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Hydrologic Analysis of a Tropical Watershed using KINEROS2

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Abstract

The application of an event based physical model, KINEROS2, on a developed tropical watershed in Malaysia was evaluated. Three storm events in different intensities and durations were required for KINEROS2 (K2) calibration. K2 validation was done using two other rainfall events before and after the calibration year. Calibration results showed excellent and very good fittings for runoff and sediment simulations based on the aggregated measure. Validation results demonstrated that the K2 was reliable for runoff modelling while the K2 application for sediment simulation was only valid for the period 1984-1997.

Keywords: KINEROS2; sediment; runoff; sensitivity analysis

1. Introduction

In recent years, application of process models has become an indispensable tool for understanding natural processes occurring at the watershed scale (Sorooshian *et al*., 1995). GIS-based spatial modelling has become a very important tool in runoff and soil erosion studies and consequently in development of appropriate soil and water conservation strategies, especially at the watershed scale. For instance, Kalin and Hantush (2003) assessed performances of KINEROS2 and GSSHA in simulating water and sediment movement. Regarding the obtained results it was realized that erosion in channels in GSSHA was not transport limited due to formulation weakness so the sediment routine in KINEROS2 was more robust than the routine used in GSSHA. In another study Smith *et al*. (1999) applied KINEROS2 to simulate runoff and sediment load by the selected events in the Catsop catchment, Netherland. The simulation results based on the data shortage represented that for successful erosion simulation, the existence of detailed hydrologic simulation was very important. Also, parameter selection was difficult without prior knowledge of the variations in soil condition between the events. They concluded that application of more physically realistic and detailed models with continuous simulation will lead to more accurate results than isolated events. Some other efforts have been made in the calibration and validation of Kineros model (Al-Qurashi *et al*., 2008; Canfield and Lopez, 2004; Duru and Allen, 1994; Kalin *et al*., 2003; Kalin and Hantush, 2003; Unkrich *et al*., 2010) but application of K2 in tropical climate is mostly limited to its ability in simulation of the impacts of forest roads on the soil erosion and sediment load (Ziegler *et al*., 2007; Ziegler and Giambelluca, 1997).

This work aimed at determining the sensitivity and validity of KINEROS2 (an event-based model) for water and sediment yield prediction at the Hulu Langat Basin, which is under intensive development in Malaysia.

2. Materials and Methods

2.1. Study Area

Based on available data about the Langat River Basin and the study objectives, the Hulu Langat sub basin with mean precipitation of 2453 mm was selected for this study. The sub basin is located between 3° 00' _ 3° 17' N and 101° 44' _ 101° 58' E with an upstream area of 390.26 km^2 on the upper part of Langat River Basin (Fig. 1). Hydrometeorologically, the basin is experiencing two types of monsoons, i.e. the Northeast (November to March) and the Southwest (May to September) (Noorazuan *et al*., 2003). In terms of land cover/use, 54.6% of the sub basin area is occupied by forest and 15.6% by rubber while urbanized areas amount to 15%. Orchards cover 2% of the sub basin area, mixed horticulture 1.8% and the rest is mostly covered by oil palm, lake, marshland and mining activities. Dominant soil types in the sub basin are steepland and Rengam-Jerangau soil series with sandy clay loam and clay textures respectively.

2.2. Data Sets

Hydrological data sets of the water discharge and sediment load for the Langat River were collected from the Department of Irrigation and Drainage, Malaysia. Precipitation data representing storm events were obtained from the rain gauge station # 3118102 closest to the basin centroid. Land use maps dated 1984, 1997, 2006 and corresponding soil maps were obtained from the Department of Agriculture, Malaysia. Digital topographic maps in the scale of 1 to 50000 were utilized for Digital Elevation Model (DEM) extraction via linear interpolation. To define the soil characteristics essential for use in K2, FAO soil database was utilized and modified based on the soil data obtained from Malaysia's reconnaissance soil maps and reports (Wong, 1970).

In this study, three storm events with different intensities and durations at the northeast monsoon, southwest monsoon and inter-monsoon periods of the year 1997 were chosen for calibration. Two other storms in the years 1984 and 2008 were selected to test the model validity before and after calibration (Table 1). Considering the scarcity[1] of accurate and adequate rainfall data in this basin, and our future need to evaluate LUCC[2] impacts on the basin hydrology regime and comparing the response of different planes to land cover change, only one rain gauge station with isolated rainfall on the basin surface was utilized for simulation.

