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SWAT-based hydrological modelling of tropical land-use scenarios

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Abstract The Hulu Langat basin, a strategic watershed in Malaysia, has in recent decades been exposed to extensive changes in land-use and consequently hydrological conditions. In this work, the impact of Land Use and Cover Change (LUCC) on hydrological conditions (water discharge and sediment load) of the basin were investigated using the Soil and Water Assessment Tool (SWAT). Four land-use scenarios were defined for land-use change impact analysis, i.e. past, present (baseline), future and water conservation planning. The land-use maps, dated 1984, 1990, 1997 and 2002, were defined as the past scenarios for LUCC impact analysis. The present scenario was defined based on the 2006 land-use map. The 2020 land-use map was simulated using a cellular automata-Markov model and defined as the future scenario. Water conservation scenarios were produced based on guidelines published by Malaysia's Department of Town and Country Planning and Department of Environment. Model calibration and uncertainty analysis was performed using the Sequential Uncertainty Fitting (SUFI-2) algorithm. The model robustness for water discharge simulation for the period 1997–2008 was good. However, due to uncertainties, mainly resulting from intense urban development in the basin, its robustness for sediment load simulation was only acceptable for the calibration period 1997–2004. The optimized model was run using different land-use maps over the periods 1997–2008 and 1997–2004 for water discharge and sediment load estimation, respectively. In comparison to the baseline scenario, SWAT simulation using the past and conservative scenarios showed significant reduction in monthly direct runoff and monthly sediment load, while SWAT simulation based on the future scenario showed significant increase in monthly direct runoff, monthly sediment load and groundwater recharge.

Key words LUCC; SWAT; calibration; uncertainty analysis; Hulu Langat basin, Malaysia

Modélisation hydrologique de scénarios d'utilisation des sols en zone tropicale à l'aide du modèle SWAT

Résumé Le bassin du Hulu Langat, stratégique en Malaisie, a connu au cours des dernières décennies d'importants changements d'utilisation des sols et par conséquent des conditions hydrologiques. Dans cette étude, nous analysons l'impact des changements d'occupation et d'utilisation des sols (COUS) sur les conditions hydrologiques du bassin (en termes de débit et de charge sédimentaire), en utilisant l'outil d'évaluation des sols et des eaux (Soil and Water Assessment Tool – SWAT). Nous avons défini quatre scénarios d'utilisation du sol pour analyser l'impact de leurs changements d'utilisation: passé, présent (référence), futur et programme de préservation de l'eau. Pour analyser les impacts des COUS nous avons utilisé les cartes d'utilisation des sols de 1984, 1990, 1997 et 2002 comme scénarios passés. Nous avons défini le scénario présent en utilisant la carte d'utilisation des sols de 2006. La carte d'utilisation des sols de 2020 a été simulée en utilisant un automate cellulaire markovien, et définie comme scénario futur. Nous avons produit les scénarios de préservation de l'eau en nous basant sur les guides publiés par le ministère malais de la planification rurale et urbaine, et celui de l'environnement. Le calage du modèle et l'analyse d'incertitude ont été réalisés en utilisant l'algorithme d'ajustement d'incertitude séquentiel (Sequential Uncertainty Fitting – SUFI-2). La robustesse du modèle pour la simulation des débits sur la période 1997–2008 a été jugée bonne. Cependant, en raison d'incertitudes résultant essentiellement d'un fort développement urbain sur le bassin, sa robustesse pour la simulation de la charge sédimentaire a été jugée seulement acceptable sur la période de calage 1997–2004. Nous avons utilisé le modèle calé avec différentes cartes d'utilisation des sols sur les périodes 1997–2008 et 1997–2004, pour les estimations respectives du débit et de la charge sédimentaire. Par comparaison au scénario de référence, les simulations SWAT utilisant les scénarios passés et de préservation ont montré une réduction significative du ruissellement direct mensuel et de la charge sédimentaire mensuelle, alors que les simulations SWAT basées sur le scénario futur ont montré une augmentation significative du ruissellement direct mensuel, de la charge sédimentaire mensuelle et de la recharge souterraine.

Mots clefs changement d'occupation et d'utilisation des sols ; calage ; analyse d'incertitude ; bassin du Hulu Langat, Malaisie

INTRODUCTION

An understanding of the implications of changes in land cover and land use is a fundamental part of sustainable land planning and development. By definition, land cover indicates the physical land type such as forest or open water, whereas land use refers to how people use the land. On the one hand, transformation of land cover and land use by human action can affect the integrity of the natural resource system and the output of ecosystem goods and services. On the other hand, by careful planning, development of new patterns of land cover and land use can enhance the well-being of people (Millennium Ecosystem Assessment 2005). Modelling tools have changed the scientific framework for analysis of land-use systems from one that is descriptive to one that is more quantitative and addresses both spatial and temporal dynamics. Land-use models have a common objective of simulating landscape dynamics in the future at multiple scales based on different coherent scenarios (Kok *et al*. 2007). They improve the understanding and sensitivity of key processes within land-use patterns (Lambin *et al*. 2000). Scenario building based on land-use models facilitates the understanding of socio-ecological dynamics and behaviour (Veldkamp and Lambin 2001).

The Soil and Water Assessment Tool (SWAT; Arnold *et al*. 1998) was developed to predict the effects of different management practices on water quantity and quality, sediment yield and pollution loading in watersheds. This model has been used in a wide range of applications around the world. Calibration and uncertainty analysis of the SWAT model has been well explored by Eckhardt and Arnold (2001), Cao *et al*. (2006), Benaman *et al*. (2006), Anand *et al*. (2007), Bekele and Nicklow (2007) and Confessor and Whittaker (2007). Abbaspour *et al*. (2007) applied the Sequential Uncertainty Fitting-Version 2 (SUFI-2) algorithm for calibration and uncertainty analysis of SWAT in hydrology and water quality modelling of the Thur watershed in Switzerland. Their results demonstrated the efficiency of SUFI-2, integrated with SWAT, in flow and transport simulation.

Due to the enormous anthropogenic manipulations of the natural systems of river basins, SWAT application for assessing Land Use and Cover Change (LUCC) and Best Management Practice (BMP) impacts on watershed hydrological status and sustainable development is gaining momentum worldwide (Fohrer *et al*. 2001, Eckhardt *et al*. 2003, Haverkamp *et al*. 2005, Heuvelmans *et al*. 2005, Bracmort *et al*. 2006, Mishra *et al*. 2007, Lam *et al*. 2011, Yevenes and Mannaerts 2011). However, limitations in the application of SWAT due to its lack of detailed spatial definition have been shown in evaluation of targeted filter strips within a watershed, simulation of grassed waterways and riparian buffer zones, and simulation of wetlands (Gassman *et al*. 2007). As confirmed by Heuvelmans *et al*. (2005) and Gassman *et al*. (2007), SWAT also needs further development of the plant parameter database to support a greater range of vegetation scenarios. Recently, integration of SWAT with land-use simulation models (Githui *et al*. 2009a, Wilson and Weng 2011, Zhang *et al*. 2011, Dixon and Earls 2012) has become a new method for hydrological assessment of future and hypothetical land-use and land cover scenarios. Moreover, introducing land-use change modules, e.g. SWAT2009_LUC tool (Pai 2011) for SWAT has created a new facility for modellers who want to integrate changes in land use/land cover over the modelling period for predicting its impact on water, sediment and chemical yields in the watershed of interest.

The efficiency of SWAT in hydrological simulation of tropical watersheds has been established in the recent literature. For example, Phomcha *et al*. (2011) applied SWAT model in central Thailand to simulate the processes of sediment discharge. They concluded that, although the model was assessed using limited data and some of the model algorithms were not suitable for tropical conditions, the model bias was within the acceptable level. Raneesh and Santosh (2011) established the capability of SWAT for evaluating the effect of climate change on streamflow and vegetative growth in a humid tropical watershed of India. The SWAT model also performed satisfactorily in a data-poor complex watershed in Tanzania for water discharge estimation (Ndomba *et al*. 2008). Githui *et al*. (2009a) integrated the Conversion of Land Use and its Effects at Small regional extent (CLUE-S) model with SWAT to estimate the impact of land cover change on runoff in a tropical catchment in Kenya. This study provided useful insights into the sensitivity of the basin hydrological system attributable to alterations in land cover. At the same location, the SWAT model integrated with global circulation models was used to simulate climate change impacts on streamflow (Githui *et al*. 2009b).

The Langat watershed, located in the southern part of Klang Valley, is the most urbanized river basin in Malaysia. It is believed that this watershed is currently experiencing "spill over" effects due to excessive development within the Klang Valley. In recent decades, the Langat watershed has experienced rapid development toward urbanization, industrialization and intense agriculture. It is also a major source of drinking water for the surrounding areas, a source of hydropower and has an important role in flood mitigation. Over the past four decades, it has served approximately 50% of the Selangor State population with freshwater. However, Selangor State is currently facing water shortage problems, especially in urban areas (Memarian *et al*. 2012a).

Recent work on the hydrology of the Hulu Langat basin (located in the upper part of the Langat watershed) demonstrated significant trends in water discharge over the period 1984–2008 (Memarian *et al*. 2012a). The Hulu Langat basin (Fig. 1) was selected for LUCC impact assessment in this work.

