Attribution of changes in stream flow to land use change and climate change in a mesoscale tropical catchment in Java, Indonesia

Hero Marhaento, Martijn J. Booij and Arjen Y. Hoekstra

ABSTRACT

Changes in the stream flow of the Samin catchment (277.9 km^2) in Java, Indonesia, have been attributed to land use change and climate change. Hydroclimatic data covering the period 1990–2013 and land use data acquired from Landsat satellite imageries for the years 1994 and 2013 were analysed. A quantitative measure is developed to attribute stream flow changes to land use and climate changes based on the changes in the proportion of excess water relative to changes in the proportion of excess energy. The results show that 72% of the increase in stream flow might be attributed to land use change. The results are validated by a land use change analysis and two statistical trend analyses namely the Mann-Kendall trend analysis and Sen's slope estimator for mean annual discharge, rainfall and potential evapotranspiration. The results of the statistical trend analysis are in the same direction as the results of the attribution analysis, where climate change was relatively minor compared to significant land uses change due to deforestation during the period 1994–2013. We conclude that changes in stream flow can be mainly attributed to land use change rather than climate change for the study catchment.

Key words | climate change, land use change, quantitative attribution, stream flow, tropical catchment

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INTRODUCTION

Hydrology in tropical regions differs from that in other regions in having greater energy inputs and faster rates of change, including human-induced changes (Wohl *et al.* 2012). Despite high annual precipitation, water availability is often insufficient for human use in tropical regions because of seasonality, droughts, and increasing water demands resulting from rapid population growth. Bruijnzeel & Sampurno (1990) and Douglas (1999) argue that high rates of deforestation, urbanization and intensive land tillage, which are commonly found in tropical regions, have large impacts on water availability.

Bosch & Hewlett (1982) and Brown *et al.* (2005) reviewed the results of numerous catchment model experiments (e.g. paired catchment studies) throughout the world, including in the tropics, and found that changes in land use type through deforestation and afforestation can significantly affect the mean annual flow and the variability of annual flow (flow duration and seasonal flow). The annual water yield in tropical regions probably increases with deforestation, with maximum gains in water yield following total clearing (Bruijnzeel & Sampurno 1990). However, these clear signals of how land use change affects hydrology were mostly found for small catchments. Evidence of land use change effects on water availability in larger catchments (>100 km^2) in tropical regions is less consistent (Costa *et al.* 2003; Beck *et al.* 2013).

Apart from land use changes, climate change is the other main driver that influences water availability in

tropical regions. Several studies have argued that climate change (particularly changes in temperature and precipitation) has a larger influence on water availability than land use change (Legesse *et al.* 2003; Khoi & Suetsugi 2014; Yan *et al.* 2016). Blöschl *et al.* (2007) argue that climate change impacts on water availability vary depending on the spatial scale, due to direct and indirect influences through feedback mechanisms between land use and climate changes. Hejazi & Moglen (2008) found that the combination of land use change and climate change might result in more significant hydrological changes than either driver acting alone.

A major challenge in the study of tropical hydrology is to assess the attribution of changes in water availability to land use and climate changes (Romanowicz & Booij 2011). A widespread belief exists among hydrologists in tropical countries that land use changes (e.g. deforestation) are the main cause of an increasing number of floods (Andréassian 2004). Only a quantitative approach that combines the effects of land use and climate change can provide a better understanding of the single effect of land use change. Knowledge on the relative impacts of changes in land use and climate on water availability will be helpful in estimating the effectiveness of land use management practices at the landscape level.

According to Zhang *et al.* (2012), there are two ways to distinguish the impacts of land use and climate changes on hydrology: a modelling and a non-modelling approach. The modelling approach has been widely used to measure the relative effects of land use and climate change on hydrology (Li *et al.* 2009; Zhan *et al.* 2013; Khoi & Suetsugi 2014). However, the ability to simulate realistic conditions is accompanied by the need for large amounts of data. Several non-modelling approaches were introduced to assess the contribution of land use and climate changes on hydrology. Wei & Zhang (2010) and Zhang *et al.* (2012) used the modified double mass curve to exclude the effect of climate change on runoff generation in a deforested area. Tomer & Schilling (2009), Ye *et al.* (2013) and Renner *et al.* (2014) used a coupled water-energy budget approach to distinguish relative impacts of land use and climate change on watershed hydrology. A classical non-modelling approach is to employ trend analysis and change detection methods (Rientjes *et al.* 2011; Zhang *et al.* 2014).

This study aims to attribute changes in stream flow to land use and climate changes in the Samin catchment in Java, Indonesia. A non-modelling approach is used to achieve our research objective. We propose an adaptation of the Tomer & Schilling (2009) approach to distinguish the impacts of land use and climate change on stream flow based on the relations between precipitation, actual evapotranspiration and potential evapotranspiration. Subsequently, we perform statistical trend analysis (i.e. the Mann-Kendall trend analysis and Sen's slope estimator) and land use change analysis to validate the attribution results. The measures used for attribution analysis and the validation of the attribution results by means of statistical analyses and land use change analysis are the novelty of the present study. The study area and data availability are then described, followed by an explanation of the methods used in the study. Subsequent sections then discuss the key findings of the study and finally, conclusions are drawn.

