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Baseflow Index Analysis for Bengawan Solo River, Indonesia

Muh Taufik and Siti Annisa'

Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Sciences, IPB University, Dramaga Campus, Bogor, Indonesia 16680

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Correspondence:
Muh Taufik
Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Sciences, IPB University, Dramaga Campus, Bogor, Indonesia 16680
Email: mtaufik@apps.ipb.ac.id

ABSTRACT

Hydrological investigation for major Java rivers remains research challenge todays, particularly in identification of runoff characteristics situated in monsoonal climate. This study aims to investigate the value of baseflow index for Bengawan Solo river. We employed daily streamflow data for period 1980-2010 to derive baseflow index (BFI) based on the smoothed minima. We utilized different approaches comprising the non-overlapping 3 days (BFI3), 5 days (BFI5), and 7 days (BFI7) of streamflow to compute the index. We found the average BFI3, BFI5 and BFI7 for this study period are 0.67, 0.56 and 0.49, respectively. It revealed that higher number of non-overlapping days would produce lower BFI, which could be an indication of less baseflow contribution to total streamflow. Additionally, our fundings show there is an increase trend of BFI in the last decade that may be associated with decreasing forest cover in the catchment area. Furthermore, the BFI value will provide a valuable information for key leader in water sector in particular during dry season, and further research is needed to integrated this BFI into sustainable water management index.

KEYWORDS

baseflow separation, smoothed minima, trend, land use change, monsoonal climate

INTRODUCTION

River water availability is an important hydrological indicator that influences the dynamics of daily socio-economic activities. In case of Java Island with dense residential areas, the availability of river water is essential because of the highly community dependency to water (Putri and Perdinan, 2018). However, the real condition shows that most of Java's rivers and their wathershed area are in critical condition (e.g. Hannum et al., (2020) and Tarigan et al., (2022)). Current condition of biophysical indicators such as low forest area and low river discharge are the common indicators for such critical watershed (Araza et al., 2021; Guzha et al., 2018). Also studies confirmed the decreased trend of river discharge in Java (Jennerjahn et al., 2022; Kuntoro et al., 2018; Nugroho, 2009). This reduced water availability not only occurred on Java Island, yet spreads to other Indonesia's wet tropical areas such as Sumatra (Taufik, 2010; Yuono et al., 2020) and Kalimantan (Herawati et al., 2018; Taufik et al., 2017), which led to the hydrometeorological disasters such frequent fires (Purnomo et al., 2021; Tan et al., 2020).

The characteristics of the river's baseflow remain research challenge especially in tropical Indonesia. Studies suggested that temporal characteristics of baseflow (Seyam and Othman, 2015; Solander et al., 2017) are often used to obtain an overview of river conditions in such area. Other studies identified and assessed riverflow regime to derive baseflow index (BFI) (Kelly et al., 2019). BFI value refers to the volume ratio of the baseflow to the total river flow (Singh et al., 2019). BFI determination refers to the method developed earlier in 1980s by the Institute of Hydrology, UK (Piggott et al., 2005). This method calculated the BFI value based on the five daily discharge data. Yet, in tropical monsoon region, the application of this method may need adjustments, considering its differences in soil physical properties that greatly affect underground flow (Taufik et al., 2015). The adjustment can be done by selecting the number of days that determines the baseflow minimum value. The different number of days will be tested on the Bengawan Solo River.

The Bengawan Solo River is the longest river in Java with more than 500 Km length. After 1997/1998, the abrupt changes on the biophysical aspects of Bengawan Solo watershed has led to the severe degradation of the watershed into a critical condition (Basuki et al., 2022). In 2005, the forest in this watershed covered 18% of the area and it has decreased by 5% in just seven years (from 1998), which was caused by land conversion (Sutadi, 2008). Land use change influences river flow, yet quantification of baseflow is still limited, especially for the tropical monsoon area in Java. So, it is needed to investigate the impact on the baseflow. This study aims to obtain the BFI value of the Bengawan Solo River and to see the long-term trend of the baseflow value. These values can be used as an underlying reference for watershed restoration.

