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Impacts of forestation on the annual and seasonal water balance of a tropical catchment under climate change

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Abstract

Background: This study aims to assess the effects of a forestation program and climate change on the annual and seasonal water balance of the Bogowonto catchment (597 km^2) in Java, Indonesia. The catchment study is rare example in Indonesia where forestation has been applied at the catchment level. However, since the forestation program has been initiated, evaluations of the program only focus on the planting area targets, while the environmental success e.g., impacts on the hydrological processes have never been assessed. This study used a calibrated Soil and Water Assessment Tool (SWAT) model to diagnose the isolated and combined effects of forestation and climate change on five water balance components, namely streamflow (Q), evapotranspiration (ET), surface runoff (Q_s), lateral flow (Q_l) and base flow (Q_b).

Results: The results show that from 2006 to 2019, forest cover has increased from 2.7% to 12.8% of the total area, while in the same period there was an increase in the mean annual and seasonal temperature, rainfall, and streamflow. Results of SWAT simulations show that changes in the mean annual and seasonal water balance under the forestation only scenario were relatively minor, while changes were more pronounced under the climate change only scenario. Based on the combined impacts scenario, it was observed that the effects of a larger forest area on the water balance were smaller than the effects of climate change.

Conclusions: Although we found that forestation program has minor impacts compared to that of climate change on the hydrological processes in the Bogowonto catchment, seasonally, forestation activity has decreased the streamflow and surface runoff during the wet season which may reduce the risk of moderate floods. However, much attention should be paid to the way how forestation may result in severe drought events during the dry season. Finally, we urge the importance of accounting for the positive and negative effects in future forestation programs.

Keywords: Forestation, Land use change, Climate change, SWAT model, Water balance, Bogowonto catchment

Introduction

Water availability in a catchment is influenced by both climate change and land use change (Romanowicz and Booij 2011; Wohl et al. 2012). However, both factors likely operate at different spatial levels (DeFries and Eshleman 2004). Land use change impacts on hydrological processes are likely more pronounced at the local scale (Bosch and Hewlett 1982; Wohl et al. 2012; Gallo et al. 2015; Marhaento et al. 2017b; Marhaento et al. 2021), while effects of climate change on hydrological processes are found to be more significant at large spatial scales (> 100 km^2) (Blöschl et al. 2007; Wohl et al. 2012; Beck et al. 2013). Combinations of land use and climate changes may not only result in accelerating effects on the water balance (Khoi and Suetsugi 2014; Marhaento et al. 2018), but may also offset each other (Zhang et al. 2016). Although it is evident that interactions between land use change and

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climate change may be operative at the catchment level, the extents and directions of the changes in the water balance are not well understood (Blöschl et al. 2007; Romanowicz and Booij 2011; Wohl et al. 2012; Marhaento et al. 2021).

For tropical regions including Indonesia, land use and climate in the future are generally characterized by continuous deforestation, an increase in the mean temperature, and changes in the spatial and temporal rainfall variability (Nobre et al. 2016). As a result, there will be an increased frequency of disastrous events (e.g., droughts and floods) for this region (IPCC 2012). It is generally agreed that deforestation may significantly reduce canopy interception and soil infiltration capacity resulting in an increase of surface runoff (Bruijnzeel 1989, 2004; Ogden et al. 2013; Marhaento et al. 2017b). With the influence of climate change (particularly changes in temperature and rainfall patterns), the combined impacts on hydrological processes are more pronounced than individual impacts of land use change or climate change (Legesse et al. 2003; Hejazi and Moglen 2008; Khoi and Suetsugi 2014). Marhaento et al. (2018) simulated individual and combined impacts of land use change and climate change on hydrological processes in the Samin catchment (278 km^2) in Java, Indonesia and found that both land use change and climate change contribute to changes in the water balance components, but each driver has a specific contribution to the water balance alteration. Land use change likely contributes to changes in annual evapotranspiration, while climate change rather contributes to changes in annual base flow (Khoi and Suetsugi 2014; Marhaento et al. 2017b; Marhaento et al. 2018). Combinations of the two drivers may result in more pronounced changes in annual streamflow and surface runoff.

In order to mitigate future risks associated with land use change (i.e., deforestation) and climate change, increasing global and regional forest cover through forestation program has been widely promoted. There is a widespread agreement in the community that planting large areas of trees may increase a more evenly spread water balance in time (i.e., wet and dry seasons), which supports the mitigation of floods during the rainy season and of drought during the dry season (Bosch and Hewlett 1982; Bruijnzeel 2004; Brown et al. 2005; Suryatmojo et al. 2011; Marhaento et al. 2019). However, although a reforestation program is considered as a long-term process with long-term benefits, existing evaluations of the success of these programs tend to focus on short-term success indicators such as planting area targets (Le et al. 2012). To date, only few evaluations have measured the impacts of forestation projects on the environment, even though restoring ecosystem functions (e.g., nutrient recycling, primary production, decomposition of dead matter) and ecosystem services (e.g., food, water, oxygen) are always stated as the main objective of forestation (Sala et al. 2000). The latest review from Bentley and Coomes (2020) shows that forestation programs may have been linked with reduced river flow and potentially detrimental effects to downstream areas. Their meta-analysis for hundreds of catchments revealed that in general forestation reduces annual river flow (by 23% after 5 years and 38% after 25 years) with greater reductions in catchments with higher mean annual precipitation and larger increases in forest cover. In addition, they argue that the impact of forests on river flow is sensitive to annual precipitation and potential evapotranspiration, but responses are highly variable due to climate change, where the role of climate change is still unexplored requiring further study.

This study aims to assess the impacts of forestation on the annual and seasonal water balance of a tropical catchment under climate change conditions. The Bogowonto catchment (597 km^2) on Java Island, Indonesia is selected as location of study because this catchment is a rare example in Indonesia where forestation has been applied at the landscape level. In this study, a modelling approach was used to achieve the research objective. A calibrated and validated Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) was used to simulate hydrological processes in the Bogowonto catchment. While most studies of hydrological processes under changing conditions (i.e., climate and land use) were mainly focused on assessing the effects of deforestation, less attention has been given to the impacts of forestation programs. Through this study, we want to investigate the long-term impacts of the forestation program in the Bogowonto catchment, which has been executed since early 2000, under climate change conditions. In order to achieve the study objective, two relevant questions are addressed: a) what is the effect of forestation in the Bogowonto catchment on the water balance under climate change conditions? and (b) what is the long-term trajectory of water availability in the Bogowonto catchment following forest establishment? Although this research is conducted in a single catchment (i.e., Bogowonto catchment), it is thought to represent problems characteristic for the hydrology in tropical catchments having forestation programs. A better understanding will give insight in the potential effects of forestation programs on water availability at catchment scale.

Study area and data availability

Catchment description

Bogowonto is one of the major rivers in Central Java Province, Indonesia and plays an important role in

supporting life within its surrounding area. It is located in the southern part of Central Java Province, shared by 4 districts namely: Purworejo, Magelang, Kebumen and Kulon Progo, but a large part is located in the Purworejo District. The river length is around 67 km with a catchment area of about 597 km^2. Geographically, it is located between latitude 7°23′–7°54′ South and longitude 109°56′–109°10′ East, where the highest part of the catchment is located on the Sumbing Mountain with an altitude of 3278 m above mean sea level (a.m.s.l.) and the catchment outlet is located close to the Indian Ocean with an altitude of 26-m a.m.s.l., as shown in Fig. 1.

The Bogowonto catchment area has a diverse topography ranging from plain (0–8%) in the downstream part and very steep slopes (> 45%) in the upstream part occupying more than 25% of the area. There are four soil types where two types are dominant namely vertic luvisols (30.6%) and lithosols (47.1%). Vertic luvisols is a tropical soil mostly used by small farmers because of its ease of cultivation and no great impediments (FAO 2001). With base saturation > 50%, this soil is greatly affected by water erosion and loss in fertility since nutrient deposits are concentrated in the topsoil. Lithosols are typical thin soils often found in steep hilly or mountainous regions where erodible material is rapidly removed by erosion (FAO 2001). Figure 2 shows the slope and soil maps of the Bogowonto catchment.

