Cent. Eur. J. Geosci. • 3(3) • 2011 • 309-317
DOI: 10.2478/s13533-011-0030-6

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Central European Journal of **Geosciences**

Comparison of Recorded Rainfall with Quantitative Precipitation Forecast in a Rainfall-Runoff Simulation for the Langat River Basin, Malaysia

Research article

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Received 12 June 2011; accepted 28 August 2011

Abstract: Observed rainfall is used for runoff modeling in flood forecasting where possible, however in cases where the response time of the watershed is too short for flood warning activities, a deterministic quantitative precipitation forecast (QPF) can be used. This is based on a limited-area meteorological model and can provide a forecasting horizon in the order of six hours or less. This study applies the results of a previously developed QPF based on a 1D cloud model using hourly NOAA-AVHRR (Advanced Very High Resolution Radiometer) and GMS (Geostationary Meteorological Satellite) datasets. Rainfall intensity values in the range of 3-12 mm/hr were extracted from these datasets based on the relation between cloud top temperature (CTT), cloud reflectance (CTR) and cloud height (CTH) using defined thresholds. The QPF, prepared for the rainstorm event of 27 September to 8 October 2000 was tested for rainfall runoff on the Langat River Basin, Malaysia, using a suitable NAM rainfall-runoff model. The response of the basin both to the rainfall-runoff simulation using the QPF estimate and the recorded observed rainfall is compared here, based on their corresponding discharge hydrographs. The comparison of the QPF and recorded rainfall showed $R^2 = 0.9028$ for the entire basin. The runoff hydrograph for the recorded rainfall in the Kajang sub-catchment showed $R^2 = 0.9263$ between the observed and the simulated, while that of the QPF rainfall was $R^2 = 0.819$. This similarity in runoff suggests there is a high level of accuracy shown in the improved QPF, and that significant improvement of flood forecasting can be achieved through 'Nowcasting', thus increasing the response time for flood early warnings.

Keywords: recorded rainfall • QPF • NAM RR model • model calibration • Runoff simulation, Langat river basin, Malaysia

1. Introduction

Hydrological models for simulating rainfall-runoff processes are important techniques in flood forecasting. These models allow the assessment of the impact of factors to optimize global and local hydrologic events while, at the same time, minimizing the negative effects of the impact of floods. The models differ in terms of their mathematical representation of the hydrological processes and data requirements in both the spatial extent and the physical and vegetation characteristics of the basin. In practice, it is the historical rainfall

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and discharge data which is input into a rainfallrunoff simulation process [17, 18, 39, 47]. These time series data may be hourly, monthly or yearly and are used to test the response of a basin to potential runoff and flooding [16, 28, 41]. When the response time of the watershed is too short for flood warning activities, it may be necessary to extend the forecasting horizon (lead-time) by the use of additional data involving flood forecasting system (FFS) estimates of the amount of rain that will fall over the watershed. These FFS rainfall estimates can be provided by the deterministic QPF originated by limited-area meteorological models, or by extrapolation and the use of trend-based techniques when the forecasting horizon is on the order of six hours or less [1, 12]. The use of these techniques is referred to as 'nowcasting' of which an extensive review can be found in [51, 52, 55].

Runoff is generated by rainstorms, and its occurrence and magnitude are dependent on the intensity, duration and the distribution of the rainfall event, which together with other important factors influence the runoff generating process. Generally rain falls on two main types of catchment surfaces – those which are permeable or impermeable and connecting ground surface areas to the stream channel. With an impermeable (impervious) surface, runoff is produced from any rainfall event no matter how small; while with the permeable surface runoff occurs when the rainfall intensity exceeds the infiltration rate. Rainfall intensity is the ratio of the total amount of rain (rainfall depth) falling in a given period and duration. It is expressed in depth units per unit time, usually as millimeters per hour (mm/hr) [20, 23, 24, 48, 52, 56]. The statistical characteristics of convective, high-intensity and short-duration rainfalls are essentially independent of location within a region and are similar in many parts of the world [44].

