Flow and sediment yield simulations for Bukit Merah Reservoir catchment, Malaysia: a case study

Zorkeflee Abu Hasan, Nuramidah Hamidon, Mohd Suffian Yusof and Aminuddin Ab Ghani

ABSTRACT

Bukit Merah Reservoir is the main potable and irrigation water source for Kerian District, Perak State, Malaysia. For the past two decades, the reservoir has experienced water stress. Land-use activities have been identified as the contributor of the sedimentation. The Soil and Water Assessment Tool (SWAT) was used to simulate and quantify the impacts of land-use change in the reservoir watershed. The SWAT was calibrated and two scenarios were constructed representing projected land use in the year 2015 and hypothetical land use to represent extensive land-use change in the catchment area. The simulation results based on 17 years of rainfall records indicate that average water quantity will not be significantly affected but the ground water storage will decrease and suspended sediment will increase. Ground water decrease and sediment yield increase will exacerbate the Bukit Merah Reservoir operation problem.

Key words | Bukit Merah Reservoir, sedimentation, simulation, soil and water assessment tool

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INTRODUCTION

Bukit Merah Reservoir is the source of water resources for irrigation and domestic water supply for Kerian District (State of Perak, Malaysia). Although the catchment area is not urbanised, the oil palm and rubber plantations that dominate the landscape are hypothesized to cause a detrimental effect in the Bukit Merah Reservoir. Observations made by the Kerian Department of Irrigation and Drainage (Kerian DID) have indicated that the reservoir has been facing water stress for the last 20 years. From Kerian DID records, the reservoir experienced water levels less than 7.9 m for 64 days in the year 2009 and more than 130 days for the year 2010.

Sedimentation in the reservoir has been identified as one of the reasons and land-use activities within the sub-basin as the major contributor to the problem. Indeed, the problems leading to the current water situation are complex and interrelated; many piecemeal attempts to solve specific problems have eventually exacerbated or created other problems (NRC 1999). In order to assist decision making, computer models have been used extensively in water resources management to evaluate the effectiveness and suitability of various control strategies and conservation programs for a particular river basin (Moriasi *et al*. 2007). The Soil and Water Assessment Tool (SWAT) developed by the US Department of Agriculture (USDA) was used in this study.

STUDY AREA

Kurau River sub-basin (Figure 1) lies between latitude 40 51′ (N) and 50 10′ (N), and longitude 100 38′ (E) and 101 01′ (E). The catchment area is approximately 359.2 km^2, and is drained by Kurau River and Ara River. The rivers meet at Pondok Tanjung town.

The reservoir, which is the main concern of this study, was constructed in the year 1906 to store and supply water for the Kerian Irrigation Scheme. Currently the reservoir is supplying water for irrigation to 23,000 ha of paddy land and is the main water source of potable water for the Kerian District (160,000 inhabitants).

The main land uses for this area are forest (46.29%) and agriculture (42.80%). Approximately 50% of the land is privately owned, which makes it very difficult to implement good land-use policies of management for this watershed.

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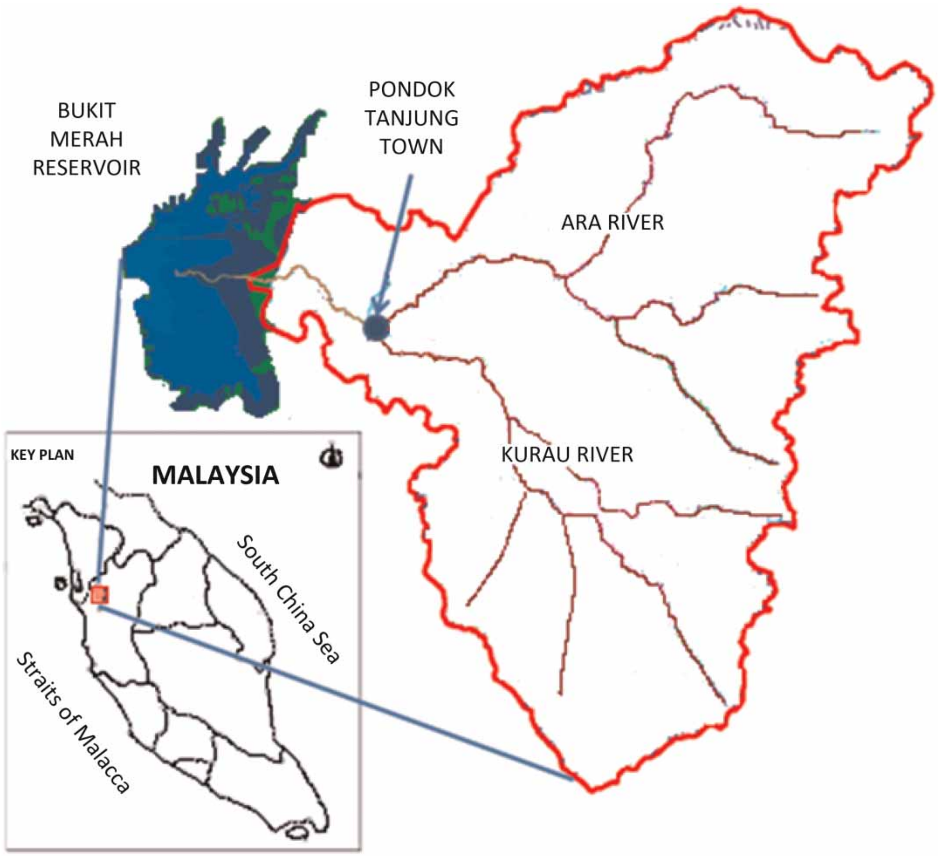

