Assessment and hydrological Application of Integrated Multi-Satellite Retrievals for GPM (IMERG) precipitation products over Thailand.

TIWAKORN WUTTIPAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR MASTER OF SCIENCE
IN GEOINFORMATICS
FACULTY OF GEOINFORMATICS
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ทิวากร วุฒิพันธุ์

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2020

The Thesis of Tiwakorn Wuttipan has been approved by the examining committee to be partial fulfillment of the requirements for the Master of Science in Geoinformatics of Burapha University

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TIWAKORN WUTTIPAN : ASSESSMENT AND HYDROLOGICAL APPLICATION OF INTEGRATED MULTI-SATELLITE RETRIEVALS FOR GPM (IMERG) PRECIPITATION PRODUCTS OVER THAILAND.. ADVISORY COMMITTEE: NENGCHENG CHEN, 2020.

Precipitation is an important component of the earth's water system. It is the major source that refills underground aquifers and surface water such as rivers and lakes and also provides freshwater for plants, animals and countless human activities. Currently, climate change is having a serious impact on the earth's temperature and global precipitation, resulting in excessive rainfalls and droughts in different regions over the world. Acquiring knowledge about precipitation characteristics is vital for improving climate prediction and water resources management, which is a significant issue in many countries including Thailand. Located near the equator, Thailand has a tropical rainforest climate and is under the influence of the Northeast and Southwest monsoons with high average rainfall. There are three seasons in Thailand, where dry weather is often experienced in winter under the influence of the Northeast monsoon, while thunderstorms are frequent in summer due to the influence of the Southwest monsoon which causes heavy rainfalls in this period. The highest rainfall occurs in the rainy season which starts in mid-May and ends in mid-October, with August and September as the wettest months of the year. Local rainfall amount data is important for many works including agriculture, irrigation, electricity production as well as for basic human activities. However, in poorly gauged areas or high-mountain areas still lacks to measure the precipitation and ground-based rainfall measurement is not yet sufficient.

In recent decades, the development of meteorological satellites, remote sensing techniques and satellite-based precipitation products is an important data source for the knowledge of climate characteristics and hydrological applications. An alternative method to measure rainfall in a large area that ground observation network measure only in a point scale, and the coverages of weather radar network has limits

capability by a blockage by high mountains. The Integrated Multi-Satellite Retrievals for GPM (IMERG) is a multi-satellite precipitation algorithm Level 3 of The Global Precipitation Measurement (GPM) to deliver next generation of satellite rainfall measurement after the success of the Tropical Rainfall Measuring Mission (TRMM). Precipitation data from the Global Precipitation Measurement (GPM) is available free download source data on website www.pmm.nasa.gov with a variety of formats for utilization precipitation data in research.

The main purpose of this research, to assess the performance of daily precipitation and spatial characteristics of Integrated Multi-Satellite Retrievals for GPM (IMERG) Version 06 (V06) products: the near-real-time (IMERG-Early and IMERG-Late) and the post-real-time (IMERG-Final) comparing with 121 ground-based observation station from the Thai Meteorology Department (TMD) that still lacks to study the performance of IMERG over the whole area of Thailand. The assessment was used reliability assessment (the correlation coefficient (CC), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Relative Bias (RB)) and quality assessment method (A probability of Detection (POD), False alarm radio (FAR), A probability of false detection (POFD) and Critical Success Index (CSI)), And evaluation the IMERG V06 precipitation product in hydrological modelling. The assessment was conducted at daily, monthly, annual, and seasonal scales on period 16 February 2014 to 15 February 2019.

The results showed All IMERG V06 precipitation products performed a good correlated and excellent precipitation detection capability compared with a ground-based observation from the Thai Meteorology Department (TMB) rain gauge station. Overall, the performance of all IMERG V06 precipitation products has tended to overestimation of rainfall over Thailand for daily, monthly, annual, and seasonal scales. The MAE and RMSE is high in the rainy season with good correlation in seasonal scale but a moderate correlation in summer. The IMERG precipitation products can successfully capture the spatial distribution of rainfall over Thailand. Similarly, to the spatial pattern of TMD gauge station. The daily precipitation accumulates increasing from the Northern to the Southern region with high among of precipitation on the Eastern coast and the Western side of the Southern region of

Thailand. In contrast, lower among of precipitation can be found in the Northern, Central and North-East region of Thailand.

For hydrological simulation, all IMERG precipitation products perform a high correlation with the inflow rate in NAM model simulation than ground-based precipitation data from the Electricity Generating Authority of Thailand (EGAT) Telemetering stations. However, IMERG precipitation products underestimated the inflow rate compared with observed inflow over Upper catchment of Vajiralongkorn Dam. Overall, IMERG precipitation products performed better performance than EGAT telemetering data. Furthermore, future research should be considering the performance of both IMERG near-real-time products (IMERG-Early and IMERG-Late) for flood events and more studies about IMERG precipitation products for hydrological modelling on a local scale. Moreover, the performance of IMERG Half-hourly precipitation products needs to study in future work in a different region of Thailand.

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Tiwakorn Wuttipan

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CHAPTER 1
INTRODUCTION

Precipitation is the fundamental component of the Earth’s system and the water cycle, and it has a significant role in meteorology and hydrological. Especially in water resource management, catchment management, flood risk assessment, and all human activities. The precise and timely are essential for understanding the Earth’s function for improving the knowledge how much it rains or snows and the prediction of climate, weather, freshwater resources, and natural hazard events (Hou et al., 2013)

The accurate observation of precipitation has an important to understanding spatial rainfall at different scales (global, regional, and local scales). For rainfall measurement techniques, the ground observation network for precipitation measurement is only reliable and accurate as the amount of rainfall is only known at a point scale. A dense precipitation gauge network is required to determine the rainfall pattern and represent the areal distribution of precipitation in an area. However, most areas of the world precipitation gauge network are usually limited by their spatial coverage and typically biased toward locations where people and infrastructure coexist (Chokngamwong & Chiu, 2008; Sultana & Nasrollahi, 2018). An alternative to rain gauges is weather radar network. However, the problem of radar coverages is blockage by high mountains still limits its capability (Chokngamwong & Chiu, 2008).

In recent decades, the development of meteorological satellites, remote sensing techniques and satellite-based precipitation products is essential for the precipitation data source. Remote sensing technology also has brought an unprecedented opportunity for better understand estimating precipitation than before (Fengrui & and Xi, 2016). Satellite-based precipitation products (SPPs) have been increasingly used for rainfall measurement, water resource management, and drought monitoring with near real-time data and extension coverage in the world. Such as Precipitation Estimation from Remotely Sensed Information using Global Precipitation Measurement (GPM) (Hou et al., 2013), Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2007), Global Satellite Mapping of Precipitation (GSMaP) (Okamoto, Ushio, Iguchi, Takahashi, & Iwanami, 2005), Climate Prediction

Center morphing technique (CMORPH) (Joyce, Janowiak, Arkin, & Xie, 2004) and Artificial Neural Networks (PERSIANN) (Sorooshian et al., 2000).

After 15 years of success of the Tropical Rainfall Measuring Mission (TRMM) satellite for precipitation measurement mission. The Global Precipitation Measurement (GPM) Core Observatory provide by NASA, and the Japan Aerospace Exploration Agency (JAXA) has launched in February 2014 to deliver next generation of satellite rainfall measurement for better understanding of energy, water cycles and improve the accuracy and consistency of precipitation estimates from all constellation radiometers in all part of the world (Hou et al., 2013). Precipitation data from the Global Precipitation Measurement (GPM) is available free download source data on website www.pmm.nasa.gov with a variety of formats for utilization precipitation data in research.

The assessment of precipitation products at local and regional scales is essential in improving satellite-based algorithms and sensors, as well as in providing valuable alternative of rainfall data for the local community (Hur, Raghavan, Nguyen, & Liong, 2016). For our knowledge, many previous researches in Thailand have been conducted to evaluate the performance of satellite-based precipitation product (SPP), such as TRMM (Chokngamwong & Chiu, 2008), GSMaP (Promasakha na Sakolnakhon, 2013), in Southeast Asia have been evaluated the performance of Integrated Multi-satellite retrievals of GPM (IMERG) such as Singapore (Yang, Yong, Hong, Chen, & Zhang, 2016), Myanmar (Fei et al., 2017) and Malaysia (Tan & Santo, 2018). In Thailand, only investigated The Integrated Multi-satellite retrievals of GPM (IMERG) comparing with ground-based measurement in some catchment area such as Mekong river basin (Wang, Zhong, Lai, & Chen, 2017) and Mun-chi River Basin in Thailand (Li et al., 2019), it still lacks to study the performance of IMERG over the whole area of Thailand.

The main target of this research is investigating the performance of the IMERG precipitation products comparing ground-based measurement over Thailand in different time scale and explore the performance of the IMERG precipitation products with the hydrological model in local scale for the knowledge of climate characteristics, hydrological and agricultural applications that are an essential source of agricultural, irrigation, electricity production and human activities in Thailand.

1.1 Research question.

1.1.1 How does the performance of the IMERG Precipitation product (Early, Late, and Final) over Thailand in multiple timescales (Daily, Monthly, Annual, and Seasonal)?

1.1.2 How does the performance of GPM IMERG precipitation products with the hydrological model on a local scale?

1.2 Objectives.

1.2.1 To evaluate the performance of the IMERG precipitation Product for Daily, Monthly, Annual and Seasonal comparing with rain gauge data over Thailand on 16 February 2014 to 15 February 2019.

1.2.2 To explore and evaluation of The IMERG Precipitation products with the hydrological model on a local scale.

1.3 Conceptual framework.

This research would like to study the performance of The Integrated Multi-Satellite Retrievals for GPM (IMERG) with Ground-Based Measurement by used statistics widely to assess both data and implement rainfall satellite data to the hydrological application over Thailand in different time scale.

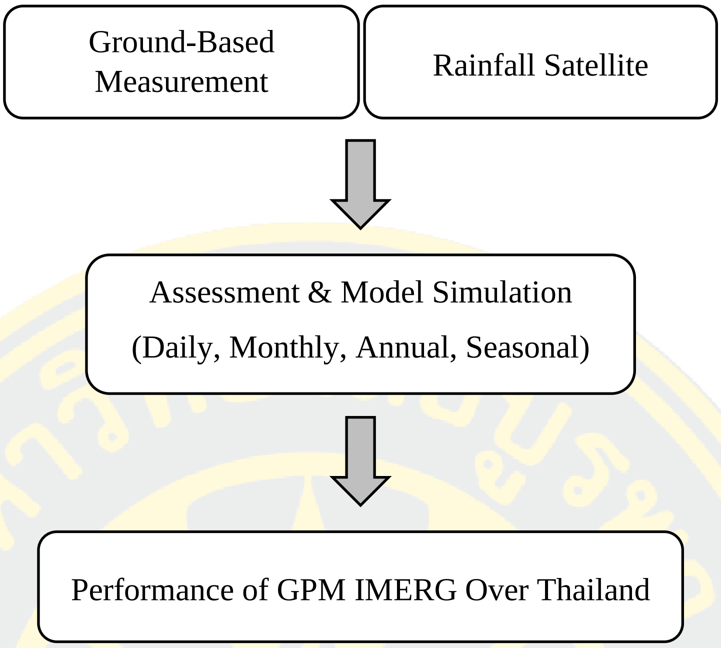


Figure 1: Conceptual framework in this research.

1.4. Contribution to the knowledge.

1.4.1 Improve knowledge of characteristics of Global Precipitation Measurement (GPM) precipitation estimates and The Integrated Multi-Satellite Retrievals for GPM (IMERG) products in terms of Climate and Water management in Thailand.

1.4.2 Provide a preliminary assessment of the Integrated Multi-Satellite Retrievals for GPM (IMERG) products over Thailand.

1.5. Scope of study.

1.5.1 Study area

Thailand is a Southeast Asia Country located in the fertile landscape in the heart of Southeast Asia composed of 77 provinces and over 69 million people. The country covers an area of 513,000 square kilometres. Bounded within 5°37’N - 20°27′N Latitudes and 97°22′E - 105°37′E Longitudes, Thailand bordered by Laos to the northeast, Myanmar and the Andaman Sea to the west, Cambodia to the southeast, the Gulf of Thailand and Malaysia to the South (Tourism Authority of Thailand, 2019). The topographic of Thailand is rolling surface and undulating hills in the northeastern region and hilly to mountainous in the southern part. The topographic map of Thailand is shown in Figure 2.