Over the years ongoing studies have shown significant improvement in numerical weather prediction [29, 31, 48, 52, 56]. These rainfall estimation techniques use numerical weather prediction and quantitative precipitation forecasting, attempting not only to represent and predict the global precipitation index, but chiefly to provide information for operational flood forecasting and to predict the impact of rainfall in natural, regional and local scale disasters such as floods [14, 20, 29, 31, 38, 43]. In this context, a QPF model was developed for operational flood forecasting for the Langat River basin, Malaysia. The 1D (one dimension) cloud model is based on the parameterization of rainfall estimates from NOAA-AVHRR (Advanced Very High Resolution Radiometer) and GMS (Geostationary Meteorological Satellite) datasets and was based on the relationship between cloud top temperature, cloud top reflectance and cloud height. The model demonstrated improved numerical estimation of rainfall for monsoon clouds in severe flood situations. Details of this model have been given in [4, 5].

Analysis of short-term rainfall data suggests that there is a reasonably stable relationship governing the intensity characteristics of this type of rainfall. Testing a rainfall-runoff process requires adequate rainfall and stream-flow supported by evaporation data. Concurrent recorded series of all data should not be less than ten years to provide a good calibration period and to allow for independent testing of the model runoff [49]. The superiority of historical data in the runoff process for operational purposes is however questionable. For an operational flood forecast to be effective, input rainfall should predict and provide warning of possible floods. Current practice of the use of historical rainfall data is limited to only testing the response of the basin to runoff and does not provide the desired flood forecast [4] thus the need for improved quantitative precipitation estimates as a precursor for runoff modeling in operational flood forecasting. The objective of this research is to test rainfall runoff response of the Langat river basin, Malaysia using the QPF estimates and also the recorded observed rainfall for the flood event of 27th Sept. to 8th Oct. 2000 and compare the runoff hydrographs estimated by the NAM model of the MIKE11 hydrological system.

2. Material and Methods

MIKE 11 is a comprehensive 1D hydrological modeling system for the simulation of flow, sediment transport, water quality, rivers, irrigation systems and other water bodies. The system is designed to have an integration modular structure with basic computational modules for hydrology, hydrodynamics, advection-dispersion, water quality and cohesive and non-cohesive sediment transport [34]. The rainfall–runoff (RR) processes can generally be modeled using either the NAM module or the Unit Hydrograph Module (UHM). Both hydrologic modules can be used independently of the MIKE11 system, where catchment runoff may be utilized directly as lateral inflows in a hydrodynamic river or channel network simulation. Whereas the NAM model is used to simulate rural catchment cycle, the UHM model is used to describe runoff from a single storm event using the unit hydrograph technique [34].

The study used hydrological data: hourly observed rainfall, water level evaporation and discharge obtained from DID (Drainage and Irrigation Department, Malaysia) and

MMS (Malaysian Meteorology Service) and the hourly QPF estimate. Data for basin surface elevation and river geometry includes contours of 20 m intervals and river cross sections at different points, with at least one at each end of the river. Other data include the network of the Langat River and its tributaries, the boundary of the sub-catchment area and the entire boundary. All GIS data including sampled location of water levels taken during the flood of September, 2000 by DID were prepared in MIKE11 basin works module as shown in Figure 1. The river network model and hydrological data were prepared in the NAM RR model where the system requires the input of at least a hydrometric point (H point) at each exit point of each river tributary and the basin. Other data include discharge and evaporation prepared for the calibration of the RR model. Output results of the runoff simulation were then exported and coupled to the basin DEM for flood inundation mapping.

2.1. Rainfall-runoff modeling using a NAM model

The NAM RR model is one of the lumped conceptual models widely applied in hydrological modelling for simulating the rainfall-runoff processes at the catchment scale [22]. In the MIKE 11 system the NAM model represents the various components of the rainfall–runoff process by continuously accounting for the moisture content in three different and mutually interrelated storages [22]. The three storages represent the physical elements of the catchment areas and comprise the surface, root zone and groundwater. As the parameters of the model cannot be generally determined directly from the catchment characteristics, they must be estimated by calibration against observed data. The auto-calibration of the NAM model involves parameters such as the U_{max} and L_{max} that defines the maximum water content in the surface and root zone storages respectively, also the overland flow runoff coefficient $CQ_{OF,}$ for which small values are expected for catchments with coarse, sandy soils and values near one would be present for low-permeable soils like clay or bare rocks. Another parameter is the time constant for overland flow routing, the CK; this is an important factor in that it is dependent on the size of the catchment and how fast it responds to rainfall. A less important factor is the interflow routing, whereas the CK_{IF} as interflow is not a dominant stream flow component and the CK_{BF} that is the time constant for routing base flow is dominant.

