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# Seasonal Analysis of Precipitable Water Vapor Variation using GNSS Observation

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**Abstract**
The amount of water that condenses from a column of humid air in a unit cross-sectional area is known as precipitable water vapor (PWV). As it is created by evapotranspiration from the surface into the sky and condenses into clouds that may return to the surface in the form of precipitation, water vapor plays a significant role in climate change and hydrological processes. Weather predictions and climatology have long focused on the variability in the amount of water vapor in the atmosphere. The variance of GNSS-derived PWV under various weather circumstances is examined using the observations from two GNSS stations in Pokhara and Nagarkot. A total of 82 days of GNSS data in the different seasons were processed utilizing the online Precise Point Positioning offered by Canadian Spatial Reference System (CSRS-PPP). The 15-second RINEX data was obtained from Pokhara and Nagarkot GNSS stations. The processing mode was static under International Terrestrial Reference Frame (ITRF), where the epoch was as the GPS data and a Universal Transverse Mercator zone was calculated from the longitude. The dry and wet component after processing was obtained in the troposphere file. This file contains the Zenith hydrostatic delay (ZHD) and Zenith Wet delay (ZWD. The sum of ZHD and ZWD is Zenith Total Delay. The Precipitable Water Vapor was determined by applying the formula developed by Saastamoinen. The mean temperature (Tm) was calculated using the weighted mean temperature model created by Bevis et al. in 1972. Meteorological information was gathered using the Automatic Weather Station, which is close to the GNSS station. Precipitable water vapor is quite sensitive to rainfall, according to an investigation of its variation. It was discovered that in around 85 percent of the data collected during a rainy month, rainfall starts 3 to 5 hours after the PWV achieves its maximum value. Additionally, 15percent of the recorded data produced a false alarm, meaning that even though the PWV value was high, there was little or no precipitation. The limitation of this study is that we cannot predict which type of rainfalls will occur because the thresholds we have established only tell us if rainfall events will occur or not. Additionally, the estimation of Precipitable water vapor would be substantially improved by the meteorological station close by the GNSS station.

**Keywords**
Precipitable Water Vapor, Zenith Total Delay, Zenith Hydrostatic Delay, Zenith Wet Delay, CORS, Rinex

## 1. Introduction

The amount of water that condenses from a column of humid air in a unit cross-sectional area is known as Precipitable Water Vapor (PWV). As it is created by evapotranspiration from the surface into the sky and condenses into clouds that may return to the surface in the form of precipitation, water vapor plays a significant role in climate change and hydrological processes. Given that it absorbs more heat than other greenhouse gases, water vapor is a crucial part of the greenhouse effect. Weather predictions and climatology have long focused on the variability in the amount of water vapor in the atmosphere. The system for determining position and time that consists of one or more satellite constellations is known as the Global Navigation Satellite System (GNSS).

The tropospheric delay of signals travelling through the Earth's atmosphere has had an impact on geodetic estimations of point coordinates on the surface of the Earth ever since space geodesy was first developed. The propagation delay of Global Positioning System (GPS) signals passing through the troposphere can be used to estimate the amount of Precipitable Water

Vapor (PWV) present in the neutral atmosphere [1]. In order to estimate PWV using GNSS observation, Bevis et al. initially encouraged the growth of GNSS meteorology. Rainfall forecasting has recently been done using Zenith Total Delay (ZTD) or PWV data derived from GNSS. PWV value increases significantly before rainfall events, demonstrated that PWV is a reliable indicator and that it can help to enhance the physics of a weather model [2]. The summer monsoon influences 80 percent of Nepal's yearly precipitation, which occurs between June and September, making monsoon rains crucial from an agricultural standpoint [3].

