>
</tr>
<tr>
<td>$l$</td>
<td>-</td>
<td>0.0051</td>
<td>20.55</td>
<td>3.30</td>
</tr>
<tr>
<td>$p$</td>
<td>-</td>
<td>0.02</td>
<td>1.98</td>
<td>2.00</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-</td>
<td>-0.94</td>
<td>-0.92</td>
<td>-0.56</td>
</tr>
<tr>
<td>$\beta$</td>
<td>-</td>
<td>0.06</td>
<td>0.08</td>
<td>0.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Brue</th>
<th>Canning</th>
<th>Namoi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>mm</td>
<td>0.0056</td>
<td>0.0001333</td>
<td>0.0051</td>
</tr>
<tr>
<td>$\tau_w$</td>
<td>hours-days</td>
<td>7.47 (h)</td>
<td>8.37 (d)</td>
<td>12.00 (d)</td>
</tr>
<tr>
<td>$f$</td>
<td>1/°C</td>
<td>7.34</td>
<td>15.00</td>
<td>0.48</td>
</tr>
<tr>
<td>$I$</td>
<td>°C</td>
<td>8.74</td>
<td>5.31</td>
<td>13.00</td>
</tr>
<tr>
<td>$l$</td>
<td>-</td>
<td>2.60</td>
<td>158.06</td>
<td>19.00</td>
</tr>
<tr>
<td>$p$</td>
<td>-</td>
<td>0.62</td>
<td>1.37</td>
<td>1.60</td>
</tr>
<tr>
<td>$\alpha_q$</td>
<td>-</td>
<td>-0.92</td>
<td>-0.77</td>
<td>-0.53</td>
</tr>
<tr>
<td>$\beta_q$</td>
<td>-</td>
<td>0.09</td>
<td>0.40</td>
<td>0.72</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>-</td>
<td>-0.23</td>
<td>-0.89</td>
<td>-0.56</td>
</tr>
<tr>
<td>$\beta_s$</td>
<td>-</td>
<td>0.03</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>$\tau_q$</td>
<td>hours-days</td>
<td>12.82 (h)</td>
<td>3.86 (d)</td>
<td>1.59 (d)</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>hours-days</td>
<td>0.69 (h)</td>
<td>8.85 (d)</td>
<td>1.74 (d)</td>
</tr>
<tr>
<td>$V_s$</td>
<td>-</td>
<td>0.05</td>
<td>0.98</td>
<td>0.01</td>
</tr>
<tr>
<td>$V_q$</td>
<td>-</td>
<td>0.95</td>
<td>0.02</td>
<td>0.99</td>
</tr>
</tbody>
</table>
model calibration and validation. The calibration period is between 12:00, 13 January 1983 and 12:00, 30 May 1985, and the validation period starts from 12:00, 12 October 1995 to 12:00, 3 June 1997.

RESULTS AND DISCUSSION

The objective for the model calibration is to maximize the value of $R^2$. In addition, the RMSE coefficient is calculated to compare the models. Investigation about the ERM and IHACRES models is performed under two routing conditions. First, the effective rainfall is routed by a single routing component and second; two routing components are connected in parallel to separate the quick and slow flows. The calibration and validation processes are performed for three different catchments and results are compared together. The reason for selecting three case studies is to check the capability of the modified model to accurately simulate catchments with different areas besides those characterized by different hydrological and climate conditions.

Calibration

Tables 3 and 4 show the calibrated parameters by the GA optimization scheme embedded in the IHACRES and ERM models structures. The parameters are estimated for one and two routing components. For running the GA optimization algorithm embedded in the models, a series of initial parameters such as the number of population, the number of generation, cross over coefficient and mutation should be defined as initial factors of GA. Furthermore, an upper bound and lower bound are needed for each parameter.

