Received: 1 December 2016 | Accepted: 2 March 2017
DOI: 10.1002/hyp.11167

WILEY

RESEARCH ARTICLE

Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model

Hero Marhaento[1,2] | **Martijn J. Booij**[1] | **T.H.M. Rientjes**[3] | **Arjen Y. Hoekstra**[1,4]

[1] Water Engineering and Management Group, Faculty of Engineering Technology, University of Twente, Enschede, the Netherlands

[2] Faculty of Forestry, Gadjah Mada University, Yogyakarta, Indonesia

[3] Department of Water Resources, Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, the Netherlands

[4] Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore, Singapore

Correspondence
Hero Marhaento, Water Engineering and Management Group, Faculty of Engineering Technology, University of Twente, Drienerlolaan 5, 7522 NB Enschede, the Netherlands.
Email: h.marhaento@utwente.nl

Funding Information
Ministry of Research, Technology and Higher Education of the Republic of Indonesia

Abstract

Changes in the water balance of the Samin catchment (277.9 km^2) on Java, Indonesia, can be attributed to land use change using the Soil Water Assessment Tool model. A baseline-altered method was used in which the simulation period 1990–2013 was divided into 4 equal periods to represent baseline conditions (1990–1995) and altered land use conditions (1996–2001, 2002–2007, and 2008–2013). Land use maps for 1994, 2000, 2006, and 2013 were acquired from satellite images. A Soil Water Assessment Tool model was calibrated for the baseline period and applied to the altered periods with and without land use change. Incorporating land use change resulted in a Nash–Sutcliffe efficiency of 0.7 compared to 0.6 when land use change is ignored. In addition, the model performance for simulations without land use change gradually decreased with time. Land use change appeared to be the important driver for changes in the water balance. The main land use changes during 1994–2013 are a decrease in forest area from 48.7% to 16.9%, an increase in agriculture area from 39.2% to 45.4%, and an increase in settlement area from 9.8% to 34.3%. For the catchment, this resulted in an increase of the runoff coefficient from 35.7% to 44.6% and a decrease in the ratio of evapotranspiration to rainfall from 60% to 54.8%. More pronounced changes can be observed for the ratio of surface runoff to stream flow (increase from 26.6% to 37.5%) and the ratio of base flow to stream flow (decrease from 40% to 31.1%), whereas changes in the ratio of lateral flow to stream flow were minor (decrease from 33.4% to 31.4%). At sub-catchment level, the effect of land use changes on the water balance varied in different sub-catchments depending on the scale of changes in forest and settlement area.

KEYWORDS

attribution analysis, land use change, Samin catchment, SWAT model, water balance

1 | INTRODUCTION

Attributing changes in stream flow to land use and climate change has been of interest for decades. Numerous studies have been carried out throughout the world focusing on the relationship between changes in stream flow and changes in land use and climate. Zhang et al. (2012) distinguishes two approaches to attribute changes in stream flow to land use change: a modelling and non-modelling approach. The latter is often carried out based on paired catchment studies (Bosch and Hewlett, 1982; Brown et al., 2005) or long-term hydrological data analyses (Rientjes et al., 2011; Zhang et al., 2014; Marhaento et al., in press). The modelling approach can be based on a single model (Niehoff et al., 2002; Rodriguez Suarez et al., 2014) or multiple models (ensemble modeling; Huisman et al., 2009). Surprisingly, very few studies investigated hydrological behavior under changing conditions in tropical regions (Douglas, 1999; Wohl et al., 2012). The impact of land use change and climate change on stream flow can be significant for tropical regions having greater energy inputs and faster rates of change, including human-induced changes (Wohl et al., 2012).

In the 1990s, Indonesia was among countries having the largest land use changes in terms of forest lost in the world, behind Brazil (Hansen et al., 2009). A high demand of land resources to accelerate the economic development and meet local needs for food and settlements resulted in land use changes at different scales. Several hydrological studies have been carried out in Indonesia to investigate the impacts of land use change on water resources (Valentin et al., 2008; Remondi et al., 2016), showing that deforestation and urbanization were the two land use changes mostly reported to affect stream flow.

Deforestation and urbanization caused increases in peak flows enhancing the flood risk during the wet season and decreases in base flow in the dry season following the loss of forest area (Bruijnzeel, 2004).

Douglas (1999) argues that most of the hydrological studies in tropical regions, including Indonesia, focus on the impacts of land use change on stream flow (e.g., seasonal flow and annual flow) and sediment yield based on small-scale plot measurements. In addition, land use change can also affect other water balance components, such as evapotranspiration (ET), soil water content, and groundwater recharge. Yet, only few studies have attempted to assess the attribution of changes in the water balance to land use change in tropical regions. Moreover, some of the results are contradictory and inconsistent, in particular for large catchments (>100 km^2; Calder et al., 2001; Beck et al., 2013).

In order to assess the impacts of land use change on the water balance, a modelling approach is typically used. Models can be used to assess impacts of historic as well as future land use changes on hydrological conditions (Huisman et al., 2009; Thanapakpawin et al., 2007). A wide range of models has been used to simulate land use change impacts on the water balance, for example, SWAT (Arnold et al., 1998), MIKE-SHE (Refsgaard and Storm, 1995), or DHSVM (Wigmosta et al., 1994). However, the contribution of land use change to changes in the catchment water balance is still not fully understood due to climatic interferences (Wang, 2014), requiring further study. A challenge is to attribute changes in the water balance to land use change under varying climatic conditions (Romanowicz and Booij, 2011).

Against this background, the goal of this study is to attribute changes in the water balance of a tropical catchment in Indonesia to land use change using a modelling approach. First, we attribute changes in stream flow to land use change in the Samin catchment in Java, Indonesia, for the time period 1990–2013, using the semi-distributed physically based SWAT model (Arnold et al., 1998) and a baseline-altered method to attribute changes in stream flow to land use change. Second, we assess causal relationships between land use change and water balance alteration in the study catchment. A diagnostic approach is followed using two widely used statistical analyses, namely, Mann–Kendall trend analysis and Pearson's test, to investigate whether the water balance has statistically changed over the study period due to land use change. We consider the water balance in terms of five water balance coefficients: the ratio of runoff to rainfall (the runoff coefficient, Q/P), the ratio of evapotranspiration to rainfall (ET/P), the ratio of surface runoff to stream flow (Q_s/Q), the ratio of lateral flow to stream flow (Q_l/Q), and the ratio of base flow to stream flow (Q_b/Q).

We propose the use of attribution analysis to test whether land use change is the main driver for changes in stream flow prior to assess the impact of land use change on the overall water balance. In addition, a diagnostic approach may provide insight on the relationship between land use change and water balance alteration that is rarely investigated in tropical regions. This study complements the study of Marhaento et al. (in press) who conducted attribution analysis of changes in stream flow to land use and climate change using a non-modelling approach for the same catchment.

The structure of the paper is as follows. Section 2 presents a description of the study area and the data availability. Section 3 describes the methods used and Sections 4 and 5 give the results and discussion of the key findings. Finally, conclusions are addressed in Section 6.

2 | STUDY AREA AND DATA

2.1 | Catchment description

The Samin River, with a total length of about 53 km, is of the Bengawan Solo River, which plays an important role to support life within its surrounding area. The catchment area of the Samin River extends over 277.9 km^2 and ranges between southern latitude 7.6°–7.7° and eastern longitude 110.8°–111.2° (see Figure 1). The main economic activity in this catchment is agriculture, which is supported by the water availability within the catchment. The highest part of the catchment is the Lawu Mountain, with an altitude of 3,175 m above mean sea level, and the lowest part is near the Bengawan Solo river in Sukoharjo district, with an altitude of 84 m above mean sea level. The average slope in the Samin catchment is 10.2%, where higher slopes are mostly in the upstream part near the foothill of the Lawu Mountain. The stream density is around 2.2 km/km^2 and streams form a parallel drainage pattern, where the tributaries tend to stretch out from east to west following the surface slope. According to the soil map from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), two soil classes, namely, Luvisols and Andosols, are dominant in the Samin catchment, which cover 57% and 43% of the study area, respectively. Luvisols are developed from parent material of accumulated silicate clay that is dominant in the midstream to downstream area. These soils are characteristic for the forested area where a leafy humus horizon can be found at the top of the soil layers. Andosols are developed from parent material of the volcanic Lawu Mountain and are mainly dominant in the upstream area. These soils are typically highly porous and fertile due to volcanic deposits from the Lawu Mountain.