STUDY AREA AND DATA

Catchment description

The Samin River is one of the tributaries of the Bengawan Solo River, which plays an important role in supporting life within its surrounding area. It is located in the western part of Central Java Province, Indonesia. The catchment area of the Samin River extends over 277.9 km^2 and ranges between latitude 7.6–7.7° South and longitude 110.8–111.2° East (see Figure 1). The highest part of the catchment is located in the Lawu Mountain with an altitude of 3,175 meters above mean sea level (a.m.s.l.) and the lowest part is located near the Bengawan Solo river with an altitude of 84 m a.m.s.l. The average slope in the Samin catchment is 10.2%, and the stream density is around 2.2 km/km^2. According to the global 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 occupy 57% and 43% of the study area, respectively. Luvisols are developed from parent material of accumulated silicate clay and Andosols are developed from parent material of the volcanic Lawu Mountain. Seasons in
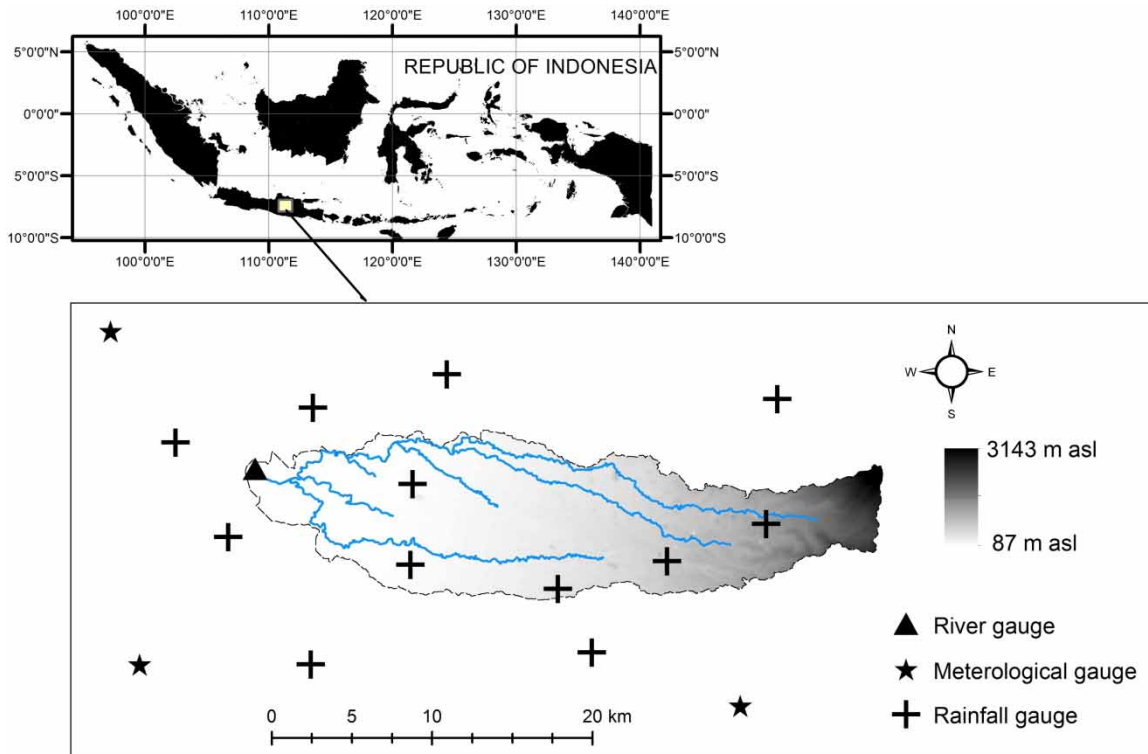
Figure 1 | Location of the Samin catchment in Java, Indonesia.

the Samin catchment are influenced by monsoon winds, where the dry season is influenced by Australian continental wind masses and generally extends from May to October and the wet season is influenced by Asian and Pacific Ocean wind masses and generally extends from November to April.

Discharge data

The Bengawan Solo River Basin office provided daily water level data of the Samin catchment for the period 1990–2013. The daily discharge data have been obtained by converting daily water level data to discharge values using the rating curves provided by the Bengawan Solo River Basin office. To test the reliability of the dataset, a quality check has been performed. A data screening process and a visual check of the hydrograph were carried out to identify missing and unrealistic values (outliers). We found an absolute error in the measured water level data where all daily water level data were systematically overestimated in the periods 1995–2008 and 2009–2013 (see Figure 2). The data provider

confirmed that this error is probably due to a change of the gauge location.

A correction of the water level was carried out based on the height difference between the lowest water level of both error periods. We used the annual minimum 7-day average to define the lowest value in both periods. We found a correction value of −0.6 m for the daily water level data within the period 1995–2008 and of −0.4 m for the period 2009–2013. Subsequently, the missing discharge data were completed using a non-linear recession model (Wittenberg 1994). We selected a non-linear recession model after a Pearson's test showed low correlation coefficients between the Samin discharge station and adjacent discharge stations (i.e. Keduang and Pidekso stations), which inhibited the use of widely used regional regression models to estimate the discharge. Note that this method was applied to fill-in data of a maximum fifteen consecutive days of missing discharge values. We excluded stream flow data that were unavailable for more than fifteen consecutive days. This fill-in procedure concerns less than 5% of the data. The discharge data included missing daily discharge values for the entire year 2007.
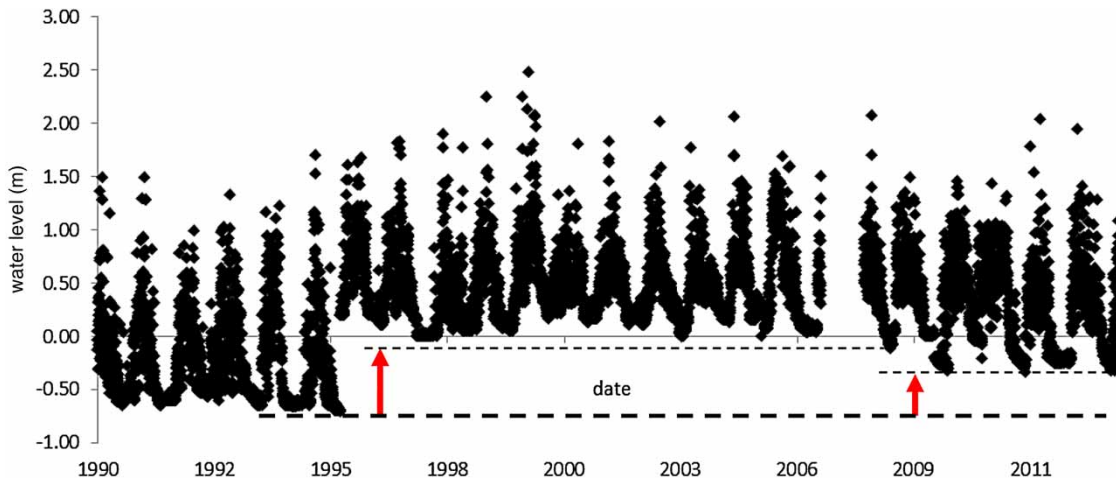
Figure 2 | Original daily water level data acquired from the data provider. The arrow shows a systematic error (shifting upward) in the water level data. Data for the entire year 2007 are missing.

