Development of Near Real-Time PWV Estimation System for Monitoring the Meteorological Events in Thailand

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DOI: https://doi.org/10.52939/ijg.v18i3.2201

Abstract
Nowadays, Global Navigation Satellite System (GNSS) observation is widely used as an alternative approach to estimate the Precipitable Water Vapor (PWV). The process of Precise Point Position (PPP) is now well developed and commonly applied to process GNSS ground-based observations. This study developed the system to acquire data from 121 permanent reference stations of GNSS CORS spatially distributed across Thailand to analyze and monitor GNSS-PWV. Several other meteorological data like surface pressure, temperature, and humidity were collected from 478 telemetry stations. The developed system reduces the time for data processing, making the approach more promising for meteorological applications. The comparison of GNSS-PWV from CODE and IGS data correction shows an average correlation of 0.29. However, there is a potential for monitoring the meteorological phenomenon based on the analysis between near real-time GNSS-PWV and average rainfall rate for specific rainfall duration and a selected frequency called rainfall intensity in the central of Thailand during the severe rainfall events.

1. Introduction

Precipitable Water Vapor (PWV) is a piece of important information regarding weather forecasting and potentially indicating the events related to disaster or drought. The PWV estimated from various data is a method to diagnose the amount of moisture/water vapor in the different layers of the atmosphere and it could be useful in applications like site testing studies (Erasmus, 2002; Erasmus and Van Staden, 2001, 2003). Traditionally water vapor was measured by launching radiosondes two times a day. But this method is expensive and has poor spatial coverage and temporal resolution. Temporal changes in atmospheric water vapor occur rapidly and water vapor measurements by radiosondes do not satisfy the needs of research for a variety of variation scales of atmospheric water vapor (Liang et al., 2015). Recently, several studies did obtain PWV derived from GNSS atmospheric delay. For instance, Alshawaf et al., (2015) studied precise PWV estimation by combining GNSS with a Precise Point Position (PPP) and Saastamoinen model to calculate zenith hydrostatic delay (ZHD) to find zenith wet delay (ZWD) which is the key feature to derive PWV variables related. Also, Gouping et al., (2009) performed similar research to obtain ZTD using the same model with meteorological data like surface pressure and temperature. Although the conventional method to measure PWV in the air which is known as MWR produces accurate atmospheric moisture content, it is not suitable for monitoring purposes due to the low temporal data collection and limited area coverage. GNSS Continuously Operating Reference Stations (CORS) therefore has near real-time capabilities to overcome shorter temporal with continuous observations. This would reduce the drawback of complicated data collection regarding precise satellite positioning.

The near real-time GNSS based approach was used to obtain the PWV time series to investigate storm disaster occurrences in Hong Kong (He et al., 2019). The applications of using near-real-time PWV estimation benefit from forecasting potential disasters and warning people in risky areas.

Mawandha et al., (2019) did a study forecasting short-term rainfall prediction in Yogyakarta Province and Central Java Province, Indonesia which has high rain intensity in mountainous areas.

The high correlation between rainfall and PWV indicated the usefulness of near-real-time estimation for precipitation disaster forecasting and mitigation. Zhao et al., (2019) have studied drought index monitoring using PWV derived from GNSS signal processing, and they achieved a considerable relationship between PWV and temperature that indicated drought. The preliminary results of PWV estimation in the central part of Thailand competed using the double differencing technique in which two types of single differences are combined, to estimate moisture content have been conducted by using six GNSS CORS stations but due to close distance between the two components it is not easy to implement in a large area. Results shows an increasing rate of PWV value in the summer season due to the high temperature which results in an increase in water vapor (Somphan et al., 2019). Double difference is simply defined as the subtraction of two receiver single difference mode between satellites and receivers (Ashour et al., 2022).

In order to develop the near real-time system for calculating PWV derived from GNSS atmospheric delay requires various data sources and is composed of many processing steps. The most complicated process is the acquisition of the Receiver INdependent EXchange (RINEX) file which contains raw satellite navigation system data that allows users to add corrections to their data and meteorological data. In this study, the system is developed to implement those procedures programmatically by fetching various data sources and formats. The system is designed to perform near real-time data acquisition and processing. Once the data are available, we can generate the required data for producing PWV maps for a nationwide scale. In this study, the primary goal is to create a near real time application for PWV calculation using ultra rapid data correction and investigate its potential by comparing its results with final data correction. The secondary goal of the study focuses on the potential of the developed method to monitor the meteorological events in Thailand that occur during severe rainfall event.

2. GNSS CORS and Meteorological Data Source

2.1 GNSS CORS Network in Thailand

Continuously Operating Reference Stations (CORS) are mainly used for precise positioning purposes. Forming the nationwide network of CORS stations can provide more reliability and is applicable for users to access precise positioning. Additionally, it is applicable for developing monitoring systems for meteorology, space weather, and geophysical applications throughout Thailand. Several Thai organizations established GNSS CORS stations for their purpose. Recently, the collaboration between different organizations of CORS Networks in Thailand was established by the Department of Public Works and Town & Country Planning (DPT), Department of Disaster Prevention and Mitigation (DPM), National Institute of Metrology Thailand (NIMT), Hydro-Informatics Institute (HII), Royal Thai Survey Department (RTSD), Geo-Informatics and Space Technology Development Agency (GISTDA) and several universities. The 234 GNSS CORS stations data are collected and serviced in the National CORS Data Center to enhance geospatial data sharing and reduce redundancy.

2.1.1 GNSS error sources

GNSS error sources are the elements that make calculating a precise location for a GNSS receiver challenging. The positioning accuracy depends on the magnitude of error in the individual pseudo range measurement. Due to their modest strength, GNSS signals are susceptible to a variety of sources of noise and inaccuracies. Because these inaccuracies taint the range measured by the GNSS receiver, it is referred to as the pseudo range (Karaim et al., 2018). Satellite Clocks errors is affected timing-related errors in both the satellite and receiver. There are three factors that can affect GNSS satellite clocks such as stability, relativistic effects, and timing group delay (Karaim et al., 2018 and Ma et al., 2021). Satellite orbital errors, the information contained in the navigation message known as satellite ephemeris is used by receivers to compute satellite location (Noureldin et al., 2013). When the signal enters the top layer of the atmosphere i.e., ionosphere at a height of roughly 1000 km above the Earth's surface it induces ionosphere error. The level of solar activity is the most important element in influencing the state of the ionosphere, but season and time of day also have a role. As a result, these three factors determine the amount of ionization, impacting the signal transit time recorded by the receiver by modifying the refractive indices of the layers of the ionosphere. Tropospheric delay, the signal must then travel through the troposphere, the lowest layer of the atmosphere that extends from the Earth's surface to a maximum altitude of 20 kilometers above sea level.

This part, dry gases and water vapor make up this section of the atmosphere. The troposphere also slows down the GNSS signal because it is the refraction layer. However, being electrically neutral, this layer is nondispersive for some GNSS frequencies. There are two components of atmospheric delays that are wet and dry. The tropospheric delay is frequency independent. As a result, unlike the ionospheric delay, it cannot be eliminated by merging L1 and L2 GPS signal data. The tropospheric delay adds roughly 2.5 to 25 meters to range estimations, depending on satellite elevation.