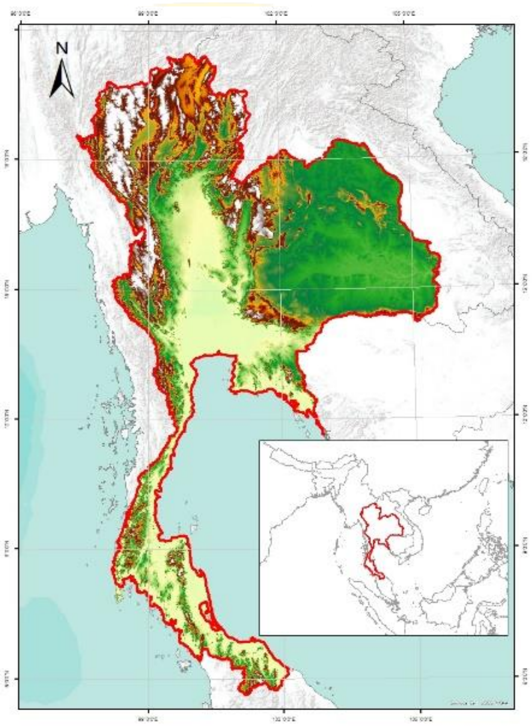


Figure 2: Topography map of Thailand.

Upper Catchment of Vajiralongkorn Dam located in Thong Pha Phum District, Kanchanaburi province, and it has an area approximately 3,689 sq.km. With consist of two sub-basins is Huai Pilok, and the Upper part of Mae Nam Khwae Noi is shown in Figure 3. Vajiralongkorn Dam, known previously name as Khao Laem Dam is a multi-purpose dam under the Development of Mae Klong River Basin Project and conducted by the Electricity Generating Authority of Thailand (EGAT) (Electricity Generating Authority of Thailand., 2019).

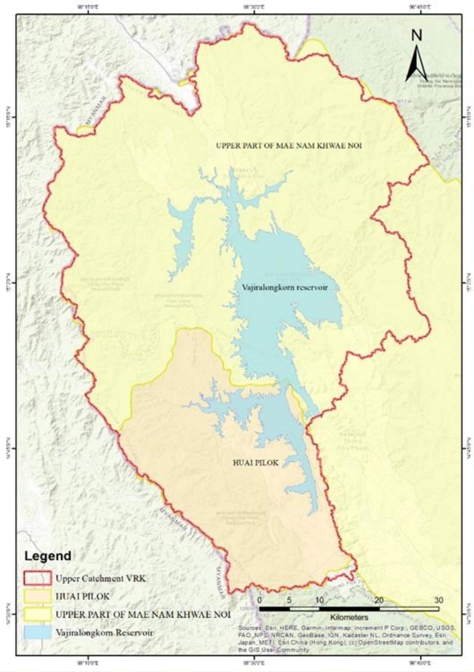


Figure 3: The upper catchment of Vajiralongkorn Dam.

1.5.2 Scope of Content

This study was to collect and evaluate IMERG precipitation products version 06 against ground-based measurement data from the Thai Meteorological Department (TMD). At different time scales, a daily, monthly, annual, and seasonal (summer (Middle of February to middle of May), rainy (Middle of May to middle of October), and winter (Middle of October to middle of February)) over Thailand on period 16 February 2014 to 15 February 2019. The validation using eight statistics method to assessment data is the correlation coefficient (CC), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Relative Bias (RB), A probability of Detection (POD), False alarm radio (FAR), A probability of false detection (POFD) and Critical Success Index (CSI).

Besides, we assessed the performance of IMERG precipitation products version 06 with a hydrological model in the Upper catchment of Vajiralongkorn Dam. By using four statistics method to assessment data is the correlation coefficient (CC), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Relative Bias (RB) by five telemetering gauge station from Electricity generating authority of Thailand (EGAT) on period 16 February 2014 to 15 February 2019.

CHAPTER 2
LITERATURE REVIEW

The propose of this literature review is to provide a general overview of the climate characteristics in Thailand that relate to rainfall over Thailand and technique to measurement rainfall. This chapter will describe information about the global precipitation measurement mission (GPM), and their product is the Integrated Multi-Satellite Retrievals for GPM (IMERG). Finally, reviewed data assessment of precipitation satellite comparing with ground-based precipitation measurement and the hydrological model was used in this study with another researcher.

2.1 Water Cycle and Rainfall.

The water cycle describes how water is an exchange with the Atmosphere, Lithosphere, Biosphere, and Hydrosphere. Figure 4 illustrates the water cycle; the water cycle has no starting point, but it will starting in the oceans since that is where most of the surface water exists. The sun, which drives the water cycle, heats water in the oceans. Some of it evaporates as water vapour into the atmosphere relatively smaller amount of moisture is combined of ice and snow sublimate directly from the solid-state into water vapour. Rising air currents take the water vapour up into the atmosphere, along with water from evapotranspiration, which is water transpired from plants and evaporated from the soil. The water vapour rises into the air where cooler temperatures cause it to condense into clouds, with these processes happening over millions of years. (United States Geological Survey., 2019)

Rainfall is liquid water that has condensed from water vapour in the atmosphere. It is the critical component of the earth's water cycle influencing the climate system. Rain is the primary factor to fills our surface water (lakes and rivers), recharges the underground aquifers, and provides fresh water for human activity, plants, and animals.

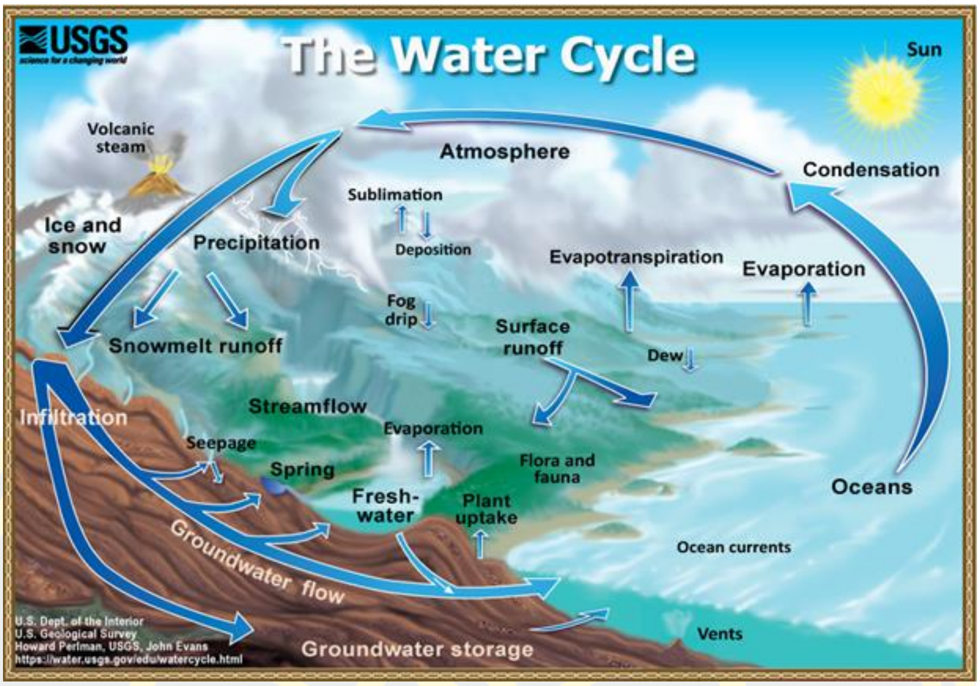
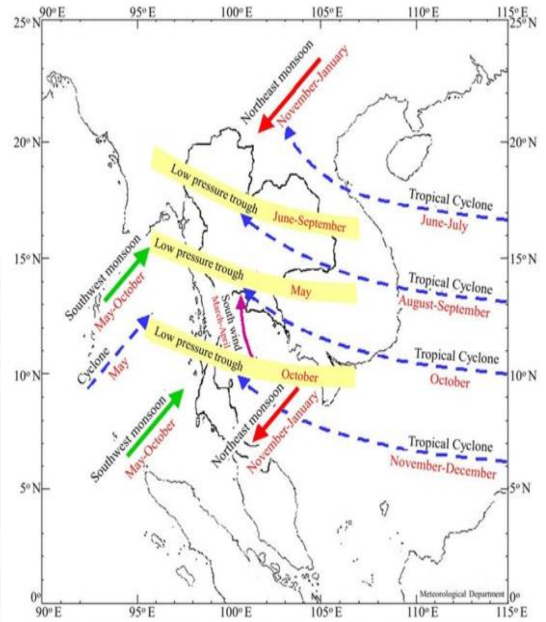


Figure 4: The Water Cycle (United States Geological Survey., 2019).

2.2 The Climate of Thailand.

Thailand is located near the equator in south-east Asia with the tropical rainforest climate under the influence of Southwest and Northeast monsoon wind of seasonal character and also the Inter-Tropical Convergence Zone (ITCZ) which produce a high among of rainfall in Thailand.

The southwest monsoon starts in mid-May until Mid-October brings a stream of warm moist air from the Indian Ocean towards Thailand that causing rainfall over the country. The Northeast monsoon starts in Mid-October brings the cold and dry air from China towards Thailand, as shown in Figure 5.



Source: The Rainfall of Thailand", A Study by Lawrence Sternstein, supported by The U.S. Army Quartermaster Corps, Research and Engineering Command, Project No. 7-83-01-006.

Figure 5: Southwest and Northeast monsoon of Thailand.

2.2.1 Thailand Seasonal.

Thai Meteorological Department has divided the climate characteristic of Thailand into three seasons as follows: (Thai Meteorological Department, 2019)

Summer (pre-monsoon season) starts in mid-February until mid-May that is a transitional period from the Northeast monsoon to Southwest monsoon. In summer the weather becomes warmer and hottest in April, especially in the upper of Thailand.

Rainy (Southwest monsoon season) starts in mid-May until mid-October. August to September is the wettest period of the year but except the Southern East Coast of Thailand, where heavy rain remains until the end of the year which is the starting period of the northeast monsoon.

Winter (Northeast monsoon season) starts in mid-October until mid-February. The upper of Thailand quite cold from December to January, but there is a high amount of rainfall in the East Coast of Southern part of Thailand from October to November.

2.2.2 Thailand Rainfall.

Thailand often experiences dry weather in winter due to the northeast monsoon, which is the main factor controlling the climate of this region. The later period, in summer, increasing thunderstorm and the beginning of the southwest monsoon causes heavy rains from mid-May to early October. The highest rainfall in August or September which some areas are probably flooded. However, dry spells usually occur for 1 to 2 weeks or more from June to early July due to the northward movement of ITCZ to southern China.

In the Southern region have a different rainfall characteristic from the upper part of Thailand. Abundant rainfall occurs on the southwest and northeast monsoon periods. During the southwest monsoon, the Western coast of the Southern region receives high among of rainfall and reaches high rainfall in September. In contrast, much rain in the Eastern coast of the Southern region, which its highest rainfall in November, continues until January of the following year, which is the starting of the northeast monsoon in Thailand.

According to spatial annual rainfall of Thailand, many areas of the country ranging from 1,200 - 1,600 mm per year. Annual rainfall less than 1,200 mm occurs in the leeward side areas, which are seen in the central valleys and the uppermost portion of the Southern Part (Thai Meteorological Department, 2019).

Table 1: Seasonal rainfall (mm) in various parts of Thailand.

Region	Winter	Summer	Rainy	Annual rainy days
North	100.4	187.3	943.2	122
Northeast	76.3	224.4	1,103.8	116
Central	127.3	205.4	942.5	116
East	178.4	277.3	1,433.2	130
South				
- East Coast	827.9	229.0	680.0	145
- West Coast	464.6	411.3	1,841.3	178

Based on the 1981-2010 period

The total average rainfall in 2018 is around 1,456 mm. The amount of rainfall in each area varies according to the season and changes according to the terrain. Upper Thailand area is usually dry, and there is little rain in the winter. In the summer, the amount of rain will increase with thunderstorms. In the rainy season, the amount of rainfall would increase with the highest amount of rainfall in August or September. The southern region has abundant rainfall throughout the year, except in the summer. Southwest area, which is the receiving side southwest monsoon there will be more rainfall than the southeast coast during the rainy season. With the highest amount of rainfall in September, See Figure 6.