2.3. KINEROS2

KINEROS2 (K2), an upgraded version of KINEROS (Woolhiser *et al*., 1990), is a physically event-based, distributed and dynamic model that predicts surface runoff, erosion losses, infiltration amount and interception depth from the watersheds declared by predominantly overland flow (Semmens *et al*., 2008; Smith *et al*., 1999). In this model, the watershed is

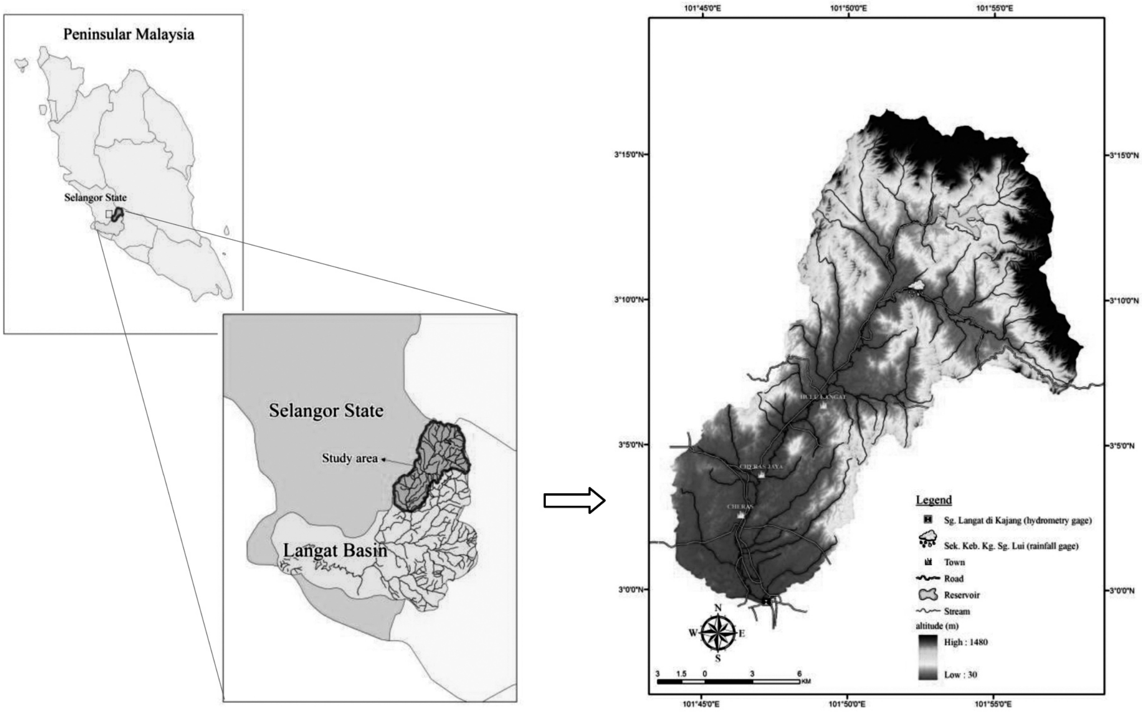

Figure 1. Study area

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[1] There is only one recorder rain gauge with data for the period 1984 - 2008 inside the basin. Outer stations suffer from lack of data.

[2] Land Use/Cover Change.

Table 1. Properties of selected storm events

Application	Date	Duration (hr)	RF		I_{15}_max (mm/hr)	I_{30}_max(mm/hr)
			mm	m^3		
Calibration	10/09/97	2.00	24.50	8415130.15	30.80	28.80
	13/10/97	2.25	14.10	4842993.27	14.40	14.40
	19/11/97	3.25	40.10	13773335.47	47.20	41.80
Validation	13/11/08	4.00	41.10	14116810.17	52.40	36.20
	03/11/84	2.00	9.90	3400399.53	10.00	8.00

I_{15}_max: maximum 15 min. intensity, I_{30}_max: maximum 30 min. intensity, RF: rainfall

approximated by a cascade of overland flow planes, channels and impoundments. Overland flow planes can be split into multiple components with different slopes, roughness, soils, etc. In this model contiguous planes can have different width (Semmens *et al*., 2008) [Fig. 2(a)]. In overland flow conceptual model, small scale spatial variability of infiltration can be represented in distribution sense and parameterized for numerical efficiency also it intercalates the microtopography in simulation. Urban element models runoff based on previous and impervious fractions [Fig. 2(b)] (Semmens *et al*., 2008). In K2, infiltration is dynamic and interacts with both rainfall and runoff. Conceptual model of infiltration incorporates two layers in soil profile and soil moisture will be redistributed during the storm hiatus.