The Hulu Langat basin, which is the most important in the upstream of the Langat watershed, is facing environmental problems due to unmanaged

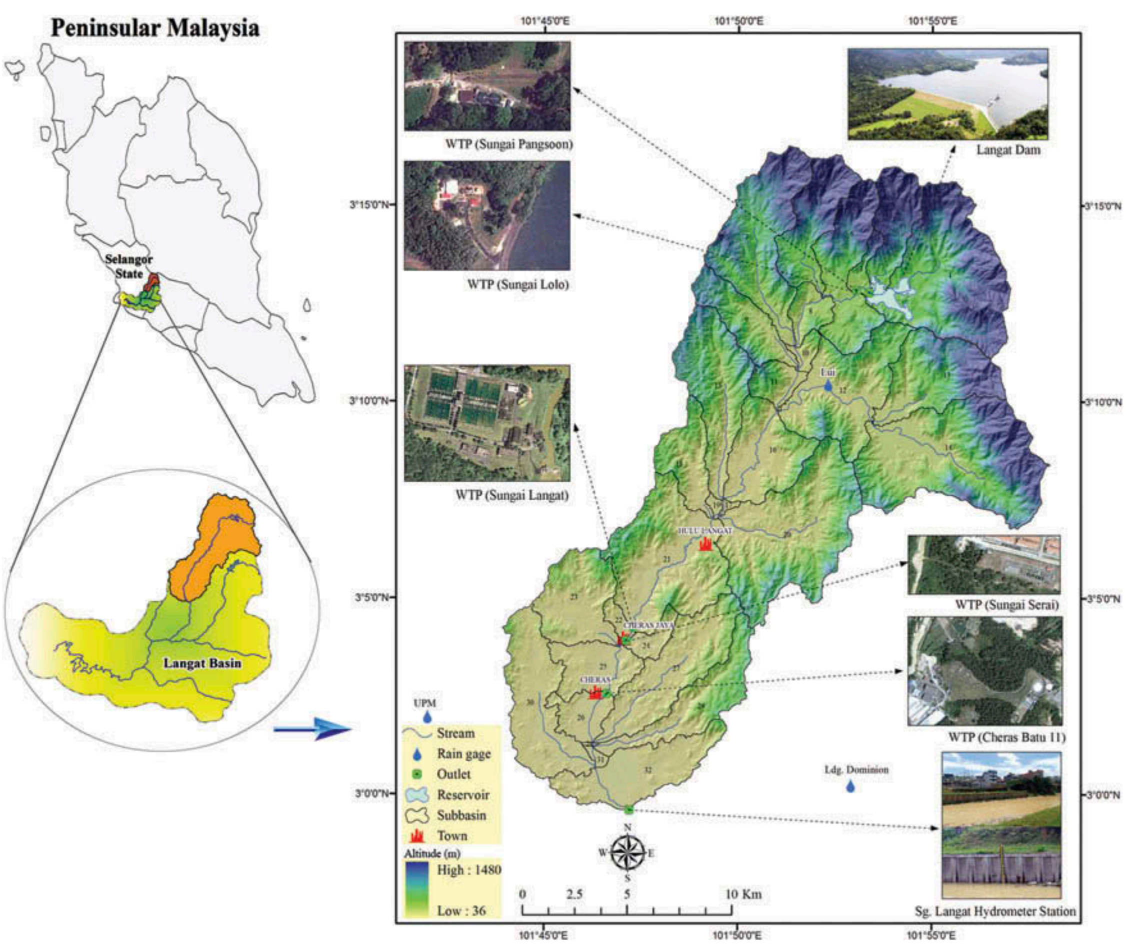

Fig. 1 Geographical location and hydrological features of the Hulu Langat basin.

urban and agricultural development. Currently, there are five water treatment plants (WTPs) and a balancing reservoir within the Hulu Langat basin, which secure clean water for downstream consumers. According to the guidelines of Malaysia's Department of Town and Country Planning and Department of Environment, there are severe limitations for urban development and agricultural activities in the upstream of water intake points. These limitations are mostly caused by the terrain and existing water supply structures within the basin. The existing development trend in the Hulu Langat basin, which does not appear to follow the development plan prescribed by the land-use authorities, has caused a drastic change in the basin's hydrological status (Memarian *et al*. 2012a, 2012b). The present trend, especially in urban and agriculture areas, may be a serious threat to soil and water resources within the basin.

This work, in contrast to other hydrological investigations within the Hulu Langat basin, aimed at developing water conservation scenarios and examining such scenarios using SWAT as a continuous hydrological model. The hydrological impact of the past, present and future land-use scenarios was also investigated.

MATERIALS AND METHODS

Study area

Hydro-meteorologically, the Hulu Langat basin is affected by two monsoon seasons, i.e. November–March (Northeast) and May–September (Southwest). The average annual rainfall is about 2400 mm. The wettest months are April and November, with an average monthly rainfall exceeding 250 mm, while the driest month is June, with an average monthly rainfall not exceeding 100 mm. The Hulu Langat basin has a rich diversity of landforms, surface features and land cover. Topographically, the Hulu Langat basin can be divided into three distinct areas relative to the Langat River, i.e. a mountainous area in the upstream, undulating land in the centre and flat floodplain in the downstream (Noorazuan *et al*. 2003, Memarian *et al*. 2012a, 2012c). Descriptions of this basin are given in Fig. 1 and Table 1.

Table 1 General information about the Hulu Langat basin.

Main river	Langat
Geographical coordinates	3°00′–3°17′N; 101°44′–101°58′E
Drainage area (km^2)	390.26
Basin length (km)	34.5
Average slope (%)	27.5
Altitude (m a.s.l.)	Max. 1480. Min. 36, Average 278
Reference hydrometer station	Sungai. Langat
Annual water discharge (× 10^6 m^3)*	289.64
Annual sediment load (× 10^3 ton)*	146.6
Annual runoff (mm km^{-2})*	742.16
Annual sediment yield (ton km^{-2})*	375.65
Reference rainfall station	UPM Serdang, Kampung Lui, Ladang Dominion
Precipitation (mm)*	2453
Land cover**	Forest (54.6%), cultivated rubber (15.6%), orchards (2%), urbanized area (15%), horticultural crops including oil palm, lake and mining land (12.8%)

* Based on data in the period 1984–2008; ** Based on the 2006 land use map.

Dataset

Monthly water discharge, monthly sediment load and daily precipitation data for the period 1984–2008, recorded at Sungai Langat hydrometric and raingauge stations were obtained from the Department of Irrigation and Drainage, Malaysia. Land-use maps dated 1984, 1990, 1997, 2002 and 2006, and a soil map, were obtained from the Soil Resource Management and Conservation Division, Department of Agriculture (DOA), Malaysia (Table 2, Fig. 2). According to the DOA, land-use maps at the scale of 1:50 000 were mapped based on Landsat satellite imagery, topographic maps and field survey. To extract the Normalized Difference Vegetation Index (NDVI), satellite images dated 1990 and 2006 scanned by the Landsat Thematic Mapper were obtained through the Global Land Cover Facility (GLCF) (http://glcf.umiacs.umd.edu/). There are two strategic dams in the Langat watershed, the Langat and Semenyih dams. The Langat Dam in Hulu Langat basin, was constructed in 1979, has a drainage catchment area of 41 km^2 and a reservoir capacity of 33 × 10^6 m^3. It supplies domestic and industrial water and is used to generate power supply at moderate capacity for consumption within the Langat Valley. Currently, there are five WTPs within the study area (Fig. 1). The Sungai Lolo, Sungai Pangsoon, Sungai Langat, Sungai Serai, and Cheras Batu 11 WTPs along the Langat River produce 0.41, 1.82, 386.4, 0.9 and 27 ×

Table 2 Land-use categories.

Land use code	Abbreviation	Description
1	AGLT	Agricultural activities in the Hulu Langat basin, including horticulture crops
2	BSVG	Barren or sparsely vegetated lands, including bare land and sand/stone mining activities
3	FRSE	Forest (evergreen)
4	RNGE	Range and idle grassland
5	WETL	Wetlands comprising swamps and marshlands
6	OILP	Oil palm
7	RUBR	Rubber
8	URLT	Urban/built-up area in the Hulu Langat basin, mostly includes urban and rural residential area
9	WATR	Waterbodies

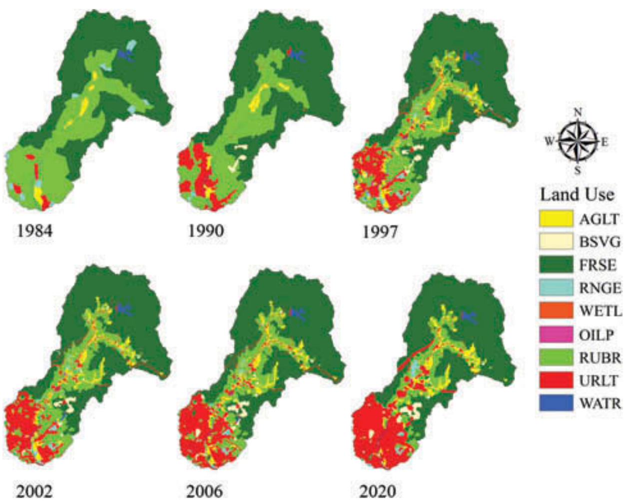

Fig. 2 Land-use maps used for scenario analysis (acronyms are defined in Table 2).

10^6 L per day (MLD) of clean water, respectively (Puncak Niaga Sdn. Bhd. 2008, Juahir 2009).

Computational framework

The computational framework of this study is depicted in Fig. 3. The work was carried out using four main steps:

1. Construction of topographic, climate, soil, hydrology and management databases. The management database contains spatial (overlay operation and cellular automata analysis in geographic information system, GIS) and stochastic (Markov chain analysis) techniques for extracting water conservation and future land-use scenarios. This database includes all Land Use/Land Cover (LULC) maps/scenarios together with their attributes.
2. SWAT simulation, including sub-basin discretization, hydrological response unit (HRU) extraction, reservoir simulation, WTP simulation, and climate simulation.
3. SWAT optimization using SUFI-2, including sensitivity analysis, calibration and uncertainty analysis.
4. Land-use scenario analysis, including past, present, future and water conservation scenario analysis based on hydrological outputs of the optimized SWAT.

