Contrasting Climate Induced Variability of the Upper Citarum River Baseflow and Eventflow during Early 20th Century and Recent Decades

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Abstract. Recorded daily flow data of the upper Citarum River from 24 October 1918 through 23 October 1935 and from 24 October 1976 through 23 October 2015 from the Nanjung Station, located near the river's outlet, is investigated for its baseflow and eventflow variabilities. Statistical analysis detects no trend in daily flow and baseflow during the study periods. However, baseflow variability during the latter period is higher than during the former period and is found to be related with the El Niño/Southern Oscillation (ENSO) events. By applying a novel approach of analysing decadal values of separated eventflow, an increasing value of the upper Citarum River basin runoff coefficient from 34 % to 41 % (up to a 20 % increase from the initial value) during a period between 1980 and 2009 (especially after 1990) is overlapping with massive land use and land cover changes during the period. Analysis on rainfall–baseflow variability shows that, after 1990, computed baseflow variability is increasingly more sensitive to rainfall variability.

1 Introduction

The goals of this study on the upper Citarum River flow are: (1) to explore its baseflow and eventflow variabilities during early 20th century and recent decades; and (2) to show the influence of climate variability and human disturbances on the baseflow and eventflow variabilities during the two periods.

River flows, as part of larger hydrologic system, are not stationary as they are affected by climate variability and human disturbances [1]. Climate variability, such as extreme phases of the El Niño/Southern Oscillation (ENSO), has been linked to affect moisture transport in the atmosphere and, hence, major floods and droughts (e.g. [2, 3, 4]). The global climate change has been shown to affect flood frequency [5]. Human activities, e.g. land use and land cover changes, water infrastructures, channel modifications, drainage works, have been affecting the connected river flows [1]. The non-stationary nature of river flows will eventually affect human systems that are dependent on river systems.

Flood and drought risks, water supply, water quality, energy generation and supply are of primary concerns in water management under the non-stationary nature of river flows. The reason is because all related hard infrastructures to the management have been designed under the assumption of stationarity, the variability of related natural systems fluctuate within certain unchanging limits [1]. The concept of precipitation return periods and flow analysis that are used in designing the infrastructures are based on the stationarity assumption. It is therefore imperative to reanalyse the natural systems in order to make adjustments in water management under the non-stationary nature of the systems.

The upper Citarum River basin lies between 6°45'57" and 7°13'39 S and 107°22'23" and 107°57'05" E within five cities and regencies in the West Java Province, Indonesia (Figure 1). With a total area of 182,700 ha and elevations between 640 and 2569 m above sea level (52 % of the area below 1000 m), the basin is surrounded by volcanic mountains and is known as the Bandung Basin [6]. The annual average rainfall of the basin is 2215 mm. The 78km upper Citarum River, that springs at Situ Cisanti, has about 20 major tributaries and supplies water to the downstream three large cascade dams (Saguling, Cirata, and Jatiluhur Dams) [7]. The length of wet season in the region is around 220 days [8]. Massive land use and land cover changes and large groundwater withdrawals has been observed within the basin [6, 7, 9]. Total population in the river basin was 7.92 million in 2015 and is projected up to 8.39 million in 2020 [9].

In addition to the upper Citarum River's importance to the population and their activities in its watershed, the river plays an important role in maintaining water supply to downstream Jakarta, the capital of Indonesia, Purwakarta, and Karawang, and Indonesia's important industrial centers in Bekasi, Karawang, and Cikarang region. The Citarum River basin, including the upper Citarum River (sub)basin, is a key rice producer in Indonesia.