Rainfall and climatological data

Daily rainfall from eleven rainfall stations and meteorological data from three meteorological stations (Adi Sumarmo station, Pabelan station and Jatisrono station) were provided by the Bengawan Solo River Basin Organization for the period 1990–2013. Outliers and missing values of rainfall and meteorological data were identified and corrected. We checked the data for errors related to data processing (e.g. human errors) since most of the rainfall and meteorological data were manually recorded from the gauges. Doubtful rainfall values, such as negative rainfall values, unrealistic values and missing data were corrected using the normal ratio method (Paulhus & Kohler 1952).

To obtain catchment average rainfall depths, we averaged daily rainfall values using the Thiessen polygon approach with elevation correction (TEC). The TEC method was selected after we compared the results from the TEC approach with three other widely known interpolation methods namely Inverse Distance Weighting (IDW), Ordinary Kriging (OK) and Ordinary Co-kriging (OCK) using 72 randomly selected sample points of mean monthly rainfall. We found that the Root Mean Square Error (RMSE) of TEC of 67 mm was comparable with the RMSE of IDW (56 mm), OK (69 mm) and OCK (60 mm) and for all methods the $R^2 > 0.8$. Moreover, the TEC

method is the simplest method to compute average rainfall values. The elevation correction for the TEC approach is based on a simple linear regression between the mean annual rainfall and elevation of thirteen rainfall stations in the surrounding catchment. This resulted in a correction factor for the Thiessen polygon method of a 153 mm increase in annual rainfall per 100 m increase of elevation.

The reference evapotranspiration (ET_0) was calculated in each meteorological station using the Penman–Monteith method as recommended by the Food and Agricultural Organization (Smith & Allen 1992). However, the daily meteorological data for Pabelan station and Jatisrono station were only available from 2008 to 2013. To complete the meteorological values in these stations, we used daily meteorological data from the National Centers for Environmental Prediction Climate Forecast System Reanalysis (Saha *et al.* 2010). They provide daily climate data at a resolution of $0.25\,^\circ \times 0.25\,^\circ$ from 1979 to 2010. Furthermore, we averaged daily ET_0 for the study catchment using the Thiessen polygon approach. An elevation correction for ET_0 was not used since our data availability was not sufficient to determine the correlation between potential evapotranspiration and elevation. However, the elevation gap between the mean elevation of the catchment and the meteorological stations is minor. Figure 3 shows the mean annual rainfall, potential evapotranspiration and discharge of the study catchment.
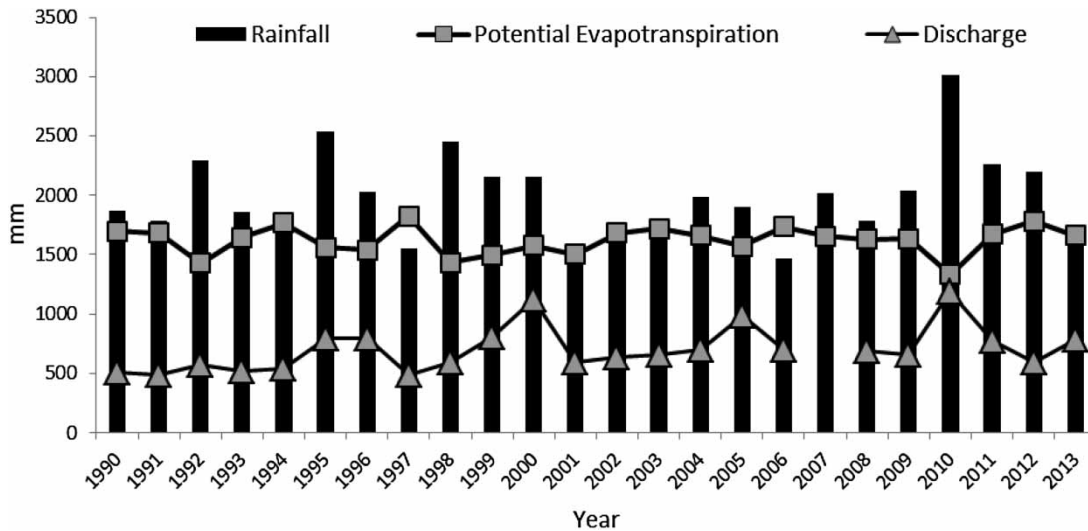
Figure 3 │ Mean annual rainfall, potential evapotranspiration and discharge for the period 1990–2013 in the Samin catchment. The data include a missing discharge value for the year 2007.