Rainfall, evaporation and/or temperature, discharge and water level time-series data are prepared in MIKE 11 format and integrated with the RR model component that comprises the NAM model to simulate different flows as a function of moisture content in each of the surface storage, root zone storage, snow storage and ground water elements. Automatic calibration is then performed for the NAM model which requires the assessment of some or all of the nine parameters [3, 15, 23, 36, 44, 46]. The calibration is continued until the best possible comparison between the simulated and observed discharge and water level hydrographs along the rivers is achieved [19, 45, 46].

2.2. Study area and hydrological characteristics of Langat Basin

The study area is the Langat river basin, Malaysia where from the 27th September to 8th October 2000 a short intense monsoon rainstorm caused severe flooding. The Langat watershed area is located approximately 27 km to the south east of Kuala Lumpur. The basin area is situated within latitudes 101°43′E to 101°58′E and longitudes 02°59′N to 03°17′N in the eastern part of the Malaysian peninsular (See Figure 1). The upper Langat area has two major dams: the Langat dam, located on the Lui tributary and the Semenyih dam on Semenyih tributary. These dams together with the upper Langat catchment area are considered to be one of the most important domestic water supply sources to over 1.9 million people in Kuala Lumpur and the surrounding areas [54].

The Langat River basin is approximately 90% mountainous, with the hills upstream having a maximum height of around 1400 m above sea level. The bedrock of the mountainous and much of the hilly terrain comprises granite, while other areas consist of metamorphosed sandstone, shale, mudstone, and schist. The low flatlands downstream are thick quaternary deposits consisting of 0.5 to 5.5 m thick Beruas Formation with a peat layer on top. This extends towards the sea coast with a 40 to 50m thick clayey formation. The soil is highly erodible consisting of deep coarse sandy clay on the foothills and lithosol on the main mountain range [15]. The general vegetation is dense tropical rain forest comprising of old trees, climbers, bamboo and palms. The lower hills and flat areas are mostly planted with rubber crops and horticultural crops [21]. There has been significant change in land-use over the years with urbanization accounting for about 20% at the expense of diminishing agriculture and forestland. Based on the Malaysian population census of 2000, the total population in the basin area was 1,176,173 with an average population density of 501.27/km^2 [7]. Moreover, with the growth rate of about 3.5% per year, the population is expected to dramatically increase in the basin area.

At 1, 988 km long, the Langat River is the main river of the

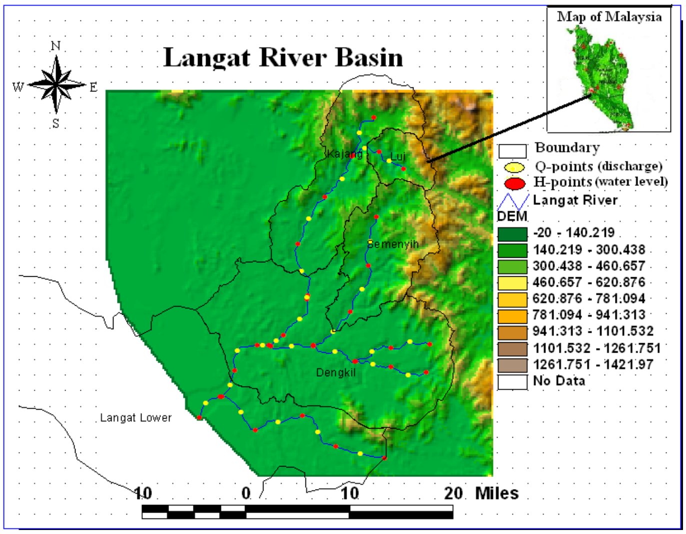

Figure 1. Location of the study area (Langat River Basin, Malaysia).