This study extends previous studies of [10] and [11] by: (1) extending the temporal coverage of analysis through the inclusion of recorded daily flow data during early 20th century and recent decades; and (2) computing

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baseflow and eventflow from the daily flow data and linking their variabilities with climate variability and human disturbances. Baseflow and eventflow are computed from daily flow data recorded at the Nanjung Station (Figure 1).
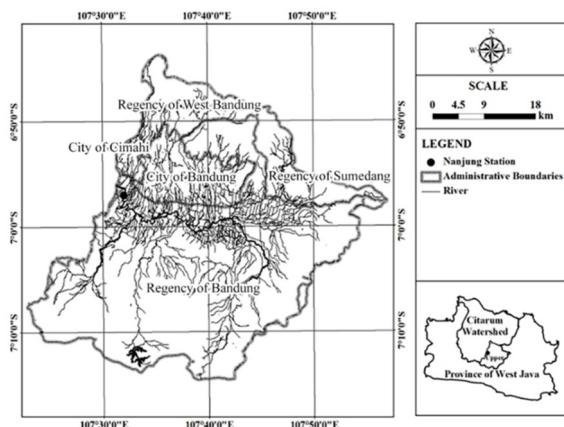

Figure 1. Location of the upper Citarum River and Nanjung Station.

2 Data and methods

Recorded daily flow data from the Nanjung Station is analysed in this study. The data has been maintained by and is collected from the Indonesian Ministry of Public Work and Housing. The station is located in the downstream end of the upper Citarum River before the river enters the Saguling Dam (Figure 1). There is no dam upstream of the station. Hence, the flow data collected at the stations represents the Upper Citarum River's flow.

Although the daily flow data is not continuous in time, its temporal availability covers the periods during which anthropogenic activities were low, if not minimum, and high. Throughout this study, the hydrologic year (starts on 24 October) as defined by [12] is used. The data periods are: (1) from 24 October 1918 through 23 October 1935 (hereinafter referred to as the low anthropogenic activities period); and (2) from 24 October 1976 through 23 October 2015 (hereinafter referred to as the high anthropogenic activities period).

Baseflow is computed from the daily flow data by applying the filtered smoothed minima method [13]. Baseflow separation in the method is done through two steps. The first step is to determine turning points and temporary baseflow values from the daily flow data. The recursive digital filter with a recession coefficient (α) of 0.975 and baseflow index maximum (BFI_{max}) of 0.80 is then applied in the second step. The computed baseflow timeseries are then subjected to statistical analyses, including wavelet analysis. Wavelet analysis is used for determining dominant modes of variability and their temporal variabilities. The difference between recorded daily and computed baseflow is a good predictor for eventflow.

This study uses the Multivariate El Niño/Southern Oscillation (ENSO) Index (MEI) [14-16] in order to evaluate the influence of ENSO on baseflow. Rainfall variability in Indonesia is strongly correlated with ENSO [17].

3 Results and discussion

The annual averages of recorded daily flow and computed baseflow from the upper Citarum River show no significant trend (Spearman–Conley test; $\alpha = 5\%$) during the two periods of this study (Figure 2). This is especially surprising for the high anthropogenic activities period (from 24 October 1976 through 23 October 2015). Interdecadal warming of tropical sea surface temperatures (SSTs) has been linked to a higher (increasing) annual precipitation in the region, including the upper Citarum River basin, within a period of 1979–2004 [18]. Theoretically, because of massive land use and land cover changes and large groundwater withdrawals in the region, the streamflow should be more sensitive to changes in precipitation. Land use and land cover changes and large groundwater withdrawals cause more overland runoff flowing into the river and reduce groundwater recharge and, hence, lowering the baseflow of the river. Despite these changes, the annual averages of daily flow and baseflow did not show any interdecadal changes during the study periods.
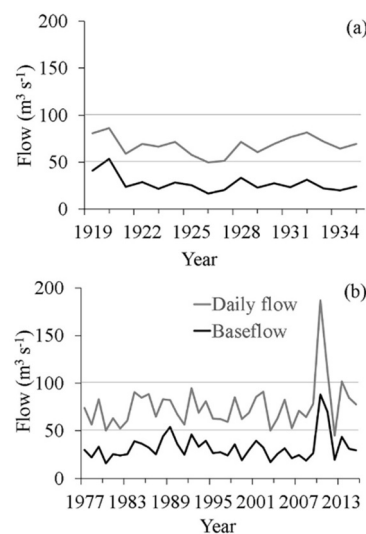

Figure 2. Annual averages of daily flow and baseflow in (a) the low and (b) high anthropogenic activities periods.