| Table 4 | Calibrated parameters of ERM obtained for the Brue, Canning and Namoi catchments |
|---|---|---|---|
| **One routing component** |
| Parameter | Units | Brue | Canning | Namoi |
| $c$ | mm | 0.000915 | 0.000493 | 0.002 |
| $\tau_w$ | hours-days | 300.02 (h) | 81.85 (d) | 12 (d) |
| $f$ | 1/ C | 4.28 | 0.66 | 0.23 |
| $t_\ell$ | °C | 1.8 | 4.8015 | 5.0 |
| $l$ | – | 0.01 | 245.03 | 30.01 |
| $p$ | – | 1.16 | 1.86 | 1.69 |
| $K$ | hours-days | 20.00 (h) | 8.15 (d) | 1.25 (d) |
| $X$ | – | 0.31 | 0.49 | 0.26 |
| **Two routing components** |
| Parameter | Units | Brue | Canning | Namoi |
| $c$ | mm | 0.000494 | 0.000278 | 0.0012 |
| $\tau_w$ | hours-days | 400 (h) | 32.02 (d) | 13.79 (d) |
| $f$ | 1/ C | 5.80 | 3.07 | 0.57 |
| $t_\ell$ | °C | 0.67 | 7.12 | 21.99 |
| $l$ | – | 0.12 | 245.00 | 39.00 |
| $p$ | – | 1.13 | 1.72 | 1.33 |
| $K_q$ | hours-days | 27.24 (h) | 8.40 (d) | 0.95 (d) |
| $X_q$ | – | 0.5 | 0.5 | 0.1 |
| $K_s$ | hours-days | 6.65 (h) | 8.51 (d) | 3.09 (d) |
| $X_s$ | – | 0.2 | 0.44 | 0.17 |
The higher values of the $R^2$ and the lower values of RMSE represent the better model performance. Table 5 shows the result obtained by the calibration methods. As can be observed, using the two routing component in the IHACRES model leads to more accurate streamflow simulation in terms of model calibration. In addition to the quantitative assessment between the models, a visual inspection between the hydrographs generated by the models is performed to show the difference between the simulation results by the models. By using the calibrated parameters, a series of streamflows is generated to show catchment drainage at any time interval. Figures 7 and 8 show the simulated streamflow hydrographs by using one and two routing components in the IHACRES model. It is clear that visible differences could be observed among them. For example, in the Brue catchment it can be observed that implementation of two routing components is able to better represent

<table>
<thead>
<tr>
<th></th>
<th>IHACRES</th>
<th></th>
<th></th>
<th>ERM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td></td>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RMSE</td>
<td></td>
<td>RMSE</td>
<td></td>
</tr>
<tr>
<td>Brue</td>
<td>0.68</td>
<td>2.788 (m$^3$/s)</td>
<td>0.77</td>
<td>2.381 (m$^3$/s)</td>
<td></td>
</tr>
<tr>
<td>Canning</td>
<td>0.77</td>
<td>0.074 (mm/day)</td>
<td>0.83</td>
<td>0.064 (mm/day)</td>
<td></td>
</tr>
<tr>
<td>Namoi</td>
<td>0.89</td>
<td>6.596 (m$^3$/s)</td>
<td>0.90</td>
<td>6.333 (m$^3$/s)</td>
<td></td>
</tr>
<tr>
<td>Brue</td>
<td>0.80</td>
<td>2.177 (m$^3$/s)</td>
<td>0.81</td>
<td>2.145 (m$^3$/s)</td>
<td></td>
</tr>
<tr>
<td>Canning</td>
<td>0.96</td>
<td>0.032 (mm/day)</td>
<td>0.95</td>
<td>0.034 (mm/day)</td>
<td></td>
</tr>
<tr>
<td>Namoi</td>
<td>0.94</td>
<td>4.929 (m$^3$/s)</td>
<td>0.95</td>
<td>4.545 (m$^3$/s)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7 | The simulated runoff by the IHACRES model using the calibration data (one routing component).

Figure 8 | The simulated runoff by the IHACRES model using the calibration data (two routing components).
the baseflow. Also, the peak flows are simulated more similar to the peak flows in the observed hydrograph by using two routing components. Better representation of peak flow becomes more considerable, especially in terms of flood forecasting. Also, the same analysis can be done for the Canning catchment. Using two routing components can improve the baseflow and peak flows significantly. Consideration about the observed

Figure 9 | The simulated runoff by the ERM model using the calibration data (one routing component).

Figure 10 | The simulated runoff by the ERM model using the calibration data (two routing components).

Figure 11 | The scatter plot by the IHACRES model using the calibration data (one routing component).
streamflow hydrograph in the Namoi catchment shows that the base flow in this catchment is not too high. Although the performance of the model under two routing component is quite similar in this catchment, the peak flows are simulated better when two routing components are used.

As discussed before, numerical and visual inspection of the observed and simulated streamflows generated by the IHACRES parameters in terms of calibration can prove that using the two routing component can lead to more feasible streamflow simulations. However, this point cannot be said about the results obtained by the ERM model. Similar to the IHACRES model, a series of streamflow hydrographs are generated (Figures 9 and 10) by using the ERM calibrated parameters with one and two routing components. In the numerical view, using two routing components in the ERM structure can improve the model performance for the (Brue and Namoi catchments), but not for the Canning catchment. In the Brue and Namoi catchments, the IHACRES and ERM models have the best performance when two routing

Figure 12 | The scatter plot by the IHACRES model using the calibration data (two routing components).

Figure 13 | The scatter plot by the ERM model using the calibration data (one routing component).
components are used based on the hydrographs generated in Figure 8 for the IHACRES model and Figure 10 by the ERM model. Comparison between the hydrographs proves the ERM model presents better simulation, especially in terms of peak streamflow simulation. In the Canning catchment, the IHACRES performance is better by using the two routing component. However, the ERM model is improved by using the one routing component and it can be observed by comparison between Figures 8 and 9. Comparison between the results obtained from calibration of the Canning catchment by the ERM and IHACRES model reports that the simulation is much more accurate when the ERM model with one routing component is used. In addition to the generated hydrographs, the scatter plots of simulated runoff versus observed runoff are provided in Figures 11 and 12 by the IHACRES model and Figures 13 and 14 by the ERM model using calibration data.