basin. In the middle section it is also called the Kajang River [8]. The Basin is divided into five main catchments comprising of the Lui, Kajang, Semenyih, Dengkil and the combined small catchments of Beranang and Labu. The Langat river headwater and its main tributaries drain the western flank of the main mountain range and flow southwest into the sea at the Straits of Malacca at the lower Langat plains. The climate of the Basin, as in most of Malaysia, is tropical, with a mean annual temperature of 32°C and a mean minimum and maximum of 23°C and 33°C respectively [49, 53]. There are two monsoon seasons in a year, the northeast monsoon from November to March and southwest occurring between May and September. The average annual rainfall depth at the basin is approximately 2,400 mm ranging from 1,800 to 3,000 mm [47] There is a gradual increase of rainfall from the coast towards the hilly areas. The highest rainfall is in the months of November and the lowest in January with a mean of 280 mm and 115 mm respectively. The average monthly rainfall for the selected rainfall stations in the Langat River Basin area is shown in Figure 4. Humidity is between 80 to 90 percent, a condition typical of areas with high temperatures resulting in high rates of evaporation. This hydrological region lies within 30% of the Malaysia Peninsular where potential runoff is 500 to 1000 mm annually [7, 9]. The groundwater recharging areas are in the upstream mountains and hilly areas. In the downstream an aquifer distributes water widely in the flat lowlands [54].

3. Results and Discussion

The methodologies adopted in this paper are illustrated in Figure 2. Two sets of rainfall data (recorded observed and QPF) and one set of discharge and evaporation data were processed to ensure a good comparison. Rainfall-runoff simulation involved the preparation of Langat River Basin parameters and modeling and analysis performed using functions available in the MIKE 11 hydrological system. The Basin was delineated into the five main sub-catchments where twenty rainfall stations were located based on their coordinates and individual rainfall time series entered [26, 41].

3.1. NAM model calibration for Langat Basin

The NAM rainfall-runoff (RR) model was applied for runoff processes based on the size and urban/rural characteristics of the Langat basin [13, 40–42]. The model was prepared and calibrated with appropriate data to create a reliable basin representation [3, 37]. Watershed parameters such as infiltration coefficients, time of concentration, and base-flow were modified to produce a best fit between model and observations. The discharge output was calibrated with observed stream-flow [6, 16, 23, 25, 32, 35]. Care was taken to achieve a good agreement between the average observed and simulated catchment runoff volume, the overall shape of the hydrographs and the root mean square error (RMSE) of the peak flows and low flows.

The study tested the possible assimilation of rainfall estimates based on a QPF for operational flood fore-

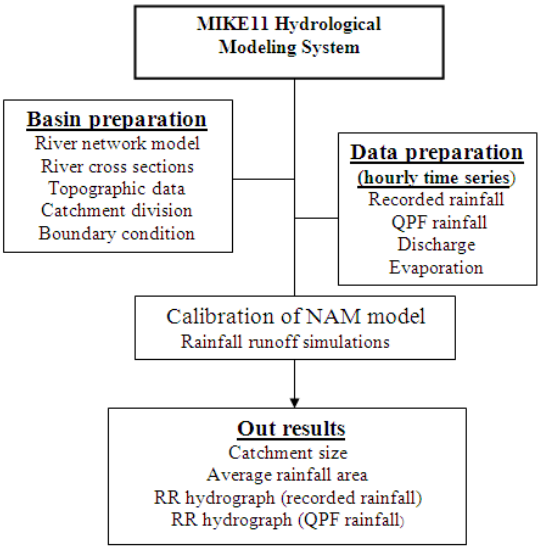

Figure 2. Preparation for recorded and QPF rainfall-runoff modeling.

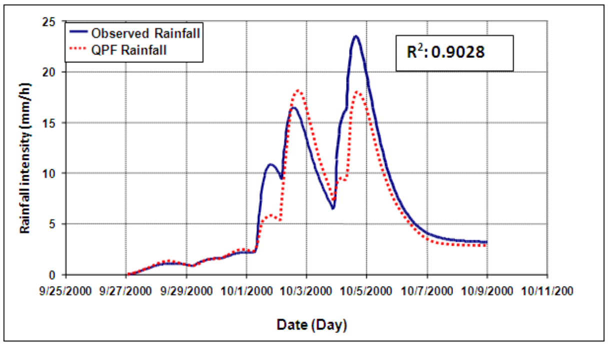

Figure 3. Comparison of recorded and QPF rainfall.

casting. Thus, the hourly rainfall estimates from the QPF were processed for runoff and subsequently the recorded observed rainfall for the same storm event was processed for runoff. The comparison of the QPF with the recorded observed rainfall showed $R^2 = 0.9028$ (Figure 3). A good rainfall runoff model should represent the characteristics and physical conditions of the actual river catchments [2, 11, 16, 23, 34] Thus the NAM model was prepared to outline the sub-catchment areas and the entire boundary of the Langat Basin in order to compute their surface areas. The combined total surface area of the five catchments were computed by the model as 2012.07 km^2 (Table 1) as against 1988 km^2 supplied in DID reports [8].