PWV is a numerical variable used in global, regional, and local climate studies. Positioning, navigation, and timing are more important aspects of the Global Navigation Satellite System. An efficient substitute for traditional methods of weather study and monitoring is the use of a ground-based GNSS station to measure the amount of precipitable water vapor in the atmosphere. An effective technique to look into climate change is to monitor atmospheric variability, particularly the tropospheric precipitable water vapor (PWV). The refractivity of the earth's atmosphere causes GNSS signals to suffer a large delay along their passage from the satellites to the ground-based receivers, making them a useful instrument for researching atmospheric characteristics. In the neutral environment, GNSS signals are not only delayed but also refracted. When processing GNSS data, it is possible to determine the zenith wet delays (ZWD) brought on by the troposphere. Since the PWV and ZWD have a strong correlation, it is possible to examine PWV variations using GNSS observations [4]. Because of its benefits of high temporal resolution, precision, low cost, and resistance to all weather situations, the ground-based GNSS could detect satellite signals delay on the atmosphere yielding PWV [5].

The troposphere can be found up to 20 kilometers above the Earth's surface. It contains almost all of the water vapor and the majority of the neutral atmosphere's mass. We can determine the tropospheric delays using GPS measurements because the troposphere impacts GPS signals, generating delays or biases. Zenith Total Delay is a significant parameter that is frequently employed in a variety of application domains. [8]. Prior to reaching the ground, the satellite signals travel via the ionosphere and troposphere, which causes delays in the signals. The dual frequency of the GPS can be used to offset the ionosphere's delays. Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay are two major categories that can be used to categorize delays brought on by the troposphere (ZWD). When the weighted mean temperature (Tm) of the atmosphere can be estimated, it is possible to calculate PWV. The ZHD is mostly caused by the surface air pressure (Ps), while the Zenith Wet delay (ZWD) is typically a function of the atmospheric water vapor profile. The proper assessment of the Tm worldwide is one of the difficulties in appropriately measuring the PWV from the delay. The atmospheric temperature and water vapor profiles needed for precise Tm estimates are typically not available. As a result, surface temperature (Ts) station data are frequently used to estimate (Tm) [9]. The amount of water vapor in the atmosphere, which is inversely proportional to the Zenith Wet Delay (ZWD), can be used to estimate the amount of precipitable water [10].

## 2. Study Area

The CORS station located in Pachimanchal Campus and Nagarkot Geodetic Survey area are selected as for my study. Geographically the Pachimanchal Campus CORS station is located at 28°15'18.4"N 83°58'35.1"E at an altitude of 933.515 m from sea level while the geographic location of Nagarkot Geodetic survey station is located at 27° 41' 31.96" N 85° 31' 11.83" E at an altitude of 2100 m from sea level. The selected date for the study is as follow: 1. WRC CORS station: 2022-July to 2022-August 2. Nagarkot CORS station a. 2021-December-1 to 31 b. 2022-August-1 to 22 c. 2022-July-1 to 31

## 3. Research Objective

### 3.1 General Objective

The General objective of this study is to:

- analyze the hourly precipitable water vapor during cold, dry, and rainy weather.

### 3.2 Specific Objective

The speic objectives of this study is to:

- find out the average PWV value during different weather condition

- study the zenith wet delay against precipitation
- find out the lag time for the occurrence of rainfall after PWV jumps

## 4. Methodology

The detail methodology of my thesis is as follow:

