Geoenvironmental Disasters

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Runoff observation in a tropical Brantas watershed as observed from long-term globally available TerraClimate data 2001–2020

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Abstract

Runoff information and its dynamics are critical for supporting watershed management; however, spatio-temporal data about runoff is rare or unavailable in data-scarce regions. Information about the performance of remote sensing-based runoff and its potential application is limitedly known. In data-scarce regions, this condition impedes comprehensive watershed assessment especially in the midst of climate change impacts. This study examined the performance of globally available monthly runoff dataset provided by TerraClimate at ~ 4 km spatial resolution and employed them to assess the runoff dynamics in a humid tropic watershed. Monthly TerraClimate data shows a moderate performance with an r of 0.63, RMSE of 57–127 mm/month and NRMSE of 18–30% to the simulated runoff from a well-calibrated model. The upper region of Brantas watershed was found to be the hotspot of high runoff. About 25% of the study area belongs to high runoff (0–33rd percentile). Over the last two decades, runoff has been slightly increased across the study area. Green vegetation fraction (GVF), precipitation, and topography are critical for regulating runoff dynamics. While topography and precipitation impact on runoff are straightforward, the GVF's role is complex and site-specific. High runoff was found mostly to be associated with high precipitation and steep slope. GVF appears to be less effective in representing ground cover against runoff generation due to high variability of actual ground cover types. Using time-series and change vector analysis (CVA) of runoff and GVF, the dynamics of watershed condition was examined. Long-term CVA analysis also found that the condition in Brantas watershed was fluctuated with slight increase in impaired condition. The study exemplified the potential use of the remote sensing-based runoff data in a tropical data-scarce region. Despite limitation of the runoff data due to its moderate performance, the globally available monthly runoff data from TerraClimate can be used to support regional water resource assessment in data-scare regions. Future improvement that includes downscaling and use of machine learning can be considered to improve the remotely sensed runoff data to deliver the bigger benefits of such data.

Keywords: Brantas watershed, Change vector analysis, Green vegetation fraction, Monthly TerraClimate runoff, Runoff characteristics

Introduction

Combined with the richness of biodiversity and soil productivity, tropical watersheds are beneficial resources for the livelihood and potential regulating systems for carbon storage, flood controls, and water supply (Hamel et al. 2018). In addition, humid tropic regions are areas mostly known with their high amount of rainfall and radiation energy intensity, which eventually result in impactful runoff generation and soil erosion (Labrière et al. 2015). The hampering condition due to increased deforestation and population pressures has caused the runoff in tropical watersheds becoming increasing concerns. Runoff generation and distribution are closely associated with

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varying ecological issues such as pollution, sedimentation, and eutrophication (Ramos-Scharrón and Thomaz 2017; Yang and Lusk 2018; Han et al. 2019). In tropics, runoff is a major factor causing land degradation (Bayabil et al. 2016; Sultan et al. 2018). In agriculturally dominated watersheds, runoff intensification has frequently led to the causes of soil erosion and eventually decreasing agricultural productivity (Wolka et al. 2018; Keesstra et al. 2019; Sartori et al. 2019). Intensified runoff triggers the loss of soils, water, and nutrients, which eventually reduces the capacity of land to support agricultural production (Zuazo and Pleguezuelo 2009; Wolka et al. 2018). In this regard, runoff is linked to the soil loss and nutrient loss, which is critical for food security and rural livelihood, especially in mountain regions (Prasad et al. 2016; Mishra et al. 2022). Runoff is also important for the carbon cycle as due to the transport of soil carbon (Wei et al. 2021a, 2021b). Traditionally, runoff is quantified through several measurements, ranging from the use of Curve Number (CN), experimental set-up, and isotopic tracers (Guo et al. 2019). In recent years, the challenges in setting field measurements and the advancement of geospatial technologies have triggered the spread of hydrological models to examine runoff characteristics and behavior (Beck et al. 2017).

Controls on runoff and behavior are often site-specific due to a degree of the uniqueness of watershed characteristics (Beven 2000). In larger areas, an understanding of such controls cannot even be understood merely by considering the contributing areas using the conventional rainfall-runoff perspective (Kuraś et al. 2008). Numerous literatures provide insight on runoff and other hydro-climatic hazards' contributing factors in the rainfall-runoff process namely climate, topography, soil, land-use, vegetation, and geological settings (Puigdefábregas 2005; Onda et al. 2006; DiBiase and Whipple 2011; Hümann et al. 2011; Jencso and McGlynn 2011; Nakileza and Nedala 2020). While roles of topography, soil, climate, and vegetation on runoff generation are more direct, the underlying geology modulates runoff process and overland flow through intermediary properties such as baseflow buffering, catchment storage, overland flow rates and infiltration capacity (Onda et al. 2006; Price 2011; Failache and Zuquette 2018). Among the factors playing a role in runoff generation, ground cover management is of importance due to its dynamics and high variability (Bartley et al. 2006; Taguas et al. 2013; Chen et al. 2018). Ground cover represents the characteristics of the vegetative cover on the ground, which physically can vary in plant types, composition, density, and arrangement. From the watershed management perspective, ground cover plays a role in regulating the magnitudes of soil erosion, nutrient leaching, and resupply for groundwater (Morvan et al. 2014; García-Díaz et al. 2017; Vijith and Dodge-Wan 2019). Remote sensing-based ground cover has been increasingly used as proxies to infer the degree of vegetative coverage on land surface, however; to derive meaningful information related to local characteristics, local parameterization is often required.

Runoff is expected to be more critical with the growing concerns of ecological impacts of global climate change issues (Dams et al. 2015; Qin et al. 2015). Studies reported most noticeable impacts that include the increase of global temperature and extreme rainfall events (Barros et al. 2014; Loo et al. 2015; Hoque et al. 2016). The intensified rainfall is expected to elevate the runoff generation, and accordingly the risk of hydrological hazards such as soil erosion, landslides, and floods (Yamamoto and Sayama 2021). This condition is naturally more profound in humid tropic regions such as Indonesia, where extreme rainfall events are predicted (Myhre et al. 2013). For example, Indonesia is predicted to experience a warmer climate to 0.3℃ per decade with most islands experiencing the delay in the annual monsoon, 10% increases of rain in the crop season, 30% wetter and 15% drier in June–August (Case et al. 2007). Despite global numerous studies on runoff simulation due to climate change (Chiew et al. 2009; Roudier et al. 2014; Dams et al. 2015), studies on runoff in Indonesia found in peer-reviewed literatures are limited to the assessment at river outlet level using hydrological modelling (Setyorini et al. 2017; Pribadi et al. 2018; Ridwansyah et al. 2020), which is limited in providing insights about the spatio-temporal perspectives. The spatio-temporal assessment is useful in building a more comprehensive understanding of such issues. In the context of spatio-temporal runoff characteristics, such assessment is of importance in that it allows quantification of patterns, trends, and distribution of runoff sources, and identification of runoff hotspots as well as the forcing factors of the issue (Kuraś et al. 2008; Lai et al. 2016).

Assessment on runoff characteristics is of importance in supporting watershed and land management practices. The most common factors contributing to runoff in tropics include climatic, topographic, and anthropogenic changes (Crespo et al. 2011; Muñoz-Villers and McDonnell 2012; Yin et al. 2018). In data-scarce regions, runoff and climatic monitoring stations are rare and mostly not available for public use. The advancement of remote sensing technologies has been leveraged to support the provision of globally and freely accessible datasets for varying earth observation purposes. To the current state, global gridded runoff datasets have been made available. This includes the G-RUN datasets, GHM models, ISMIP, and TerraClimate datasets (Frieler et al. 2017; Abatzoglou et al. 2018; Ghiggi et al. 2019). Among these datasets, the gridded runoff data from TerraClimate has the finest spatial resolution, which is ~ 4 km, while the rest is at ~ 50 km. While information on gridded runoff is beneficial, the potential for the use is limited by their spatio-temporal coverage. To support regional assessment, the TerraClimaate-4 km dataset is the most suitable one. Unfortunately, at this point, assessment on its performance has limitedly been carried out and even has not been available for a tropic watershed system. An understanding to the performance of satellite-based runoff and its potentials in depicting watershed condition is valuable, especially in scare-data regions where runoff information is unavailable. In a broader view, such information could help for delivering an insight for parameterizations to improve the future runoff estimates, as well as identifying the potential drawbacks of satellite-based runoff data applications in certain conditions. Given this condition, this study therefore aims at (1) evaluating the performance of the monthly gridded 4-km runoff TerraClimate data in the topographically complex tropical Brantas watershed, (2) assessing the spatio-temporal runoff characteristics of Brantas watershed for the last two decades 2001–2020 using the TerraClimate runoff data, and simulating the runoff with the expected rainfall increase (3) examining the potential forcing factors of the runoff in Brantas watershed from the publicly available dataset, and (4) assessing implications for ground cover management.

