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HOW LAND USE/LAND COVER CHANGES CAN AFFECT WATER, FLOODING AND SEDIMENTATION IN A TROPICAL WATERSHED: A CASE STUDY USING DISTRIBUTED MODELING IN THE UPPER CITARUM WATERSHED, INDONESIA

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Abstract

Human activity has produced severe LULC changes within the Upper Citarum watershed and these changes are predicted to continue in the future. With an increase in population parallel to a 141% increment in urban areas, a reduction of rice fields and the replacement of forests with cultivations have been found in the past. Accordingly, LCM model was used to forecast the LULC in 2029. A distributed model called TETIS was implemented in the Upper Citarum watershed to assess the impact of the different historical and future LULC scenarios on its water and sediment cycles. This model was calibrated and validated with different LULCs. For the implementation of the sediment sub-model, it was crucial to use the bathymetric information of the reservoir located at the catchment's outlet. Deforestation and urbanization have been shown to be the most influential factors affecting the alteration of the hydrological and sedimentological processes in the Upper Citarum watershed. The change of LULC decreases evapotranspiration and as a direct consequence, the water yield increased by 15% and 40% during the periods 1994 to 2014 and 2014 to 2029, respectively. These increments are caused by the rise of three components in the runoff: overland flow, interflow and base flow. Apart from that, these changes in LULC increased the area of non-tolerable erosion from 412 km2 in 1994 to 499 km2 in 2029. The mean sediment yield increased from 3.1 Mton yr-1 in the 1994 LULC scenario to 6.7 Mton yr-1 in the 2029 LULC scenario. An increment of this magnitude will be catastrophic for the operation of the Saguling Dam.

Keywords: Citarum, land use change, distributed hydrological modeling, water, erosion.

Introduction

In recent decades, the environment has been severely affected on a global scale by Land Use/Land Cover (LULC) changes and this has become a subject of interest for many researchers (Price 2011; Baker and Miller 2013; Bosmans et al. 2017; Rogger et al. 2017). LULC changes pose a significant threat to watershed sustainability and negatively affect many human activities due to the possible exacerbation of water scarcity, flood frequency, erosion and sedimentation rates (Defra 2004; Kheereemangkla et al. 2016; Garg et al. 2017; Boongaling et al. 2018).

Tropical regions are located in the mid-latitude zone, an area mainly characterized by its large energy input for evapotranspiration and intense rainfall (De Graff et al. 2012; Wohl et al. 2012). During the rainy season, rainfall amounts can be 100 times more than during the dry season (Bruijnzeel 2004). These characteristics generate numerous environmental problems such as frequent flooding and high erosion rates (Gupta 2011). Humid tropical watersheds are considered unique due to their rapid evolution that affects the hydrological cycle (Calijuri et al. 2015; Mir et al. 2016). However, human activities in humid tropical regions have profoundly altered the LULC conditions due to economic activities (Costa 2005). In general, these changes decrease canopy interception, evapotranspiration (Marhaento et al. 2018), soil productivity and soil water storage

(Zuazo and Pleguezuelo 2008). As a consequence, it is clear that in most cases they increase water yield, overland flow (Marhaento et al. 2018) and flood occurrence (Wheater and Evans 2009; Sinha and Eldho 2018).

LULC changes will affect both erosion rates (Fenli et al. 2002; Happ 2014; Mushtaq and Lala 2017; Vaighan et al. 2017; Zare et al. 2017) and sediment yield (Mir et al. 2016). For example, in the Dong Nai watershed (38,788 km2) in Vietnam, the sediment yield had increased from 24.96 to 38.66 ton ha-1 yr-1 between 2000 and 2008 (Loi 2010). For a reservoir, this increase in sediment yield will reduce its effective storage by sediment accumulation (Fonseca et al. 2016). On average, the annual reduction of global reservoir storage due to sediment deposition is around 0.5–1% (Verstraeten et al. 2003), and in tropical regions it is 1% each year (Nagle et al. 1999). Moreover, for many reservoirs, the annual storage reduction rates are much higher: they can even reach 4 or 5 % such that they lose the majority of their capacity after only twenty five to thirty years.

Therefore, the impact of LULC changes on the hydrological and sediment cycles in a tropical watershed can be significant, and studying this process is extremely important (Gyamfi et al. 2016). To achieve this, it is necessary to simplify the hydrological processes in a mathematical model (Xu 2002). Physically based distributed models are preferred as they better reflect the impact of LULC changes on the model's parameters (Legesse et al. 2003; Ghaffari et al. 2010; Naabil et al. 2017). Furthermore, a distributed model has more advantages, such as the ability to explore the spatial variability of inputs, processes and characteristics and also the capability to obtain results from any specific location (Carpenter and Gergakakos 2006). This study has used the TETIS distributed model which has been satisfactorily applied in different catchment areas (from less than 1 km2 up to 60,000 km2), hydrological problems, spatial resolutions (cells from 5 m to 500 m) and climate types all around the world, including an implementation in the humid tropical climate of the Combeima River in Colombia (Peña et al. 2016). Meanwhile, the Land Change Modeler (LCM) has been widely used to assess LULC changes for various purposes as implemented by Leh et al. (2013), Calijuri et al. (2015) and Sinha and Eldho (2018).

Our case study is the Upper Citarum watershed, which drains into the Saguling reservoir located in West Java, Indonesia. The Upper Citarum River provides the water supply for agricultural and urban areas as well as supplying the hydroelectricity for the region. The LULC changes in the watershed can be identified by the 40% deforestation that occurred between 1997 and 2005, and 35% between 2005 and 2014, meanwhile the increase of agricultural areas was noted as 8% and 2% from 1997 to 2005 and from 2005 to 2014, respectively (Agatona et al. 2015). Dasanto et al. (2014) and Siswanto (2010) stated that deforestation in a large catchment, such as the Upper Citarum watershed, will definitely generate more overland flow and finally increase the catchment erosion as well as the reservoir sedimentation rates. In fact, the erosion rate in the Upper Citarum watershed had increased from 62.04 to 137.66 ton ha-1 yr-1 between 1990 and 2013 (Chaidar et al. 2017), and the reservoir sedimentation rate had increased from 1.05 to 4.80 million ton yr-1 from 1982 to 2004 (Apip et al. 2010). As pointed out by Ilyas (2002), this increase in sedimentation will decrease the reservoir lifetime, concluding that in 100 years from 1984, this reservoir will lose its storage capacity by 21%.

In this context, it is crucial to investigate the impact of LULC changes on the Upper Citarum watershed. Previous studies related with the water cycle have been addressed by Agus et al. (2004), Harlan et al. (2009), Poerbandono et al. (2009), Tommi (2011), Hidayat et al. (2013) and Julian et al. (2013). Flood frequency studies have been performed by Dharma et al. (2011) and Mauliana (2016). Ayuningtyas (2012) and Chaidar et al. (2017) have studied the catchment erosion by implementing the USLE method, while Wibowo (2011) has deployed a model to interpret the sediment cycle. However, these studies have dealt with different hydrological aspects separately. Moreover, none of these studies have considered the future evolution of the LULC and the historical reservoir sedimentation data.