2.2 Meteorological Data source

Meteorological data are essential data for calculating PWV derived from GNSS atmospheric delay. These data required suitable coverage distance and less time difference with the GNSS observation to provide a precise PWV model. In this study, two meteorological data sources were selected.

2.2.1 Local automated telemetry stations

Local automated telemetry stations are hosted and serviced by HII. The 10 minutes intervals observations during rainfall and 1-hour intervals in normal situations are publicly accessed through the http://www.thaiwater.net website. The data access Application Programming Interface (API) for recent observation endpoints are serviced to facilitate the data sharing for other developers. The observation data are encapsulated in the JavaScript Object Notation (JSON) format. 950 stations are nationwide installed in Thailand. There are two main types of automated telemetry stations including the weather stations and water level stations. The air temperature, humidity, atmospheric pressure, precipitation, wind speed, and direction are commonly available in all stations.

2.2.1 Global Forecast System (GFS) data

Global Forecast System (GFS) is the numerical weather forecasting data by the U.S. National Weather Services (NWS), Environmental Modeling Center, and NOAA. The simulated GFS model provides necessary meteorological data such as water vapor content, air surface pressure, etc. The mathematical model updates 4 times a day or every 6 hours, and it can forward forecasts up to 16 days (NCEP, 2007). The observed meteorological data of local automated telemetry stations is the primary data source but sometimes there are technical problems of poor communication in rural areas or electric shortage therefore the observed meteorological data are missing. Therefore, the GFS model data are selected as the supplementary data source for PWV model calculations to ensure the availability of meteorological data of each CORS station. GFS humidity, pressure, surface temperature and precipitation at $0.25^{\circ} \times 0.25^{\circ}$ horizontal resolution is used in this study.

3. System Components

The system components were designed and separated based on their roles and related data source. As shown in Figure 1, there are three components in this system to enable smooth near real-time PWV calculations from GNSS data. Python programming and various libraries like pandas, gnsscal are selected as the main development tools for process control, data acquisition, data manipulation, and PWV calculation. The Bernese GNSS Software version 5.2 is used for processing GNSS data to calculate ZTD for each hour Dach et al., (2015). R Script is developed for creating a PWV map at a resolution of 0.1 degree for Thailand region by interpolating the calculated PWV from each station. All software and tools are summarized in Table 1.

Table 1: Software and tools for near real-time PWV estimation system development

Software and tools	Purpose
Python (gnsscal, pandas, geopandas, cfgrib, pygrib, ftplib)	Prepare schedule and automated workflow, download RINEX observations data, GFS weather data, Thaiwater API weather and compute GNSS-based PWV
Bernese 5.2 (perl API)	ZTD using PPP approach calculation
R script (4.1.0)	PWV mapping and spatial interpolation

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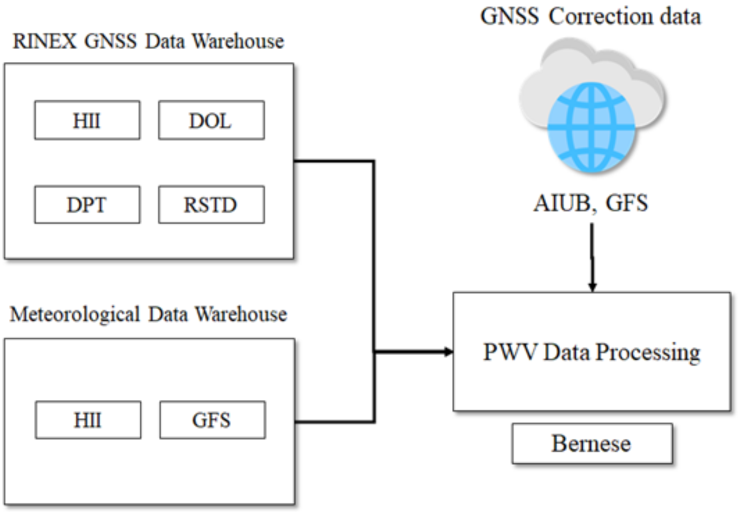

Figure 1: Near real-time PWV estimation system component

Table 2: The GNSS CORS network in four regions of Thailand

Region code	Region	Number of stations
1	North	28
2	Northeast	38
3	Center, East and West	36
4	South	19

3.1 RINEX GNSS Data Warehouse

GNSS observations of the Thailand CORS network are regularly collected and stored in this component. In the early stage of prototype development, 121 GNSS CORS stations are selected to cover the Thailand region as shown in Figure 2. The stations are categorized into four regions based on the geographic location. The number of stations and coverage are well distributed as shown in Table 2. The 15-seconds sampling rate observation data from GPS and GLONASS satellites are prepared for near real-time purposes. The hourly RINEX data of each station are separately archived in RINEX V2 format and ready to be used for near real-time correction and post-processing. The filename encodes the station name, DOY, and hour are defined.

3.2 Meteorological Data Warehouse

The meteorological data warehouse is the key essential datastore for providing air temperature and pressure. To support both near-real-time and post-data PWV processing, the meteorological data are prepared in advance from automated telemetry and GFS data sources in the same time interval.

The automated telemetry station from the thaiwater.net provider is considered the highest priority. Since the distance between the automated telemetry station and the GNSS CORS station can affect the accuracy of the PWV model.

Thus, three nearest automated telemetry stations of each GNSS CORS station are selected to acquire air temperature and pressure for every hour. The 1st nearest automated telemetry station of each GNSS CORS station is considered as the main data source. The 2nd and 3rd order of nearest station will be used if the closer automated telemetry station data is not available.

The GFS runs two analysis cycles, an early run and a late run regularly updated every 6 hours at 00:00 06:00 12:00, and 18:00 (UTC). However, the late run is least affected by data latency, but the early run is affected. Every GFS data acquisition process request hourly forecast data from the current time to the next 12 hours. The recent forecast data is replaced in the next round of data acquisition which is in 6 hours intervals. This forecast dataset is used to fill in the blank data of the automated telemetry dataset. The air temperature at 2 meters above surface, pressure, humidity, and rainfall are collected at the particular location of each GNSS CORS station using nearest neighbor resampling from 0.25-degree GFS grid data. Both processes of meteorological data acquisition are controlled by the python script and regularly invoked by setting the crontab in the Ubuntu system. The output of both processes stores the data in CSV format.