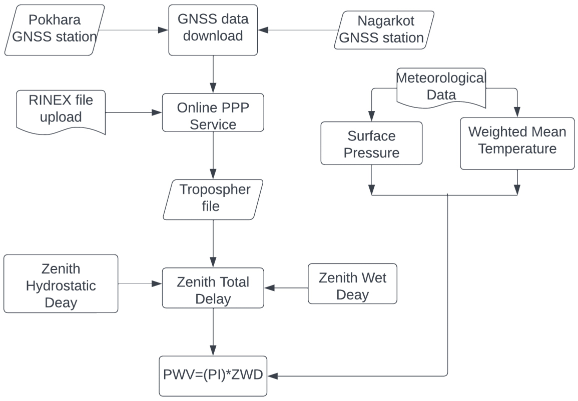


**Figure 1:** A Flow chart representation of the estimation of PWV values

The RINEX data were download from Pokhara and Nagarkot GNSS station. Each day RINEX data records observation at an interval of 15-second, providing a total of 5760 observation each day. The data files from Pokhara GNSS station had extension name ".220". The Nagarkot GNSS station had a GNSS raw data in .RNX extension. To study the general information about satellite system, RINEX version, data sampling rate and time, etc. each of the GNSS raw data were processed in RTKLIB to extract the observation and navigation file. Each of this file type contains two sections: Header and Data section. The header section consists of global information for the entire file and data consists of the data taken from the respective station. The obtained RINEX file were than uploaded into the online Precise Point Positioning Service. To process the RINEX data, Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) was used. CSRS-PPP is an online application for global navigation satellite systems (GNSS) data post-processing Regardless of the user's distance from reference stations, it employs exact satellite orbit, time, and bias adjustments determined from a worldwide network of receivers to compute an accurate user position anywhere on the planet. The uploaded RINEX file were processed and sent back to the user through mail. The processed file contains the Troposphere file. The troposphere file contains the tropospheric dry component and tropospheric wet component. The hydrostatic or dry part (ZHD), which makes up about 95 percent of the observable delay, and the wet part (ZWD) caused by the water vapor along the signal route together account for the tropospheric delay of the GNSS signal, which is dependent on the elevation angle. The surface pressure and temperature in case of Pokhara GNSS station were obtained from the office of hydrology and meteorology, Pokhara. The Automatic Weather Station located at Pokhara airport records the surface pressure and temperature in hourly basis. The GNSS station located at Pashchimanchal Campus and Automatic Weather station at Pokhara airport were six kilometers apart. For the case of Nagarkot GNSS station the Automatic Weather station was already functioning near the Nagarkot GNSS station. The hourly precipitation data were also available from Department of Hydrology and meteorology.

### 4.1 Estimation of Precipitabel Water Vapor

Precipitable water vapor can be computed using ZWD as:

$$PWV = \pi * ZWD \tag{1}$$

In above equation, $\pi$ is the conversion factor and can be calculated based on the following formula:

$$\pi = \frac{10^6}{\rho * Rv[(\frac{K3}{Tm} + k'2)]} \tag{2}$$

In Eq. (4), $\rho$ is the constant of the liquid water density and is equal to 999.97 kg/m3. Rv is the specific gas constant of water vapor (461.525JK-1kg-1), k'2 is 22.1 k/hPa, k3 is 3739 K2/hPa, TS is the surface temperature and Tm is the weighted mean temperature of atmosphere which varies in space and in time.

### 4.2 Modelling the weighted mean temperature

The assumption made by Bevis et al. (1992) that Tm is linearly related to surface temperature, (Ts) [14], has been used to determine Tm in the majority of published investigations to date.

$$Tm = 70.2 + 0.72Ts \tag{3}$$

Tm is the weighted mean temperature and Ts is the surface temperature, both of which are given in Kelvin in Eqn. (2). In a later conference presentation, Bevis et al. (1995) revised this equation to:

$$Tm = 85.63 + 0.668Ts \tag{4}$$

The above equation, is based on an analysis of about 250,000 radiosonde profiles with a nearly global distribution. The second version of the equation has been most widely adopted [14].