Methods

Study area

Brantas is a tropical watershed system with distinct ecological and social characteristics. With seven complexes of mountains within the watershed, Brantas poses a gradient of temperature and rainfall where orographic influence is evident. The annual total rainfall from long-term observation ranges from 1200 to 3600 mm. The elevation ranges from 0 to 3666 m above sea level. With these elevation bands, the slopes in the watershed range from the very flat area to the steep regions with slopes higher than 45 degrees. The long-term average temperature ranges from 24 to 35℃ on the coast. The hydrologic area itself covers an extent of 11,823 km^2. Being home to 15 cities and regencies, the watershed has been increasingly populated. More than 21 million dwellers are housed, creating increasing pressures to the watershed due to its growing population. Ethnically, Brantas is home to most Javanese ethnicity, followed by other groups such as Madurese and Tenggerese as part of the indigenous in Bromo mountain complex. Brantas watershed is a watershed dominated by agricultural land-uses such as rice-fields, mixed gardens, and croplands, accounting for more 60% of the total area (Bappenas, 2012). Settlement areas accounts for approximately 15%, while forested lands in the watershed occupied roughly less than 10%. This configuration shapes the labor structure in Brantas to be dominated by agricultural sectors followed by manufacture and trades. However, increasing population growth and urbanization has triggered structural transformation from agriculture into manufacture and industry (Ibrahim and Mazwan 2020).

In the last two decades, the watershed has been observing a decline in agricultural land-uses and massive conversion from dryland forest and agricultural land-uses to settlement. In the upper region, mix gardens and horticulture dominate the land-use, while rice-field and cropland farming dominate the lowland (Fig. 1).

In recent years, the Brantas watershed has been reported to increasingly undergo varying ecological issues. This can include illegal logging, soil erosion and sedimentation, eutrophication, lowland nutrient enrichments, as well as the escalated drying of springs in upper region (Fulazzaky 2009; Widianto et al. 2010; Schroeder and Knauth 2013; Roestamy and Fulazzaky 2021). The degrading conditions in Brantas are apparently linked to the increasingly multifaceted pressures on the watershed. From a socio-economic setting, this includes as a very high population density (400 people/km2), uneven per capita income distribution and poverty level (Jariyah 2019). A technical report highlights several socio-environmental aspects of the watershed such as protection of indigenous people, potential conflicts of land-uses, low condition sanitation level (JICA, 2002).

Performance of TerraClimate-based runoff datasets.

Ideally, field runoff / soil erosion measurements were used to measure the performance of satellite-based runoff data. Unfortunately, there are no available runoff monitoring stations. To obtain insight about the performance of the TerraClimate's runoff, we utilized the Soil Water Assessment Tool SWAT hydrological modelling results from our previous study (Astuti et al. 2019). We acknowledged this approach introduced a limitation in this study in providing a very accurate performance of satellite-based runoff estimates due to the error contribution from the modeling results. The model was parameterized using local weather, elevation, soil, and

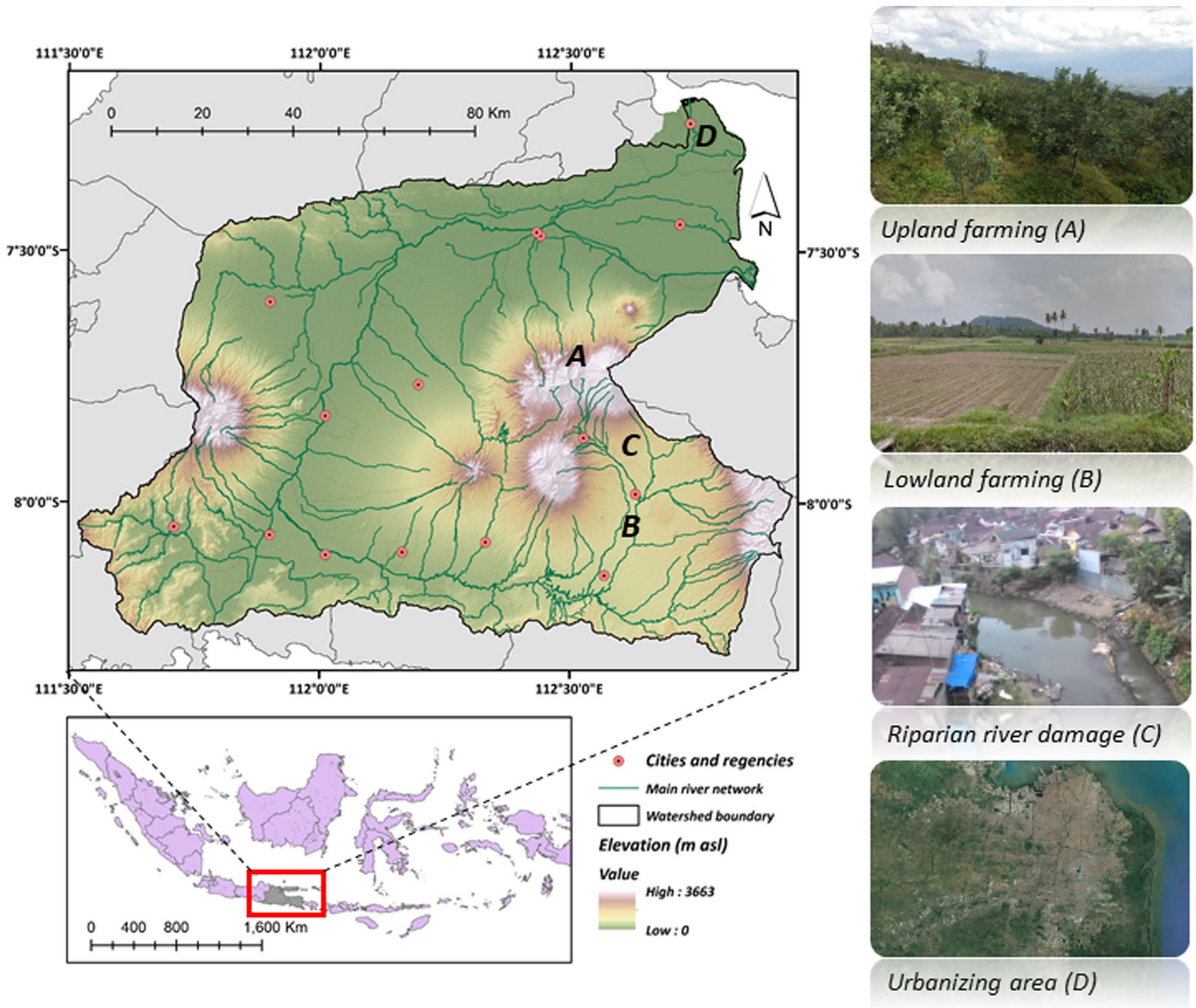

Fig. 1 Overview of the study area Brantas watershed with some backgrounds of the ground conditions (insert picture **A**, **B**, **C** and **D**)

land-use data obtained from national agencies. The daily rainfall 2003–2013 were gathered from the local water resource center (PUSAIR). The SWAT modeling for upper Brantas had been well calibrated and validated on the selected sites using 2003–2013 monthly flow observation with an R^2 and a Nat-Sutcliffe Efficiency (NSE) value both higher than 0.91 (see (Astuti et al. 2019) for details). The monthly surface runoff in the selected gauge for the 2003—2013 period resulting from this modeling was then compared with the monthly runoff estimated from TerraClimate for the same area. To evaluate the performance, the R^2, Root Mean Squared Error (RMSE) and Normalized Root Mean Squared Error (NRSME) were used as the statistical performance. The whole approach for the study was summarized as a schematic diagram in Fig. 2.

Assessing the TerraClimate-based runoff in Brantas watershed.