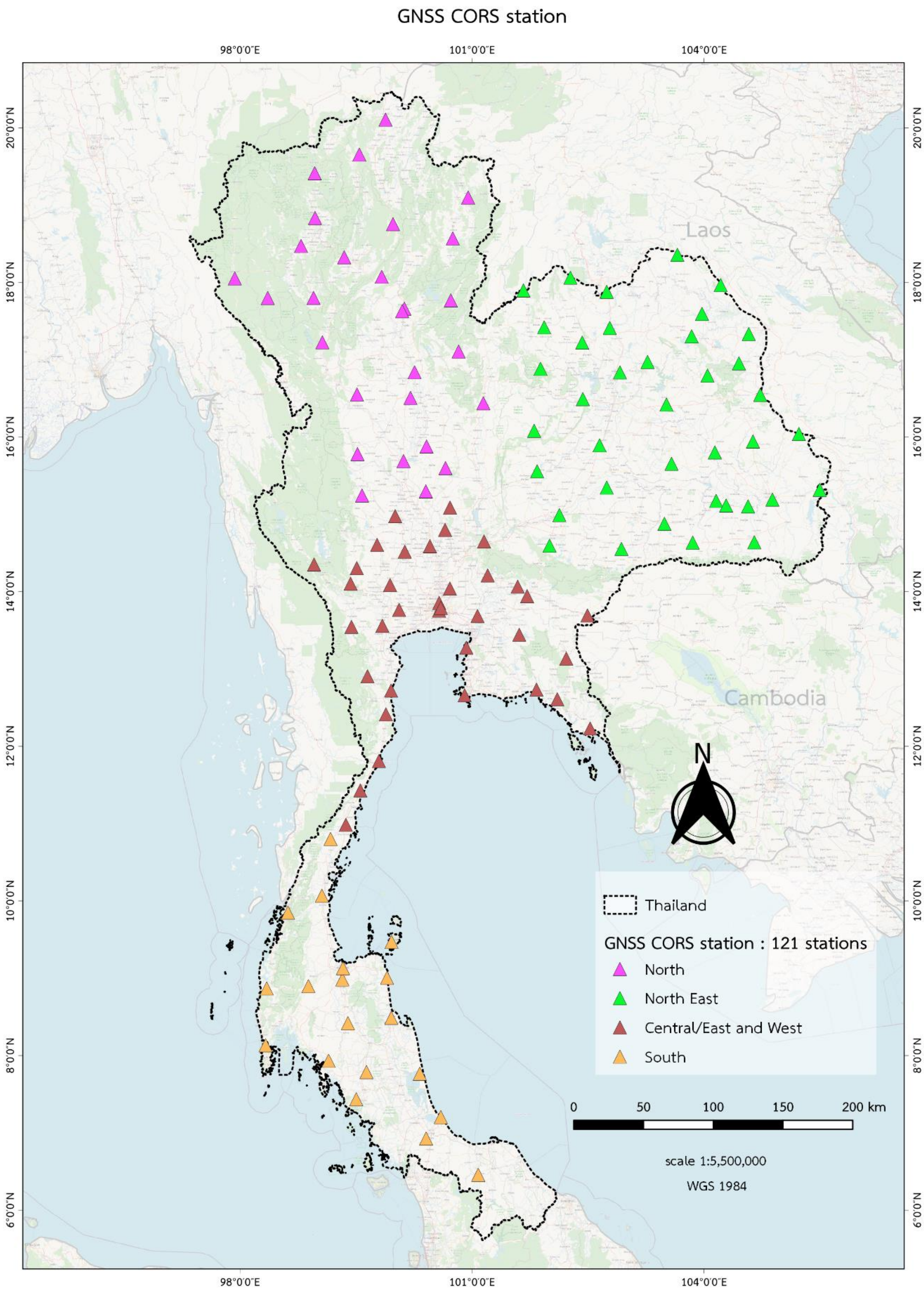

Figure 2: Map of the GNSS CORS network

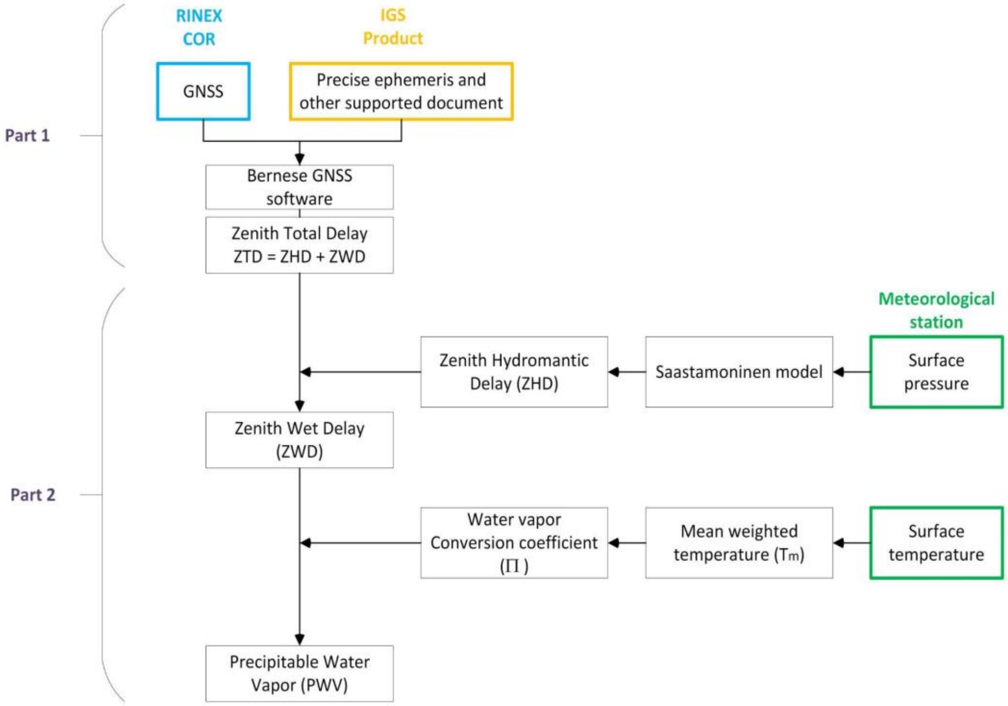

Figure 3: PWV data processing flow

Table 3: Used error correction product from IGS and CODE

GPS/GNSS Error Correction product	GPS/GNSS Correction Source	
	IGS	CODE
Orbit correction	IGS Final Daily ephemeris (igswwwd.sp3.z)	Ultra Rapid/2 days forecast Daily ephemeris (CODwwwd.eph.z)
Ionospheric Delays correction	IGS Final Daily ionosphere (igswwwd.yyi.z)	Ultra Rapid/2 days forecast Daily ionosphere (CODwwwd.ION.Z)
Geophyical correction	IGS Final Weekly pole solution (igswwwd.erp.z)	Ultra Rapid/2 days forecast Daily pole solution (CODwwwd.ERP.Z)
CODE Bias correction	IGS Final differential code bias (P1P2yymm.dcb.z)	Last 30-days Monthly differential code bias (P1P2yymm.DCB.z)
Clock correction	IGS Final Daily satellite and station clock (igswwwwd.clk.z)	Ultra Rapid Daily satellite and station clock (CODwwwwd.CLK.Z

3.3 PWV Data Processing

The PWV data processing component is the main key component for this system. The series of data acquisition, data manipulation, and data processing is performed in this part. As shown in Figure 3, at first, the precise orbital, ionosphere correction, carrier phase observation, and clock products were downloaded from the Center for Orbit Determination in Europe (CODE). The ultra-rapid and prediction products are selected since they are the most suitable for the near real-time purpose. The final version of IGS products is also possible to use for the post-processing to derive higher precise ZTD using the PPP method. Detailed description about used error correction product from IGS and CODE is shown in Table 3. PPP is a positioning method that uses a single receiver to eliminate the error from GNSS system and give a high levels of position accuracy with a precision of up to 3cm. The approach is based on GNSS satellite clock and orbit corrections obtained from a worldwide network of reference stations.

For calculating PPP, combination of dual-frequency pseudo range and carrier phase measurements is used and each GNSS station can be processed independently, therefore simultaneous observation of the same satellite of the two stations are not needed (Arief and Gatti, 2020).

