Chapter 6. GNSS Meteorology and land subsidence at heavy rainfall in Jakarta on January 1, 2020

6.1 Introduction

In the GNSS data analysis to obtain tropospheric parameters and station positions, study GNSS meteorology in Arief and Heki (2020), did not estimate them myself but downloaded them from appropriate data sets available from various research centers, such as UNR and GSI. Arief and Heki (2020), studies are performed for heavy rain episodes in the Japan area where large number of GNSS stations are available. In this study, I try to analyze the GNSS data taken in Indonesia. Here, I estimate tropospheric parameters as well as station positions using an alternative way, i.e. data analysis made by myself using an appropriate GNSS software package.

UNAVCO (https://www.unavco.org/software/data-processing/postprocessing/postprocessing.html) says 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 considering that it is easy to obtain and simple to operate to get results.

The goal of this chapter is simply to show that GNSS meteorology can be applied in Indonesia as well as in Japan (Arief and Heki 2020), by estimating zenith tropospheric delays (ZTD) from continuous GNSS stations in Indonesia, using one such software package "goGPS".

In this chapter, I try to apply the GNSS meteorology to the heavy rain events in early 2020 in Jakarta, and to study 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 was the 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 covers a large area and is quite high in value as in Figure 6.1

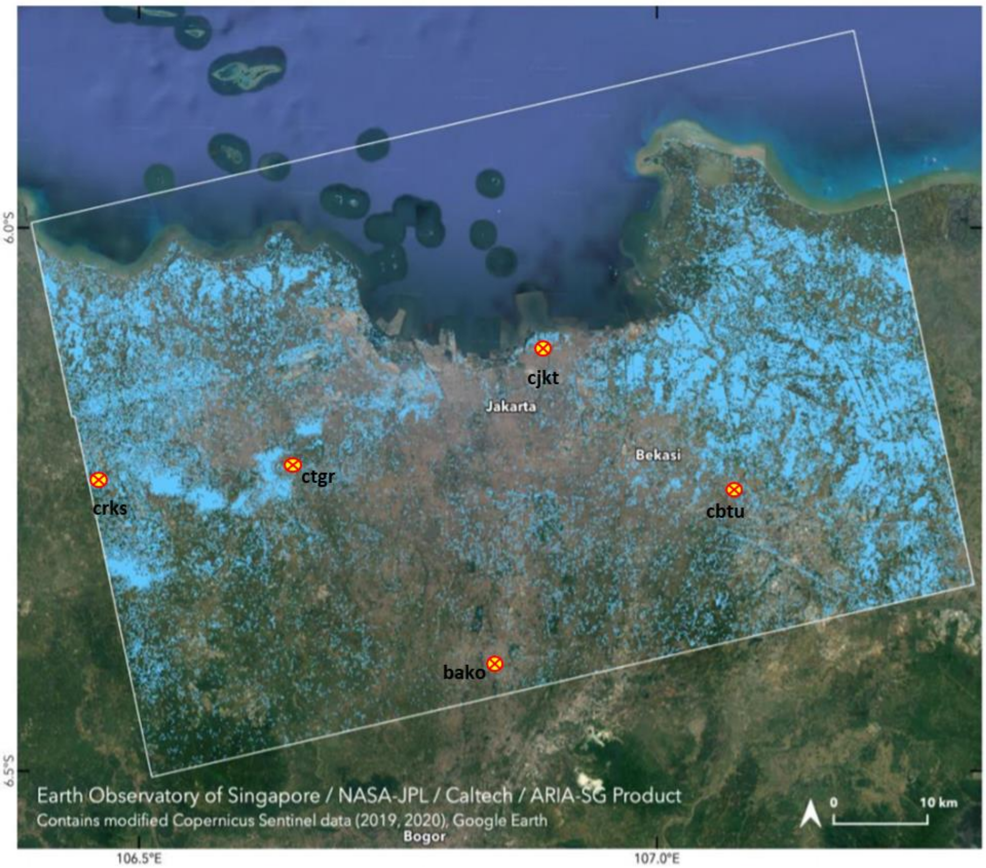

Figure 6.1, Map of the areas in Greater Jakarta showing the likely flooded areas (light blue pixels), based on synthetic aperture radar satellite data before (21 December 2019) and during (02 January 2020) the flood event. Based on the web page https://earthobservatory.nasa.gov/images/146113/torrential-rains-flood-indonesia, I identified at least 5 GNSS stations with separations of ~30 km from each other.

