Analysis and modelling of runoff from two distinct river basins in Peninsular Malaysia

C. L. WONG[1, 2], R. VENNEKER[1] & S. UHLENBROOK[1, 3]

1 *UNESCO-IHE Institute for Water Education, Westvest 7, 2611AX, Delft, The Netherlands*
c.wong@unesco-ihe.org

2 *Department of Irrigation and Drainage, Kuala Lumpur, Malaysia*

3 *Section of Water Resources, Delft University of Technology, The Netherlands*

Abstract A land surface model of feedbacks between the atmosphere and hydrological processes is applied to model water and energy balance fluxes in Peninsular Malaysia. The model is extended with a component for simulating the daily rainfall-runoff at a grid size of 0.05 degree resolution (~5.5km) from two river basins with different landuse, i.e. forest (26,000 km^2) and agricultural area (4000 km^2). Two methodologies, i.e. a lumped basin approach and a distributed routing approach were compared to investigate the effects of spatially variable topography and subgrid variability in runoff generation. Both methods employ a simple linear reservoir technique. A Muskingum-Cunge routing scheme is incorporated into the distributed model in order to route the grid box surface and groundwater runoff production through the drainage network. The simulated streamflows are tested and verified using the observed hydrographs at the outlet gauging stations in both catchments. Although the daily runoff simulations compare favourably to the observations, the results indicate that there is still considerable uncertainty in the process relations between atmospheric forcings and runoff hydrology.

Keywords large-scale hydrology; water balances; rainfall; runoff and streamflow; evaporation

INTRODUCTION

The last decade has seen a rapid development of comprehensive large scale hydrological models that focus on modelling of runoff and streamflow at scales ranging from large river basins to entire continents (Todini, 1996, Abdulla and Lettenmaier, 1997, Nijssen *et al.*, 1997, Nijssen *et al.*, 2001, Oki *et al.*, 2001, Yang and Musiake, 2003, Xie *et al.*, 2004, Kerkhoven and Gan, 2006, Maskey and Venneker, 2006, Decharme and Douville, 2007). Land surface models (LSM) are introduced in atmospheric general circulation models (AGCMs) to provide realistic surface boundary conditions and understand the hydrological cycle at various scales. The accuracy in quantifying the climate change by AGCMs is dependent on the LSM which acts as medium in predicting the future climate, especially future streamflow characteristics (see Kleinn *et al.*, 2005, Vicuna and Dracup, 2007).

To accurately simulate streamflow, it is important to incorporate a realistic description of all relevant land surface processes or parameterization schemes, which represents the physical characteristics of vegetation and soils into the hydrological model. LSMs, in this case, carry the potential to more accurately estimate hydrological processes (and thus streamflow) than any conceptual water balance models. Therefore, LSMs are in principle able to provide more information required in water resources applications, especially in smaller spatial scales of interest to hydrology. Several LSM schemes (e.g. Liang *et al.*, 1994, Mo *et al.*, 2009), including the model for the present study (LSM-A), are typically designed for use in hydrological studies at large basin or regional scales.

In order to simulate the runoff phenomena, a hydrological process component that describes the streamflow generation and the integration of flows over delineated basin areas can be coupled to the LSM (e.g. Lohmann *et al.*, 1998, Yang and Musiake, 2003, Xie *et al.*, 2004, Niu *et al.*, 2005, Kerkhoven and Gan, 2006). Such additions are composed of routing schemes that convey the the runoff production computed by the LSM over the model grid towards the outlet of the basin. A particular problem of this coupling technique is that the grid box scales of LSMs are often quite large, in the order of 5 to 100 km, whereas the runoff hydrology may be strongly influenced by small scale terrain features, such as local hillslope configurations. It is therefore required to obtain a better insight into the subgrid variability of the runoff processes.

