E3S Web of Conferences **94**, 05004 (2019) https://doi.org/10.1051/e3sconf/20199405004
ISGNSS 2018

Zenith Wet Delay (ZWD) Seasonal Correlation with Rainfall in Cikapundung River Discharge, North Bandung Region, Indonesia

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Abstract. In a GPS survey study, the biases produced by the ionosphere and troposphere layers are known as ionospheric biases and troposphere bias. The distance deviation due to the slowing travel time of GPS signals in troposphere is commonly referred to as Zenith Tropospheric Delay (ZTD). The magnitude of this ZTD can also be used to characterize and analyze the troposphere conditions around the GPS observation area. This can be done by separating the wet delay component from ZTD, so as to obtain Zenith Wet Delay (ZWD) and dry component so as to obtain Zenith Hydrostatic Delay (ZHD). The total moisture content in the troposphere (precipitable water vapor, PWV) of an area can be estimated based on the bias characteristics of zenith wet delay (ZWD). The ZWD pattern is very important in the study of atmospheric water cycles which are associated with rainfall patterns and flood events. The methods used in the research include preliminary data processing and estimation of ZTD value using RTKLIB 2.4.2. This article analyzes the correlation between ZWD, rainfall and Cikapundung river discharge in the North Bandung Region (KBU), based on the daily average data in the 2011-2015 observation period. Based on the reconstruction of harmonic components, it was found that the seasonal pattern of river discharge is correlating with the seasonal pattern of rainfall and moisture content in the troposphere. The pattern of the three variables is strongly influenced by the Asian and Australian Monsoon exchanges phenomena. Linear correlation between ZWD and river discharge exhibits clear results, which is based on the Pearson correlation value is 88.84% with a 95% confidence level using t-student statistic. Based on cross-spectrum analysis, the three variables are dominated by the seasonal cycle of one-year monsoon (annual) and the six-month cycle phenomenon (semi-annual).

1. Introduction

The Cikapundung watershed starts from the upstream area in the north mountainous zone of Bandung into Citarum river as a part of the fluvial system. This system can be divided into three zones: production zones, transfer zones, and deposition zones [1]. The production zone is defined in the Lembang drainage basin (Cikapundung upstream watershed), where the entire river network in this basin at the Maribaya estuary. The transfer zone is defined starting from the Maribaya estuary (A) to Dago Curug (E), where the riverbed is closed by the basal layer. The deposition zone is defined from Dago waterfall to Citarum, which rivers flow on the alluvial base of pyroclastic sediments of the Sunda volcanic complex and lake sediments.

2. Data and Method

The data used in this study are: (1) Zenith wet delay (ZWD), at the ITB GPS-Continuous station (6^o 53 '29,501 "LS, 107^o 36' 43,229" BT) which has an elevation of 816,517 m with period of data collection from 2011-2015. (2) Daily debit of the Cikapundung river at Maribaya station (6^o 50 '11,000 "LS, 107^o 39' 23,500" BT) with an elevation of 1091 m from 1971-2016 discharge data observation. The Daily debit data obtained from West Java Province of PSDA. (3) BMKG Lembang station daily rainfall data (6^o 49 '35,600" LS, 107^o 37' 3,600 "BT), has an elevation of 1275 m with the 1977-2012 rainfall observation period. The location of the three observation stations (A, B, C) can be seen in Figure-1. The series of daily average times of ZWD and Cikapundung Maribaya river discharge for the 2011-2015 period can be seen in Figure-2.

To see the seasonal correlation between ZWD and river discharge, we calculate an averaging estimation of ZWD and river watershed from 2011-2015 data based on the reconstruction of seven dominant harmonic components. Then, the harmonic average pattern of river discharge from the period 2011-2015 (5 years) is then compared with the long period of 1971-2016 (46 years) normal harmonic average pattern. For Lembang rainfall data, because daily data is only available until 2012, only the normal harmonic average is reconstructed for the period 1977-2012 (36 years).