For these reasons, the general objective of this paper is to understand and analyze the impact of LULC changes on all hydrological process and their relationship with historical and future LULC changes by using spatially distributed modeling on the Upper Citarum catchment. To do this, the available historical meteorological data with three different LULC scenarios (two historical scenarios and one future scenario) will be used. Therefore, the specific objectives of this study are: (1) analyzing historical and predicting future LULC changes, (2) implementing a robust distributed hydrological and sediment model in this changing environment and (3) assessing the impact of LULC changes on water balance, flood regimes, catchment erosion and reservoir sedimentation.

Case Study

The Upper Citarum watershed is located in West Java (Fig. 1) and it is the upstream part of the Citarum River. The Upper Citarum watershed covers an area of 2,316 km2. Bandung is the main city, and the total population within the catchment is about nine million. The topography is described as being relatively flat in the central area and mountainous at the outer limits of the catchment area, especially in the northern and southern parts. The river network configuration is a “bowl shape” and it is highly vulnerable to flooding. The Saguling reservoir (initial capacity of 889 Hm3) is the outlet for this watershed, and it acts as the main water and hydroelectricity supply source.

The Upper Citarum has a humid tropical climate characterized by two different seasons (Molion 1993): a rainy season from November to April and a dry season from May to October. The mean rainfall and temperature have been recorded as 1840 mm yr-1and 25.6 °C, respectively. It has 6 orders of soil consisting of Entisols, Inceptisols, Andisols, Mollisols, Alfisols and Ultisols. These orders are then divided into 8 suborders, 19 great groups, 40 subgroups and 72 families (ICALRRD 1993). LULC is constituted by primary and secondary forests, shrubs, grass, dry cultivations, plantations, rice fields, residential areas, industrial zones, mining, bare lands and water bodies. Forests, plantations and dry cultivations areas generally occupy the hilly parts of the catchment, meanwhile urban areas and rice fields occupy the central flat part. The remaining LULC types are spread throughout the catchment. However, LULC is highly dynamic as described later in the sub-section analyzing its historical evolution.

Fig. 1 Digital Elevation Model of Upper Citarum watershed (outlet at Saguling reservoir), including main river network and hydrometeorological stations.

Methodology

General Description

The initial step in this study was the preparation of hydrometeorological and spatial information for data input, including the use of GIS software for spatial manipulation. The future LULC of 2029 as a scenario was obtained by utilizing the LCM developed by Clark Labs (Eastman 2016). The selection of the year 2029 was based on the two decades of government projection plans which were previously made in 2009.

The TETIS distributed hydrological model (Francés et al. 2017) was used as the tool for the simulations of the water and sediment cycles. The calibration and validation of TETIS was performed by using parameter maps corresponding to the appropriate historical LULC. Therefore, the model validation can be classified as a Differential Split-Sample test (Klemes 1986).

The calibration and validation of the water component of TETIS was achieved by comparing the simulations of TETIS with the discharges of a flow gauge station located upstream of the Saguling reservoir. For the sediment sub-model, the bathymetric information of the reservoir has been exploited, as it was done previously by many authors such as Alatorre et al. (2010) or Bussi et al. (2014).

After model validation, a long period of meteorological data (1985-2014) was simulated using LULC of 1994, 2014 and 2029 to quantify the impact of LULC changes on water balance, flood regime, catchment erosion and reservoir sedimentation. In order to accurately predict the expected lifetime of the reservoir, the recirculation of this historic meteorological input is required to obtain long-term results.

TETIS Hydrological Model

Water sub-model

TETIS (Francés et al. 2007) is a distributed conceptual hydrological model with physically based parameters. For each cell, TETIS conceptualizes the water cycle in a set of interconnected virtual tanks as shown in Fig. 2. The interception tank (T6) represents the amount of rainfall intercepted by the plant canopy that subsequently experiences evaporation. The static tank (T1) represents water detention in puddles and capillary water storage (below field capacity) in the upper soil. The infiltration capacity below field capacity is assumed to be infinite and the only output from this tank is evapotranspiration. The surface tank (T2) conceptualizes the amount of water over the surface that moves either in the form of gravitational infiltration (above field capacity) or overland flow. The gravitational tank (T3) represents the storage in the upper soil between field capacity and saturation, and its outputs are deep percolation and interflow. This deep percolation recharges the aquifer tank (T4). The aquifer flow can be connected with the river network within the watershed (base flow) or not (deep aquifer flow). Finally, the river channel tank (T5) collects overland flow, interflow and base flow, and then distributes them through the catchment drainage network.

Fig. 2 Vertical tank conceptualization of TETIS model for each cell.

TETIS deals with the effective model parameters using a split parameter structure (Francés and Benito 1995; Francés et al. 2007). In this way, the effective parameters of each cell are the result of the multiplication of the initially estimated parameter map by nine Correction Factors (CFs).

As there will be only nine variables to be calibrated (the CFs), this internal structure is extremely effective with regards to the calibration process. For this reason, in TETIS it is possible to use optimization algorithms for the automatic calibration of the model. In addition to that, TETIS allows the adjustment of parameter maps without interfering with the calibrated CFs in different LULC situations. Parameters that need to be altered for the changes of LULC are: monthly vegetation coefficients for evapotranspiration, the canopy interception capacity, the static storage capacity due to changes in the effective root depth and puddle retention capacity, and the gravitational infiltration capacity in the case of urbanization.

Sediment Sub-Model

The TETIS sediment sub-model (Bussi et al. 2013) uses the CASC2DSED concept as a base (Julien and Rojas, 2002). Sediment erosion, transport and deposition are determined by comparing the sediment availability and the sediment total transport capacity. TETIS uses two total transport capacities, one for hill slopes and the other for river channels. Each of these transport capacities has its corresponding CF that can be calibrated.

The transport capacity for hill slopes are determined by the Kilinc and Richardson (1973) equation and modified by Julien (2010) by implementing the USLE factors of soil erodibility, soil cover and soil practice-management (Wischmeier and Smith 1961). The Engelund and Hansen equation (Engelund and Hansen 1967) is used for the total transport capacity of river channels.

In terms of different LULC, it is required to change the map of USLE land cover factor and with regards to urbanization, the soil erodibility factor also needs to be amended.

LULC Change Model

LCM (Eastman 2016) is a powerful tool for the analysis and prediction of LULC changes. Among other methods, LCM uses a multi-layer perceptron (MLP) neural network to model the transition potentials based on analysis of physic, environment, and socio-economy of historical LULC evolution. And to make the predictions, LCM uses a spatio-temporal Markov Chain to quantify the change based on transition potentials.