The objective of this paper is to provide a description and assessment of the influence of topography, the subgrid topographic variability on the runoff simulation performance of a coupled hydrological land surface model, applied to two relatively large river basins in Peninsular Malaysia. The basins selected for this study are the Pahang River (26,000 km^2) and the Muda River (4,000 km^2). Both basins are characterized by different landuse i.e. mostly forest (Pahang basin) and agriculture (Muda basin). Comparisons between a lumped basin runoff simulation and a distributed runoff routing approach are made. The simulated flows are tested against observed daily and monthly discharges for the period 1999-2004. The spatial grid resolution for the LSM and the distributed routing component is 0.05 degrees, or approximately 5.5 km.

This paper first introduces the application river basins and then describes the modelling methodology applied in this study. Subsequently, the simulation results are presented and discussed, and conclusions are drawn.

STUDY AREAS

Two large basins in Peninsular Malaysia are chosen for the present study and are shown in Fig. 1. The Pahang basin is located in the inland of the Peninsula. The catchment has an area of approximately 26,000 km^2 and a main stream length of about 440 km. The Muda river basin is located in the northwestern part of Peninsular Malaysia. The river, which has a length of 180 km, flows toward the Malacca Straits and covers a drainage area of about 4,000 km^2.

The Pahang basin covers elevations from sea level to some 2000 m in the most inland parts of the basins. The area is mostly covered by tall natural broadleaf forest, while rubber, oil palm and some paddy are planted in the undulating and lowland parts of the area. Granites and associated soils are found in the mountainous terrains in the east and west of Pahang. The lower parts of the basins are characterized by sedimentary covers.

The Muda basin has a different topography and landuse compared to the Pahang basin. The northeastern part of Muda basin is mountainous, fringed by hilly lands with elevations higher than 76 m. Due to the existence of the Muda dam at the upstream watershed, several areas are designated as forest reserves. The dominant vegetation along the river are rubber trees, oil palm trees and nippa palms. Paddy is widely planted along the floodplains of the basin. The soils of the river basin are primarily composed of alluvium, sedentary soils and lithosols (JICA, 1995).

The Pahang has an annual mean rainfall of about 2100 mm. A large proportion of the annual rainfall in Pahang basin occurs in November and December during the Northeast monsoon. The mean annual temperature and relative humidity for the basin are approximately 25 °C and 83%, respectively.

For the Muda basin, located at the west coast of Peninsular Malaysia, April and October are predominant in the annual rainfall contribution. The annual mean rainfall in this study area is about 2300 mm. The mean annual temperature and relative humidity for the basin are approximately 26 °C and 79%, respectively.