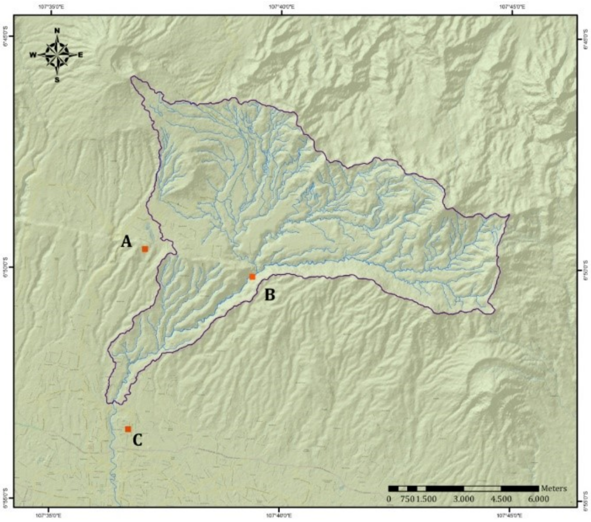

Fig. 1 Site location A. Lembang, B. Cikapundung-maribaya, and C. ITB-CORS

To measure the strength and linear relationship between ZWD and river discharge in the time domain, statistical tests were performed with Pearson Correlation. The linear correlation between harmonic components of the two variables mean was carried out in the frequency domain based on Cross Spectrum Analysis and Coherence.

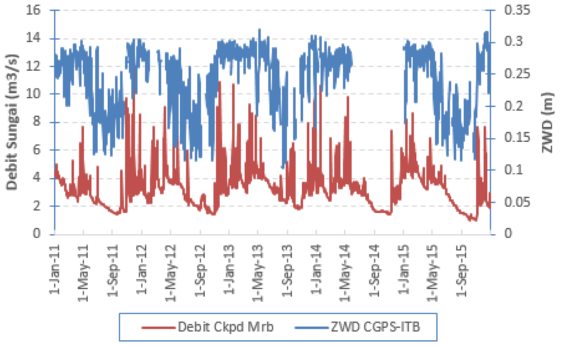

Fig. 2 Daily mean ZWD in ITB-CORS (b) and Maribaya station (r).

3. Results

Based on the data extraction of ZTD and ZHD from the ITB-CGPS results within 5 years observation (2011-2015) with interval epcoh of 30 seconds, ZWD data were obtained. The daily ZWD averaging process was carried out, i.e. 2880 total epochs. Based on the ZWD chart, there are some empty data, especially in 2014, indicating that there is no GPS measurement. The process of averaging ZWD in the daily database was done from Cikapundung river discharge data in the format of daily average data (the average of three times of manual observation from river water levels, at 07.00, 12.00 and 17.00 Indonesia Time). The average of debit represents daytime discharge conditions, hence the daily debit that obtained reduces the fluctuating value at night, while the daily ZWD data is the average result of day and night for 24 hours. ZWD charts and daily river discharge can be seen in Figure-2. The River debit data was estimated based on water level data through a rating curve. The daily debit of the Cikapundung River measured at Maribaya Station is an outlet discharge from the Cikapundung upstream watershed, covering all the rainfall patterns that caught by the Lembang Drainage Basin, hence all surface water flowing in river canals in this basin estuary into Maribaya's floodgate. Due to the unavailability of completed daily rainfall data within the Cikapundung Hulu watershed, the characteristic of the daily rainfall pattern that falls into the Lembang Basin was approached by rainfall data at the Lembang station which is located not far from the watershed area boundary (Figure-1).

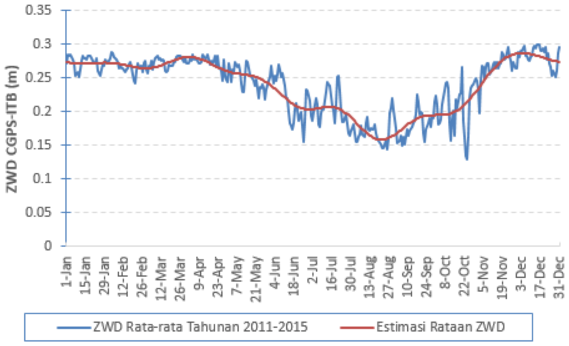

Fig. 3 Annual mean ZWD(b) and harmonic pattern reconstruction.