## 5. Result and Discussion

### 5.1 Zenith Total Delay

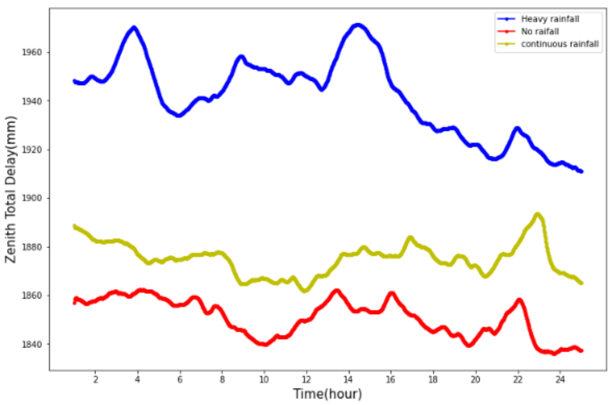


**Figure 2:** Comparison of Zenith Total delay at Nagarkot GNSS Station

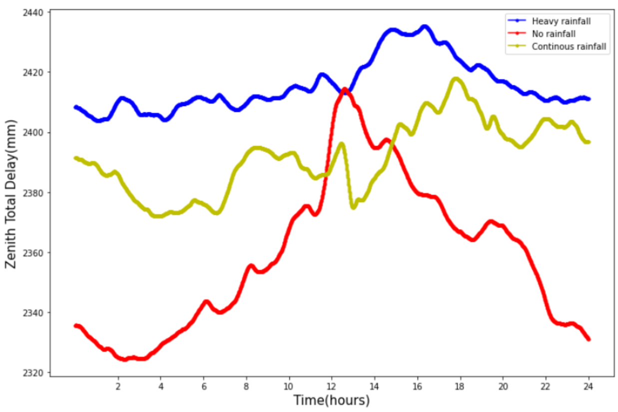


**Figure 3:** Comparison of Zenith Total Delay at Pokhara GNSS Station.

The above figures show the Zenith total delay against hourly time. The ZTD during heavy rainfall day is indicated by blue line, the ZTD during no rainfall day is indicated by red line whereas the continuous rainfall day is indicated by yellow line. From these two figures we can say that for the heavy rainfall day the tropospheric delay is higher than that of day without rainfall and little continuous rainfall day.

### 5.2 Zenith Wet Delay

One of the components of Zenith Total delay is Zenith Wet delay which is also the wet component of the ZTD. The wet component is responsible for the occurrence of rainfall.

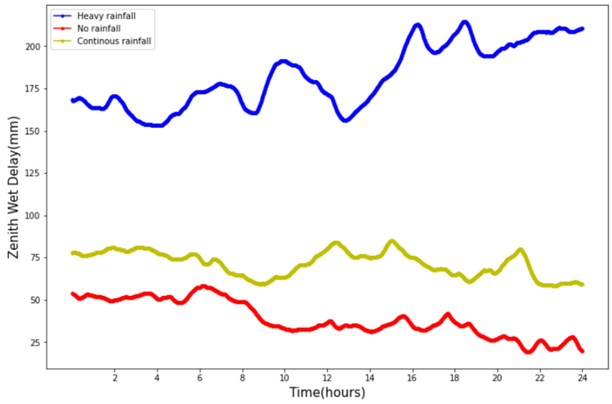


**Figure 4:** Comparison of Zenith Wet Delay at Nagarkot GNSS Station.

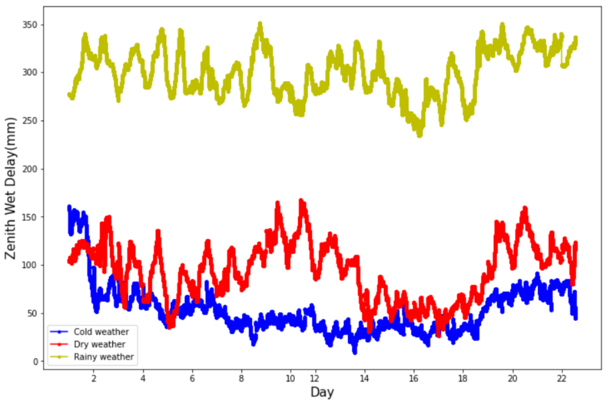


**Figure 5:** Zenith Wet Delay during different weather condition.

Above figures represent the zenith wet delay of GNSS signal due to the water vapor present the troposphere. It was observed that during heavy rainfall day the wet delay is higher than that of wet delay during no rainfall day and a day with little but continuous rainfall. Also, during the heavy rainfall day indicated by blue line reaches to ZWD of 360 mm/cm2, at 15:00 clock UTC time. At that time the maximum rainfall for that day was recorded to be 44.2 mm. This clearly shows that just before the occurrence of heavy rainfall the zenith wet delay starts increasing. The value of ZWD during rainy month of July ranges from 240 mm to 350 mm. The case for dry month (April) the value ranges from 40 mm – 160 mm. While in the cold month (December) the ZWD value ranges from 20 mm - 160mm.