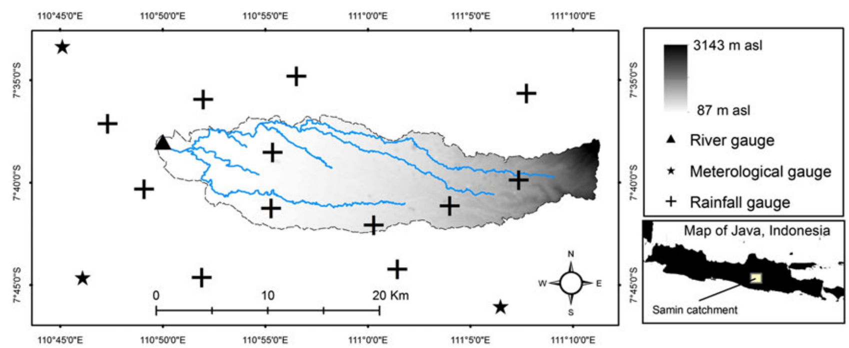

FIGURE 1 Samin catchment in Java, Indonesia, with the locations of hydrological gauges

2.2 | Hydro-climatic conditions

The climate of the Samin catchment is tropical monsoon with distinct dry and wet seasons. The dry season is influenced by Australian continental masses and generally extends from May to October, whereas the wet season is influenced by Asian and Pacific Ocean wind masses and generally extends from November to April. The spatial rainfall pattern likely follows the orography, with a larger amount of rainfall in the upstream area than in the downstream area. Based on a simple linear regression between the mean annual rainfall and elevation of 13 rainfall stations in the surrounding catchment, it was found that the mean annual rainfall increases about 150 mm per 100 m increase of elevation. This is comparable with the finding of Subarna et al. (2014) who estimated an increase in the mean annual rainfall of about 140 mm per 100 m increase of elevation for the Cisangkuy catchment in West Java, Indonesia. The mean daily temperature is approximately 26 °C with a mean daily minimum of about 21.5 °C and a mean daily maximum of about 30.5 °C. The daylight length is approximately 13 hr with a small difference between the wet and dry seasons resulting in a mean daily solar radiation of about 17 MJ/m^2. During the period 1990–2013, the mean annual rainfall, potential ET, and stream flow of the Samin catchment ranged from 1,500 mm–3,000 mm, 1,400 mm–1,700 mm, and 500 mm–1,200 mm, respectively, where a high Q/P (i.e., >0.5) was found for the years 2000 and 2005 (see Figure 2). The trend analysis of the mean annual rainfall, potential ET and stream flow showed an increase of approximately 48 mm, 31.2 mm, and 290 mm, respectively (Marhaento et al., in press). Whereas long-term changes in the mean annual rainfall and potential ET were statistically not significant, changes in the mean annual stream flow were significant at a significance level of 5%. Figure 2 shows the mean annual rainfall, potential ET, and stream flow of the Samin catchment for the period 1990–2013.

2.3 | Data collection

The SWAT model requires a digital elevation model (DEM), land use data, soil data, and climate data as model inputs. The DEM data were generated from a contour map with a contour interval of 12.5 m, which was made available by the Indonesia Geospatial Information Agency. Land use information was available for a 30-m resolution for the years 1994 and 2013 from Marhaento et al. (in press). Two additional land cover images were acquired from the LANDSAT satellite (USGS, 2016) for September 9, 2000 and ASTER images (ERSDAC, 2016) for November 9, 2006 to represent land use for the years 2000 and 2006. Soil data were taken from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). The soil characteristics required as SWAT input that were not available in the global soil map (i.e., available water content, saturated hydraulic conductivity, and bulk density) were obtained from the Soil-Plant-Atmosphere-Water (SPAW) model (Saxton & Willey, 2005). The SPAW model uses pedotransfer functions, including information on soil texture, soil salinity, organic matter, gravel and soil compaction, to determine water retention characteristics. The model has been developed based on an extensive number of laboratory datasets of soil characteristics from the USDA/NRCS National Soil Characterization database and has been validated using thousands of sample subsets (Saxton & Willey, 2005). Even though the SPAW model has been developed in the United States, the application of the SPAW model is worldwide and often performed with a model calibration (Botula et al., 2014).

For model calibration, we used daily stream flow. The Bengawan Solo River Basin office provided daily water level data in the Samin catchment for the period 1990–2013. The daily discharge data have been obtained by converting the daily water level data to discharge values using the rating curves provided by the Bengawan Solo River Basin office. We assume that the available rating curve is sufficient to represent the river flows (i.e., high flows and low flows) considering the limited information on how the rating curve has been checked and updated by the data provider. This study used the same discharge and climate data as Marhaento et al. (in press) who have corrected erroneous water level data due to shifts in gauge location and corrected rainfall data based on the relationship between rainfall and elevation. In addition, the missing discharge data were completed using a nonlinear recession model (Wittenberg, 1994) that was applied to fill-in data of maximum 15 consecutive days of missing discharge values. We excluded stream flow data that were unavailable for more than 15 consecutive days. This fill-in procedure concerns less than 5% of the data. For the missing climate data, a normal ratio method based on values from surrounding stations was used.

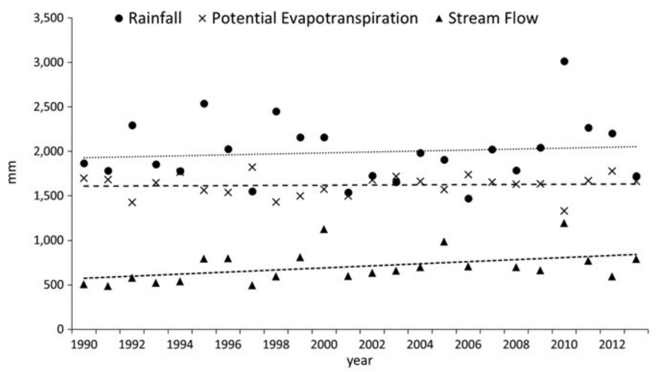

FIGURE 2 Mean annual rainfall, potential evapotranspiration, and stream flow for the period 1990–2013 in the Samin catchment (after Marhaento et al., in press)

3 | METHODS

3.1 | Land use changes

Because land use information for the years 1994 and 2013 is available from Marhaento et al. (in press), we carried out satellite image analysis for LANDSAT and ASTER images for the years 2000 and 2006. These images were completed by preprocessing analysis through a nonsystematic geometric correction to avoid distortion on map coordinates and masking analysis to remove the area beyond the study area. The ASTER image resolution was resampled from 15 × 15 m^2 grid-size to 30 × 30 m^2 grid-size to be similar to the grid size of LANDSAT images. We used a maximum likelihood approach to perform image classification using thousand ground-control points (GCPs; see Marhaento et al., in press) and then made a confusion matrix to measure classification accuracy. We divided the GCPs into two sets: Half of the GCPs were used to perform image classification and half of them were used to perform accuracy assessments by means of the overall accuracy and the Kappa coefficient. The overall accuracy is defined as the number of correct samples divided by the total number of samples. The Kappa coefficient measures the agreement between the classification map and the reference data. Land use change analysis was performed based on differences in areal coverage of each land use class between different years.

3.2 | SWAT model set up and calibration

3.2.1 | Water balance estimation

For this study, we used the water quantity module of the SWAT model, a physically based semi-distributed model operating on a daily time step with proven suitability for hydrologic impact studies around the world (Wagner et al., 2013; Memarian et al., 2014). The SWAT model divides a catchment into sub-catchments and then further divides each sub-catchment into hydrological response units (HRUs) for which a land-phase water balance is calculated (Neitsch et al., 2011). An HRU is defined as a lumped area within a catchment assumed to have uniform behavior and is characterized by a dominant land use type, soil type, and slope conditions (Arnold et al., 1998). For each simulation time step (daily in this study), a water balance is computed for each HRU and for each sub-catchment. Runoff is routed through channels to the catchment outlet and used to calculate the catchment water balance.