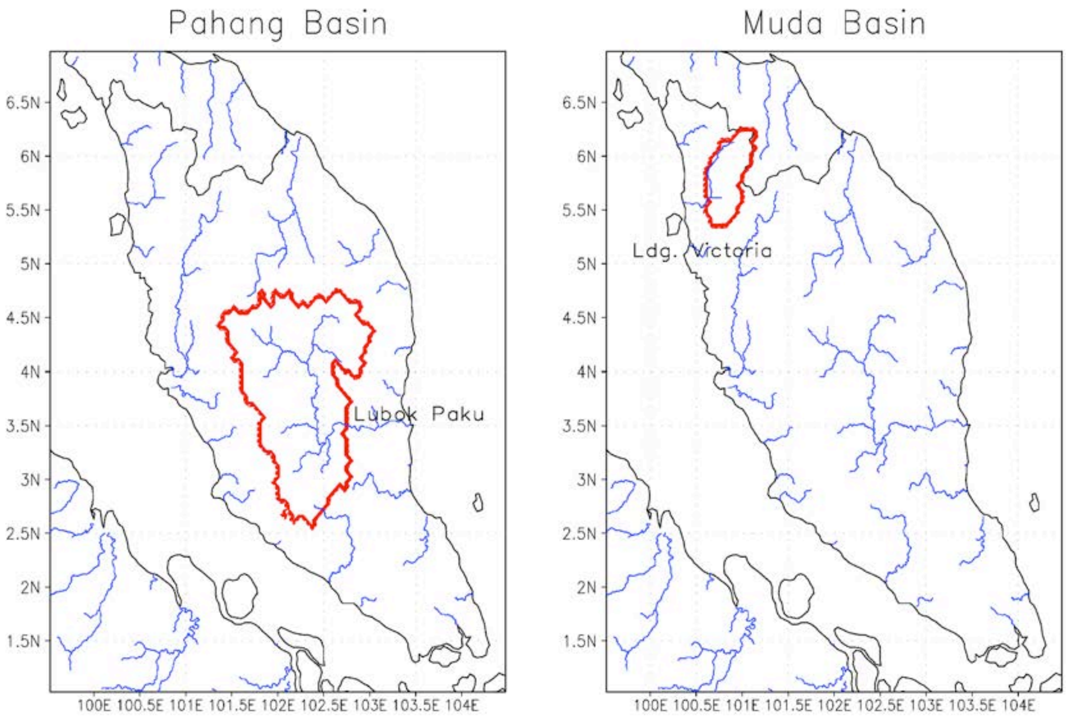

Fig. 1 Location of the study basins in Peninsular Malaysia. The Pahang basin is taken up to the Lubok Paku discharge station. The Muda basin is taken up to the Victoria estate discharge station.

MODEL DESCRIPTION

Fig. 2 shows a schematic representation of the fluxes accounted for by the LSM-A land surface model used in this study. The model input and output are represented in daily time steps. The atmospheric forcing consists of downward shortwave and longwave radiation, precipitation, windspeed, and air temperature, pressure and humidity. These are obtained from the gridded daily data set described by Wong *et al.* (2010a, 2010b), augmented with radiation computed from the surface meteorological fields in combination with cloud properties from the NASA/GEWEX Surface Radiation Budget (SRB) Release-3.0 data archive.

The computed fluxes include the upward radiation, the latent, sensible and ground heat fluxes, the potential and actual evaporation, the surface runoff production from infiltration or saturation excess, and the soil percolation flux at the bottom of the soil profile. In addition, the model provides the soil water content and soil temperature. The following paragraphs provide a brief description of the model, restricting to the water balance components that are most relevant for the present study.

The evapotranspiration flux E (mm s^{-1}) is obtained from solving the surface energy balance, given by

$$C\frac{dT_{sk}}{dt} = R_N - H - \lambda E - G \quad (1)$$

where C is the surface heat capacity (J m^{-2} K^{-1}), T_{sk} is the skin temperature (K), R_N is the net radiation (W m^{-2}), H is the sensible heat flux (W m^{-2}), λ is the latent heat of vaporization (J kg^{-1}) and G is the ground heat flux (W m^{-2}). The energy balance is solved numerically mostly as described in Essery *et al.* (2003), which linearizes the non-linear fluxes to obtain an extended Penman-Monteith formulation for the evaporation potential. The actual evapotranspiration is subsequently derived by limiting the evaporation flux to the available water in the soil and vegetation storages.