Despite no detected interdecadal signal (as previously shown), Figure 2 shows that higher interannual variability is much more apparent during the high anthropogenic activities period than during the other period. The annual averages of daily flow and baseflow in 2010 are the highest in Figure 2. Box–and–whisker plots in Figure 3 show the differences in the variabilities of annual average baseflow during both periods. The minimum, maximum, and interquartile range (IQR) values of annual average baseflow during the low anthropogenic activities period is lower than during the other period. During the former period, the baseflow of 1920 is detected as an outlier. The baseflows of 2010 and 2011 are also detected as outliers during the latter period. The years were strong La Niña

years based on MEI. Less and more rain periods have been link to El Niño and La Niña events, respectively, in the region [19, 18, 10, 11, 17].
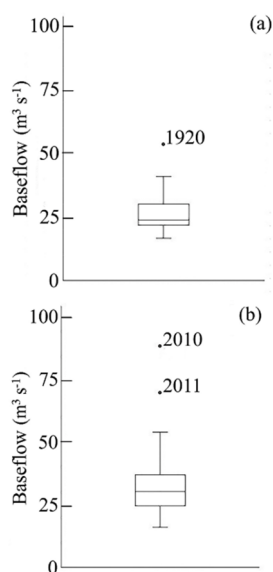

Figure 3. Box–and–whisker plots of baseflow in (a) the low and (b) high anthropogenic activities periods.

Figure 4 lends a further insight into the distributions of daily baseflow during the two study periods and shows that the distributions are significantly different (Kolmogorov–Smirnov Test; α = 5%). The distributions show that computed daily baseflows during the high anthropogenic activities period were occurring more often in all categories, except the lowest category, than during the other period. Daily baseflows in the lowest category (0–15 m³ s⁻¹) occurred more often during the low anthropogenic activities period than during the other period. On the other end, daily baseflows in upper categories (> 50 m³ s⁻¹) occurred more often during the high anthropogenic activities period than during the other period, especially in the highest category (150–300 m³ s⁻¹) in which no baseflow from the low anthropogenic activities period can be categorized. The recorded daily flows (Figure 5) show that higher daily flows were observed more often during the high anthropogenic activities period than during the other period. Because of the computation of baseflow in this study is based on the recorder daily flow, it is only logical that higher computed daily baseflows during the high anthropogenic activities period were occurring more often than during the other period (as shown in Figure 4).
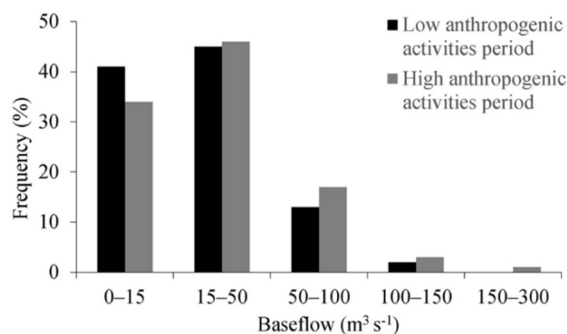

Figure 4. Bar chart plots of daily baseflow during the low and high anthropogenic activities periods.