This study focused on the land-phase water balance, where land use change has its main impact. The components of the land-phase water balance in the SWAT model include inflows, outflows, and variations in storages. Rainfall (P) is the main inflow in the model. The outflows are ET, surface runoff (Q_s), lateral flow (Q_l), and base flow (Q_b). There are four storages in SWAT, namely, snowpack, soil moisture (SM), shallow aquifer (SA), and deep aquifer (DA). We excluded the snowpack storage in the model because snowfall is not relevant in the study area. Flows between storages are percolation from the soil moisture storage to the shallow aquifer storage (Perc), water movement upward from the shallow aquifer to the soil moisture storage (Revap), and deep aquifer recharge (DA_Rchg). Figure 3 shows the SWAT model schematization used in this study. For a more detailed description of the SWAT model, reference is made to Neitsch et al. (2011).

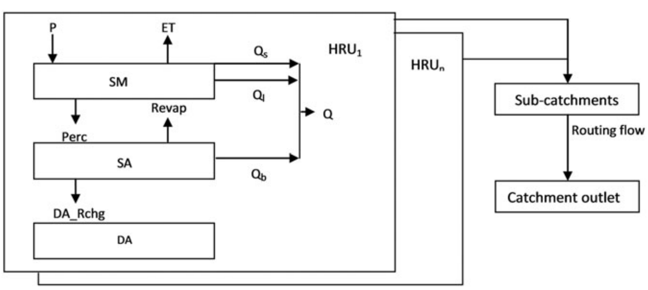

FIGURE 3 The Soil Water Assessment Tool model structure. DA = deep aquifer; ET = evapotranspiration; HRU = hydrological response unit; Q_b = base flow; Q_l = lateral flow; Q_s = surface runoff; SA = shallow aquifer; SM = soil moisture

3.2.2 | Model setup

The DEM was used to delineate boundaries of the catchment and to divide the catchment into sub-catchments. We used a stream network from the Indonesia Geospatial Information Agency to "burn-in" the stream network to create accurate flow routing and to delineate sub-catchments. This procedure resulted in 11 sub-catchments, ranging in size from 0.12 to 83 km^2. In addition, the DEM was used to generate a slope map based on the slope classification from the Guideline of Land Rehabilitation from the Ministry of Forestry (1987). Land use codes from the SWAT database, namely, AGRR, FRSE, FRST, RICE, URMD, and LBLS, were assigned to denote dryland farming, evergreen forest, mixed garden, paddy field, settlement, and shrub, respectively. For the settlement, we used the assumption that the settlement area is not fully impervious providing some pervious spaces in between the houses that are often used for house yards. Thus, we used the class Urban Residential Medium Density (URMD) in the SWAT model to assign parameters in the settlement area. URMD assumes an average of 38% impervious area in the settlement area (Neitsch et al., 2011), which is relatively similar to the settlement conditions in the study catchment. In addition, as a typical rural area in Java, the artificial drainage network in the study area is not well developed. Thus, we consider that the impacts of the artificial drainage network of the settlements on the long-term water balance of the system are not significant. Furthermore, we modified the SWAT crop and management database for each land use type in order to match the conditions in a tropical region. We note that SWAT is designed for temperate regions so that it is necessary to modify the crop parameters for application in a tropical region (Kilonzo, 2013; Van Griensven et al., 2014). Table 1 shows the adjusted values in the SWAT crop and management database applied in this study. Forest includes evergreen forest and mixed garden, whereas agriculture includes paddy field and dry-land farming.

HRUs were created by spatially overlying maps of land use, soil, and slope classes. The Penman–Monteith method was used to calculate reference ET. For runoff simulations, we selected the Soil Conservation Service Curve Number (SCS-CN) method because it has a direct link to land use types. In addition, we also adjusted the CN values for slope effects based on the equation from William (1995), since the default CN value in the SWAT model is only suitable for a slope up to 5%, which is not appropriate for our study catchment. For flow routing, we used the Muskingum method that models the storage volume as a combination of wedge and prism storage (Neitsch et al., 2011).

3.2.3 | Model calibration

Model calibration aims to produce a robust SWAT model that is able to simulate land use change impacts on the water balance. Identification of SWAT parameters to be calibrated was based on the procedure from Abbaspour et al. (2015). Within the procedure, the SWAT model was executed using the default SWAT parameters. The simulated hydrograph was visually compared with the observed hydrograph. Based on the characteristics of the differences between observed and simulated hydrograph (e.g., underestimation/overestimation discharge and shifted discharge), relevant SWAT parameters were identified. Furthermore, one at a time sensitivity analysis was carried out to detect the most sensitive parameters among the relevant parameters.

TABLE 1 Adjusted values in the Soil Water Assessment Tool crop and management database (adapted from Kilonzo, 2013)

	Land use/land cover class					
	Forest		Shrub		Agriculture	
Variable	Original	Adjusted	Original	Adjusted	Original	Adjusted
LAI_INIT (-)	0	5	0	3	0	3
BIO_INIT (kg/ha)	0	1,000[a]	0	0	0	0
PHU_LT (-)	0	3,500[a]	0	3,500[a]	0	3,500[a]
GSI (mm/s)	2	7	5	5	7	7
CANMX (mm)	0	5	0	2	0	2

Note. Definitions for each variable are available in Neitsch et al. (2011).

[a]The maximum value allowed in Soil Water Assessment Tool.

(-) means no units

We calibrated the model using the Latin hypercube sampling approach from the Sequential Uncertainty Fitting version 2 in the SWAT Calibration and Uncertainty Procedure (SWAT-CUP) package. First parameter ranges were determined based on minimum and maximum values allowed in SWAT. A number of iterations were performed, where each iteration consisted of 1,000 simulations with narrowed parameter ranges in subsequent calibration rounds. The new parameter ranges were determined based on the minimum and maximum parameter value of the 10% best parameter sets according to the objective function value. We stopped the calibration process and obtained the optimum parameter values after the objective function value showed insignificant changes (smaller than 0.01). Simulations for model calibration were assessed on a monthly basis and the NSE (Equation 1) was used as the objective function.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{i=N} [Qs(i) - Qo(i)]^2}{\sum_{i=1}^{i=N} \left[Qo(i) - \overline{Qo}\right]^2} \qquad \text{(Eq.1)}$$

where i is the time step, N the total number of time steps, Qs the simulated discharge, Qo the observed discharge, and $\overline{Qo}$ the mean of Qo over the period of analysis.

3.3 | SWAT simulations

The SWAT simulations were carried out in two steps. The first step included simulations to attribute changes in stream flow to land use change. These simulations aimed to investigate whether land use change is the main driver for changes in stream flow. We used a baseline-altered approach, which divides the dataset into four sequential periods: the first period is regarded as the baseline period, and other periods are regarded as altered periods, periods when the hydrological regime within a catchment is expected to be changed due to land use changes. The method assumes that by calibrating a model in the baseline period and applying the calibrated model in the altered periods using updated land use maps will enable the simulation of impacts of land use change on streamflow (Li et al., 2009 and Wagner et al., 2013).

In this study, we divided the simulation period (1990–2013) into four equal periods to accommodate gradual changes in land use in the study catchment. The first period (1990–1995) was regarded as the baseline period and the other periods (1996–2001, 2002–2007, and 2008–2013) were regarded as altered periods. The four land use maps available for the years 1994, 2000, 2006, and 2013 represent the land use conditions for each period. We ran the calibrated SWAT model for the baseline period (1990–1995) using land use of the year 1994 and then applied the calibrated model for the altered periods. We carried out two simulations for the altered periods, that is, with land use change (using land use maps of 2000, 2006, and 2013) and without land use change in order to investigate the attribution of changes in stream flow to land use change. We followed the method from Refsgaard et al. (1989) and Lørup et al. (1998), which used model performances as an indicator of land use change impacts. Land use change is regarded as the important driver to changes in stream flow when model simulations with land use changes show a better model performance than simulations without land use change. Updating land use cover in the simulations will adapt the HRU information in the simulation and thus affect stream flow simulation. Figure 4 shows the hypothetical scenario of our simulations. We note that the changes in the model performance values are not necessarily linearly related to changes in land use as suggested by the straight lines in the diagram. To incorporate land use change in the simulations, we used the Land Use Update tool in ArcSWAT.