Figure 1 | Location of study area.

DATA SOURCES

Brief descriptions of the data used in the SWAT modelling are as follows.

Suspended sediment data

The suspended sediment data were collected by the DID Malaysia at regular intervals from 1977 to 2004. The data were taken daily from Batu 14 and Pondok Tanjung stations.

Rainfall data

The rainfall data for this study were obtained from the DID Malaysia, covering the years 1950 to 2007. There are sixteen rainfall stations in and around the study area. All stations are daily rainfall stations, except one of them (Station 4908018) Pusat Kesihatan Kecil at Batu Kurau, which is an hourly station.

Discharge data

There are three water level stations in the study area. All are hourly stations and records cover from 1961 until 2005. From the list of data acquired from the year 1950 to year 2007, only year 2004 has a complete set of required data, and hence was selected for the study.

Geographical information system (GIS) layers

These are important tools for river basin management due to their ability to create, store and analyse spatially and temporally distributed data (Ruggles *et al.* 2001). Geographical information systems (GIS) have been successfully linked to various distributed watershed-scale simulation models, including SWAT (Ogden *et al.* 2001) and Martin *et al.* (2005) listed more than 20 mathematical models and their GIS interfaces.

GIS data were used as base map analysis as well as for input into watershed numerical models. The GIS layers included in the database are the land use/landcover, river system, Digital Elevation Model (DEM), soil map, and hydrologic stations.

MODEL DESCRIPTION

The Soil and Water Assessment Tool (SWAT) is a physical river basin-scale model developed by the USDA to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. SWAT is a continuous time model, i.e. a long-term yield model and physically based, uses readily available inputs, is computationally efficient, and is a continuous model that operates on a daily time step (Neitsch *et al*. 2005).

SWAT interfaces with GIS software (ArcView®) using AVSWAT-X extension (AVSWAT). AVSWAT can be used to input and designate land use, soil, weather, ground water, water use, management, pond and stream water quality data, and the simulation period (Di Luzio *et al*. 2002).

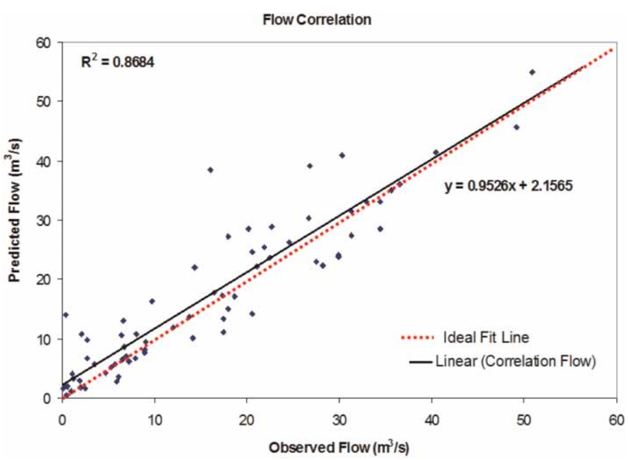

Figure 2 | Value of R^2 for flow from October to December 2004.