It is also noticeable from Figure 5 that daily flows of 300 m³ s⁻¹ or higher occurred more often during the second-halves of the high anthropogenic activities period than during the period's first-halves. It should be noted that, during the second-halves of the high anthropogenic activities period, MEI shows more El Niño events with increasing intensity (not shown). This should translate to lower precipitation in the region during the events [19, 18, 10, 11, 17]. Because no trend in the computed baseflow during the period can be linked to the increasing annual precipitation in the region and no changes in physiography and morphology of the upper Citarum River basin, it is interesting to see if there were changes in the basin's runoff coefficient during the high anthropogenic activities period. Theoretically, land use and land cover changes can cause more overland runoff flowing into the river and, hence, higher streamflow.
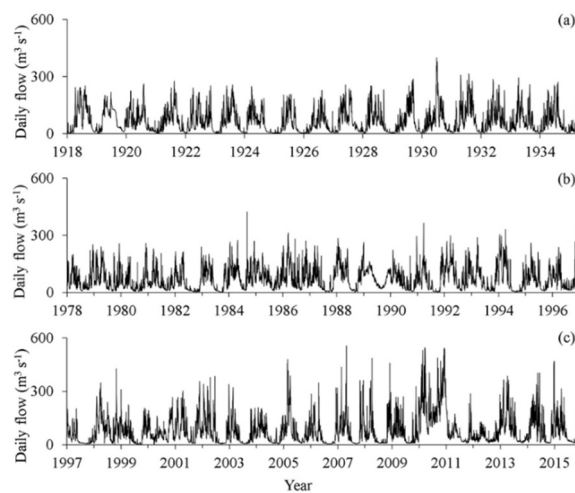

Figure 5. Recorded daily flows during (a) the low anthropogenic activities and (b) first-halves and (c) second-halves of high anthropogenic activities periods.

Figure 6 shows the increasing runoff coefficients of upper Citarum River basin from 1980 through 2009. The decadal runoff coefficient values are the ratios between total decadal volume of computed eventflow and total decadal volume of rainfall. Eventflow is the difference between recorded daily flow and computed baseflow, i.e. surface runoff that flows into the river. Rainfall daily data

(started from 1980) has been maintained and is collected from the Indonesian Meteorological, Climatological, and Geophysical Agency. Decadal values are used in order to get discernible results. It is shown from Figure 6 that the basin runoff coefficient is increasing by almost 20 % from its initial value (from 34 % to 41 %) during the 1980–2009 period, and significantly after 1990. Based on land use and land cover maps of the basin in 1994 and 2014 (not shown) from West Java Province Development Planning Council, massive land use and land cover changes happened between 1994 and 2014 resulting in changes of forested area (from around 51,400 to 17,700 ha) and urban area (from 46,300 to 62,200 ha).
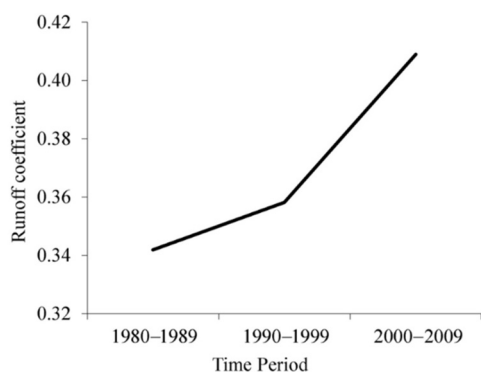

Figure 6. Computed decadal runoff coefficients of the upper Citarum River basin between 1980 and 2009.

On the interannual covariability side, Figure 7 shows results from wavelet analysis between MEI and baseflow during the low and high anthropogenic activities periods and between rainfall and baseflow during the 1980–2009 period. A very low number of correlations is shown in Figure 7 between MEI and baseflow during the low anthropogenic activities period. Significantly, more correlations are shown during the high anthropogenic activities period; during which MEI and baseflow are out-of-phase with MEI leading. Also shown in Figure 7 that rainfall is frequently correlated with baseflow, significantly more after 1990; during which rainfall and baseflow are in-phase with rainfall leading.