The LCM application consists of three main steps: change analysis, transition potential and prediction. The change analysis step identifies gains and losses, persistence and transition trends from one previous land cover state (T1) to another (T2). The transition potential step determines the potential of the area to transition based on the transition trend. Transition may consist of a single or a group of land cover categories related to its driver variable called the sub-model. For the transition potential modeling, the MLP performs the training and testing by identifying two groups. The first one is the group of pixels that have been transitioned from T1 to T2, meanwhile the other group consists of persisted pixels. The performance of training and testing is expressed in the accuracy rate. Based on historical changes and the transition potential model, the prediction process will determine the relative change of transition in the future. The validation step is conducted by comparing the predicted and observed maps to determine whether the transitioned pixels are correctly predicted or not. Three results exist in validation: hits (model correctly predicted the change), false alarms (model predicted the change, but it did not actually occur) and misses (model did not predict the change, but it actually occurred).

Models Input Information

Hydrometeorology

This study used twenty stations of daily rainfall (Fig. 1) from 1985 to 2014. The rainy season normally occurs around November to April. Meanwhile, the summer season occurs from May to October (Fig. 3). The reference evapotranspiration (ET0) was estimated using the Hargraves equation method based on mean, maximum and minimum temperatures (Berti et al. 2013). However, daily temperature datasets were only available from 1985 to 2014 at the Bandung meteorological station. Due to this data limitation, the temperature data from that station was transferred to nine modified temperature points based on altitude using the ISA method (NASA 1976). The mean temperature spatially results in the narrow range of 22.6-23.7oC and a relatively constant ET0 of approximately 130 mm/month was computed (Fig. 3). In order to obtain the precipitation and ET0 at each pixel, TETIS performs spatial interpolation by the inverse of the square of the distance method. The discharges for the period 1985 to 2014 came from the Nanjung station (Fig. 1), and they presented the same temporal pattern as precipitation (Fig. 3).

Fig. 3 Monthly averages (1985-2014) of: discharges (Q) at Nanjung flow guage station and mean areal rainfall and reference evapotranspiration (ET0) for the whole catchment.

Reservoir Sedimentation and Sediment Yield

The annual deposited sediment was computed by the differential bathymetry method, taking into account the temporal evolution of the sediment density using the Miller formula (Miller 1953). Reservoir bathymetries were collected annually by the public company responsible for the reservoir management from 1985 to 2013, with a mean decrease of reservoir volume of 3.83 Hm3 yr-1. After sediment density correction, the mean deposition is 3.44 Mton yr-1. As explained in the methodology section, for the calibration and validation of the TETIS sediment sub-model, it is necessary to determine the catchment sediment yield. Therefore, the annual deposited sediment was modified due to the un-trapped sediment in the reservoir using the Dendy (1974) equation, resulting in a mean of 3.68 Mton yr-1 during the historical period of observations. No dredging of sediment occurred in the reservoir during the observational period.

Spatial Information

Basic spatial inputs for TETIS and LCM parameterization are comprised of topography (in the form of a DEM), soil, geology and LULC maps (Table 1). All map manipulations were done using ArcGIS with a final spatial resolution of 90 m.

Table 1 Spatial information used by TETIS and LCM models
Data Type Scale (resolution) Source Input, driver or parameter Utilized by
Topographic map 2 arc-second (90m) Digital Elevation Model USGS - Slope
- Flow
- Direction
- Flow accumulation
- Overland flow velocity
- Elevation LCM and TETIS
TETIS
TETIS
TETIS
TETIS
LCM and TETIS
Soils (survey) map 1:50,000 Indonesian Center for Agricultural Land Resources Research and Development (ICALRRD) Report - Static storage
- Infiltration capacity
- Percolation capacity
- Available water content
- Texture
- Erodibility TETIS
TETIS
TETIS
TETIS
TETIS
TETIS
Geology/hydrogeology map of Bandung 1: 100,000 Ministry of Public Work, Indonesia - Percolation capacity
- Aquifer permeability TETIS
LULC 1994, 2009 and 2014 Landsat TM
30 meters (supervised classification) Planning Board of West Java, Indonesia - Vegetation coefficient
- Static storage capacity
- Infiltration capacity
- Interception TETIS
TETIS
TETIS
TETIS
Road and city map 1: 100,000 Planning Board of West Java, Indonesia - Distance from road
- Distance from city LCM
LCM

The required maps for TETIS such as flow accumulation, flow direction, overland flow velocity and slope maps were extracted directly from DEM. Overland flow velocity is not an influential parameter and it was computed as a function of slope exclusively. Soil data was derived from 77 samples with depths of approximately 200 cm. From this soil information, infiltration capacity, field capacity and available water content were calculated using the pedotransfer function developed by Saxton and Rawls (2006). Erodibility was estimated using the formula proposed by Wischmeier et al. (1971). The hydrogeological map of Bandung Regency was used to estimate deep percolation capacities and aquifer saturated conductivities.

The LULC maps for 1994, 2009 and 2014 have been corrected manually by comparison with Landsat TM imagery. As the LULC maps did not have the same classification, a proper reclassification has hence been implemented. The driver maps of distance from road and city were generated based on the road and city map from the Planning Board of West Java, Indonesia.

Models Implementation

Land Change Modeler (LCM)

Initially, the gains, losses, persistence and transition trends between LULC 1994 and 2009 were assessed. Subsequently, the LULC categories (sub-models) of transition potential were estimated. In this study, the transitions smaller than 500 hectares were eliminated to be more focus in significant transitions. Incorrect transitions such as from urban or industrial area to vegetation land cover were eliminated because such transitions are hardly found in real conditions. Driver variables such as elevation, slope, distance from road and distance from city (Table 1) were used in the training and testing step. This step was carried out based on the accuracy rate estimation index as the performance evaluator (Eastman 2016). In this study, a minimum accuracy rate of 65% was the result of the training and testing process of all LULC category transitions. All driver variables resulted significant. Validation was then performed by comparing the actual and predicted map of 2014 (Fig. 4). Year 2014 was selected for validation, because in this study was more important to test the “predictive” ability of the model (going from 2009 to 2014), than its “descriptive” ability (interpolating 2009 using previous and posterior information), as Cunnane (1986) referred to in a similar context. The validation showed that 68.4% (184,671 pixels) were hits, 19.8% (53,542 pixels) were false alarms and 11.7% (184,671 pixels) were missed. After completing the validation process, the future prediction of 2029 was generated. The prediction for year 2029 was based on the transitional potential between LULC 1994 to 2009 which is reflected in the implemented model.

Fig. 4 Comparing the actual and predicted map of LULC 2014 in the validation process.

TETIS Model

The calibration of the water sub-model has been performed with parameter maps corresponding to LULC 2009 in the period 2008 to 2010 in Nanjung flow gauge station and with one year of warm-up period. The Nash Sutcliffe Efficiency index (NSE), Standard Deviation Ratio (RSR) and Volume Error (VE) were used to measure the model performance (Moriasi et al. 2007). The NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance. RSR represent the ratio of the RMSE and standard deviation of measured data. Meanwhile, the VE calculates the average tendency of the simulated data to be larger or smaller than its observed counterpart. The calibration of the model was started manually by adjusting the CFs to find realistic values based on an acceptable threshold of NSE, RSR and VE. Once these values were obtained, the calibration continued automatically using the SCE-UA optimization algorithm (Duan et al. 1994) implemented in TETIS. Calibrated CFs were satisfactorily validated for the periods 2012-2014 and 1994-1996, corresponding to LULC 2014 and LULC 1994, respectively. The selected periods for calibration and validation were based on the availability of common and complete hydrometeorological and LULC data.