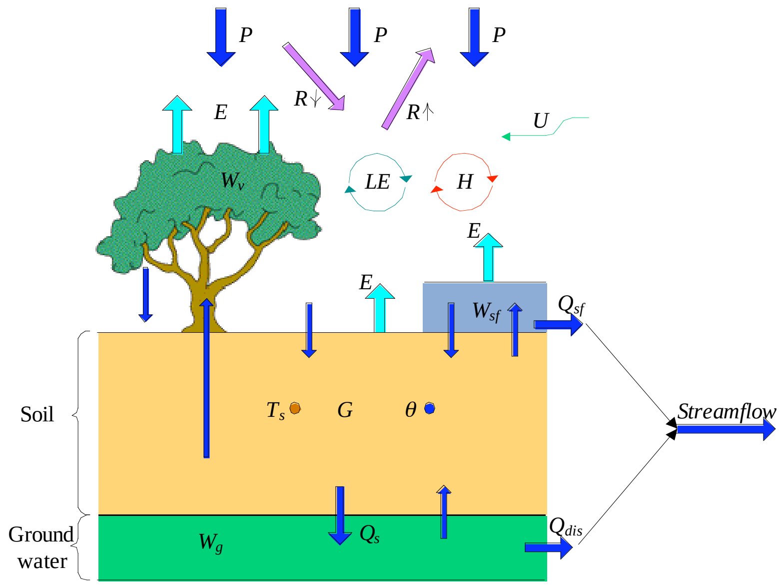

Fig 2 Schematic representation of the LSM-A model showing the major energy and water balance fluxes. R: radiation, U: wind, LE: latent heat flux, H: sensible heat flux, G: ground heat flux, T_s: soil temperature, θ: soil water content, P: precipitation, E: evaporation, W_{sf}: surface water storage, W_g: groundwater storage, Q_{sf}: surface runoff production, Q_s: soil percolation; Q_{dis}: baseflow. Small arrows indicate the subgrid water fluxes.

Soil water transport is computed for five layers of downward increasing thickness up to 2 m depth by solving the Richards equation (e.g. Dickinson *et al.*, 1993), i.e.

$$\rho\frac{\partial\theta}{\partial t} = -\frac{\partial q_w}{\partial z} - \rho S_w \quad (2)$$

where ρ is the density of water (kg m^{-3}), θ is the soil water content (m^3 m^{-3}), z is the depth below surface (m) and S_w is the volumetric soil water extraction (m^3 m^{-3} s^{-1}) by plant roots and evaporation from the topsoil.

Infiltration and surface runoff production from canopy interception drainage and precipitation on the unvegetated part of the grid boxes are modelled using the parameterization described by Schaake *et al.* (1996). The grid box average infiltration excess flux per unit area q_{sf} (mm s^{-1}) over a time step Δt is described by

$$q_{sf} = \frac{1}{\Delta t}\frac{P_n^2}{P_n + I_c} \quad (3)$$

where P_n is the time step cumulative input (mm) from rainfall and canopy interception drainage at the soil surface and I_c is the time step cumulative infiltration capacity (mm). The soil percolation flux Q_s is assumed to be described as gravity flow, limited to field capacity water content.

The model accounts for spatial variability of altitude, land cover type and soils. The terrain data are aggregated into the 0.05 degree spatial grid on the basis of majority or averaging, depending on the nature of the data. Elevation data are derived from 1 km SRTM 30 version 2 data (Farr *et al.*, 2007). Land cover type and leaf area index were derived from MODIS satellite products for the period 2003-2007. USDA Soil texture classes (U.S. Department of Agriculture, 2007) are obtained from global 5 arc min resolution maps of sand, silt and clay separates that have been extracted from the ISRIC-WISE global soil properties data base linked to the FAO-UNESCO Digital Soil Map of the World (Batjes, 2006).

Two modelling approaches for integration of the runoff over the entire basin, i.e. a lumped basin runoff model and a distributed hydrological routing approach were applied. For the lumped model, the surface runoff production and the soil water percolation from all grid boxes within the basin (see Fig. 2) are spatially aggregated into a surface reservoir and a groundwater reservoir, respectively, at each daily time step. The linear storage and flow relations for both reservoirs are given by

$$\frac{dS}{dt} = I - Q \tag{4}$$

$$S = kQ \tag{5}$$

where S is the reservoir storage (mm), I is the inflow (mm s^{-1}) from the LSM, Q is the outflow (mm s^{-1}) to the stream channel network and k is the storage coefficient (s^{-1}). In this case, the surface flow and groundwater storage coefficients, k_{surf} and k_{gw} respectively, are taken as uniform constants over the entire basin.