Details of these four steps are discussed in the following sections.

Theory of SWAT

Watershed hydrology simulation in SWAT features two major phases. The land phase controls the amount of water, sediment, nutrient and pesticide loading into the main channel in each sub-basin. The water or routing phase controls the movement of water, sediments and nutrients through the channel network of the watershed to the outlet (Neitsch *et al.* 2011). Each sub-basin in SWAT is discretized into a series of HRUs, which are unique in their soil–land-use–slope combinations (Abbaspour *et al.* 2007). In this work, surface runoff was estimated based on the Soil Conservation Service curve number procedure (USDA Soil Conservation Service 1972), which requires only daily precipitation data and does not assume soil profile homogeneity, as considered by the Green-Ampt method (Green and Ampt 1911). In SWAT, soil erosion caused by rainfall and runoff is computed by the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975).

In the routing phase, SWAT uses Manning's equation to calculate the rate and velocity of flow. Due to existing limitations in the Muskingum routing method in SWAT (Kim and Lee 2010), the variable storage routing method (Williams 1969) was used for

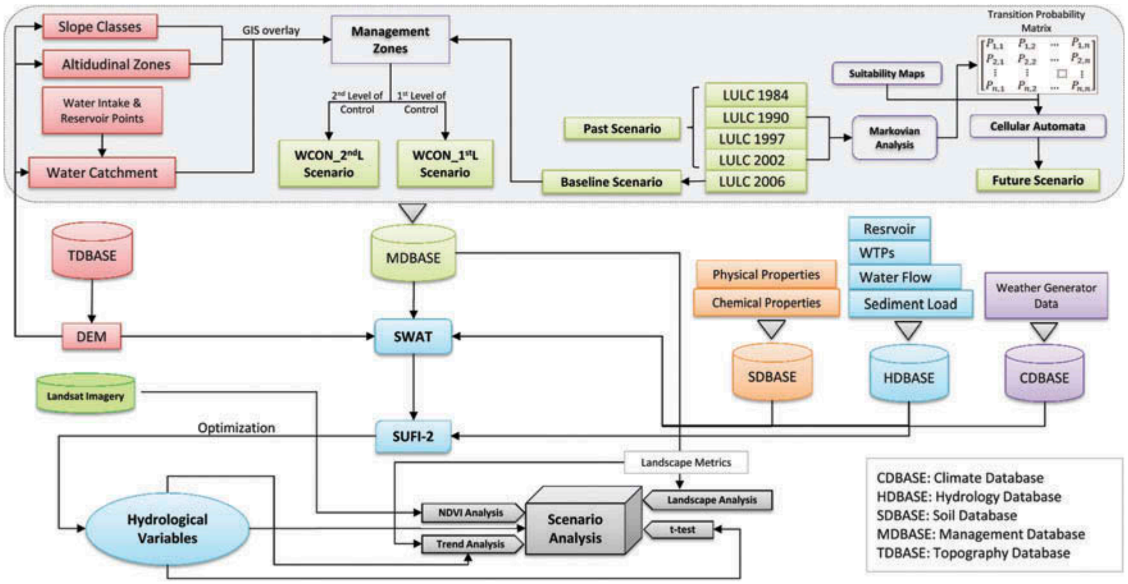

Fig. 3 The computational framework of the study.

flow routing through the channel network. The maximum amount of sediment that can be transported from each segment of the stream is calculated by the simplified Bagnold equation (Williams 1980). The maximum amount of sediment concentration, $conc_{sed,ch,mx}$ is compared to the amount of sediment concentration in the reach at the beginning of the time step, $conc_{sed,ch,i}$. Deposition will occur in the reach segment when $conc_{sed,ch,i} > conc_{sed,ch,mx}$; thus, the net amount of deposited sediment can be calculated. Degradation will occur in the reach segment when $conc_{sed,ch,i} < conc_{sed,ch,mx}$; thus, the amount of re-entrained sediment can be calculated (Neitsch *et al*. 2011).

Growth parameters in the crop growth database of SWAT are used to define plant growth under ideal circumstances and determine the impact of water stresses on plant growth. Several parameters are identified for 110 crop/vegetation types in the crop database attached to the SWAT model. SWAT is able to discriminate between annual and perennial plants. Annual plants grow from the planting date through to the harvest date or until the accumulated heat units equal the potential heat units for the plant. Perennial plants preserve their root systems throughout the year, becoming dormant in the winter months. They continue growth when the daily average temperature exceeds the minimum, or the required base temperature (Neitsch *et al*. 2011, Raneesh and Santosh 2011). The beginning and end of dormancy are defined by a threshold day length. The dormancy threshold varies with latitude and is defined as zero for tropical areas (Neitsch *et al*. 2011). According to the program code, dormancy should not occur in tropical and sub-tropical latitudes, i.e. at latitudes of less than 20 degrees.

Model set-up

The Hulu Langat basin was divided into 32 sub-basins and 647 HRUs. A digital elevation model (DEM) was extracted from the contours at a scale of 1:50 000 using linear interpolation. A digitized stream map extracted from the topographic data was used to construct a hydrographical network and to discretize the sub-basins. Water intakes and reservoir locations along the Langat River were digitized and used as the manually added outlets. Land-use maps were reclassified into nine categories (Table 2). The soil map comprised five categories, as shown in Table 3. The slope map was reclassified into three categories, i.e. <5%, 5–12% and >12%, and overlain with the land-use and soil maps to construct HRUs.

For climate simulation, 24 years of historical data from the weather stations Universiti Putra Malaysia (UPM) (Station ID: 44302) and Petaling Jaya (PJ) (Station ID: 48648) were used to construct the weather generator files. The precipitation files were constructed based on the precipitation records at UPM, Lui (Station ID: 3118102) and Dominion (Station ID: 3018107) stations over the period 1984–2008. Precipitation gauges were chosen to give the greatest possible coverage over the basin (Fig. 1).

In this study, the codes FRSE, RUBR, OILP, RNGE and WETL were assigned to denote forest,

Table 3 Soil map categories.

Abbreviation	Type	Texture	Depth (mm)	Areal proportion (%)
LNGTMNGSBN	Munchong-Seremban soil series	Clay	1296	3.6
LNGTRNMJRU	Rengam-Jerangau soil series	Clay	1370	23.0
LNGTTGABLA	Telemong-Akob-Local alluvium soil series	Clay	966	7.3
LNGTSTPLND	Steepland soils	Sandy clay loam	600	56.6
LNGTMINLND	Mining land	-	-	0.7
LNGTURBLND	Urban land	-	-	7.8
LNGTWATBDY	Water bodies	-	-	1.0

rubber, oil palm, rangeland and wetland, respectively, in the SWAT database. Orchard farming is the dominant agricultural activity within Hulu Langat basin. A new code, AGLT, was defined for agricultural activities and its growth parameters were determined using the average of growth parameters of the available tropical fruit trees attached in the SWAT database. The values of radiation-use efficiency and harvest index were adjusted to obtain biomass and yield production figures close to the average values reported in the literature (Kamil *et al*. 1996, Abdul Ghani *et al*. 1999, Ismail and Mamat 2002, Ahmad and Abdul Ghani 2004, Kuala Lumpur Kepong Berhad 2010, Muhamat *et al*. 2011) and the statistics presented by the Malaysian Department of Agriculture and Department of Forestry. The WATR and BSVG codes in the SWAT database were assigned to water bodies and bare land (including mining activities). Another new code, i.e. URLT, was defined for urban/residential area using the weighted average of urban area parameters from industrial, commercial, transportation and residential areas.

In reservoir simulation, target release was selected as the method to calculate reservoir outflow. In this method, water releasing from the reservoir is a function of the desired target storage. The target release method attempts to follow general release rules that may be used by reservoir operators. Although this approach is simplistic and does not consider all decision criteria, it reasonably simulates major outflow and low-flow periods (Neitsch *et al*. 2011). According to the data obtained from the National Hydraulic Research Institute of Malaysia and Puncak Niaga Sdn Bhd, the Langat Reservoir was simulated so that it can secure at least 30% of the water requirement for downstream WTPs from November to April and 270 $\times 10^6$ L d^{-1} balancing capacity from May to October. A direct abstraction (0.41 $\times 10^6$ L d^{-1}) from the reservoir for Sungai Lolo WTP was also considered in reservoir simulation. Water-use files were written based on the water intake quantity for each sub-basin. The target level of water supply in this study was computed as 469 $\times 10^6$ m^3 year^{-1}. This target level took into account the amount of water needed for operational WTPs along the Langat River, the 47% projected growth rate of domestic/industrial water demand in 2020 as compared to that in 2006 (Azhari and Zainal 2007), and the available demand for irrigation and other downstream uses. According to Azhari and Zainal (2007), there is no significant difference in irrigation water demand between the year 2006 and that projected for 2020. SWAT simulation was performed using a 7-year warm-up period. Baseflow separation was accomplished using the recursive digital filter method (Eckhardt 2004, Lim *et al*. 2005).

Calibration and uncertainty procedure

The SUFI-2 algorithm, under the SWAT-Calibration and Uncertainty Procedure (SWAT-CUP) interface, was used for calibration and uncertainty analysis. SUFI-2 accounts for all sources of uncertainties, such as uncertainty in the controlling variables, conceptual model, parameters and measured data. In this method, the P factor represents the degree to which all uncertainties are accounted for and is computed as the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU). Using the Latin Hypercube sampling, the 95PPU is computed at the 2.5% and 97.5% levels of the cumulative distribution of an output variable (Abbaspour *et al*. 2007, Yang *et al*. 2008, Abbaspour 2011). The robustness of a calibration/uncertainty process is quantified by the D factor, which is the average thickness of the 95PPU band divided by the standard deviation of observed data. Hence, SUFI-2 attempts to bracket most of the observed data (large P, optimum 95%) with the smallest possible value of D (minimum 0) (Abbaspour *et al*. 2007, Yang *et al*. 2008, Abbaspour 2011).