Table 1. NAM calculations of Langat sub-catchment areas.

Catchment	Model	Area km^2
Lui	NAM	70.7625
Dengkil	NAM	234.273
Kajang	NAM	310.77
Semenyih	NAM	695.548
Lower Langat	NAM	698.713
Langat Basin	Combine	2012.07

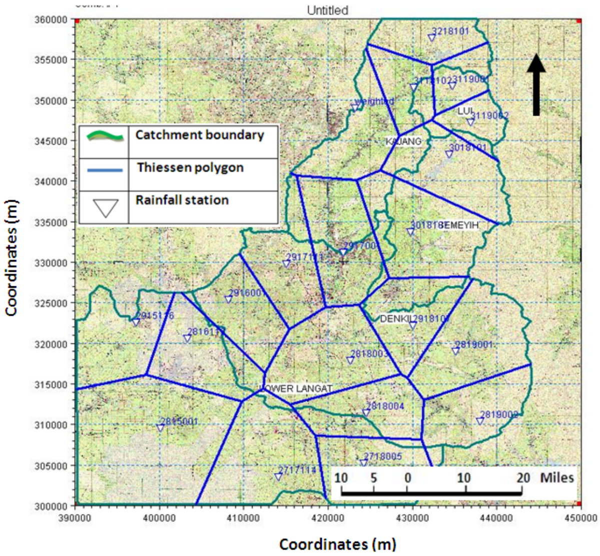

Figure 4. Averaged monthly rainfall for selected rain-guages.

Twenty rainfall station coordinates were identified in the delineated catchment and used to compute the mean weighted rainfall using the Theissen's polygon method (Figure 4). Auto-calibration was achieved by adjusting values of parameters such as the daily water balance (U_{max}, CQ_{OF}) and physical measured data (L_{max}, Sy) recommended in the DHI (Danish Hydrological Institute) user manuals. Other parameters were adjusted to fit the measured discharges through sensitivity analysis using trial-and-error method for CK, CK_{IF} and CK_{BF} calibration coefficients. Considering that the catchments had were similarly vegetated, but have major differences in topography from mountainous upstream to lowland downstream, the U_{max} was varied by catchment as this is related to moisture intercepted on the vegetation as well as to water trapped in depressions. Sensitivity analysis performed to examine uncertainties for some parameters showed that variations in CK_{IF} and CK_{BF} had significant impact in the computation.

The calibration considered multiple objectives that include a good simulation of water balance, overall similarity of the shape of the hydrographs, agreement of peak flows

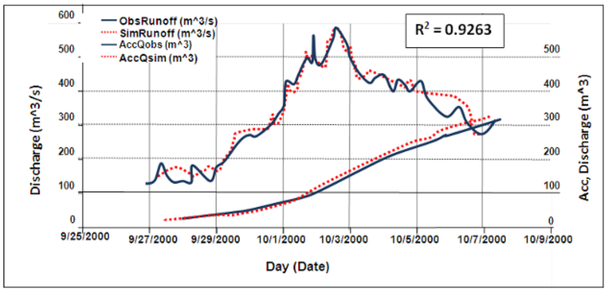

Figure 5. Record Rainfall-runoff and accumulated discharge (Kajang catchment).

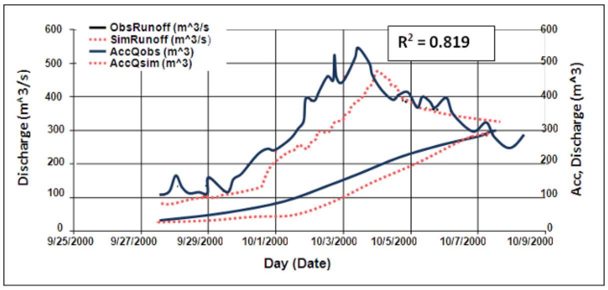

Figure 6. QPF Rainfall-runoff and accumulated discharge (Kajang catchment).

and a good conformity for low flow. These four objectives were optimized simultaneously during the calibration process. The average values used in the model simulation for Kajang catchment were $U_{max} = 10.4$ and $L_{max} = 233$ mm, other model parameters included are $CQ_{OF} = 0.202$, CK = 10.4 hr, $CK_{IF} = 329.2$ hr, TOF = 0.889, TIF 0.324, TG = 0.179 and $CK_{BF} = 1917$ hr. All nine NAM model parameter estimates were defined in the calibration process that included two of the significant NAM parameters (overland flow runoff coefficient and time constant for overland flow routing) that have a direct impact on the shapes and peaks of the discharge hydrographs.