The largest rainfall of 377 mm/day is recorded in BMKG, and this is the highest value in the history of rain records in Jakarta. Jakarta, as the capital city of Indonesia, is an important area that should get attention related to the occurrence of floods due to heavy rains. Today, GNNS has been widely used for meteorological purposes, as explained in (Arief and Heki 2020), in addition to the primary function for measuring crustal movement and for mapping surveys. Here, I tried to analyze the link of heavy rainfall to the temporary land subsidence using the GNSS data. The data were provided from the INACORS network of the Indonesian Geospatial Information Agency (BIG).

6.2 Data and Methods

6.2.1 GNNS data set

The primary format of the GNSS data that I use in this study is the Receiver Independent Exchange (RINEX) format. Next, I process RINEX files 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, I identified at least 5 GNSS stations 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. I obtained the GNSS data on the INACORS network in the RINEX format. I used the data over 7 days, from29th December 2019 to 4th January 2020 in order to see the phenomenon including the changes several days before and after the flood and heavy rain.

The wet tropospheric delays are converted to PWV (Precipitable Water Vapor) every 30 seconds. Large PWV brings intensive rainfall, and the record-making rainfall data from BMKG on 1 January 2020 would have been associated with high PWV values. I also analyze the vertical crustal movements using coordinates obtained by analyzing the RINEX data using the goGPS software.

6.2.2 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 by 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,

goGPS 1.0 Beta	
Strategy	Constellation: multi GNSS Processing technique: precise point positioning (PPP) Elevation cut-off angle: 7° Data processed in a two 24 h sessions (from 00:00 to24:00 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

6.2.3 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 since 1920 until now (Figure 6.2). Jakarta is vulnerable to further land subsidence, especially when heavy rain occurs and rainwater pools to cause a flood.

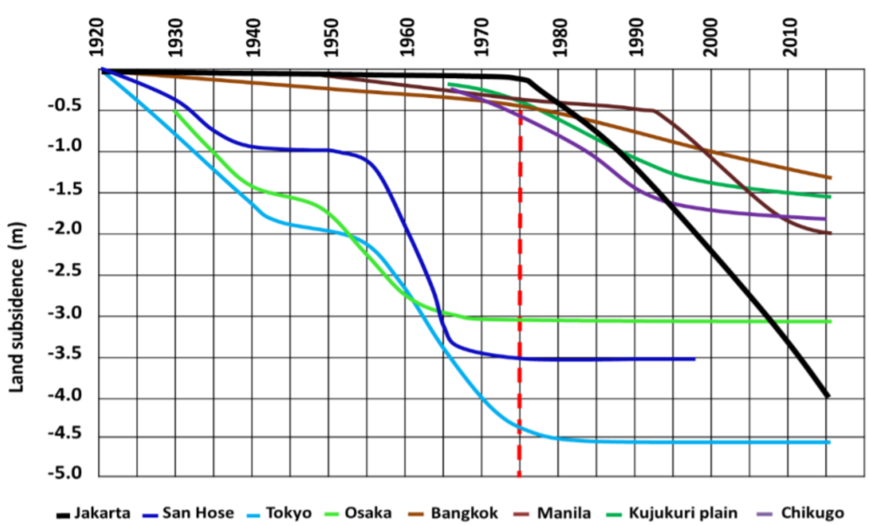

Figure 6.2, Land subsidence in several coastal city in different countries including Jakarta, Indonesia, from 1920 until recent years (Andreas et al., 2019).

In this study, I discuss 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 the 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.

6.3 Result and discussions

6.3.1 Determination of PWV values at 5 INACORS stations.

Here I try to study the crustal movements for the recent of 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.

I analyzed the RINEX data obtained from INACORS-BIG network, using the goGPS open-source software package, as explained in sub section 6.2.2. Before studying crustal deformation, I estimated the ZTD value, and then isolated the ZWD value, and converted the ZWD value into the PWV. In Figure 6.3, I show the result of the PWV time series at five INACORS stations evenly distributed within the flooded area on January 1, 2020.