The sediment sub-model calibration was done for the year 2009, comparing the observed sediment yield (obtained from the reservoir data) and the simulated with TETIS using LULC 2009. Meanwhile, the validation was conducted during the period 2008-2012. In this case, the balance error was used to measure the model's performance for sediments. After the model validation was completed, a long period of simulation using different LULCs from 1994, 2014 and 2029 were implemented.

Results and Discussion

Analysis of LULC Changes

LULC maps for years 1994, 2009, 2014 and the predicted for 2029 in the Upper Citarum watershed are displayed in Fig. 5a. In 1994, the main LULC types were rice fields, forests and plantations (32.3, 23.7 and 19.0% of the catchment, respectively), whereas for 2029 it is predicted that the main types will be urban areas, rice fields, dry cultivations and plantations (23.3%, 22.9%, 16.1% and 16.1% of the catchment, respectively). Spatially, the increase of urban and the reduction of rice field areas can be clearly observed in the center of the catchment. Meanwhile, deforestation can be detected in the southern part of the study area.

Forest and rice fields are the larger areas that have changed into another LULC during the period 1994-2009 (Fig. 5b); there were reductions in forests and rice fields by 40.9% (225 km2) and 10.9% (81 km2), respectively. Deforestation in the southern part of the study area was presumably caused by land conversion from dry cultivations by about 53.5% (121 km2). This conversion was caused by its fertile soil condition and the lack of supervision by the government. The increment of urban by about 113% (197 km2) was due to rice field conversion in the center of the study area. This change was caused by urban necessity due to the high increase in population. These trends of conversion were continued until 2014.

Meanwhile, from 2014 to 2029 forests and rice fields will decrease by 3.13% (8.33 km2) and 15.0% (93.5 km2), respectively. Deforestation occurs at a slower pace from 2014 to 2029 and this is presumably due to the decrease of available forested areas for other human related use (forest makes up only 11.50% in LULC 2014). Moreover, the remaining forests are located in hillier areas, hence making them unsuitable for cultivation.

Fig. 5 LULC analysis: a) LULC maps in three historical periods (1994, 2009 and 2014) and one future scenario (2029); b) percentage of LULC areas from 1994 to 2029.

From a more detailed LULC analysis of the LCM results from 1994 to 2014, it can be concluded that large forested areas have been removed; these areas now consist of predominantly bush/shrub, urban areas, dry cultivation, plantations and rice fields, with plantations holding the biggest portion (Fig. 6a). The conversion of the forest into cultivation areas (dry cultivations, plantations and rice fields) was caused by the rise of food requirements due to the population growth as reflected in the increase of urban areas. This situation also occurs in the Netravati watershed in India (Sinha and Eldho 2018) and the Samin watershed in East Java, Indonesia (Marhaento et al. 2018). The settlement area (urban and industrial) in the Upper Citarum increased from 7.76% to 18.87% in the period of 1994-2014, mainly due to the conversion of cultivation areas (Fig. 6b). This result aligns with those obtained by Tarigan and Tukayo (2013). They concluded the settlement area in Upper Citarum has increased by more than double during the period 2000 to 2009. Meanwhile in 2029, the settlement area will be three times that of the settlement area in 1994. A similar trend was also predicted in the Netravati watershed (Sinha and Eldho 2018).

Area (ha)

Area (ha)

Fig. 6 Contribution of different LULC to the net change between 1994 and 2014 for: a) forest; b) urban area

Beyond all validated results of the LCM model, the representation of the real conditions in the transition of LULC categories cannot be expressed perfectly due to uncertainties. The complex relationship between driver variables and transition potential, or the representation of complex human behaviours in the transition trends may affect the quality of LCM results.

Calibration and Validation of TETIS Model

Water Sub-Model

The most influential parameters for this sub-model and case study were maximum static storage, evapotranspiration, infiltration, percolation and channel flow velocity. Therefore, the corresponding CFs were particularly considered in the calibration process. The simulated and observed discharges during the calibration and validation are presented in Fig. 7a and 7b, respectively. In general, the observed discharge has been successfully simulated by the model, except for high flows at the beginning of the calibration period and in certain flood events. The main reason for these problems is the quality of the precipitation data, especially regarding the spatial distribution of rain gauges.

Fig. 7 Implementation of TETIS hydrological sub-model in Nanjung flow gauge station: a) calibration in the period 2007 to 2009; b) validation in two different periods.

In any case, the results of hydrological calibration and validation are presented in Table 2. The model performance in the calibration can be classified as “good”. Meanwhile, both validations can be classified as “satisfactory”. Based on the performance index category and the difficulties of the type of validation (Differential Split-Sample), the TETIS model can be used with confidence to describe the hydrology of the Upper Citarum watershed.

Table 2 Model performance categorization based on Moriasi et al. (2007).

Name	Calibration		Validation 1994-1996		Validation 2012-2014	
	Value	Category	Value	Category	Value	Category
NSE	0.7	good	0.54	satisfactory	0.52	satisfactory
RSR	0.54	good	0.58	satisfactory	0.59	satisfactory
VE	-9.2%	-	-30%	-	-34%	-

Sediment Sub-Model

The recorded deposited sediments in the Saguling reservoir during 2009 were 4.14 Mton. After being corrected by trap efficiency, this is equivalent to 4.43 Mton yr-1. This figure was used to calibrate the sediment sub-model of TETIS, considering the LULC in 2009. The most sensitive CFs in this case study was the hill slope transport capacity. Hence, this CF plays an important role in the calibration process. The validation was conducted by comparing the observed deposited sediment volume during the period 2008-2012 with corresponding simulations using TETIS. The results for the whole period were 21.49 and 22.04 Mton respectively, i.e. the balance error was only 2.5% in validation (annual maximum error of 3.9% and minimum error of 0.2%), which is an excellent outcome.

Changes in Water Balance

The effects of the assumed LULC scenarios on the proportions of hydrological cycle elements are illustrated in Fig. 8. The simulated evapotranspiration for LULC 1994, 2014 and 2029 scenarios are 997, 875 and 489 mm yr-1, respectively. The strong decline of evapotranspiration is clearly induced by the loss of natural vegetation cover, especially the dense forested areas. Forested areas play an important role in balancing the evapotranspiration within the watershed. A forest is able to maintain a relatively constant evapotranspiration rate over time (Zhang et al., 2001) and any alteration in this flux subsequently changes other elements of the water cycle such as overland flow, infiltration, interflow, percolation, base flow and water yield. The direct consequence of a reduction of actual evapotranspiration (for the same precipitation) is the increase in water yield; in fact, the water yield increased by 15% and 40% from LULC 1994 to 2014 and from LULC 2014 to 2029, respectively. In this case study, this is due to the increase of all components of the water yield (overland flow, interflow and base flow) as seen in Fig. 8. As stated by many authors (Zhang et al. 2001 and Costa 2005), water yield increases with the decrease in forest cover. Furthermore, the change from forested areas to cultivated areas will also alter the flow paths, flow velocities, and water storage capacity (Rogger et al., 2017). The decline of vegetation generates less canopy interception, increasing the rainfall reaching the soil surface (also referred to as direct rainfall in Fig. 2) and, therefore, increasing the possibility of infiltration and overland flow.