Data availability

To set up the hydrological model, spatial and non-spatial data were used. For the spatial data, land use maps for the years 2006 and 2019 were available for the study area from the Ministry of Forestry (MoF). It is freely accessible (with a permission) at the scale of 1: 250,000. Furthermore, field visits were carried out to validate the land cover map classification. The Digital Elevation Model (DEM) of the study was generated from DEMNAS (http://tides.big.go.id/DEMNAS/), which was made available through the Geospatial Information Agency of Indonesia at around 8-m spatial resolution. A soil map at 30 arc-second spatial resolution was taken from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC 2012).

For the non-spatial data, daily rainfall (R) from 12 rainfall ground stations located within the vicinity of the Bogowonto catchment was provided by the Serayu Opak River Basin Organization. However, the data only covered the period 2002–2011 and contained missing values for almost 10% of the data. Since the available R data from the ground stations were not sufficient for the analysis, a grid-based daily R dataset from the Climate Hazards Group Infrared Precipitation with Station data

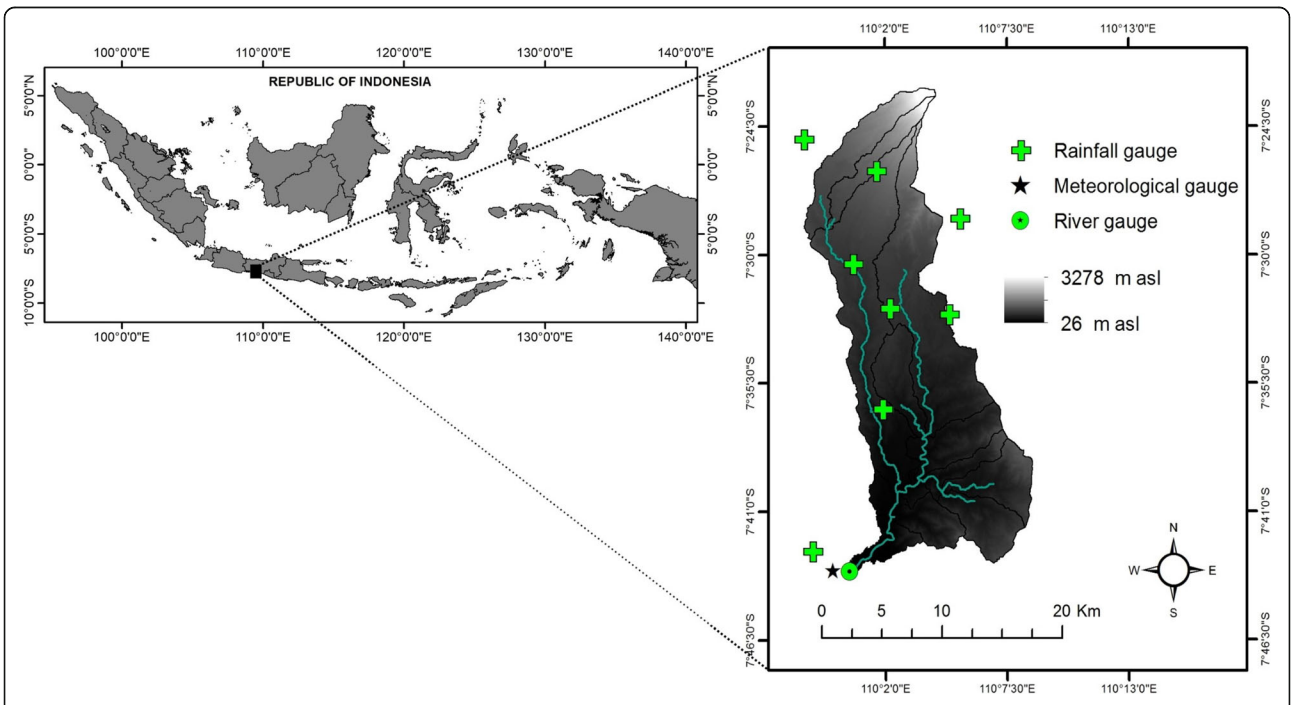

Fig. 1 Map of Bogowonto catchment area with locations of rainfall, meteorological and river gauges

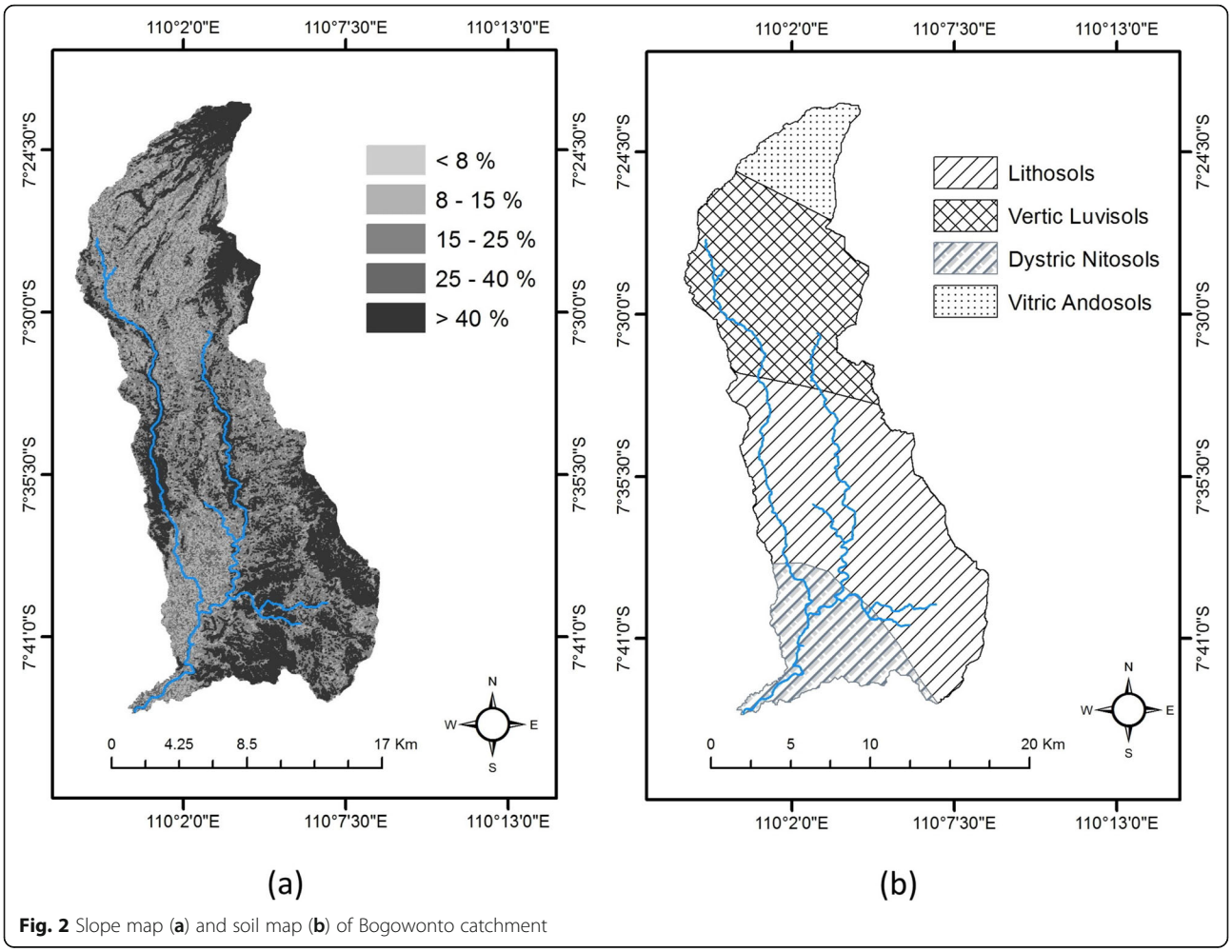

Fig. 2 Slope map (**a**) and soil map (**b**) of Bogowonto catchment

(CHIRPS) for the period 2000–2019 were used. CHIRPS is a 30+ year quasi-global (50° S–50° N) daily *R* dataset with 0.05° spatial resolution and is available from 1981 to present (Funk et al. 2015). It has been applied and validated in many hydrological simulations across various regions and it has been suggested that this satellite product can be applied to data-scarce locations (Tuo et al. 2016; Beck et al. 2017; Paredes-Trejo et al. 2017). We corrected the CHIRPS dataset using the ground *R* stations data with a simple scaling method where we calculated monthly correction factors based on the ratio of monthly satellite-based *R* values to monthly ground-based *R* values (Katiraie-Boroujerdy et al. 2020).