RESEARCH METHODS

Description of Bengawan Solo River

Bengawan Solo River extends from Central Java to East Java Province, with a catchment area of ca. 12% of Java Island. Bengawan Solo watershed covers ±16,100 km^2 area, which comprises of: upper Bengawan Solo sub-watershed (±6,072 km^2), Kali Madiun sub-watershed (±3,755 km^2), and lower Bengawan Solo sub-watershed (±6,273 km^2). This study used data on water level from Babat Station (Figure 1), which has adequate and sufficient observation data for period 1980-2010.

Geologically, the rock formations in the Bengawan Solo watershed generally include tertiary sedimentary rocks, quaternary sedimentary rocks, volcanic rocks, and carbonate rocks (Sukamto et al., 1996). The upstream area is dominated by conglomerate pumice, breccia, tuff, quartz containing andesite, and volcanic rock formations from the Merapi-Merbabu and Lawu volcanoes activity. The lower part of Bengawan Solo is classified as an alluvial plain bordered by tertiary mountains consisting of tuff sandstone, claystone, and limestone (Bemmelen, 1949).

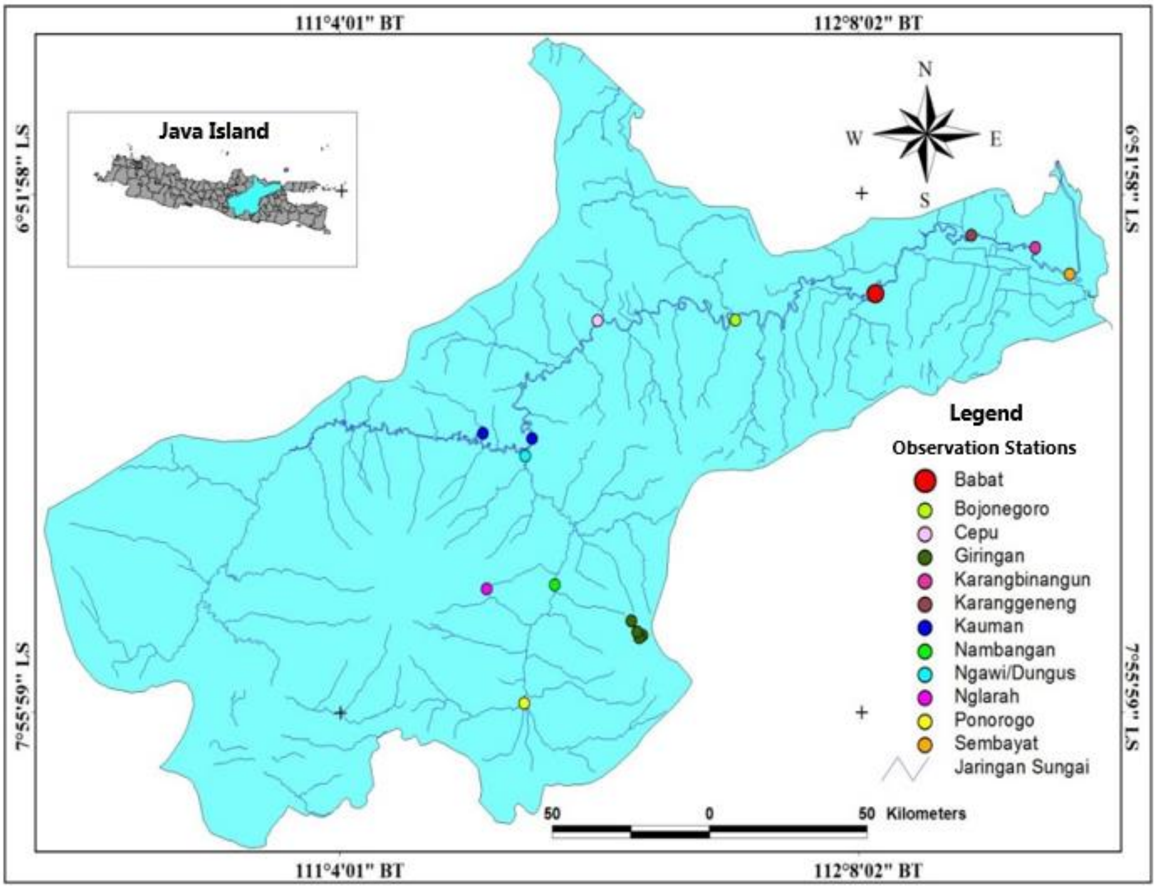

Figure 1. Location of Bengawan Solo watershed in Java, Indonesia with its stream networks. Locations of watershed observations are in dots. Babat Station is indicated by the bigger dot.

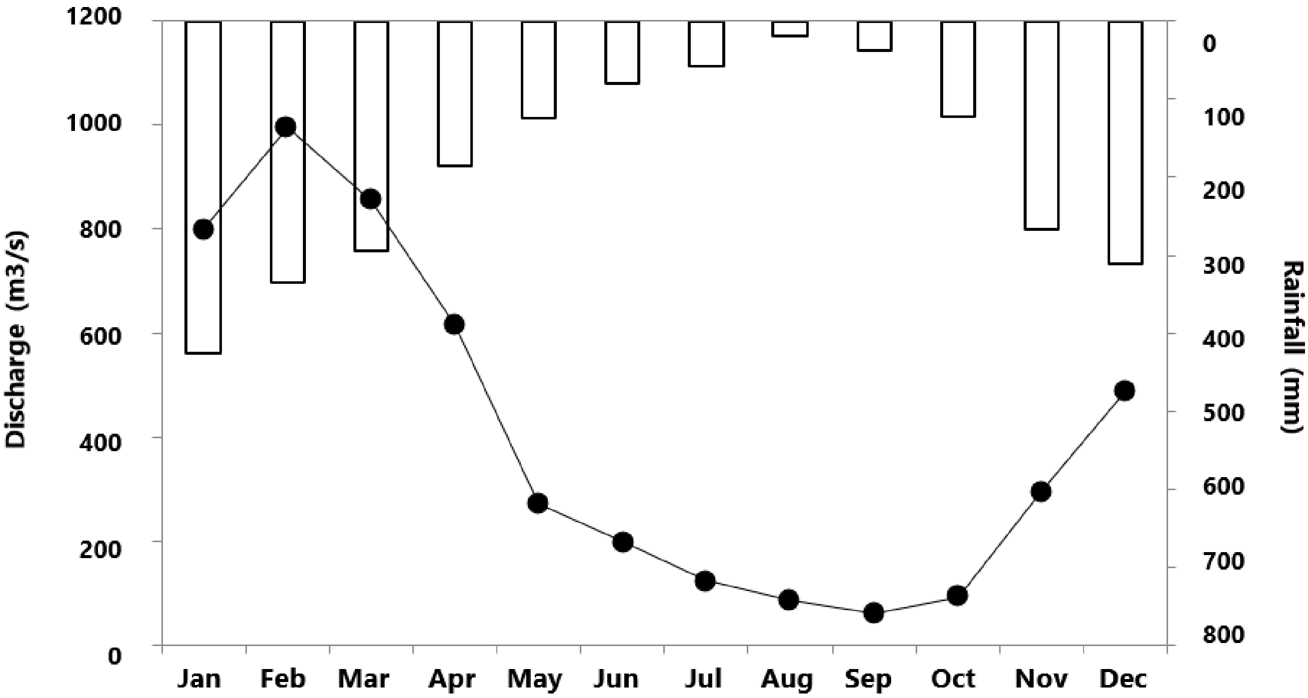

Figure 2. Average monthly discharge (black dot-line), and monthly rainfall (bar chart) at Babat Station, Bengawan Solo. The observation period for discharge data is 1980-2010, whereas rainfall data is 1980-2006.