To understand the nature of the runoff dynamics in Brantas watershed for the last two decades. We gathered all the monthly runoff datasets using Google Earth Engine and further processed them for time-series analysis. First, we applied the Mann–Kendall test to examine the presence of trends of the runoff in Brantas watershed using the R platform. Mann–Kendall test has been widely applied to detect the trends in hydroclimatic data (McLeod 2005; Hamed 2008; Da Silva

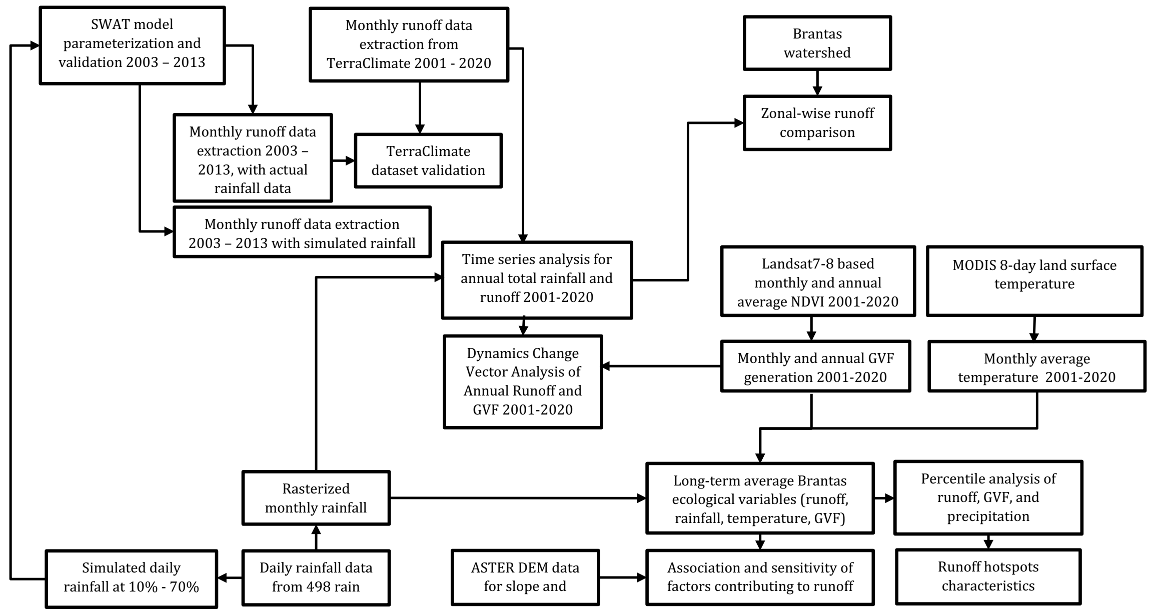

Fig. 2 Schematic diagram of the study's methodological approach

et al. 2015; Wang et al. 2020). To examine the trends across the watershed, the spatial patterns of Sen's slope estimates and *p* values were extracted. In addition, temporal boxplot was also derived to provide a better insight about the trend of the runoff in Brantas watershed. To examine the spatial pattern of long-term runoff characteristics in Brantas watershed as observed by the TerraClimate, the gridded monthly runoff data were aggregated at the watershed morphological zone boundaries obtained from the Directorate of Watershed Planning and Evaluation, KLHK. The delineation of the morphological zones into upper, middle, and lower was carried out by KLHK by considering several aspects namely elevation, landform, precipitation, land-uses, and targeted functions of its zone for protection, buffer, or production, which were specified in detailed KLHK's guidelines (Kementrian Kehutanan, 2009). In support of the understanding of the potential increase in rainfall, the parameterized SWAT model in Sect. 2.2 was then applied to simulate the impact of the increased rainfall to the generated surface runoff. The rainfall increased from 10 to 70% of the existing rainfall. The generated surface runoff from the simulated rainfall classes were then assessed to look at the impact of the increased rainfall.

Examining the potential factors driving the runoff dynamics

In tropics, runoff has been considered as a major source of watershed degradation. To support a sound watershed management, assessment of drivers of watershed ecological issues is of importance (Hassen and Bantider 2020). An understanding of the runoff drivers is needed to prove a deeper understanding of the runoff process in Brantas. We derived four runoff variables namely rainfall, elevation, slope, and green vegetation fraction (GVF). The rainfall raster data were derived monthly using daily observation 2001–2020 from 498 stations within the Brantas watershed. The data were then interpolated and aggregated to a resolution identical to runoff data. Similar process was repeated for the slope and elevation gathered from the 30 m ASTER DEM. The GVF was computed from the monthly average of NDVI images following the equation (Vahmani and Ban-Weiss 2016). All datasets used in this study was summarized for clarity (Table 1). The determination of the 0% was selected from the permanent bare areas in the study area and the 100% was assumed from the permanent dryland forest in the region. All datasets gridded in ~ 4 km resolution and were calculated for the correlation among variables. The data were then inputted to an Artificial

Table 1 List of datasets used in this study

Datasets	Scale/resolution	Source/links
Daily rainfall 2000–2020 from 498 stations	Daily	PU Sumberdaya Air (PUSAIR)
Monthly gridded runoff data	Monthly/ ~ 4 km	University of California Merced / Google Earth Engine https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE
Watershed boundary, morphological zone, and river network	Shapefile	Directorate of Watershed Planning and Controlling—KLHK
Elevation- DEM	30 m	https://earthdata.nasa.gov/learn/articles/new-aster-gdem
Land surface temperature	8 day/1 km	MODIS – MOD11 https://modis.gsfc.nasa.gov/data/dataprod/mod11.php
NDVI – GVF	16 day/30 m	Landsat 7 – 8 https://landsat.gsfc.nasa.gov/data/

Neural Network (ANN) using the R platform. The purpose was not to model the relationship between runoff and the four selected variables, but to quantify the sensitivity of the four variables to runoff. The Garson's and Olden's profile were generated and used to portray the sensitivity of each variable to runoff due to its ability for a neural network system (Bhattacharjee and Tollner 2016; Gajowniczek and Ząbkowski 2020; Srivastava et al. 2021).

Implication for watershed condition and ground cover management in Brantas watershed

In humid tropic, runoff contributes to the degradation intensity occurring within the watersheds. While most variables namely climatic and topographic variables are beyond the control, factors related to anthropogenic activities such as land-use/land-cover and population are to some degree manageable. Brantas, despite its intensified urbanization, is an agriculturally dominated watershed. Thus, the nature of vegetation cover is critical. To assess the dynamics of watershed condition in Brantas, two variables namely runoff and GVF were used as the factors affecting the overall condition in Brantas watershed. A change vector analysis (CVA) was employed to assess the dynamics of the runoff and GVF. CVA represents two aspects of land surface state: magnitudes and direction.

The direction of change (alfa) measures the angle between the two vectors: vectors of runoff and GVF. It represents the changes from the pixel calculated on time 1 to time 2 (Vorovencii 2017; Jiang et al. 2019). The direction was determined by considering a pair of changes from two vectors (Table 2). Four categories were derived to represent four differing conditions: improving, degrading, persistence negative, and persistence upward.

To obtain relative ranks of runoff and each contributing factors, we classified every pixel of these variables (runoff, rainfall, slope, elevation, and GVF) based on their percentiles and classified them as high when a pixel was ranked as 0–33rd percentile, moderate (34th–66th percentile), and low (67th–100th percentile). We performed a ground visit to runoff pixels classified as high because we focused on runoff hotspots identification. We collected information about existing land-uses and physical details such as elevation, slope, and coordinates. Due to difficult terrain, the visits were focused on accessible areas and within road proximity. Another limitation posed by this study is the unavailability of field runoff and/or erosion plots and therefore, we only collect signs of runoff and erosion processes for a comparative qualitative judgement.

Table 2 Possible change direction based on types of changes of runoff and GVF from the t-0 (target year) and t-1 (the previous year)

Category	Runoff	GVF	Remarks
C1—Recovered	–	+	Pixel experiencing increase in GVF and decrease in runoff
C2—Impaired	+	–	Pixel experiencing decrease in GVF and increase in runoff
C3—Persistence upward	+	+	Pixel experiencing increase in both GVF and runoff
C4—Persistence downward	–	–	Pixel experiencing decrease in both GVF and runoff

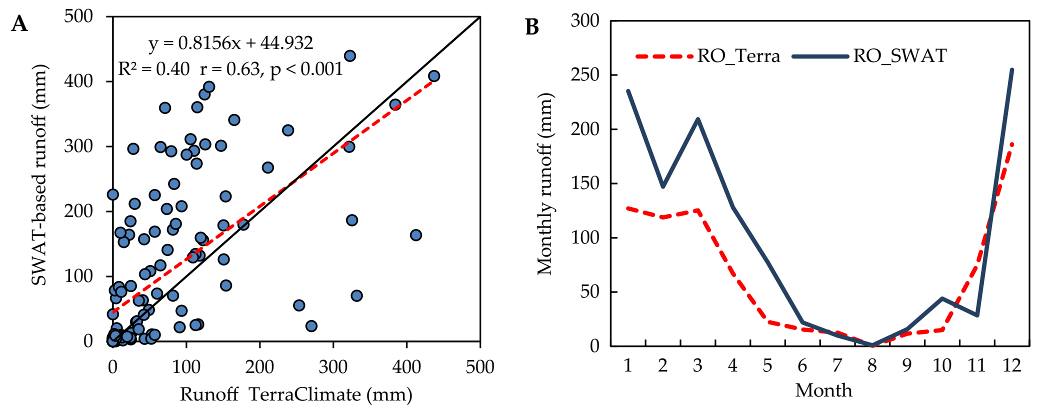

Fig. 3 The validation plot of monthly runoff from period 2003–2013 (**A**), and monthly pattern of long-term average runoff 2003–2013 (**B**)