### 5.3 Precipitable water vapor

The Precipitable Water Vapor (PWV) and Precipitation during cold, dry, and rainy weather condition were analyzed and following statistical graphs were developed.

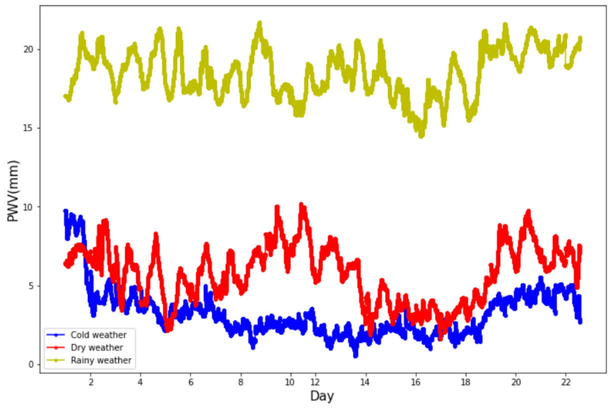


**Figure 6:** Precipitable Water Vapor during different weather condition.

The average precipitable water vapor during the cold weather (December, 2021) indicated by blue line was 4.09 mm. The average value for the month of April (dry) was 5.89mm. But the average value of PWV for the rainy season was found to be 17.29 mm. This indicates that the PWV during rainy month was much higher than the cold and dry month.

### 5.4 Precipitable Water Vapor and Precipitation relationship during different weather condition

In about 85 percent of the data observed it was seen that PWV jumps was seen 3-5 hours before the occurrence of rainfall during the rainy season (July, 2022). And about 15 percent of the data observed, it gave the false alarm i.e. even if the PWV value was low there was occurrence of rainfall.

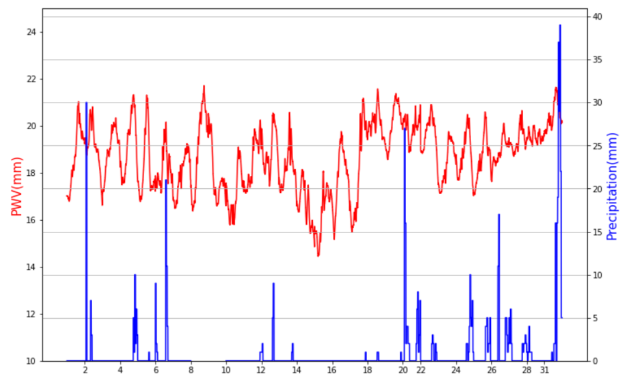


**Figure 7:** Precipitable water vapor versus Precipitation (July-2022, Pokhara GNSS station)

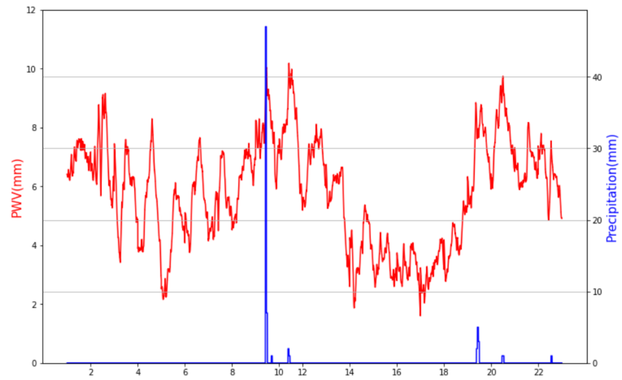


**Figure 8:** Precipitable water vapor versus Precipitation (April, 2022- Nagarkot GNSS station)

Normally there was not much precipitation during this month. But a heavy rainfall of 47 mm was encountered on 9th of April, when the PWV value reaches its maximum value of 10 mm.