Fig. 8 Water balance of two historical and one future LULC scenarios using TETIS with meteorological data from 1985 to 2014 (precipitation equals to 1845 mm yr-1)

The infiltration capacity of the soil is reduced in areas where deforestation has occurred, areas of increased settlement (such as urban and industrial areas), as well as in plantations and dry cultivations. The total infiltration is reduced in settlement areas, but due to the significant increase of direct rainfall in the rest of LULCs, watershed infiltration increased by 6% and 48% from LULC 1994 to 2014 and from LULC 2014 to 2029, respectively. With more infiltration, soil moisture increases and consequently interflow, percolation and base flow also intensify.

The expansion of settlement areas together with increased agricultural activity produce greater areas of impervious surfaces and soil compaction, that possibly escalates the overland flow (Rogger et al. 2017). With regards to our case study, an increment of 30% overland flow was observed when comparing the changes from the LULC scenario in 1994 to the LULC scenario in 2014 and a similar value (28%) from LULC 2014 to 2029.

Changes in Flood Regime

Flood frequency analysis in this study follows a standard approach (see for example the book of Kottegoda and Rosso, 2008), using the software AFINS (http://lluvia.dihma.upv.es/EN/software/software.html) to: i) estimate the parameters of different probability distribution functions by the Maximum-Likelihood-Method; and ii) to perform the statistical model selection, mainly using the comparison with the sample plotting positions (also called empirical distribution). The annual maximum daily discharge simulated with TETIS (1985-2014) using the different LULC scenarios were used as samples for this flood frequency analysis.

Fig. 9 Comparison of flood regimes for LULC 1994, 2014 and 2029, representing the corresponding plotting positions (dots) and the fitted (lines) Gumbel distribution function (simulation period 1985-2014).

Fig. 9 represents the empirical and the fitted Gumbel distribution function for the three LULC scenarios. The calculated quantiles for specific return periods can be found in Table 3. It is evident that the evolution of LULC in time increases flood quantiles, because it is increasing both interflow and overland flow, which are the two components of the surface runoff. To summarize, it is accurate to predict that there will be an increase in both the frequency and magnitude of floods in the region. The increase in frequency and magnitude of floods will occur for all return periods as indicated in Fig. 9 and Table 3. However, this change is not homogeneous, being larger in percentage for lower return periods than for higher ones. For example, LULC changes from 2014 to 2029 increases the flood quantile by 16.14% for the five-year return period, but only increases it by half (8.96%) for the hundred-year return period quantile. Also, it can be highlighted that the change in the future will be larger than it was in the past. One of the main reasons behind these increments is the decrease in forested areas, as forests are able to intercept rainfall, decrease soil humidity, increase transpiration and increase soil permeability (Rogger et al. 2017).

Table 3 Comparison of flood quantiles between five to hundred years return period for LULC 1994, 2014 and 2029

Return period (yr)	Max discharge (m3s-1)			Change (%)	
	1994	2014	2029	1994 - 2014	2014 - 2029
5	346	374	434	7.90	16.14

10	411	440	500		7.09	13.58
25	493	525	584		6.37	11.27
50	554	587	646		5.97	9.99
100	614	649	707		5.65	8.96

Changes in Catchment Erosion

The areas within the Upper Citarum watershed that are susceptible to soil erosion for LULC scenarios in 1994, 2014 and 2029 are illustrated in Fig. 10 and summarized numerically in Table 4. Both Fig. 10 and Table 4 follow the Hammer (1981) classification for erosion rates, plus a tolerable erosion threshold of 13.5 ton ha-1 yr-1 as specifically proposed for Indonesia by Arsyad (2000). In general, the low erosion class (< 1 ton ha-1 yr-1) affected the flat areas, whereas the hilly areas possessed higher erosion rates due to higher overland flow velocities for erosion and transportation. The lower rate of erosion in flat areas in this case study is caused by two factors. Firstly, the flat area does not suffer high erosion rates due to low overland flow velocities associated with small slopes. Secondly, the majority of the flat areas are occupied by either urban zones, industrial zones or by rice fields. The soil in the urban and industrial areas is mostly covered by buildings, pavements and/or miscellaneous structures. Hence, the soil does not receive the necessary exposure needed for erosion to occur. Meanwhile, the rice fields are designed to be practically horizontal.

Throughout the evolution of erosion from 1994 to 2029, it seems in a first approach there are no significant changes as seen in Fig. 10. However, from a more detailed analysis, it is possible to detect two main changes. The first change noted is the clear increase in erosion due to deforestation in the northern and southern parts of the watershed. The same increment of erosion due to deforestation was also found in the Samin catchment, East Java (Marhaento et al. 2018). As explained in previous sections, deforestation induces more overland flow and consequently this results in higher erosion and sediment transport capacities. Also, the removal of canopy increases the probability of rainfall detaching soil aggregate in large quantities, due to the direct impact of rainfall on the bare soil. Experts such as Mohammad and Adam (2010) have always seen forests as the optimum type of vegetation to reduce overland flow and erosion. The reduction of rice field areas could be another factor contributing to the increment of erosion. Rice fields are normally cultivated in a terraced landscape that permit them to collect water, thus lowering the overland flow and erosion (Rogger et al. 2017).

Fig. 10 Spatial distribution of erosion rates simulated with TETIS for the different LULC scenarios

The second main change refers to the evolution of areas exceeding tolerable erosion, which is the major part of the severe erosion rate class (Table 4). Comparing the historical LULCs, the non-tolerable erosion increases by 4.7% (19.22 km2) mostly in the hillier parts of the watershed. This areal increase is compensated in space by a similar decrease of the low erosion rate class, located predominantly in the West, due to the conversion into urban areas. However, regarding the future, the difference in non-tolerable erosion between LULC 2014 and 2029 is higher: 67.86 km2 representing an increment of 15.7%.