Spatial data

Landsat imageries from the year 1994 and 2013 were available for the study area through the United States Geological Survey archives (USGS 2016). The data scene (path/row) number is 119/65 and the acquisition dates are September 1, 1994 and October 7, 2013. These images have cloud cover of less than 5% so these are sufficient for further analysis of land use images classification. The catchment boundaries and the stream network of the study area were delineated based on a Digital Elevation Model from a contour map with a Contour Interval of 12.5 meters that was available from the Geospatial Information Agency of Indonesia.

METHODS

Separating effects of land use and climate change on stream flow

We extend the idea of Tomer & Schilling (2009) who distinguish the impacts of land use and climate change on hydrology using the changes in the proportion of excess water relative to changes in the proportion of excess energy. The amount of excess water within the system (i.e.

catchment) can be expressed as precipitation (P) minus actual evapotranspiration (ET) and the amount of excess energy as potential evapotranspiration (ET_0) minus actual evapotranspiration (ET). The amounts of excess water and excess energy divided by the available water and energy amounts result in dimensionless values P_{ex} and E_{ex} on a scale of 0 to 1, which can be expressed as follows:

$$P_{ex} = 1 - \mathrm{ET}/\mathrm{P} \qquad (1)$$

$$E_{ex} = 1 - \mathrm{ET}/\mathrm{ET_0} \qquad (2)$$

where P_{ex} is the proportion of excess water, E_{ex} the proportion of excess energy, P the precipitation (is referred to rainfall), ET_0 the potential evapotranspiration and ET the actual evapotranspiration.

The Tomer & Schilling (2009) framework follows two basic assumptions for separating land use and climate change impacts on hydrology based on excess water and energy. First, land use changes will affect ET, which will decrease or increase P_{ex} and E_{ex} simultaneously because ET is in the numerator of both fractions. As a result, P_{ex} and E_{ex} will move creating an angle close to 45° or 225° compared to the x-axis (see Figure 4) if there is a change in land use while climate is unchanged (i.e. $\Delta P \sim 0$ and $\Delta ET_0 \sim 0$). A movement creating an angle of 45° indicates
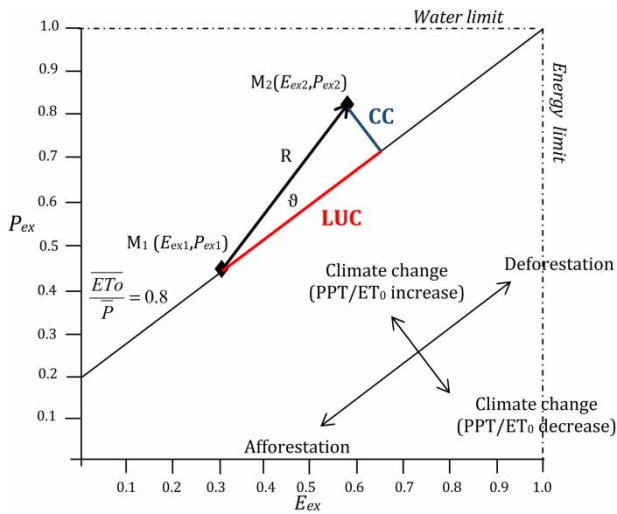
Figure 4 | Adapted Tomer & Schilling (2009) framework to illustrate how the fractions of excess water and energy respond to land use changes and climate change. The points M_1 and M_2 are the fractions of excess water and energy of the baseline period (P_{ex1}, E_{ex1}) and altered period (P_{ex2}, E_{ex2}), respectively.

an increase in water and energy consumption (e.g. more ET because of a more densely vegetated area), while a movement creating an angle of 225° indicates a decrease in water and energy consumption (e.g. less ET because of a less vegetated area). Second, climate change will affect P and/or ET_0, which will be reflected by a change in the ratio of P to ET_0. If the ratio of P to ET_0 increases while ET remains unchanged (i.e. no land use changes), the P_{ex} value will increase and/or the E_{ex} value will decrease, and vice versa, creating a movement along a line with an angle close to 135° or 315° compared to the x-axis (see Figure 4). Within the framework, a change in stream flow can be equally attributed to land use change and climate change if movements of P_{ex} and E_{ex} are parallel to the P_{ex} axis or E_{ex} axis. We refer the reader to Tomer & Schilling (2009) for a more detailed explanation about the concept.

However, Renner *et al.* (2014) argue that the Tomer & Schilling (2009) concept cannot be applied to all hydro-climatic conditions and works only for a region where precipitation equals evaporative demand. They proposed an adaptation of the concept by considering the aridity index (ET_0/P) to determine the climatic state of the study catchment. Within their improved concept, a land use change impact on hydrology is defined as a change in ET, but with a constant aridity, and a climate change impact on hydrology is defined as changes in the average supply

of water and energy. As a result, a change of P_{ex} and E_{ex} for the same aridity index is considered as a land use change impact and a change of P_{ex} and E_{ex} moving away from a constant aridity index is considered as a climate change impact.