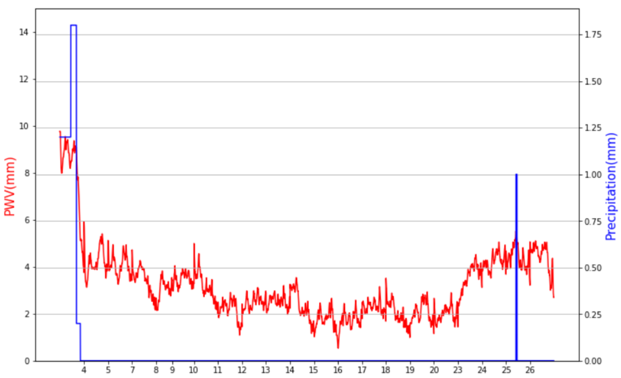


**Figure 9:** Precipitable water vapor versus precipitation during (December-2021, Nagarkot GNSS station).

The rainfall of 1.75 mm was encountered when the PWV value ranges between 8 mm to 9mm. Also, on the 25th of the December it was seen that the precipitation of 1 mm was noted when the PWV value start to increase sharply for about 3 hours. The overall average of PWV for this month was 3.82 mm, which is less than the average PWV value during dry and rainy months.

### 5.5 Time Gap Between highest PWV and peak precipitation

Out of twenty-eight days of observation during rainy season in Pokhara, about 85 percent of the data gave the true alarm for the occurrence of rainfall after 3-5 hours when the PWV value reaches its peak point at that day. And about 15 percent of data gave false alarm i.e. even at low PWV there has been rainfall.

## 6. Conclusion and Recommendation

Utilizing the GNSS technology in estimation of Precipitable water vapor and its analysis during heavy rainfall in country like Nepal could be a milestone in forecasting and nowcasting the occurrence of heavy rainfall based upon the changes in the value of Precipitable water vapor (PWV). Here we have studied the Precipitable water vapor in two GNSS station. One in Pashchimanchal Campus, Pokhara-16, Lamachour, and another in Nagarkot. A total of 82 days GNSS data were processed in Online Precise Point Positioning Service i.e. in, Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP). At Pokhara GNSS station a total of 30 days RINEX data, during the month of July 2022 were processed, while at Nagarkot GNSS station a total of 52 days RINEX data including the month of December-2021, April-2022 were processed. The processed data include the dry and wet component of troposphere, which when combined gave the Zenith Total Delay. From the observation it was seen that during the rainy month the wet component was higher than the wet component during dry and cold month. Also the wet component which is major factor for the occurrence of rainfall validates with the occurrence of rainfall i.e. precipitation increases when wet component values increases and decrease when wet component decrease. In winter season there was a huge decrease in Zenith Wet component as compared to the rainy season. The ZWD during the rainy season was 4 times higher than the ZWD during winter and summer season. From this fact we can say that the Zenith wet delay will be high during the rainy season than that of winter and summer season. The analysis of Precipitable water vapor and its variation shows high sensitivity to the rainfall. In about 85 percent of the data observed during rainy month it was seen that the rainfall occurs after 3 to 5 hours when the PWV reaches its peak value. The maximum PWV was seen 3-5 hours before the occurrence of the rainfall during the rainy season (July, 2022). And about 15 percent of the data observed, it gave the false alarm i.e., even if the PWV value was high there was a little or no rainfall. Also, if the PWV value was low there was rainfall.

The online precise positioning service that we have used for our study processed the GNSS data considering 7.5 degree elevation cut-off angle. And the signal from GPS and GLONASS were used. The estimation could be more reliable if the user can have their choices in setting the elevation cut-off angle, and the signal selection while processing the data. The meteorological station nearby the GNSS station would greatly enhance the estimation of Precipitable water vapor. The thresholds that we have determined only give us information about the occurrence or non-occurrence of rainfall events without knowing which class of rainfalls will occur.

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