To obtain seasonal characteristics of ZWD, river discharge and rainfall, an annual cross-process is carried out on each corresponding date. For the Cikapundung Maribaya river discharge data, the seasonal pattern was obtained from averaging of 46 years observation (1971-2016), and the seasonal pattern of Lembang rainfall based on averaging of 36 years observation (1977-2012). As for the ZWD seasonal pattern, because the data is still limited to 30 years, the seasonal pattern obtained is only based on the average results over a period of 5 years (2011-2015). The seasonal pattern of ZWD and mean estimation can be seen in Figure-3.

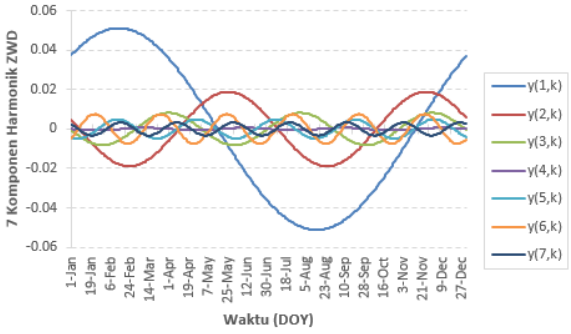

Fig. 4 7-harmonic components

The Harmonic Analysis method was carried out to estimate the average pattern of ZWD seasonal characters. By using the seven most dominant harmonic components, the estimated seasonal mean of ZWD can be reconstructed (Figure-3). The seven ZWD harmonic components that were successfully extracted can be seen in Figure-4. Using the same method, a seasonal average pattern for river discharge and rainfall was obtained. Especially for the river discharge, the estimated seasonal pattern was carried out both on the population scale (1971-2016 period) and the sample scale (2011-2016 period).

The average seasonal characteristics of the Cikapundung-Maribaya discharge pattern that are closer to the population conditions are shown by the 46-year average results (1971-2016), compared to the 5-year sample average results (2011-2015). Therefore, the seasonal characteristics of the average ZWD are more appropriate than the average discharge based on longer observations. In the graphical relationship between ZWD and river discharge on the sample scale, it appears to be a harmony between the two, especially around September to October (Figure-5).

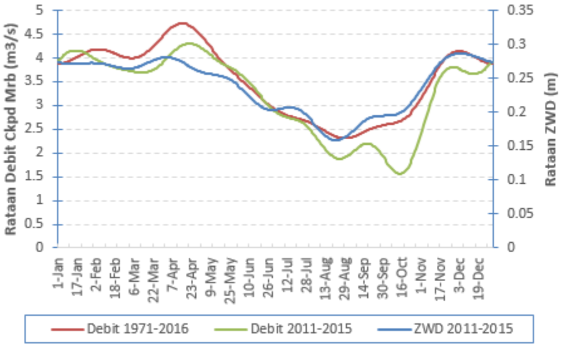

Fig. 5 Seasonal pattern ZWD and Cikapundung watershed

The most important results obtained from ZWD reconstruction are about seasonal character patterns, where the pattern of water vapor content in the troposphere of the North Bandung region is controlled by the dynamics of the monsoon wind circulation. Based on Figure-5 it can be seen that the average pattern of ZWD is closer to the average pattern of river discharge based on population averages. The closeness of the linear correlation value between the average ZWD and the average population discharge and the average sample discharge can be expressed by the correlation coefficient or determination of R2 coefficient, which have a value of 0.8956 and 0.7893. It means, almost 90% of the sample ZWD correlates with the average population discharge compared to the average sample discharge which only correlates around 79%, because the special conditions of the sample have been eliminated. The relationship between the two quantities is very strong at the 95% significance level.

ZWD measurement is very important in the study of the hydrological cycle, because the ZWD value can estimate the value of PWV (precipitable water vapor), which is about the potential of water vapor in the troposphere that can be transformed into water precipitation in the earth's surface, especially in the form of rainfall (Rakhecha & Singh, 2009). Because rainfall is a climatic element between the tropospheric moisture content and river discharge as surface water flow, the discussion is divided into two parts. First, about the response of river discharge to rainfall (Figure-6). Second, about the rainfall response to the accumulation of water vapor in the troposphere (Figure-7).