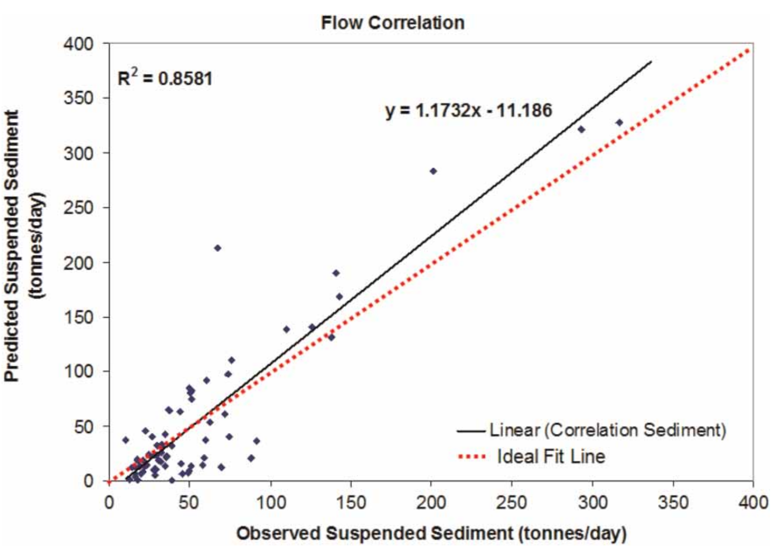

Figure 3 | Value of R^2 for suspended sediment from October to December 2004.

MODELLING

SWAT model setup process

The AVSWAT interface creates two views namely the Watershed View and the SWAT View. The Watershed View is used to process all maps while the SWAT View is used to edit input data, run the SWAT model and analyze output.

The primary data needed in model preparation for the study area are DEM, Land-use Map and Soil Map. Database tables for land use, soil type and weather stations for the study area are also needed. The precipitation data table uses six stations within the sub-basin and data from year 1990 to 2006. The interface automatically overlaid these maps against each other, and divided the river basin into Hydrologic Response Units (HRU) based on land use and soil type. Finally, the extracted model inputs data from map layers and related databases for each HRU will form a SWAT project.

Model calibration

Model calibration and validation are indispensable for mathematical simulation, which is used to assess model prediction results (Neitsch *et al.* 2002). Calibration was performed by adjusting the parameters until the simulated values were within the acceptable range as compared with the observed values. There are numerous parameters in

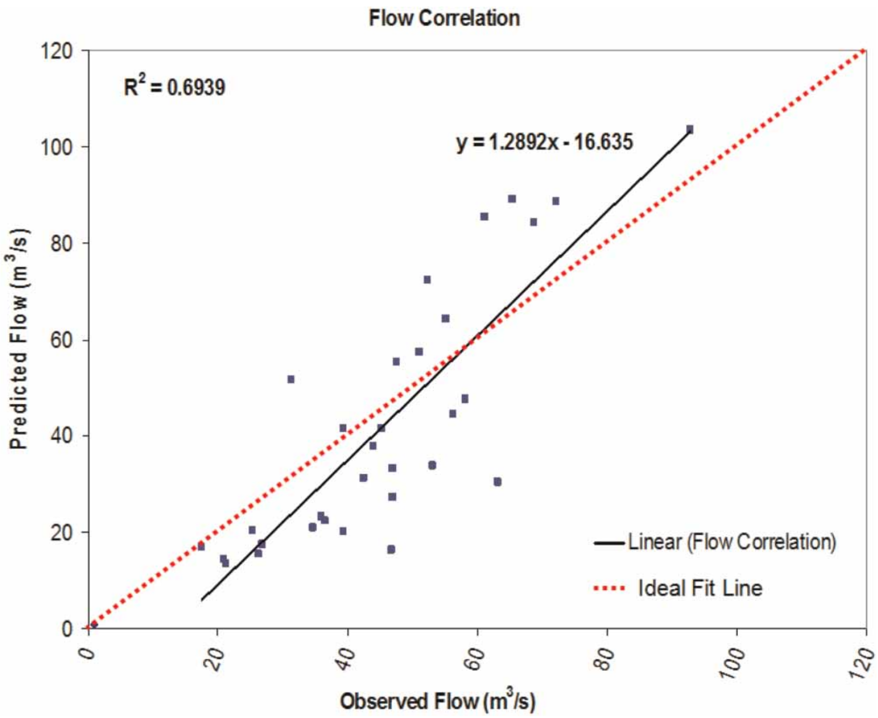

Figure 4 | Value of R^2 for flow in October 1993.