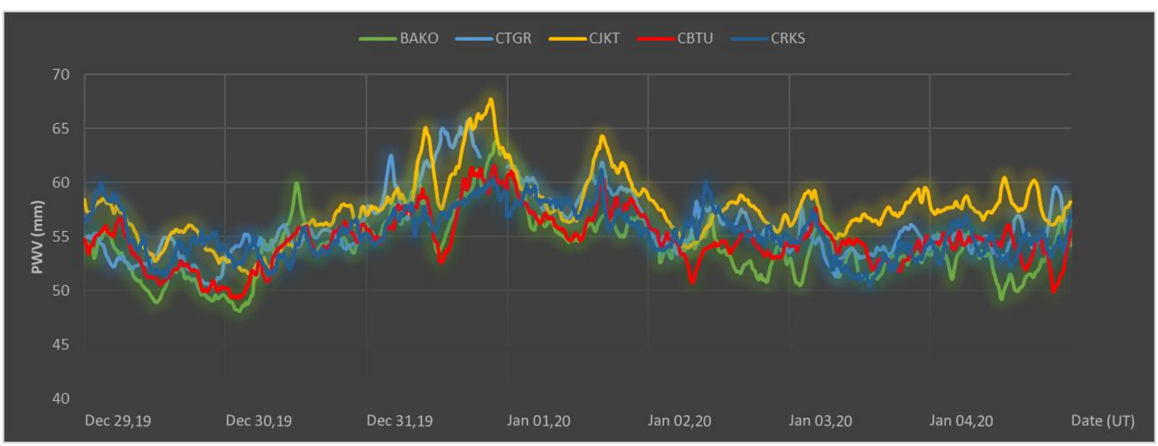

Figure 6.3. Time series of PWV values at 5 INACORS GNSS stations in the Jakarta flood area. The time spans from 29 December 2019 to 4 January 2020 (UT), and the highest PWV value occurred on December 31, 2019.

As seen in Figure. 6.3, the PWV values at the five GNSS stations show similar patterns even in spite of 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 in Section 6.2.

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 was recorded at the CJKT station.

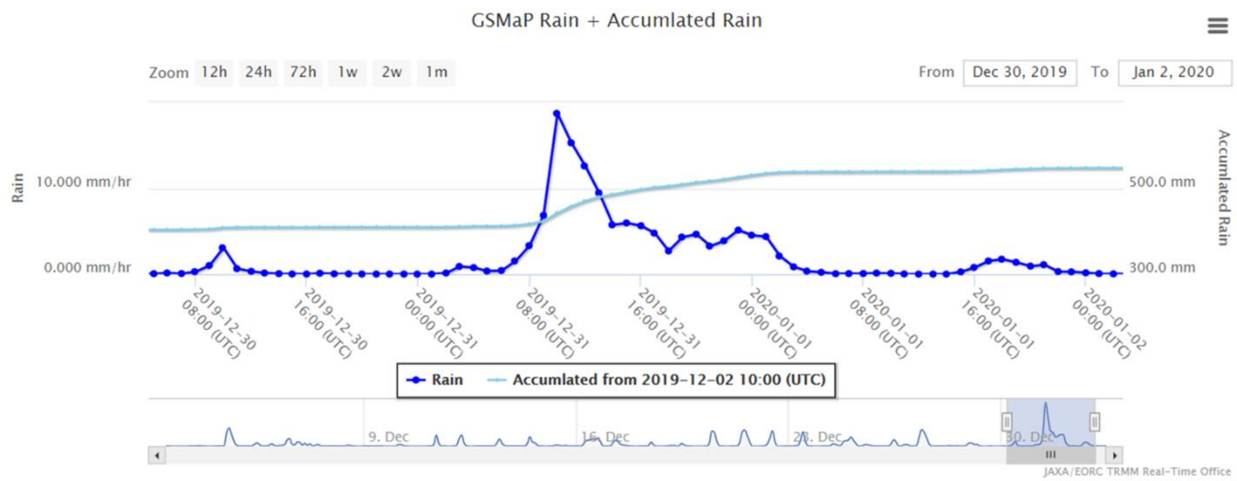

Figure 6.4. Rain rate and cumulative rain on December 31, 2019, according to the hourly rainfall data set from JAXA Global Rainfall Watch. The highest rainfall peak occurred around at 10.00 am (UT) on that day.