Subsequently, the processing of GNSS data for estimating the ZTD for each hour is carried out by the Bernese GNSS version 5.2 using the PPP approach. The distribution of ZTD processing tasks for each region can be parallel performed with a multi-core processing approach. Based on the preliminary experience, the processing time is also based on the total number of GNSS CORS stations Then, the performance of this system can be enhanced in the future for the expansion of the CORS network and still possible for near real-time application purposes. According to the error of the signal, neutral atmospheric delay is affected while the signal from satellite travel through the troposphere from the precipitation content in the air. This delay was termed as Zenith total delay (ZTD) that can be calculated by phase of signal. ZTD was defined in the summation of Zenith hydrostatic delay (ZHD) and Zenith wet delay (ZWD). ZWD therefore can be derived from Equation 2 by subtracting ZTD by ZHD. ZHD is obtained by using the Saastamoinen Model (Luzum and Petit, 2013) calculating with surface pressure (P_s) in millibar unit, latitude in radians (ϕ) and height of surface above ellipsoid (H), as shown in Equation 1 for all CORS stations. Eventually, the parameters π from Equation 5 is computed taking T_m which is mean temperature of water vapor in Kelvin unit from Equation 5, before calculating the PWV are obtained in Equation 4. Determination of T_m is a very crucial process to acquire precise calculation of PWV. In this study, the equation of T_m is adopted from previous studies (Kongmuang and Wichai, 2018) (T_m model is used here applies to only the Thailand region). The equation is shown in Equation 5 (Suwantong et al., 2016) and the necessary parameters of Equation 3 are listed in Table 4.

$$ZHD = \frac{0.0022768 \cdot P_s}{1 - 0.00266cos(2\phi) - 0.00000028H}$$

Equation 1

$$ZWD = ZTD - ZHD$$

Eqation 2

$$\pi = \frac{10^6}{pw \cdot R_v\left(\frac{k_3}{T_m} + k_2'\right)}$$

Equation 3

$$PWV = \pi \cdot ZWD$$

Equation 4

$$T_m = 0.6066T_s + 113.2914$$

Eqaution 5

Then, the Inverse Distance Weight (IDW) interpolation which is deterministic spatial interpolation approach is used to generate the PWV grid map covering Thailand using known values of PWV of each COR stations with corresponding weighted values and this part is constructed with the R Script. The PWV grid map is saved in the PNG file format and publicly accessible from the Thaiwater website as shown in Figure 4. The near real-time PWV map is regularly updated every 3 hours during the prototype stage. The processing time and the limitation of several data latencies will be evaluated to improve the performance and procedure to make the near real-time hourly maps.

4. GNSS PWV Estimation for Monitor the Meteorological in Thailand

The main purpose of this system focuses on the near real-time PWV estimation using GNSS observation from the CORS network for monitoring the meteorological cover in Thailand. There are various constraints and limitations for enabling near real-time processing that leads to the uncertainty of results. However, the performance and precision of results could be maintained. Additionally, Mawandha et al., (2019) reported the relationship between the PWV time series and rainfall events' occurrences and intensity. The near real-time GNSS PWV estimation for monitoring the meteorological event is investigated.

4.1 GNSS PWV Estimation Accuracy Analysis

To assess the performance of the GNSS PWV estimation and evaluate the accuracy of a developed near the real-time system, the analysis of calculated PWV from GNSS data is carried out in this study.

Table 4: Related parameters for calculation

Parameter	Value (unit)
pw (Water Density in a liquid state)	999.97 (kg/m^3)
R_v (Steam constant)	461.525 (J/kg.kelvin)
k_2' (Refraction in Troposphere constant)	22.1 (Kelvin/millibar)
k_3 (Refraction in Troposphere constant)	3,739 (Kelvin^2/millibar)

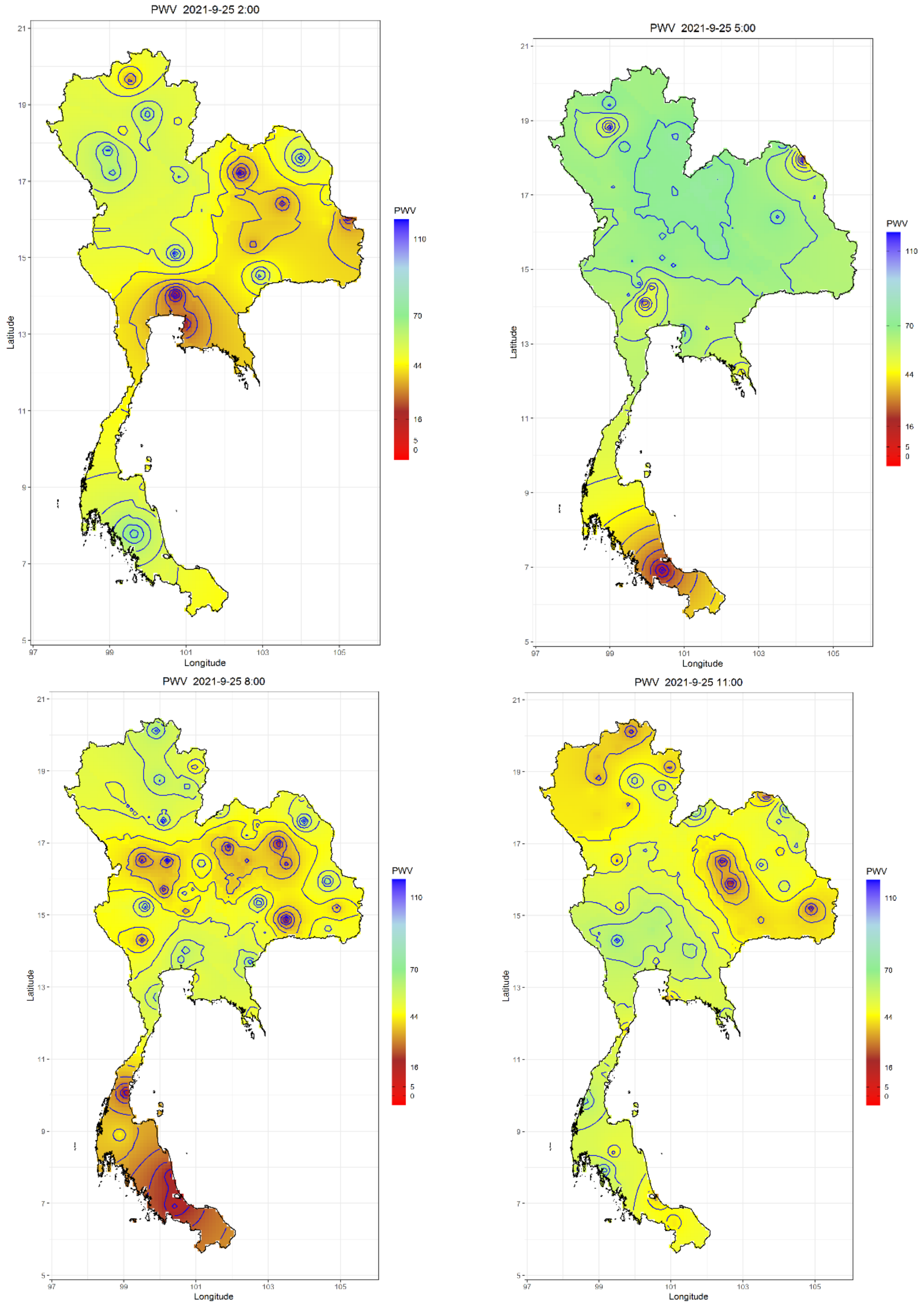

Figure 4: PWV map cover Thailand region

First, the comparison between the near real-time GNSS PWV estimation by using ultrapid and prediction data correction products from CODE and the final product data correction from IGS are investigated. The scatter plot, Pearson correlation coefficients which measure the strength and direction of a linear relationship between two variables and root mean squared error (RMSE) are used to determine the level of correlation. Generally, the correlation coefficient of PWV calculated using COD and IGS data correction shows the low and medium correlation in many stations. As shown in Table 5, the maximum Pearson correlation coefficient of PWV is 0.930 the average value is 0.294 and it is also the same as the ZTD.