The first step of the simulations shows the land use change contribution to changes in stream flow. As a second step in the study, the changes in the mean annual water balance as a result of land uses change were assessed at both catchment level and sub-catchment level. We focused on five water balance coefficients, namely, Q/P, ET/P, Q_s/Q, Q_l/Q, and Q_b/Q. A diagnostic approach using statistical analyses (Mann–Kendal statistic and Pearson statistic) was carried out to test the statistical significance of the long-term trends in the

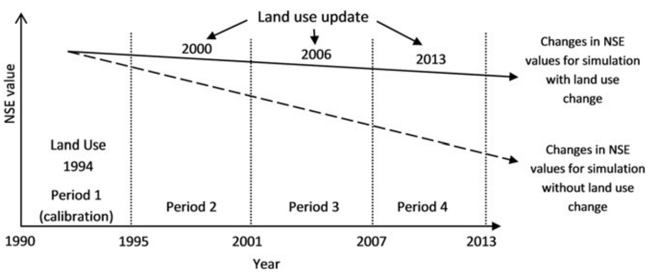

FIGURE 4 A hypothetical scenario for the model simulations to test the hypothesis regarding the effects of land use changes on the model performance. NSE = Nash–Sutcliffe efficiency

mean annual water balance coefficients and to investigate the correlation between changes in the water balance and land use change.

4 | RESULTS

4.1 | Land use change analysis

Table 2 shows the relative areas of each land use class for the years 1990, 2000, 2006, and 2013. In general, we found that there was an increasing human influence in the Samin catchment through the development of settlements and agriculture area (i.e., paddy field and dryland farm). Figure 5 shows the spatial distribution of land use change in the Samin catchment. It shows that in the period 1994–2000, agriculture area was converted to settlements in the downstream area and evergreen forest area was converted to mixed garden in the upstream area. However, these changes do not significantly reduce the tree-dominated area because the conversion of evergreen forest into mixed garden area basically is a change from a state forest into a community forest. A dramatic change has occurred in the period 2000–2006 when agriculture land was converted to mixed garden area in the upstream area that resulted in a major decrease of tree-covered area in the Samin catchment. At the same time, the settlement area significantly increased in the downstream area converting agricultural area into impervious area. In the period 2006–2013, the development of settlement areas expanded in the upstream part of the catchment at the expense of mixed garden area resulting in major deforestation. In total, during the period 1994–2013, deforestation by decreasing evergreen forest area and mixed garden area was about 30%. At the same time, settlements and agricultural area have increased by 25% and 6%, respectively. We note that the average overall accuracy and Kappa coefficient of land use maps used for this study were 89% and 87%, respectively, which is sufficient for producing a land use map (Congalton, 1991). Detailed descriptions of each land use class are available in Marhaento et al. (in press).

4.2 | Model calibration and simulations

4.2.1 | Model calibration

Six SWAT parameters were calibrated, namely, CN2, SOL_AWC, ESCO, CANMX, GW_DELAY, and GW_REVAP. CN2 is the curve number parameter, which controls the fraction of water to infiltrate into the soil or to generate surface runoff by overland flow. A large CN value causes less infiltration and results in more surface runoff. SOL_AWC is the available water capacity of the soil layer. It controls the soil water storage between soil moisture conditions at field capacity and permanent wilting point. GW_DELAY is the ground water delay time. It controls the lag time between water leaving the soil layers and entering the shallow aquifer. A larger GW_DELAY will enable more evaporation from the unsaturated zone. GW_REVAP is the ground water revap coefficient, a SWAT term to describe the movement of water into overlying unsaturated layers as a function of water demand for ET. The GW_REVAP parameter controls the amount of water in the capillary fringe that separates the unsaturated zone and the saturated zone to move upward (to fulfill evaporative demand). A larger GW_REVAP value results in a larger transfer rate from the shallow aquifer to the unsaturated zone. ESCO is the soil evaporation compensation factor and controls the soil evaporative demand that is to be met. When the value of ESCO gets closer to 0, the model will receive more water from the lower soil level to fulfil evaporative demand. CANMX is the maximum canopy storage to intercept rainfall. It controls the density of plant cover so that it significantly affects infiltration and ET. A larger CANMAX results in a larger plant canopy capacity. We calibrated CANMX only for forested areas (i.e., FRSE and FRST).

These parameters were calibrated in different ways. For parameters CN2 and SOL_AWC, we calibrated a scaling value at the HRU level so that the default parameter value was multiplied by (1+ calibrated scaling value). In this way, the default parameters will not lose their original spatial patterns. For parameters GW_DELAY, GW_REVAP, ESCO, and CANMX, we calibrated parameter values at the catchment level so that the calibrated parameter values are homogeneous over the entire catchment. After three rounds of calibration, we found optimum calibrated parameter values with a NSE value of 0.78 (see Figure 6). Table 3 shows the calibrated values used in this study.

TABLE 2 Area percentage (%) of each land use class in the year 1994, 2000, 2006, and 2013

Land use class	1994	2000	2006	2013
1. Forest area	48.7	42.2	26	16.9
a. Evergreen forest	16.1	3	2.4	2.3
b. Mixed garden	32.6	39.2	23.6	14.6
2. Agriculture area	39.2	36.9	44.3	45.4
a. Paddy field	30.2	28.2	28.9	28
b. Dryland farm	9	8.7	15.4	17.4
3. Settlements	9.8	16.3	25.6	34.3
4. Shrub	2	4.3	3.8	3.1
5. Water body	0.3	0.3	0.3	0.3

4.2.2 | Performance of model simulations with and without land use changes

Table 4 shows the model performance for simulations with and without land use changes for the altered periods. The results of the simulations without land use change show that the NSE value has continuously decreased, with a significant decrease in the period 2008–2013 (Figure 7). In this period, the calibrated model fails to simulate peak flows, which explains the relatively low value of NSE (<0.6). After land use change was incorporated in the simulations, the NSE values of the altered periods (periods 2, 3, and 4) were higher than the NSE values from simulations without land use changes. The simulated peak flows and low flows of the simulations with land use change are better than in the simulations without land use change. While the mean NSE value of simulations without land use change is around 0.6, the mean NSE value of simulations with land use change is around 0.7.

In order to validate the method, a similar procedure was applied in an independent sub–catchment, namely, Tapan catchment (±200 ha), that is located in the upstream part of the study catchment. The stream flow data of the Tapan catchment were made available by Retnowati (2012) at annual basis from the period 1993 to 2007. We created a new outlet in the simulated catchment that is similar to the outlet