In the first step of the SUFI-2 algorithm, the objective function and meaningful parameter ranges are defined. Then a Latin Hypercube sampling is carried out, the corresponding objective functions are evaluated, and the sensitivity matrix and the parameter covariance matrix are calculated. In the next step, the 95% predictive interval of a parameter is computed (Abbaspour 2011). After computation of the 95PPU, the indices *P* and *D* are calculated. The *D* factor is computed using:

$$D = \frac{\frac{1}{n}\sum_{t_i=1}^{n}\left(y^M_{t_i,97.5\%} - y^M_{t_i,2.5\%}\right)}{\sigma_{\text{obs}}} \tag{1}$$

where $y^M_{t_i,97.5\%}$ and $y^M_{t_i,2.5\%}$ represent the upper and lower boundary of the 95PPU, and σ_{obs} is the standard deviation of measured data (Abbaspour 2011).

The goodness of calibration and prediction uncertainty is judged based on the closeness of *P* to 0.95 and *D* to 0. The parameter uncertainties are initially large; therefore, further sampling rounds are required with updated parameter ranges. The top *p* solutions (behavioural solutions) are used to calculate the lower and upper limit of the hypercube and the largest range is used for the updated parameter range. These criteria ensure that the updated parameter ranges are centred on the top *p* current best estimates, where *p* is a user-defined value. For subsequent iterations, however, it results in narrower parameter ranges. In SUFI-2, a threshold for the objective function is given to separate the behavioural solutions from the non-behavioural ones (Abbaspour *et al*. 2007, Yang *et al*. 2008, Abbaspour 2011).

In this work, the Nash-Sutcliffe (NS) coefficient (Nash and Sutcliffe 1970) was employed as the objective function. Average diversions from the model predicted values to their corresponding measured values were estimated using the percentage bias (PBIAS). Positive values indicate model underestimation, while negative values indicate model overestimation (Gupta *et al*. 1999, Parajuli *et al*. 2009). The SUFI-2 was run using 12 parameters for water discharge calibration and eight parameters for sediment load calibration (Table 6). Calibration and uncertainty analysis was performed based on 79 records of the observed data for the period 1997–2004. The period 2005–2008, with 40 measured records, was used for validation analysis. Simulation was performed based on the 1997 land-use map which features both conditions of the Hulu Langat basin, i.e. partial urban development and intense urban development. The first condition includes the period 1984–1990, while the second condition is matched with the period 2002–2008.

Sensitivity analysis

In SUFI-2, the parameter sensitivities are determined using a multiple regression approach that relates the Latin Hypercube generated parameters to the objective function values, using:

$$g = \alpha + \sum_{i=1}^{m} \beta_i b_i \tag{2}$$

where α and β are the intercept and the slope of the regression line, respectively; *m* defines the number of model runs; and *g* is the objective function.

The significance of differences in multiple runs for the parameter b_i is examined using the *t*-test. A *t*-test determines the relative significance of each parameter b_i and the *t* statistic is a measure of sensitivity (larger absolute values are more sensitive) (Abbaspour 2011). However, this approach provides relative sensitivities based on linear approximations and, therefore, only gives partial information about the sensitivity of the objective function to model parameters. Furthermore, using the *t*-test, relative sensitivities of different parameters are dependent on the range of parameters. Hence, the ranking of sensitive parameters may change in each iteration of the algorithm (Abbaspour 2011).

Scenario development

Baseline scenario The 2006 land-use map was set as the baseline scenario for comparison with the past, future and water conservation scenarios.

Past scenarios In this study, land-use maps dated 1984, 1990, 1997 and 2002 were defined as the past scenarios for LUCC impact analysis. These land-use scenarios were designed to show how the hydrological regime of Hulu Langat basin has been influenced by anthropogenic alterations during the past three decades of development. Frequency percentages of different land-use categories and changes relative to the baseline scenario across the total landscape are given in Table 4. Table 4 shows that AGLT, BSVG and URLT for the period 1984–2002 have areal proportions smaller than those of the baseline

Table 4 Proportions of different land-use categories across the total landscape and changes relative to the baseline scenario (acronyms are defined in Table 2).

Scenarios	Past				Baseline	Future	Water conservation	
Land-use code	1984	1990	1997	2002	2006	2020	WCON_1stL	WCON_2ndL
Proportion (%)								
AGLT	1.82	1.88	5.52	5.73	5.84	6.19	0.82	5.75
BSVG	0.00	0.76	0.95	1.16	1.96	1.95	0.78	0.78
FRSE	55.60	57.46	56.89	55.76	55.88	54.93	57.84	57.60
RNGE	2.28	0.23	1.72	1.46	1.09	1.42	1.09	1.09
WETL	0.00	0.10	0.45	0.42	0.39	0.37	0.39	0.39
OILP	0.00	0.00	0.13	0.06	0.05	0.09	0.01	0.05
RUBR	37.81	30.69	22.27	20.98	17.80	11.90	28.55	17.55
URLT	1.52	7.91	10.95	13.29	15.90	22.00	9.44	15.71
WATR	0.97	0.97	1.13	1.14	1.09	1.15	1.09	1.09
Changes relative to the baseline scenario (%)								
AGLT	–68.86	–67.73	–5.51	–1.76	0.00	6.04	–85.91	–1.54
BSVG	–100.00	–61.22	–51.56	–40.80	0.00	–0.69	–60.34	–60.34
FRSE	–0.51	2.82	1.80	–0.22	0.00	–1.71	3.49	3.07
RNGE	109.34	–78.81	57.95	33.88	0.00	30.54	–0.02	–0.02
WETL	–100.00	–74.50	16.35	7.81	0.00	–4.22	0.02	0.02
OILP	–100.00	–100.00	136.91	15.45	0.00	65.08	–72.53	0.02
RUBR	112.49	72.46	25.12	17.89	0.00	–33.13	60.41	–1.39
URLT	–90.44	–50.29	–31.15	–16.43	0.00	38.32	–40.63	–1.22
WATR	–10.66	–10.66	4.29	4.50	0.00	5.86	0.02	0.02

scenario. However, RNGE and RUBR show higher areal proportions, relative to the baseline scenario. FRSE and RNGE show higher fluctuations than the OILP, WATR and WETL categories, while FRSE has a higher areal proportion in the period 1990–1997, than in the baseline scenario.

Future scenario The Cellular Automata-Markov (CA-Markov) approach was used to model the 2020 land-use map. The year 2020 is the target time for Malaysia to become a fully developed country. Therefore, hydrological simulation based on the future scenario can be a projection of present land-use planning decisions to 2020. The CA-Markov modelling allows simulation of land changes between the multiple categories, and combines CA and Markov chain procedure (Markov 1907) for land cover prediction (Eastman 2003). This procedure relaxes strict assumptions associated with the Markov approach and explicitly considers both spatial and temporal changes (Agarwal *et al*. 2002). The CA-Markov approach in the IDRISI program involves two techniques, i.e. Markov chain analysis to produce a transition probability matrix, and cellular automata to map the probabilities of land-use transitions (Araya and Cabral 2010). Cellular automata underlie the dynamics of change events based on the proximity concept so that the regions closer to existing areas of the same class are more likely to change to a different class. A cellular automaton is a cellular entity that independently varies its condition based on its previous state (according to a Markov transition rule) and adjacent neighbours (Eastman 2003). Calibration of the CA-Markov approach was based on the changes in land cover for 1990–2002 (12 years) (Memarian *et al*. 2012c). The 2006 land-use map was used for validation analysis using the Kappa measurement (Cohen 1960).

Table 4 shows a marked increase in URLT proportion and decrease in RUBR proportion in 2020, relative to the baseline scenario. Other land-use categories are projected to change marginally in 2020.

Water conservation scenarios These scenarios can be preferred as the replacement plans for the past, present and future land-use scenarios. According to the guidelines prepared by the Department of Town and Country Planning, Malaysia (as cited by Anuar *et al*. 2000), a catchment that is required to produce clean surface water and groundwater should have the following characteristics:

– be situated above a water intake point,
– be situated more than 100 m above sea level,
– have slopes of more than 10°,
– contain balancing reservoirs,
– include drainage areas, which recharge the aquifer (for groundwater usage).

Table 5 Management plan for each zone in the water conservation scenario (adapted from Anuar *et al*. 2000).