We extended the framework adapted by Renner *et al.* (2014) by developing quantitative measures to estimate the land use and climate change impacts on stream flow alteration based on the changes of P_{ex} and E_{ex}. The period of analysis 1990–2013 for which hydro-meteorological time series were available was divided into two periods: a baseline and an altered period, when land use change and climate change might have contributed to stream flow change. We regarded the years 1990–1997 as the baseline period and the years 2006–2013 as the altered period, since during the period 1998–2003 significant land use changes have occurred due to deforestation. In 1998, which is considered to be the starting year of the 'reformation era', many local communities reclaimed their customary rights inside state forests and converted forest area to other land uses as alternative sources of livelihood after the economic crisis in Indonesia (Resosudarmo *et al.* 2012). Subsequently, we compared P_{ex} and E_{ex} for the baseline period and altered period, later symbolized as point M_1 (P_{ex1}, E_{ex1}) and M_2 (P_{ex2}, E_{ex2}), respectively, and determined the change of P_{ex} and E_{ex} relative to the long-term aridity index ($\overline{ET_0/P}$) of the study catchment (Figure 4). The contribution of land use and climate change to stream flow changes is estimated based on the changes of P_{ex} and E_{ex} relative to the long-term aridity index line ($\overline{ET_0/P}$). For example, if the long-term aridity index is 0.8, the change along the constant aridity index line is attributed to land use change (i.e. LUC line) and the line perpendicular to this line is attributed to climate change (i.e. CC line). The movement direction will determine whether land use change or climate change has a more dominant contribution to changes in stream flow.

The magnitude of land use and climate change impacts that causes a shift from point M_1 (P_{ex1}, E_{ex1}) to M_2 (P_{ex2}, E_{ex2}) is estimated based on three measures: (1) the resultant length (R); (2) the angle (θ) of change; and (3) the attribution (in %) to land use change and climate change. The resultant length (R) indicates the magnitude of the changes of excess water and energy where a higher resultant length (R)

represents a higher magnitude of changes of excess water and energy. A higher change of excess water and energy then corresponds to a higher rate of land use and climate change impacts on stream flow change. The magnitude of the resultant length (R) from M_1 to M_2 can be calculated based on Pythagoras' theorem as follows:

$$R = \sqrt{(E_{ex2} - E_{ex1})^2 + (P_{ex2} - P_{ex1})^2} \qquad (3)$$

The angle (θ) of change indicates the contribution of land use and climate changes with a higher slope reflecting a higher contribution of climate change. The angle (θ) can be calculated based on the gradient of the vector M_1–M_2 relative to the gradient of the long term aridity index using the following equations:

$$\tan(\vartheta) = \left| \frac{\dfrac{\overline{ET0}}{\overline{P}} - \dfrac{P_{ex2} - P_{ex1}}{E_{ex2} - E_{ex1}}}{1 + \left(\dfrac{\overline{ET0}}{\overline{P}}\right) * \left(\dfrac{P_{ex2} - P_{ex1}}{E_{ex2} - E_{ex1}}\right)} \right| \qquad (4)$$

$$\theta = \arctan(\theta) \qquad (5)$$

We measured the attribution (in %) of stream flow changes to land use change and climate change by determining the length of the changes along the aridity index line and the line perpendicular to the aridity index line, which are denoted as LUC and CC, respectively. The lengths of LUC and CC can be calculated as follows:

$$LUC = R * \cos\theta \qquad (6)$$

$$CC = R * \sin\theta \qquad (7)$$

The relative magnitudes of *LUC* and *CC* are denoted as *L* (%) and *C* (%) and calculated using the following equations:

$$L(\%) = \frac{LUC}{LUC + CC} * 100\% \qquad (8)$$

$$C(\%) = \frac{CC}{LUC + CC} * 100\% \qquad (9)$$

Validation of attribution assessment

Two analyses were carried out to validate the results of the attribution analysis: a statistical trend analysis to validate the contribution of climate change to stream flow change and a land use change analysis to validate the contribution of land use change to stream flow change.

Trend analysis of climate variables

Trend analysis was performed to check whether the mean annual discharge (Q), rainfall (P) and evapotranspiration (ET_0) have significantly changed over time (long-term). We hypothesized that if climate change has a larger contribution than land use change to stream flow alteration, the trends in climate variables (P and ET_0) will be in the same direction and have the same magnitude as the stream flow trend. The trend direction and magnitude were determined using the Mann-Kendall test and Sen's slope estimator. The Mann-Kendall test and Sen's slope estimator were selected since they are widely used to detect trends in long-time series of hydrological and climatological data (Rientjes *et al.* 2011; Zhang *et al.* 2014).

Land use change analysis

Land use change analysis was carried out to measure the rate of land use change in the study catchment, and to validate the contribution of land use change to stream flow changes. We hypothesized that if land use change has a larger contribution than climate change to stream flow alteration, the type of change in land use will be in line with the attribution results, e.g. deforestation will affect an increase in P_{ex} and E_{ex} simultaneously.

We used image processing of Landsat imageries from the years 1994 and 2013 to assess land use changes within the study area. These two imageries represent the land use condition of the baseline period (1990–1997) and altered period (2006–2013). Before image processing, a pre-processing analysis had been applied for the selected images including geometric correction to avoid distortion on map coordinates and masking analysis to obscure the area beyond our study area. After the pre-processing analysis was completed, we applied a maximum likelihood algorithm

Table 1 | Measures of the attribution of changes in stream flow to land use and climate changes

Period	P	ET_0	Q	ET	P_{ex}	E_{ex}	R	ϑ	L	C
1990–1997	1,962	1,644	588	1,374	0.30	0.16				
2006–2013	2,072	1,639	771	1,301	0.37	0.20	0.1	21.0	72	28

