GNSS METEOROLOGY AND LAND SUBSIDENCE OF HEAVY RAINFALL IN JAKARTA ON JANUARY 1, 2020

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ABSTRACT

This study aims to demonstrate that GNSS meteorology can be applied in Indonesia, by estimating the zenith troposphere delay (ZTD) of sustainable GNSS stations in Indonesia, using one of the "goGPS" software packages. As a calculation with rain conditions, the ZTD value was converted into precipitation water vapor (PWV). This research is using GNSS meteorology to be applied into heavy rains at the end of 2019 in Jakarta which was hit by floods on December 31, 2019. According to a report by Geophysical Meteorology and Climatology Agency (BMKG), the main cause of this flood is a high rainfall. The rainfall gauge at Halim Perdana kusuma Station showed 377 mm of rainfall that day. Rain gauges at Taman Mini and Jatiasih stations record rainfall of 335 mm/day and 260 mm / day, respectively. From the GNSS data processing, the PWV values at the five GNSS stations show a similar pattern even though the average between stations is ~ 30 km. The PWV value appeared to be increased at noon on December 30, 2019, and the peak occurs at the end of the day on December 31, 2019. The PWV value showed a sudden drop at midday on January 1, 2020. In the end, the PWV increased again, but not as high as the first peak. From 2 January 2020, the PWV has decreased and has been maintained almost constantly until 4 January. Within this time frame, there were two peak PWV events. The PWV of the first peak was ~ 70 mm and the second peak was ~ 65 mm, and the largest peak PWV was recorded at the CJKT station.

Keyword: GNSS, troposphere, PWV, heavy rain

Introduction

In GNSS data analysis to obtain tropospheric parameters and station positions of the study of GNSS meteorology, Arief and Heki (2020), has downloaded the data from appropriate data sets available from various research centers, such as UNR and GSI. Arief and Heki (2020), studies were performed for heavy rain episodes in the Japan area where a large number of GNSS stations are available. This study analyzed the GNSS data taken in Indonesia and estimating tropospheric parameters as well as station positions using an alternative way, such as analyzing the data using an appropriate GNSS software package. UNAVCO(https://www.unavco.org/software/datapro cessing/potprocessing/postprocessing.html) stated that there are 3 distributions of GNSS software based on their use: "Research-Level", "Open-Source" and "Commercial". The usage of Open-Source software in Indonesia is quite promising and will develop rapidly in the future, considering that it is easy to obtain and simple to operate in order to get results. The concept of ground- based GNSS meteorology was proposed initially by Bevis et al. (1992). Nowadays, GNSS meteorology has become one of the essential means to observe precipitable water vapor (PWV), and PWV data from GEONET have been assimilated in the mesoscale model of JMA to improve weather forecast accuracy since 2009 (e.g. Shoji, 2015).

Miyazaki et al. (2003) focused on such atmospheric delay gradients and showed that the temporal and spatial variations of the gradients were compatible with the humidity fields derived from ZWD and with the meteorological conditions in 1996 summer over the Japanese Islands (especially during a front passage). Shoji (2013) and Brenot et al. (2013) demonstrated the important role of the atmospheric delay gradients to detect small- scale structures of the troposphere than ZWD.

Recently, Zus et al. (2019) have successfully processed the Central Europe GNSS network data to show that the interpolation of ZWD observed with a sparse network can be improved by utilizing tropospheric delay gradients. They showed significant accuracy improvement for the simulation of the numerical weather model, and for the agreement of the simulation results with real observations, relative to the cases without utilizing tropospheric delay gradients.

Figure 1. Map of the areas in Greater Jakarta showed the likely flooded areas (light blue pixels), based on synthetic aperture radar satellite data before (21 December 2019) and during (02 January 2020) the flood event. Based on the web page https://earthobservatory.nasa.gov/images/146113/tor rential-rains-flood-indonesia

The purpose of this study is to show that GNSS meteorology can be applied in Indonesia with a limited number of GNSS Networks, unlike in Japan, where the GNSS network is very large (Arief and Heki 2020). GNSS meteorology was calculated by estimating the peak tropospher- ic delay (ZTD) of continuous GNSS stations in Indonesia, using one of the “goGPS” software packages. In this study, GNSS meteorology was applied to the heavy rain events in ear- ly 2020 in Jakarta to analyze the correlation between rainfall and the land subsidence in the heavy rainfall area. Jakarta suffered from a flood on January 1, 2020.