Management zone	Properties	Activities allowed	Immediate action
Conservation	Upstream of the dam	No development allowed except very passive activities such as research, education and nature tourism	Need to be conserved and controlled strictly especially to the approved development inclusive the development project nearby the reservoir
Preservation	Altitude >300 m, Slope >25°, Upstream of the water intake point	No development allowed except very passive activities such as research, education and nature tourism, agro-based tourism, recreation and controlled logging activities	Same as above and camping activities are not allowed within the existing water catchment area boundary
Control (1st level)	Altitude: 0–300 m, Slope: 0°–25°, Upstream of the water intake point	Low-scale development (environment friendly)	Monitoring, assessing and reducing proposal at hill slope. Development at 25° slope is not allowed immediately
Control (2nd level)		Very controlled logging, certain types of crop, certain developments allowed, no mining activity, no nuclear or radioactive based activities allowed	Industrial activities not allowed especially at the bank of river
Free	Downstream of the water intake point	Without any limitation in development	Existing developments remain active

As mentioned previously, there are five WTPs along the Langat River within Hulu Langat basin, and the catchment area upstream of the WTP at Cheras Batu 11 was discretized as a water catchment area. Based on the Guidelines for Uphill Development (Department of Town and Country Planning 1995), Environmental Quality Order (Department of Environment 1987) and Riverfront Development Guidelines (Department of Irrigation and Drainage 1993), as cited by Anuar *et al.* (2000), four management zones, i.e. conservation, preservation, control and free, were defined within the Hulu Langat basin (Table 5 and Fig. 4). For mapping water conservation scenarios, the slope, altitude and catchment maps were classified into three categories:

– Slope:
  [1] <10° (low risk);
  [2] 10–25° (medium risk);
  [3] >25° (high risk)
– Altitude:
  [1] <100 m (low risk);
  [2] 100–300 m (medium risk);
  [3] >300 m (high risk)
– Catchment:
  [1] Downstream of the water intake point (low risk);
  [2] Upstream of the water intake point (medium risk);
  [3] Upstream of the dam (high risk)

The above categories were defined based on the environmental risk for land development, according to the Guidelines for Uphill Development. The area upstream of Langat Dam was delineated as "conservation zone" and downstream of the water intake point was delineated as "free zone". The "preservation zone" and "control zone" are situated between the free zone and conservation zone. As shown in Table 5, two levels of control were defined for the control zone using GIS overlay (Fig. 3). Land-use changes within the control area were executed according to the degree of risk and Table 5.

As described in Table 5, WCON_1stL and WCON_2ndL are water conservation scenarios

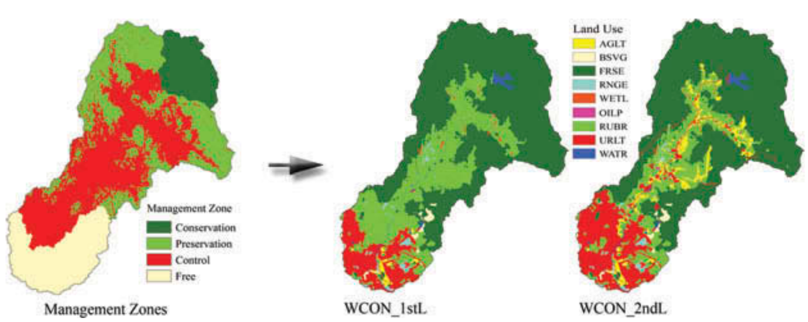

Fig. 4 Water conservation scenarios and management zones (acronyms are defined in Table 2).

based on the 1st and 2nd levels of control, respectively. WCON_1stL is similar to the 1990 scenario in terms of land-use acreage within the total landscape. As presented in Fig. 4 and Table 4, AGLT, BSVG, OILP and URLT in WCON_1stL show 86%, 60%, 73% and 41% reduction in areal proportions, as compared to those of the baseline scenario, respectively. WCON_1stL plays an influential role in soil and water conservation; therefore, 60% and 3.5% increases in RUBR and FRSE acreage in this scenario are expected, relative to the baseline scenario. In WCON_2ndL, BSVG and FRSE show the highest areal change relative to the baseline. Although the areal changes of AGLT, RUBR, and URLT in WCON_2ndL are minimal, their influences are substantial for soil and water protection.

Trend analysis

Detection of significant gradual trends in the data, as a supporting analysis for the results of LUCC impact assessment, was performed using the Mann-Kendall (MK) and pre-whitening Mann Kendall (PWMK) tests (Memarian *et al*. 2012a). The non-parametric MK test was chosen because of its strength in dealing with missing data and non-normally distributed data (Zhang *et al.* 2008).

NDVI analysis

The relationship between land degradation and cover change, established based on NDVI, has been widely reported by Wessels *et al.* (2004), Zhou *et al.* (2008), Ouyang *et al*. (2010) and Memarian *et al.* (2012b). NDVI is computed using:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{ir}} - \rho_{\mathrm{r}}}{\rho_{\mathrm{ir}} + \rho_{\mathrm{r}}} \quad (3)$$

where ρ_r and ρ_{ir} are spectral reflectance from the red and near infrared bands, respectively (Rouse *et al.* 1973).

In this work, results of NDVI analysis, mapped in 1990 and 2006, were compared with the results of LUCC impact analysis, simulated by the SWAT.

Landscape analysis

Changes in land-use patterns over the period 1984–2006 in various land-use maps were assessed using the Patch Analyst 3.0 (Grid) extension in ArcView, GIS program. Four main landscape metrics (Elkie *et al.* 1999), namely Patch Size Coefficient of Variation (PSCOV), Edge Density (ED), Shannon's Diversity Index (SDI) and Number of Patches (NUMP) were used as indices to detect trends in land-use change and to substantiate results emanating from LUCC impact assessment (Ouyang *et al.* 2010, Memarian *et al*., 2012a).

RESULTS AND DISCUSSION

Calibration, uncertainty and sensitivity analyses

Sensitivity analysis was performed for 12 parameters related to water simulation and eight parameters related to sediment simulation. Table 6 shows the sensitivity of input parameters in water discharge and sediment load calibration. The range of variations for these parameters is based on a listing provided in the SWAT manual (Neitsch *et al*. 2011) and the authors' experience.

The global sensitivity analysis shows that the most sensitive parameters in river flow simulation are those representing groundwater recharge, surface runoff and soil properties. In this study, the most sensitive parameter in water yield estimation was RCHRG_DP. This parameter controls percolation from the root zone which recharges the deep aquifer (Neitsch *et al*. 2011). In addition, CN2, SOL_K, SOL_AWC and ESCO also showed considerable sensitivity in water yield simulation (Table 6). The ranking of importance for CN2, SOL_K, SOL_AWC and ESCO in water yield simulation, as reported by Arnold *et al*. (2011), is evident in this study. The parameters CH_K1´ and CH_N1 were more sensitive than CH_N2 (Table 6). This finding conforms to results from a previous study conducted in the Langat watershed (Ayub *et al*. 2009).

Based on the sensitivity analysis, USLE_P (especially for high slopes), ADJ_PKRand SPCON had more effect on sediment load estimation than other parameters, as reported by Oeurng *et al.* (2011). There is usually a large amount of uncertainty in slope length measurements by SWAT (Arnold *et al*. 2011); thus, this parameter was considered in sediment load calibration and showed a significant sensitivity that was even higher than SPCON. In this area, the most sensitive parameters in channel degradation/deposition modelling were SPCON, CH_EROD and SPEXP, as reported by Arnold *et al*. (2011) and Oeurng *et al*. (2011). CN2, CH_N2, ALPHA_BF, SOL_AWC_C, SOL_K_SCL,

Table 6 Sensitivity ranking of parameters used in simulation of water discharge and sediment load (ranked in descending order).

Parameter	Description	Parameter range	Initial value	Optimized value	Degree of sensitivity (t-stat)
Water discharge					
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0–1	0.03	0.026	–30.66
r__CN2.mgt	Initial SCS runoff curve number for moisture condition II	35–98	55–92	{1+(–0.3022)}	15.67
r__SOL_K.sol_SCL	Soil saturated hydraulic conductivity for SCL texture (mm/h)	0–2000	20	{1–(0.2149)}	11.19
r__SOL_AWC.sol_SCL	Soil available water capacity for SCL texture (mm H_2O/mm soil)	0–1	0.2	{1+(0.235)}	7.41
v__ESCO.hru	Soil evaporation compensation factor	0–1	0.5	0.5246	3.10
v__CH_K1.sub	Effective hydraulic conductivity in tributary channel alluvium (mm/h)	0–300	10	5.330	–2.47
v__CH_N1.sub	Manning's n value for tributary channel	0.01–30	0.15	0.09865	–1.96
v__CH_N2.rte	Manning's n value for the main channel	–0.01 to 0.3	0.1	0.08925	–1.59
r__SOL_K.sol_C	Soil saturated hydraulic conductivity for C texture (mm/h)	0–2000	10–15	{1+(–0.0755)}	1.55
v__ALPHA_BF.gw	Baseflow alpha factor for bank storage (d)	0–1	0.3	0.4955	1.08
v__GW_DELAY.gw	Groundwater delay time (d)	0–500	50	63.04568	1.03
v__EPCO.hru	Plant uptake compensation factor	0–1	0.5	0.62115	1.01
Sediment load					
v__USLE_P. mgt_12-9999	USLE equation support practice factor for the slopes >12%	0–1	0.25	0.213	–13.24
v__ADJ_PKR.bsn	Peak rate adjustment factor for sediment routing in the sub–basin	0.5–2	1.5	1.38209	–9.05
r__SLSUBBSN.hru	Average slope length (m)	10–150	10.15–121.95	{1+(0.1351)}	–4.65
v__SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.0001–0.01	0.005	0.005581	–3.05
v__USLE_P. mgt_5-12	USLE equation support practice factor for the slopes 5–12 %	0–1	0.25	0.14865	–1.36
v__CH_EROD.rte	Channel erodibility factor	0–1	0.25	0.4045	–1.30
v__SPEXP.bsn	Exponent parameter for calculating sediment re-entrained in channel sediment routing	1–1.5	1	1.16307	1.12
v__USLE_P. mgt_0-5	USLE equation support practice factor for the slopes <5 %	0-1	0.25	0.18316	1.04

v__ means the existing parameter value is to be replaced by a given value, for parameters with single values.
r__ means the existing parameter value is multiplied by {1+(a given value)}, for parameters with different values in different HRUs, soil series or cover types.

Table 7 Fitting metrics for water discharge and sediment load simulation at monthly time step.

Period	Years	NS	R^2	PBIAS (%)
Water discharge				
Calibration	1997–2004	0.88	0.88	–1.90
Validation	2005–2008	0.73	0.75	6.81%
Total	1997–2008	0.84	0.84	2.44%
Sediment load				
Calibration	1997–2004	0.66	0.70	–10.91%
Validation	2005–2008	0.21	0.41	33.21%
Total	1997–2008	0.52	0.55	16.56%

and CH_N1 were sensitive during both water and sediment yield simulation.