Table 4 Aggregated erosion results simulated with TETIS for different LULC scenarios

Erosion rate class (ton ha-1 yr-1)	Area (% of watershed| km2)		
	1994	2014	2029
<1 (low)	67.0 | 1552	65.8 | 1524	63.0 | 1459
1-4 (moderate)	8.2 | 189	8.1 | 188	8.2 | 189
4-10 (high)	5.0 | 115	5.0 | 115	5.1 | 117
>10 (severe)	19.9 | 460	21.1 | 489	23.8 | 551
Non-tolerable erosion	17.8 | 412	18.6 | 431	21.5 | 499

Changes in Reservoir Sedimentation

The gross sediment input that enter the Saguling reservoir is equal to its watershed sediment yield. The sediment yield increased from 14 ton ha-1 yr-1 in the LULC 1994 scenario to 18 ton ha-1 yr-1 in 2014 and 29 ton ha-1 yr-1 in 2029 (Table 5). Sinha and Eldho (2018) found a similar increase in sediment yield, studying the past and future of the Netravati watershed in India . The increment of the sediment yield can be explained not only by the increase in erosion rates, but also by the increase of river channel transport capacity, mainly during flood events. The transport capacity of water on the eroded material increases simultaneously with the increase in watershed overland flow (Yu et al. 2015), and also affects the remobilization of previously deposited materials (Bussi et al. 2014).

A direct consequence of a greater quantity of sediment draining into the reservoir, is the reduction of its lifetime. For this study, a minimum operational volume of 50 Hm3 has been considered. With this hypothesis, the reservoir lifetime is noted as 239, 182 and 113 years for LULC scenarios 1994, 2014 and 2029, respectively. These results are more pessimistic than the half lifetime of 189 years obtained by the Ministry of Public Works of Indonesia using a simpler methodology and a LULC map of 2009 (Ministry of Public Works 2011). The severity of this situation is further emphasized when considering the problem of hydroelectric power production: hydropower water intake corresponds to a storage capacity of 722 Hm3, which means that there will be serious hydropower production problems within the next twenty years if no immediate action is taken.

Table 5 Comparison of sediment yield and the lifetimes of reservoir and hydropower for the different LULC scenarios

	1994	2014	2029
Sediment yield	3.1 Mton yr-1 (14 ton ha-1yr-1)	4.1 Mton yr-1 (18 ton ha-1 yr-1)	6.7 Mton yr-1 (29 ton ha-1 yr-1)
Reservoir lifetime	239 yr	182 yr	113 yr
Hydropower lifetime	20 yr	15 yr	8 yr

Conclusions

Since Indonesia gained independence eighty years ago, hHuman activity has produced severe LULC changes within the Upper Citarum watershed in. The historical changes of the last thirty years have required the reconstruction of the LULC maps for years 1994, 2009 and 2014. . During this period, these significant LULC changes have occurred primarily due to the demands of the constant population growth, with a significant and continuous transformation of urban areas, forests and rice fields. This rise in population equates to a 141% increase in the development of urban areas, significantly reducing .With the expansion of these urban areas, there was a significant reducestion in the quantity amount of land utilized exploited by rice fields in the central part of the catchment. Actually, the net balance of rice fields in 2014 was a reduction of 16.5% from its original area in 1994. At the same timelso, forested areas have been sacrificed for cultivation purposes (plantations, dry cultivations and rice fields) in order to meet the increased demand for food. In addition, the conversion of forests into bush has contributed to a total of 51.5% historical forest areal reduction.

The LCM model was used to forecast the LULCs in 2029. The training and validation of this model using the three historical maps was satisfactory. The transitional potential of historical LULC changes was used to forecast the future LULC. The forecasted results show a continuation in the expansion of urban areas at the expense of the contiguous rice fields but, simultaneously, it also shows a significant decrease in the future deforestation rate. This positive consequence is mainly due to the fact that most of the remaining forests do not currently have the appropriate conditions for anthropogenic LULC types.

A distributed hydrological model called TETIS was implemented in the Upper Citarum watershed. The water component of the model was calibrated using the LULC of 2009 and validated satisfactorily for the period 1994-2014 using different LULC maps. This extrapolation of the calibration to different hydrological conditions is possible in TETIS as only the CFs of the parameter maps are calibrated through a split structure of the model's effective parameters. In this wayTherefore, LULC changes only affect the parameter maps and not the calibrated CFs. Regarding the sediment component, it was highly useful to assess the bathymetric information in the Saguling reservoir for its calibration and validation, despite the understanding that there are uncertainties in the reconstruction of the observed annual sediment yields.

The results determined that deforestation and urbanization were the most influential factors for the alteration of the hydrological and sedimentological processes. During the period 1994-2014, the change in LULC decreased evapotranspiration by 12%. As a direct and expected consequence, water yield increased by 15%. Meanwhile, from 2014 to 2029, evapotranspiration is expected to decrease by an additional 44%, which will then increase water yield by 40%. At catchment scale, the combined effects of deforestation and urbanization in this case study are increasing and will increase the water yield by increasing all its components (overland flow, interflow and base flow). Also, there is over time a greater quantity of water with irregular regime, mainly due to the overall increase of overland flow. Also, the increase of overland flow and its higher irregularityThis situation areis producing over time an increase in theof flooding frequency and magnitude of floods. With regards to erosion, the changes in LULC will produce a relatively small increment in erosion rates in the future, increasing the area of non-tolerable erosion from 412 km2 in 1994 to 499 km2 in 2029. However, in terms of sediment yield, the situation is worse. From 3.1 Mton yr-1 in the LULC 1994 scenario, the watershed will have a mean sediment yield of 6.7 Mton yr-1 in the LULC 2029 scenario. This situation will be catastrophic for the hydropower operation at the Saguling Dam.

All that being said, one of the biggest challenges in mathematical modeling is model implementation with changing conditions. It is our opinion that tThe implementation of a distributed hydrological model is essential in order to seamlessly alter the parameters that are represented on the LULC at pixel scale. Also, the selected model should be able to extrapolate its calibration to different LULC scenarios and to consider all the potential interactions within and between the water and sediment cycles. Based on all these considerations, the TETIS hydrological distributed model has been shown to be a robust tool to assess the effects of LULC changes on water resources, flood regimes, erosion rates and sediment yield in the Upper Citarum watershed.

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References

Agatona M, Setiawan Y, Effendi H (2016) Land use/land cover change detection in an urban watershed: a case study of upper Citarum Watershed, West Java Province, Indonesia. Procedia Environ Sci 33: 654 – 660.

Agus F, Wahyunto, Watung R L, Talaohu S H, Sutono (2004) Land use changes and their effects on environmental functions of agriculture. Indonesian Soil Research Institute, Bogor, Indonesia

Apip, Takara K, Yamashiki Y, Ibrahim A B (2010) Distributed sediment budget and potential shallow landslide area for investment prioritization in sediment control of ungauged catchment : a case study on the Upper Citarum river, Indonesia. Annual of Disaster. Prev. Rest. 53: 45–59

Alatorre LC, Beguería S, García-Ruiz JM (2010) Regional scale modeling of hillslope sediment delivery: a case study in the Barasona Reservoir watershed (Spain) using WATEM/SEDEM. J Hydrol 391:109–123

Arsyad S (2000) Soil and water conservation. IPB pers, Bogor, Indonesia. (in Indonesian)

Ayuningtyas D W (2012) Impact analysis of rainfall amount on sedimentation in Upper Citarum watershed with RUSLE2 method. Thesis, Institut Teknologi Bandung. (in Indonesian)

Baker T J, Miller S N (2013) Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed. J Hydrol 486: 100–111