3.2. Rainfall runoff simulation

By using all four objective functions in the optimization process based on the balanced aggregated objective function, the overall RMSE for the NAM calibration of the Kajang station showed a high coefficient of determination between the observed and simulated at $R^2 = 0.9263$ for the hydrological data modeling (Figure 5). This figure shows the comparison between the recorded (as observed) shown as a line, and simulated runoff shown as a dashed line, in m^3/s, while the graph below shows the accumulated discharges of the observed and simulated respectively. As well as this, the hourly rainfall estimates based on the cloud model QPF were used for rainfall runoff simulation, where it was converted to lateral flow in relation to the same catchment parameters calibrated by using the observed data [10]. The runoff of the QPF is shown in Figure 6, where a value of $R^2 = 0.819$ was achieved by comparing the observed and simulated hydrographs. The comparison between the observed and simulated accumulated discharge is also shown in the same figure.

Although both runoff simulations (recorded rainfall and QPF) for the Kajang sub-catchment showed a high coefficient of determination, the simulation of the QPF rainfall showed a value for R^2 slightly lower at about 80%. The reason for this lower R^2 value was that the QPF is based on rainfall estimates in the range of 3-12 mm/hr [5, 36] which varied significantly from the recorded observed rainfall. The size of the basin and sub-catchments was not considered a constraint in the model application as the study [34] has shown that the model can be employed in bigger catchments. Since the overall RMSE was $R^2 = 0.873$ for the total basin (2012 km^2) and in using the same time-interval the runoff hydrographs for both datasets showed a suitable relation between the observed and the simulated values, and the calibration was considered valid for the model application in the Langat Basin and may be valuable for other basins with similar physical characteristics.

4. Conclusion

Hydrological simulations are important techniques in flood forecasting where historical data, such as rainfall, and concurrent data are available. The effectiveness of historical rainfall data in this process may be questionable in operational flood forecasting, as this data does not provide a forecast of impending flood, but rather represents response of the catchment/environment to runoff from a given past rainfall. Therefore, in order to improve operational flood forecasting and also to extend the forecast horizon, improved QPF techniques also referred to as 'nowcasting' are being introduced. These techniques when coupled with a suitably calibrated model for rainfall-runoff simulation will provide pre-flood time forecasts extending peak runoff time and emergency response. In a rainfall-runoff simulation for operational flood forecasting a suitably calibrated runoff model is required, and depending on the size, environment and physical characteristics of the catchment area various types of models such the NAM rainfall runoff model may be applied. Since modeled runoff simulation with observed rainfall is very accurate with reliable precipitation forecasts as input, it is possible to obtain useful discharge future estimates for watershed characterized by very short response times. The NAM RR model which forms part of the MIKE11 hydrological system was calibrated in this study for rainfall-runoff simulation in the Langat river basin, Malaysia. The model was tested for runoff on an observed rainstorm (27 September – 8 October 2000) and then again on QPF (pre-real time estimates for the same rainstorm). The comparison of both runoff simulation hydrographs showed similarities in shape, characteristics and time of peak with a basin $R^2 = 0.873$ These results demonstrate that, with this improved QPF, an operational flood forecast can be made pre occurrence of the actual flood allowing for a forecast horizon adequate for flood management activities.

Acknowledgements

Authors acknowledge the support and contributions of the Malaysia Department of Irrigation and Drainage (DID) for providing the recorded rainfall, coordinates of rainfall stations, basin and catchment size, together with other supporting documents, records and reports for the Langat Basin and the flood event of 27th September to 8th October 2000. Authors are also very thankful to the anonymous referees who in the review provided useful comments and suggestions to improve the paper making it publishable in the Central European Journal of Geosciences.

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