Baseflow Index (BFI)

BFI value is calculated based on the smoothed minima approach developed by the UK Institute of Hydrology. Yet, this method has the weakness of producing sharp peaks of data in the baseflow data sequence (Aksoy et al., 2009; Shao et al., 2020). Further BFI value calculation uses the revised method proposed by Piggott et al., (2005). The BFI calculating procedures as follows: (i) separation of the flow hydrograph using the smoothed minima method, and (ii) calculating BFI as the ratio of the baseflow volume to the total discharge. Furthermore, BFI is calculated with 3-daily, 5-daily, and 7-daily non-overlapping block discharge data. Example to produce 3-daily BFI:

- Selecting minimum data from 3-daily non-overlapping data blocks.
- Using the smallest data as a reference point in the preparation of the interpolation curve of the minimum discharge value (baseflow).
- Calculate the minimum discharge volume or baseflow (Vbase) then compare it with the total flow volume (Vtotal) to obtain the BFI value (Aksoy et al., 2009). So, the BFI formula is as follows:

$$BFI = \frac{Vbase}{Vtotal} \qquad (1)$$

In the same way, BFI5 (5-daily) and BFI7 (7-daily) will be generated.

RESULTS AND DISCUSSION

Hydroclimatology

The Bengawan Solo River position in Java is characterized by a distinct rainfall pattern between rainy and dry seasons (monsoon). The peak of rainfall comes on December-February (Figure 2), with the highest average rainfall of 426 mm in January (1980-2006). Climatologically, the lowest average rainfall is 20 mm which occurs in August. Bengawan Solo is located in an area with a strong monsoon, which can be indicated by six consecutive months of low rainfall (May-October).

River discharge at the Babat Station follows the monsoonal rain pattern. The highest recorded monthly discharge was 996.2 m^3/s in February (1980-2010), while the lowest monthly discharge was 61.6 m^3/s (September, Figure 2). The low flow period starts in May and ends in November. The data shows that there is a gap between rainfall and river discharge, which is 1 month from rainfall to propagate into river flow. For example, the highest monthly discharge occurs in February while the maximum rainfall is in January. Similar lags can be identified in the hydroclimatological minimum events (rainfall and discharge).

Baseflow Characteristics

Baseflow was separated from the river flow by the smoothed minima method. There were three approa-

