Application of mathematical models for flood forecasting in Sri Lanka

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Abstract With the introduction of micro computers, the application of mathematical models in water resources planning and forecasting became increasingly popular during the last decade in Sri Lanka. The selection of a particular model for a specific river basin was done as far as possible on the basis of an objective criteria to judge the model efficiency. Among the black box models, HEC 1 of the US Army Corps of Engineers, and the Linear Perturbation Model (LPM) of the University College of Galway, Ireland were adopted. Of the conceptual models SMAAR (Ireland), NAM (Danish), and Xinanjiang (Chinese) models were widely tested. Due to location of many important coastal cities near river estuaries, the pure hydrological models cannot adequately describe the hydrodynamics of these estuaries due to tidal influence of the sea. Therefore, while using hydrological models to represent head basins, hydrodynamics models were interfaced to represent the lower parts of the rivers. Mike II package developed by the Danish Hydraulic Institute was successfully used to simulate one dimensional unsteady flow in these estuaries. The application of different models indicated that a wide variety of models can be successfully applied to Sri Lankan rivers, instead of a particular model. However conceptual models gave superior results specially for rivers subject to prolonged droughts.

GENERAL

Numerical models for simulation of river flows are used in the planning of water resources projects and real time flood forecasting. The purpose of this paper is to highlight some applications of mathematical modelling techniques for flow simulation in Sri Lanka. In water resources planning, when a designer wants to obtain historical streamflow series to determine design parameters, such data is not generally available. While it is possible to overcome this problem by the development of mathematical models, it is very important to note that these models have become increasingly significant, when anthropogenic changes have affected the hydrologic regime.

Due to tidal variation of the sea, hydraulics in river estuaries become complex and therefore in addition to the application of hydrological models for headwater catchments, hydrodynamics models have to be applied for estuaries. Figure 1 shows the locations of seven river basins selected for modelling.

River basins and hydrological information

Most of the rivers in Sri Lanka originate at 2500 m a.m.s.l. and end their journey in the Indian ocean. The annual rainfall varies from 5000 to 1000 mm and the country is divided into two distinct climatic zones, based on annual rainfall. Rainfall iso height of 1750 mm divides the country into the wet zone and the dry zone. Selected
river basins for model testing and some hydrological characteristics are given in the Table 1.

A hydrodynamic model has been tested for lower reaches of two major rivers near the city of Colombo. These are Kelani and Kalu, which discharge the largest annual volume of water to the sea. As the river traverses from the mountainous region, influence of the tidal action of the sea is experienced during the last 30–40 km.

Fig. 1 Location of river basins.
Table 1: Selected river basins for catchment modelling.

<table>
<thead>
<tr>
<th>Name of gauging stations</th>
<th>River basin</th>
<th>Catchment area (km²)</th>
<th>Period of calibration</th>
<th>Period of verification</th>
<th>No. of rainfall stations</th>
<th>No. of evaporation stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glencourse</td>
<td>Kelani</td>
<td>1423</td>
<td>1961–1965</td>
<td>1965–1968</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

Structure of selected models

Both black box and conceptual models have been used in hydrological modelling and the detailed description of the structure of these models is not intended to be discussed here due to restriction of space. Regarding the hydrodynamics modelling, since the development of one dimensional unsteady flow equations by St Venant, a vast number of river flow computational schemes have emerged. In this paper the application of the fully dynamic one dimensional model developed by the Danish Hydraulic Institute (1991) will be discussed.

BLACK BOX MODELS

Linear Perturbation Model

The Linear Perturbation Model (LPM) assumes that the perturbation from the smoothened seasonal input rainfall and that of discharge are linearly related.

HEC 1 model

Of the different options available in the model, the unit hydrograph developed by Snyder for the generation of overland flow and Muskingum method for flood routing are adopted. There are two parameters in the Snyder model, $C_i$ and $C_p$ with usual notations. During the calibration of the model the entire basin is subdivided into lumped sub-basins and the parameters $C_i$ and $C_p$ are optimized from observed flood hydrographs at river gauging stations for each sub-basin.

Muskingum parameters, $K$ and $X$ which can be estimated from observed hydrographs were estimated from hydrograph analysis.

CONCEPTUAL MODELS

The deficiency in the models of the systems approach (black box) is overcome in the conceptual models as it permit the grouping together of the non linear operations and leave open the possibility of representing the subsequent transformation of the
generated runoff by a linear routing component.

The following conceptual models were applied to different basins with varying results. Figure 2 shows the structure of selected conceptual models.

**SMAAR model**

This conceptual model is a Soil Moisture Accounting and Routing model (SMAAR) developed by O'Connell in 1970. There are five parameters in the model.

**NAM model**

This model was originally developed by the hydrological section of the Institute of

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**Fig. 2** Structure of conceptual models.
Hydrodynamics and Hydraulic Engineering at the Technical University of Denmark and then subsequently developed by the Danish Hydraulic Institute. There are 13 parameters in the model (Danish Hydraulic Institute, 1991).