Table 3 The performance of TerraClimate monthly runoff in Brantas watershed

Period	r	RMSE (mm/month)	NRSME (%)
Dry season	0.64	57.14	18.96
Wet season	0.51	127.06	29.54
All combined	0.62	98.49	22.91

Results and discussion

Month TerraClimate runoff performance

Result from accuracy assessment shows that the performance of monthly runoff from TerraClimate were not very satisfactory (r = 0.63, R^2 = 0.4). The validation plot between runoff from TerraClimate and from the validated SWAT model was shown in Fig. 3A, while comparison of the long-term monthly runoff was shown in Fig. 3B. The association between runoff TerraClimate and the SWAT-based data was noticeable. Overall, the R^2 values from differing periods (dry season, wet season, and all combined) were moderate ranging from 0.51 to 0.64 (Table 3). The RMSE varied from 57 to 127 mm, with NRMSE values in the range of 20–30% from the given data.

The performance of the runoff TerraClimate worsened in wetter months. This was shown consistently by the decreasing r and increasing RMSE and NRMSE, which were almost triple in wetter months, compared to those of drier months.

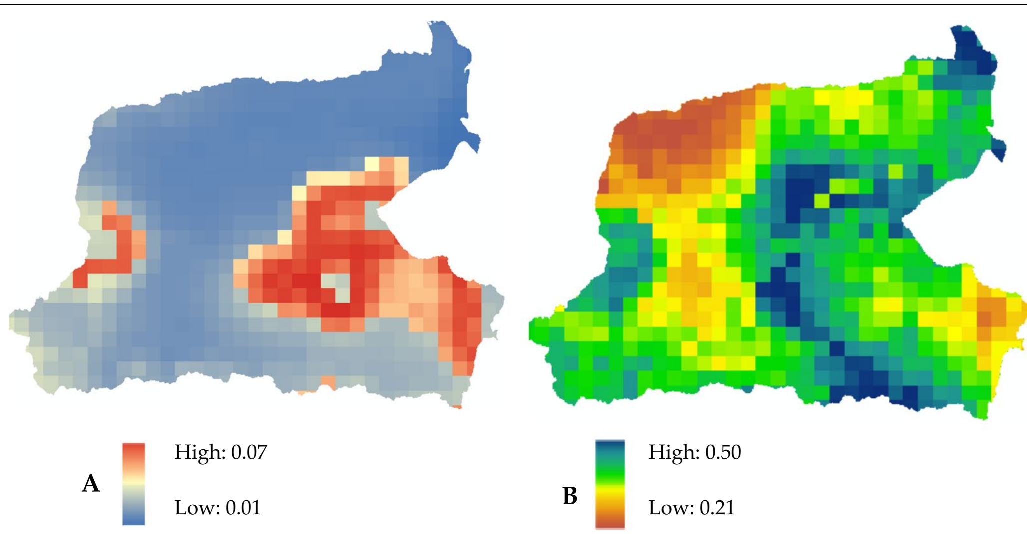

Fig. 4 The Sen's slope estimator of Man–Kendall from monthly TerraClimate runoff 2001–2020 (**A**), and *p*-value of Man–Kendall test (**B**)

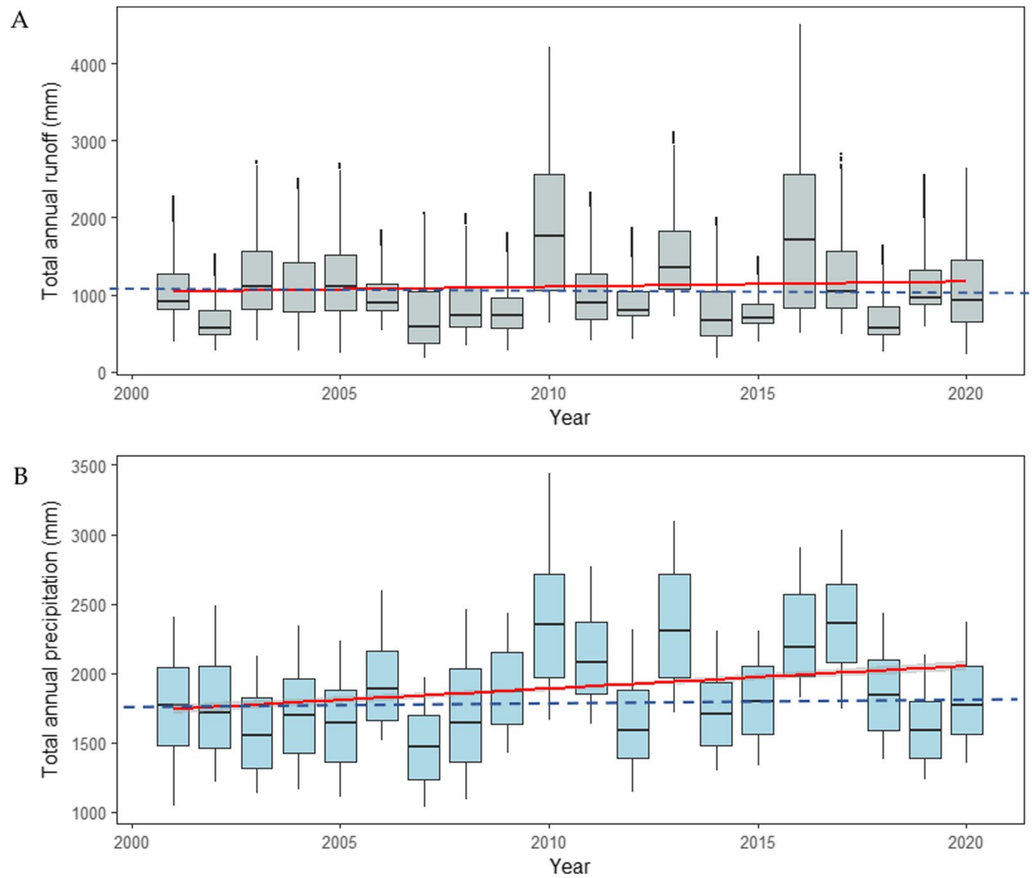

Fig. 5 Annual trend of surface runoff in Brantas watershed 2001–2020 as observed by TerraClimate (**A**) and total annual precipitation in Brantas 2001–2000 as measured from rain gauges (**B**). The red line represents the trend line of annual mean values, and the blue dashed line indicates the baseline of mean value in the reference year (2001)

The long-term monthly pattern in Fig. 3B shows a moderate agreement between the two runoff datasets. With this result, we consider that runoff data from TerraClimate could potentially be used for rapid and initial assessment supporting watershed management where extensive ground data is not available.

Spatio-temporal TerraClimate-based runoff dynamics 2001–2020

For about 20 years, the runoff in Brantas slightly increased. Figure 4A shows that the Sen's Slope values in the watershed were all positive, indicating the upward trends. The areas circling the mountain showed relatively higher slope than in lowland regions, suggesting that runoff increase was more intensified in higher altitudes. Despite the positive trends, the significance of such trends was not obvious. The result from the non-parametric Mann–Kendall test of runoff in Brantas was shown in Fig. 4B. It was clear that for about the last 20 years, there have been no significant trends in Brantas as indicated by the low p-value in Brantas.

The positive trend of runoff in Brantas was also observed from the annual time-series runoff during 2001–2020. Figure 5A reveals the weak increasing trend of the runoff. In comparison, the increased runoff was apparently linked to the increased rainfall in the region. Figure 5B clearly shows the increase in precipitation during the 2001–2020 period.