Meteorological data other than *R* data in the study area were made available from a single meteorological station (i.e., Kradenan station). Similarly, to the rainfall dataset, it was only available for the period 2002–2011 with missing values for almost 20% of the data. For this reason, we used satellite-based meteorological data for the analysis. We used minimum and maximum daily temperature (T_{min} and T_{max}) data from the National Aeronautics Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset with a 0.25° spatial resolution on a daily basis (Thrasher et al. 2012). The NEX-GDDP products have been cited to be a promising source of climatic data as input for hydrological models at regional and local scales (Bokhari et al. 2018; Song et al. 2020) including the South East Asia region (Nauman et al. 2019). For this study, we applied the multi-model averaging concept (i.e., ensemble) for T_{min} and T_{max} from the NEX-GDPP dataset for the period 2000–2019. Subsequently, we corrected the temperature (*T*) dataset using the ground meteorological station data using, again, the simple scaling method.

For the model calibration, monthly streamflow (*Q*) data were provided by the Serayu Opak River Basin Organization for the period 2002–2015. The reliability of the *Q* data was ensured through data screening and a visual check of the hydrograph. Figure 3 shows the observed mean annual *R* and *Q* of the Bogowonto River.

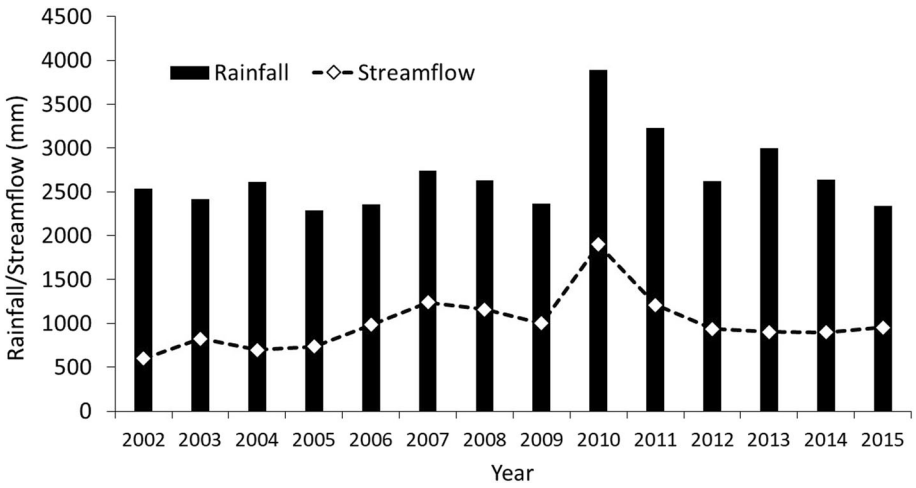

Fig. 3 Mean annual rainfall and streamflow for the period 2002–2015 in the Bogowonto catchment

Methods

Land use change and hydro-climatic trend analysis

Field visits were carried out to collect information about the land use classes such as trees and crops species as well as settlement patterns. The land use information together with the land use map produced by MoF were used to determine the SWAT land use database.

Trend analysis was carried out to check whether the continuous time-series of annual and seasonal hydro-climatic variables of the Bogowonto catchment have significantly changed over time (long-term). We used the Mann-Kendall statistical test to detect trends in the annual and seasonal T_{max}, T_{min}, average temperature (T_{av}) and R for the period 2000–2019 and Q for the period 2002–2015 and employed Sen's slope estimator (Sen 1968) to determine the magnitude of the trend. The Mann-Kendall statistical test and Sen's slope estimation were selected since they have been widely used to detect trends in long-time series of hydrological and climatological data (Rientjes et al. 2011; Zhang et al. 2014; Marhaento et al. 2017a).

SWAT model set up

This study used the Soil Water Assessment Tool (SWAT) model (Arnold et al. 1998) to simulate hydrological processes of the study catchment. It is a semi-distributed model operating on a daily time step with proven suitability for hydrologic impact studies around the world including South East Asia region (Khoi and Suetsugi 2014; Marhaento et al. 2017b; Marhaento et al. 2018; Tarigan et al. 2018).

The water balance in the SWAT model includes inflows, outflows and variations in storages (Arnold et al. 1998). R is the main inflow in the model. The outflows are actual evapotranspiration (ET), surface runoff (Q_s), lateral flow (Q_l) and base flow (Q_b). There are four water storage possibilities in SWAT namely snowpack, soil moisture, shallow aquifer, and deep aquifer. However, we excluded snowpack storage because snowfall is not relevant in the study catchment. Flows between storages are percolation from the soil moisture storage to the shallow aquifer storage, capillary rise from the shallow aquifer to the soil moisture storage, and deep aquifer recharge. Q is the sum of Q_s, Q_l, and Q_b. For a more detailed description of the SWAT model, reference is made to Neitsch et al. (2011).

The model set-up was started by delineating the catchment boundaries and dividing the catchment into sub-catchments based on the DEM data. To do so, we used a stream network map from the Indonesia Geospatial Information Agency to "burn-in" the simulated stream network from SWAT to create accurate flow routing. It resulted in 13 sub-catchments, ranging in size from 3.6 to 90.9 km^2. In addition, the DEM was used to generate a slope map with five classes namely 0–8% (flat), 8%–15% (moderate), 15%–25% (moderate steep), 25%–45% (steep), and > 45% (very steep).

According to the land cover map from MoF, land use in the Bogowonto catchment consist of eight classes, namely: forest, plantation, dryland farming, paddy field, shrub, bareland, settlement and water body. Then, these land use classes were given codes from the SWAT database, namely FRST, AGRC, AGRR, RICE, RNGB, BARR, URMD and WATR, respectively. In the SWAT land use database, there are several options to define settlements. In this study, we chose the class Urban Residential Medium Density (URMD) to assign the settlement area due to the conditions that the settlements in the study area are not fully impervious providing some pervious spaces in between the houses that are often used for house yards. 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.

Soil characteristics of four soil types were taken from the Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). The soil characteristics required as SWAT input that were not available in HWSD such as available water content, saturated hydraulic conductivity and bulk density, were obtained from the Soil-Plant-Atmosphere-Water (SPAW) model (Saxton and Willey 2005). This soil model uses pedotransfer functions including information on soil texture, soil salinity, organic matter, gravel and soil compaction to determine water retention characteristics (Saxton and Willey 2005).

HRUs were created by spatially overlying maps of land use, soil and slope classes. A temperature-based evapotranspiration method namely the Hargreaves method was used to calculate potential evapotranspiration (*ETo*). The actual evapotranspiration (*ET*) then was simulated based on the calculated *ETo*, water availability in the soil and plant characteristics. For runoff simulations, the Soil Conservation Service Curve Number (SCS-CN) method adjusted for slope effects was selected because it has a direct link to land use types and assumes an average slope of more than 5% (Williams 1995). For flow routing, the Muskingum method that models the storage volume as a combination of wedge and prism storage was used (Neitsch et al. 2011). After completing the model set-up, a hydrological simulation was run from 2000 to 2019 including 2 years "warming-up" period.