Digitized geological data of the Hulu Langat basin indicate that the igneous rock (acid intrusive rock) was the dominant geological formation (about 90% of the basin area). Igneous rock is non-porous to water and so there is a low magnitude of deep percolation within this basin. Therefore, the optimized value for RCHRG_DP seems reasonable. Optimal values of the other parameters related to water flow and sediment load simulation also seem reasonable.

Water discharge calibration using SUFI-2 resulted in a NS efficiency and a coefficient of determination (R^2) of 0.88 (Table 7). Based on Table 6, PBIAS indicates 1.9% overestimation in water discharge simulation. Uncertainty analysis indicates that 72% of the measured data are bracketed by the 95PPU and the *D* factor has a reasonable value of 0.63 (Fig. 5(a)). Values of *D* factor smaller than one are desirable (Faramarzi *et al*. 2009). In sediment load calibration, as illustrated in Fig. 5(b), the percentage of observed data bracketed by the 95PPU is good, i.e. 53%. A *D* factor of 0.32 is also desirable. Additionally, NS and R^2 indicate a good calibration (Parajuli *et al*. 2009) for SWAT in the sediment load simulation (Table 6). The estimated PBIAS shows 10.9% overestimation in sediment load modelling, which is classified as an excellent fit (Parajuli *et al*. 2009). As depicted in Fig. 5(a) and (b), some significant errors in sediment load simulation are associated with peak flow prediction errors. Similar observations were reported by Tolson and Shoemaker (2004) and Rostamian *et al*. (2008).

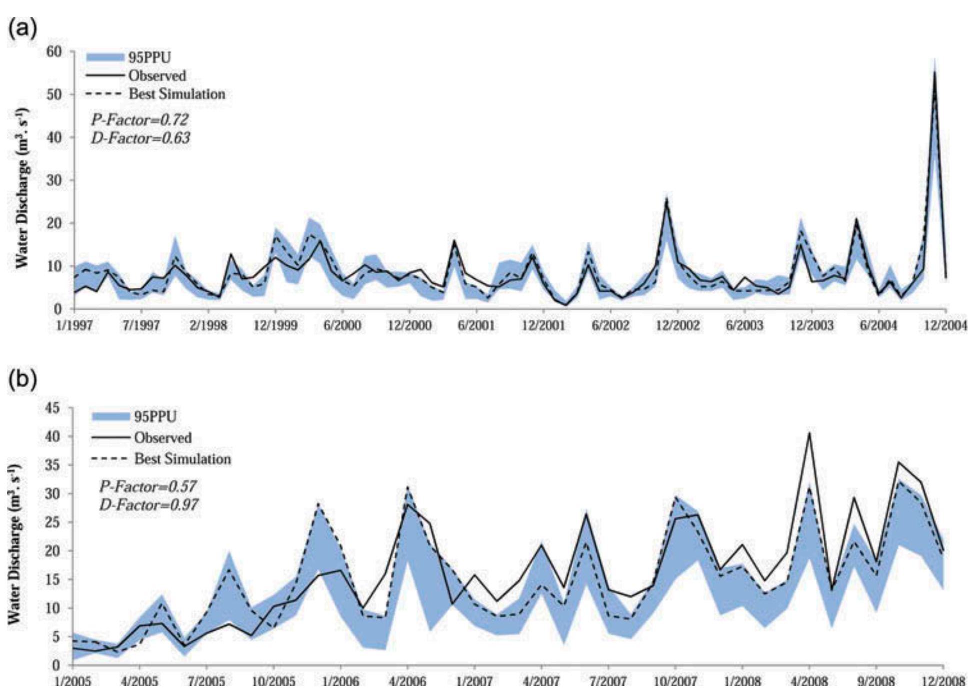

Fig. 5 (a) Monthly flow calibration, and (b) monthly sediment calibration, represented by 95PPU bound and measured water discharge values.

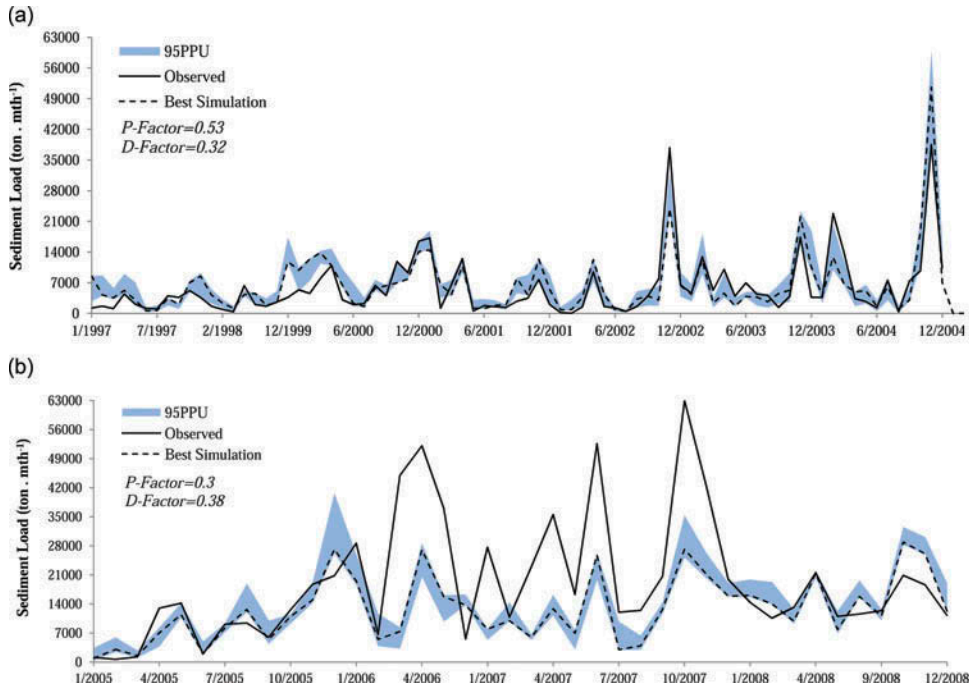

Fig. 6 (a) Monthly flow validation, and (b) monthly sediment validation, represented by 95PPU bound and measured water discharge values.

The results of monthly water discharge validation are shown in Fig. 6(a). Validation analysis (Table 7) demonstrates a good efficiency in water discharge simulation (NS = 0.73, R^2 = 0.75 and PBIAS = 6.8%) for the period 2005–2008. In this period, *P* and *D* were 0.57 and 0.97, respectively, which indicates a desirable certainty. Figure 6(b) shows that only 30% of the measured sediment load data are bracketed by the 95PPU with a *D* factor of 0.38. The simulation performed poorly for sediment load (NS = 0.21, R^2 = 0.41 and PBIAS = 33.2%) for the same period (Table 7).

Calibration of SWAT in the Hulu Langat basin is challenging due to the uncertainties that are driven by process simplification, processes not accounted for by the model and processes in the basin that are unknown to the modeller (Abbaspour *et al*. 2007, Memarian *et al*. 2012c). In this basin, the main sources of uncertainties in water discharge and sediment load simulation are:

- *Reservoir operation and water use* The effect of Langat Reservoir on sediment transport is not well known. Additionally, sediment transport is a complicated process and can be influenced by dam management and operations, operational decision making of WTPs, and temporary as well as unidentified water withdrawal for irrigation use (Abbaspour *et al*. 2007, Abbaspour 2011, Xie *et al*. 2011).
- *Land-use and soil map resolution* In the Hulu Langat basin, 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, which can affect water discharge and sedimentation quantity (Memarian *et al*. 2012b, 2012c). The soil map used had a scale of 1:100 000, which is too coarse and could have contributed to some degree of uncertainty in the SWAT modelling (Geza and McCray 2007, Moriasi and Starks 2010).
- *Spatial variability of rainfall distribution* The Hulu Langat basin is a tropical watershed and is exposed to high spatial and temporal variability in rainfall distribution that cannot be captured exactly using only three raingauges (Cho *et al*. 2009, Memarian *et al*. 2012b). Such a limitation could have contributed to some degree of simulation uncertainty.
- *Urban development, infrastructure construction and landslide impact* Infrastructure constructions and landslide occurrences can produce large amounts of sediment for a number of years that can affect water quantity and quality, especially during the period of intense urbanization within

the Hulu Langat basin, i.e. 2005–2008. Wastewater discharges into streams are also unquantified in the Hulu Langat basin. These could be sources of uncertainty in the hydrological modelling (Abbaspour *et al*. 2007, Jones *et al*. 2008, Abbaspour 2011).

- *Process simplification by SWAT* In this study, two types of simplification may have contributed to uncertainty, i.e. simplification in MUSLE as used in SWAT (Abbaspour *et al*. 2007) and simplification in the target release approach with a volume limitation for reservoir modelling (Arnold *et al*. 2011).

Despite these uncertainties, model robustness for water discharge simulation for the period 1997–2008 is good. However, model robustness for sediment load simulation is limited to the calibration period 1997–2004. Consequently, LUCC impact analysis on water discharge and sediment load was performed over the periods 1997–2008 and 1997–2004, respectively.

The efficiency of SUFI-2 in SWAT optimization for LUCC impact analysis has been reported by Ghaffari *et al*. (2010) and Mango *et al*. (2011). This work also reveals the efficiency of SUFI-2 in SWAT optimization, especially in accounting for the uncertainties present in the model, measured data and controlling variables.

LUCC impact analysis

The CA-Markov approach for future land-use projection (year 2020) presented 88% overall accuracy in the validation process (Memarian *et al*. 2012b). The optimized SWAT was run using different land-use maps over the periods 1997–2008 and 1997–2004 for water discharge and sediment load simulation, respectively.