Overland flow is considered as a one-dimensional flow, in which flux is estimated as:

$$Q = \alpha h^m \tag{1}$$

where: Q is discharge per unit width and h is the storage of water per unit area. Slope, roughness and flow regime are determinants of coefficients α and m (Semmens *et al*., 2008). The continuity equation of a channel can be estimated with kinematic assumption in which Q can be expressed as a unique function of A.

Sediment simulation of K2 considers multiple particle class size sediment routing, raindrop impacts and hydraulic shear entrainments. K2 simulates upland erosion caused by raindrop energy (splash erosion) and by flowing water (hydraulic erosion) for upland, channel, and pond elements. General mass-balance equation can be written as:

$$\frac{\partial(AC_s)}{\partial t}+\frac{\partial(QC_s)}{\partial x}-e(x,t)=q(x,t) \tag{2}$$

where, C_s is sediment concentration [L^3/L^3], Q is water discharge rate [L^3/T], A is cross sectional area of flow [L^2], e is rate of erosion of the soil bed [L^2/T], and q_s is rate of lateral sediment inflow for channels [$L^3/T/L$] (Semmens *et al*., 2008; Smith *et al*., 1999).

Compound channel routing in K2 differentiates main and overbank infiltration (Semmens *et al*., 2008).

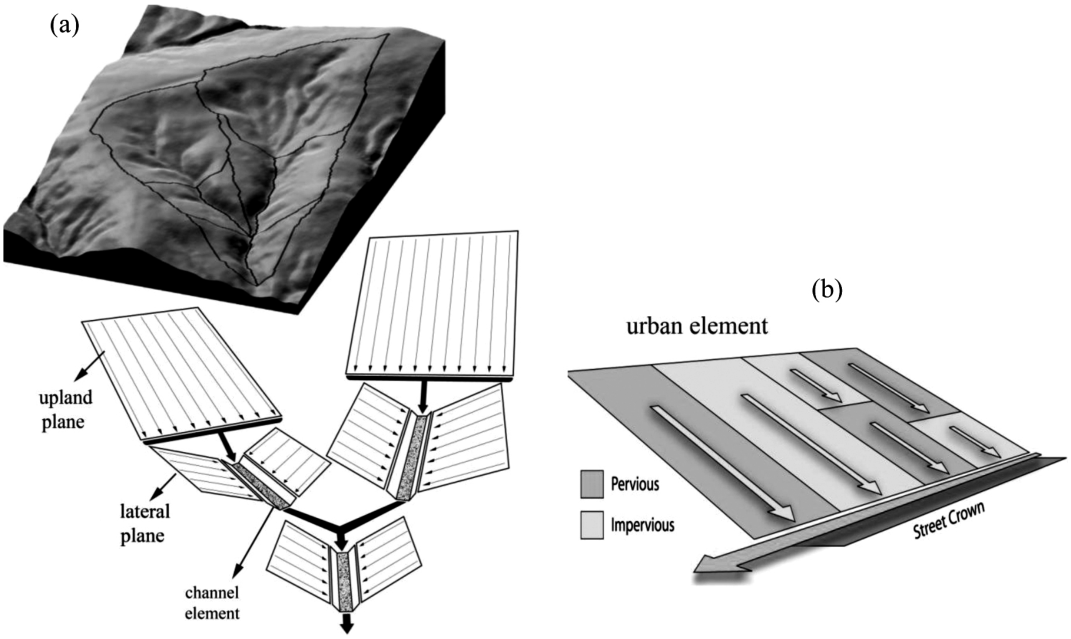

Figure 2. (a) Watershed topography schematically discretized into areas of predominantly overland flow and channel network, (b) Urban element (Adapted from Unkrich *et al*., 2010)

Since the model cannot simulate non-releasing ponds, drainage area of the Langat reservoir was eliminated hydrologically from the simulation. Microtopographic properties on the planes and base flow rate at the watershed outlets were initialized and to separate the base flow, local minimum method was applied on the data.