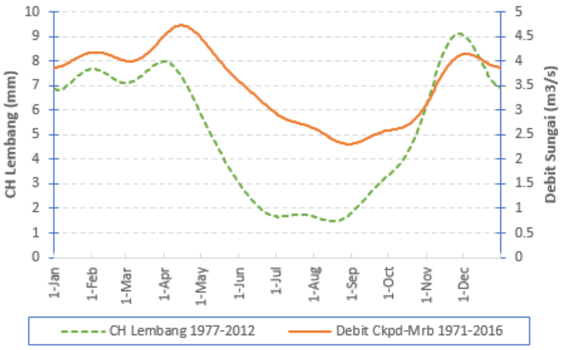

Fig. 6 Seasonal pattern ZWD 2011-2015 and seasonal debit 1971 - 2016

The measured discharge at Maribaya Station is from the Upper Cikapundung watershed which is a rain catchment area with an area of 74.881 km^2. Based on the average of the river discharge, the largest discharge occurred in April and the smallest discharge occurred in August. In general, the maximum discharge occurs at the peak of the rainy season and minimum discharge occurs at the peak of the dry season. Based on the normal nature of rainfall at Lembang station, the peak of rain occurs twice a year, namely in November (Asian Monsoon) and April (Australian Monsoon), where rainfall generated by the Asian Monsoon is greater than the Australian Monsoon.

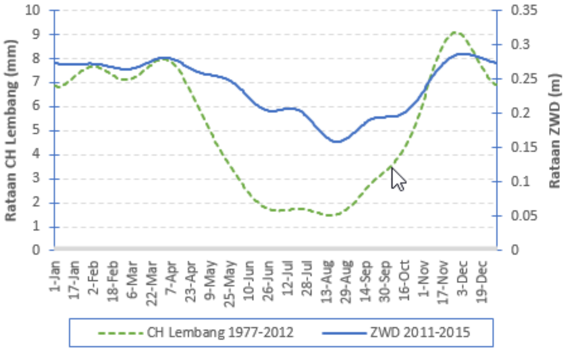

Fig. 7 Seasonal ZWD 2011-2015 and river debit (1971-2016)

The increase of delay in discharge responds related with the increase in the rainfall curve in the interval of several days to one week. This means, the overflow of river discharge waiting the land filling time by rainwater until reaches saturation. When the soil is saturated, rainwater will flow on the surface of the earth as runoff and then run into the river channels and increase the discharge quantity. Therefore, the peak of Cikapundung discharge occurs in the first week of April, after the peak of the second rainy season at the end of March. Although the peak of the rainy season occurs around the third week of November, the peak does not occur at the end of November because more rainfall is saturate to the soil. When a monsoon break occurs, the rate of discharge recession is not as deep as the rate of decline in rainfall because percolation of water in the soil takes longer. After a minor post-Monsoon discharge recession around the end of December and early January, discharge increases again due to Australian Monsoon rainfall and reaches its peak annual discharge after the land is saturated with Asian Monsoon rainfall. River discharge also responds to delay in the peak events of the Australian Monsoon (Figure-6).

Rainfall response to accumulation of water vapor in the troposphere. Based on the graph of rainfall and ZWD average (Figure-7), the maximum and minimum rainfall peaks appear in phase with the maximum and minimum conditions of ZWD. Because ZWD is related to PWV (precipitable water vapor), according to the graph it appears that rainfall is part of the realization of the total content of water vapor in the troposphere. Not all tropospheric moisture content is condensed further into cloud drops and becomes rainfall, because the rain clouds are formed random to space and time, the rainfall recorded at one Lembang station point does not represent the character of the whole bulk rain falling in the rain catchment area of the Lembang Basin. As the atmosphere is open, the condition of the total moisture content above the Lembang rainfall station and above the CGPS-ITB device is still assumed not significantly different. The horizontal distance between the two stations is around 7 km with a height difference of around 458.5 m.