Table 5: Correlation coefficient and RMSE of calculated PWV and ZTD from CODE and IGS

	PWV		ZTD	
	Pearson correlation coefficient	**RMSE**	**Pearson correlation coefficient**	**RMSE**
Average	0.294	13.39	0.301	0.0796
Max	0.930	23.00	0.920	0.1349
Min	-0.050	2.00	-0.097	0.0131

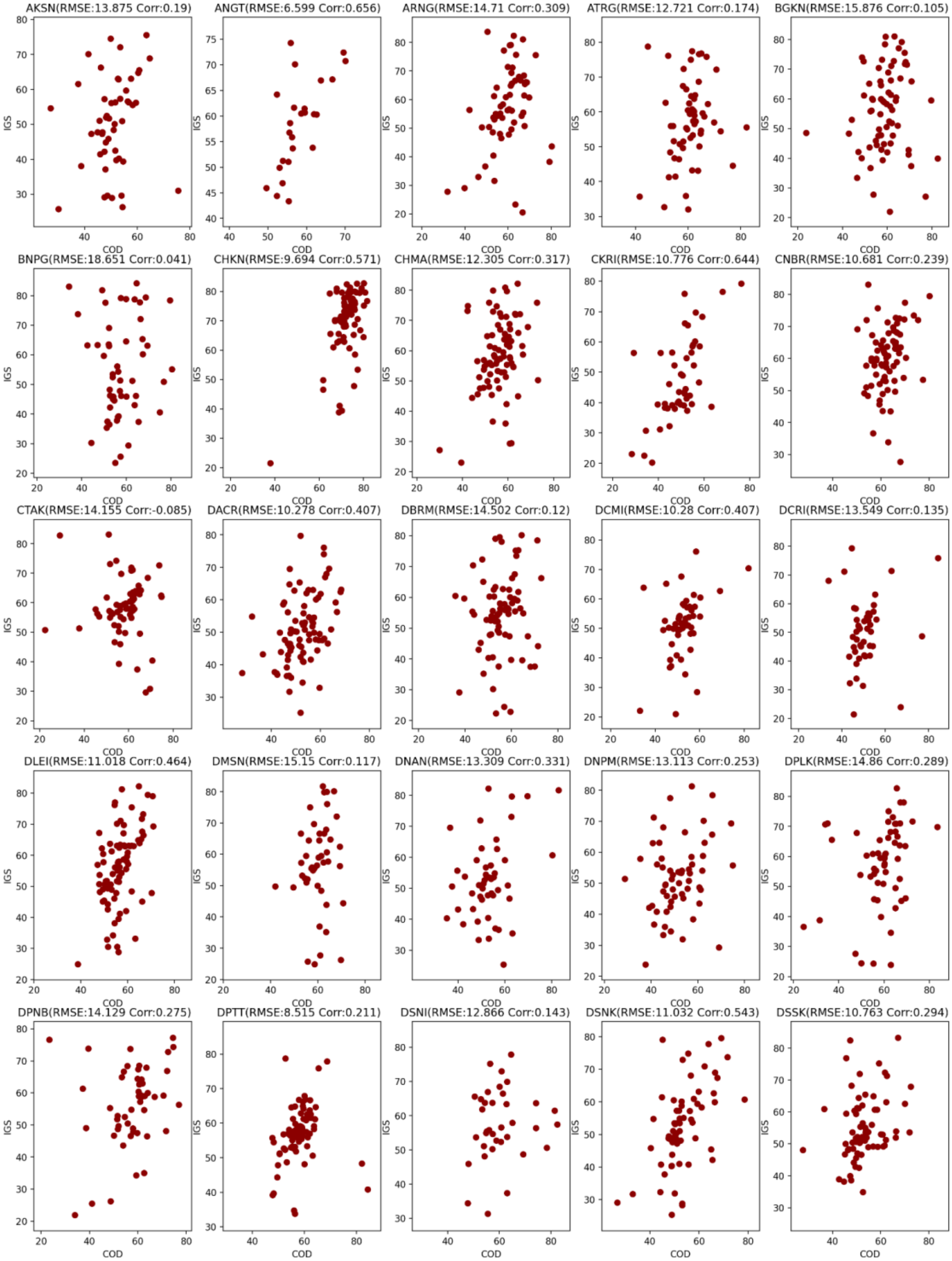

Figure 5: Scatter plot of COD and IGS PWV of 113 stations (Continue next page)