Next, I analyze the rainfall events on 31 December 2019, using data from JAXA Global Rainfall Watch, which offers hourly rainfall data. Figure 6.4 shows the hourly rainfall in the 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, I compare this information with the hourly PWV values at GNSS stations shown in Figure 6.5,

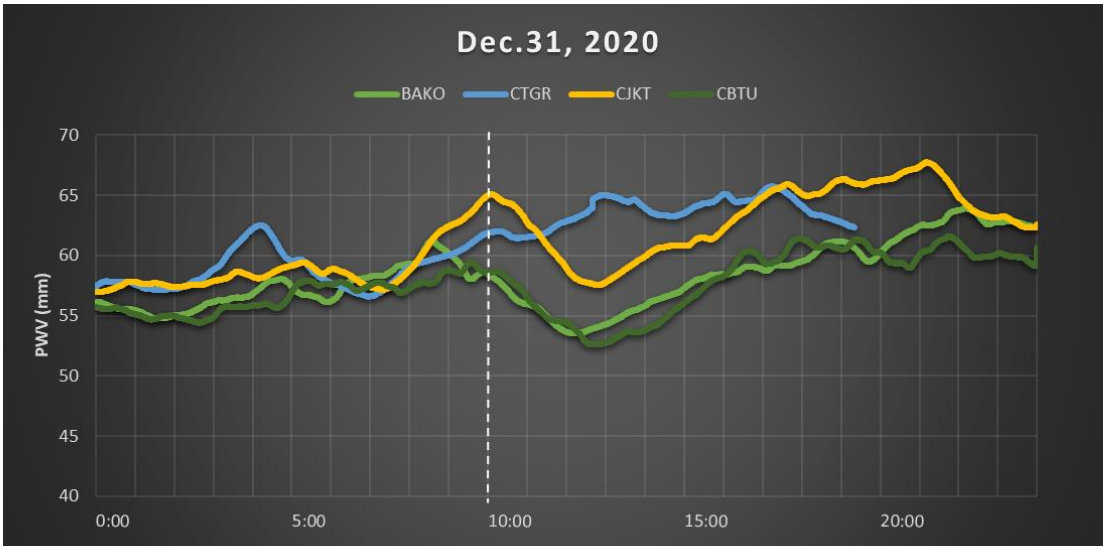

Figure 6.5. Hourly PWV values at 4 INACORS GNSS stations, BAKO, CTGR, CJKT, and CBTU stations during the day of December 31, 2019. PWV time series show maxima at 10.00, the peak rain rate time, at CJKT and BAKO stations.

As seen by comparing Figure 6.4 and Figure 6.5, the rainfall and PWV time series show consistent behaviors. This explains that the heavy rain peak occurs when the PWV value is at its peak. It also indicates that the heavy rain caused a sudden drop of PWV from 10:00 to 12:00, which means that water vapor changed into liquid water (heavy rain). This suggests that monitoring the GNSS-meteorology data from INACORS is useful as a meteorological observation.

6.3.2 Comparison of PWV INACORS with Jakarta Radiosonde Station

To compare the GNSS-PWV values with those by other sensors, I obtained the PWV data by radiosondes at BMKG, Jakarta. BMKG serves not only as 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 in Figure 6.6.

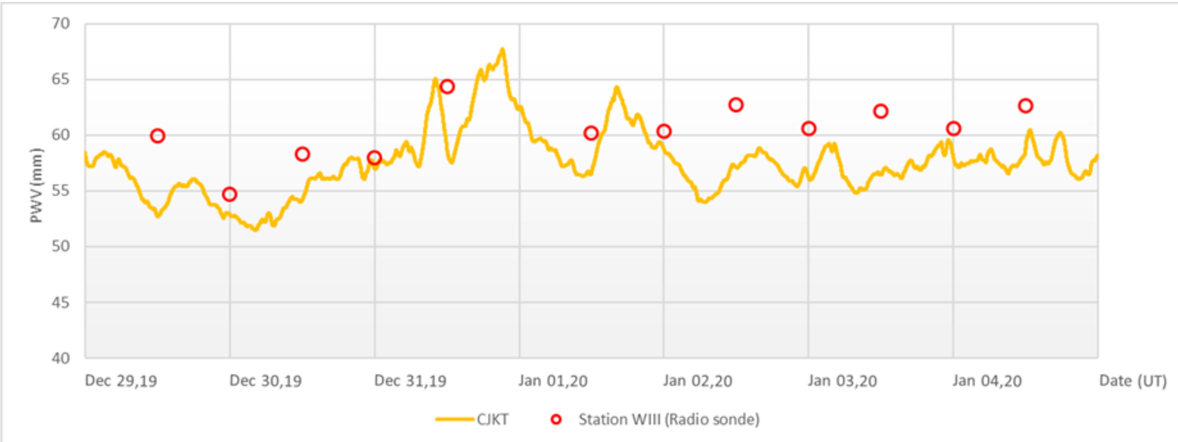

Figure 6.6 Comparison of PWV values between GNSS-PWV at CJKT stations estimated every 30 seconds (orange curve) and radiosonde-PWV recorded every 6 hours at the WIII station (red circle). Correlation coefficient between PWV data from GNSS and radiosonde is 0.541. The difference between the two stations is around 26 km.