Results from wavelet analysis imply that ENSO events-related variability of the upper Citarum River flow is significantly more observable during the high anthropogenic activities period than during the other period. The low anthropogenic activities period is overlapping with unusually low variability, i.e. nearly quiescent, (1920–1960) period of ENSO system in which the correlation of the Citarum River reconstructed streamflow with Niño 3.4 SSTs is low [10]. After 1990, baseflow variability is more sensitive to rainfall variability. As the upper Citarum River basin's runoff coefficient is increasing during the 1980–2009 period (as previously shown), more overland runoff flows into the river and, hence, increasing the direct connection between rainfall and streamflow through overland runoff.
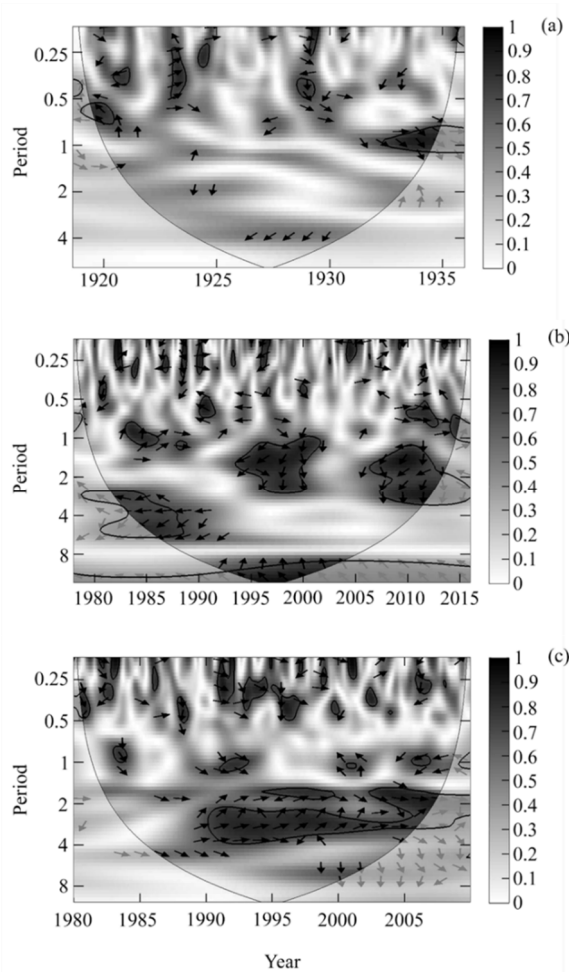

Figure 7. Wavelet analysis between MEI and baseflow during (a) the low and (b) high anthropogenic activities periods and (c) between rainfall and baseflow during the 1980–2009 period.

4 Conclusion

This study has analysed the upper Citarum River computed baseflow and eventflow variabilities during two periods: (1) from 24 October 1918 through 23 October 1935 (referred to as the low anthropogenic activities period); and (2) from 24 October 1976 through 23 October 2015 (referred to as the high anthropogenic activities period). Although no trend in daily flow and baseflow is detected during the two periods, higher interannual variability is shown during the latter period than during the former period. Further analysis shows that the two periods have significantly different baseflow distributions. The higher variability during the high anthropogenic activities period is found to be related with ENSO events. Analysis on rainfall–baseflow variability shows that, after 1990, computed baseflow variability is increasingly more sensitive to rainfall variability.

By applying a novel approach of analysing decadal values of separated eventflow, it is found that runoff coefficient of the upper Citarum River basin is increasing during a period between 1980 and 2009, especially after

1990. The period overlapped with a period of massive land use and land cover changes in the basin. Theoretically, the changes cause more overland runoff flows into the river and, hence, increasing the direct connection between rainfall and streamflow through overland runoff. Further study physically connecting the runoff coefficient and land use and land cover changes in the basin in order to explain their variabilities is needed.

Further intensification of tropical climate variability due to greenhouse warming has been suggested by [20]. With our results showing that ENSO events and human disturbances affect baseflow variability (this implicitly includes daily flow variability), water resources management, including water allocations for different activities, in the upper Citarum River basin and its downstream areas should be planned accordingly in order to support water security in the region.

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