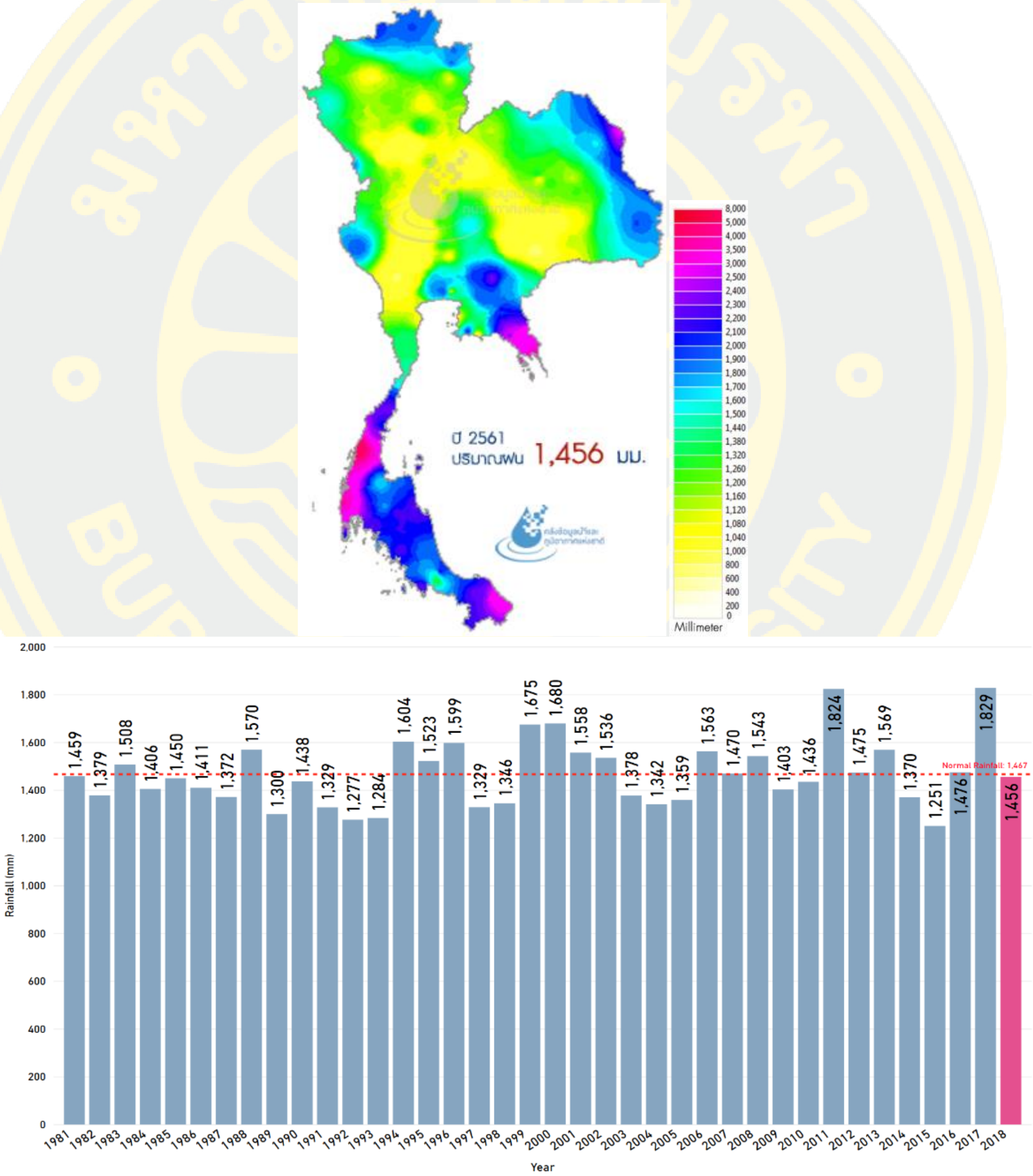


Figure 6: The average rainfall in 2018 is 1,456 mm and average annual rainfall from 1981-2018 in Thailand. (National Hydroinformatics and Climate Data Center., 2018).

2.3 Rainfall Measurement Technique.

The location of precipitation stations within the area of interest is important for meteorology, agricultural and water resources management because the number and locations of the gauge sites determine how well the measurements represent the actual amount of precipitation falling in the area (WMO, 2018).

Rainfall data can be measured with many types of measuring instruments. It can be classified into three groups according to the kind of device used to measure is Rain gauge, Ground-based weather radar, and Meteorological Satellites.

2.3.1 Ground-Based Measurement (Rain gauge).

The rain gauge is the most widely used approach to measure rainfall (Sene K., 2013). It is a type of instrument tool that has been used for a long time, and it is the simplest primary method for Hydrologists and Meteorologists to measure rainfall. The rain gauge can be divided into two types is Non-recording and Recording types.

2.3.1.1 Non-recording Rain Gauge.

Non-recording type rain gauge consists of funnel and water receiver mainly that can measure only the total of rainfall occurred during a particular period. It is a common type of rain gauge used by meteorological department such as Standard 8-inch Rain Gauge (Figure 7).

Figure 7: Standard 8-inch Rain Gauge (Northern Meteorological Center., 2004).

2.3.1.2 Recording Rain Gauge.

Recording Rain Gauge is an instrument that automatically records the total of rainfall that collected as a function of time. There are three common types of recording rain gauge. Tipping Bucket Rain Gauge (Figure 8), Weighting Bucket Rain Gauge (Figure 9), and Natural Syphon or Float Type Rain Gauge (Figure 10).

Figure 8: Tipping Bucket Rain Gauge

Figure 9: Weighting Bucket Rain Gauge (Northern Meteorological Center., 2004).

Figure 10: Natural Syphon or Float Type Rain Gauge.

2.3.2 Ground-based Weather Radar.

RADAR Stands for Radio Detecting and Ranging uses a transmitter operating at either radio or microwave frequencies to emit electromagnetic radiation and a directional antenna or receiver to measure the time of arrival of reflected or backscattered pulses of radiation from distant objects. Distance to the object can be determined since electromagnetic radiation propagates at the speed of light.

A Ground-based weather radar is a type of Radar that is an active remote sensing instrument which allows observation of precipitation using electromagnetic waves used to calculate precipitation motion and estimate type of precipitation for meteorology, research military, aviation, maritime, traffic, and agriculture.

The current ground-based weather radar station of the Thai Meteorological Department (TMD) called Doppler Weather Radar can be divided into three types as appropriate for the Thai Meteorological Department is X-band, C-band, and S-band (Thai Meteorological Department, 2019).

X-band type is a radar that is suitable for detecting light to moderate rainfall in the distance near the radius of about 100 kilometres.

C-band type is a radar that is suitable for measuring moderate to heavy rainfall or detecting a powerful storm such as a tropical storm, a radius of about 250 kilometres.

S-band type is a radar that is suitable for measuring heavy rainfall or used to detect the centre of a powerful storm, such as typhoons, a radius of over 300 kilometres.

Table 2: The different properties types of Radar.

Type of Radar	**Wavelength (cm.)**	**Frequency (MHz)**
X-band	3	10,000
C-band	5	6,000
S-band	10	3,000

2.3.3 Meteorological Satellites.

Meteorological satellites are a type of satellites that used to study and monitor the weather and climate of the earth's surface (Sahoo et al., 2017). Rainfall intensity retrievals from space-borne sensors have been based on passive sensors using visible (VIS), infrared (IR), and passive microwave (PMW) wavelength on Geostationary Satellites and Polar Orbital Satellites (Michaelides et al., 2009).

2.3.3.1 Geostationary Satellite.

Geostationary Satellite or High-Orbital Satellite placed at an altitude of approximately 36,000-kilometres above the equator of the earth. The speed of revolution of the satellite is the same direction of the earth’s rotation (West to East) and takes 24 hours to remain in the same place and the same length of time as the earth rotation that can monitor the same area on the earth continuously. The example of Geostationary Satellite is NOAA, GOES, METEOSAT, and MTSAT.

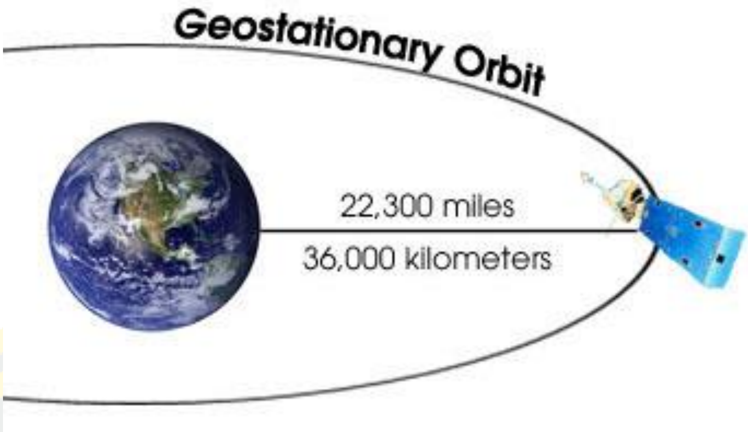


Figure 11: Geostationary Satellite or High-Orbital Satellite (CIMSS., 2019).

2.3.3.2 Polar Orbital Satellites.

Polar Orbital Satellites or Sun-synchronous orbit are placed at an altitude approximately 850-880 kilometres above the earth's surface, and move around the world from pole to pole takes approximately an hour and a half for full rotation and can acquire observe of the whole surface of the earth within a couple of days. An example of Geostationary Satellite is Landsat, SPOT.

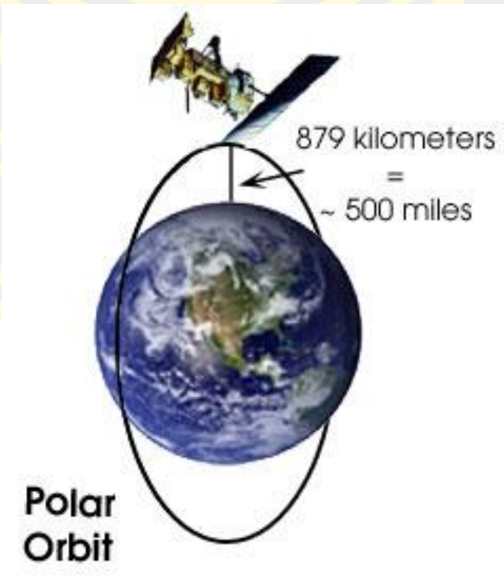


Figure 12: Polar Orbital Satellites or Sun-synchronous orbit Satellite (CIMSS., 2019).

Besides, there are some of the low-orbital satellites moving in a flattened circle or oval different according to tilt or the angle that made to the equatorial plane and not moving closer to the pole. For example, the Tropical Rainfall Measuring Mission (TRMM) extending between 35° North and 35° South at 350 kilometres and the Global Precipitation Measurement (GPM) core observatory covers the area from the Arctic Circle (65° North) to the Antarctic Circle (65° South) every 3 hours to see all rainfall in that zone.

2.4 Global Precipitation Measurement (GPM).

The Global Precipitation Measurement (GPM) mission is an international collaboration between The Nation Aeronautics and Space Administration (NASA) and The Japan Aerospace and Exploration Agency (JAXA) to provide the GPM core observatory. An essential advancement of GPM more than TRMM is the extended capability to detect light rain (i.e., <0.5 mm hr-1), solid precipitation, and the microphysical properties of precipitating particles (Global Precipitation Measurement., 2019). The GPM has designed to provide the next era of Meteorological satellites to measure rain and snow from the space to improve our knowledge of the earth’s water cycle and energy cycle and serve as a reference standard to unify precipitation measurements from a constellation of research and operational satellites.

There are three different of The Integrated Multi-Satellite Retrievals for GPM (IMERG) products. The IMERG system is run twice in near-real-time, which includes IMERG-Early Run, IMERG-Late Run, and after monthly gauge data analysis is IMERG-Final Run products (Hou et al., 2013).

2.4.1 GPM Core Observatory

GPM Core Observatory carries the Dual-frequency Precipitation Radar (DPR)(Ku/Ka-band) and Multi-channel GPM Microwave Imager (GMI) as shown in Figure 13. which improves advanced precipitation instruments and expanded coverage area on the earth’s surface and allows scientists to better understand inside the cloud (Hou et al., 2013).

2.4.1.1 Dual-frequency Precipitation Radar (DPR)

The Dual-frequency Precipitation Radar (DPR) has developed by The National Institute of Information and Communications Technology (NICT) and the Japan Aerospace and Exploration Agency (JAXA). The DRP compose of a Ka-band precipitation radar (KaPR) that will measure frozen precipitation and light rain operating at 35.5 GHz, and a Ku-band precipitation radar (KuPR) will measure moderate rain to heavy rain operating at 13.6 GHz.

DPR will provide a 5-kilometre resolution on the earth’s surface with a scanned swath 245 kilometre for KuPR and 120 kilometres for KaPR, as shown in Figure 13. Simultaneous measurements from an inner swath of KaPR and KuPR data will provide new information on particle drop size distributions.