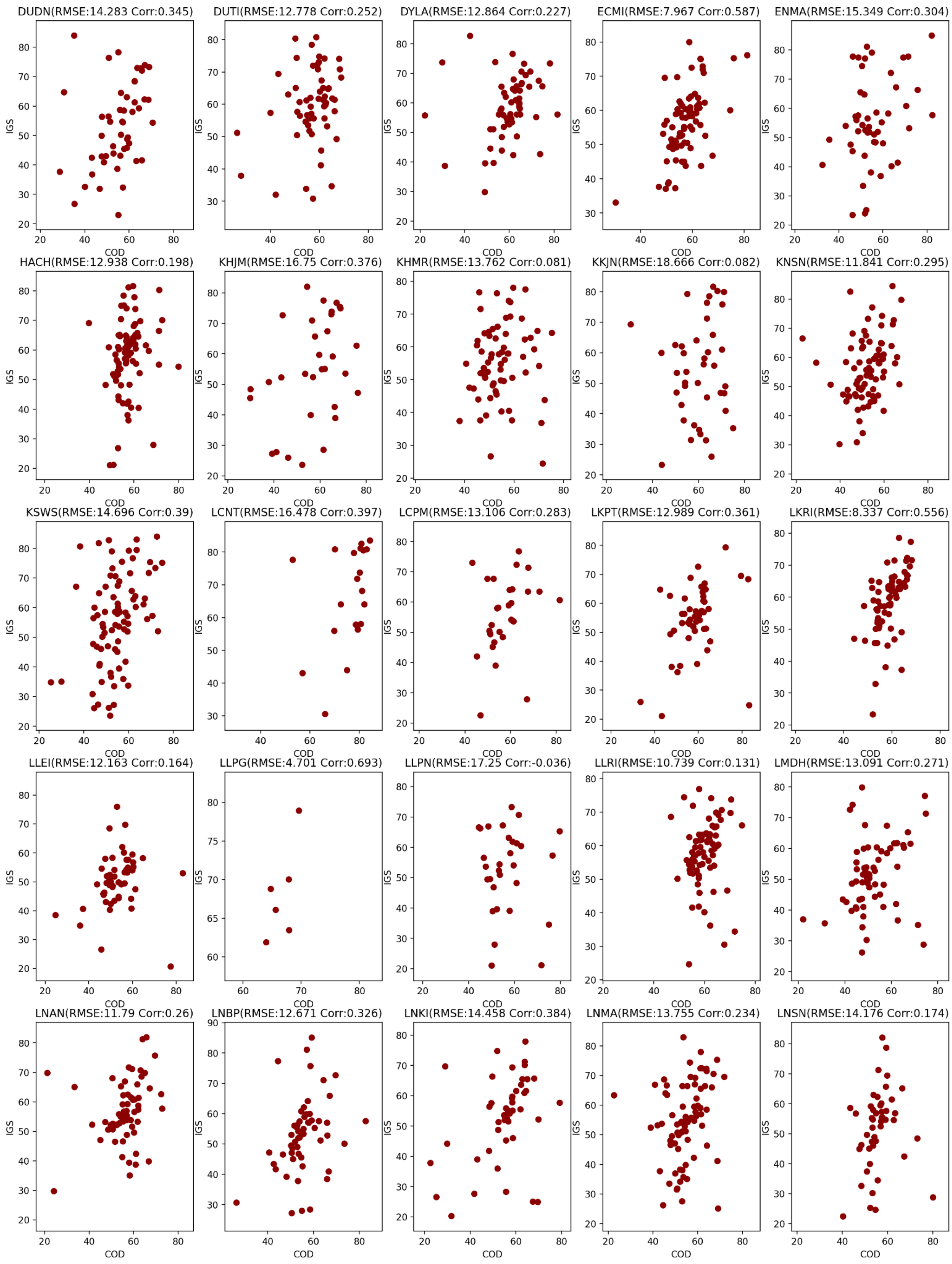

Figure 5: Scatter plot of COD and IGS PWV of 113 stations (Continue next page)

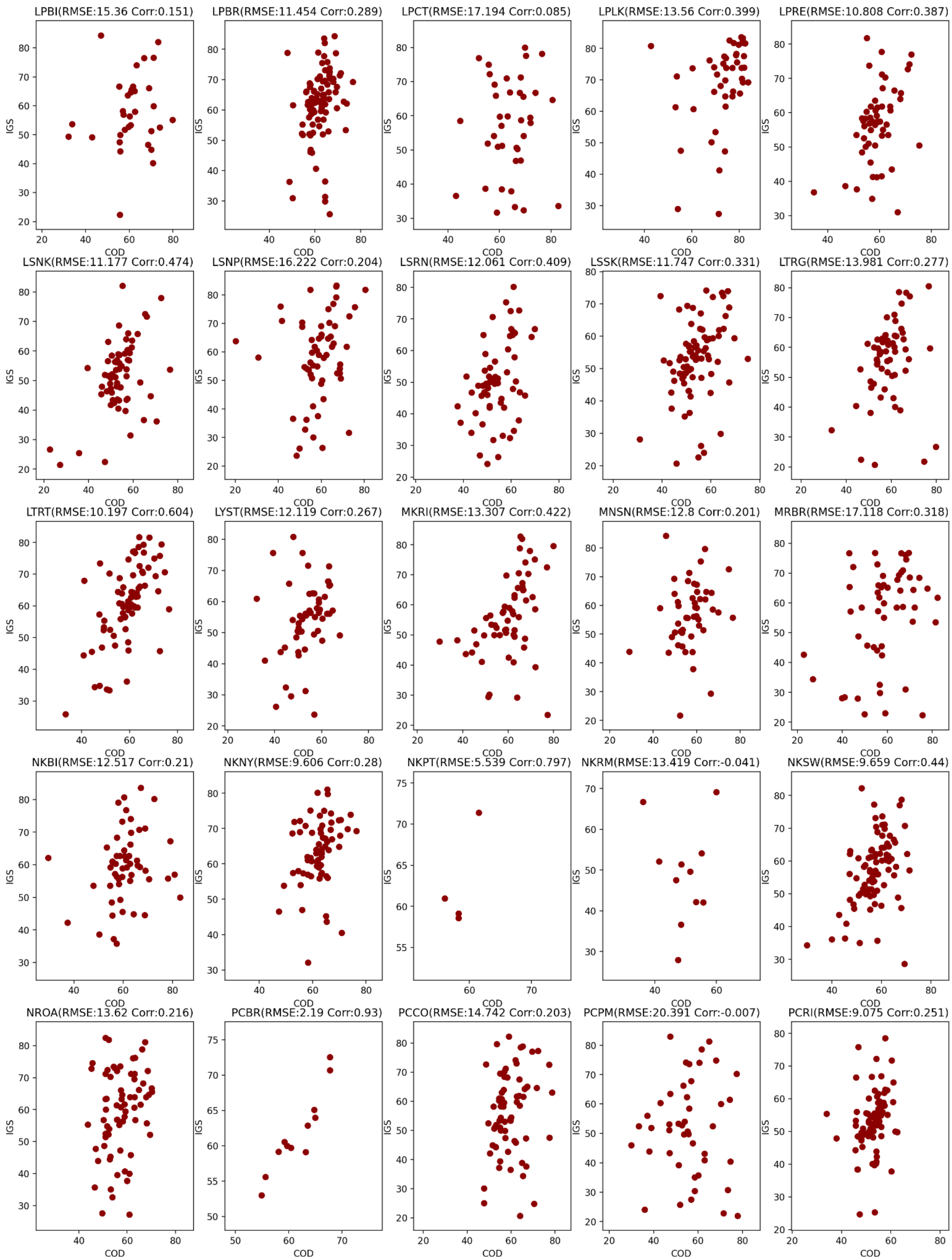

Figure 5: Scatter plot of COD and IGS PWV of 113 stations (Continue next page)