The differences in runoff trend slope as depicted by Fig. 4B suggests the presence of spatial pattern of runoff in Brantas. Zonal statistics of runoff magnitudes using the watershed morphological boundary showed that the upper watershed is the region where runoff was concentrated. The average runoff in this region was nearly threefold to that of the lower region (Fig. 6). In the wet season, it is natural that runoff was highly elevated, while that of dry season was relatively negligible. Runoff in the upper region could be up to 500 mm. This is

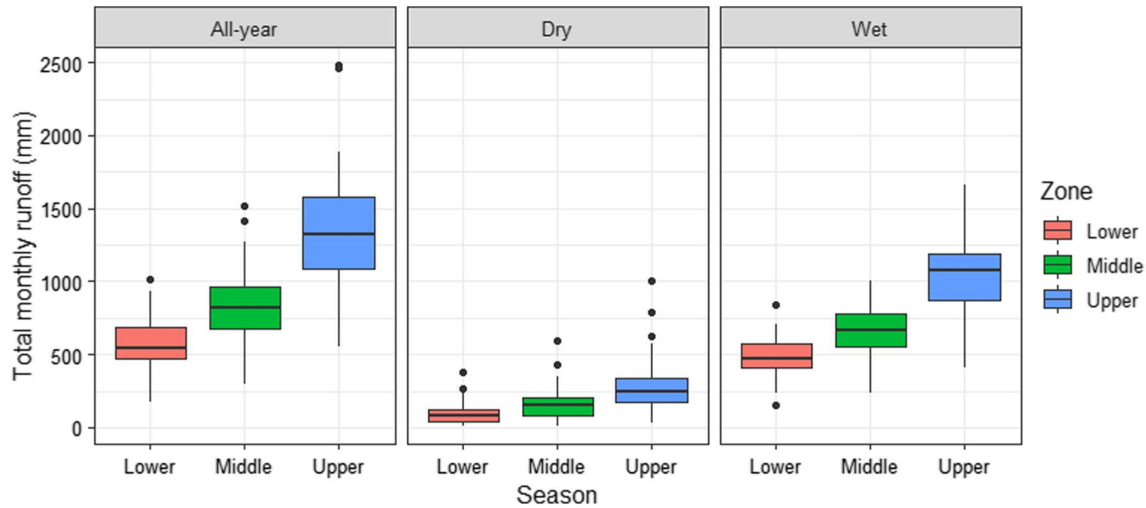

Fig. 6 Comparative runoff magnitudes among three morphological watershed zones: total annual runoff all year, in dry seasons, and in wet seasons 2001–2020

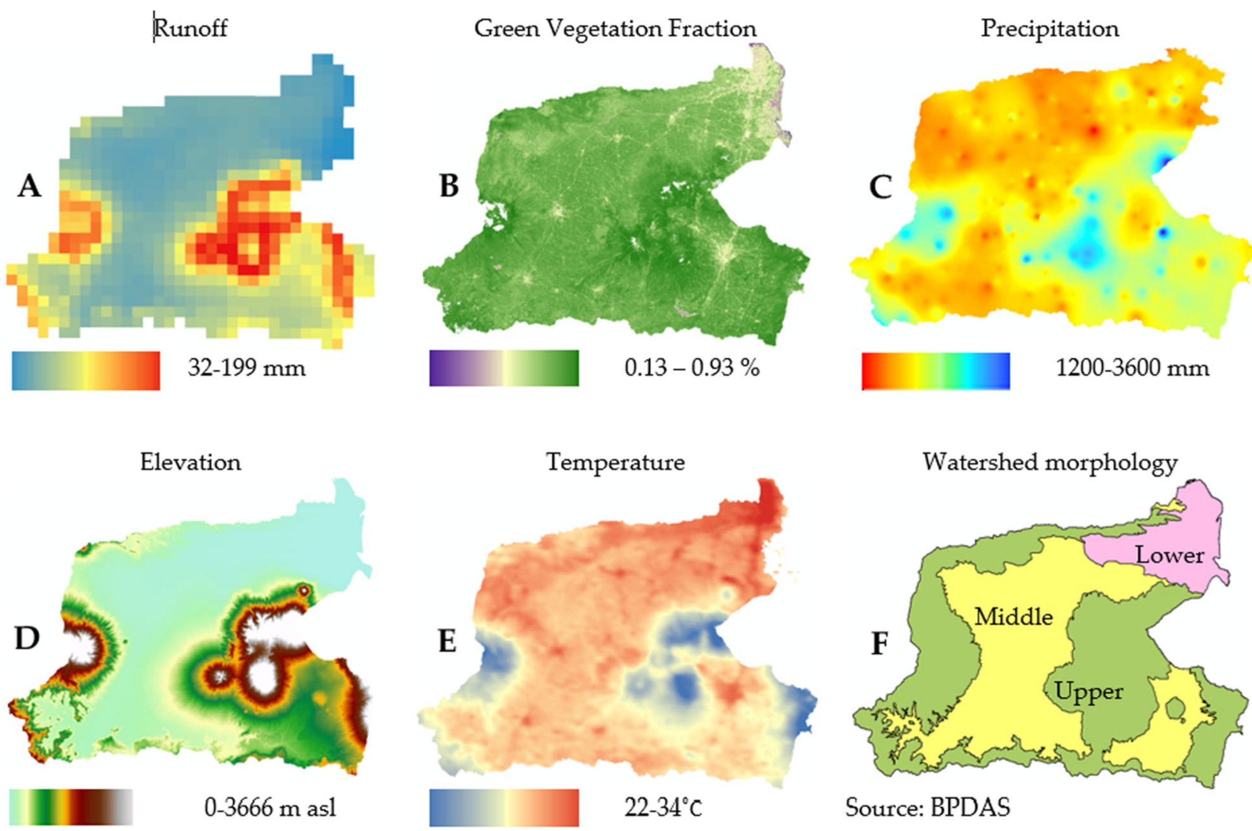

Fig. 7 Biophysical characteristics of Brantas watershed: average runoff (**A**), green vegetation fraction (**B**), precipitation of Brantas watershed 2001–2020 (**C**), elevation (**D**), temperature (**F**), and watershed morphology (**F**)

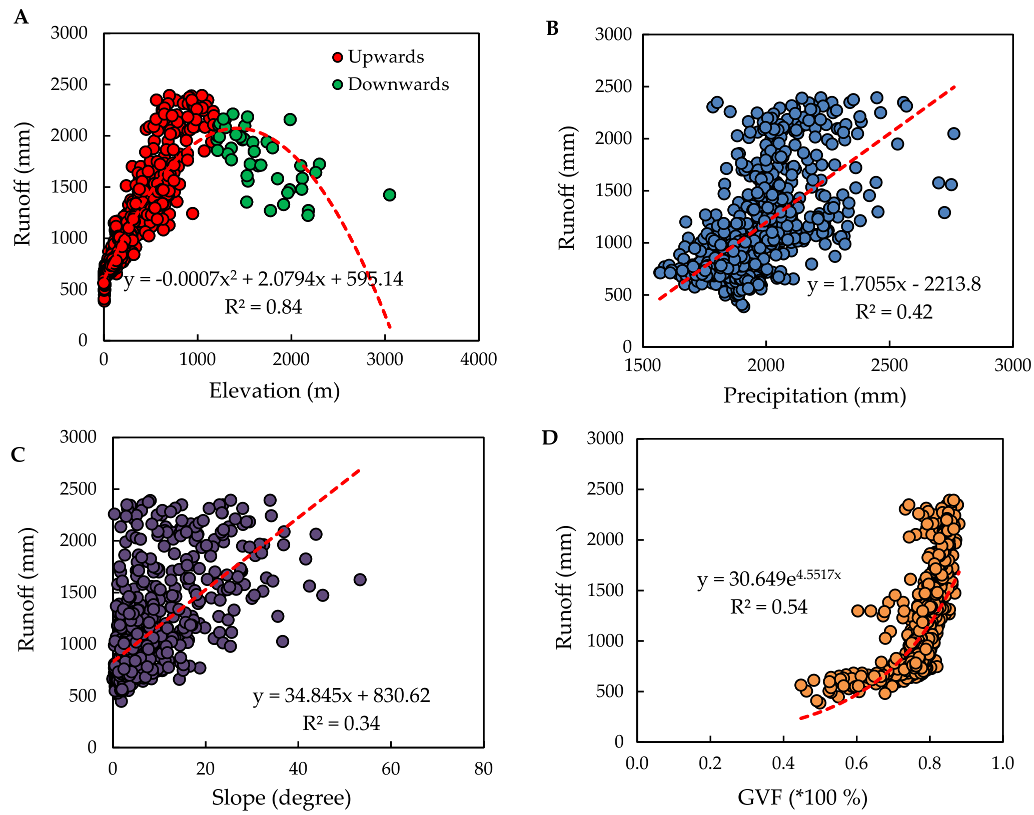

Fig. 8 Scatter plots of runoff and topographic-vegetative factors in Brantas watershed: runoff-elevation (**A**), runoff-precipitation (**B**), runoff-slope (**C**), and runoff-GVF (**D**)

because the Brantas watershed can be considered as a wet tropic watershed with rainfall distribution can be up to 8–10 months in a year. The intensified runoff in the upper region was alarming, given the fact that the upper region has been designated as the recharge area and conservation purposes.