The distributed routing approach employs a surface and groundwater reservoir for each grid box within the basin. The slope of the subgrid topography is used to parameterize the effective storage coefficients. It is assumed that the effective surface storage coefficient scales with the square root of the terrain slope, as in the Manning flow equation, viz.

$$k_{\mathrm{surf}} = k_{\mathrm{surf},0} S^{-1/2} \tag{6}$$

where $k_{\mathrm{surf},0}$ represents a basin-wide constant surface flow storage coefficient for a unit slope and S is the terrain slope. The effective groundwater storage coefficient is assumed to scale linearly with the terrain slope, as in the Darcy equation, viz.

$$k_{\mathrm{gw}} = k_{\mathrm{gw},0} S^{-1} \tag{7}$$

in which $k_{\mathrm{gw},0}$ denotes the basin-wide constant groundwater storage coefficient for a unit slope. The effective subgrid slopes are obtained by averaging all slopes computed from the 1 km elevation grid that fall with the target grid box. The combined outflows of the surface runoff and groundwater reservoirs are treated as input to the river network in each grid box. The stream channel flow is routed towards the basin outlet following the steepest downward descent path through the model grid. Streamflow continuity is described by

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial s} = cq_l \tag{8}$$

where Q is the discharge (m^3 s^{-1}), c is the wave celerity (m s^{-1}), s is the channel reach length (m) and q_l is the lateral inflow (i.e. summed outflow of the reservoirs) per unit length of channel reach (m^2 s^{-1}). This is solved using a Muskingum-Cunge routing scheme (Cunge, 1969) in combination with the Manning flow equation, assuming a wide rectangular channel cross-section (Ponce, 1986).

RESULTS AND DISCUSSION

Adjustment of the reservoir coefficients for the lumped models was carried out separately for both basins by trial and error such that best-fit results were obtained for daily simulations over the full period 1999-2004. The optimized reservoir parameters for the distributed models for daily simulations were shown in Table 1. Calibration of the distributed models typically involves comparing simulated streamflow with observations and adjusting the parameters to improve the agreement goodness-of-fit indicators. The resulting parameter values in the Pahang basin for daily simulations were then used in Muda basin, and were further calibrated in a trial and error procedure. The identified best-fit result of Manning's roughness coefficient in Muda basin was found agree well with the findings by Julien *et al.* (2010). To establish initial conditions, all models were spun up for four years prior to the start of the simulations.

Table 1 Calibrated basin parameters for the distributed hydrological model.

Parameter	Pahang Basin	Muda Basin
River channel Manning's roughness coefficient, n	0.05	0.03
Surface flow storage coefficient, k_{surf} (days)	0.5	0.5
Groundwater storage coefficient, k_{gw} (days)	1.2	1.2

Results of the daily model simulations are shown in Fig. 3 for the Pahang basin and in Fig. 4 for the Muda Basin. The summary statistics of the daily simulation performance are presented in Table 2.

Fig. 3 and Fig. 4 demonstrate that the distributed hydrological model simulation results provide a better overall fit to the observations during the period taken into account. For both basins, the peak flow simulation of the distributed model is improved with respect to that of the lumped model. A notable discrepancy between observed and simulated discharge in the Pahang basin is observed between November 2002 and February 2003 (Fig. 3). This is probably due to either unrealistic rainfall input or error in the observation measurements. The simulation improvement of the distributed models is supported by the performance statistics shown in Table 2. The correlation measured by the coefficient of determination R^2 and the Nash-Sutcliffe efficiency *NSE* are substantially improved from the lumped model approach. The Pahang distributed model shows a reduction in mean absolute error (MAE), as well as for the Muda distributed model. Overall, the improvements of the distributed model results suggest that the topographic variability is an important control in the basin runoff mechanism.