2.4.1.2 GPM Microwave Imager (GMI)

The GPM Microwave Imager (GMI) instrument developed by Ball Aerospace & Technology Corporation under contract with NASA Goddard Space Flight Center (GSFC), is a multichannel, conical-scanning, microwave radiometer serving an essential role in near-global coverage and frequent revisit time requirements of GPM (Tang et al., 2016).

The GMI uses thirteen microwave channels ranging in frequency from 10 to 183 GHz to measure the intensity of microwave radiation emitted from the atmosphere and earth's surface. The lower frequency channels ranging from 10 to 89 GHz similar to those on The TRMM Microwave Imager (TMI) to measure heavy to moderate rainfall. Furthermore, to carrying channels similar to those on the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), the GMI carries four high frequency, millimetre-wave, channels about 166 GHz and 183 GHz that will measure moderate to light precipitation (Global Precipitation Measurement., 2019).

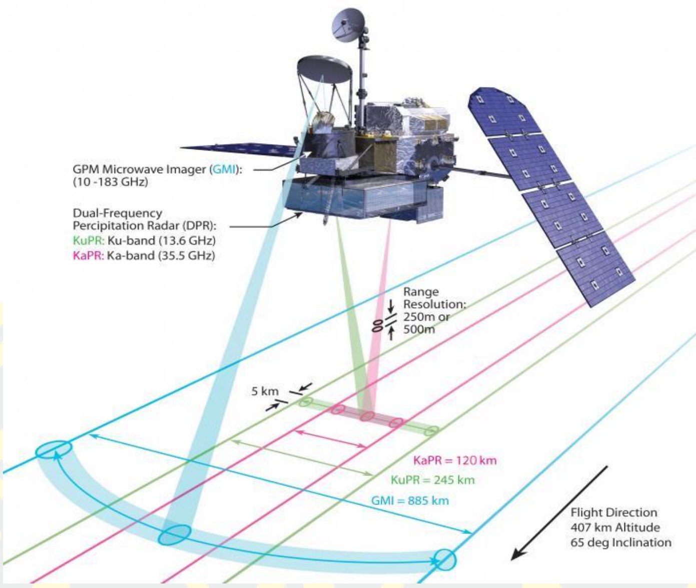


Figure 13: Swath covered and scanning pattern of GPM Core Observatory and instrument (Global Precipitation Measurement., 2019).

2.4.2 GPM Constellation

The GPM mission concept centers on deploying a GPM "Core" satellite, partnership co-led by NASA and JAXA carries two instrument active and passive sensor packages to establish new reference standards for precipitation measurements from space. The combined active and passive sensor measurements can also be used to derive consistent precipitation estimates from a constellation of satellites provided by a consortium of international partners. (Global Precipitation Measurement., 2019) The GPM constellation is consists of many satellites with radiometers or microwave sounder instruments, including the DMSP F19 and F20, GCOM-W1, JPSS-1, Megha-Tropiques, MetOp B and C, NOAA 19 and NPP satellites. (Tang et al., 2017) Shown in Figure 14.

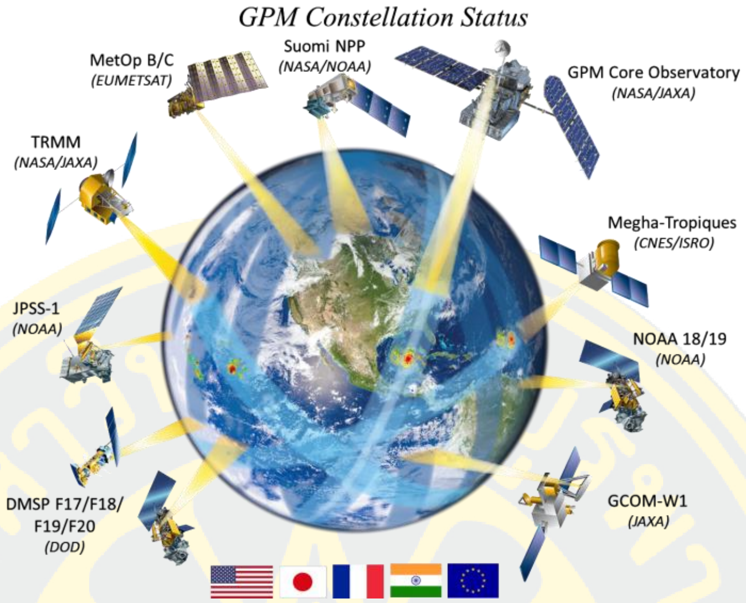


Figure 14: GPM Constellation status (Global Precipitation Measurement., 2019).

2.4.3 IMERG Version 06

The Integrated Multi-Satellite Retrievals for GPM (IMERG) is the Level 3 multi-satellite precipitation algorithms of GPM, which combines intermittent precipitation estimates from all constellation microwave sensors, IR-based observations from geosynchronous satellites, and monthly gauge precipitation data at 0.1° × 0.1° spatial and half hour temporal resolutions (Huffman et al., 2007). There are three different of The Integrated Multi-Satellite Retrievals for GPM (IMERG) products that can download from the Precipitation Measurement Missions (PMM) website (https://pmm.nasa.gov/data-access/downloads/gpm). The IMERG system is run two times in near-real-time which includes IMERG-Early Run (4 hr. after observation time with the multi-satellite product), IMERG-Late Run (14 hr. after observation time with the multi-satellite product) and once after monthly gauge analysis is IMERG-Final Run (3.5 months after observation months with the satellite-gauge product) products is shown as Table 3. Therefore, IMERG-Final Run will provide more precise accuracy, particularly over land and IMERG-Early, and Late Run products have better timeliness, which is appealing to flood forecast and rainfall monitoring application.

Table 3: Summary of characteristics of GPM IMERG Products.

Product	Temporal Resolution	Latency	Special Resolution	Special Coverage	Period
IMERG-Early	30 min, 3 hours, 1 day, 3 days, 7 days	4 hourly	0.1°×0.1°	Gridded 90°N-90°S	March 2014-present
IMERG-Late	30 min, 3 hours, 1 day, 3 days, 7 days	14 hourly			
IMERG-Final	30 min, 1 day, monthly	3.5 Monthly			

2.5 Precipitation Data Assessment Technique.

Precipitation Data Assessment Technique can divide into two types, is reliability assessment and quality assessment. The reliability assessment is widely statistical metrics method that can be found in many research (He et al., 2017; Promasakha na Sakolnakhon, 2013; Tan & Santo, 2018) to assessment accuracy of satellite data with ground-based observation data such as correlation coefficient (CC), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Relative Bias (RB). The Quality assessment was used to evaluate the detection ability of satellite data with ground-based observation data such as A probability of Detection (POD), False alarm radio (FAR), A probability of false detection (POFD), and Critical Success Index (CSI).

2.6 MIKE11 NAM Model.

NAM Model is a model that part of the MIKE 11 module. It was developed by the Danish Hydraulic Institute (DHI) for a rainfall-runoff model. The NAM (Nedbør Affstrømnings Model) is a deterministic, lumped, and conceptual rainfall-runoff model that operates by continuously accounting for the moisture content in three different and mutually interrelated storages the present overland flow, interflow and base flow (DHI, 2003).

In the NAM model structure, the hydrological cycle is the basis of the quantitative simulation of water storage. It flows in the watershed, and its parameters represent an average value for the whole watershed, as shown in Figure 15. There are four different structures of the model with its flows and mutually interrelated storages and their corresponding. The snow storage, surface storage, lower zone storage, and underground storage are four storage layers, and the flow (QOF), interflow (QIF), an underground flow (QBF) are three flows surface. Generally, rainfall, potential evaporation, and temperature are the input data required for this model, and the output of the model is the watershed outflow over time (DHI, 2009).

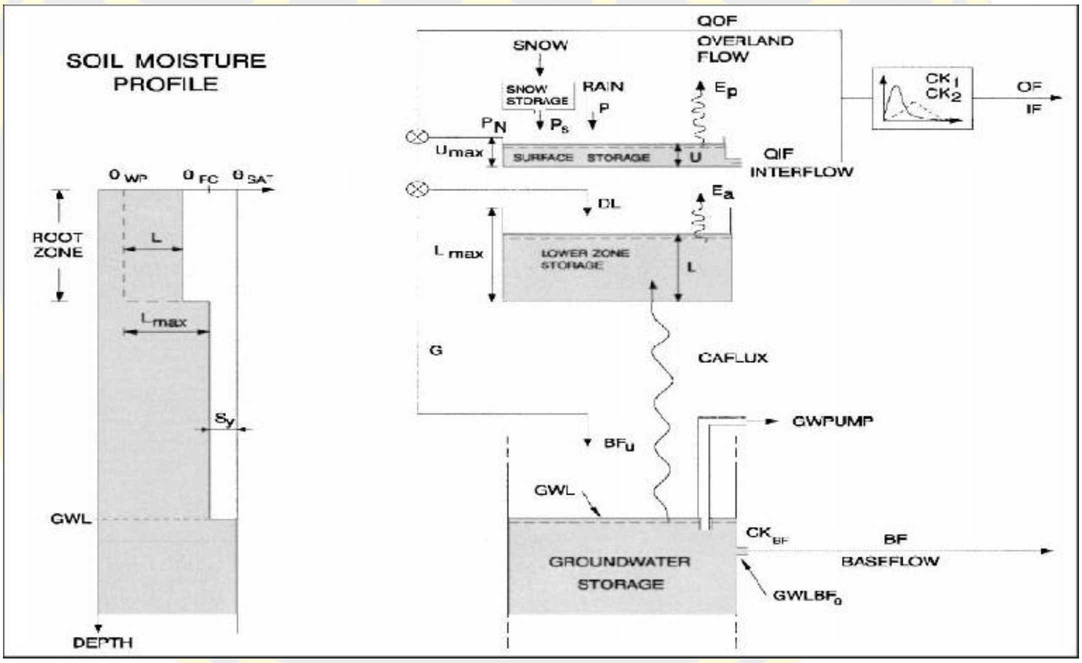


Figure 15: Structure of the NAM model for rainfall-runoff simulation.

2.7 Research Review.

The propose of this literature review is to provide a general research overview of the assessment method and results of previous research of precipitation measurement for Integrated Multi-Satellite Retrievals for GPM (IMERG) rainfall products with ground observation measurement.

Wei Wang (2016) is evaluated and compared to GPM Level 3 IMERG half an hour (3IMERGHH) and TRMM3B42 Version 7 final products (TRMM3B42 v7) from 1 April 2014 to 31 March 2015 at daily scale with 53 rain gauge cover Mekong River Basin (MRB). This research shows that 1) both 3IMERGHH and TRMM3B42 v7 have an underestimation of rainfall over MRB. 2) The performance of two precipitation products in the wet season is better than the dry season. 3) TRMM3B42 v7 can achieve better estimation than 3IMERGHH during the wet and dry season. 4) The Probability of Detection (POD) and Critical Success Index (CSI) of 3IMERGHH have a better than TRMM3B42 v7, and 5) 3IMERGHH is more likely to make false alarms but TRMM3B42 v7 more likely to miss a rainfall event. This study has shown there is work needed to be improved GPM's performance in MRB, especially in n dry season.

Fei Yuan (2017) are studied the capability of the Integrated Multi-satellite Retrievals for GPM (IMERG) final run and TRMM 3B42V7 over the Chindwin River basin, Myanmar from April 2014 to December 2015. The result shows that IMERG and 3B42V7 an ability to capture the spatiotemporal patterns of historical precipitation, but IMERG not significantly improves compared with 3B42V7 from TRMM precipitation satellite. 3B42V7 outperformance IMERG at daily and monthly scales. This research suggested that IMERG developers refine the algorithms and improve the more precise of IMERG in Myanmar.

Mou Leong Tan and Zheng Duan (2017) were compared and evaluated satellite precipitation products (SPPs) that are GPM (IMERG) and TRMM TMPA 3B42 and TMPA 3B42RT with 48 rain gauges over Singapore at different timescales (Daily, Monthly, seasonal and annual) during 1 April 2014 to 31 January 2016. This study showed 1) All SPPs performed well correlated with gauges measurements at the monthly scale but moderately on a daily scale. 2) SPPs performed well in the northeast monsoon season than in the inter-monsoon 1, southwest monsoon and inter-monsoon two seasons. 3) IMERG had a good performance in the spatial characterization and precipitation detection capability of precipitation variability compared with the TMPA products. 4) IMERG had the lowest systematic bias at the daily precipitation estimates, followed by 3B42 and 3B42RT and 5) most of the satellite precipitation products overestimated for moderate precipitation events but underestimating in light and heavy precipitation events. Overall, IMERG is greater but with the only slight improvement compared to the TMPA products over the study area. This research recommends that bias correction should be conducted to daily precipitation estimates from Satellite precipitation products before implementing them to any research and operational work. Therefore, future research should be carried out to establish efficient regional satellite precipitation products with bias-correction algorithms.