P = mean annual rainfall (mm); ET_0 = mean annual potential evapotranspiration (mm); Q = mean annual discharge (mm); ET = mean annual evapotranspiration (mm); P_{ex} = excess water divided by available water; E_{ex} = excess energy divided by available energy; R = resultant length (dimensionless); ϑ = angle of changes (degrees); L = attribution to land use change (%); C = attribution to climate change (%).

to retrieve the land cover map using a thousand sample points that were generated from an institutional land use map (scale 1:25,000) from the Geospatial Information Agency of Indonesia. We divided the sample points into two parts: half of the sample points were used to perform image classification and another half were used to perform accuracy assessment. An error matrix (Congalton 1991) was made to calculate the accuracy using four measures: the producer's accuracy, the user's accuracy, the overall accuracy and the Kappa coefficient. The producer's accuracy is to measure how well a certain area can be classified. The user's accuracy is to measure how well labels on a map represent each category on the ground. The overall accuracy is to measure the total number of correct samples divided by the total number of samples. The Kappa coefficient is the coefficient of agreement between the classification map and the reference data. Subsequently, land use change analysis was performed based on the area differences of each land use class from different years.

Figure 5 | Change of excess water (P_{ex}) and excess energy (E_{ex}) relative to long term aridity index line ($\overline{PET}/\overline{P}$). The arrow shows the change of P_{ex} and E_{ex} between the baseline period (1990–1997) and the altered period (2006–2013). The natural variations of P_{ex} and E_{ex} for each period are represented by the standard deviation lines.

RESULTS

Attribution of changes in stream flow to land use change and climate change

The results for the three measures (see Table 1 and Figure 5) show a simultaneous increase in P_{ex} and E_{ex} in the study catchment. The increase in P_{ex} and E_{ex} occurred because ET has significantly decreased, which is probably due to deforestation, while P and ET_0 remain relatively unchanged. The aridity index was found to be 0.8 and the movement of P_{ex} and E_{ex} relative to the aridity index line has created an angle of 21°. The angle is less than 45° indicating that
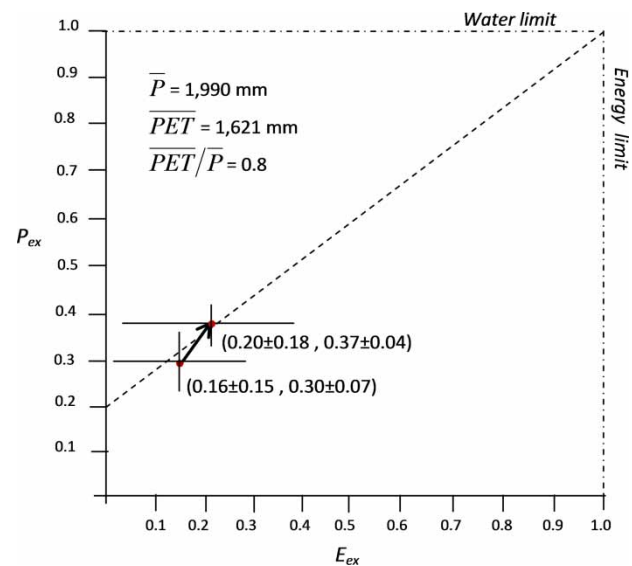
climate change (P and ET_0) is minor and has a smaller contribution than land use change on the stream flow alteration. In addition, the change of P_{ex} and E_{ex} is relatively low with a Resultant value (R) of 0.1. The attribution of changes in stream flow to land use change and climate change was estimated to be about 72% and 28%, respectively. Note that the discharge data includes uncertainty during measurements that might influence the attribution results considerably. Using the original discharge data (i.e. before the mean annual discharge has been corrected by a decrease of 60% for the years 1995–2008 and a decrease of 40% for the years 2009–2013 due to a systematic error), the attribution results were found to be 98% and 2% for land use change and climate change contribution, respectively.

Trend analysis of climate variables

The trend analysis was carried out for mean annual climate variables (i.e. P and ET_0) and discharge (Q). The results of the Mann-Kendall test and Sen's slope estimator (see Table 2) show that the trends in P and ET_0 are not significant while the trend in Q is significant at a significance level of 5%. The trend magnitude determined by Sen's slope for Q (i.e. Sen's slope = 12.1 mm/year) is larger than for ET_0 (i.e. Sen's slope = 1.3 mm/year) and P (i.e. Sen's slope = 2.0 mm/year). In general, the statistical results from the Mann-Kendall trend test and Sen's slope estimator showed that the mean annual rainfall and potential evapotranspiration have not significantly changed while the mean annual discharge has changed significantly. The results are in line with the attribution results, which generally revealed a small contribution of climate change to changes in stream flow.

Land use change detection

Following the land use classification from the Geospatial Information Agency of Indonesia, we found eight dominant land use classes in the study area: evergreen forest, mixed garden, settlement, paddy field, dryland farming, shrubs, bare land and water body. Evergreen forest is homogeneous forest area that consists of *Pinus merkusii* tree species; mixed garden is community forest that consists of multipurpose trees (e.g. fruits, fuel woods, etc.) and often combined with seasonal crops on the same unit of land; settlement is building area and its surroundings; paddy field is agricultural area that consists of paddy rice fields with an intensive irrigation system; dry land farming is agricultural area for seasonal crops production; shrub is abandoned area covered by herbaceous plants; bare land is rocky

abandoned area without vegetation cover; and water body refers to rivers and ponds. By applying an error matrix (Congalton 1991) using 500 (unit) samples, we found an average producer's accuracy of 87.6%, an average user's accuracy of 91.5%, an overall accuracy of 89.3% and a Kappa coefficient of 87.6%. According to Anderson (1976), our accuracy assessment results may represent a strong agreement and high accuracy for producing a land use map.