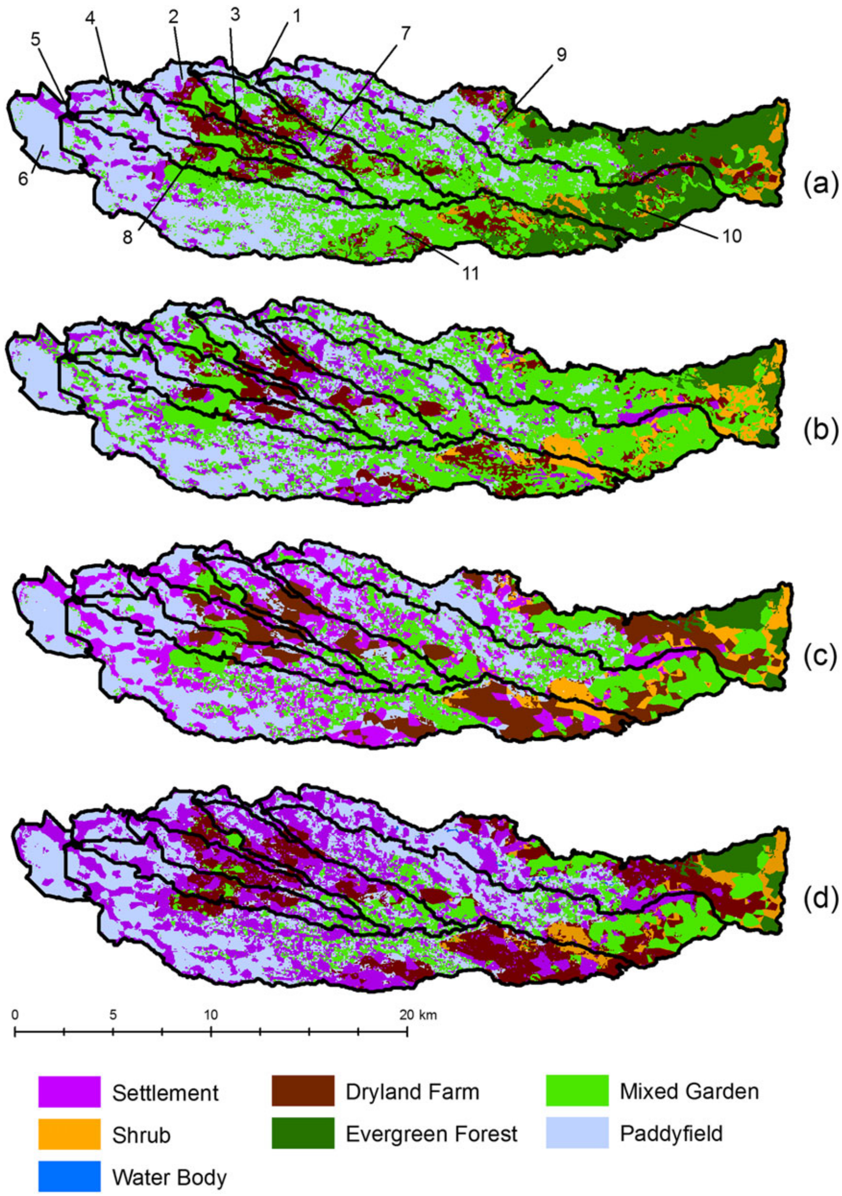

FIGURE 5 Land use distribution in the Samin catchment in the years (a) 1994, (b) 2000, (c) 2006, and (d) 2013. Numbers in Figure 5a show the sub-catchment identity number

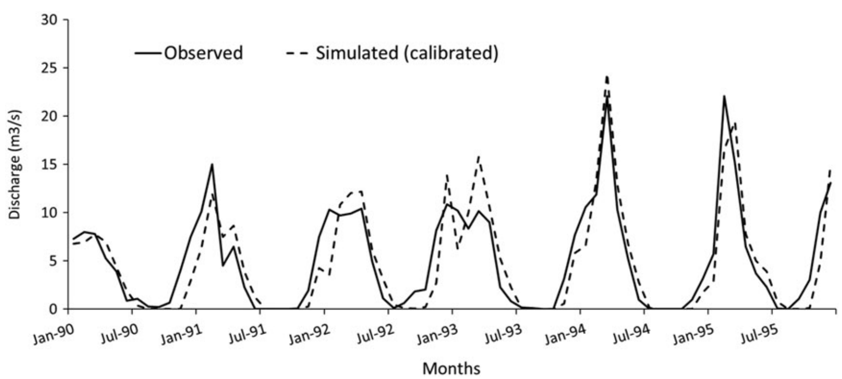

FIGURE 6 Hydrograph of simulation with calibrated parameter values for the baseline period

location of the Tapan catchment and executed the model with and without land use change. Furthermore, we compared the NSE values between simulations with and without land use change for the period 1993–2007. The results show that simulation with land use change has a better performance than the simulation without land use change with NSE values of −0.75 and −4.03, respectively (see Figure 8). Although the model showed a poor performance, a better model performance for simulations with land use change than simulations without land use change could be an indication of the importance of land use change to changes in stream flow.

TABLE 3 Values of calibrated Soil Water Assessment Tool parameters

Parameters	Units	Prior range	Default value	Calibrated values
CN2	(-)	−0.3–0	0	−0.1
SOL_AWC	mm	0–1	0	0.6
ESCO	(-)	0–0.5	0.95	0.1
GW_DELAY	days	30–80	31	55
GW_REVAP	(-)	0.02–0.1	0.02	0.05
CANMX	mm	0–10	5	9

(-) means no units

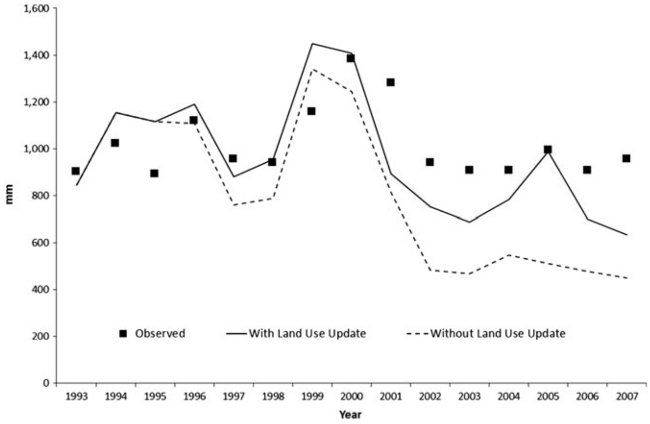

FIGURE 8 Hydrograph simulations with and without land use change for years 1993–2007 in the validation catchment

4.3 | Changes in water balance coefficients

A good model performance of simulations with land use change confirmed the contribution of land use change to changes in stream flow. The results of the simulation with land use change showed that the water balance of the Samin catchment has changed in the 24-year time period at both catchment and sub-catchment level. At the catchment level, the Mann–Kendall trend analysis showed that the changes in Q/P and ET/P were not significant at a significance level of 5%. Between period 1 and period 4, Q/P has increased from 35.7% to 44.6%, and ET/P has decreased from 60% to 54.8%. Our results are in line with the findings from Marhaento et al. (in press), but we found smaller increases for the mean annual stream flow. Despite changes in Q/P were not statistically significant, changes in Q_s/Q and Q_b/Q were significant at a significance level of 1%. Between period 1 and period 4, Q_s/Q has increased from 26.6% to 37.5% whereas Q_b/Q has decreased from 40% to 31.1%. For Q_l/Q, the long-term changes were not significant at a significance level of 10% (decrease from 33.4% to 31.4%). Figure 9 shows the long-term changes in the water balance coefficients for the period 1990–2013.

At the sub-catchment level, long-term trends were consistent for three water balance coefficients, namely, Q/P, Q_s/Q, and Q_b/Q. We found that Q/P and Q_s/Q increased while Q_b/Q decreased for all sub-catchments. However, long-term trends were not consistent for the other two water balance coefficients ET/P and Q_l/Q. Several sub-catchments experienced a positive trend of ET/P as well as Q_l/Q while other sub-catchments showed negative trends. The opposite directions of ET/P and Q_l/Q at sub-catchment level have balanced each other so that the differences of ET/P, and Q_l/Q at catchment level were minor. As a result, changes in ET/P were not equal to changes in Q/P at catchment level indicating that there was a change in the water storage (ΔS). Table 5 shows the results of the Mann–Kendall trend analysis of the water balance coefficients at sub-catchment level.

4.4 | Effect of land use change on the water balance

In order to relate changes in the water balance and changes in land use, we performed Pearson correlation tests at the sub-catchment level. The results showed that changes in the water balance were significantly correlated with changes in forest area (i.e., combination of evergreen forest and mixed garden) and settlements, whereas the other land use classes did not show a correlation with the water balance coefficients at a significance level of 5%. Figure 10 shows the changes in the water balance coefficients as a function of changes in forest and settlement area. Changes in the forest area had a positive correlation

TABLE 4 Nash–Sutcliffe efficiency values of simulations with and without land use update

Simulations	Baseline period 1990–1995	Altered periods 1996–2001	2002–2007	2008–2013
Without land use update	0.78	0.7	0.65	0.53
With land use update	0.78	0.72	0.71	0.68

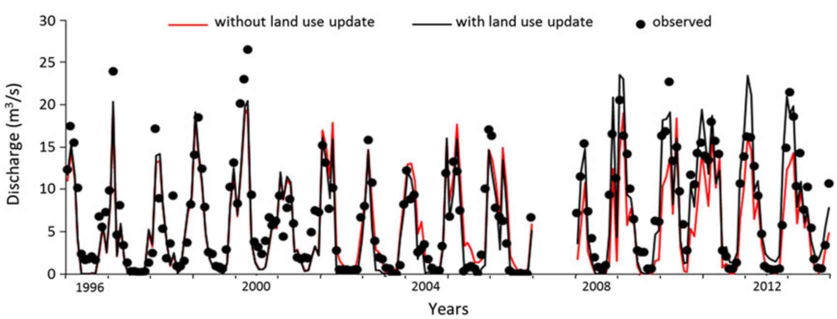

FIGURE 7 Hydrograph of simulations with and without land use change for the altered periods