Ran Xu (2017) are evaluated two satellite rainfall products Global Precipitation Measurement Integrated Multi-Satellite Retrievals of GPM (IMERG) and Tropical Rainfall Measurement Mission 3B42V7 (TRMM 3B42V7) in Southern Tibetan Plateau region on the rainy season from May to October in 2014. The result showed, 1) GPM product performs better than TRMM at all time scales and elevation ranges in detecting daily rainfall accumulation, 2) Negative correlated for accumulated rainfall over the rainy season with mean elevation for rain gauges, while TRMM has significant correlates with topographic variations 3) False alarming ratio of TRMM is larger than GPM, while Missing ration of GPM larger than TRMM and GPM tends to underestimate of light rain event but overestimate for TRMM. For light rainfall events, GPM shows better detecting ability, but there is no detection skill for both satellite at high elevation (>4500 m) regions. This research also comments to further improve on the rainfall retrieval algorithm that is needed by considering topographical influences for both satellite rainfall products.

Sungmin O (2017) are evaluated half-hourly rainfall estimates from three IMERG Version 3 (V03) products (IMERG-Early, Late and Final runs) half an hour rainfall estimates comparing with rain gauge based gridded data from the WegenerNet Feldbach region (WEGN) climate station network in South-eastern of Austria on April to October in 2014 and 2015. The results show that IMERG Final rainfall estimates are in the best follow by IMERG Late and IMERG Early, particularly for the hot season.

Zhaoli Wang (2017) are evaluated the accuracy and performance of IMERG product (IMERG-Early, Late and Final) compared with TRMM 3B42-V7 product and intercompare the hydrological simulation utility of four satellite precipitation products (IMERG-Early, Late, Final and TRMM 3B42-V7) by used nine statistical assessment index and Variable Infiltration Capacity model (VIC) over Beijiang River Basin. They were suggestion for the evaluation of the hydrological utility of IMERG products in the high-latitude, and altitude area would be necessary.

Z. E. Asong (2017), in this study, is evaluated GPM IMERG final Run version 3 with ground-based observation measurement at time scales 6-hourly, daily, and monthly over different ecozones of Southern Canada within 23 months from 12 March 2104 to 31 January 2016. IMERG tends to overestimate higher monthly precipitation amount over the Pacific Maritime ecozone and more satisfactory agreement at the daily and six-hourly of June to September, unlike November to March. For extremes precipitation, IMERG tends to overestimate of heavy precipitation events but captured well the distribution of heavy precipitation amounts and observed wet/dry spell length distributions over most ecozones. However, the low skill was found over large portions of the Montane Cordillera ecozone and a few stations in the Prairie ecozone.

Cheng Chen (2018) is evaluated and compared GPM IMERG version 5 (IMERG v5) and TRMM3B42 v7 over the Huaihe River basin that is a climate transition area in China from 2015 to 2017. The results show that both satellite precipitation have a high correlation with gauge observations. Still, IMERG v5 has a larger mean Pearson Correlation Coefficient (r), and lower mean relative root means square error (RRMSE) than TRMM3B42 v7. The IMERG v5 has a higher probability of detect (POD), Critical Success Index (CSI), and lower false alarm ratio (FAR) than TRMM3B42 v7. Both satellites are overestimated precipitation at monthly and annual scales, also overestimate precipitation with intensity ranging between 0.5 to 25 mm per day but underestimate heavy and light rainfalls, especially for torrential rains (>100mm/day). IMERG v5 performs better in detecting the observed precipitations and provided more accurate precipitation than TRMM3B42 v7 at different rainfall rates indicates.

Mou Leong Tan and Zheng Duan (2018) are studied the performance of three GPM IMERG products (IMERG-Early, IMERG-Late, and IMERG-Final), the TMPA 3B42 and 3B42RT products and a long-term PERSIANN_CDR product over Malaysia by used widely statistical metrics (CC, RMSE, RB, POD, FAR, CSI and PDF) evaluated with 501 rain gauge during 12 March 2014 to 29 February 2016 in annual, seasonal, monthly and daily time scales. The results show the all six-satellite precipitation product perform well in annual and monthly but moderate correlation at daily precipitation estimates in many regions of Asia. The IMERG shows excellent precipitation detection ability about 73-75% of the success rate in detecting precipitation and non-precipitation days. Still, overall the IMERG final run product does not exhibit significant improvement to its near-real-time product.

Chunguang Wang (2018) are intercompared GPM IMERG Version 05, 04 and 03 products and assess the differences and improvement with intercompared with Global Precipitation Climatology Project (GPCP) version 2 and version 3, Multi-Source Weighted-Ensemble Precipitation (MSWEP) Version 2.1 and rain gauge network in China. The results show that IMERG product V05 Final run has significant differences and improvements from V03 and V04 and has the best performance among the seven standard IMERG products.

Wan-Ru Huafng (2018) has studied and evaluated the performance of IMERG data with surface rain gauge observations in Taiwan at multiple time scales from March 2014 to February 2017. The results show IMERG underestimated of precipitation over most of Taiwan for all the examined timescales. The bias was lager over the mountainous areas than over the plain areas and also more significant in warm seasons in the cold seasons. Also, IMERG was capable of qualitatively over Taiwan in most seasons, except for the winter season**.**

Shanhu Jiang (2018) was studied on statistical and hydrological valuations of GPM IMERG version 05 comparison with TRMM product (3B42RT and 3B42V7) over the mid-latitude humid Mishui basin in South China on 2014-2015. IMERG products present satisfactory preliminary accuracy and hydrological simulation utility, while different types of IMERG products might have distinct hydrological utility in different regions.

Rui Li (2019) The main objectives are comparing the performance of TRMM, GPM, and WMO interpolated precipitation. Validate runoff simulations by using the VIC model. An analyze the influence of runoff on MODIS LAI variations during dry seasons. This research is a suggestion for the potential of microwave precipitation products for water management and runoff simulations. The Watershed runoff is essential for water resource management but is lacking in the poorly gauged catchment.

There are many pieces of research evaluated capability of The Integrated Multi-satellite retrievals of GPM (IMERG) in a different version of IMERG products with ground-based measurement and other weather satellites. Most of the literature review focusing on comparing IMERG precipitation products with a ground observation by using reliability assessment and quality assessment to investigates the performance of satellite precipitation on a different time scale. Moreover, Implement the satellite precipitation data to hydrological modelling and water resources management while different types of IMERG products might have distinct hydrological utility in different regions.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter is describing the detail of methods that were used to assess precipitation products using The Integrated Multi-Satellite Retrievals for GPM (IMERG) from The Global Precipitation Measurement (GPM) mission comparing with a ground-based observation from Thai Methodological Department (TMD) over Thailand. The purpose of this chapter includes data collection, data preparation, and data Validation/Assessment.

Figure 16 shows the conceptual framework and methodological diagram for the assessment of GPM IMERG precipitation products with rain gauge stations data from Thai Meteorological Department (TMD) by using standard statistical for assessing both data at different timescales Daily, Monthly, Annual and Seasonal over Thailand on period 16 February 2014 to 15 February 2019.

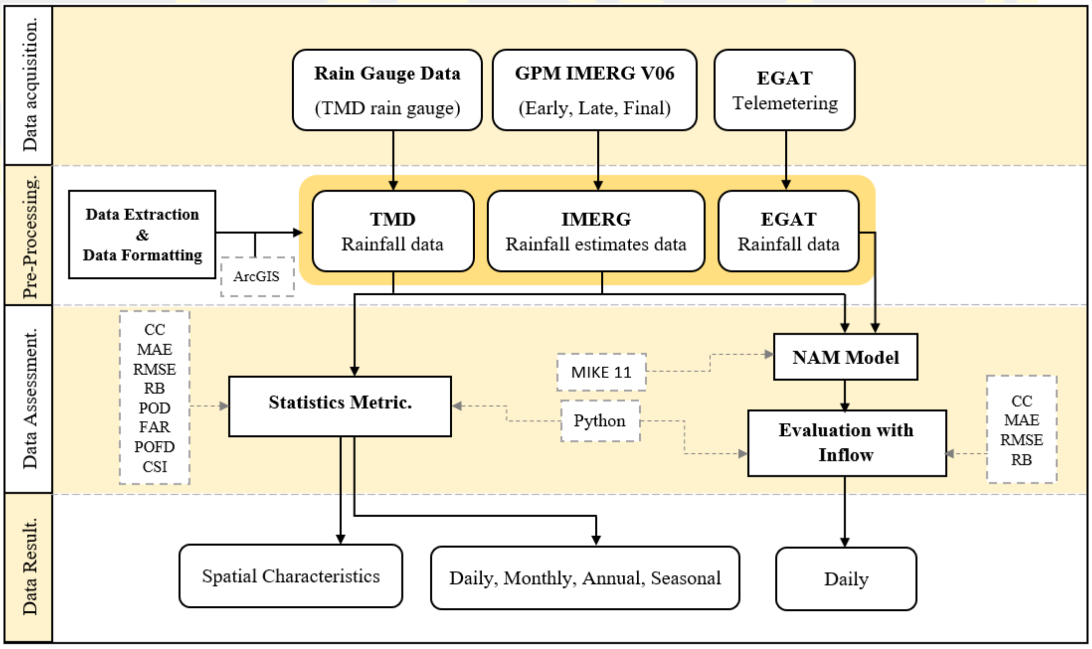


Figure 16: Methodological diagram of precipitation assessment framework in this study.

3.1 Data Acquisition.

3.1.1 IMERG Version 06.

In this study were collected latest IMERG precipitation products (IMERG-Early, IMERG-Late, and IMERG-Final) version 06 at a special resolution of 0.1°× 0.1°. With a daily temporal resolution scale on the study period. The IMERG precipitation products version 06 is available online at https://pmm.nasa.gov/data-access/downloads/gpm. The source of precipitation data has many formats NetCDF, HDF5, GeoTIFF, ASCII, PNG, KMZ, OpenDAP, GrADS service by THREDDS on Goddard Earth Sciences Data and Information Service Center (GES DISC) site at https://disc.gsfc.nasa.gov/.In this research used NetCDF (.nc4) files to extract rainfall data of all IMERG product over Thailand as an example of IMERG-Early data as shown in Figure 17.

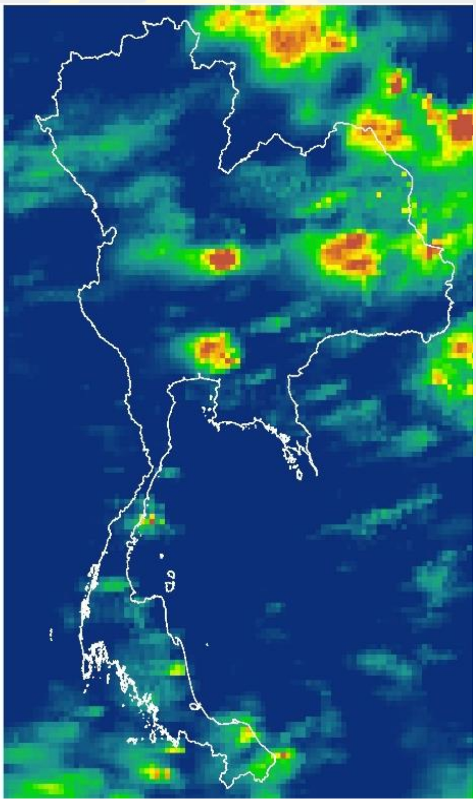


Figure 17: Example of IMERG-Early data on 21 September 2014 in NetCDF format.

3.1.2 TMD Rainfall data.

The ground-based precipitation data used in this study are daily precipitation from Thailand rain gauges data are obtained from the Thai Meteorological Department (TMD). TMD ground-based observation composed of 121 stations over Thailand as shown in Figure 18. The daily precipitation data were collected from 7.00 a.m. to 7.00 p.m. in Thailand local time, which is equivalent to 00Z (00:00 UTC) on period 15 February 2014 to 16 February 2019 as example data in Table 4.