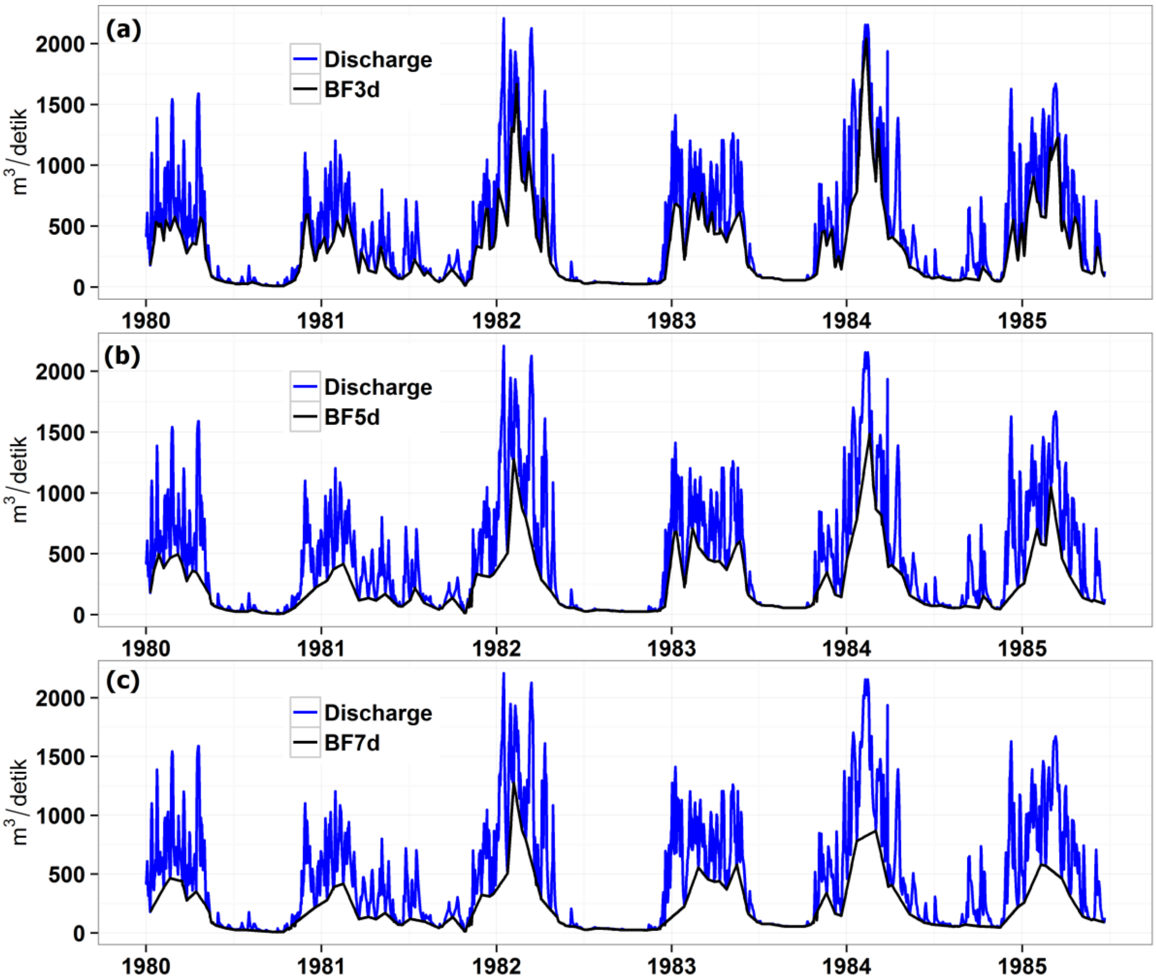

Figure 3. A snapshot of the hydrograph of the Bengawan Solo at Babat Station. The blue line shows the daily discharge value, whereas the black line represents the baseflow timeseries, which was separated using the smoothed-minima method:(non-overlapping) 3-daily (a, BF3d), 5-daily (b, BF5d), and 7-daily (c, BF7d).

ches used, namely with a minimum block value (non-overlapping) from 3-daily, 5-daily, and 7-daily data. The analysis showed that the baseflow value varied throughout the year regardless of the approach used. The amount of baseflow is influenced by the contribution of rainfall, soil type, and local hydrogeology. In the dry season (May-October), the baseflow of Bengawan Solo mostly comes from groundwater which is determined by the hydrogeological characteristics of the area. Figure 3 presents a hydrograph of the river flow that describes baseflow and total discharge.

The calculation indicated that the baseflow value from 3-daily tend to be high, especially in the rainy season in response to the high discharge from the rainfall in the watershed. For illustration, at the high discharge period in 1982, the baseflow value from the separation approach was very big, which was almost 90% of the total flow (Figure 3a). Similar behavior was detected in 1984.

On other hand, the baseflow value separated by 7-daily (non-overlapping) data showed smoother fluctuations following the discharge. Figure 3c indicates that the baseflow pattern tends to be more stable, except for the peak discharge period in 1982. Whereas the 5-daily (non-overlapping) data, the baseflow pattern is relatively similar to the 3-daily (non-overlapping) baseflow (Fig. 3b). This could inform that the longer the number of non-overlapping days used to calculate the baseflow would result in a more stable baseflow due to high contribution of groundwater.