2.4. Calibration and Sensitivity Analyses

Both calibration and sensitivity analyses used a multiplier approach. In this approach, all initial estimates are increased or decreased by multiplying a factor. The statistical criteria used in this study were Model Bias (MB), Modified Correlation Coefficient (rmod), and Nash-Sutcliffe Efficiency (NS) (Richard and Gratton, 2001; Safari *et al*., 2009). Following equations describe these criteria:

$$MB = \left[\frac{\sum_{i=1}^{n}(Q_{s_i} - Q_{o_i})}{\sum_{i=1}^{n} Q_{o_i}}\right] \tag{3}$$

$$r_{mod} = \left[\frac{min\{\sigma_O, \sigma_S\}}{max\{\sigma_O, \sigma_S\}} * r\right] \tag{4}$$

$$NS = 1 - \left[\frac{\sum_{i=1}^{n}(Q_{s_i} - Q_{o_i})}{\sum_{i=1}^{n}(Q_{o_i} - \bar{Q}_O)}\right] \tag{5}$$

where: Q_{s_i} and Q_{o_i} are the simulated and observed water/sediment discharges at the time step *i*, Q_O is the average of observed flow in the simulation period, σ_O and σ_S define the standard deviations of observed and simulated discharges, respectively, *r* is the correlation coefficient between observed and simulated data, and *n* is number of observations in the simulation period. The perfect value for Model Bias is 0 while that for the other evaluators is 1. For assessing the size, shape and volume of simulated hydrographs/sedigraphs, an Aggregated Measure (AM) is calculated as follows:

$$AM = \frac{r_{mod} + NS + (1 - |MB|)}{3} \tag{6}$$

An AM value of 1 reflects a perfect fit. Table 2 presents classes of fit goodness based on AM value.

Sensitivity of the model to change was based on a set of parameters selected, and by modifying these parameters from their initial value, the degree of change in peak runoff and sediment load was determined for each event. Finally, mean change for all storm events was calculated and illustrated as Fig. 3. Coefficient of Variation (CV) was utilized for comparing the change magnitude of peak discharge and sediment load among the different parameters (Nearing *et al*., 2005). The parameters evaluated for sensitivity were saturated hydraulic conductivity for channels and for hill slopes (Ks_CH and Ks_HS), Manning's Roughness for channels and for hill slopes (n_CH and n_HS), mean capillary drive for channels and for hill slopes (G_CH and G_HS), coefficient of variations of Ks (CV_Ks), and rainsplash coefficient (C_f). The calibration year selected in this work was 1997, which reasonably represented watershed characteristics of both developed and undeveloped areas.

Table 2. Model performance categories (Adopted from Safari *et al*., 2009)

Goodness of fit	Aggregated Measure (AM)
Excellent	>0.85
Very good	0.70-0.85
Good	0.55-0.70
Poor	0.40-0.55
Very poor	<0.4

3. Results

3.1. Sensitivity Analysis

Sensitivity analysis of K2 showed that the model was very sensitive to changes in Ks and n parameters. Variations in n_HS and Ks_HS could lead to 193.87% and 114.67% variations in sediment yield, respectively. However, sensitivity of the model to variations in Ks and n for runoff simulation was not as high as that for sediment simulation. Sediment load variations resulting from changes of Ks and n over hill slopes were higher than changes across the channels. This condition allowed for reliable prediction of peak runoff for Ks variable but not for the parameter n. K2 was not sensitive to the changes in mean capillary drive of hill slopes (G_HS) but presented little sensitivity (about 2.7%) to G_CH variations. The mean of K2 sensitivity to CV of Ks for sediment and peak runoff was 12.27% and 8.41%, respectively. K2 sensitivity to variation of rainsplash coefficient was very low (0.17%). Mean CV of the water/sediment values for rainfall storm on 13/10/97 was higher than the variations for other storm events. Also the storm dated 19/11/97 showed the lowest sensitivity among the events under study (Table 3). As shown in Fig. 3, changes in Ks and n impacted the simulation results more than the other variables. These impacts were more pronounced on sediment simulation than on runoff simulation. The gradient of changes resulting from variations in Ks and n in the range 0 to -100 strongly increased while the slope of change due to CV_Ks variations in the range 0 - 400 was greater than the negative confine.