Model calibration and validation

Model calibration and validation aim to produce a robust SWAT model. In this study, the available monthly *Q* data from 2002 to 2015 were split into two periods: 2002–2010 (i.e., calibration period) and 2011–2015 (i.e., validation period). We followed the procedure from Abbaspour et al. (2015) to calibrate the model. First, a simulation was executed using the default SWAT parameters. Second, the resulting hydrograph was visually compared with the observed hydrograph. Third, based on the characteristics of the differences between observed and simulated hydrographs (e.g., underestimation or overestimation of *Q*, shifted *Q*), relevant SWAT parameters were identified. Fourth, one-at-a-time sensitivity analysis was carried out to identify the most sensitive parameters among the relevant parameters (Abbaspour et al. 2015; Marhaento et al. 2017b, 2018). Finally, the selected sensitive parameters were calibrated. We chose to follow the calibration procedure from Abbaspour et al. (2015) because they provide a general protocol for SWAT model calibration which helped to select the appropriate parameters to be calibrated and thus shorten the parameterization time.

We have used the Latin Hypercube Sampling approach from the Sequential Uncertainty Fitting version 2 (SUFI-2) in the SWAT-Calibration and Uncertainty Procedure (SWAT-CUP) package to calibrate the selected parameters. 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 1000 simulations with narrowed parameter ranges in subsequent calibration rounds. We stopped the calibration when the objective function value did not significantly change anymore in subsequent iterations. In this study, evaluations of model calibration were carried out on a monthly basis and the Kling-Gupta Efficiency (KGE; Gupta et al. 2009) (Eq. 1) was used as the objective function. We chose KGE as objective function since it combines the three components of the Nash-Sutcliffe efficiency (NSE) (i.e., correlation, bias, ratio of variances) in a balanced way (Liu 2020). Moreover, it has been widely used for calibration and evaluation of hydrological models in recent years (Pool et al. 2018; Knoben et al. 2019). The model performs well when the KGE value is close to 1.

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{\mathrm{sim}}}{\sigma_{\mathrm{obs}}} - 1\right)^2 + \left(\frac{\mu_{\mathrm{sim}}}{\mu_{\mathrm{obs}}} - 1\right)^2} \quad (1)$$

where r is the linear correlation coefficient between the observed and the simulated data set, σ_{obs} is the standard deviation of the observations, σ_{sim} the standard deviation of the simulations, μ_{sim} the simulated mean, and μ_{obs} the observed mean.

Assessing the impacts of forestation under varying climatic conditions

To assess the effect of forestation and climate change on the hydrological processes, we used the one-factor-at-a-time method (Li et al. 2009; Lyu et al. 2019). In this method, meteorological data of 2002–2019 excluding 2 years warming-up period were equally split representing the baseline period (i.e., 2002–2010) and a change period (i.e., 2011–2019). The land use maps of 2006 and 2019 were used to represent the land use conditions in the two time periods, respectively. Furthermore, four simulations were carried out using the calibrated SWAT model: a combination of the land-use map for 2006 with the climate data for 2002–2010 (S1), the land use map for 2019 with the climate data for 2002–2010 (S2), the land use map for 2006 with the climate data for 2011–2019 (S3), and the land-use map for 2019 with the climate data for 2011–2019 (S4). Scenario S1 was regarded as the baseline condition. Scenarios S2 and S3 minus scenario S1 can be used to determine the impacts of individual land use change (i.e., forestation) and climate change, respectively. Scenario S4 minus scenario S1 can

be used to determine the combined impacts of land use change (forestation) and climate change on hydrological processes. Finally, we diagnosed changes in five annual and seasonal water balance components, namely Q, ET, Q_s, Q_l and Q_b for each scenario. The annual water balance was calculated based on the annual mean, while the seasonal water balance was calculated based on the accumulation of each water balance component in December–January-February (DJF), March–April–May (MAM), June–July-August (JJA), and September–October-November (SON). The DJF period represents the wettest period (wet season) of the year, while the JJA period represents the driest period (dry season) of the year. MAM and SON periods represent transition periods from wet to dry season and from dry to wet season, respectively. These annual and seasonal water balance components have been used as indicators of land use change and climate change impacts on hydrological processes in a tropical catchment (Marhaento et al. 2017b; Marhaento et al. 2019).

Results

Forestation in the Bogowonto catchment

According to the land use map from the MoF, land use in the Bogowonto catchment in 2019 was mostly dominated by forest (12.76%) and agriculture area (i.e., dryland farming, 77.2%). Forest area mostly covered the upper and middle part of the catchment (see Fig. 4). Based on the ownership, there are two types of forests in the Bogowonto catchment. The first one is state forest which is associated with soil-water protected areas and mostly located at elevations higher than 2000 m, a slope ≥ 45° and mostly occupied with homogenous evergreen trees like *Pinus merkusii*, and *Schima wallichii*. This forest type is dominant in the upper part of the catchment on the slopes of the Sumbing Mountain. The second one is private forest that is owned by the public, or commonly called community forest. This forest type adopts an agroforestry system, which is a planting system dominated by multipurpose trees (e.g., fruits and woods), often combined with seasonal crops on the same unit of land. *Swietenia mahagoni*, *Paraserianthes falcataria*, and *Tectona grandis* are the most tree species planted for wood production, while for fruit production, the most frequently occurring tree species planted are *Durio* sp., *Mangifera indica*, and *Cocos nucifera.* This community forest can mainly be found in the middle part of the catchment. The agriculture area in the Bogowonto catchment is mainly dominated by dry land farming. This land use type is spread over the catchment