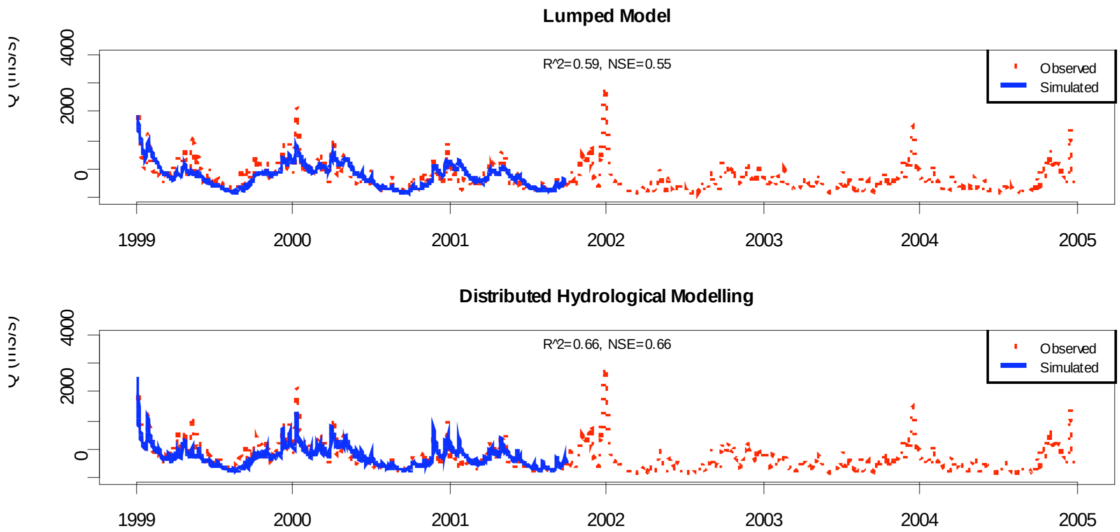

Fig. 3 Simulated daily hydrographs for the lumped (top) and distributed (bottom) hydrological modelling approaches compared with observed discharge for 1996-2004 in the Pahang basin.

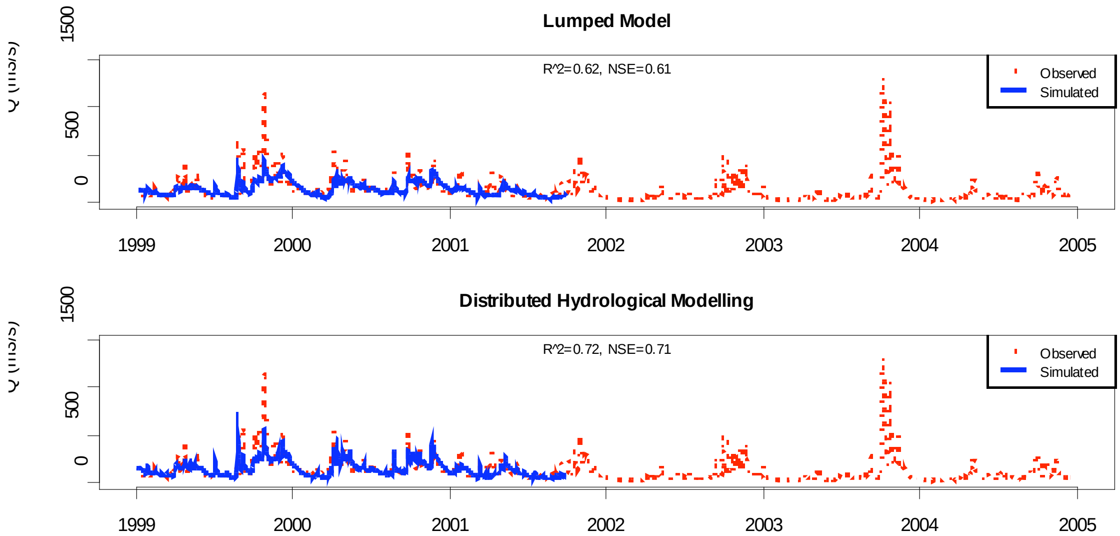

Fig. 4 Simulated daily hydrographs from the lumped (top) and distributed (bottom) hydrological modelling approaches compared with observed discharge for 1999-2004 in the Muda basin.

The performance of both the lumped and distributed models, as measured by the R^2 and *NSE* statistics is better in the Muda basin. This may be related to the smaller size of the basin. However, it is also possible that the rainfall distribution for the Pahang basin is less well defined due to a smaller density of available raingauges in the upper parts of the Pahang basin (Wong *et al.*, 2010b).