3.2. Calibration

Initial estimate of the parameters was done using

Table 3. Coefficient of variations in peak runoff and sediment load associated with the changes in model parameters

Event	Type	CV (%)								Mean
		Ks_HS	Ks_CH	n_HS	n_CH	G_HS	G_CH	CV_Ks	C_f	
10/9/1997	PR	75.67	40.93	79.15	96.64	0.00	3.01	4.32		44.24
	SL	88.00	37.74	161.11	85.91	0.00	2.54	13.22	0.02	48.57
13/10/1997	PR	136.29	74.82	99.26	148.46	0.00	4.02	6.40		67.04
	SL	196.50	128.15	309.07	179.88	0.00	4.63	17.11	0.33	104.46
19/11/1997	PR	48.73	14.61	43.78	62.41	0.00	0.98	4.52		25.00
	SL	59.52	15.01	111.43	47.37	0.00	0.87	6.48	0.15	30.10
Mean	PR	86.90	43.45	74.06	102.50	0.00	2.67	8.41		45.43
	SL	114.67	60.30	193.87	104.39	0.00	2.68	12.27	0.17	61.04

PR: Peak Runoff (m^3/s), SL: Sediment Load (t/ha)

the KINEROS Manual (Woolhiser *et al.*, 1990) and other literature sources (Abdul Ghaffar *et al.*, 2004; Arcement and Schneider, 1984). Silty loam and clay soils had the highest and lowest Ks and G values, respectively (Table 4). In order to optimize the model, these parameters were reduced within the channel. Due to special conditions of the Hulu Langat Basin, i.e. anthropogenic manipulations in channels and urban development particularly on the lower parts of basin, Manning's Roughness for channels was specified in three parts from upstream to downstream (Table 5).

Calibration results of the runoff simulation (Table 6) indicated that the model bias was highest for the event dated 13/10/97 (MB=-0.18) while the storm on 19/11/97 presented the highest r_{mod}, NS, and AM. Categorically, events dated 10/09/97 and 19/11/97 were classed as excellent class while the event dated 13/10/97 was classed as very good. Aggregated measures in sediment simulation were almost the same for all events except for 19/11/97. But this storm indicates more efficiency (AM=0.85) because of lower bias (MB=0.04) and higher NS (0.77) than the other events. Fig. 4 illustrates simulated and observed hydrographs and sedigraphs of the selected events. Simulated hydrograph of the 13/10/97 event was more matched to the observed data in terms of peak discharge than other storm events but not for sediment simulation. Some diversions are observed in rising and recession limbs of the simulated hydrographs than the real data which are higher for the event dated 13/10/97 than for other events.

3.3. Validation

Model validation was done based on storm events before (1984) and after (2008) the calibration year. Validation results (Table 7, Fig. 5) showed that K2 was able to simulate runoff with high accuracy (both before and after calibration year). Sediment yield simulation, however, only showed high accuracy for the 1984 event. K2 overestimated sediment load for events after 1997, especially in the developed parts of the basin; the simulated sediment load for 2008 (based on 2006 land use map) was five times the actual amount. Fig. 6 depicts the trend of sediment change with and without the simulation years after 1997.