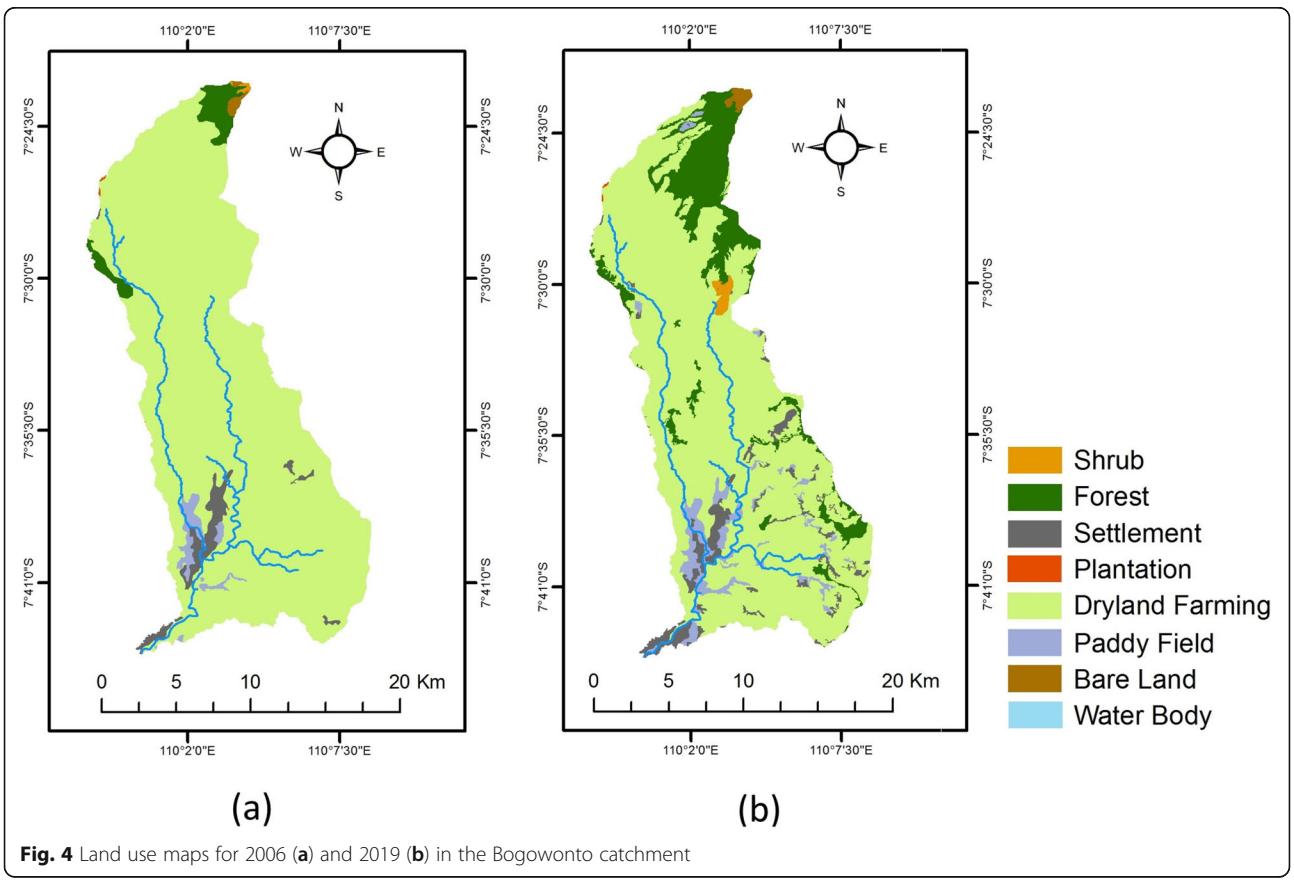

Fig. 4 Land use maps for 2006 (**a**) and 2019 (**b**) in the Bogowonto catchment

area, including the upland area, and used for the production of seasonal crops (*palawija*) like maize, peanuts, soya beans, and chili. In the downstream area, the land use is mainly settlements and paddy field area. Bare land and shrubs are abandoned areas where the land is not available for agricultural purposes (i.e., critical land) and was mostly located in the up and middle part of the catchment in hilly regions.

In 2006, according to the land use map from the MoF, land use in the Bogowonto catchment was also dominated by forest and agriculture area (i.e., dry land farming), but with different relative areas compared to 2019. Forest only included about 2.7% of the catchment area, while dry land farming occupied 92.3% of the total area. Forests in 2006 only occupied a small part of the upstream catchment inside a state forest. However, in 2019, forest has been largely spread in the upper and middle part of the catchment. Apparently, during the last 13 years, the forestation through the forest and land rehabilitation program initiated by the MoF and the development of community forests in the Bogowonto catchment has been successfully implemented and thus significantly increased the forest cover by around 10.1% of the total area. Table 1 shows the changes in land use from 2006 to 2019 in the Bogowonto catchment, while Fig. 4 shows the distribution of land use classes for 2006 and 2019 in the Bogowonto catchment.

Hydro-climatic trends and magnitudes

Table 2 shows the results of the Mann-Kendall test and Sen's slope estimator of trends in T_{max}, T_{min}, T_{av}, R and Q for both seasonal and annual time scale were statistically not significant, except for T_{max} during DJF and SON periods. In these periods, it was observed that there was a significant increase (p-value > 0.5) in the maximum temperature.

Model calibration and validation

Ten SWAT parameters related to groundwater flow (i.e., SHALLST, GWHT, and GW_DELAY), flow routing (i.e., CH_K2), surface runoff (i.e., CN2 and SLSUBBSN), evapotranspiration (i.e., ESCO), and soil infiltration (i.e., SOL_AWC, SOL_BD, and SOL_K) were calibrated. We refer to Neitsch et al. (2011) for a more detailed description of these SWAT parameters. Table 3 shows the calibrated values of the selected SWAT parameters. Figure 5 shows the observed and simulated hydrograph for the calibration and validation periods.

The results of the model calibration show that the simulated mean monthly Q in the calibration period (2002–2010) agrees well with the observed records with a KGE value of 0.79. However, in the validation period (2011–2015), the KGE model performance decreases to 0.74.

Changes in water balance

Annual water balance

Table 4 shows the results of the simulated annual water balance components for all four hypothetical scenarios. Compared with the baseline scenario (S1), a significant change of the annual Q occurred under the climate change scenario (S3) with an increase of 104.8 mm (5.2%). Forestation activities (S2) apparently did not significantly change the annual Q as it caused only a 23.6 mm (1.1%) decrease, while the combined effect of forestation and climate change (S4) has increased the annual Q by 79.5 mm (3.9%). These results indicated that both forestation and climate change have increased Q, with a larger contribution from climate change than that of forestation activity. For the annual ET, all scenarios resulted in an increase of ET compared to that in the baseline scenario. The largest increase occurred under the combined forestation and climate change scenario (S4) followed by S3 and S2 scenarios, respectively. After forestation, the evaporative demand was larger than in the baseline period (i.e., 4% increase). However, the ET rate was doubled under the climate change scenario (S2) with a 10.5% increase, and much larger under the combined scenario (S4) with a 15% increase. These results showed that there was actually a large evaporative demand in the catchment.

Table 1 Land use distribution in 2006 and 2019 in the Bogowonto catchment

No.	Land use class	Area				Changes (ha)	Changes (%)
		2006 (ha)	2006 (%)	2019 (ha)	2019 (%)		
1	Forest	942.6	2.66	4519.0	12.76	3576.4	10.1
2	Shrub	39.3	0.11	220.4	0.62	181.1	0.5
3	Plantation	9.7	0.03	9.2	0.03	−0.5	0
4	Settlement	922.5	2.60	1528.9	4.32	606.5	1.7
5	Bareland	121.5	0.34	170.4	0.48	48.9	0.1
6	Dryland farming	32,702.6	92.32	27,348.4	77.20	− 5354.3	− 15.1
7	Paddy field	652.8	1.84	1595.1	4.50	942.3	2.7
8	Water body	33.3	0.09	32.4	0.09	−0.9	0

Table 2 Results of statistical trend analysis for annual and seasonal maximum temperature (T_{max}), minimum temperature (T_{min}), average temperature (T_{av}), rainfall (R), and streamflow (Q) of the Bogowonto catchment for the period 2000–2019

Period	T_{max}		T_{min}		T_{av}		R		Q	
	p-value	S_s	*p*-value	S_s	*p*-value	S_s	*p*-value	S_s	*p*-value	S_s
DJF	0.011**	0.014	0.385	0.005	0.291	0.009	0.115	10.819	0.5	−0.098
MAM	0.461	0.001	0.436	−0.006	0.361	0.006	0.410	−2.522	0.371	0.911
JJA	0.269	0.013	0.461	−0.004	0.247	0.011	0.436	1.215	0.078	0.338
SON	0.056*	0.015	0.268	−0.02	0.436	−0.005	0.436	−4.78	0.371	0.385
Annual	0.157	0.011	0.385	0.007	0.410	0.004	0.337	3.093	0.255	2.018

DJF is from December to February, MAM is from March to May, JJA is from June to August, SON is from September to November, S_s is Sen's slope value. ** trend is significant at $\alpha = 5\%$, * trend is significant at $\alpha = 10\%$. (–) sign indicates a decreasing trend

Besides affecting the outflows, forestation and climate change also changed the fractions of Q. Most significant changes occurred in the Q_l and Q_b under the combined effects of forestation and climate change scenario (S4), where the components increased by 18.9 mm (12.7%) and 91.8 mm (10.1%), respectively. For Q_s, the forestation activity scenario (S2) significantly decreased Q_s compared to that of climate change (S3 scenario). Under the combined effects of forestation and climate change scenario (S4), Q_s decreased by 38.4 mm (4.2%). These results show that climate change in terms of an increase of R has largely affected the fraction of Q becoming Q_l and Q_b, while forestation activity mostly controlled the amount of Q_s occurring in the study catchment. Figure 6 shows the changes in the mean annual water balance components under different scenarios compared to the baseline scenario.