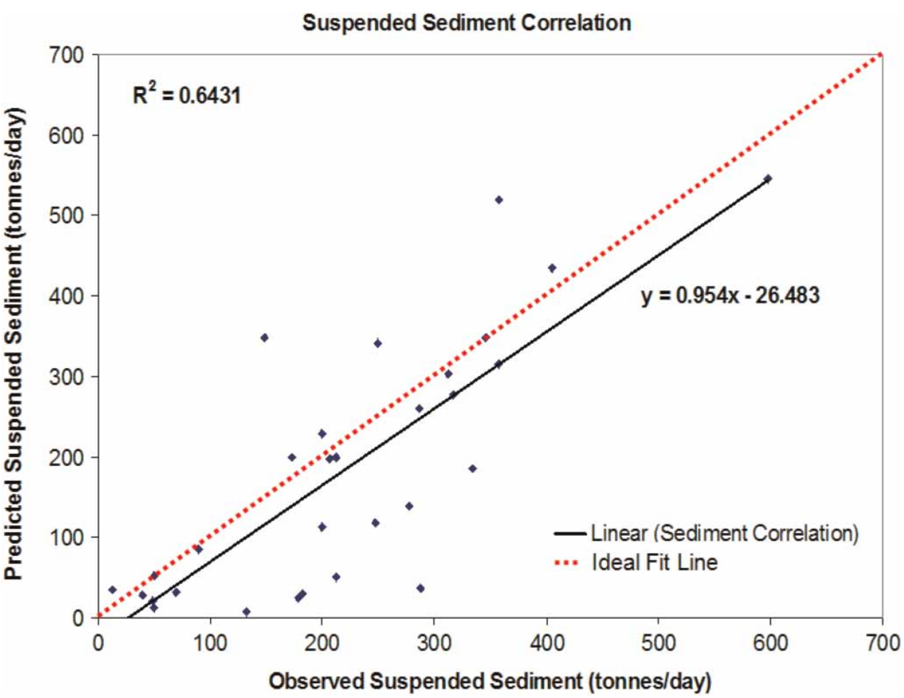

Figure 5 | Value of R^2 for suspended sediment in October 1993.

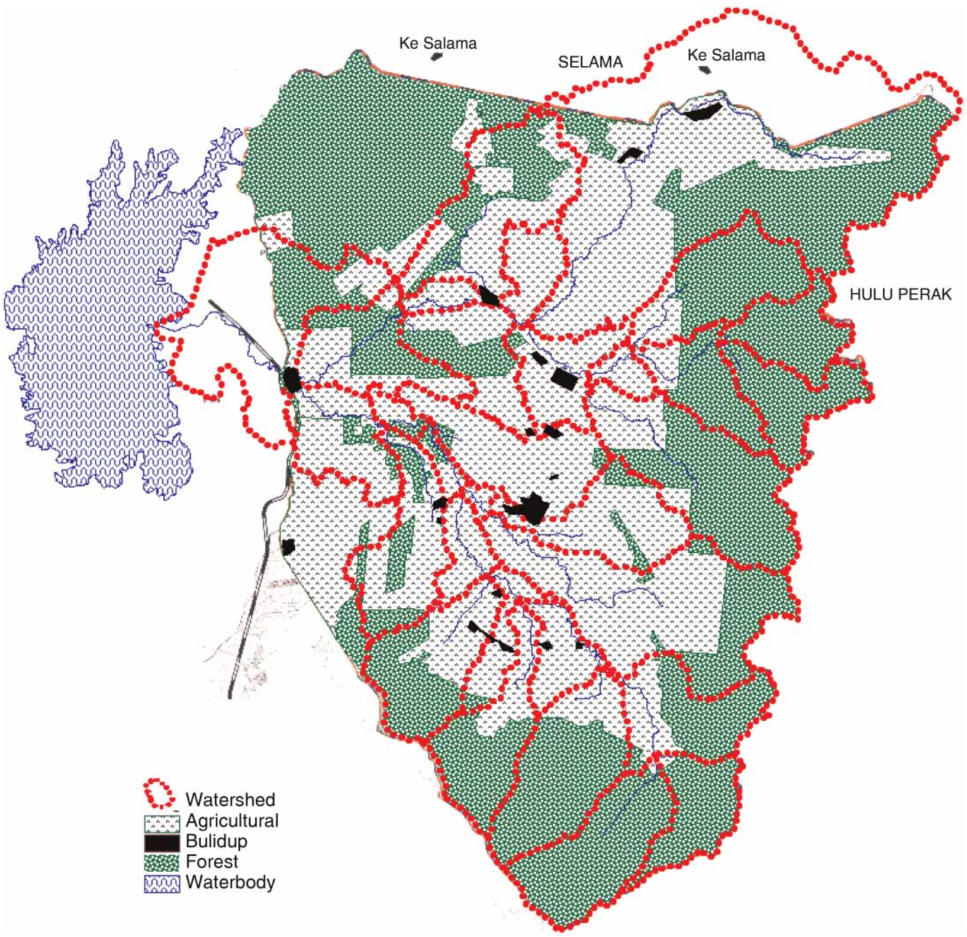

Figure 6 | Selected HRUs overlaying the projected 2015 land use of Kurau River Sub-basin for Scenario 1.