Figure 7 provides a deeper insight about the runoff characteristics in the Brantas watershed. Here, we clearly see the similarity in the spatial patterns of temperature, rainfall, topography, and land-cover in the watershed. From Fig. 7A, high runoff areas were concentrated on areas that are relatively colder (7E), steeper (7D), wetter (7C), and vegetatively denser (7B). These areas are morphologically categorized as the upper region of Brantas watershed (7F). Figure 7 suggests the multiple controls on runoff in the watershed. The seven mountain complexes in Brantas watershed created an intense orographic system within the watershed, where there was a strong association between elevation, temperature, and precipitation.

Ecological factors in association to the runoff generation in Brantas watershed

The association between runoff and ecological variables (slope, elevation, rainfall, and land-cover (GVF)) was quantified using correlation measurements between long-term average total runoff and Fig. 8 highlights these associations. The runoff naturally increased in areas receiving higher precipitation (8A). The same is true for the slope, despite its weaker association (8C). We observed that runoff and elevation was linearly related to some degree. Between 0 and 1100 m altitude ranges, the runoff rose with increase of elevation, however, after 1100 m, their relationship was reversed (8B). The runoff tended to decrease. Interestingly, GVF covaried with the runoff variation. As opposed to the common studies where high GVF was expected to halt the runoff process, Fig. 8D shows that GVF in Brantas displayed an agreement with runoff variations.

Further analysis of the decreased runoff in higher elevation reveals that the areas generating lower runoff

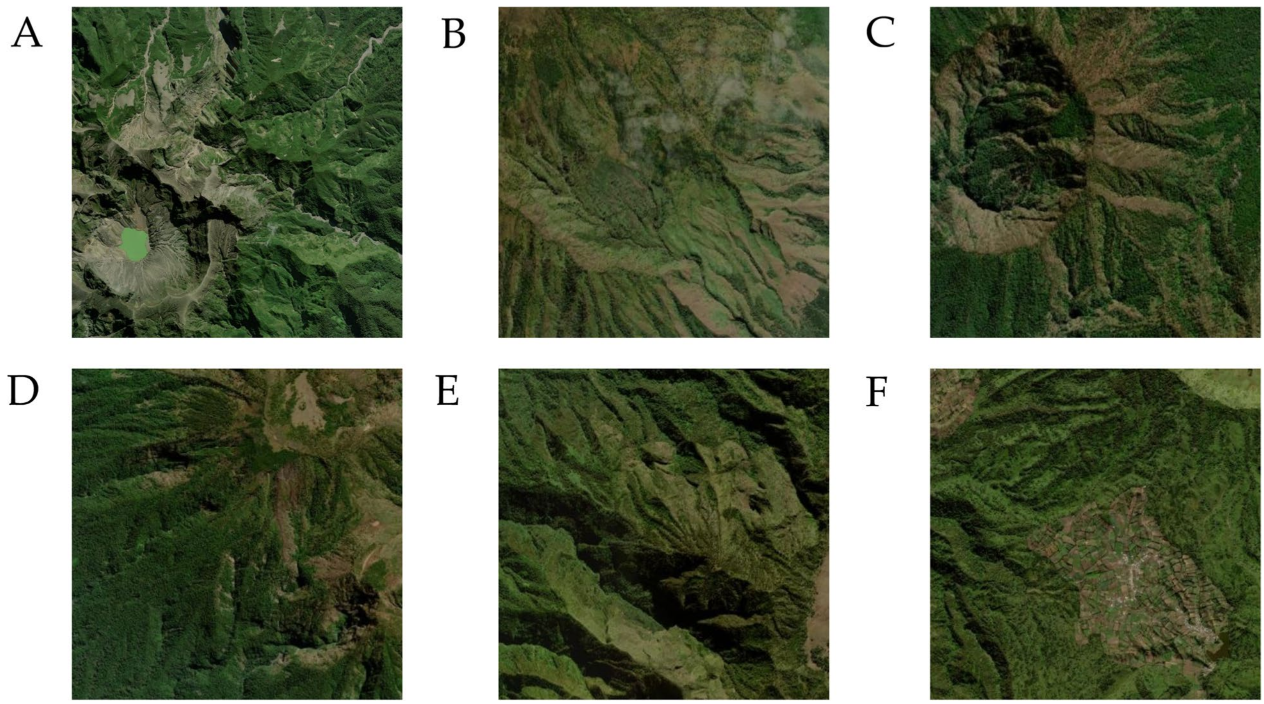

Fig. 9 Examples of six sites with topography and land cover conditions in areas experiencing lower runoff in higher elevation and steep terrain (**A**–**F**)

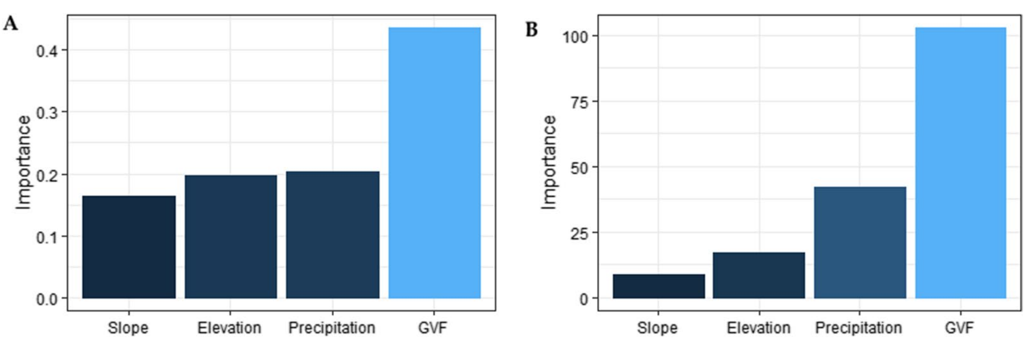

Fig. 10 Garson's (**A**) and Olden's (**B**) profiles of Sensitivity of runoff as a response of ecological factors in Brantas

in higher altitudes were areas with steeper slopes. The average slope in the downward trend in Fig. 8C was 26 degrees, much higher than that of the upward trend, which is only 8 degrees. Detailed observation using Google Earth view showed that these areas are topographic depressions. Some examples of these areas were given in Fig. 9. The sites in this figure show that areas in steeper slopes might not always induce extreme off-site runoff. The convex shape due to the surrounding depression retained or impeded the runoff generation.

The sensitivity profiles from the ANN-based approach showed the relative sensitivity of each variable to the runoff variations in Brantas watershed (Fig. 10). The three profiles evaluated the effect of explanatory variables by returning a plot of the predicted response across the range of values for each separate variable. Overall, all variables showed a degree of sensitivity to runoff. GVF consistently was identified as the most sensitive variable in Garson's and Olden's profile, followed by precipitation. The direction of GVF to runoff response in Olden's profile

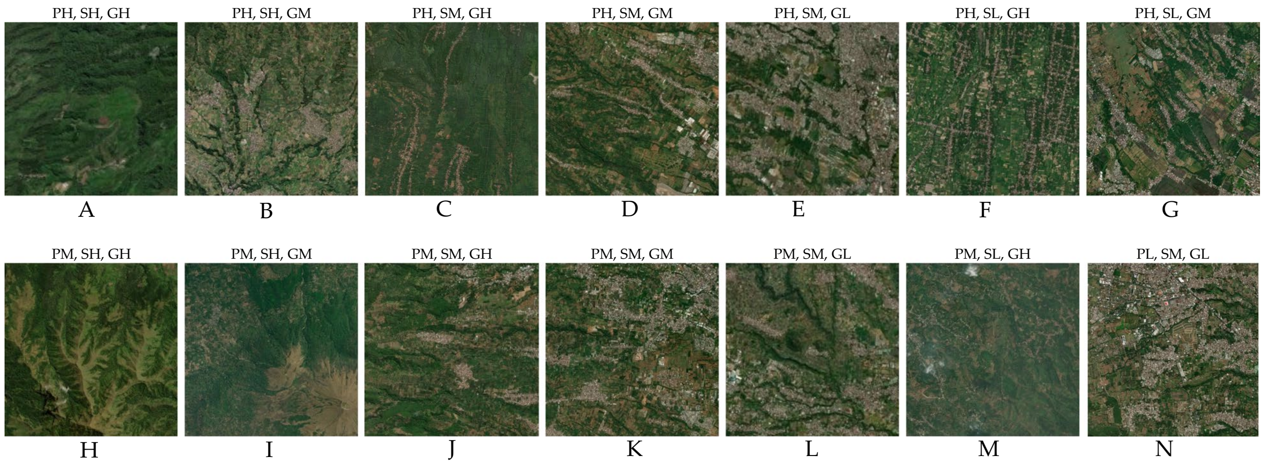

Fig. 11 Varying combination of precipitation (P), Slope (S), and GVF (G) resulting in high runoff classes (0–33rd percentile) in the study area, with H means high percentile (0–33rd), L is low percentile (67–100th) and M is medium percentile (34–66th). High runoff prone areas represent roughly 25% of the total study area. Most sites are from high percentile precipitation (**A**–**G**), followed by medium percentile (**H**–**M**), and low percentile in one site (**N**)

must be interpreted in a comprehensive manner. The upward trend of GVF to runoff might not be considered that the increase in GVF was the cause of the increased runoff. The positive association of GVF and runoff might be attributed to several possible factors. First, GVF might not be able to completely represent the ground coverage. As derived mathematically, the meaning of numbers could vary depending on ground condition.