For application to water resources monitoring it is convenient to assess the model performance at a monthly basis. Restricting to the distributed model, the aggregation of the daily simulation results and observations into monthly hydrographs are presented in Fig. 5, showing a favourable fit for both basins. The performance statistics in Table 3 indicate that the model simulates the water resources in both basins at monthly time scales quite reasonably during the period covered by this study.

Table 2 Lumped and distributed model performance statistics of daily flow simulations for 1999-2004.

	Bias (m^3/s)	MAE (m^3/s)	Coefficient of determination, R^2	Nash-Sutcliffe efficiency, *NSE*
Pahang Basin (mean = 689 m^3/s)				
Lumped model	30	228	0.59	0.55
Distributed model	12	167	0.66	0.66
Muda Basin (mean = 125 m^3/s)				
Lumped model	−2	46	0.62	0.61
Distributed model	1	40	0.72	0.71

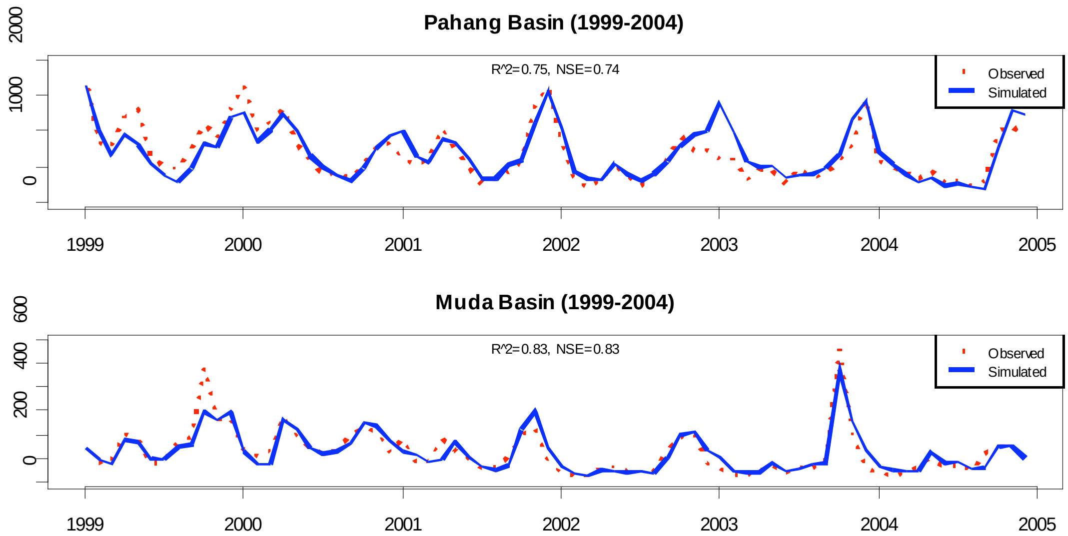

Fig. 5 Monthly hydrographs obtained from distributed model simulations in the Pahang (top) and Muda (bottom) basins for 1999-2004.

Table 3 Monthly model performance statistics for 1999-2004.

	Bias (m^3/s)	MAE (m^3/s)	Coefficient of determination, R^2	Nash-Sutcliffe efficiency, *NSE*
Pahang Basin (mean = 689 m^3/s)				
Lumped model	32	166	0.69	0.60
Distributed model	13	167	0.75	0.74
Muda Basin (mean = 125 m^3/s)				
Lumped model	−2	33	0.73	0.73
Distributed model	1	27	0.83	0.83

The uncertainty in the simulated streamflow by each model was qualitatively assessed from the model residuals. The model residual of streamflow is defined as the difference between simulated and observed flow normalized by the mean observed flow to enable comparison between the basins. Fig. 6 shows boxplots of the distributions of the model residuals in both basins. The plots show a generally symmetric distribution of the residuals in both basins for the lumped as well as the distributed models. For the Muda basin, the stretched tails for under prediction are mostly due to the mismatch in peak flow simulation of both the lumped and the distributed model. The figure shows furthermore that the variation between the whisker-ends is smaller in the distributed model, which is cross-confirmed by the performance statistics. A Shapiro-Wilk test for normality (Shapiro and Wilk, 1965) showed that the residuals for all models are not normal-distributed at 95% interval levels. It can therefore be concluded that part of the simulation error is not random and possibly related to the lack of process representation.