According to a report from the Indonesian Meteorology and Climatology Geophysics Agency (BMKG), the main cause of this flood was a heavy rainfall. The rain gauge at the Halim Perdanakusuma station showed the rainfall of 377 mm on that day. The rain gauge at the station Taman Mini and Jatiasih recorded rain amounting to 335 mm/day and 260 mm/day, respectively. This rainfall distribution covered a large area and was quite high in value as shown in Figure 1.

Methodology

GNNS Data Set

The primary format of the GNSS data used in this study is the Receiver Independent Exchange (RINEX) format. Next, RINEX files was processed to estimate tropospheric parameters using sophisticated open-source GNSS software called goGPS, version 1.0 Beta, from Geomatics Research and Development s.r.l. - Lomazzo, Italy (Realini, 2009). In the flood area, there were at least 5 GNSS stations has been identified and managed by BIG in the INACORS network. The 5 stations include CJKT in Jakarta, BAKO in Bogor, CBTU in Cibitung, CRKS in Cirakas, and CTGR in Tangerang. GNSS data was obtained on the INACORS network using RINEX format. The data was used over 7 days, from 29th December 2019 to 4th January 2020 to obtain the phenomenon including the changes in several days before and after the flood and heavy rain.

The wet tropospheric delays were converted to PWV (Perceptible Water Vapor) in every 30 seconds. Large PWV brings intensive rainfall, and the record- making rainfall data from BMKG on 1 January 2020 have been associated with high PWV values. The vertical crustal movements have been analyzed as well using coordinates obtained by analyzing the RINEX data of goGPS software.

Software goGPS

The leading software for processing RINEX data, goGPS. (Realini, 2009), is an open-source software initially developed by Dr. E. Realini (with contributions from the various thesis works by master students) since 2007 at the Geomatics Laboratory of Politecnico in Milano, Como Campus. It is specifically designed to improve the positioning accuracy of low- cost GNSS devices by relative positioning and the Kalman filtering technique. goGPS code was published online as free and open- source software in 2009. The project is open to collaborations since its publication, and it has received supports and code contributions from users working in both academy and business companies in different countries (including Italy, Japan, Switzerland, Spain, and Germany). Strategies for processing RINEX data with goGPS are as shown below.

Table 1. Strategies for processing RINEX data with goGPS

	goGPS 1.0 Beta
Strategy	Constellation: multi GNSS Processing technique: precise point positioning (PPP) Elevation cut-off angle: 7° Data processed in two 24 h sessions (from 00:00 to 24:00 UTC and from 12:00 UTC on day *D* to 12:00 UTC on day *D*+1) Frequency: L1, L2
Orbits and clocks	Fixed to JPL final orbits and clocks
Observation rate	30s sampling rate
Observation weighting	Uniform - all observations equally weighted
Tropospheric modeling	Niel Mapping Function Macmillan Mapping function for gradients A-priori zenith delay - VMF gridded zenith delays Meteorological data - Standard Atmosphere
Tropospheric estimates	One ZWD per 30 seconds, One tropospheric gradient per 30 seconds

Land Subsidence in Jakarta

Secular land subsidence in Jakarta, due to urbanization, has been studied over a long time. For example, Andreas et al. (2019) showed that Jakarta, compared with major cities on the coast of other countries, occupies the first position in terms of land subsidence from 1920 until now (Figure.2). Jakarta is vulnerable to further land subsidence, especially when heavy rain occurs and rainwater pools to cause a flood.

This study discussed the temporary land subsidence related to the occurrence of heavy rain on January 1, 2020, using the GNSS data analyzed with the open-source software goGPS. When heavy rain occurs, the water will gather at the surface of the land. This makes water loads to depress the ground surface and make it subside.

Result and Discussion

Determination of PWV values at 5 INACORS stations

This study analyzed the crustal movements for the recent heavy rainfall event in Indonesia on January 1, 2020. This rain caused severe flooding around the Jakarta area and would be an appropriate case to study crustal deformation by surface rainwater load.

RINEX data obtained from the INACORS-BIG network has been analyzed using the goGPS open-source software package, as explained in Software goGPS section. Before studying crustal deformation, the ZTD value was estimated, and then it was isolated and converted into PWV. Figure.3 shows the result of the PWV time series at five INACORS stations evenly distributed within the flooded area on January 1, 2020.