Statistically, the various baseflow values resulting from the discharge separation depend on the approach used. The range of quartile 3 (Q3) and quartile 1 (Q1) were 414, 335, and 389 m^3/s, respectively, for 3-daily, 5-daily, and 7-day block data. The range value indicates the tendency of the distributed baseflow data. The wider the range (Q3-Q1), the more fluctuation of baseflow as occurred in the 3-day method. Figure 3a can confirm this occurrence. The average baseflow of the three calculation methods is in the range of 221-295 m^3/s.

Baseflow Index (BFI) of Bengawan Solo Watershed

Baseflow is influenced by the geological formation of the watershed. The baseflow expressed

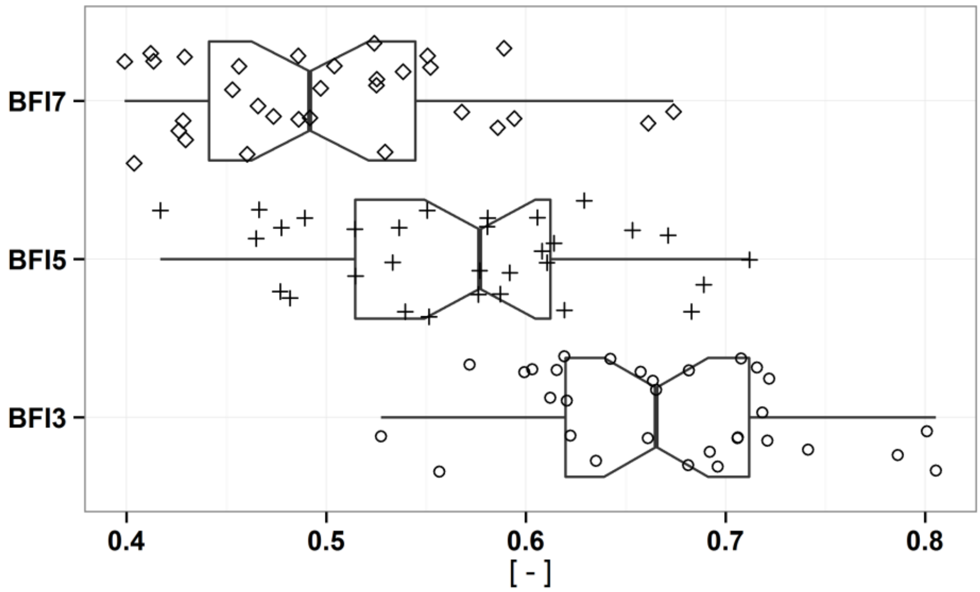

Figure 4. The distribution of baseflow index (BFI) in Bengawan Solo based on three different approaches. BFI unit is dimensionless.

by BFI values also has interannual variations. For 3-daily block data (BFI3), BFI value varies from 0.53 to 0.81 (1980-2010). This implied that the contribution of baseflow to the total discharge flow ranging from 53-81%. While for BFI5 and BFI7 in the range of 0.42-0.71 and 0.40-0.67 respectively, which indicates that the baseflow contribution to the total discharge flow is about 42-72% and 40-67%. The results indicated that the more days for BFI calculation, the lower of BFI would be. Figure 4 presents the distribution of BFI values in the Bengawan Solo watershed. Figure 3, which presents a snapshot of the baseflow value is equal to Figure 4 which shows the highest baseflow value with 3-daily block calculations.

The lowest BFI value from all methods is about 40%, which indicates the contribution of baseflow to this watershed is still relatively fine. The average BFI value was 57%, which means the contribution of base flow is very dominant for Bengawan Solo. However, with this high value, Bengawan Solo watershed can be characterized as a low storage watershed according to the Institute of Hydrology classification (Piggott et al., 2005). Another study in the eastern part of Java obtained relatively similar BFI's value (Beck et al., 2013). This high BFI value may be related to the geological formation of the Bengawan Solo watershed, which is dominated by tertiary sedimentary rocks, quaternary sedimentary rocks, volcanic rocks and carbonate rocks. (Sukamto et al., 1996). Geological formation will physically determine the soil permeability and infiltration rate. Areas with volcanic and plutonic rock formations tend to have a high permeability (Ayuningtyas *et al.* 2018; Alonso *et al.* 2019), hence a high percolation to deep groundwater. Interestingly, the BFI value can reach 70-80% under certain conditions (see Figure 4).