Land use change analysis was performed based on the area differences for each land use class from different years. We reclassified the eight land use classes into four land use classes to have more general land use classes namely forest area (i.e. combination of evergreen forest and mixed garden), agricultural area (i.e. combination of paddy field and dry land farming), settlements and others (i.e. combination of shrub, bare land and water body) (see Table 3). The results show that settlements and agricultural area have increased 24% and 6%, respectively, during the period 1994–2013. These expansions caused large-scale deforestation, decreasing the forest area by 32%. Since climate changes have a minor contribution to the stream flow alteration, significant changes in land use (i.e. deforestation) validate the results of the attribution analysis, which revealed a larger contribution of land use change than climate change to stream flow alteration. Figure 6 shows the land use maps for the years 1994 and 2013.

DISCUSSION

Land use changes, which are related to deforestation due to expansion of agriculture areas and settlement areas, were

Table 2 | Results of statistical trend analysis for mean annual rainfall, mean annual potential evapotranspiration and mean annual discharge for the period 1990–2013

Analysis	Rainfall	ET_0	Discharge
Mann-Kendall Z-statistic	0.1	0.4	2.7*
p-value	1.0	0.4	0.01*
Sen's slope	2.0	1.3	12.1

*Trend is significant at 5%.

Table 3 | Land use distribution of the Samin catchment in the year 1994 and 2013 including its change

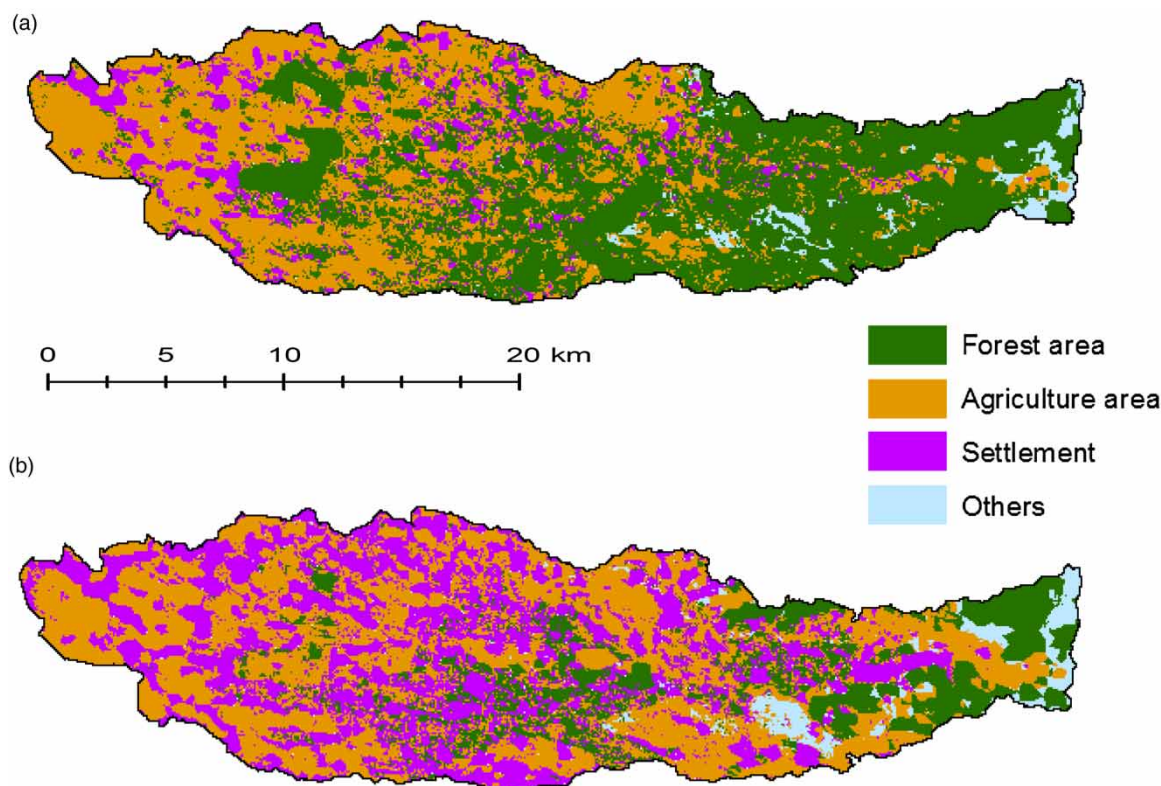| Land use class	1994 (hectares)	%	2013 (hectares)	%	Change (%)
Forest area	13,542.7	49	4,687.1	17	−32
Agriculture area	10,896.6	39	12,628.6	45	6
Settlements	2,711.6	10	9,531.5	34	24
Others	647.1	2	950.9	4	2
Total	27,798.0	100	27,798.0	100.0	0

Figure 6 │ Land use maps in the Samin catchment for (a) 1994 and (b) 2013.

probably the cause of significant changes in stream flow generation. Using the three measures we developed, land use change was found to contribute to about 72% of the stream flow alteration in the study catchment. These results are in the same direction as the results of the statistical trend analysis, where we found that the annual ET_0 and P have not significantly changed (at a significance level of 5%) over the period of analysis. In contrast, the annual Q has significantly changed (at a significance level of 5%) and at the same time, land use has dramatically changed, where a large increase of settlements and agricultural area has decreased the forest area during the period 1990–2013. These findings validate the attribution results where changes in stream flow can be largely attributed to land use changes rather than to climate change in the Samin catchment. Numerous studies argue that a continuous decline of tree-areas in catchments may lower the infiltration rate, reduce the groundwater recharge and inhibit water to be stored in the soil (Bosch & Hewlett 1982; Brown *et al.* 2005). As a result, a larger volume of rainfall was transformed into surface runoff.