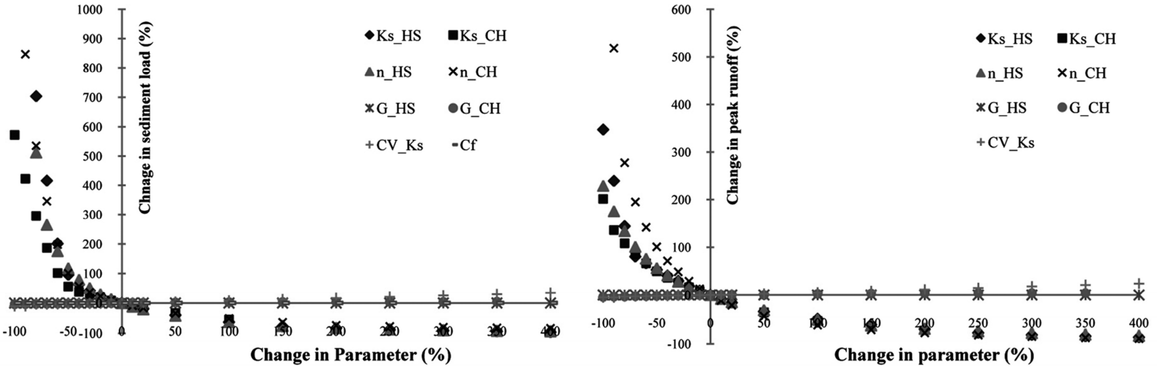

Figure 3. Change in sediment yield and peak runoff with change in selected parameters

Table 4. Initial and averaged optimized values for different soil physical properties in runoff and sediment modelling

Soil Texture	Ks_HS		CV_Ks	
	Initial	Optimized	Initial	Optimized
Direct Runoff Simulation				
C	0.60	1.46	0.50	2.00
L	13.00	31.63	0.40	1.60
SCL	4.30	10.46	0.60	2.40
SIL	6.80	16.55	0.50	2.00
SL	26.00	63.27	1.90	7.60
Sediment Load Simulation				
C	0.60	1.58	0.50	1.33
L	13.00	34.23	0.40	1.07
SCL	4.30	11.32	0.60	1.60
SIL	6.80	17.91	0.50	1.33
SL	26.00	68.47	1.90	5.07

Type of Simulation	Ks_CH		G_CH	
	Initial	Optimized	Initial	Optimized
Direct Runoff Simulation	210.00	38.50	10.00	2.33
Sediment Load Simulation		68.60		5.67

Table 5. Initial and averaged optimized values of the Manning's n for different land covers and channels in runoff (DR) and sediment (SL) modelling

Land cover	Initial	Optimized	
		DR Sim.	SL Sim.
Commercial/Industrial/Transportation	0.013	0.052	0.060
Bare Rock/Sand/Clay	0.033	0.133	0.152
Quarries/Strip Mines/Gravel Pits	0.033	0.133	0.152
Evergreen Forest	0.150	0.605	0.690
Agriculture (Except oil palm and rubber)	0.120	0.484	0.552
Grasslands/Herbaceous	0.100	0.403	0.460
Swamp/Marshland	0.060	0.242	0.276
Rubber	0.130	0.524	0.598
Oil palm	0.200	0.607	0.620

Region	Initial	Optimized	
		DR Sim.	SL Sim.
Upper Streams	0.035	0.112	0.281
	0.040	0.128	0.321
Middle Streams	0.050	0.160	0.402
Lower Streams	0.060	0.192	0.482
	0.070	0.224	0.562

Table 6. Fitting metrics of calibration events for runoff and sediment modelling

Fitting Metrics	Direct Runoff Simulation			Sediment Load Simulation		
	10/9/1997	13/10/1997	19/11/1997	10/9/1997	13/10/1997	19/11/1997
MB	-0.04	-0.18	-0.15	-0.02	0.13	0.04
r_{mod}	0.84	0.77	0.93	0.84	0.85	0.81
NS	0.81	0.78	0.84	0.69	0.80	0.77
AM	0.87	0.79	0.87	0.84	0.84	0.85
Goodness of Fit	Excellent	Very Good	Excellent	Very Good	Very Good	Very Good