Further analysis of runoff and ground cover could be obtained from Fig. 11. Focusing on areas characterized with high runoff (0–33rd percentile), we identified differing possible combinations of precipitation, slope and GVF in Brantas. The fact that high GVF could also be associated with high runoff, information about combinations resulting in high runoff could enrich the understanding of the runoff generation process in the watershed. In Fig. 11, we found that high runoff in Brantas can be linked to differing sets of combinations. In most cases, high runoff is naturally linked to high precipitation with low to high slope and GVF. On the other hand, high runoff can also occur in areas where precipitation is even medium and even low. This finding suggests that runoff cannot be solely triggered by the intense precipitation. In previous Fig. 6 above, it shows that Brantas watershed is a humid tropic watershed where

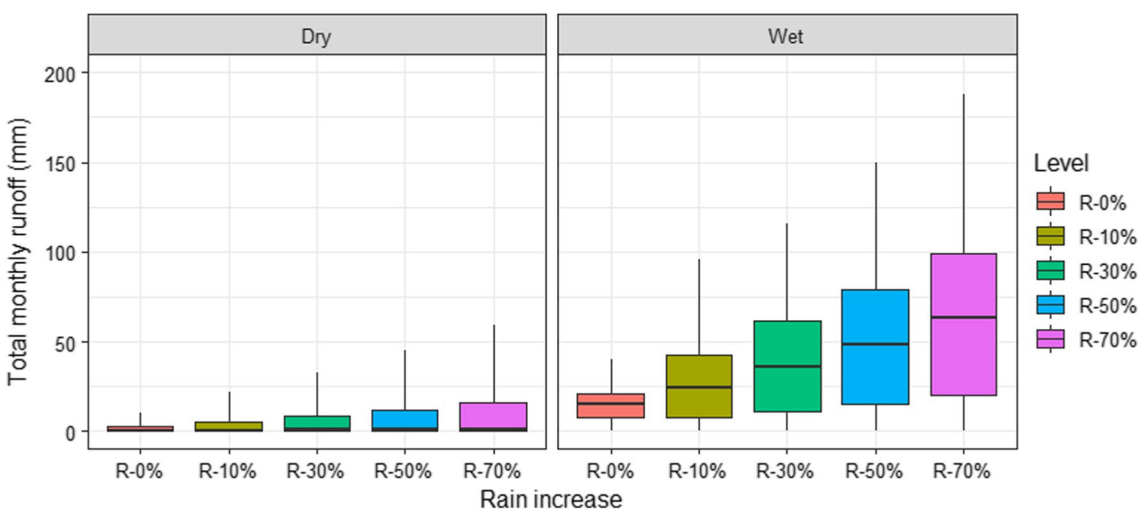

Fig. 12 SWAT simulated monthly runoff from combined, wet, and dry season datasets at varying increased rain level (10–70%)

precipitation is intense, topographically complex, and has orographic influence. This condition shapes the complexity of rainfall-runoff-GVF interaction in the watershed. The areas with higher GVF fractions occurred in areas having higher slopes and elevation and rainfall, and thus produced a positive correlation to runoff in this study area. Compared to topographic influence, the stronger association between rainfall to runoff suggests that rainfall is the primary driver of the runoff generation in Brantas watershed, which was then magnified with the improper ground cover condition.

Implications for watershed condition and ground cover management in BRB

Considering the potential increase of rainfall due to climate change, information about the potential generated runoff could provide insights about potential future conditions. Results from SWAT modelling (Fig. 12) showed that increased rainfall might lead to the intense runoff generation. An increase of 10 to 30% of the 2003–2013 rainfall showed to generate runoff almost at a double level. In extreme cases, where rainfall increased up to 50% and 70% of the current rainfall could result in runoff three times larger than the existing runoff (mean values: approximately 50 and 70 mm/month). The intensified runoff generation might be expected to occur in all months, especially in wet seasons (October to March). As presented in previous section, one limitation in this study was acknowledged that the simulation was performed with the unavailability of actual field runoff data; and therefore, limits the use for benchmarking purposes. However, despite this condition, the result might be considered to support future runoff management that should be put at a higher priority, when climate change mitigation and adaptation measures are to be implemented.

To observe the general condition about Brantas watershed during 2001–2020, Fig. 13 presented the annual variability of land conditions. During this period, persistence conditions dominated the watershed areas, both upward and downward. The persistence upwards conditions were observed in several years: 2002–2203. 2009–2010, 2012–2013, 2015–2016, and 2018–2019. In these periods, increased runoff was observed together with increased GVF. The recovered condition only dominated the watershed in 2006–2007, 2010–2011, and 2019–2020. On the other hand, the impaired condition was significant in 2004–2005, 2007–2008, 2011–2012, and 2018–2019. In these periods, decreased GVF occurred together with the increased runoff from the previous years.

Information about the direction change mapping as pictured in Fig. 13 could help outline the characteristics of Brantas watershed from the perspective of runoff and GVF. Period exhibiting dominating impaired conditions apparently corresponded to periods with elevated rainfall inducing higher runoff but were not followed with the greener conditions. On the other hand, periods with recovered conditions were linked to the drier period in the following year, generated lessened runoff and benefitted from elevated GVF lasting from the previous year. Figure 13 was useful in providing remotely based assessment of watershed utilizing long-term remote sensing data.

Discussion

Assessment on the performance of the runoff data using the well calibrated SWAT modeling shows that the performance of the TerraClimate runoff data was not very satisfactory, given the result of moderate r value (0.62), and relatively high errors up to 30% of NRMSE. Overall, the TerraClimate monthly runoff data experienced

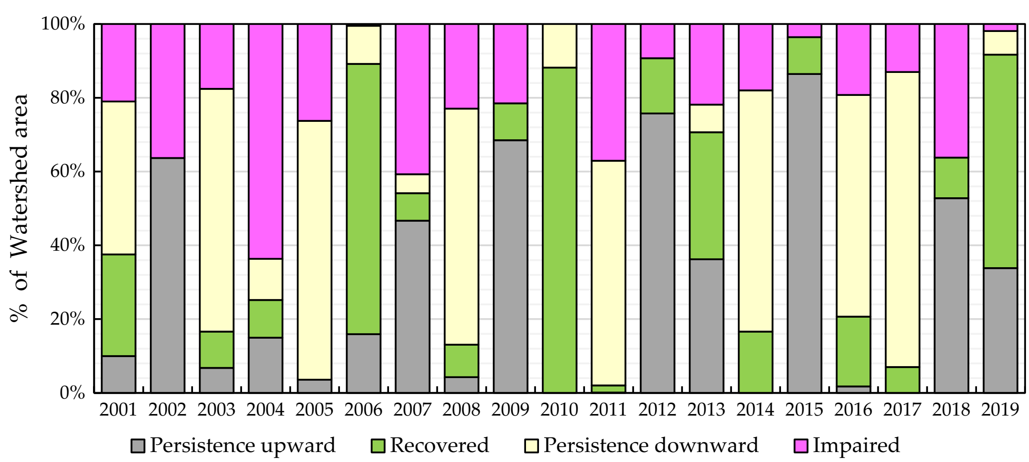

Fig. 13 Brantas watershed conditions during 2001–2020 using the change direction types of runoffs and GVF changes in every year

overestimation, which was larger in wetter months. Despite this level of performance, the TerraClimate monthly runoff data remains useful and potential for supporting watershed conditions, especially in scare-data regions where ground measurements are limited or even unavailable. It is also to be noted that the accuracy assessment was also based on the modeling, where—despite the very good validation results –, such models are also subject to a degree of errors and uncertainty.