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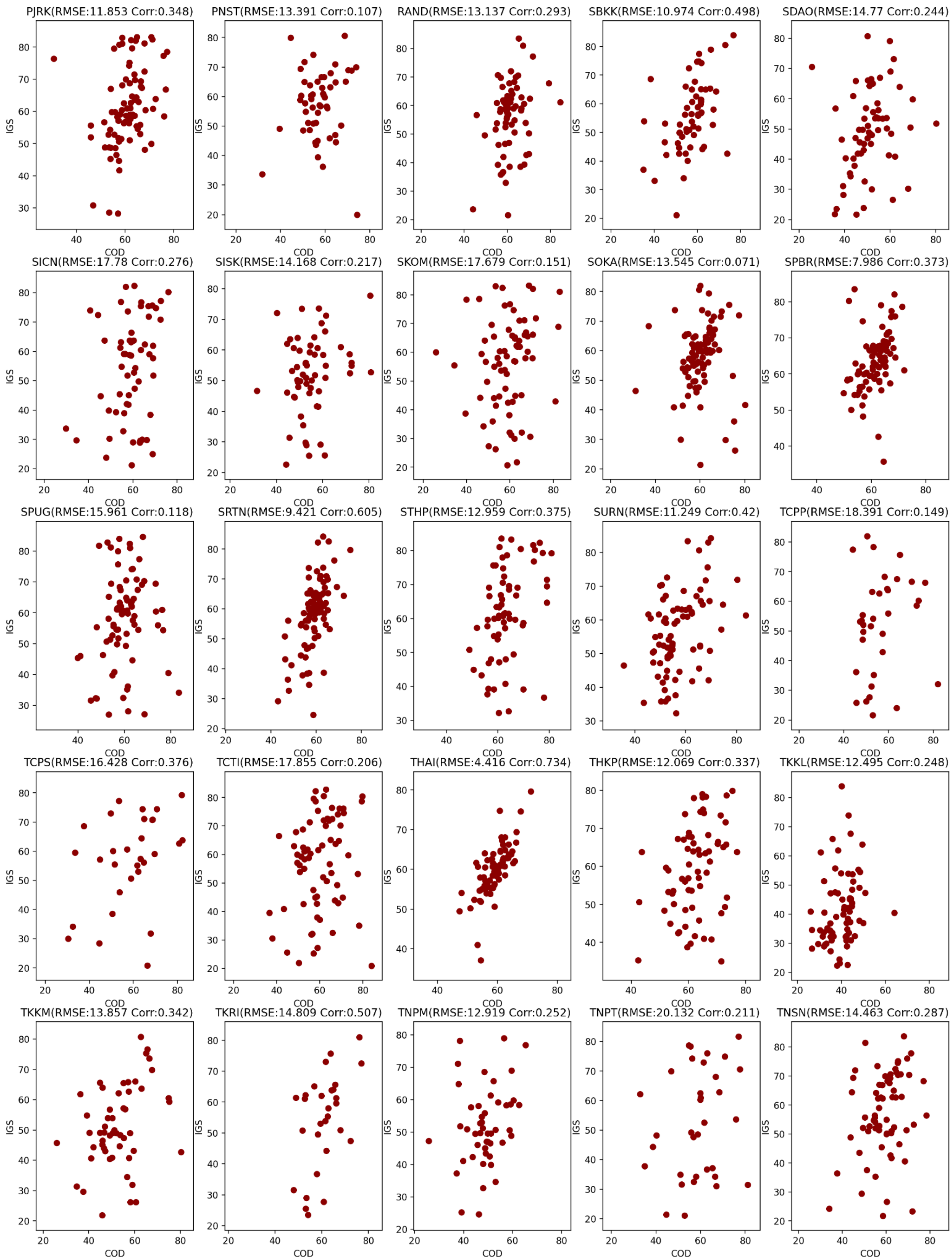


Figure 5: Scatter plot of COD and IGS PWV of 113 stations (Continue next page)

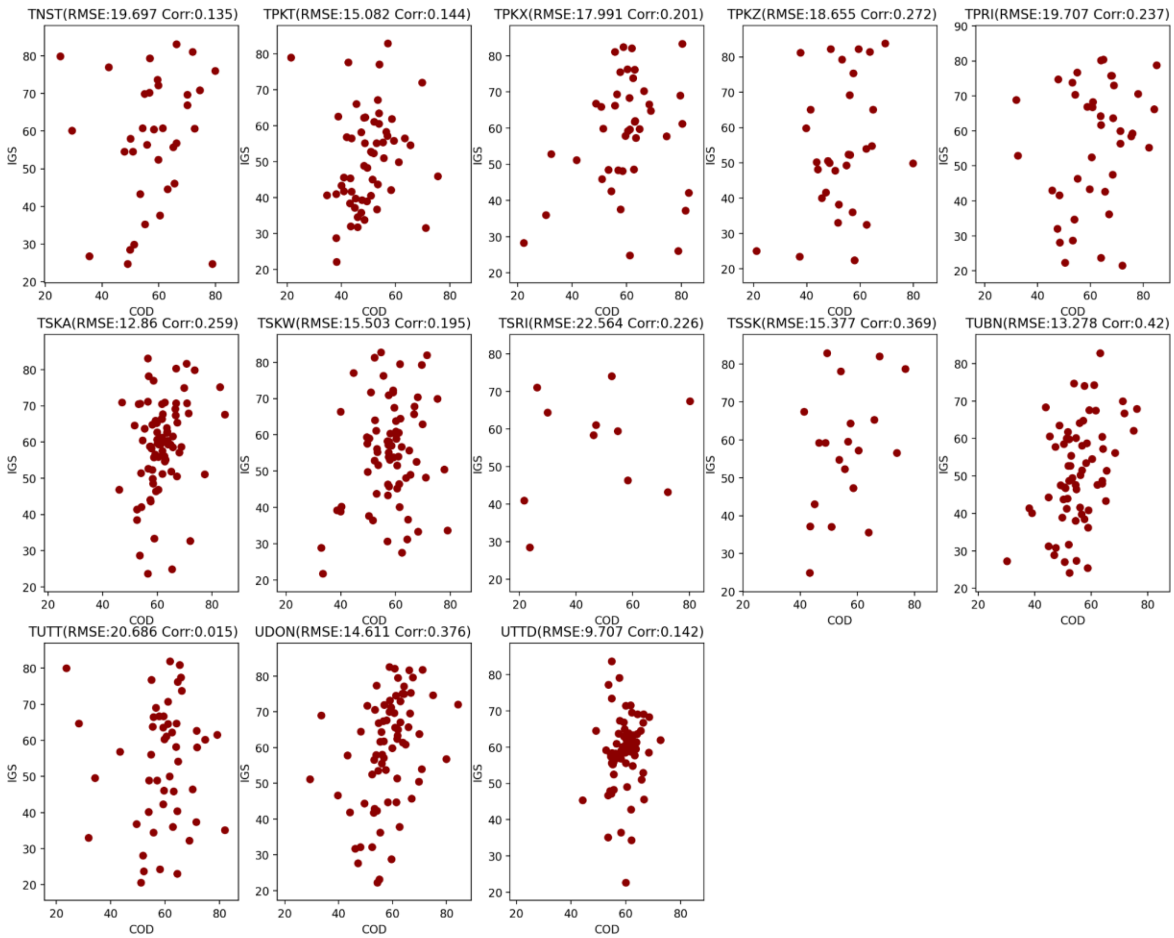


Figure 5: Scatter plot of COD and IGS PWV of 113 stations

From the scatter plot of PWV as shown in Figure 5, it can be observed that there are many higher and lower values of estimated PWV from CODE correction data and the average RMSE of 113 stations is 13.38. There is still uncertainty in the results by using the ultrarapid and prediction data correction product. However, some stations show very good correlation coefficients and low RMSE including THAI and ANGT. Further analysis and investigation will be conducted.

4.2 Near Real-Time GNSS PWV Estimation for Rainfall Monitoring

The tropical storm "Dianmu" moves along the monsoon through the Northeast and the central region of Thailand. There is a severe rainfall event from September 24 to 26, 2021. It brings flooding to 24 provinces in the North, Northeast, and Central regions of Thailand. In this study, the potential of near real-time PWV calculation for rainfall monitoring is investigated. The study period is from 13 September 2021 to 2 October 2021. A network of 7 GNSS CORS stations in the central region around the flooding area is shown in Figure 6. The stations LNSN and NKSW are selected since the distance between them is within 35 km. As shown in Figure 7, the GNSS PWV value is slightly increased from 19 September 2021 and the maximum GNSS PWV is on 25 September 2021. It is also the same as the rainfall which has a maximum on the same date. Subsequently, the GNSS PWV and daily accumulated rainfall intensity continue to decrease. Most values of GNSS PWV before 25 September 2021 are also slightly higher than the value after that.