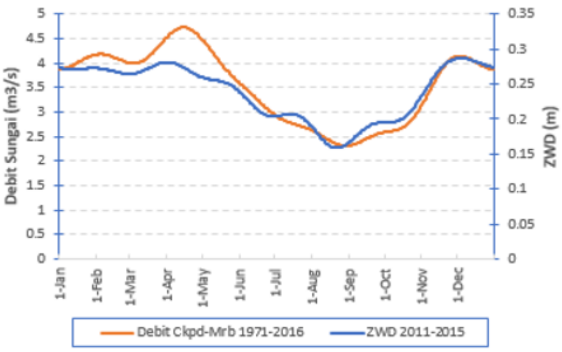

Fig. 8 Seasonal ZWD 2011-2015 and rainfall (1977-2012)

The water vapor content in the troposphere comes from the evaporation process of the ocean and the earth's surface by solar radiation. Therefore, seasonal fluctuations are controlled by variations in earth-sun distance and projections of the movement of the sun above the earth's surface in one year of revolution. This condition starts the dry season around the Lembang station which peaks around mid-August coincides with the minimum tropospheric water vapor condition.

Within one year there are two peaks of water accumulation (ZWD) and rainfall formed by two different monsoon mechanisms. The two peaks occur in November and April, where between the two peaks there is a decrease in rainfall (monsoon break), which is in the range from January to February. The rainy season in Java generally occurs when the sun's pseudo position is in the southern hemisphere, between the Equinox Autumnal (September 22) and Vernal Equinox (March 20). The North Bandung region experiences the peak of the first rainy season in mid-November, where the peak of the rain occurs before the sun reaches the southern turning point (Winter Solstice) on December 21th and before the earth reaches its closest distance to the sun on January 3rd (perihelion). The peak of the second rainy season occurs in the first week of April after the sun moves north past the equator. The first rainy season is generated by the westerlies of the Asian Monsoon, while the first rainy season is generated by the Australian Monsoon easterlies. Low pressure belts (monsoon troughs) migrate in the north-south direction and control winds that undergo a process of convergence in the intertropical convergence zone which accumulates water vapor in the troposphere and generates rainfall. This low-pressure belt migration follows the apparent movement of the sun that crosses Java twice a year. The peak of the rainy season does not occur when the sun is above the North Bandung horizon, which is in early October or early March, but occurs after the sun has passed the two months. This means that monsoon rainfall is not generated spontaneously through a pure convection mechanism, so the wind speed factor that lifts the air mass and the quantity of water vapor that condensed in the troposphere becomes very decisive.

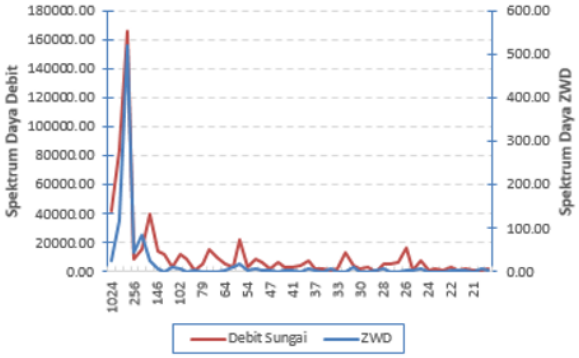

Fig. 9 ZWD power spectrum and Cikapundung debit

The peak of the first rainy season (November) occurs when the sun's projection has moved far south of Java, when the island is crossed by winds originating from Asia, where wind movements are controlled by temperature differences between the Asian region in the north and the Indian Ocean in the south. Winds that enter the Javanese land carry abundant water vapor which is supplied especially by the Java Sea when undergoing radiative heating. The abundance of water vapor from the Java Sea and Karimata Strait is caused by the shallow Sundaland Craton warming. In general, the sea surface temperature of these shallow waters is higher than the temperature of the deeper Indian Ocean.

It appears that monsoon rainfall in the North Bandung region is largely determined by the trade wind speed factor. Rainfall in this region is more a product of interaction between the trade winds that carry water vapor and local topographic factors, therefore rainfall in the Bandung Basin area is known as local type rainfall. The tropospheric moisture content and rainfall at the peak of the first rainy season are relatively higher than the second rainy season, because the supply of water vapor from the warming of the Sunda Shelf is more abundant than originating from the Indian Ocean.