Berti A, Tardivo G, Chiaudani A, Rech F, Borin M (2013) Assessing reference evapotranspiration by the Hargreaves method in North-Eastern Italy. Agric water manag 140:20–25

Boongaling C G K, Faustino-Eslava D V, Lansigan F P (2018) Modeling land use change impacts on hydrology and the use of landscape metrics as tools for watershed management: The case of an ungauged catchment in the Philippines. Land Use Policy 72: 116–128

Bosmans J H C, Van Beek L P H, Sutanudjaja E H, Bierkens M F P (2017) Hydrological impacts of global land cover change and human water use. Earth Syst Sci 21: 5603–5626

Bruijnzeel L A (2004) Hydrological functions of tropical forests: not seeing the soil for the trees?. Agric Ecosyst Environ104: 185–228

Bussi G, Francés F, Horel E, López-Tarazón JA, Batalla R (2014). Modelling the impact of climate change on sediment yield in a highly erodible Mediterranean catchment. J Soils Sediments, 14 (12): 1921-1937

Bussi G, Francés F, Montoya JJ, Julien P (2014) Distributed sediment yield modelling: Importance of initial sediment conditions. Environ Model Softw 58: 58-70.

Bussi G, Rodríguez-Lloveras X, Francés F, Benito G, Sánchez-Moya Y, Sopeña A (2013) Sediment yield model implementation based on check dam infill stratigraphy in a semiarid Mediterranean catchment. Hydrol Earth Syst Sci 17(8): 3339–3354

Calijuri M L, Castro J de S, Costa L S, Assemany P P, Alves J E M (2015) Impact of land use/land cover changes on water quality and hydrological behavior of an agricultural subwatershed. Environ Earth Sci 74(6): 5373–5382.

Carpenter T M, Gergakakos K P (2006) Intercomparison of lumped versus distributed hydrologic model ensemble simulations on operational forecast scales. J Hydrol 329(1–2): 174–185

Chaidar A N, Soekarno I, Wiyono A, Nugroho J (2017) Spatial analysis of erosion and land criticality of the upstream citarum watershed. International Journal of GEOMATE 13(37): 133–140

Costa M H (2005) Large-scale hydrological impact of tropical forest conversion, in: Bonell, M., Bruijnzeel, L. A. (eds) Forests, water and people in the humid tropics: past, present and future. Cambridge University Press, Cambridge, pp 590–597.

Cunnane C (1986) Review of statistical models for flood estimation, in: Singh V D (ed) Hydrologic Frequency Modeling. D. Reidel Pub. Co. Lousiana State University, Baton Rouge

Dasanto D B, Boer R, Pramudya B, Suharnoto Y (2014) Simple method for assessing spread of flood prone areas under historical and future rainfall in the Upper Citarum watershed. Enviro Asia 7(1): 104–111

Defra (2004) Making space for water developing a new government strategy for flood and coastal erosion risk management in England. Department for Environment, Food and Rural Affairs, London

De Graff J V, Sidle R C, Ahmad R, Scatena F N (2012) Recognizing the importance of tropical forests in limiting rainfall-induced debris flows. Environ Earth Sci 67(4): 1225–1235

Dendy F E (1974) Sediment trap efficiency of small reservoirs. J Soil Water Conserv 39(4): 278–280

Dharma N G G Y, Deguchi C and Yoshitake T (2011) Evaluation of land use plan in Citarum Hulu watershed considering environmental degradation of soil erosion. Miyazaki University 40: 151–158

Duan Q, Sorooshian S, & Gupta V K (1994). Optimal use of the SCE-UA global optimization method for calibrating watershed models. J Hydrol, 158(3–4), 265–284

Eastman J R (2016) TerrSet Manual. Clark University, Worchester, UK

Engelund F, Hansen E (1967) A monograph on sediment transport in alluvial streams. Denmark Tech University, Copenhagen, Denmark

Fenli Z, Keli T, Cheng-e Z, Xiubin H (2002) Vegetation destruction and restoration effects on soil erosion process on the loess plateau. ISCO conference 208–213

Fonseca R, Pinho C, Oliveira M (2016) The influence of particles recycling on the geochemistry of sediments in a large tropical dam lake in the Amazonian region, Brazil. J South Am Earth Sci72: 328–350

Francés F, Upegui J V, Múnera J C, Medici C, Bussi G et al (2017) Description of the distributed conceptual hydrological model TETIS V.8. Valencia, Spain

Francés F, Vélez J I, Vélez J J (2007) Split - parameter structure for the automatic calibration of distributed hydrological models. J Hydrol 332: 226–240

Francés, F. and J. Benito (1995). Floods distributed modeling with few parameters. Ingeniería del Agua, v 2 (4), 7-24. (in Spanish)

Garg V, Aggarwal S P, Gupta P K, Nikam B R, Thakur P K, Srivastav S K, Senthil Kumar A (2017) Assessment of land use land cover change impact on hydrological regime of a basin. Environ Earth Sci 76:635

Ghaffari G, Keesstra S, Ghodousi J, Ahmadi H (2010) SWAT-simulated hydrological impact of land-use change in the Zanjanrood basin, Northwest Iran. Hydrol Process 24(7): 892–903

Gupta A (2011) Tropical geomorphology. Cambridge University Press, New York, United States of America

Gyamfi C, Ndambuki J, Salim R (2016) Hydrological responses to land use/cover changes in the Olifants basin, South Africa. Water 8(12): 588

Hammer W I (1981) Second soil conservation consultant report. Centre for Soil Research, Bogor

Happ M (2014) Impacts of land-cover change and high rainfall on soil erosion among three farms in Cerro Punta, Chiriquí, Panamá. College of Wooster, Panama

Harlan D, Wangsadipura M, Munajat C M (2009) Determination of daily discharge using rainfall runoff GR4J model for hydrograph unit analysis in Upper Citarum watershed. Jurnal Teknik Sipil 16(1): 1–12 (in Indonesian)

Hidayat Y, Murtilaksono K, Wahjunie E D, Panuju D R (2013) The characteristics of river discharge of Citarum Hulu. Jurnal Ilmu Pertanian Indonesia 18(2): 109–114. (in Indonesian)

ICALRRD (1993) Optimisation of land usage in watershed report. Badan Penelitian dan Pengembangan Pertanian, Bogor. (in Indonesian)

Ilyas M A (2002) Sedimentation and its impact on Upper Citarum watershed. Jurnal Teknologi Lingkungan 3(2): 159–164. (in Indonesian)

Julian M M, Fink M, Fischer C, Krause P, Flügel WA (2013) Implementation of J2000 hydrological model in the Western part of Java Island, Indonesia. The Journal of MacroTrends in Applied Science 1(1): 1–25

Julien P, Rojas R (2002) Upland erosion modeling with CASC2D-SED. International Journal of Sediment Research 17(4): 265–274

Julien P Y (2010) Erosion and sedimentation. Cambridge University Press, Cambridge, United Kingdom.