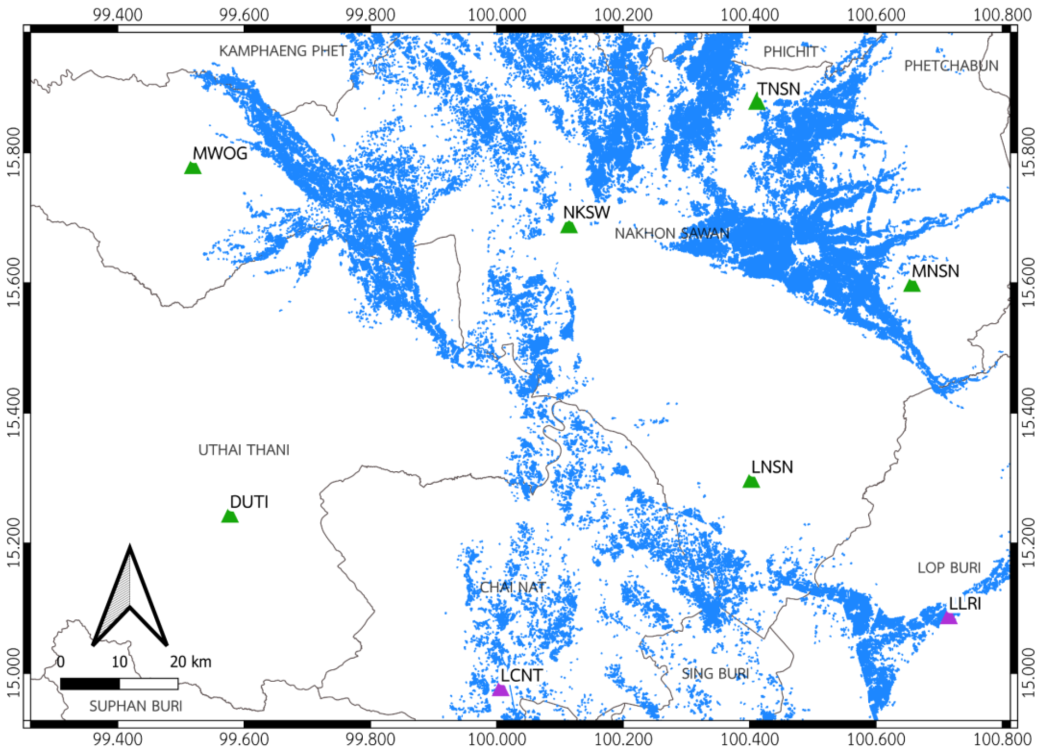
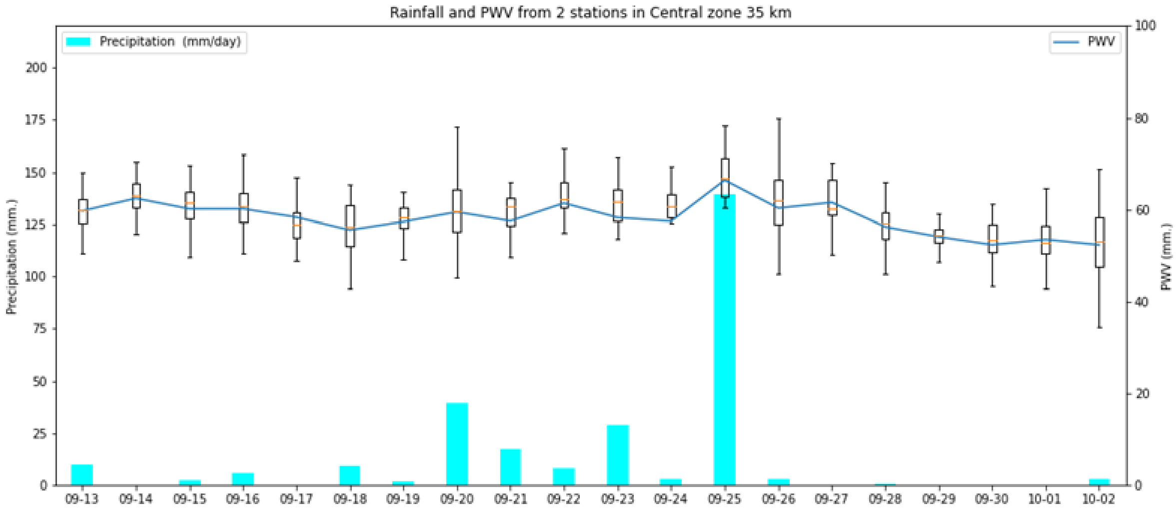


Figure 6: The GNSS CORS station around the flood area of central region, Thailand



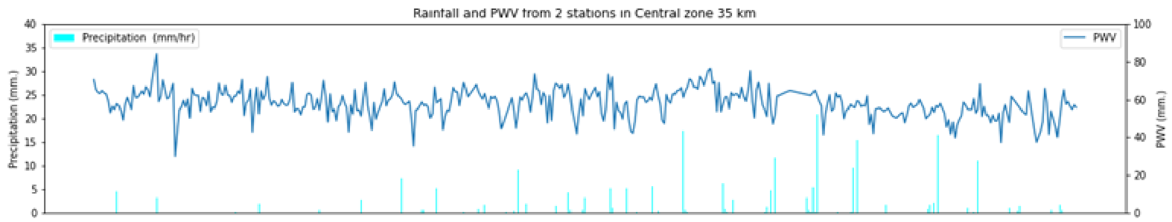


Figure 7: Comparison between GNSS-PWV and rainfall in central area

5. Conclusions

The key success of this research is development of a system which monitors all the regions in Thailand in near real-time. This system design will also enable the collaboration among organizations who are handling CORS stations and meteorological data which are widely distributed in Thailand to facilitate study using historical data to develop better models to find relationship. The goals were achieved since the system is currently running in operational mode at HII providing timely GNSS PWV that can be used to support and facilitate the analysis of atmospheric and meteorological phenomena in near-real-time. The recent research of the utilization of GNSS signals for sensing the Earth's atmosphere, ionosphere, and troposphere phenomenon enhance and enables various near real-time monitoring systems and applications. The GNSS CORS stations which are distributed cover the Thailand region continuously observed and near real-time released data. The ultrarapid and prediction necessary corrections data from CODE enables near real-time GNSS PWV estimation at national scales. The historical data used in the study is centralized in 2020 and we require more historical data to have robust research. Although, the overall results of GNSS PWV calculated with COD data correction show a slightly low correlation with the results from the final product of IGS. However, the comparison between GNSS PWV near real-time and rainfall during the severe rainfall events in September 2021 show high potential for meteorological monitoring purposes. Both PWV and daily accumulated rainfall are peak on 25 September 2021 in this severe rainfall event. This study mainly aims to develop the near real-time PWV mapping system generated from GNSS observation for monitoring the meteorological in Thailand.

Acknowledgements

This research was part of the project "Development of Near Real-Time Precipitable Water Vapor (PWV) Estimation System for Monitoring and Forecasting the Meteorological Changes" supported by Hydro-Informatics Institute.

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