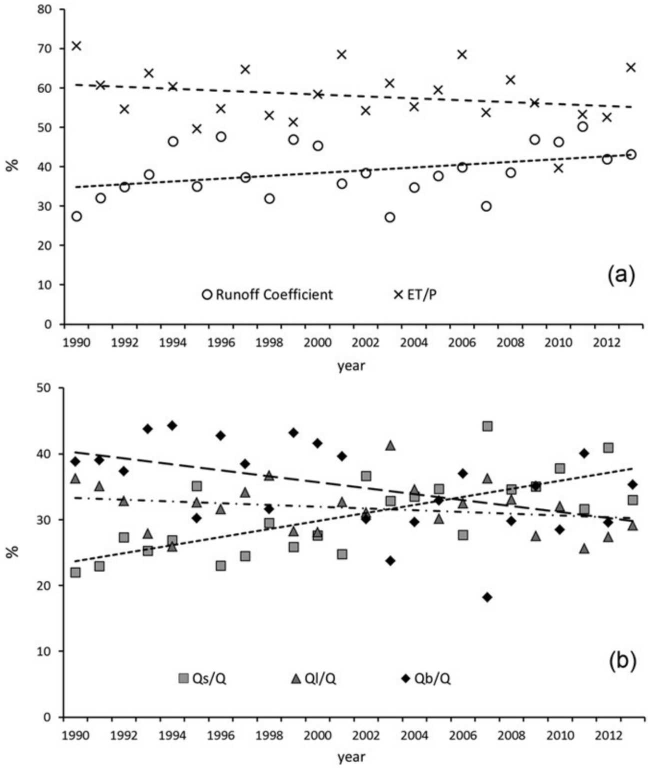

FIGURE 9 (a) Simulated runoff coefficient and ratio of evapotranspiration to rainfall (ET/P) and (b) simulated ratio of surface runoff to stream flow (Q_s/Q), ratio of lateral flow to stream flow (Q_l/Q), and ratio of base flow to stream flow (Q_b/Q), including their long-term trend for the period 1990–2013 in the Samin catchment

TABLE 5 Trend directions from the Mann–Kendall trend analysis for the water balance components per sub-catchment for the period 1990–2013

Sub catchment	Area (km^2)	ET/P	Runoff coeff.	Q_s/Q	Q_l/Q	Q_b/Q
1	2.5	−	+	+*	−*	−*
2	8.2	−	+	+*	−	−*
3	13.7	−	+*	+	−	−
4	4.6	+	+	+*	+	−*
5	0.1	+	+	+	+	−
6	9.5	+	+	+*	+	−*
7	21.3	−	+*	+*	−*	−
8	17.8	−	+	+	−	−
9	60.8	−	+	+*	−	−
10	55.4	−	+	+	+	−
11	84	−	+	+*	−	−

Note. A (−) shows a decreasing trend, while a (+) shows an increasing trend. An asterisk means that the trend is significant at a significance level of 5%.

with Q/P and a negative correlation with ET/P at a significance level of 1%. In addition, changes in the settlement area had a positive correlation with Q/P at a significance level of 1% but relatively low impacts on ET/P. Changes in Q/P and ET/P at sub-catchment level were higher than changes at catchment level. For the fractions of stream flow, changes in Q_s/Q could be related to changes in the settlement area with a positive correlation at a significance level of 5%. Changes in Q_b/Q had the same magnitude but in an opposite direction than changes in Q_s/Q. The contribution of changes in forest area to changes in Q_s/Q and Q_b/Q were minor in particular for the latter. Changes in forest area significantly affected changes in Q_l/Q with a positive correlation at a significance level of 5%.

5 | DISCUSSION

Based on hydrological modelling, this study provides a strong indication that changes in land use altered the water balance in the Samin catchment. Findings show that land use change due to deforestation and expansions of settlement area (i.e., urbanization) have reduced the mean annual ET and increased the mean annual stream flow. Moreover, the fraction of the stream flow originating from surface runoff has significantly increased compensated by a decrease in base flow. The directions of changes in the water balance by land use change (i.e., deforestation and urbanization) in this study are in line with hydrological studies in tropical regions from Bosch and Hewlett (1982), Bruijnzeel (2004), and Brown et al. (2005). It is well known that a reduction of forest area may cause not only a reduction in the tree stands which significantly reduces ET from both canopy interception and plant transpiration, but also diminishes ground vegetation and leaf litter. The absence of ground vegetation and leaf litter affects top soils to lose protection from raindrop splashes and to have less biotic activity (Guevara-Escobar et al., 2007). Thus, processes in the top soil resulting in lower organic matter contents cause a lower permeability and storage capacity resulting in a lower infiltration capacity. As a result, a larger fraction of rainfall is transformed into surface runoff. In this study, we find that changes in forest area significantly contributed to changes in ET/P and Q_l/Q, whereas changes in Q_s/Q and Q_b/Q were profoundly affected by the expansion of settlement area. A rapid increase of settlement area (see Table 2) is probably the main reason of the significant impacts on the water balance. Expansion of settlement area will reduce vegetation coverage thus leading to a decrease in ET. Expansion of impervious area (e.g., buildings and roads) can alter both surface and subsurface flow as a result of reduced infiltration. As impervious area increases, less water infiltrates into the soil resulting in lower soil water storage. Several studies have investigated the correlation between urbanization and the water balance in tropical regions (Wagner et al., 2013; Remondi et al., 2016; Gumindoga et al., 2014), and results are similar to ours.

In this study, changes in the water balance due to land use change occurred at both catchment and sub-catchment level. However, we found that changes at sub-catchment level were diverse where some sub-catchments showed different directions of change in the water balance coefficients compared to others. Apparently, the positive and negative trends on ET/P and Q_l/Q at sub-catchment level have compensated each other, so that long-term changes of those variables at catchment level were relatively small. This is similar to the findings from Wagner et al. (2013) and Wilk and Hughes (2002) who argue that the complexity of large catchments that can mask the impacts of land use changes on hydrological processes at the local scale. Furthermore, the land use change impacts on the water balance differ for each sub-

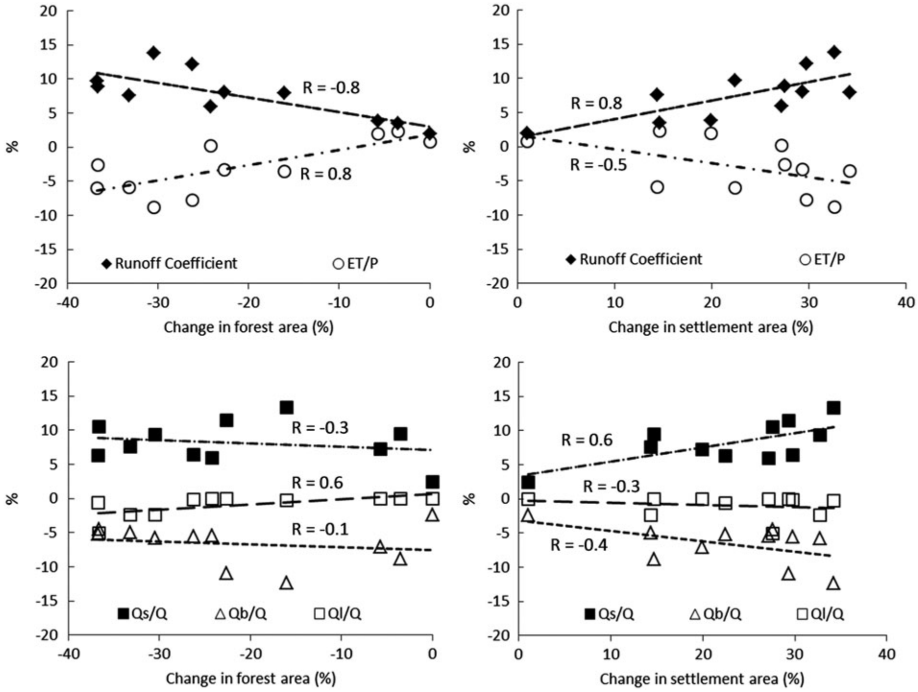

FIGURE 10 Changes in water balance components as a function of changes in forest area and settlements, including Pearson correlation coefficients (R). ET/P = ratio of evapotranspiration to rainfall; Q_b/Q = ratio of base flow to stream flow; Q_l/Q = ratio of lateral flow to stream flow; Q_s/Q = ratio of surface runoff to stream flow