Determination of the best N value (the number of days) for each BFI can be approached by the standard deviation value (Chen and Teegavarapu, 2020). Based on this value, BFI3 can be considered as the best method with the smallest deviation value. However, refer to the baseflow definition, namely dry weather flow, the determination of BFI3 as the best method becomes meaningless. Figure 3a shows high baseflow fluctuations and even reaches 90% at peak discharge conditions (BFI3). Thus, the smallest deviation method needs to be revised for application in Bengawan Solo. Perhaps the method proposed by Longobardi and Villani, (2008) is only applicable locally in the Mediterranean region.

The results of the BFI calculation using the smoothed-minima method can provide an overview of groundwater contribution to river flows, and the results of this study show that the BFI value is relatively comparable to the findings of Beck et al., (2013), which estimated the BFI value worldwide. More researches on BFI with other approaches are required to get a convincing results, such as using the filter method (Eckhardt, 2008). In the Pasuruan area, which is smaller than Bengawan Solo, BFI value can reach 0.8 (Indarto et al., 2016).

The BFI3 value is the highest compared to BFI5 and BFI7 (Figure 4). The smaller N-daily used for the baseflow separation, the greater the BFI produced. The value of N is the time required for direct runoff to stop after peak discharge occurs, for example, if N = 5 it means direct runoff stops approximately 1-5 days after peak discharge occurs. A small N value in a watershed