Seasonal water balance

Table 5 shows the simulated seasonal water balance components for all four hypothetical scenarios. It was observed that under the forestation scenario (S2), changes in seasonal Q were relatively minor, although it showed a consistent decrease throughout the months. Changes in Q were significant under the climate change scenario (S3), in particular during the wet months (i.e., DJF) with an increase of 129.3 mm (13.9%), while it decreased by 39.6 mm (17.1%) in SON months. Under the combined forestation and climate change scenario (S4), Q in DJF months increased by 117 mm (12.6%) and decreased by 50.3 mm (21.8%) SON months. These results showed that seasonal Q in the Bogowonto catchment has been mainly affected by climate change, where forestation activity contributed to amplify water loss during the dry season, but reduced Q during the wet season. For ET, an increase of ET in all seasons under all scenarios was observed. However, a significant increase of ET occurred under the combined forestation and climate change scenario (S4), with the largest changes occurring in the dry season (i.e., JJA months) with an increase of 45.6% (+ 20.9 mm) followed by SON (15.3%, + 15.2 mm), MAM (13.2%, + 33.1 mm), and DJF (10.1%, + 20.5 mm). These results showed that the forestation activity significantly increased the ET rate of the Bogowonto catchment in particular during the dry season and thus potentially caused more severe drought periods in the study catchment.

The Q components Q_b and Q_l significantly increased under the combined effects of forestation and climate change scenario (S4) especially during the wet seasons

Table 3 Values of calibrated Soil Water Assessment Tool parameters

No.	SWAT parameters	Method	Range parameter		Initial value	Calibrated value
			Min	Max		
1	SHALLST.gw	Replace	0	1000	1000	949
2	GW_DELAY.gw	Replace	0	200	31	16.6
3	GWHT.gw	Replace	0	25	1	6.87
4	CH_K2.rte	Replace	0.01	150	0	10.06
5	CN2.mgt	Relative	−1	1	74 to 92	−0.07
6	ESCO.hru	Relative	−1	1	0.95	0.82
7	SLSUBBSN.hru	Relative	−1	1	9.14 to 60.97	0.38
8	SOL_AWC.sol	Relative	−1	1	0.098 to 0.178	−0.84
9	SOL_BD.sol	Relative	−1	1	1.1 to 1.4	−0.87
10	SOL_K.sol	Relative	−1	1	4.94 to 56.05	0.95

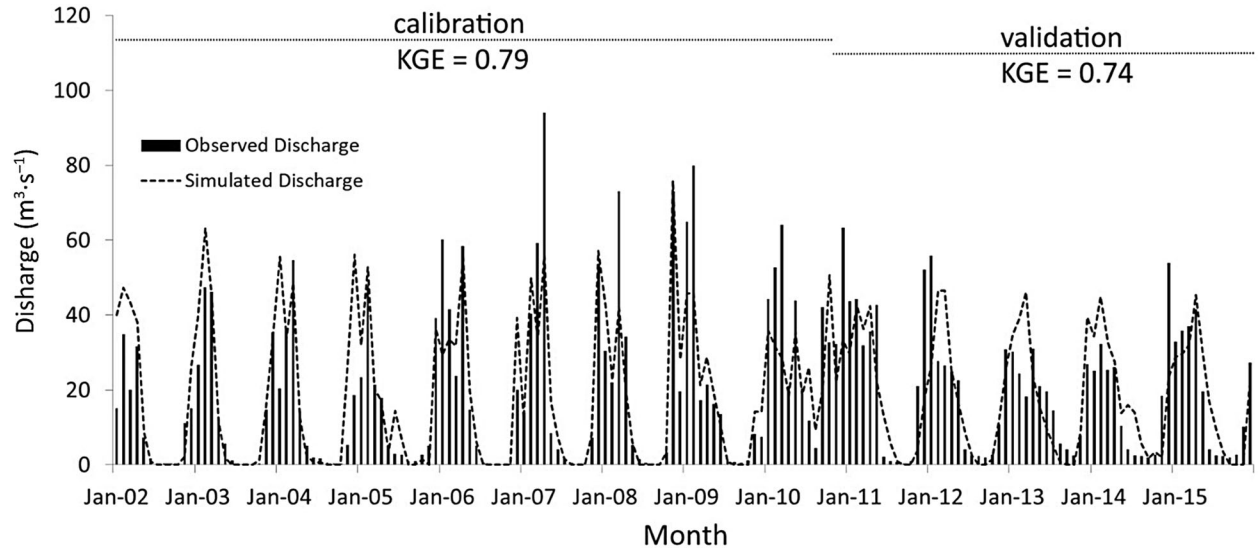

Fig. 5 Observed and simulated hydrograph for the calibration period (2002–2010) and validation period (2011–2015)

(DJF and MAM). In the DJF months, Q_b and Q_l increased by 74.1 mm (19.8%) and 13.3 mm (18.7%), while during the MAM months, Q_b and Q_l increased by 32.8 mm (8.2%) and 4.8 mm (9.7%), respectively, compared to the baseline scenario. However, a more pronounced impact of the combined forestation and climate change scenario occurred during the dry months (SON), where Q_b decreased by 20.4 mm (34.7%) compared to the baseline scenario. Q_s decreased in all periods under the forestation scenario (S2) with a pronounced decrease only in DJF by 16.9 mm (3.5%). However, under the climate change scenario (S3), there was an increase in Q_s of 45.2 mm (9.5%) during the wet season (DJF). For the combined effect of forestation and climate change scenario (S4), Q_s increased by 27 mm (5.7%) in the DJF months, while in the other periods, Q_s significantly decreased by 27.4 mm (11.2%) in the MAM months, by 8.7 mm (19.4%) in the JJA months, and by 29.3 mm (20.1%) in the SON months, compared to the baseline scenario. These results showed that during the wet months, forestation activity significantly reduced Q_s and increased Q_b and Q_l. However, in the dry months, both forestation and a drier climate resulted in a significant water loss in the catchment. Figure 7 shows the changes in the mean seasonal water balance components under different scenarios compared to the baseline condition.

Discussion

Based on hydrological model simulations, this study shows that changes in the annual and seasonal water balance components of the study catchment can be attributed to both land use change (i.e., forestation) and climate change (i.e., an increase of R and T). Under the forestation only scenario, it was observed that the presence of forests has increased mean annual and seasonal ET and at the same time reduced the mean annual Q. In addition, it decreased the mean annual and seasonal Q_s, while the mean Q_l and the Q_b increased. It is widely known that forestation is associated with a decrease in annual Q, primarily as a result of increasing transpiration and interception rates since trees are generally known to have higher ET rates than other land uses

Table 4 Simulated average annual water balance components under different climate and land use conditions

S	R	Water balance components									
		Q	Δ	ET	Δ	Q_s	Δ	Q_l	Δ	Q_b	Δ
S1	2651.1	2014.1	–	597.5	–	910.6	–	149.3	–	905.9	–
S2	2651.1	1990.5	−23.6	621.4	23.9	875.8	−34.8	155.8	6.5	910.4	4.5
S3	2812.6	2118.9	104.8	660.4	62.9	908.4	−2.3	161.5	12.2	993.7	87.8
S4	2812.6	2093.6	79.5	687.2	89.7	872.2	−38.4	168.2	18.9	997.7	91.8

S is simulation scenarios, R is the mean annual rainfall (mm), Q is mean annual streamflow (mm), ET is mean annual evapotranspiration (mm), Q_s is mean annual surface runoff (mm), Q_l is mean annual lateral flow (mm), and Q_b is mean annual base flow. Δ is a relative change compared to the baseline scenario (S1)