catchment. The changes in the downstream area, where land conversion from agriculture to settlement is dominant, are larger than in the upstream area, where land conversion from forest to agriculture is dominant. As we noted, the rapid increase of impervious area is probably the main cause for changes in the overall water balance. We agree with Wagner et al. (2013) who argue the significant impacts of urban expansion to changes in the surface runoff and stream flow. In addition to these factors, Van Dijk et al. (2007) and Bruijnzeel (2004) mention slope variation, soil types, and geological conditions which could contribute to the impact of land use change on the water balance. Nonetheless, changes in climate can also accelerate changes in the water balance of the study catchment. Aldrian and Djamil (2008) argue that the climate in East Java has changed over the past decades with a decrease in the accumulated monthly rainfall and annually, an increase of the ratio of total rainfall in the wet season to the total annual rainfall and an increase of the dry spell period. However, climate changes in East Java likely occurred in the low altitude area closer to the seashore and relatively less in the mountainous area due to regular orographic effects. Marhaento et al. (in press) argue that the contribution of climate change to changes in the stream flow in the study catchment is less significant than the contribution of land use change but not negligible. As can be seen in Figure 2, Q/P of the years 2000 and 2005 was higher than in other years, which is probably due to climatic variability (e.g., higher rainfall intensity) rather than land use. Thus, combination of land use change and climate change might result in more significant hydrological changes than either driver acting alone (Hejazi & Moglen, 2008). A more thorough study, however, need to be done in the future focusing on the role of climate change (e.g., changes in the rainfall intensity and extreme rainfall events) to changes in the water balance of the study catchment.

The SWAT model used in this study has been successful to attribute changes in the water balance to land use changes. However, a good model performance only was found at the catchment level, for which the model calibration has been carried out. At the sub-catchment level, the model errors increased. A significant deterioration of the model performance at smaller scale sub-catchments probably result from model parameters that cannot represent detailed hydrological processes at a finer scale, such as flow concentration during heavy downpours. In addition, accumulation of errors from the model structure (e.g., model assumptions and equations) as well as data inputs (e.g., lack of relevant spatial and temporal variability of data inputs from rainfall, soils, land uses, and DEM) was increasing when the model was applied under changing conditions (e.g., land use change; Ewen et al., 2006).

It should be noted that parameterization is the key yet most challenging part in the model simulation. Identification of parameters to be calibrated was essential for the subsequent steps. In this study, we followed the guideline from Abbaspour et al. (2015) to select parameters to be calibrated based on the model performance of the default simulation. However, these parameters were different from the parameters that were found by the global sensitivity analysis in the SWAT-CUP package (CN2, CH_N2, GWQMN, GW_DELAY, GW_REVAP and CNCOEF). Calibration of both parameter sets resulted in a comparable model performance in terms of NSE, where parameters from the global sensitivity analysis resulted in an average NSE value of 0.77 for simulations with land use change and 0.6 for simulations without land use change. Although a similar conclusion could be drawn by using the parameter set from the global sensitivity analysis, we found that the model simulated a (very) low ratio of catchment averaged ET to rainfall (in mm) with an average annual value of 34%. According to Bonell et al.

(2005), in forested tropical catchments with distinct wet and dry seasons, the average annual ET is more than 50% of the annual rainfall. Our findings resemble Van Griensven et al. (2012), who reported the equifinality problem in SWAT simulations for tropical regions where satisfactory simulated discharges does not guaranty a good performance of the ET simulation.

The SWAT model has been developed for temperate regions and the default SWAT database is not applicable to other regions including the tropics. The SWAT model considers dormancy for the perennial trees (Neitsch et al., 2011), which is not the case in a tropical forest. Because of the dormancy, the leaf area index for the tree species is set to a minimum value during the dormancy period, and this result in a low annual ET. Kilonzo (2013) argues to adjust several crop SWAT parameters (initial leaf area index, initial biomass, heat units for perennial trees, and plant-harvest schedule for crops) necessary to simulate stream flow in forested areas of tropical regions. In addition, Van Griensven et al. (2014) argue that parameters of the CANMX and maximum stomatal conductance at high solar radiation and low vapor pressure deficit (GSI) are sensitive to ET, and therefore, it is necessary to adjust the values in order to increase ET. Adjusting the crop parameters and management database as seen in Table 1 prior to model calibration has resulted in a more realistic simulation as demonstrated in this article. We note that this adjustment caused an increase of ET by 10% compared to default crop parameters.

For further research on the impacts of land use change on the water balance in tropical regions, we suggest to include ET in the calibration process. The use of remote sensing products to generate spatially and temporally distributed ET can contribute to this process (Rientjes et al., 2013 and Van Griensven et al., 2014).

6 | CONCLUSIONS

We were able to attribute changes in the water balance to land use change in the Samin catchment using the approach described in this paper. The results show that land use change was the dominant driver for changes in the water balance as shown by the better model performance for a simulation with land use change compared to a simulation without land use change. The simulation without land use change generally failed to simulate peak flows where the error was increasing in time and thus resulted in a worsening model performance.

Land use change in the study catchment was mainly shown as an increase in settlement area and a decrease in forested area. At catchment level, these land use changes caused an increase in Q/P and decrease in ET/P. Q_s/Q substantially increased and Q_b/Q substantially decreased. At the sub-catchment level, the impacts of land use changes on the water balance were diverse for the ET/P and Q_l/Q. Positive and negative trends at sub-catchment level have compensated each other, so that long-term changes of those variables at catchment level were relatively small. In addition, changes in forest and settlement area have resulted in different impacts on the water balance. A reduction in the forest area significantly contributed to a higher Q/P and lower ET/P and Q_l/Q. An increase in the settlement area significantly contributed to a higher Q/P and Q_s/Q and a lower Q_b/Q.

ACKNOWLEDGMENTS

The authors acknowledge the Bengawan Solo River Basin Organization, Ministry of Public Works, Indonesia and the Bengawan Solo Watershed Research Centre, Ministry of Environment and Forestry, Indonesia for providing the hydrological and climatological data. The first author would like to express his appreciation to the Ministry of Research, Technology and Higher Education of the Republic of Indonesia, for the financial support during his PhD project.

REFERENCES

Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., & Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, *524*, 733–752.

Aldrian, E., & Djamil, Y. S. (2008). Spatio-temporal climatic change of rainfall in East Java Indonesia. *International Journal of Climatology*, *28*(4), 435–448.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association*, *34*(1), 73–89.

Beck, H. E., Bruijnzeel, L. A., Van Dijk, A. I. J. M., McVicar, T. R., Scatena, F. N., & Schellekens, J. (2013). The impact of forest regeneration on streamflow in 12 mesoscale humid tropical catchments. *Hydrology and Earth System Sciences*, *17*(7), 2613–2635.

Bonell, M., Hufschmidt, M. M., & Gladwell, J. S. (2005). *Hydrology and water management in the humid tropics: Hydrological research issues and strategies for water management*. New York: Cambridge University Press.

Bosch, J. M., & Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, *55*(1), 3–23.

Botula, Y. D., Van Ranst, E., & Cornelis, W. M. (2014). Pedotransfer functions to predict water retention for soils of the humid tropics: A review. *Revista Brasileira de Ciência do Solo*, *38*(3), 679–698.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, *310*(1–4), 28–61.

Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: Not seeing the soil for the trees? *Agriculture, Ecosystems & Environment*, *104*(1), 185–228.

Calder, I. R., Young, D., & Sheffield, J. (2001). *Scoping study to indicate the direction and magnitude of the hydrological impacts resulting from land use change on the Panama Canal Watershed: Newcastle upon Tyne*. UK: Centre for Land Use and Water Resources Research.

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, *37*(1), 35–46.

Douglas, I. (1999). Hydrological investigations of forest disturbance and land cover impacts in south-east asia: A review. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, *354*(1391), 1725–1738.

ERSDAC. (2016). http://www.jspacesystems.or.jp/ersdac/GDEM/

Ewen, J., O'Donnell, G., Burton, A., & O'Connell, E. (2006). Errors and uncertainty in physically-based rainfall-runoff modelling of catchment change effects. *Journal of Hydrology*, *330*(3), 641–650.

FAO/IIASA/ISRIC/ISSCAS/JRC. (2012). Harmonized World Soil Database (version 1.2) . FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Guevara-Escobar, A., Gonzalez-Sosa, E., Ramos-Salinas, M., & Hernandez-Delgado, G. D. (2007). Experimental analysis of drainage and water storage of litter layers. *Hydrology and Earth System Sciences*, *11*(5), 1703–1716.