Table 8 shows hydrological outputs resulting from application of different land-use scenarios in the Hulu Langat basin. The WCON_2ndL scenario acted comparably to the baseline scenario but with some noticeable differences in sediment quantities using soil and water conservation. The efficiency of WCON_1stL in soil and water conservation was similar to the 1990 scenario. The *t*-test analysis showed that all differences in monthly baseflow, SURQ, GWQ and sediment variables between the baseline and other land-use scenarios were significant at $p < 0.05$ (Table 8). However, differences in BFI between the baseline and other land-use scenarios were not statistically significant, except for differences between 1984 and the baseline scenario. Because of similarities between the baseline and WCON_2ndL scenarios, differences in monthly water discharge and monthly direct runoff between these scenarios were also not statistically significant at $p < 0.05$. As described in the validation and uncertainty analyses, some impacts of urban development and infrastructure construction on the basin's hydrological condition are unknown and cannot be captured by SWAT. In fact SWAT underestimated sediment discharge by 33% in the validation period. Therefore, sediment load values that are simulated under future scenario conditions are expected to be considerably underestimated. As a consequence, differences in sediment load related parameters between the future scenario and the baseline scenario would be statistically significant.

Table 9 shows significant decreasing trends for BFI, GWQ and in-stream sediment change at $p < 0.05$. All other hydrological variables exhibit significant increasing trends in the period 1984–2020. These results are consistent with the findings reported by Memarian *et al*. (2012a), who applied the PWMK test with Sen's slope estimator (at $\alpha = 0.05$) to annual water discharge and sediment load time series for 1984–2008 and found that the Hulu Langat basin showed a significant increasing trend in water discharge at a rate of 9.899×10^6 m^3 $year^{-1}$. They also revealed that an increasing trend in the rainfall time series was significant at UPM Serdang, which corresponded to increasing trends in water discharge and sediment load at Sungai Langat station. They concluded that the increasing trend in water discharge from Hulu Langat basin is originally controlled by significant alterations in land use and rainfall.

Due to increase in number of patches, landscape diversity and landscape fragmentation from 1984 to 2006, all selected landscape metrics showed significant increasing trends, as analysed by the MK test (Fig. 7) (Memarian *et al*. 2012a). Using cluster analysis, Memarian *et al*. (2012a) showed that discriminant points between the clusters of landscape metrics occurred within the period 1990–1997. These points corresponded to the points of change in water discharge and sediment load time series. The relationships between landscape metrics and hydrological time series in Hulu Langat basin have been established by correlation analysis and reported by Memarian *et al*. (2012a), and conform to Weng (2007).

Table 8 Results of land-use scenario analysis using SWAT.

Hydrological variable	Past scenarios				Baseline scenario	Future scenario	Water conservation scenario	
	1984	1990	1997	2002	2006	2020	WCON_1stL	WCON_2ndL
Monthly water discharge (m^3 s^{-1})	9.80	10.02	10.33	10.49	10.69	10.98	10.09	10.69
Monthly direct runoff (m^3 s^{-1})	4.65	4.77	4.93	5.01	5.11	5.28	4.83	5.12
Monthly baseflow (m^3 s^{-1})	5.15	5.25	5.40	5.48	5.58	5.69	5.26	5.57
Base Flow Index (BFI)	0.526	0.524	0.523	0.522	0.522	0.519	0.522	0.521
SURQ (mm)	415.62	439.02	488.49	514.62	549.63	615.05	481.67	548.72
GWQ (mm)	790.25	786.30	766.64	758.52	746.39	713.13	749.40	747.29
Monthly sediment load (ton)	4117.24	4169.56	6532.08	7589.56	8820.26	11201.39	6180.61	8703.80
Average upland sediment yield (t ha^{-1})	0.13	0.12	1.44	1.87	2.32	3.79	0.77	2.06
In-stream sediment change (t ha^{-1})	1.17	1.19	0.60	0.50	0.43	–0.30	1.15	0.64
Annual sediment load (t ha^{-1})	1.30	1.31	2.04	2.37	2.75	3.49	1.93	2.71
Changes relative to the baseline scenario (%)								
Monthly water discharge[1]	–8.36 *	–6.26 *	–3.41 *	–1.92 *	0	2.66 *	–5.64 *	–0.05 ns
Monthly direct runoff[1]	–9.08 *	–6.65 *	–3.51 *	–1.98 *	0	3.36 *	–5.56 *	0.13 ns
Monthly baseflow[1]	–7.64 *	–5.83 *	–3.25 *	–1.82 *	0	2.04 *	–5.65 *	–0.09 *
Base Flow Index[2]	0.79 *	0.45 ns	0.16 ns	0.10 ns	0	–0.6 ns	–0.01 ns	–0.04 ns
SURQ[2]	–24.38 *	–20.12 *	–11.12 *	–6.37 *	0	11.90 *	–12.36 *	–0.16 *
GWQ[2]	5.88 *	5.35 *	2.71 *	1.63 *	0	–4.46 *	0.40 *	0.12 *
Monthly sediment load[3]	–53.32 *	–52.73 *	–25.94 *	–13.95 *	0	27.00 *	–29.93 *	–1.32 *
Average upland sediment yield[4]	–94.45 *	–94.82 *	–37.83 *	–19.69 *	0	63.12 *	–66.68 *	–11.11 *
In-stream sediment change[4]	173.78 *	177.81 *	40.52 *	17.42 *	0	–169.52 *	169.76 *	50.00 *
Annual sediment load[4]	–52.78 *	–52.47 *	–25.66 *	–13.92 *	0	26.98 *	–29.95 *	–1.62 *

SURQ: Amount of surface runoff to main channel from HRU during simulation (ignores impact of transmission losses).
GWQ: Amount of lateral flow and groundwater flow contribution to main channel from HRU during simulation.
* Significant at the level of 0.05; ns: not significant.
[1] *t*-test based on 144 monthly records; [2] *t*-test based on 12 annual records; [3] *t*-test based on 96 monthly records; [4] *t*-test based on 8 annual records.

Table 9 Trend analysis of hydrological variables simulated by the past, present and future scenarios.

Hydrological variable	Direction	Trend	Trend_P
Monthly water discharge (m^3 s^{-1})	↑*	0.04	1.40
Monthly direct runoff (m^3 s^{-1})	↑*	0.02	0.72
Monthly baseflow (m^3 s^{-1})	↑*	0.02	0.63
Base Flow Index (BFI)	↓*	0.00	–0.01
SURQ	↑*	6.35	235.12
GWQ	↓*	–2.42	–89.55
Monthly sediment load (ton)	↑*	252.85	9355.52
Average upland sediment yield (t ha^{-1})	↑*	0.13	4.710
In-stream sediment change (t ha^{-1})	↓*	–0.05	–1.73
Monthly sediment load (t ha^{-1})	↑*	0.08	2.90

Trend: magnitude of trend per unit time; Trend_P: Magnitude of trend over the time period.
* Trend is significant at the 0.05 level; ↑: increasing; ↓: decreasing.

Moreover, NDVI comparison demonstrated a negative effect of land cover change on the basin's hydrological status. Figure 8 illustrates NDVI changes in the period 1990–2006. The sub-basins with the highest change in land-use acreage, urban development and hydrological condition, i.e. sub-basins 22–32, are well matched

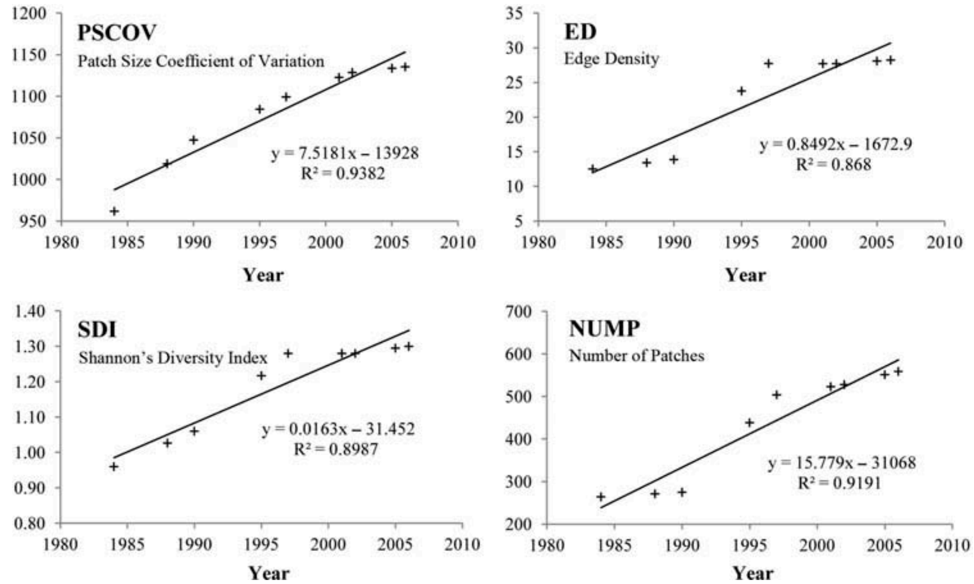

Fig. 7 Trends of selected landscape metrics for the period 1984–2006.