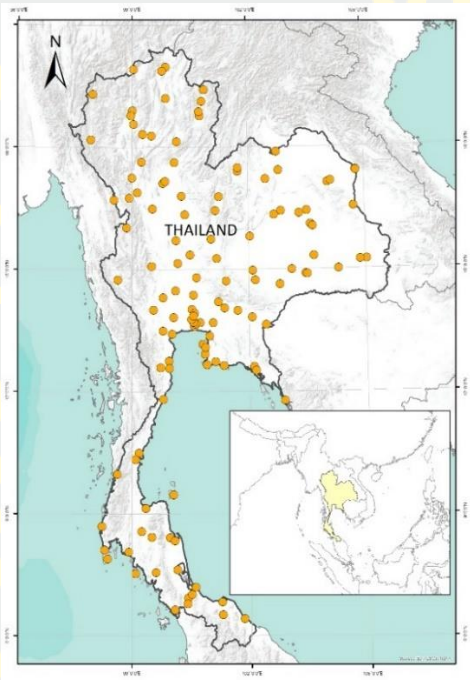


Figure 18: Distribution of Thai Meteorological Department Rain Gauge.

Table 4: Example daily rainfall data from TMD.

No.	Station name	Month	Date																					Total
			1	2	3	4	5	6	7	8	9	10	…	21	22	23	24	25	26	27	28	29	30	31	
1	300201-Mae Hong Son	Jan-13	0	0	0	0	0	0	0	0	0	0	….	0	0	0	0	0	0	0	0	0	39.1	0	**39.1**
2	300201-Mae Hong Son	Feb-13	0	0	0	0	0	0	0	0	0	0	….	0	0	0	0	0	0	0	0	-	-	-	**0.4**
3	300201-Mae Hong Son	Mar-13	0	0	0	5.1	0	0	0	T	0	0	….	0	0	0	0	0	0	0	0	T	0	0	**5.1**
4	300201-Mae Hong Son	Apr-13	0	0	0	0	0	0	0	0	0	0	….	0	12.4	0	0	0	0	0	0	4.2	0	-	**16.6**
5	300201-Mae Hong Son	May-13	0.6	3.2	55.2	0.5	8.5	2.8	10.8	0.2	9.5	0	….	0	0	5.4	2.2	0	0	0	0	0	3.8	0	**131.8**
6	300201-Mae Hong Son	Jun-13	1.8	0	11.7	9.9	28.5	8.3	0.9	T	0	0.5	….	5	0	0	1	13.5	16.8	9.7	0.3	0.6	5.4	-	**128.9**
7	300201-Mae Hong Son	Jul-13	0	0.1	0.1	0	0	0.6	0	18.3	0	0.2	….	8	6.6	31.1	16.4	9.5	10.5	6.7	8.2	14.5	25.6	0	**182.1**
8	300201-Mae Hong Son	Aug-13	7.9	T	0	0	T	1.5	41.1	56.2	8	1.9	….	51.8	4.2	3.4	0	5.2	5.1	26	0	9.1	4.3	6.1	**320.6**
9	300201-Mae Hong Son	Sep-13	4	0.4	1	2.3	4.6	5.1	4.3	4.8	3	1.2	….	0	0	7.9	20.8	19.5	5.9	18.9	10.9	7.8	0	-	**235.7**
10	300201-Mae Hong Son	Oct-13	-	-	1.1	-	0	1.8	0.6	-	-	-	….	18.9	5.4	-	0.6	0.6	10.5	21.5	35.3	4.2	1.5	-	**126**
11	300201-Mae Hong Son	Nov-13	-	-	-	-	-	-	-	-	-	-	….	-	-	-	-	-	0.3	-	-	-	0.3	-	**7.4**
12	300201-Mae Hong Son	Dec-13	-	-	-	-	-	-	-	-	-	0.4	….	-	-	-	-	-	-	-	-	-	-	-	**56.9**
13	300201-Mae Hong Son	Jan-14	-	-	-	-	-	-	-	-	-	-	….	0	-	-	0	-	0	-	-	0	-	-	-
14	300201-Mae Hong Son	Feb-14	-	-	-	0	0	-	0	-	-	-	….	-	0	-	-	-	0	0	-	-	-	-	-
15	300201-Mae Hong Son	Mar-14	0	0	0	-	-	0	0	-	-	0	….	-	-	0	-	0	-	0	-	-	0	0	-
16	300201-Mae Hong Son	Apr-14	-	-	0	6.7	0	1.6	-	-	-	-	….	-	-	0	0	1.5	T	-	-	T	0	-	**14.3**
17	300201-Mae Hong Son	May-14	-	0	-	0.1	15.3	0.6	0.7	-	3.3	T	….	T	5	-	-	0	3.5	-	2.4	37.7	-	17.9	**152.4**
18	300201-Mae Hong Son	Jun-14	6.1	-	-	-	-	0.6	0.1	20.1	9.1	43	….	7.6	0.3	0.4	0.6	0.5	T	0	T	20.1	1.6	-	**164.6**

3.1.3 EGAT Telemetering and Inflow data.

The daily rainfall data and observation of Inflow rate was collected during study period from telemetering stations of Electricity generating authority of Thailand (EGAT) over Vajiralongkorn reservoir. The rainfall data was collected from EGAT telemetering station, namely AU01, AU02, AU03 AU04, and AU05 as shown in Figure 19. In 2007, the rainfall value from EGAT telemetering are missing because all EGAT telemetering station out of operation over Upper catchment of Vajiralongkorn reservoir and back to operation in 2018. For inflow data, this research was collected inflow data from water resource management division of Vajiralongkorn Dam.

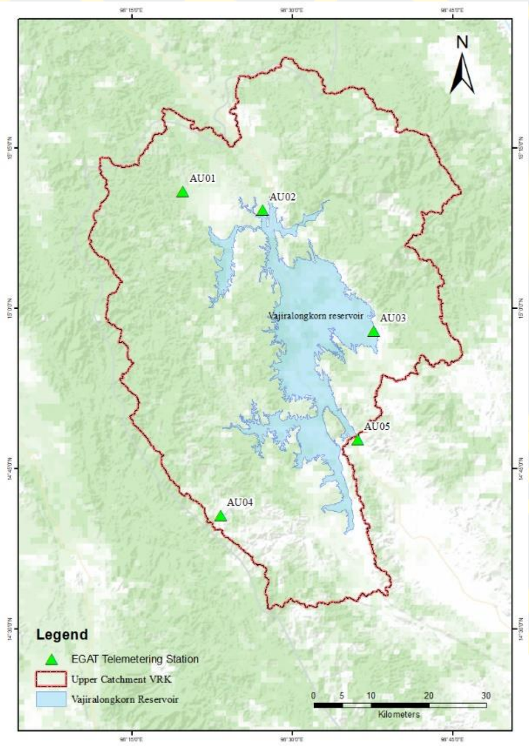


Figure 19: Location of EGAT telemetering stations.

3.2 Data Pre-Processing.

3.2.1 Data extraction.

A pixel-to-point method was used for extracting the pixel values of daily precipitation from the latest IMERG daily precipitation products version 06 at a special resolution of 0.1°×0.1°. The 121 ground-based observation from Thai Meteorological Department (TMD) were used as the benchmark to quantify the IMERG precipitation products. To avoid the additional error by interpolating of the rain gauge data, we considered only the grids covering at least one rain gauge, other girds without rain gauge data were excluded from the evaluation (Chokngamwong & Chiu, 2008; Mou Leong & Zheng, 2017; Wang et al., 2017; Yang et al., 2016) as shown in Figure 20.

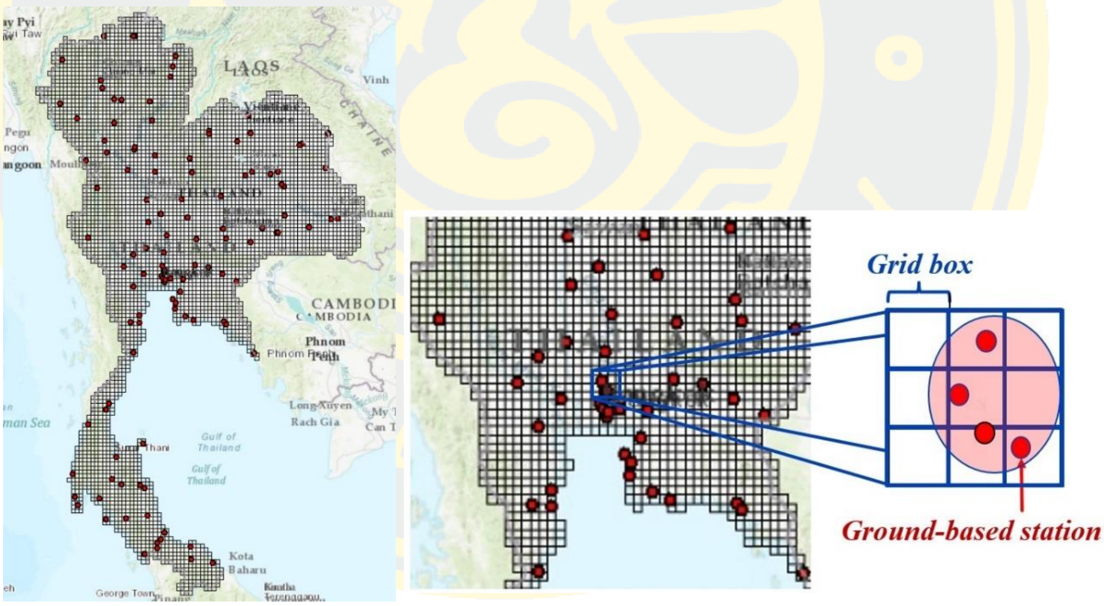


Figure 20: Ground-based observation station (Redpoint) and IMERG grid data with a special resolution of 0.1°× 0.1°

To extract the IMERG data rainfall value in this research was used Model builder (Figure 21) from Geographic information program namely ArcGIS 10 to automatically extract rainfall value from IMERG precipitation products to shapefiles format that has a Geographic Coordinate system matched with location of rain gauge station from Thai meteorological department (TMD).

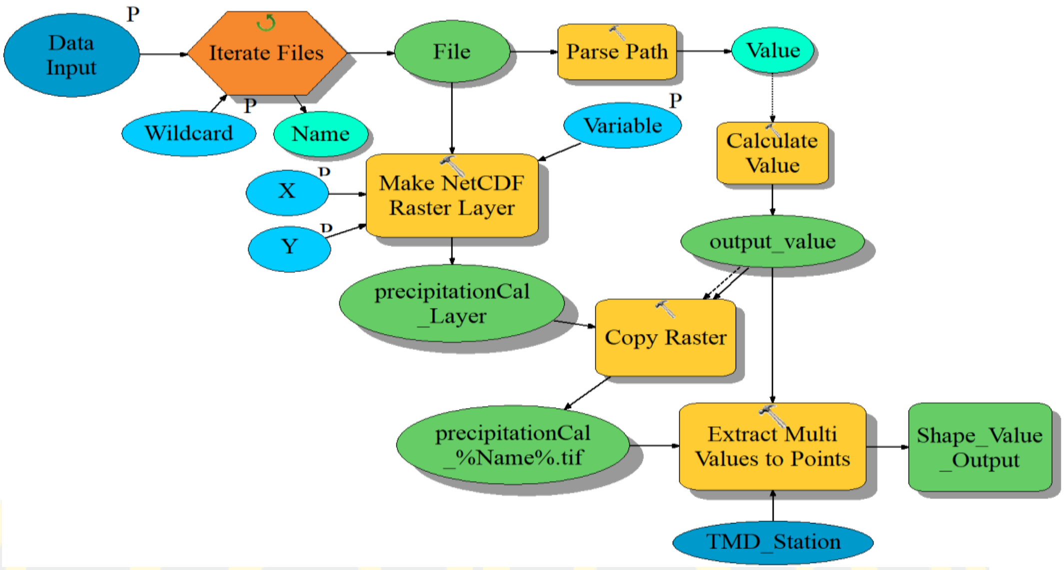


Figure 21: Model Builder processing diagram to extract GPM IMERG rainfall value.

3.2.2 Data Formatting.

The daily precipitation data from IMERG precipitation products and the Thai meteorological department (TMD) will be reformatting to form that suitably to assessment between satellite data and ground-based measurement. For precipitation data from TMD, there are some of rainfall data from TMD need to cleanup "no rain" value (show as a symbol "-") to 0 (Zero) and reformat text files to be example table as Table 5 before data assessment step. For precipitation data from IMERG, after the data extraction process the raster value in NetCDF files format will transfer to numeric value and keep it in shapefile format (.shp). IMERG precipitation data can export to table file and reformat to be the same pattern with TMD precipitation data as example in Table 5. There are four tables separated by a source of precipitation data (TMD, IMERG-Early, IMERG-Late, and IMERG-Final), each table has a table component consisting of the station name, geolocation (Latitude and Longitude) and rainfall values on each date between study period.