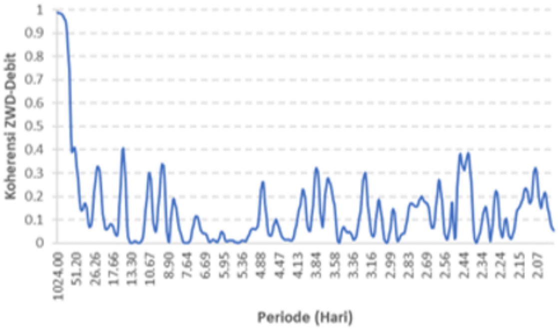

Fig. 10 ZWD coherence

Based on the graph of ZWD and river discharge (Figure-8) in general, the temporal patterns of the two quantities appear to be more correlated than rainfall, except in the second rainy season there appears to be an amplification of the discharge when the soil has reached saturation. Thus, ZWD can potentially be a good predictor of river hydrology systems rather than rainfall. Because the measured discharge at a river outlet includes all rainfall that falls on the watershed area instead of measured rainfall only on one observation station. The area of a watershed covers the area of the atmosphere above it and all possible events of condensation and precipitation that occur that fall into the watershed area.

Based on the ZWD power spectrum and river discharge (Figure-9), the two quantities are dominated by the components of the one-year monsoon cycle (11.22 monthly), while the discharge contains an intermediate component (6.70 monthly). Because the two spectra are processed based on a daily database that is limited to a data sample of only five years (2011-2015), the seasonal signals fall in the low-resolution spectral area. Meanwhile, based on the 46-year data range (1971-2016) several other important cycles can emerge with more accurate period values. With a longer daily data range, we obtained river discharge cycles 11.91 (annual), 6.02 (semi-annual), 4.0 monthly in respectively. These three cycles are the main rainfall generators which generate seasonal patterns of rainfall and river discharge in the North Bandung area (Tanuwijaya et al., 2018). Not every rainfall station in Java has a semi-annual and 4-month component, especially at stations located in coastal areas (Tanuwijaya & Liong, 2002)

Because the length of ZWD data is still limited, it cannot be confirmed about the existence of the mid-year and 4-month cycles of the moisture content in the troposphere. However, for a one-year dominant cycle, it can be confirmed that there are relatively no phase differences between the seasonal patterns of ZWD and river discharge, as visually shown by the temporal pattern of both (Figure-8). Both quantities have the same dominant spectrum period value of 341.33 daily (Figure-9), the coherence value or linear correlation in the frequency domain is close to 1 namely 0.985 (Figure-10), and the cycle phase difference value is close to zero which is 0.0084 (Fig. 11).

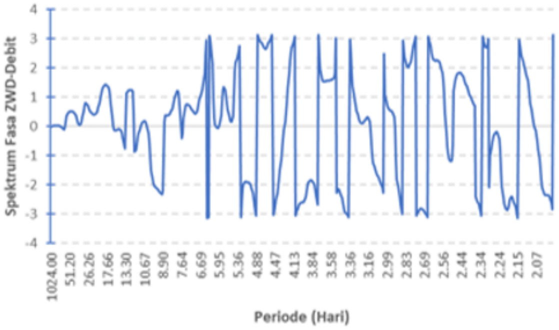

Fig. 11 ZWD phase spectrum

4. Conclusions

The amount of ZWD in the CGPS-ITB data for the period 2011-2015 is between 10-35 cm/year. The mean values of harmonic from ZWD daily correspondent with the harmonic mean of the daily average Cikapundung river discharge at Maribaya station, even though the horizontal distance and the height difference of the two stations are about 7 km and 458.5 m respectively. The sample ZWD average (2011-2015) correlates with the average debit based on a long-range data (1971-2016) compared to the average debit based on the sample data in the same year (2011-2015), the correlation around 90 % and 78%. Due to the data continuous, ZWD has the potential to be an excellent predictor of river hydrology systems compared to rainfall data from a single station.

Concerning with rainfall and river discharge, ZWD as the quantity associated with the moisture content of the troposphere in the North Bandung region which controlled by the exchange dynamics of Asian Monsoon and Australian Monsoon. The three data have the same one-year cycle (annual) component as the most dominant component. Daily ZWD data in the 5-year sample range (2011-2015) have not been able to generate semi-annual and 4-monthly cycles, as can be seen in rainfall data and river discharge.

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