**Xinanjiang model**

The Xinanjiang model was developed in 1973 and published in 1980 (Zhao, 1991). The configuration of the model is somewhat similar to the SMAAR model, but this consists of three soil layers at the top. There are 15 parameters in the model.

**Mike II Hydrodynamics model**

Mike II is a microcomputer based one dimensional mathematical model developed by the Danish Hydraulic Institute (DHI) for simulation of water flows, sediment transport, dispersion and transport of dissolved materials and water quality in rivers. This is one of the most extensively used numerical models for river flow computations based on the finite difference solution of St Venant equations (Danish Hydraulic Institute, 1991).

**DATA REQUIREMENT FOR MODELLING**

**Hydrological models**

Except for the HEC1 model, all other models are continuous models and therefore continuous data for a few years are required for model calibration and verification. The HEC1 model is an event type model and therefore for model calibration, rainfall and streamflow records are required only for several events. In conceptual modelling, daily rainfall, streamflow discharge and pan evaporation data in the basin are generally required as input data. The length of records required for model calibration is generally between 3 and 4 years. Model verification has to be done with two to three years of additional data outside the calibration period. Whereas in the case of black box models, only rainfall and streamflow data are required. In this paper modelling is done on a daily basis, except in the HEC1 application and therefore daily data were used in all models. For HEC1, 3-h to 6-h data were used. Calibration and verification of HEC1 model was done using several flood events.

**Hydrodynamic model**

An output hydrograph from hydrological models of the upper reaches of rivers was taken as the upstream boundary conditions for the hydrodynamics modelling. The downstream boundary was the tidal action of the sea as the rivers under consideration discharge finally to the sea. The time step in modelling is either hourly or three-hourly. Detailed topographical information on the river reaches are also required in
hydrodynamics modelling and cross-section of the rivers and observed water levels at 2-3 km intervals were used in their application. Manning roughness between cross-sections and between different water elevations for each cross-section was suitably adjusted to match the computed water levels with the observed water levels during the model calibration.

**Model efficiency criteria**

To judge the performance of a model, there are a number of statistical and graphical criteria available. But none of these methods are free from drawbacks. The criterion which is used in this paper to verify model efficiencies of hydrological models is an objective method and it is the sum of squares of differences between the observed discharge and the estimated discharge. This criterion was recommended by the World Meteorological Organization (WMO) (Nash & Sutcliffe, 1970).

However efficiencies of Mike II, hydrodynamics model and HEC 1 model were judged by subjective graphical methods.

**Parameter optimization**

The least squares method is used to optimize the objective function in the model calibration of the LPM model. However in conceptual models, as the models are nonlinear, different optimization methods which are applicable to nonlinear functions have to be used.

In order to harness the full benefit of a conceptual model, all parameters of the model have to be optimized manually. Only then, the results obtained by such calibration become truly conceptual. However such an exercise becomes laborious and time-consuming and therefore numerical optimization techniques to optimize the model parameters were used. In this paper, model parameters are optimized by using optimization algorithms and therefore it may be argued that the output from the models are not truly conceptual even though model structures are conceptual.

In this study some of the squares of difference between computed and observed outputs will form the objective function as explained earlier.

Normally constraints are imposed to the movement of model parameters based on experience and also to obtain physically realistic results.

The methods adopted in this paper to optimize model parameters are,
- genetic algorithm (Wang, 1991);
- Rosenbrock’s method;
- Simplex method (Spendly et al., 1962).

**Results of model simulation**

The hydrological models mentioned above were applied to seven river basins and varying results were obtained during model calibration and verification. Table 2 provides the results of model calibration and verification for continuous models for
Table 2 Comparison of model efficiencies.

<table>
<thead>
<tr>
<th>Name of the river</th>
<th>Catchment conditions</th>
<th>SMAAR</th>
<th>Xinanjiang</th>
<th>NAM</th>
<th>LPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kelani</td>
<td>Wet</td>
<td>65.0</td>
<td>79.1</td>
<td>71.2</td>
<td>22.7</td>
</tr>
<tr>
<td>Kalu</td>
<td>Wet</td>
<td>83.9</td>
<td>83.4</td>
<td>84.5</td>
<td>84.8</td>
</tr>
<tr>
<td>Nilwala</td>
<td>Dry</td>
<td>64.5</td>
<td>-13.8</td>
<td>61.3</td>
<td>-1.1</td>
</tr>
<tr>
<td>Kirindi</td>
<td>Dry</td>
<td>55.4</td>
<td>-35.2</td>
<td>52.4</td>
<td>-14.4</td>
</tr>
<tr>
<td>Kotmale</td>
<td>Wet</td>
<td>83.9</td>
<td>82.8</td>
<td>84.6</td>
<td>85.2</td>
</tr>
<tr>
<td>Uma-Mahaweli</td>
<td>Dry</td>
<td>61.9</td>
<td>50.6</td>
<td>78.8</td>
<td>61.5</td>
</tr>
<tr>
<td>Maha</td>
<td>Wet</td>
<td>63.8</td>
<td>50.1</td>
<td>67.4</td>
<td>55.6</td>
</tr>
</tbody>
</table>

which objective criteria were adopted to measure the model efficiency. Figure 3 shows the results of model verification graphically for the River Kalu by the Xinanjiang model and for the River Kotmale by the NAM model.