SWAT models to be calibrated to match observed flows and sediment yield values. In this study a total of 22 parameters under four functions (surface water response – three parameters; subsurface water response – five parameters; basin response – eight parameters; and suspended sediment response – six parameters) were adjusted. The calibrated parameters were used for simulation purposes.

RESULTS AND DISCUSSION

Flow and suspended sediment calibration

Calibration of SWAT was performed using October to December 2004 flow and suspended sediments data. The accuracy of the watershed model is determined based on the coefficient of determination (R^2) value. Predicted flow versus observed data are considered good with $R^2 = 0.868$ as shown in Figure 2. Suspended sediment results also fit quite well with the observed data with $R^2 = 0.858$ as shown in Figure 3.

Flow and suspended sediment validation

Validation was performed using October 1993 flow and suspended sediments data. Predicted flow versus observed

Table 1 | List of the land-use distribution for the simulation

	Simulation		
Land-use group	Land use 2004	Scenario 1 Land use 2015	Scenario 2 Fully developed
Agriculture	42.8%	38.5%	0.0%
Built-up	10.4%	14.7%	53.3%
Forest	46.4%	46.3%	46.3%
Waterbody	0.4%	0.4%	0.4%

Table 2 | Summary of the results of the two scenarios

Location	Variables	Scenario Land use 2004	Scenario 1	Scenario 2	Percentage difference Scenario 1	Scenario 2
Outlet	Average flow (m^3/s)	23.3	23.3	23.4	0%	0%
	Average sediment load (ton)	41860	45420	57360	9%	26%
	Average sediment concentration (mg/l)	29.9	34.5	49.2	16%	42%
For whole basin	Average ground water (mm)	469.3	417.0	229.9	−11%	−45%
	Average water yield (mm)	2077.4	2080.0	2086.6	0%	0%
	Average sediment yield (ton/ha)	3.3	3.5	5.4	7%	52%

data are moderately strong with $R^2 = 0.69$ as shown in Figure 4. Suspended sediment results are also moderately strong with $R^2 = 0.64$ as shown in Figure 5.

Nonetheless, Borah & Bera (2003) noted that to simulate and validate the natural process is a very complex and challenging task.

Land-use simulation

The impact of land-use changes on flow and sediment yield was simulated under two different scenarios. Land use was categorised into four groups, which are agriculture, built-up, forest, and waterbody. The built-up area utilizes the SWAT's Residential - Medium Density urban area data.

Scenario 1: The land use was adjusted for the sub-basins as shown in Figure 6 to suit the proposed Larut-Matang 2015 Local Plan land use. Hydrological and meteorological data for the year 1990 until 2006 were used in this simulation.

Scenario 2: All the agricultural areas were converted into built-up areas to represent hypothetical extensive land-use change within the study area. Hydrological and meteorological data for the year 1990 until 2006 were used in this simulation (Table 1).

RESULTS

Scenario 1 shows that land use in 2015 will increase the sediment delivery into Bukit Merah Reservoir by 9% and by 26% if the area is fully developed. Average sediment yield for the whole basin will increase by 7% for Scenario 1 and by 52% for Scenario 2. Average flow and water yield are not affected by the land-use change but the ground water yield decreases by 11% for Scenario 1 and 45% for Scenario 2. Results of the simulations are summarized in Table 2.

CONCLUSIONS

Increase in development will enhance human activities including rapid land conversion which normally involves converting a vegetated area to a less or non-vegetated one. These activities will definitely result in a higher runoff and sediment yield. For this study area, land use change will increase the sediment yield which will accelerate the storage deficiency of Bukit Merah Reservoir. The simulation results show that change in land use will not affect the average water quantity but reduction in ground water potential will affect the reservoir storage especially during drier periods. Combining the effect of sediment yield increase and ground water depletion will have a detrimental impact on the Bukit Merah Reservoir operation. This will finally affect the population that relies on water resources from this reservoir.

Watershed modelling using SWAT and GIS techniques, as demonstrated in this study, show the usefulness of utilising the available technologies to assist in decision making while still at the planning stage.

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