Figure 3. Time series of PWV values at 5 INACORS GNSS stations in the Jakarta flood area. The time spans from 29 December 2019 to 4 January 2020 (UT), and the highest PWV value occurred on December 31, 2019

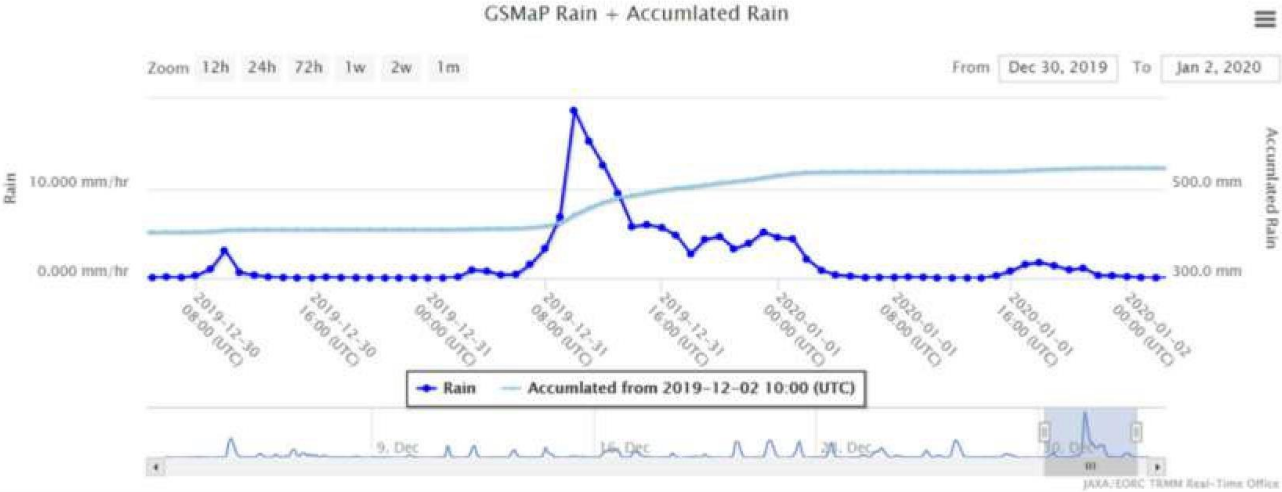

Figure 4. Rain rate and cumulative rain on December 31, 2019, according to the hourly rainfall data set from JAXA Global Rainfall Watch. The highest rainfall peak occurred around 10.00 am (UT) on that day.

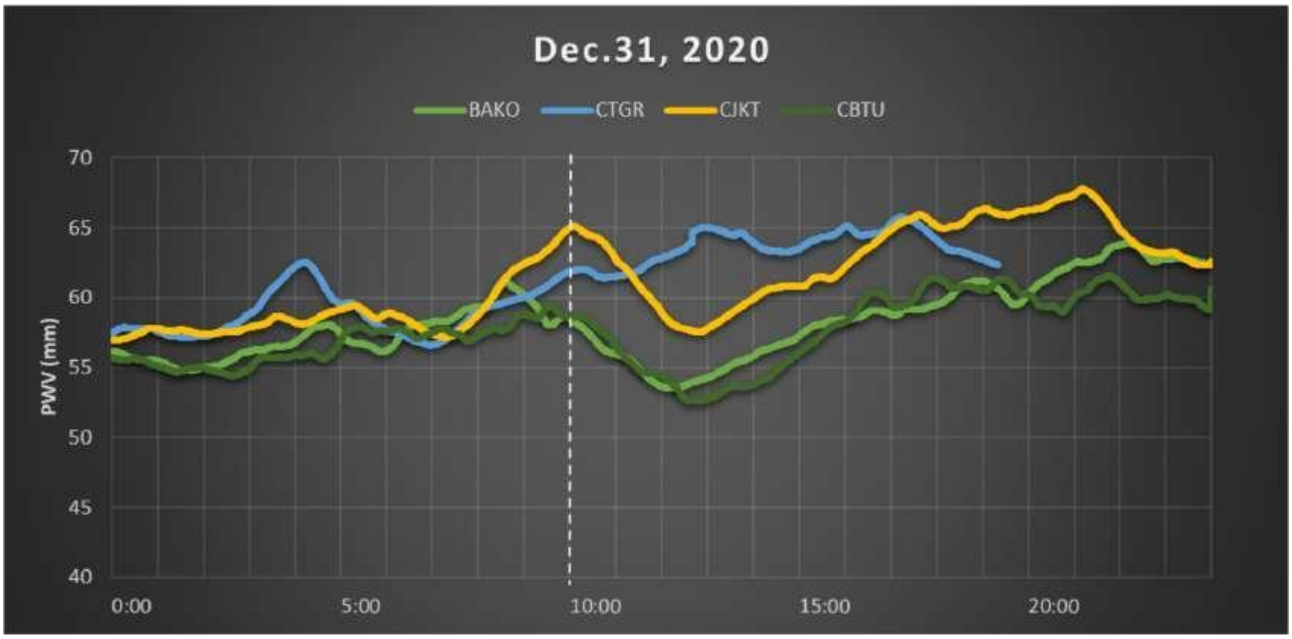

Figure 5. Hourly PWV values at 4 INACORS GNSS stations, BAKO, CTGR, CJKT, and CBTU stations during the day of December 31, 2019. PWV time series show maxima at 10.00, the peak rain rate time, at CJKT and BAKO stations.