Using the TerraClimate runoff data, spatio-temporal analysis of runoff dynamics in Brantas watershed reveal several findings. First, that runoff has slightly increased since 2001. The increase was linked to the clearly observed increase of precipitation in the study area. The relationship among runoff, precipitation and ground cover expressed as GVF appears to be complex in Brantas watershed. The linearity in scatter plots must be carefully interpreted. For example, the evident positive relationship between GVF and runoff should not be manifested to the understanding of causation. The fact that high runoff is observed in high GVF areas could be attributed to several potential conditions. First, GVF merely represents the estimated degree of vegetative surface coverage. While variations of canopies or vegetation structure play a role in soil erosion (Miyata et al. 2009; Ma et al. 2014; Li et al. 2019); GVF is limited in inferring the volumetric or vertical structure of vegetation. Thus, GVF measures might not be able to accurately represent the coverage ability of soil against soil detachment. High GVF values were found in a wide range of elevations. Studies demonstrated that similarity in GVF values do not necessarily show similarity in vegetation cover type. High GVF values can be present in mature stage crops to forest pine (Rundquist 2002; Scheftic et al. 2014; Imukova et al. 2015; Valayamkunnath et al. 2019). In this study, in low land or lower elevation, high GVF pixels are associated with high intensity cropping and homogeneous green cover such as rice or sugar cane. In higher altitudes, high GVF is found to be linked to densely grown trees such as dryland forest and pine plantation. A visit to ground conditions found that high GVF areas are present in varying vegetation structure from evergreen forest, mixed pine-intercropping plants, high intensity vegetable farming, and shrubs (pictures are in Appendix 1). In medium percentile slope areas, low to medium GVF represents dryland agriculture with higher density of settlement. In contrast, lower GVF in this region is associated with the presence of settlement mosaics triggering impervious surface-induced runoff generation in higher altitudes.

Classifying runoff, topography, GVF, and precipitation based on their percentiles, especially to areas with high runoff, allows a deeper understanding of these variables. In higher elevation, high runoff is associated with high precipitation and steeper slopes as the primary governing factors to runoff generation. The presence of high GVF in this area suggests that the role of GVF in controlling runoff is minimal. Despite its economic benefit, highly intensified agriculture in these areas appears to be less effective in reducing the runoff generation risk. Finding shows that high runoff also presents in flatter areas (low to medium percentile slope). In these areas, varying GVF (low to high percentile GVF) appear to be less influential in reducing the runoff. Dryland agriculture in middle slopes represents agricultural systems with mosaics of trees and shrubs in varying density and composition. The denser settlement areas apparently intensified the surface imperviousness. Therefore, despite being flatter, highly intensified precipitation appears to be very impactful for runoff generation in these areas. While in most areas high runoff is associated with high precipitation, high runoff areas are also found in areas exhibiting medium to low percentile precipitation classes. In these areas, the presence of steep slopes (high percentile) appears to intensify the runoff generation, despite the lower precipitation and high GVF values.

Similar to findings in other studies, high runoff areas in Brantas are found mostly in steep areas with high precipitation (Alexakis et al. 2013; Zhang et al. 2018; Zhao et al. 2022), and this notion highlights the importance of land cover management in Brantas watershed. Vegetation cover fraction has been used as a practical variable in monitoring land cover changes. Field vegetation cover measurement is impractical and remote sensing-based indicators are increasingly used. However, our study shows that reliance on solely a satellite-based vegetation fraction variable might not be sufficient as a single instrument to represent the degree of field vegetation cover. This is exemplified by the presence of high runoff areas on flatter slopes with low to high GVF percentiles. In Brantas, simplification to vegetation cover monitoring using generic indices such as NDVI and GVF appears to be insufficient in capturing actual cover variability and its practical interpretation in refer to erosion protection. This difficulty was magnified by the complexity of social setting. Low to medium percentile GVF values exhibit varying patterns and intensity degrees of settlement. The fact that settlement patterns are different in high, medium, and low percentile GVF pixel areas suggest that in Brantas context, settlement pattern is influenced by social setting. This complicates the generalization and interpretation of such indices. The implication of this condition includes (1) that the designation of runoff hotspots should not be based solely on the use of physical indices especially the remotely derived ones. The underlying social factors such as rural–urban connectivity, settlement pattern and density, as well as land-use intensity might be considered as well, (2) GVF might be appropriate for quick monitoring on ground cover condition. However, GVF values seem to be insufficient in representing land-use characteristics such as vegetation structure, composition, and density. While operational and periodic national land-use dataset has not yet been available, GVF-based assessment should be accompanied additional measures. This will be more critical when GVF values are to be used as a surrogate of degrees of protection against soil loss.

Assessment using change vector matrix as shown in Fig. 13 allows richer information about dynamics in runoff and its expected inhibitor, which is the green vegetation fraction. Such classification using "Impaired" and "Recovered" can provide more insight about a measure to evaluate landscape condition in a particular time window. From a practical of view, spatial and temporal visualization of this information should be useful in supporting national and regional watershed management prioritization and evaluation. What should be sought in the future is how to provide more accurate data in a finer resolution so that target actions could be designed in a more site-specific manner.

Conclusion

This study demonstrated a study of runoff dynamics in a humid tropical watershed utilizing publicly available remote sensing dataset. Validation results using SWAT hydrological modeling approach showed a moderate performance of the monthly runoff TerraClimate dataset (r of 0.63, RMSE of 57-127 mm/month and NRMSE of 18–30%). The dataset was, however, useful in providing continuous and consistent estimates of spatio-temporal runoff dynamics in the watershed, especially in data-scarce regions like Indonesia. As in many other studies, the results showed that the upper region of the watershed has been the major runoff hotspots. This finding highlights the importance of watershed management prioritization in the area. Results show a complex relationship among topography, climate, and vegetation in modulating the runoff dynamics in Brantas (r values range from 0.59 to 0.95), with vegetation cover and precipitation identified as the two most important variables. While the role of precipitation is more straightforward and well understood, the vegetation cover is more complex and provides varying implications to ground condition and watershed management. High GVF does not necessarily lead to high protection of soil. High runoff spots are linked to varying GVF conditions in Brantas, from high intensity agriculture, forest with intercropping, and settlement mosaics with agricultural landscapes. Simulated model results show a profound increase of runoff (average values: 25–74 mm/month) due to rainfall increase of 10%—70%. Altogether, the study highlights the implication of ground cover management and potential risk of climate change with the expected rainfall increase. The monthly runoff dataset from TerraClimate was helpful in portraying runoff dynamics in the watershed. However, with the limitation of the used datasets, the future research is needed for improving the result and this includes improving runoff estimates at a finer spatial and temporal scale by means of downscaling and sub-pixel interpolation, exploring the plausible runoff generation mechanism, as well as identifying more accurate green vegetation fraction measures that can better represent the ability of vegetation cover protection against soil detachment.

Appendix 1

See Fig. 14.

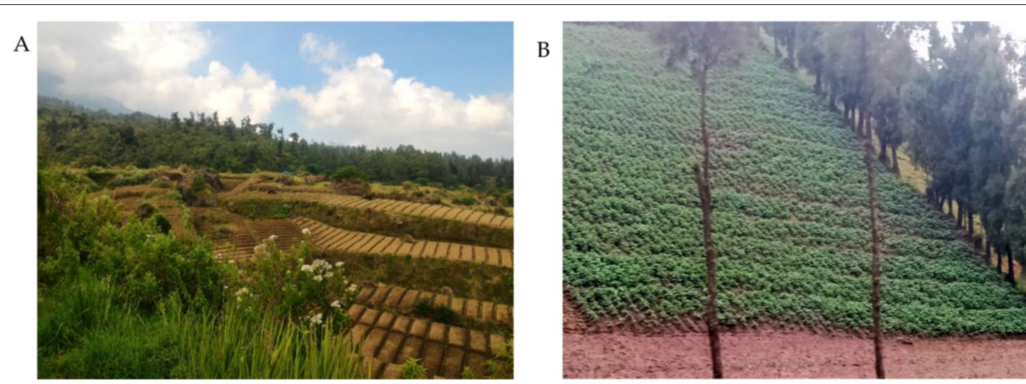

Fig. 14 Picture of mixed shrubs and vegetables (**A**), and mixed vegetables and forest in high percentile slope areas (**B**)

Acknowledgements
Not applicable.

Author contributions
The work presented here was carried out in collaboration between all authors. Conceptualization, B.S.W, and I.S.A.; methodology, Conceptualization, B.S.W, and I.S.A.; software, B.S.W.; validation, I.S.A.; formal analysis, B.S.W.; resources, B.S.W; writing—original draft preparation, B.S.W.; writing—review and editing, I.S.A.; visualization, B.S.W; project administration, I.S.A.; funding acquisition, I.S.A. All authors read and approved the final manuscript.

Funding
This research was funded by PNBP Universitas Negeri Malang 2020.

Availability of data and materials
Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interest
The authors declare that we have no competing interests.

Received: 30 March 2022 Accepted: 13 May 2022
Published online: 02 June 2022

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