Generally, comparison between the results obtained by the ERM and IHACRES models proves that using the Muskingum routing components in the ERM structure increases the model accuracy significantly in comparison with the linear unit-hydrograph used in the IHACRES model.

Validation

After the calibration process, the model accuracy of the estimated parameters should be evaluated by a different set of data, i.e. the validation data. In the validation stage, an independent assessment is presented to prove the model’s predictive ability. Basically, in mathematical model development, comparison between different models must be based on the validation data instead of calibration data. The model performance in the calibration stage represents the accuracy of the model in predicting the streamflow under the conditions of the calibration period. In contrast, the validation data represent the performance of the model in predicting the streamflow under different hydrological conditions, which are not used in the calibration process.

Table 6 | $R^2$ and RMSE values calculated by the IHACRES and ERM models for the three catchments by the validation data

<table>
<thead>
<tr>
<th>Catchment</th>
<th>IHACRES</th>
<th>ERM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brue</td>
<td>R² 0.62</td>
<td>RMSE 4.085 (m³/s)</td>
</tr>
<tr>
<td>Canning</td>
<td>R² 0.60</td>
<td>RMSE 0.079 (mm/day)</td>
</tr>
<tr>
<td>Namoi</td>
<td>R² 0.58</td>
<td>RMSE 16.434 (m³/s)</td>
</tr>
<tr>
<td>Brue</td>
<td>R² 0.78</td>
<td>RMSE 3.095 (m³/s)</td>
</tr>
<tr>
<td>Canning</td>
<td>R² 0.94</td>
<td>RMSE 0.030 (mm/day)</td>
</tr>
<tr>
<td>Namoi</td>
<td>R² 0.63</td>
<td>RMSE 15.355 (m³/s)</td>
</tr>
</tbody>
</table>
Figure 15 | The simulated runoff by the IHACRES model using the validation data (one routing component).

Figure 16 | The simulated runoff by the IHACRES model using the validation data (two routing components).

Figure 17 | The simulated runoff by the ERM model using the validation data (one routing component).

Figure 18 | The simulated runoff by the ERM model using the validation data (two routing components).
the fitting of the model to the calibration data, but not the model’s predictive ability. The performance indicators calculated by the validation data for three catchments are listed in Table 6. Similar to the calibration process, using two routing components in the IHACRES model makes the model more accurate. Comparison between Figures 15 and 16 proves model improvement in the case of using two routing components in terms of model validation. According to Table 6 and Figures 17 and 18, using two routing components in the ERM model has improved the model in terms of validation, except the Canning catchment. Comparison between Figures 16 and 18 shows better performance of the ERM model with two routing components to streamflow simulation of the Brue and Namoi catchments. Also, modeling streamflow in the Canning catchment by the ERM model with one routing component leads to the most accurate baseflow and peak flow simulation in terms of model validation. However, even by using two routing components in the IHACRES model this performance is not achievable. As a general inspection, it can be seen that the ERM model has a
better performance in terms of model validation. The scatter plots of simulated runoff versus observed runoff are provided in Figures 19 and 20 by the IHACRES model and Figures 21 and 22 by the ERM model using validation data.

**CONCLUSION**

This paper introduces a new rainfall-runoff model, lumped type, consisting of two components: a non-linear loss module and a module for converting effective rainfall into streamflow. The model has been adopted from the well-known IHACRES model and the runoff routing method in the ERM model has been changed to the Muskingum routing method for improving the model performance in streamflow simulation. The new routing scheme was investigated with one and two routing components for responding to slow and quick runoffs. The GA optimization method was embedded in the ERM model structure as a global optimization method to calibrate the model parameters. Also, the GA model was used to replace the grid search calibration scheme used
in the original version of the IHACRES model to overcome its weakness in terms of parameter calibration and to avoid being trapped into the local optima. Comparison between the new model and the IHACRES model was performed by two sets of data (calibration and validation) obtained from three different catchments with different characteristics. In addition, the ability of each model was evaluated with one and two components of runoff routing modules. Visual and numerical comparison between the hydrographs simulated by the ERM and IHACRES models confirms that the ERM model has more accurate performance in both calibration and validation. Since the Muskingum routing method is widely used in the hydrological community, the ERM model has the potential to be accepted by many hydrological modelers. However, all hydrological models have their suitable/unsuitable application areas and further exploration of the ERM model to a wide range of catchments should be carried out so that its strengths and weaknesses could be found out for its better adoption in practice.

REFERENCES


First received 7 January 2013; accepted in revised form 10 April 2013. Available online 22 May 2013.