Table 5: The example formatting data of IMERG extracted from NetCDF files and rainfall Data from TMD.

Station ID	Station Name	Latitude	Longitude	16/02/2014	..	..	15/02/2019
300201	Mae Hong Son	19.2998	97.9733	0	..	..	0
…	…	…	…	…	..	..	…
…	…	…	…	…	..	..	…
…	…	…	…	…	..	..	…
…	…	…	…	…	..	..	…
583201	Narathiwat	6.42339	101.8260	0	..	..	0

3.3 Data Assessment.

To quantitive assessment the IMERG precipitation products against ground-based observation, using a widely statistical method to assessment data is the correlation coefficient (CC), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Relative Bias (RB) For the precipitation detection ability, A probability of Detection (POD), False alarm radio (FAR), A probability of false detection (POFD) and Critical Success Index (CSI) were computed to quantitively assess the GPM IMERG precipitation products against TMD rain gauge data. The assessment statistics detail as Table 6 and Table 7. The assessment is performed at different timescales Daily, Monthly, Annual, and seasonally over Thailand on period 16 February 2014 to 15 February 2019.

3.3.1 The Correlation Coefficient (CC).

The correlation coefficient is a statistical method to calculate the strength of the relationship between the relative movements of two variables. The values of the CC ranging from -1.0 to 1.0. A correlation of -1.0 means a perfect negative correlation, while a correlation of 1.0 indicates a perfect positive correlation. A resulted number after calculation if it was higher than 1.0 or less than -1.0 means that there was an error in the correlation measurement. While the correlation equal to 0.0 means no relationship between the movement of the two variables.

3.3.2 Mean Absolute Error (MAE).

The Mean Absolute Error measures the average magnitude of the error between the estimations and observations without considering their direction. The range of MAE is zero to infinity, and the perfect score is zero.

3.3.3 Root Mean Square Error (RMSE).

The Root Mean Square Error is the standard deviation of the residuals (prediction errors). RMSE used a measure of the differences between values (Sample or population values) predicted by a model or an estimator and the values observed. RMSE is similar to MAE to measure the mean of the error magnitude; only it gives higher weight to the more significant error because the differences are square before adding (Promasakha na Sakolnakhon, 2013). The range of RMSE between zero to infinity and the perfect score is zero.

3.3.4 Relative Bias (RB).

Relative Bias is usually determined as the difference between the mean obtained from a large number of replicate measurements with a sample having a reference value. The range of RB between -100% to 100% and the perfect score is 0%.

3.3.5 A Probability of Detection (POD).

A probability of Detection or hit rate is a fraction of the observed that were forecasted ‘yes’ events. The POD ranges from 0 to 1, and the perfect score is 1.

3.3.6 False alarm ratio (FAR).

False alarm radio is the number of false alarms per the total number of warnings or alarms in a given study. The FAR ranges from 0 to 1, and the perfect score is 0.

3.3.7 A probability of false detection (POFD).

A probability of false detection is a fraction of the observed ‘no’ events (Kamol., 2013). This score ranges from 0 to 1, and the perfect score is 0.

3.3.8 Critical Success Index (CSI).

Critical Success Index is used as a measure of the accuracy of yes/no forecasts, particularly for rare events or in situations in which the not forecast, not observed frequency, is unavailable. It is also used to select threshold probabilities to convert probabilistic forecasts to categorical forecasts (Mason, 1989).

The Correlation Coefficient (CC), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Relative Bias (RB) were used to quantities assessment the type of correlation and dependence between satellite precipitation products compared with rain gauge data in elementary statistics.

A probability of detection (POD), A probability of false detection (POFD), false alarm ratio (FAR) and critical success index (CSI) was calculated at a daily time step to quantitatively examine the potential of satellite products for precipitation detection at different rainfall thresholds (Chen et al., 2018).

Table 6: The standard comparison method for evaluating GPM IMERG products.

Index	Formulas	Domain	Perfect score
The correlation coefficient (CC)	$CC = \frac{\sum_{i=1}^{N}(S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(S_i - \bar{S})^2 \sum_{i=1}^{N}(O_i - \bar{O})^2}}$	[-1,1]	1
Mean Absolute Error (MAE)	$\text{MAE} = \frac{\lvert\sum_{i=1}^{n}(S_i - O_i)\rvert}{N}$	(0, ∞)	0
Root Mean Square Error (RMSE)	$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{N}}$	(0, ∞)	0
Relative Bias (RB)	$\text{RB} = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \times 100$	-100% to 100%	0%
A probability of Detection (POD)	$\text{POD} = \frac{hists}{hits + misses}$	[0,1]	1
False alarm radio (FAR)	$\text{FAR} = \frac{false\ alarm}{hits + false\ alarm}$	[0,1]	0
A probability of false detection (POFD)	$\text{POFD} = \frac{false\ alarm}{false\ alarm + correct\ rejection}$	[0,1]	0
Critical Success Index (CSI)	$\text{CSI} = \frac{hits}{hits + false\ alarm + misses}$	[0,1]	1

Where S_i indicates the estimated value at grid box in i, O_i indicates the observed values, and N is the number of samples.

Table 7: Contingency table for the calculation of precipitation estimates indices.

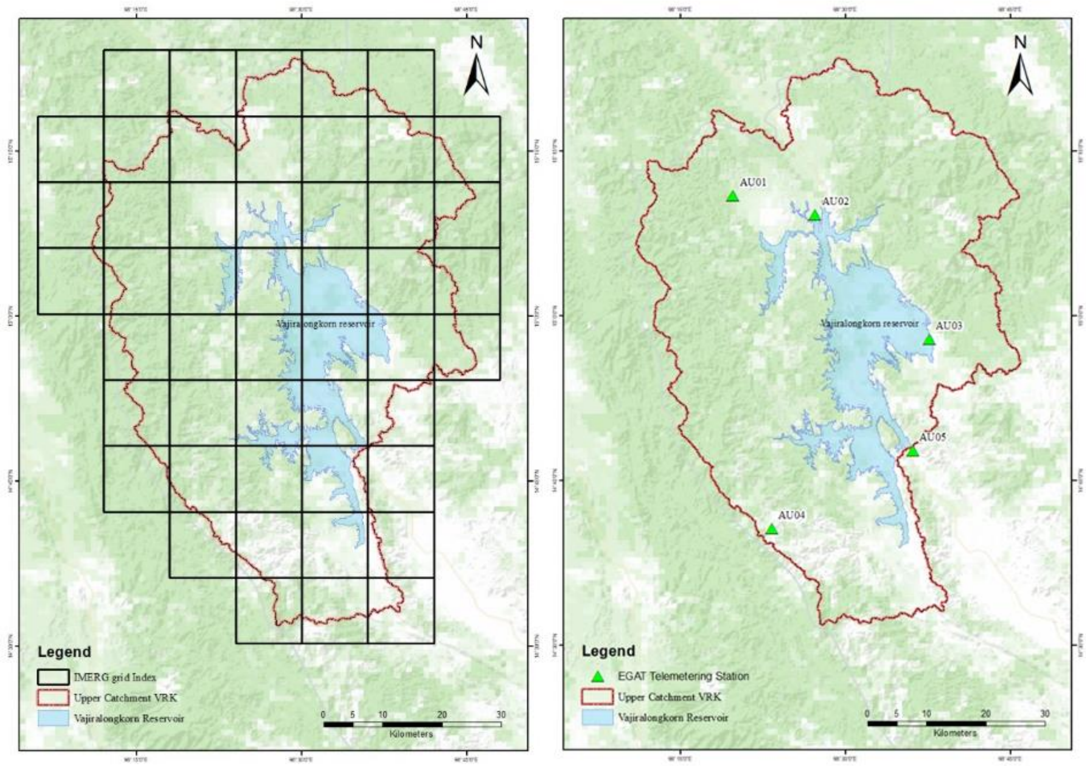
		Rain Gauge Observed		
		Yes	**No**	**Total**
Satellite Precipitation estimates	**Yes**	*(a)*	*(b)*	*(a)+(b)*
	No	*(c)*	*(d)*	*(c)+(d)*
	Total	*(a)+(c)*	*(b)+(d)*	*(a)+(b)+(c)+(d)=n*

Where (*a*) refers to *hits*, (*b*) refers to *false alarm*, (*c*) refers to *misses*, (*d*) refers to correct rejection.

3.4 NAM Model simulation

3.4.1 Input rainfall data

In this study were using grid value daily rainfall data from IMERG precipitation products at 0.1° × 0.1° spatial in Upper Catchment area of Vajiralongkorn reservoir is shown in Figure 22(a), to simulate water inflow in MIKE11 NAM Model in Vajiralongkorn reservoir area comparing with water inflow from a simulation by using daily rainfall data from telemetering stations of Electricity generating authority of Thailand (EGAT) namely AU01, AU02, AU03 AU04, and AU05 is shown in Figure 22(b).



(a) (b)

Figure 22: IMERG grid index and EGAT telemetering stations in the Upper Vajiralongkorn reservoir.

3.4.2 Model parameter

This study was kept NAM model parameters the same as the operation model of Electricity generating authority of Thailand (EGAT) as Table 8. However, it will change only rainfall value from IMERG precipitation products to be the input of rainfall value to simulate water inflow to the upper catchment of Vajiralongkorn reservoir.

Table 8: Model parameter values

Sr. No.	Parameter	Model Parameter Final Values	Parameter Range
1	U_{max} (mm)	10.7	5.76 - 20
2	L_{max} (mm)	100	100 - 300
3	C_{QOF}	0.834	0.1 - 1
4	C_{KIF} (hrs)	200.1	200 - 1000

5	C_{K1K2} *(hrs)*	49.1	10-15
6	T_{OF}	0.634	0-0.99
7	T_{IF}	0.686	0-0.99
8	T_G	0.009	0-0.99
9	C_{KBF} *(hrs)*	1016	500 - 1000

Where U_{max} : Maximum water content in surface storage, L_{max} : Maximum water content in root zone storage, C_{QOF} : Overland flow runoff coefficient, C_{QOF} : Time constant for interflow, C_{KIF} : Time constants for routing overland flow (CK1,2), C_{K1K2} : Root zone threshold value for overland flow, T_{OF} : Root zone threshold value for overland flow, T_{IF} : Root zone threshold value for interflow, T_G : Root zone threshold value for groundwater recharge, C_{KBF} : time constant for routing baseflow.

3.4.3 Model Calibration and Verification

Calibration and Verification is a standardizing predicted value process by using deviations from observed values. In MIKE 11 NAM model was calibrated period from 1 January 2012 to 31 December 2015 and 1 January 2018 to 31 December 2018 for verification period by used rainfall data from EGAT Telemetering station and model parameter in Table 9 to Calibration and Verification model in Vajiralongkorn Dam area. The result of Calibration and Verification shown in Table 9 and Figure 23-24.

Table 9: Result of calibration and verification

	Calibration				**Verification**			
Catchment Item	***R²***	***WB***	***EI***	***RMSE***	***R²***	***WB***	***EI***	***RMSE***
Vajiralongkorn Dam	0.819	19.63%	80.28%	149.02	0.850	-1.87%	84.40%	164.29

Where R^2: coefficient of determination, *WB*: Water Balance, *EI*: Efficiency Index, *RMSE*: Root mean square error.