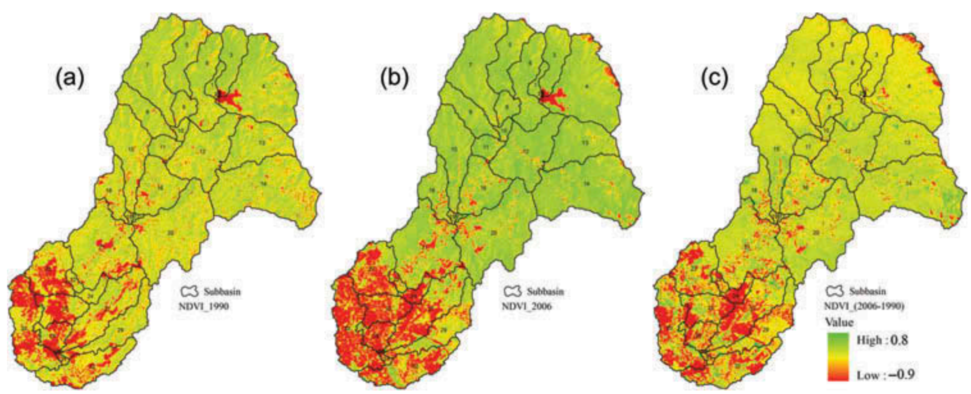

Fig. 8 (a) NDVI map dated 1990, (b) NDVI map dated 2006, and (c) NDVI difference between 2006 and 1990 based on standardized values.

with the sub-basins that show a large NDVI reduction (Fig. 9). Curve number (CN) comparison between 2006 and 1990 also provides evidence that land-use change significantly influenced the hydrological condition of the basin. As illustrated in Fig. 9, all sub-basins with agriculture and urban development in 2006 showed significant increase in CN, as compared to 1990. These sub-basins were also matched with the sub-basins that showed NDVI reduction, surface runoff and upland sediment yield increase. Taken together, these observations support the results obtained from SWAT simulation and scenario analysis, and confirm the negative effect of land-use change on the hydrological regime of Hulu Langat basin.

Based on the scenario analysis (Table 8), 1984 and 2020 are the most and the least efficient scenarios, respectively, for water conservation and environmental protection. However, returning to the 1984 scenario is impossible. With regard to the present, future and conservative land-use scenarios in the basin, the following six options for land development post 2006 can be projected:

1. Rural and urban development within the Hulu Langat basin must be stopped.
2. The development trend will continue until 2020 without any limitation.
3. The baseline scenario will show some minor alterations in land-use acreage in response to

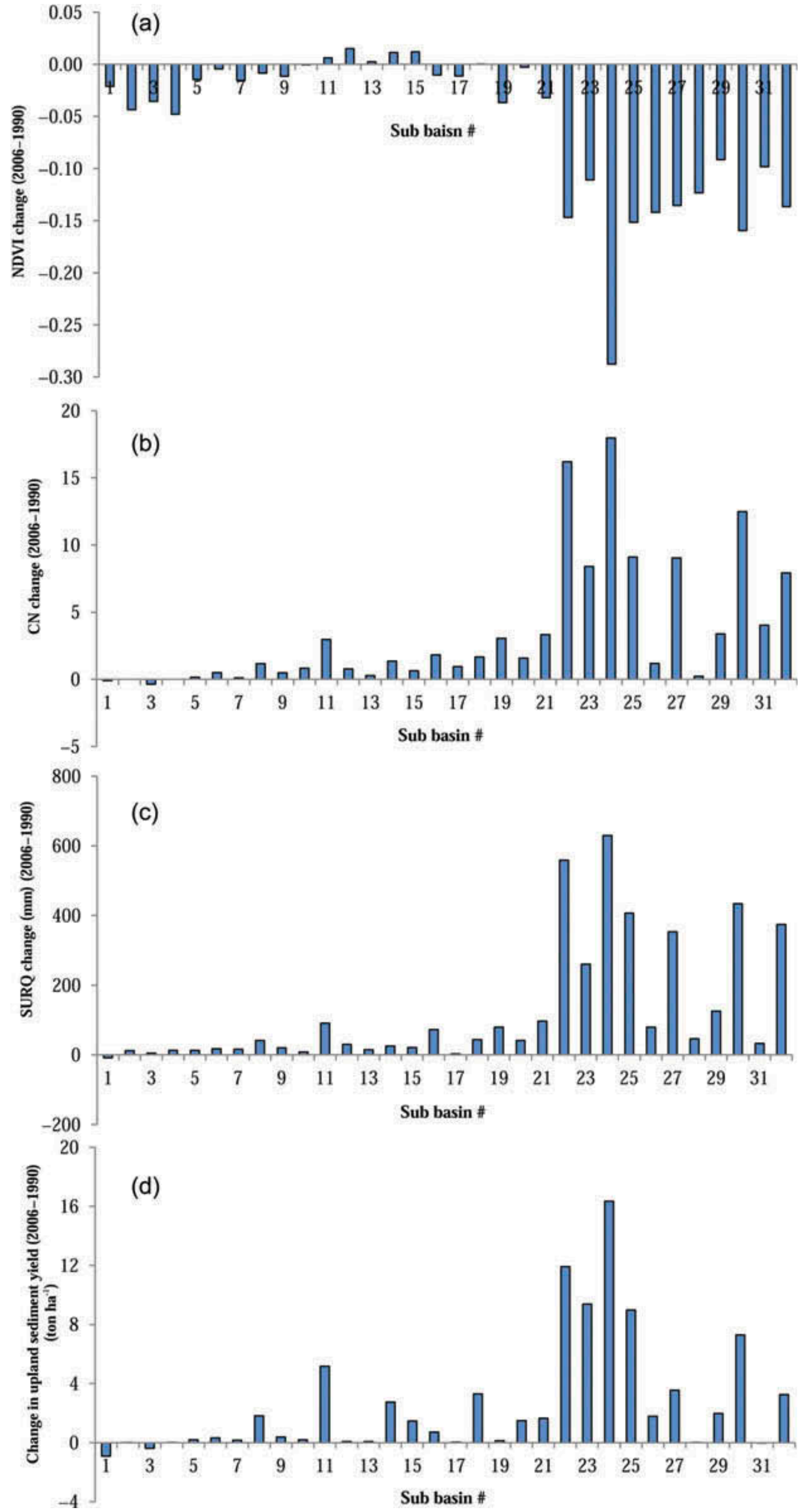

Fig. 9 Relative changes in: (a) NDVI, (b) CN, (c) SURQ, and (d) upland sediment yield in the period 1990–2006 for different sub-basins.

the WCON_2ndL scenario. The WCON_2ndL scenario will continue until 2020 yielding a marginally more environmentally-friendly outcome as compared to the baseline scenario.

4. The baseline scenario with a significantly high transition cost changes to the WCON_1stL scenario. The WCON_1stL scenario will continue until 2020 playing an influential role in soil and water conservation.
5. The baseline scenario with some constraints in land-use transition changes to the WCON_1stL scenario. The optimized scenario will continue until 2020. This option would impose a lesser amount of transition cost than the fourth option in order to capture all or parts of the WCON_1stL objectives.
6. The development trend will continue until 2020, but with some constraints in land-use transition. This option is aimed at achieving urban and agricultural development in 2020 and captures a reasonable level of environmental targets, as contained in the WCON_1stL scenario.

In examining these options, the first can be rejected due to existing development trends within the basin. The second option does not follow the water conservation objectives as outlined by the Department of Town and Country Planning and the Department of Environment. Thus, option 2 can also be rejected. The third option seems reasonable but its outcomes are not matched with the water conservation objectives. The fourth option is extremely costly due to large changes in agricultural and urban acreages to other land-use categories. Therefore, options 3 and 4 can also be rejected. The fifth and the sixth options are more reasonable to apply due to the lower transition costs and moderate level of achievable outcomes. Therefore, further land-use optimization studies, e.g. goal programming, should be done to engineer a land-use scenario which imposes a reduced amount of transition cost and captures all or parts of the WCON_1stL objectives.

This work demonstrates the impact of LUCC on hydrological response in the Hulu Langat basin. The negative effect of land-use change on the hydrological status of river basins has been reported in several other studies (Hernandez *et al*. 2000, Nearing *et al*. 2005, Kepner *et al*. 2008, Li *et al*. 2011, Palamuleni *et al*. 2011, Qiu *et al*. 2011, Wilson and Weng 2011, Cai *et al*. 2012).

CONCLUSION

The SWAT-based calibration and uncertainty analysis using SUFI-2 revealed that the model robustness for water discharge simulation for the period 1997–2008 was good. However, the model showed a poor performance with significant uncertainty (mainly resulting from intense urban development) for the validation period for sediment load estimation. Therefore, LUCC impact analysis on water discharge was performed over the total period 1997–2008, but sediment load simulation for LUCC impact assessment was limited to the calibration period 1997–2004.

Application of the past and WCON_1stL scenarios using an optimized SWAT model resulted in significant reduction in monthly direct runoff and monthly sediment load in comparison to the baseline scenario. The WCON_2ndL scenario was similar to the baseline scenario but with minor differences, especially in sediment load quantities toward soil and water conservation. SWAT simulation based on the future scenario caused significant increase in monthly direct runoff, monthly sediment load, upland sediment yield and groundwater recharge, as compared to the baseline scenario. Using time series analysis, all hydrological variables showed significant trends for the period 1984–2008. These results, taken together with results from NDVI and landscape analyses, indicate a negative impact of LUCC on hydrological response of the Hulu Langat basin.

The outcomes of the WCON_1stL scenario were most consistent with the water conservation objectives outlined by the Department of Town and Country Planning, and the Department of Environment. However, given the current development trend within the Hulu Langat basin, this scenario seemed enormously costly. The application of the WCON_2ndL scenario for land-use development within the basin appeared reasonable, but its outcomes were not matched with the water conservation objectives. Therefore, further land-use optimization studies are suggested in order to engineer a land-use scenario that requires a lower transition cost and complies with the WCON_1stL objectives for long-term sustainability.

This work has demonstrated that the integration of land-use and land cover simulation models with SWAT can be used to investigate the impacts of LUCC on the hydrological conditions of a basin. Such integration can be applied as a tailored approach for land-use planning, particularly in tropical watersheds that are still developing.

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