Verification of model efficiencies of the HEC1 model and Mike II models were subjective as mentioned before. A specific application of HEC1 model was attempted for the Kelani River basin, which has a drainage area of 885 square miles. The river basin was divided into 12 lumped sub-basins and parameters for each of these sub-units were determined. Results of model verification of HEC1 as shown in Fig. 4. Figure 4(a) shows the model verification just before the estuary where there is no tidal influence. When the HEC1 model is extended to the estuary as shown in Fig. 4(b) it is clear that results are not promising. Therefore Mike II model was applied to the estuary and Fig. 5 shows the results of verification.

**Fig. 3 Model verifications.**
Updating of model output during flow forecast

When a calibrated model is used in real time flow forecasting the model can be updated to obtain a higher efficiency in operation. In general, it is possible to identify some persistence structure in the residual series from the output of a model. The autoregression analysis provides the basis for an updating procedure, whereby

**HECI MODEL**

(a) VERIFICATION FOR 1989 JUNE FLOOD AT HANWELLA

(b) VERIFICATION FOR 1989 JUNE FLOOD AT NAGALAGAM

Fig. 4 Verification for 1989 June flood (a) at Hanwella and (b) at Nagalagam.
previously obtained model output can be further refined prior to the issue of the flow forecast in real time.

Table 3 shows the efficiencies of different models when adopted for Kelani and Kalu rivers in the forecasting mode.

Flood forecasting activities are still in their infancy in Sri Lanka and therefore at present emphasis is on the calibration of models to check their suitability. It is planned to install suitable real time data acquisition systems to provide input data to selected models in future for operational purpose. The paper will discuss the results

**MIKE II MODEL**

(a) **VERIFICATION FOR 1967 OCT. FLOOD AT NAGALAGAM**

![Graph showing discharge in cubic meters per second for 1967 October flood at Nagalagam.]

(b) **VERIFICATION FOR 1966 SEP./OCT. FLOOD AT NAGALAGAM**

![Graph showing discharge in cubic meters per second for 1966 September-October flood at Nagalagam.]

Fig. 5 Verification (a) for 1967 October flood at Nagalagam, (b) for 1966 September-October flood at Nagalagam.
Table 3 Efficiency of updated models for forecasting.

<table>
<thead>
<tr>
<th></th>
<th>LPM:</th>
<th>Nash model:</th>
<th>SMAAR model:</th>
<th>NAM model:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalu Ganga 1-d</td>
<td>91.1</td>
<td>92.9</td>
<td>89.8</td>
<td>93.0</td>
</tr>
<tr>
<td>Kalu Ganga 2-d</td>
<td>87.2</td>
<td>86.5</td>
<td>85.1</td>
<td>86.9</td>
</tr>
<tr>
<td>Kalu Ganga 3-d</td>
<td>85.5</td>
<td>83.6</td>
<td>83.4</td>
<td>84.3</td>
</tr>
<tr>
<td>Kalani Gang 1-d</td>
<td>78.7</td>
<td>87.8</td>
<td>74.9</td>
<td>82.6</td>
</tr>
<tr>
<td>Kalani Gang 2-d</td>
<td>-</td>
<td>-</td>
<td>69.5</td>
<td>78.1</td>
</tr>
<tr>
<td>Kalani Gang 3-d</td>
<td>-</td>
<td>-</td>
<td>67.2</td>
<td>76.9</td>
</tr>
</tbody>
</table>

of the application of different types of models in several river basins. Experience gained during these applications is summarized under Conclusions.

CONCLUSIONS

(a) From the efficiencies found in model fittings, it can be concluded that a wide variety of models can be satisfactorily used in Sri Lanka for flow forecasting.

(b) In general, it can be concluded that even linear black box models provide a satisfactory tool for simulation of flows in river basins in the wet zone of Sri Lanka and therefore these models can be satisfactorily used in forecasting instead of complicated conceptual models.

(c) For basins in the dry zone of Sri Lanka, under the study it was observed that this gesture of linear models is due to the poor quality of evaporation data. The LPM model gave satisfactory results, for these dry basins, while all three conceptual models gave poor performances. Otherwise in the dry zone, conceptual models are expected to provide superior results.

(d) Regarding the results obtained from updating, it is clear that most of the models provide similar efficiencies in the forecasting mode, irrespective of their updated rainfall runoff transformation model. This is due to the efficiency of the autoregressive updating model component in identifying the persistence in each model residuals.

(e) Xianjiang and NAM models were found more appropriate for flood studies as flood peaks are represented by separate parameters in these models.

(f) Some of the parameters obtained from optimization techniques are not physically realistic and therefore needs further verifications of input data and modifications to the model parameters before using for real applications.

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