Gumindoga, W., Rientjes, T. H. M., Shekede, M. D., Rwasoka, D. T., Nhapi, I., & Haile, A. T. (2014). Hydrological impacts of urbanization of two catchments in Harare. *Zimbabwe Remote Sens*, *6*, 12544–12574. doi:10.3390/rs61212544

Hansen, M. C., Stehman, S. V., Potapov, P. V., Arunarwati, B., Stolle, F., & Pittman, K. (2009). Quantifying changes in the rates of forest clearing in Indonesia from 1990 to 2005 using remotely sensed data sets. *Environmental Research Letters*, *4*(3), , 034001.

Hejazi, M. I., & Moglen, G. E. (2008). The effect of climate and land use change on flow duration in the Maryland Piedmont region. *Hydrological Processes*, *22*(24), 4710–4722.

Huisman, J. A., Breuer, L., Bormann, H., Bronstert, A., Croke, B. F. W., Frede, H., … Graft, T. (2009). Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM) III: Scenario analysis. *Advances in Water Resources*, *32*(2), 159–170.

Kilonzo, F. N. 2013. Assessing the impacts of environmental changes on the water resources of the upper Mara, Lake Victoria Basin. Ph.D, Vrije Universiteit Brussel.

Li, Z., Liu, W. Z., Zhang, X. C., & Zheng, F. L. (2009). Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology*, *377*(1), 35–42.

Lørup, J. K., Refsgaard, J. C., & Mazvimavi, D. (1998). Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe. *Journal of Hydrology*, *205*(3), 147–163.

Marhaento, H., Booij, M. J., & Hoekstra, A. Y. (in press). Attribution of changes in stream flow to land use change and climate change in a mesoscale tropical catchment in Java, Indonesia. *Hydrology Research*, nh2016110.

Memarian, H., Balasundram, S. K., Abbaspour, K. C., Talib, J. B., Boon Sung, C. T., & Sood, A. M. (2014). SWAT-based hydrological modelling of tropical land-use scenarios. *Hydrological Sciences Journal*, *59*(10), 1808–1829.

Ministry of Forestry (1987). *A guideline of land rehabilitation and soil conservation*. Jakarta, Indonesia: Ministry of Forestry . Available in Indonesian.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.

Niehoff, D., Fritsch, U., & Bronstert, A. (2002). Land-use impacts on storm-runoff generation: Scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology*, *267*(1–2), 80–93.

Refsgaard, J. C., & Storm, B. (1995). MIKE SHE. In *Computer models of watershed hydrology*. , edited by: Singh, V.P. (pp. 809–846). Highland Ranch, Colorado: Water Resources Publications.

Refsgaard, J. C., Alley, W. M., & Vuglinsky, V. S. (1989). *Methods for distinguishing between man's influence and climatic effects on the hydrological cycle ()IHP-III Project 6.3*. Paris: Unesco.

Remondi, F., Burlando, P., & Vollmer, D. (2016). Exploring the hydrological impact of increasing urbanisation on a tropical river catchment of the metropolitan Jakarta, Indonesia. *Sustainable Cities and Society*, *20*, 210–221.

Retnowati S., 2012, Impact of land use changes to hydrological condition, MSc Thesis. Graduate School of Universitas Sebelas Maret. Surakarta. Indonesia. Available in Bahasa. Online access at https://digilib.uns.ac.id/

Rientjes, T. H. M., Haile, A. T., Kebede, E., Mannaerts, C. M. M., Habib, E., & Steenhuis, T. S. (2011). Changes in land cover, rainfall and stream flow in Upper Gilgel Abbay catchment, Blue Nile basin–Ethiopia. *Hydrology and Earth System Sciences*, *15*(6), 1979–1989.

Rientjes, T. H. M., Muthuwatta, L. P., Bos, M. G., Booij, M. J., & Bhatti, H. A. (2013). Multi-variable calibration of a semi-distributed hydrological model using streamflow data and satellite-based evapotranspiration. *Journal of Hydrology*, *505*, 276–290.

Rodriguez Suarez, J. A., Diaz-Fierros, F., Perez, R., & Soto, B. (2014). Assessing the influence of afforestation with *Eucalyptus globulus* on hydrological response from a small catchment in northwestern Spain using the HBV hydrological model. *Hydrological Processes*, *28*(22), 5561–5572.

Romanowicz, R. J., & Booij, M. J. (2011). Impact of land use and water management on hydrological processes under varying climatic conditions. *Physics and Chemistry of the Earth, Parts A/B/C*, *36*(13), 613–614.

Saxton, K., & Willey, P. (2005). The SPAW model for agricultural field and pond hydrologic simulation. *Mathematical modeling of watershed hydrology*, 401–408.

Subarna, D., Purwanto, M. Y. J., Murtilaksono, K., & Wiweka (2014). The relationship between monthly rainfall and elevation in the Cisangkuy watershed Bandung regency. *International Journal of Latest Research in Science and Technology*, *3*(2), 55–60.

Thanapakpawin, P., Richey, J., Thomas, D., Rodda, S., Campbell, B., & Logsdon, M. (2007). Effects of landuse change on the hydrologic regime of the Mae Chaem river basin, NW Thailand. *Journal of Hydrology*, *334*(1), 215–230.

USGS. 2016. http://landsat.usgs.gov

Valentin, C., Agus, F., Alamban, R., Boosaner, A., Bricquet, J. P., Chaplot, V. T., … de Guzman, A. (2008). Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. *Agriculture, Ecosystems & Environment*, *128*(4), 225–238.

Van Dijk, A. I., Hairsine, P. B., Arancibia, J. P., & Dowling, T. I. (2007). Reforestation, water availability and stream salinity: A multi-scale analysis in the Murray-Darling Basin, Australia. *Forest Ecology and Management*, *251*(1), 94–109.

Van Griensven, A., Ndomba, P., Yalew, S., & Kilonzo, F. (2012). Critical review of SWAT applications in the upper Nile basin countries. *Hydrology and Earth System Sciences*, *16*(9), 3371–3381.

Van Griensven, A., Maharjan, S., & Alemayehu, T. (2014). Improved simulation of evapotranspiration for land use and climate change impact analysis at catchment scale. *International Environmental Modelling and Software Society (iEMSs) 7th International Congress on Environmental Modelling and Software.*

Wagner, P. D., Kumar, S., & Schneider, K. (2013). An assessment of land use change impacts on the water resources of the Mula and Mutha rivers catchment upstream of Pune, India. *Hydrology and Earth System Sciences*, *17*(6), 2233–2246.

Wang, X. (2014). Advances in separating effects of climate variability and human activity on stream discharge: An overview. *Advances in Water Resources*, *71*, 209–218.

Wigmosta, M. S., Vail, L. W., & Lettenmaier, D. P. (1994). A distributed hydrology-vegetation model for complex terrain. *Water Resources Research*, *30*(6), 1665–1679.

Wilk, J., & Hughes, D. A. (2002). Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment. *Hydrological Sciences Journal*, *47*(1), 19–30.

Williams, J. R. (1995). Chapter 25: The EPIC model. In V. P. Singh (Ed.), *Computer models of watershed hydrology* (pp. 909–1000). Highland Ranch, CO.: Water Resources Publications.

Wittenberg, H. (1994). Nonlinear analysis of flow recession curves. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences*, *221*, 61–68.

Wohl, E., Barros, A., Brunsell, N., Chappell, N. A., Coe, M., Giambelluca, T., … Goldsmith, S. (2012). The hydrology of the humid tropics. *Nature Climate Change*, *2*(9), 655–662.

Zhang, M., Wei, X., Sun, P., & Liu, S. (2012). The effect of forest harvesting and climatic variability on runoff in a large watershed: The case study in the upper Minjiang River of Yangtze River basin. *Journal of Hydrology*, *464*, 1–11.

Zhang, Y., Guan, D., Jin, C., Wang, A., Wu, J., & Yuan, F. (2014). Impacts of climate change and land use change on runoff of forest catchment in Northeast China. *Hydrological Processes*, *28*(2), 186–196.

How to cite this article: Marhaento H, Booij MJ, Rientjes THM, Hoekstra AY. Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. *Hydrological Processes*. 2017;31:2029–2040. https://doi.org/10.1002/hyp.11167