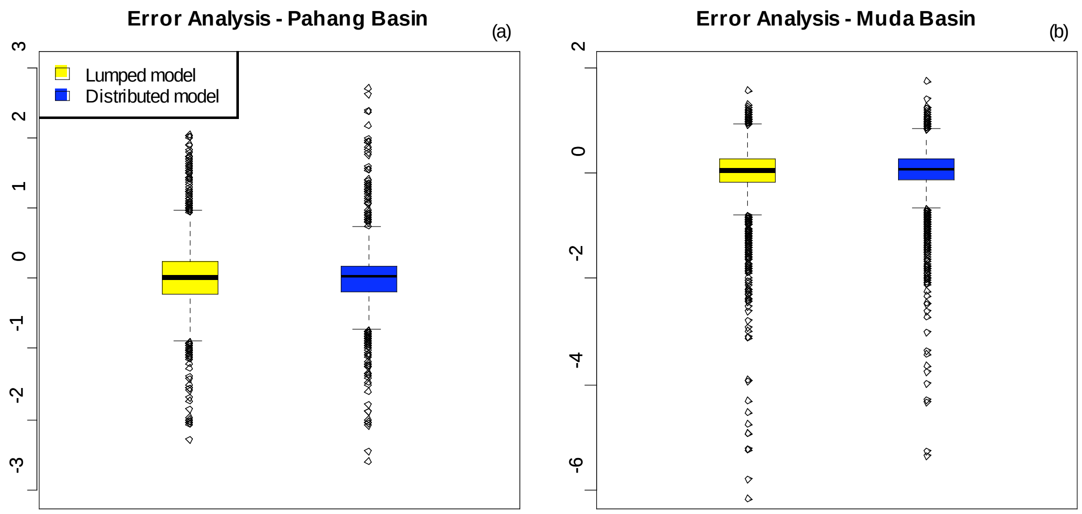

Fig. 6 Box plot of model residuals for (a) Pahang and (b) Muda basins. The height of the box is the difference between the third and first quartiles (IQR). Any data observation which lies 1.5 IQR lower than the first quartile or 1.5 IQR higher than the third quartile can considered an outlier in the statistical sense, indicated by open circles.

CONCLUSIONS

This paper has presented daily and aggregated monthly simulation results of a coupled hydrological land surface model applied to the Pahang (26,000 km^2) and Muda (4,000 km^2) river basins in Peninsular Malaysia for 1999-2004. A simple linear reservoir formulation was used to convert the runoff production from the LSM into basin runoff. Compared to a lumped-basin approach, a distributed model accounting for effects of variable topography and also incorporating a streamflow routing component significantly improves the discharge simulation at the basin outlets.

In order to provide the inflow towards the stream channel network at a spatial grid resolution of approximately 5.5 km, it is necessary to consider the subgrid runoff generation. In this study, the average grid box slope has been used to parameterize the effective grid box reservoir coefficients. A better description of the subgrid flow processes may potentially further improve the overall model results at daily time intervals. A good flow simulation at daily or shorter time scales may provide useful input to hydrodynamic models used in flooding assessments.

On aggregated monthly time scales the model provides adequate simulations of the seasonal surface water resources for both basins. As such, the modelling approach described here may provide a useful monitoring tool for water resources management applications. Examples include irrigation and reservoir operation, water allocation, inter-basin water transfers and water supply.

It is noted that calibration of the distributed model was carried out in the Pahang basin. The calibrated runoff parameters employed in the Pahang basin were subsequently applied to the Muda basin, with minor adjustment over the Manning roughness coefficient. The distributed hydrological modelling in the Muda basin yields a relatively higher R^2 of 0.72 and 0.83 for daily and monthly river flow, respectively. The analysis of model residual was carried out in both basins and showed that improvement in the process representation may further increase the model performance.

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