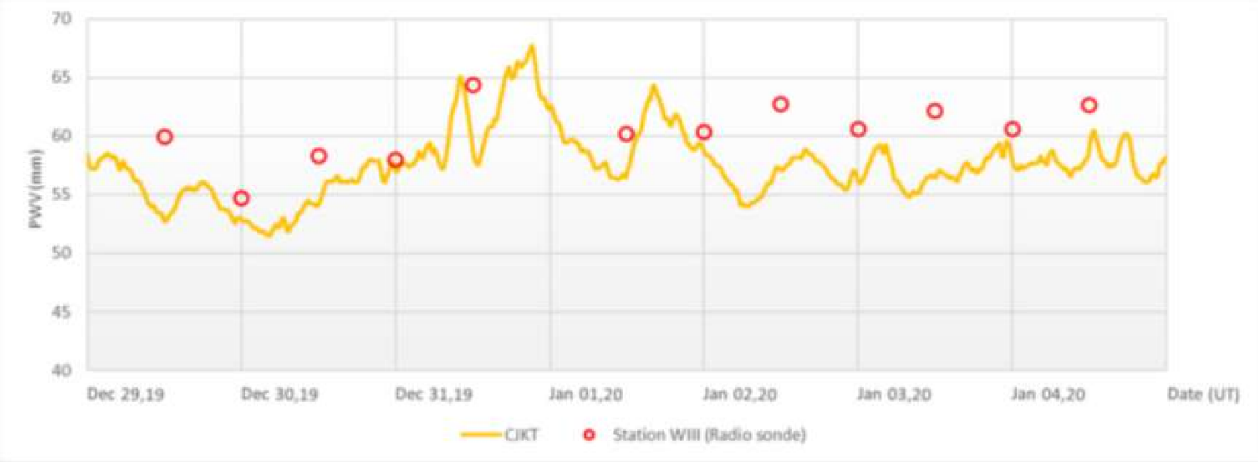

Figure 6. Comparison of PWV values between GNSS-PWV at CJKT stations estimated every30 seconds (orange curve) and radiosonde-PWV recorded every 6 hours at the WIII station (red circle). The correlation coefficient between PWV data from GNSS and radiosonde

As seen in figure 3, the PWV values at the five GNSS stations show similar patterns despite the average inter-station of ~30km. PWV values appear to increase in the middle of the day of 30 December 2019, and the peak occurred at the end of the day of 31 December 2019. This condition is consistent with the date of heavy rain as discussed.

The PWV value showed a sudden drop in the middle of the day 1 January 2020. At the end of the day, PWV increased again, but not as high as the first peak. From January 2, 2020, PWV decreased and kept nearly constant until January 4. In this time range, there were two peak PWV occurrences. The first peak PWV of ~70 mm and the second peak of ~65 mm, and the largest PWV were recorded at the CJKT station. Next, the rainfall events on 31 December 2019 were analyzed using data from

JAXA Global Rainfall Watch, which offers hourly rainfall data. Figure.4 shows the hourly rainfall in Jakarta and surrounding areas obtained from this data set. The increase in rainfall starts at 07.00 (UT) until the peak at 10:00 (UT). Next, this information was compared with the hourly PWV values at GNSS stations shown in Figure 5.

Comparison of PWV INACORS with Jakarta Radiosonde Station

To compare the GNSS-PWV values with those by other sensors, the PWV data was obtained by radiosondes at BMKG, Jakarta. BMKG serves not only as of the GNSS stations but also as a radiosonde station in Jakarta with the name WIII station. Its primary purpose is to serve for flight at the Soekarno Hatta Airport, Cengkareng, Jakarta.

The radiosonde PWV data are compared with the PWV data obtained by an INACORS station in Jakarta CJKT as shown in Figure.6.