Despite the fact that the impacts of land use change and climate change on stream flow alteration were evident, the magnitude of change in excess water and energy represented by the Resultant (R) length, was relatively low. Besides land use and climate change, the magnitude of change in stream flow seems to be affected by other factors for instance by the catchment size, the slope variation and the soil type. Several studies reported the impacts of land use change on stream flow generation for different catchment sizes (e.g. D'Almeida *et al.* 2007; Blöschl *et al.* 2007; Gallo *et al.* 2015). These studies generally argue that the magnitude of land use change impacts on hydrology became smaller with increasing catchment area. In addition to the catchment size, the slope variation may also influence the impact magnitude. van Dijk *et al.* (2007) argue that a larger topographic variation results in shallower soils, less infiltration and therefore generating more runoff. Thus, the impact of land use change on stream flow generation in a catchment with a large topographic variation will be amplified and vice versa. Bruijnzeel (2004) addressed the role of

soil conditions on the magnitude of land use change impacts on hydrology in tropical regions. He argues that soil protection measures following deforestation, for instance by applying the Reduce Impact Logging technique during land clearing for agriculture or plantations, might decrease the impact magnitude of forest removal in hydrological processes. Nonetheless, underlying natural geology and soil types in a system are important to control catchment hydrological behaviour after land use has changed. A porous soil of volcanic deposits in the study area might have a lower impact magnitude than an area with similar land use change condition having a low porosity and low hydraulic conductivity. However, the influence of these factors (i.e. catchment size, slope variation and soil type) on the resultant value could not be assessed in the present study due to limited data availability in other catchments. More research is needed to test the applicability of the resultant value under different catchment conditions.

The present study proposes a framework to quantitatively assess the attribution of changes in stream flow to land use and climate changes. Although promising results were obtained, we suggest two challenges for further study.

First, the basic conceptual design proposed by Tomer & Schilling (2009) depends on strong assumptions, which are not realistic in the real world. The framework uses the assumption that climate change only results in changes in P and ET_0 and land use change only results in changes in ET. In this way, the basic concept neglects the natural complex system where changes in ET are caused by an interaction between climate change and land use change (Budyko 1974; Wang 2014; Jiang *et al.* 2015). Furthermore, the basic concept used the assumption of a linear correlation between the fractions of excess water and energy that is represented by a straight line in a two-dimensional plot. This simplification differs from the widely known Budyko curve (Budyko 1974), but is in line with the study of Pike (1964). Renner *et al.* (2012) argue that the concept of Tomer & Schilling (2009) is not valid for wet catchments (i.e. P is much higher than ET_0) or dry catchments (i.e. P is much lower than ET_0) so that is not applicable in many parts of the world. The basic concept that was originally developed for a temperate climate only works for conditions where precipitation meets evaporative demand (i.e. the middle part of the Budyko curve). Using the aridity index

as a correction for the basic concept (Renner *et al.* 2014), the results have improved but do not reduce the uncertainty inherent in the basic assumption. The proposed approach requires a condition in which changes in the water supply have the same impacts as a change in energy supply, but in opposite directions (i.e. $\Delta P = -\Delta ET_0$). Thus, for conditions where P and ET_0 changes in the same direction (i.e. both decrease or increase), the attribution of changes in stream flow to climate change will interfere with land use change impacts. The results of the present study were found to be convincing, because the hydro-climatic state of our study catchment met the conditions imposed. Although a sharp attribution is not possible due to the assumptions used, the movements of P_{ex} and E_{ex} compared to the aridity index line can provide a rough indication. A validation through trend analysis of climate variables (i.e. P and ET_0) and land use change analysis as applied in this study appears to be useful to verify the attribution results. The proposed method needs more practical applications across various climatic regions to make the approach more reliable and robust.

Second, we agree with Tomer & Schilling (2009), Ye *et al.* (2013) and Renner *et al.* (2014) that the basic concepts of excess water and energy are sensitive to the data quality, particularly for rainfall, potential evapotranspiration and stream flow data. Reliable time series of hydrological data are rarely found in developing countries, including Indonesia (Douglas 1999). However, we performed data checks for errors and made data corrections using well established methodologies to arrive at more reliable datasets. Moreover, our analysis was carried out over a long time period and on an annual basis, which may reduce random errors. We note that more convincing results are expected if hydrological datasets are available for a long time period and data gauges are well distributed over the area of interest.

CONCLUSIONS

A quantitative assessment of land use and climate change contribution to stream flow alteration has been carried out using measures described in this paper. The results show that changes in stream flow of the Samin catchment during the period 1990–2013 can be attributed to land

use change for 72% and climate change for 28%. The results were validated by the results of statistical trend analyses (Mann-Kendall trend analysis and Sen's slope estimator), and land use change analysis. The results of the statistical trend analyses show that the climate (i.e. mean annual P and ET_0) has not significantly changed while the mean annual discharge has significantly changed at a confidence level of 5%. At the same time, land use has significantly changed due to deforestation where the forest area has decreased by 32% mostly due to an increase of settlements and agricultural area of 24% and 6%, respectively. Our results are in line with the results from other tropical hydrological studies on the contribution of land use and climate change to stream flow alteration ranging from small-scale experiments (Bosch & Hewlett 1982; Bruijnzeel & Sampurno 1990; Brown *et al.* 2005) to large-scale modelling studies (Thanapakpawin *et al.* 2007; Alansi *et al.* 2009).

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