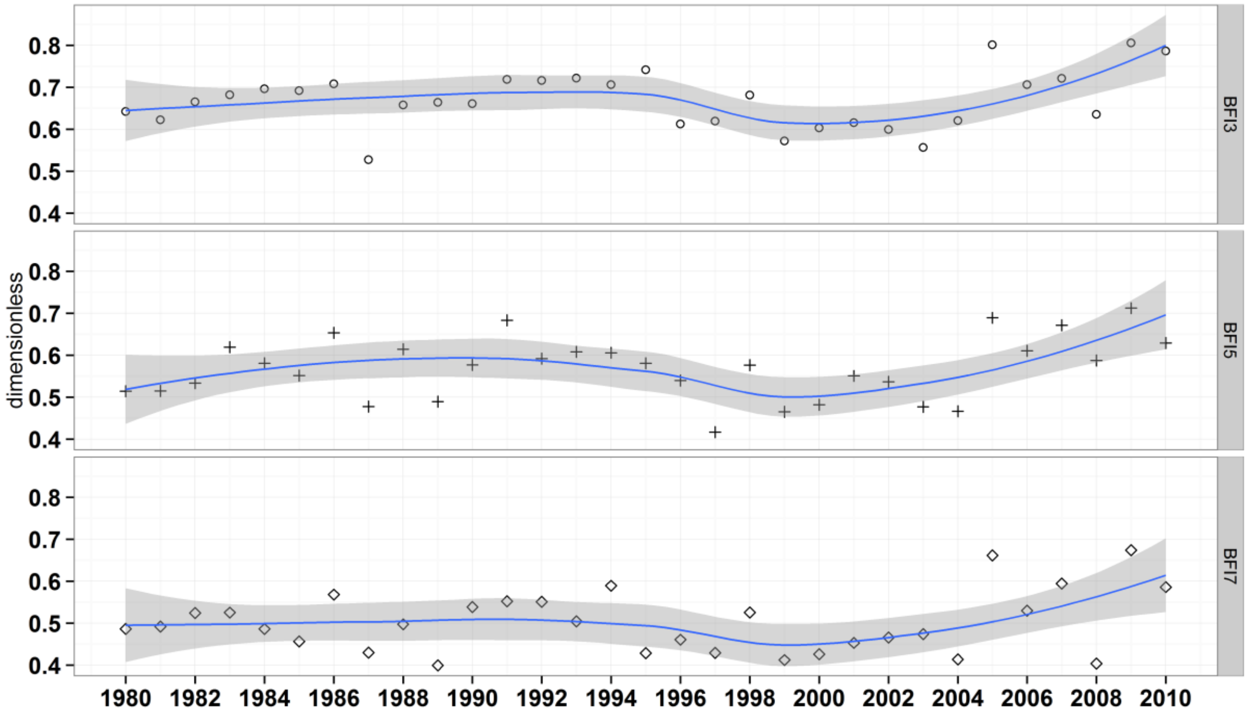

Figure 5. Baseflow index (BFI) values using three approaches, namely: (i) BFI3 which calculates baseflow with 3-daily blocks of data, (ii) BFI5 using 5-daily blocks of data, and (iii) BFI7 using 7-daily blocks of data. The period of river discharge data used is 1980-2010. BFI unit is dimensionless. The three approaches show the same pattern, which shows no trend in the data before 1998, and indicates that there is an indication of a positive trend after 1998.

will result in a smaller direct runoff contribution to the total discharge flow compared to the baseflow contribution.

The output BFI shows consistent results for all three approaches. Figure 5 shows that there was a decline in the BFI after 1997, and then a gradual increased until 2009. There may be two reasons for this phenomenon. First, a decreased forest cover since 1998 (Sutadi 2008) from 23% to 18%. The previous studies reported that by declining forest cover, the total discharge will increase (Ding et al., 2022), otherwise, the discharge value tends to decrease with afforestation (Buechel et al., 2022; Kumar et al., 2021; Schwärzel et al., 2020). The BFI value shows a relatively low in the period 1998-2000 which can confirm an increased discharge. Furthermore, the effect of reforestation and afforestation on the increased water availability in downstream areas is still debatable (Ellison et al., 2017; Filoso et al., 2017). In the case the decline of BFI caused by reduced forest cover could be biased.

Then, there is another argument related to this phenomenon, namely the very strong El Ninõ incident in 1997/1998. In 1997, rainfall fell by almost 25% from normal conditions, while the average value of river discharge fell drastically by more than 35%. Interestingly, it seemed there is a connection between the ENSO condition in 1997 and the BFI value of the following years. Figure 5 shows a downward trend in the value of BFI after 1997 to 1999. It may be concluded here that the effect of ENSO on the value of BFI takes up to 2 years. In other words, the hydrological drought caused by ENSO can have an impact on the decline in groundwater storage after two years of the ENSO incident. Further research needs to be carried out to look at this connection comprehensively by looking at various contributing factors such as land use, hydrogeological formation, and climate change.

In the last decade, there are indications of an increased BFI (Figure 5). More research on the topic is required to identify the factors influencing BFI. Does the increase relate to climate change, land use change, or hydrogeological formations. The last factor doesn't seem to take effect considering the changes in hydrogeological formations require millions of geological years. Further studies on two other factors (i.e. climate change and land use change) will benefit to water resource management in the Bengawan Solo watershed. There may be a decrease in river discharge as a result of land use change so that the BFI value becomes even greater. However, the effect of decreasing or increasing discharge as a result of land use change is still debatable as discussed by Filoso et al., (2017). Climate change with a decreased rainfall can also be the subject of further discussion and research.

CONCLUSIONS

This study provides the results of the baseflow index (BFI) varies. The presence or absence of rain greatly influences the behavior of the BFI value. Generally, the BFI value based on the smoothed minima method showed that 3-daily block data calculations present a higher BFI value. The BFI values fluctuated during the 1980-2010, and it showed an increased BFIafter 1998.

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