The correlation between the two PWV values is not so high, probably because of the distance between the two stations. Nevertheless, at least the PWV from GNSS stations can complement the radiosonde data with their high spatial and temporal resolution.

Crustal movement analysis, GNSS station (INACORS-BIG)

Next, the hypothesis about temporary vertical movements of GNSS stations reflect has been tested to some extent of surface loads such as rainwater. The vertical positions of the GNSS stations have been estimated to study vertical crustal movements during the floods on January 1, 2020, and heavy rains on December 31, 2019. The vertical positions have been calculated during a period from

10 days before the flood (December 22-31 December 2019) to 9 days after the flood. (2- 10 Jan 2020).

The GNSS data in RINEX format was used in this research, with supporting data for the sat- ellite ephemeris. The software outputs topo centric coordinates, composed of north-south, east-west, and vertical movement compo- nents. The vertical movements are very inter- esting because the water load will depress the ground vertically. The vertical coordinate time series have been plotted in Figure 7.

From the 5 GNSS-INACORS stations located in the Jakarta flood area, data on 1 Jan 2020 from the BAKO station could not be processed because the data had experienced an interruption during the acquisition process.

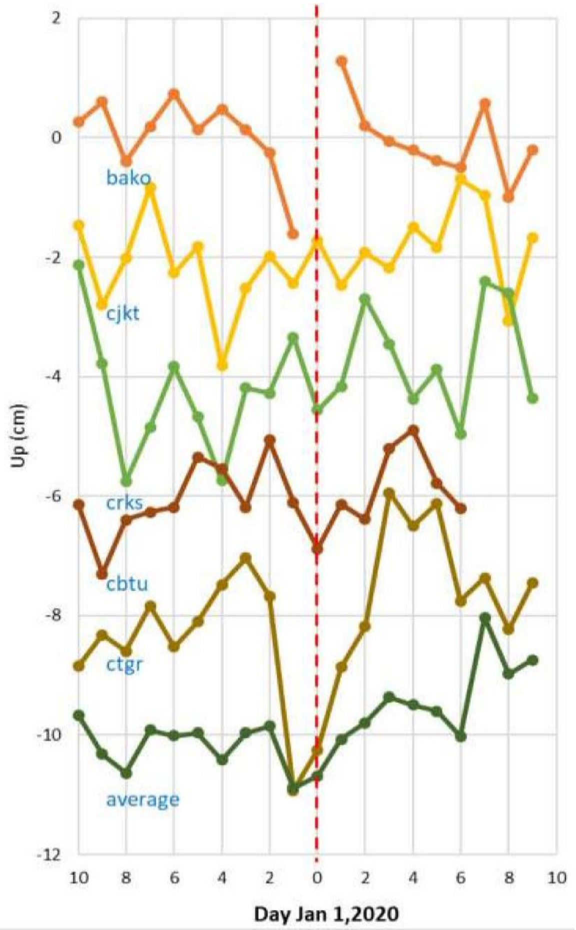

Figure 7. Vertical position time series spanning 20 days for the 5 GNSS stations in the region flooded by the January1st, 2020, Jakarta heavy rain. The station Bako had a data interruption on January 1, 2020.

Figure 7 shows that the average vertical coordinates show significant subsidence of nearly 1 cm on December 31, 2019, and January 1, 2020. However, coordinates of the individual stations behave differently. For example, subsidence on December 31, 2019, was seen only at BAKO and CTGR stations. Subsidence on January 1, 2020, was clear for the CRKS, CTGR, and CBTU stations. These stations were located in the flooded area (a light blue colored region in Figure 1). On the other hand, CJKT was close to the coast and not included in the flooded area. These results suggest that subsidence due to flood water load is quite non-uniform in space, and a dense network would be needed to fully understand the crustal response to the surface storm water load in Indonesia.

Conclusion

Using the method from goGPS, GNSS data was analyzed from INACORS, Indonesia's permanent GNSS network. to study tropospheric parameters and scale descent. In the first result, the PWV value was obtained from GNSS data from Jakarta when there was heavy rain on January 1, 2020. Then, the consistency was compared with the closest radiosonde observation results. This showed a suitable correlation between the PWV value although it is small since it has been influenced by the distance of GNSS and radiosonde stations.

Finally, the crust movement has been analyzed using goGPS method with similar GNSS data. The results showed vertical movements during heavy rain in Jakarta, namely all GNSS stations in the Jakarta area showed a significant change from December 31, 2019, to January 1, 2020. This shows that flooding in Jakarta caused temporary land subsidence. Therefore, further study is needed to compare other times or places with the occurrence of the same phenomenon.

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