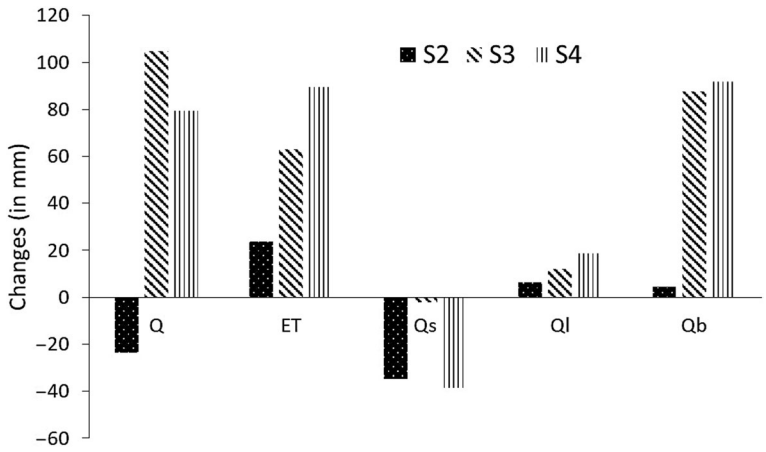

Fig. 6 Change in the mean annual water balance components namely streamflow (Q), evapotranspiration (ET), surface runoff (Q_s), lateral flow (Q_l) and base flow (Q_b) under different scenarios compared to the baseline scenario

(Bosch and Hewlett 1982; Bruijnzeel 1989, 2004; Brown et al. 2005; Marhaento et al. 2018; Bentley and Coomes 2020). In addition, a larger vegetated area as a result of successful forestation activity generally leads to an increase in the water storage capacity of the soil due to greater root penetration resulting in a larger infiltration rate and ground water recharge (Bruijnzeel 1989, 2004; Guevara-Escobar et al. 2007). Thus, the fraction of the Q originating from Q_s has significantly decreased. The directions of changes in the water balance by forestation activity in this study are in line with other hydrological studies in tropical regions from Bruijnzeel (2004), Valentin et al. (2008), Remondi et al. (2016) and Marhaento et al. (2017a).

However, it should be noted that in this study the changes of the mean annual and seasonal water balance components under the forestation only scenario was relatively minor. It was observed that the changes of water balance components were more pronounced under the climate change only scenario, indicating changes in the mean annual and seasonal R and T may have large impacts on the water availability of the

Table 5 Simulated average seasonal water balance components under different climate and land use

S	Months	R	Water balance components									
			Q	Δ	ET	Δ	Q_s	Δ	Q_l	Δ	Q_b	Δ
S1	DJF	1291.0	931.4	–	202.4	–	475.8	–	71.1	–	372.7	–
	MAM	779.0	708.8	–	250.1	–	244.4	–	49.2	–	396.9	–
	JJA	131.4	143.4	–	45.8	–	44.8	–	9.1	–	77.6	–
	SON	449.7	230.5	–	99.2	–	145.7	–	19.9	–	58.7	–
S2	DJF	1291.0	919.5	−11.9	203.7	1.3	458.9	−16.9	74.7	3.6	374.2	1.5
	MAM	779.0	708.1	−0.7	256.6	6.5	235.1	−9.3	51.5	2.3	402.9	6.1
	JJA	131.4	141.4	−2.0	55.7	9.9	42.4	−2.4	9.5	0.4	77.5	−0.1
	SON	449.7	221.5	−9.0	105.4	6.2	139.4	−6.2	20.2	0.2	55.8	−2.9
S3	DJF	1413.5	1060.6	129.2	221.7	19.3	521.0	45.2	80.3	9.2	444.9	72.2
	MAM	813.6	722.5	13.7	276.2	26.1	226.2	−18.1	51.7	2.5	423.5	26.7
	JJA	140.4	144.9	1.5	54.5	8.7	38.1	−6.7	10.3	1.2	83.2	5.5
	SON	445.1	190.9	−39.6	108.0	8.8	123.1	−22.6	19.3	−0.7	42.1	−16.6
S4	DJF	1413.5	1048.4	117.0	222.9	20.5	502.8	27.0	84.4	13.3	446.8	74.1
	MAM	813.6	722.0	13.2	283.1	33.1	217.0	−27.4	54.0	4.8	429.7	32.8
	JJA	140.4	143.0	−0.4	66.7	20.9	36.1	−8.7	10.6	1.5	82.9	5.3
	SON	445.1	180.2	−50.3	114.4	15.2	116.3	−29.3	19.2	−0.7	38.3	−20.4

S is simulation scenarios, R is the mean monthly rainfall (mm), Q is mean monthly streamflow (mm), ET is mean monthly evapotranspiration (mm), Q_s is mean monthly surface runoff (mm), Q_l is mean monthly lateral flow (mm), and Q_b is mean monthly base flow. Δ is a relative change compared to the baseline scenario (S1). DJF is from December to February, MAM is from March to May, JJA is from June to August, SON is from September to November

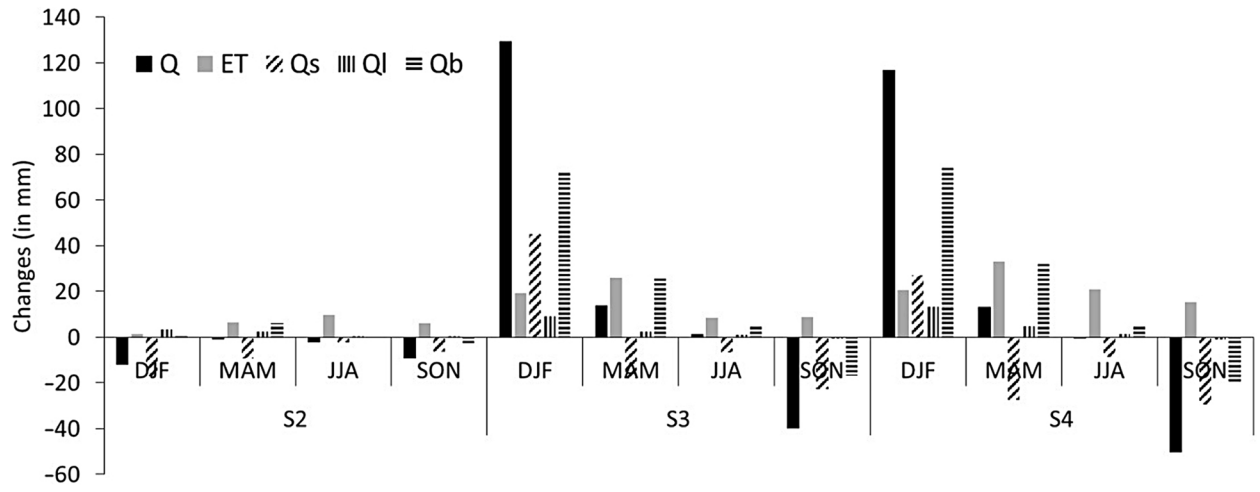

Fig. 7 Change in the mean seasonal water balance components, streamflow (*Q*), evapotranspiration (*ET*), surface runoff (Q_s), lateral flow (Q_l) and base flow (Q_b), under different scenarios compared to the baseline scenario

Bogowonto catchment. We found that an increase in the mean annual *R* may result in a large increase in the *Q* and *ET*. In addition, the *Q* components Q_b and Q_l significantly increased, while changes in the Q_s were relatively minor. Apparently, small increases in mean annual *R* (statistically not significant) are likely to have large impacts on the water balance of the study catchment. Our results are in line with the findings of Legesse et al. (2003), Khoi and Suetsugi (2014), and Shi et al. (2013), who argue that climate change (i.e., in *T* and *R*) has a larger influence on water availability than land use changes. However, it should be noted that climate change impacts on water availability vary depending on the spatial scale, due to direct and indirect influences through feedback mechanisms (Pielke 2005; Milly et al. 2005; Blöschl et al. 2007). In addition, it was observed that changes in annual and seasonal *ET* can likely be attributed to changes in annual and seasonal *R*, where the variations in *ET* follow the variations in *R*. Thus, an increase in *ET* is found during the wet seasons (DJF and MAM), while a decrease in *ET* is found during the dry seasons (JJA and SON). We agree with Budyko (1974), who argues that changes in *ET* are determined by the balance between *R* and evaporative demands.