Kheereemangkla Y, Shrestha R P, Shrestha S, Jourdain D(2016) Modeling hydrologic responses to land management scenarios for the Chi river sub-basin part II, Northeast Thailand. Environ Earth Sci 75(9): 793

Kilinc M, Richardson E (1973) Mechanics of soil erosion from overland flow generated by simulated rainfall. Colorado State University, Colorado, United States of America

Klemes V (1986) Operational testing of hydrological simulation models. Hydrol Sci J, 31:1, 13-24

Kottegoda N, Rosso R (2008) Applied statistics for civil and environmental engineers. The McGraw-Hill Companies Inc, Milan, Italy

Legesse D, Coulumb C V, Gasse F (2003) Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. J Hydrol 275(1–2): 67–85

Leh M, Bajwa S, Chaubey I (2013) Impact of land use change on erosion risk: an integrated remote sensing, geographic information system and modeling methodology, Land Degrad & Develop, 24: 409-421

Loi N K (2010) Assessing the impacts of land use/land cover changes and practices on water discharge and sedimentation using SWAT: case study in Dong Nai watershed – Vietnam. International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences, VietnamMarhaento H, Booij M J, Hoekstra AY (2018) Hydrological response to future land-use change and climate change in a tropical catchment. Hydrol Sci J 1368–1385.

Mauliana P (2016) Flood prediction in Citarum using Fuzzy logic from particle Swarm optimization algorithm. Jurnal Informatika 3(2): 269–276. (in Indonesian)

Miller C R (1953) Determination of the unit weight of sediment for use in sediment volume computations. Bureau of Reclamation, Denver, United States of America

Ministry of Public Works (2011) TA 7189-INO: Institutional strengthening in the 6 ci's river basin territory - package B for integrated water resources management (IWRM). Bandung, Indonesia

Mir S I, Ismail B S, Tayeb M A (2016) Hydrology and sediment loading in a degrading natural lake system in Malaysia. Environ Earth Sci 75(3): 231

Mohammad A G, Adam M A (2010) The impact of vegetative cover type on runoff and soil erosion under different land uses. Catena 81(2): 97–103

Molion L C B (1993) Amazonian rainfall and its variability. in: Bonell, M., Hufschmidt, M. M., Gladwell, J. S (eds) Hydrology and water management in the humid tropics : hydrological research issues and strategies for water management. Cambridge University Press, New York pp 55-62

Moriasi D N, Arnold J G, Van Liew M W, Bingner R L, Harmel R D, Veith T L (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE 50(3): 885–900

Mushtaq F, Lala M G N (2017) Assessment of hydrological response as a function of LULC change and climatic variability in the catchment of the Wular Lake, J&K, using geospatial technique. Environ Earth Sci 76(22): 760

Naabil E, Lamptey B L, Arnault J, Olufayo A, Kunstmann H (2017) Water resources management using the WRF-Hydro modelling system: case-study of the Tono dam in West Africa. J Hydrol Reg Stud 12: 196–209

Nagle G N, Fahey T J, Lassoie J P (1999). Management of sedimentation in tropical watersheds. Environ Manag 23(4): 441–452

NASA (1976) U.S. Standard atmosphere, 1976. US Government Printing Office, Washington DC, United States of America
Nurliani, Rosada I (2016) Rice-field conversion and its impact on food availability. Agriculture and Agricultural Science Procedia 9: 40 – 46
Peña L E, Barrios M, Francés F (2016) Flood quantiles scaling with upper soil hydraulic properties for different land uses at catchment scale. J Hydrol 541: 1258–1272
Poerbandono, Ward P J, Julian M M (2009) Set up and calibration of a spatial tool for simulating river discharge of Western Java in recent decades: preliminary results and assessments. J Eng Technol Sci 41(1): 50–64Price K (2011) Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. Phys Geogr 4: 465–92Rogger M, Agnoletti M, Alaoui A, Bathurst J C, Bodner G, Borga M, Chaplot V, Gallart F, Glatzel G, Hall J, Holden J, Holko L, Horn R, Kiss A, Kohnová S, Leitinger G, Lennartz B, Parajka J, Perdigão R, Peth S, Plavcová L, Quinton J N, Robinson, M, Salinas J L, Santoro A, Szolgay J, Tron S, van den Akker J J H, Viglione A, Blöschl G (2017) Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. Water Resources Research 53(7): 5209–5219
Saxton KE, Rawls WJ (2006) Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci Soc Am J 70:1569–1578
Sinha R K, Eldho T I (2018) Effects of historical and projected land use/cover change on runoff and sediment yield in the Netravati river basin, Western Ghats, India. Environ Earth Sci 77(3): 1–19
Siswanto SY (2010) Land degradation assessment in West Java Island, Indonesia. Thesis, Ghent University.
Tarigan S D, Tukayo R K (2013) Impact of land use change and land management on irrigation water supply in Northern Java coast. J Trop Soils 18(2): 169–176
Tommi (2011) The impact of land use on hydrological charactersitic in Upper Citarum watershed. Thesis, Bogor Insitute of Agriculture. (in Indonesia)
Vaighan A A, Talebbeydokhti N, Bavani A M (2017) Assessing the impacts of climate and land use change on streamflow, water quality and suspended sediment in the Kor River Basin, Southwest of Iran. Environ Earth Sci 76(15): 1–18
Verstraeten G, Poesen J, de Vente J, Koninckx X (2003) Sediment yield variability in Spain: a quantitative and semiqualitative analysis using reservoir sedimentation rates. Geomorphology 50:327–348
Wheater H, Evans E (2009) Land use, water management and future flood risk. Land Use Policy 26: 251–264
Wibowo M (2011) Statistical model of river discharge and sediment relation, study case in Citarum-Nanjung watershed. Jurnal Teknologi Lingkungan 2(3): 255–260. (in Indonesian)
Wischmeier W H, Johnson C B, Cross B V (1971) A soil erodibility nomograph for farmland and construction sites. J Soil Water Conserv 26: 189-193
Wischmeier W H, Smith D D (1961) A universal equation for predicting rainfall-erosion losses : an aid to conservation farming in humid regions. Agricultural Research Service USDA, Washington DC, United States of America
Wohl E, Barros A, Brunsell N, Chappell N A, Coe M, Giambelluca T, Goldsmith S, Harmon R, Hendrickx J M H, Juvik J, Mcdonnell, J (2012) The hydrology of the humid tropics. Nat Clim Change 2: 655–662
Xu C (2002) Hydrologic models. Uppsala University, Sweden
Yu B, Zhang G, Fu X (2015) Transport capacity of overland flow with high sediment concentration. J. Hydrol. Eng. 20(6): 1–10
Zare M, Panagopoulos T, Loures L (2017) Simulating the impacts of future land use change on soil erosion in the Kasilian watershed, Iran. Land Use Policy 67: 558–572

Zhang L, Dawes W R, Walker G R (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res 37(3): 701–708

Zuazo V H D, Pleguezuelo C R R (2008) Soil-erosion and runoff prevention by plant covers. Agron Sustain Dev 28(1): 65–86