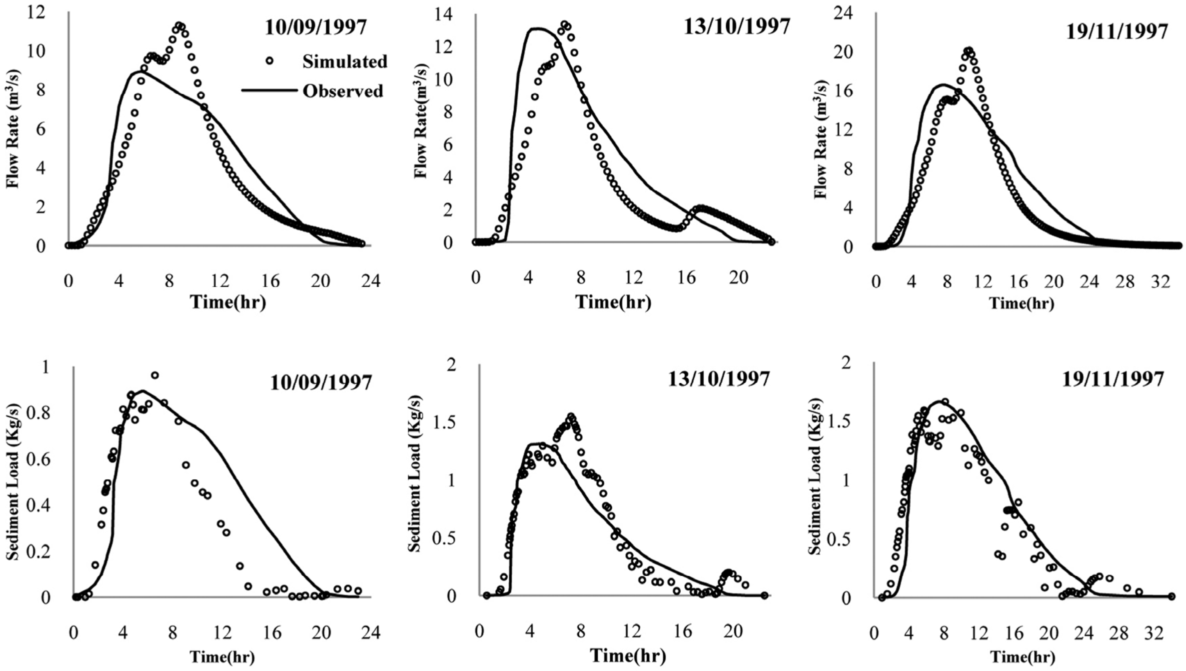

Figure 4. Simulated and observed hydrographs and sedigraphs of selected events

Table 7. Fitting metrics of validation events for runoff and sediment modelling

Fitting Metrics	Direct Runoff Simulation		Sediment Load Simulation	
	03/11/1984	13/11/2008	03/11/1984	13/11/2008
MB	0.28	0.10	0.11	-
r_{mod}	0.81	0.81	0.77	0.39
NS	0.71	0.79	0.84	-0.37
AM	0.75	0.83	0.83	-
Goodness of Fit	Very Good	Very Good	Very Good	Very Poor

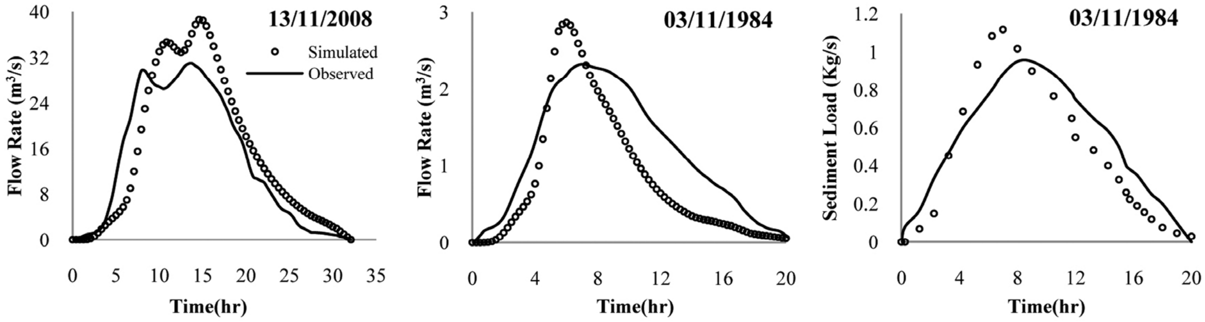

Figure 5. Simulated and observed hydrographs and sedigraph of the events used for validation