Under the combined forestation and climate change scenario, we found a relationship between changes in water balance components in response to forest establishment and climate change. However, it is observed that the magnitude of changes in the annual and seasonal water balance is mainly determined by climate change, whereby the directions of change in annual and seasonal water balance under the combined scenario are similar to those under the climate change only scenario. Apparently, with a 10.1% increase of forest area in the study catchment, it results in small changes in the annual *Q* and its flow components. The presence of a larger forest area which can result in more subsurface flow (i.e., Q_l and Q_b) due to an enhanced groundwater recharge are offset by climate change. Despite minor effects on the overall water balance, it was found that forestation activity has decreased the *Q* caused by much less Q_s during the wet season. Thus, it may reduce the risk of moderate floods (Bruijnzeel 1989, 2004; Ibanez et al. 2002; Ogden et al. 2013; Remondi et al. 2016). However, on the other hand, the larger forested area due to forestation has negative impacts in the dry season. It was found that in the SON period, the *ET* rate slightly reduced while *Q* significantly decreased, mainly caused by a decrease in the Q_s and Q_b. In the dry season, the *ET* capacity is mainly determined by the antecedent soil moisture and influenced by different land cover types (Liu et al. 2011). With a significant decrease of *R* during the dry months and at the same time a rise in *T*, soil moisture has been soaked up to fulfil evaporative demand (Calder 1998; Calder et al. 2001; Bentley and Coomes 2020).

Our simulation results show the potential importance of accounting for positive and negative effects in future forestation programs. Although forest establishment widely showed increased rates of ground water recharge as a result of increased infiltration (Ilstedt et al. 2016; Remondi et al. 2016; Marhaento et al. 2017a, b) and potentially result in a more balanced distribution of *Q* between the dry and wet season (Marhaento et al. 2019), the actual behaviour depends on many interacting factors. Marhaento et al. (2019) found that besides the percentage of forest area that obviously affect the water balance, the spatial land use configuration (e.g., shape and connectivity of land use types) may have an influence on hydrological processes. Clustered forests tend to

have a more positive and pronounced impact on the water balance than scattered forest (Lin et al. 2007; Zhang et al. 2013; Li and Zhou 2015). For our study catchment, the forestation is spread in the upper and middle catchment area as it mainly occurs as private land (i.e., community forest) resulting in scattered forest area over the catchment. As a result, impacts of forestation on the water balance might be dampened. Bentley and Coomes (2020) argue that the historical land use prior to forestation plays an important role as well. Forestation in catchments that were previously fallow showing a more pronounced *Q* reduction than those that were reported as having been used for agriculture. In addition, effects of forestation to increase infiltration and ground water recharge rates are pronounced for forest establishment on degraded land (Bruijnzeel 2004; Ilstedt et al. 2007; Beck et al. 2013). For our study area, forestation has been established on agriculture area (i.e., dryland farming), which probably resulted in minor impacts on the water balance. It should be noted that dryland farming occupied a large area (77.2% in 2019), so that a small change (< 10%) of this land use type into forest area did not significantly change the overall catchment water balance. Moreover, agricultural management applied in dry land farming usually aims to preserve soil moisture which may offset the positive impacts of forest on soils (Bruijnzeel 2004). Another factor that potentially decelerate or accelerate the impacts of forestation on the water balance is tree characteristics. Sprenger et al. (2013) found that planting mixtures of pioneers and shade tolerant tree species may lead to moderate seepage rates compared to monocultures of either fast or slow growing tree species due to tree heights and canopy openness that are leveled out. In addition, Ellison et al. (2017) revealed that tree species and their root architecture are highly important for hydraulic redistribution of water in soils. Coniferous trees like *Pinus merkusii* that are dominant in the upper part of the study catchment may significantly increase *ET* rates. Thus, small deciduous trees species are in favor for future forestation to improve catchment yield since they can reduce interception losses (Hirsch et al. 2011). In addition, tree age is also an important factor controlling the water balance as young forests typically consume more water than old-growth forests (Delzon and Loustau 2005).

Although promising results were obtained, several parts in this modeling study can be a source of uncertainty which may affect the results. The data and models used can be a source of uncertainty. For the data, it is a challenge to obtain long-term and reliable hydrometeorological data for the study catchment. This is typically for South-East Asian countries including Indonesia where meteorological gauge networks generally include a limited number of stations which, commonly, are not well distributed over catchments (Douglas 1999), which was the case for our study as well. A corrected satellite-based data source used in this study has successfully overcome this limitation, but does not omit the biases (Ebert et al. 2007; Vila et al. 2009). As input for the SWAT model, this study used a soil map from FAO/IIASA/ISRIC/ISSCAS/JRC (2012) with a coarse spatial resolution. This global soil map was used because of limited information on soil characteristics in the local soil map available for the study catchment. Because of this soil generalization, several details important for hydrological processes for different soil conditions might be obscured. In addition, sources of uncertainty can be present due to model choice and structure (e.g., model assumptions, equations, parameterization). For instance, the SWAT model has been developed for temperate regions and the default SWAT database is possibly not applicable to the tropics (Marhaento et al. 2017b), which may affect the results. The selection of the equation to calculate *ETo*, where we used a temperature-based calculation (i.e., Hargreaves) due to limited climate data availability, may also contribute to uncertainty in the results. Finally, the equifinality problem during parameterization was the most challenging part in the model simulations. Although we got satisfactory simulated *Q*, we found a decrease in model performance between the calibration period and validation period. This decrease could be an indication of a significant contribution of climate change and/or land use change in *Q* alteration (Refsgaard et al. 1989; Lørup et al. 1998, and Marhaento et al. 2017b), but could also be an indication of errors in parameters. It should also be noted that satisfactory simulated *Q* do not guarantee a good model performance for other variables such as *ET* that is important in this type of study. Therefore, in future research we suggest to include *ET* in the calibration process as well (Rientjes et al. 2013).

Conclusion

This study assessed the impacts of forestation activity and climate change on the annual and seasonal water balance of the Bogowonto catchment. Land use of the study catchment changed during the period 2006–2019, where the forest cover increased by 10.1% of the total area indicating a successful forestation program. In the same period, it was observed that there was an increase in the mean annual *T*, *R* and *Q*. Seasonally, the *R* pattern also changed with an increase in the wet season (DJF) and dry season (JJA), while in the transition periods from the wet to dry season and vice versa (i.e., MAM and SON) there was a decrease in *R*. Results based on the SWAT modelling approach showed that changes of the mean annual and seasonal water balance components under the forestation only scenario were relatively

minor. Changes were more pronounced under the climate change only scenario, indicating changes in the mean annual and seasonal R and T may have large impacts on the water availability of the Bogowonto catchment. Based on the combined scenario, it was observed that the effects of the presence of a larger forest area on the water balance were relatively minor compared to climate change. Despite minor impacts, forestation activity has decreased the Q and Q_s during the wet season (DJF) which may reduce the risk of floods. However, it also has serious drawbacks, with significantly reduced Q and Q_b resulting in more severe drought events during the dry season.

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Authors' contributions
HM designed research, collected and analyzed data, and wrote the initial manuscript; MJB and NA analyzed hydrological data; NR analyzed land use change; all authors discussed the results and revised the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed in this study are available from the corresponding author on request.

Declarations

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Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that there is no conflict of interest.

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