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.

6.3.3 Crustal movement analysis, GNSS station (INACORS-BIG)

Next, I test my hypothesis that temporary vertical movements of GNSS stations reflect, to some extent, surface loads such as rainwater. Here I estimate vertical positions of the GNSS stations to study vertical crustal movements during the floods on January 1, 2020, and heavy rains on December 31, 2019. I calculated vertical positions during a time span from 10 days before the flood (December 22-31 December 2019) to 9 days after the flood. (2-10 Jan 2020).

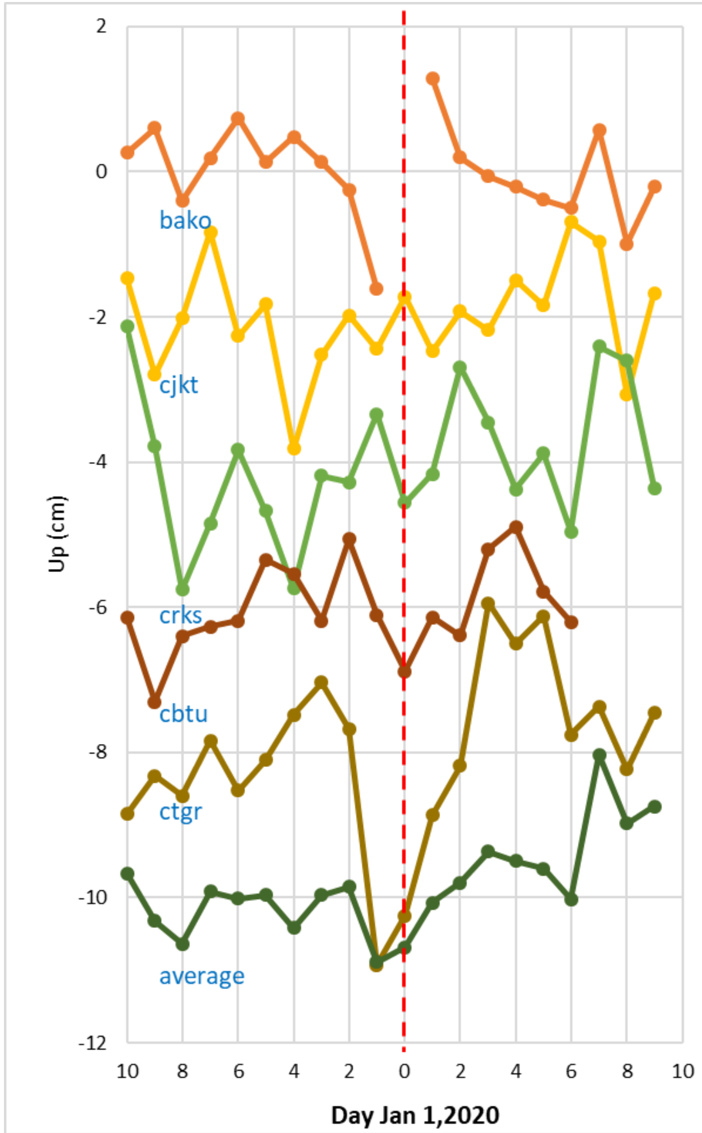

Figure 6.7, Vertical position time series over a period spanning 20 days for the 5 GNSS stations in the region flooded by the January 1st, 2020, Jakarta heavy rain. The station bako had a data interruption on January 1, 2020.

I used the GNSS data in RINEX format, with supporting data for the satellite ephemeris. The software outputs topocentric coordinates, composed of north-south, east-west, and vertical movement components. Here I am interested in the vertical movements, because the water load will depress the ground vertically. I plot the vertical coordinate time series in Figure 6.7. 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 6.7 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 is clearly seen only at BAKO and CTGR stations. Subsidence on January 1, 2020 is clear for the CRKS, CTGR and CBTU stations. These stations are located in the flooded area (light blue colored region in Figure 6.1). On the other hand, CJKT is close to the coast and not included in the flooded area. Anyway, these results suggest that subsidence due to flood water load is quite non-uniform in space, and dense network would be needed to fully understand the crustal response to the surface stormwater load in Indonesia.