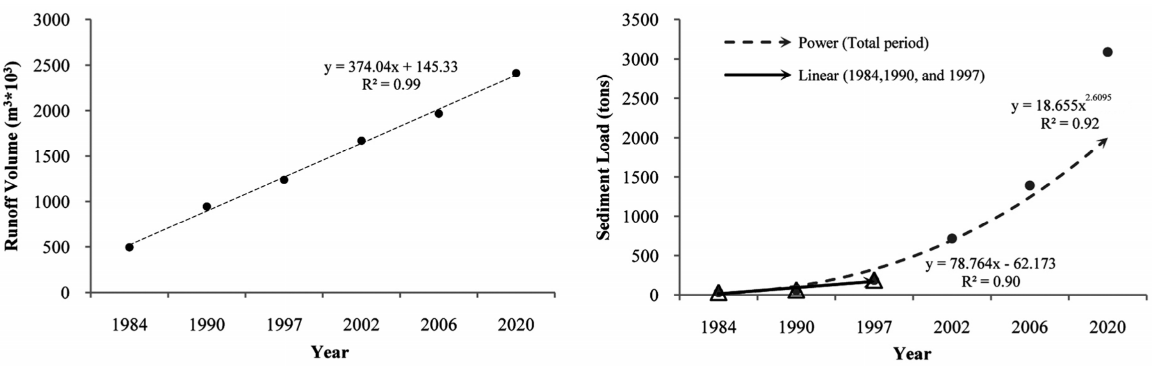

Figure 6. Trend of runoff volume and sediment load (sum of events) with the change in land use

4. Discussion

The sensitivity analysis showed that the parameters Ks and n had the most effect on K2 simulation outputs. This was also reported in a previous study by Al-Qurashi *et al.* (2008), who performed global sensitivity analysis on K2 by uniform random sampling of the parameter space and showed that K2 was highly sensitive to the parameters Ks, G, and n. Canfield (2006) stated that the Manning's Roughness on hill slopes was more sensitive than the Manning's Roughness in channels. In addition, reductions in both roughness values and Ks produced higher peak flow values. It was also declared that it is unlikely that a single, unique combination of parameter values will be found that reproduces the predicted peak discharge for different events. These results seem to endorse our outcomes about sensitivity analysis in this study.

The time for peak sediment discharge is most sensitive to n_CH and n_HS while total sediment yield is most sensitive to Ks. These findings are supported by Kalin and Hantush (2003). C_f and G were ineffective parameters on the simulation results, possibly due to the high saturation index (S_i=0.85) for all events in this study. Clearly, K2 was more sensitive to the parameters used for sediment simulation than those for runoff simulation (Martinez Carreras *et al.*, 2007; Nearing *et al.*, 2005).

Calibration results confirmed that K2 overpredicts peak water discharge for the events with high intensities and durations (10/09/97 and 19/11/97), and also overpredicts peak sediment discharge for the event with low intensity (13/10/97). This could be caused by the fact that only one rain gauge station was used and only one isolated storm event on the watershed surface was considered.

K2 was not validated for sediment simulation of events after 1997. As shown in Fig. 6, with increasing urbanization in southern planes of the basin, surface runoff is increased substantially. Increased surface runoff accelerates the stream transport capacity thus reducing the deposition amount. Water and sediment from the upstream planes flow towards the outlet and due to high transport capacity in the stream, a second peak was created in the sedigraph. This led to overprediction of the sediment discharge. Based on Fig. 6, direct runoff follows a linear trend while the sediment load trend is in power form. This demonstrates K2 overprediction of sediment load after the year 1997. The Hulu Langat watershed has been subjected to extensive anthropogenic manipulations in hydrological status. Some landforms resulting from urban development and agricultural activities were not captured in the land use and topography maps. This omission included most of the ponds at the Hulu Langat Basin, which can affect the sedimentation process through increased deposition rate. Taken together, this will cause a reduced sediment load from the planes (Fig. 7).

5. Conclusion

Based on the sensitivity analysis, it was found that Saturated Hydraulic Conductivity (Ks) and Manning's Roughness coefficient (n) are the most effective parameters for KINEROS2 (K2) simulation of runoff and sediment load. Based on the calibration, it was clear that in spite of close fits between observed and predicted values for runoff and sediment load, overprediction occurred with the peak discharge for events with high intensities and durations, and with the peak sediment discharge for events with low intensity. Based on the validation analysis, sediment load simulation using K2 was not valid for events after 1997, mostly attributable to missing features in the land use maps, such as ponds which trap sediments. To sum up, the results of this study established that K2 could simulate runoff well but, its capability in sediment load estimation was mostly limited to the accuracy of input data mainly land use maps.

Figure 7. Ponds not mapped in the existing land use maps (extracted from SPOT 5 satellite images dated 2007) arising from urban and agriculture development in the Hulu Langat Basin

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