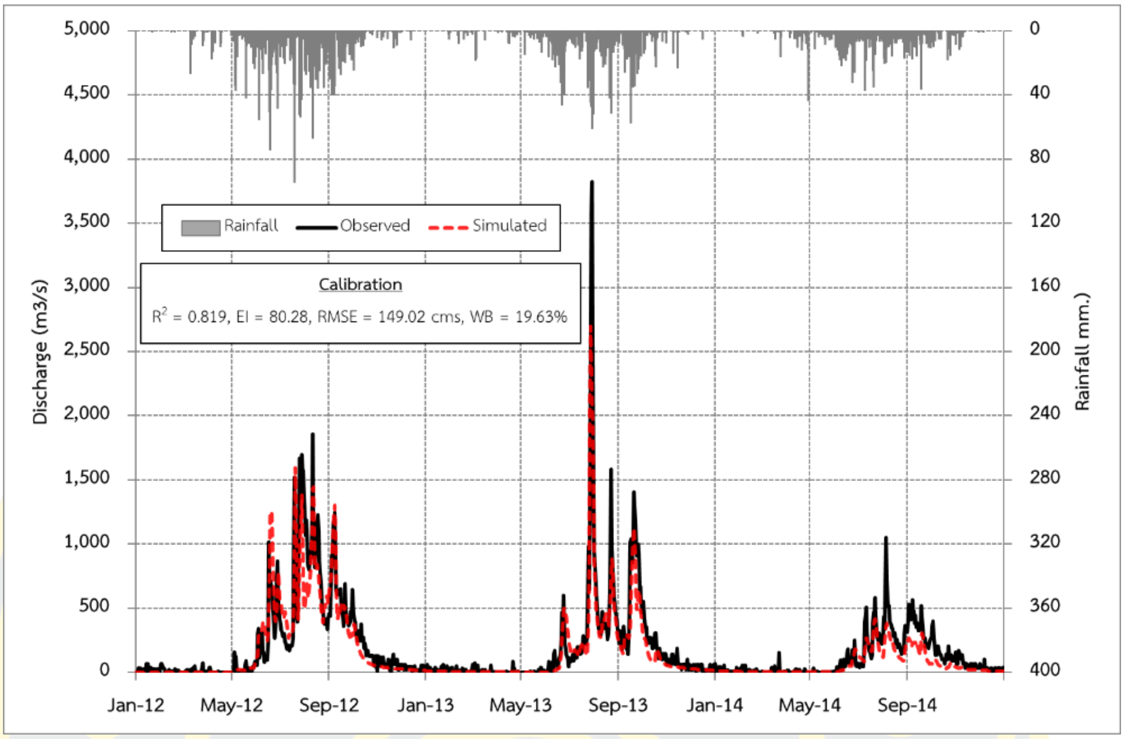


Figure 23: Observed and simulated hydrograph of model Calibration.

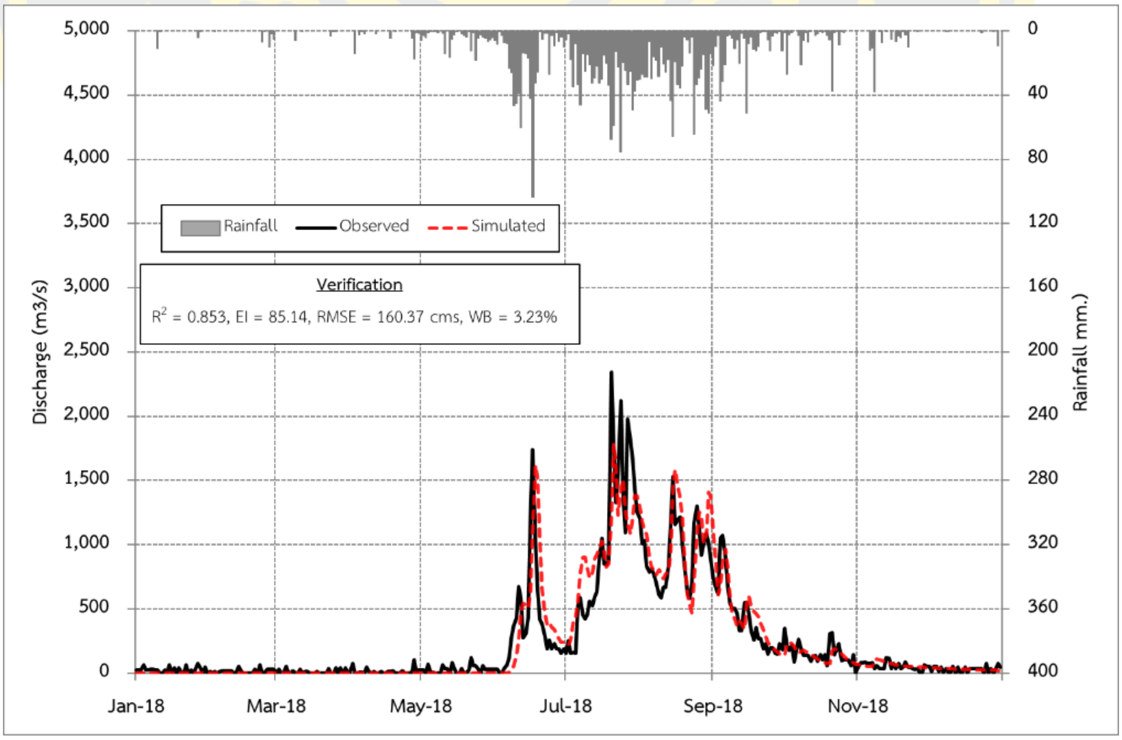


Figure 24: Observed and Simulated hydrograph of model Verification.

CHAPTER 4
RESULTS AND DISCUSSION

This chapter reports the performance of IMERG daily precipitation estimates against ground-based observation from TMD at Daily, Monthly, annually, and seasonally time scales. The assessment was used the statistical metrics and hydrological modelling described in chapter 3 over Thailand. The results are the following.

4.1 Statistical assessment of IMERG rainfall estimates

4.1.1 Data Assessment at Daily scale

On a daily scale, the daily rainfall data from 121 rain gauge stations of the Thai Meteorology Department (TMD) were derived and compared with all IMERG precipitation products on a pixel-to-point method. The scatter plot of Figure 25 and Table 10 presents the assessment results of IMERG precipitation products against ground rainfall observation from TMD on a daily scale across the study periods. The IMERG precipitation products have a moderate correlation of daily precipitation comparing with TMD ground-based observation. The best CC value in the post-real-time product, IMERG-Final has 0.684, followed by the near-real-time product, IMERG-Late has a CC value of 0.655, and IMERG-Early has a CC value of 0.642. This result is similar to nearby countries in South-East Asia that have a moderate correlation of IMERG precipitation products with ground-based measurements such as in Malaysia (Tan, M. L. and H. Santo 2018) and Singapore (Mou Leong et al., 2017). All IMERG precipitation trend to overestimates of daily precipitation with RB values ranging from 7.304% to 9.118%. The MAE values of IMERG precipitation products ranged from 3.999 to 4.199 mm/day, and The RMSE ranged from 9.673 to 10.169 mm/day. For the precipitation detection ability, all IMERG shows a good performance with the same POD value of 0.9948 for IMERG-Final and IMERG-Late, while IMERG-Early has POD value of 0.9935. For FAR values ranged from 0.5385 to 0.5412, POFD values ranged from 0.8491 to 0.8596, and CSI values ranged from 0.4577 to 0.4601.

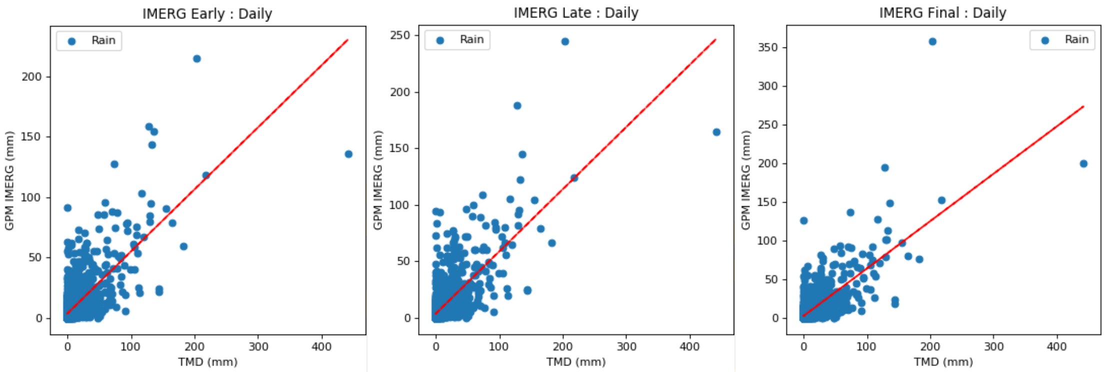


Figure 25: The assessment results of the GPM IMERG daily scale.

Table 10: The assessment results of IMERG precipitation products on the Daily scale.

SPPs	IMERG-Early	IMERG-Late	IMERG-Final
CC	0.642	0.655	0.684
MAE (mm)	4.199	4.090	3.999
RMSE (mm)	10.169	10.134	9.673
RB (%)	7.304	7.340	9.118
POD	0.9935	0.9948	0.9948
FAR	0.5385	0.5387	0.5412
POFD	0.8491	0.8510	0.8596
CSI	0.4601	0.4602	0.4577

Average daily precipitation from TMD and IMERG precipitation products shown in Figure 26. The pattern of average daily precipitation will be increasing from the beginning of the year until peck value in the middle of each year. After that, the rainfall value is decreasing to the end of each year.

According to assessment results, the average daily precipitation of IMERG precipitation product overestimates compared with TMD ground-based observation during the study period. IMERG post-real-time product is the higher amplitude of average daily precipitation than the near-real-time product.

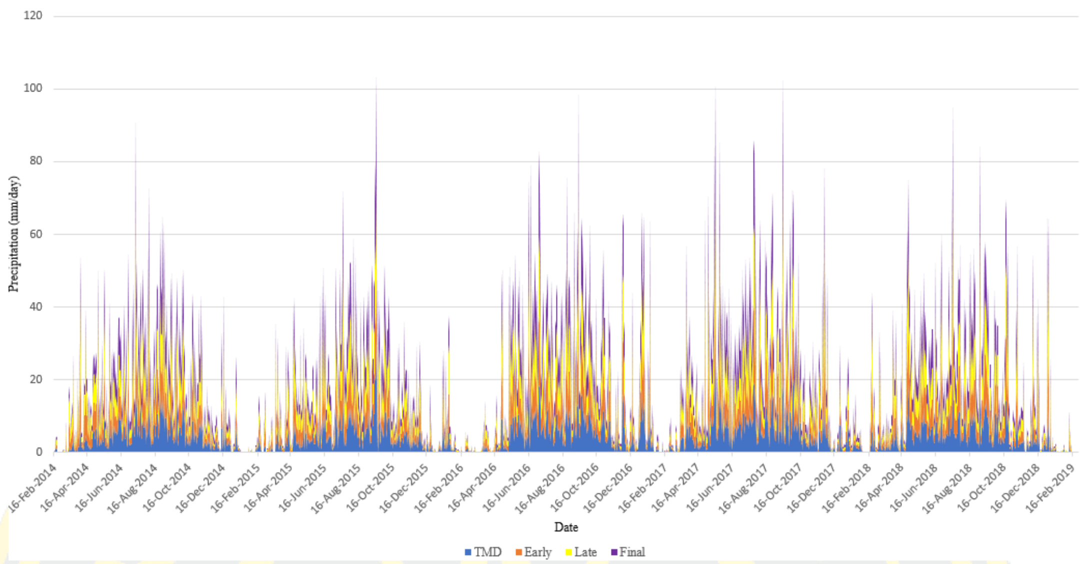


Figure 26: Average of daily precipitation of TMD ground-based station and IMERG precipitation product on the study period.

Furthermore, the performance of IMERG precipitation products at ground-based stations was assessed, as shown in Figure 27. The CC values at the gauge station of IMERG near-real-time products (IMERG-Early and IMERG-Late) are a similar pattern in the Northern and Central region of Thailand with moderate CC value. While IMERG post-real-time product (IMERG-Final) perform moderate CC value but better correlation than of IMERG near-real-time products in this region. MAE and RMSE are high value in the Eastern and Southern parts of Thailand at all IMERG precipitation products. At the ground-based stations which are located close to the c are overestimated precipitation with high RB value. In contrast, the Northern and North-East regions are underestimated with low RB value in all IMERG precipitation products.

The Spatial distribution of daily accumulated precipitation on period 16 February 2014 to 15 February 2019 from 121 rain gauge stations of TMD ground-based stations and All IMERG precipitation products over Thailand, as shown in figure 28. The spatial patterns of rainfall from TMD represent a point scale in figure 28(a) and gridded data in IMERG precipitation products as figure 28(b), (c), (d). The rainfall data from TMD gauge station shows the pattern of precipitation in Thailand was increasing from the Northern to the Southern region, with a high among of precipitation in the Eastern coast and the Western side of the Southern region of Thailand. In contrast, lower precipitation is found over the Northern, Central, and North-East regions of Thailand.

In general, IMERG precipitation can successfully capture the spatial distribution of rainfall over Thailand. Similarly, to the spatial pattern of TMD gauge station, all IMERG precipitation products have a high among of precipitation on the Eastern coast and the Western side of the Southern region. In contrast, lower among of precipitation can be found in the Northern Central and North-East region of Thailand.

Overall, the spatial distribution of all IMERG precipitation products and TMD rainfall data have the same spatial pattern. Mainly, IMERG seemed to overestimate precipitation compared with TMD rainfall data in the Northern and the Central region with low and medium accumulated precipitation. In contrast, high accumulated precipitation seemed to underestimate in Eastern and the Southern region of Thailand.

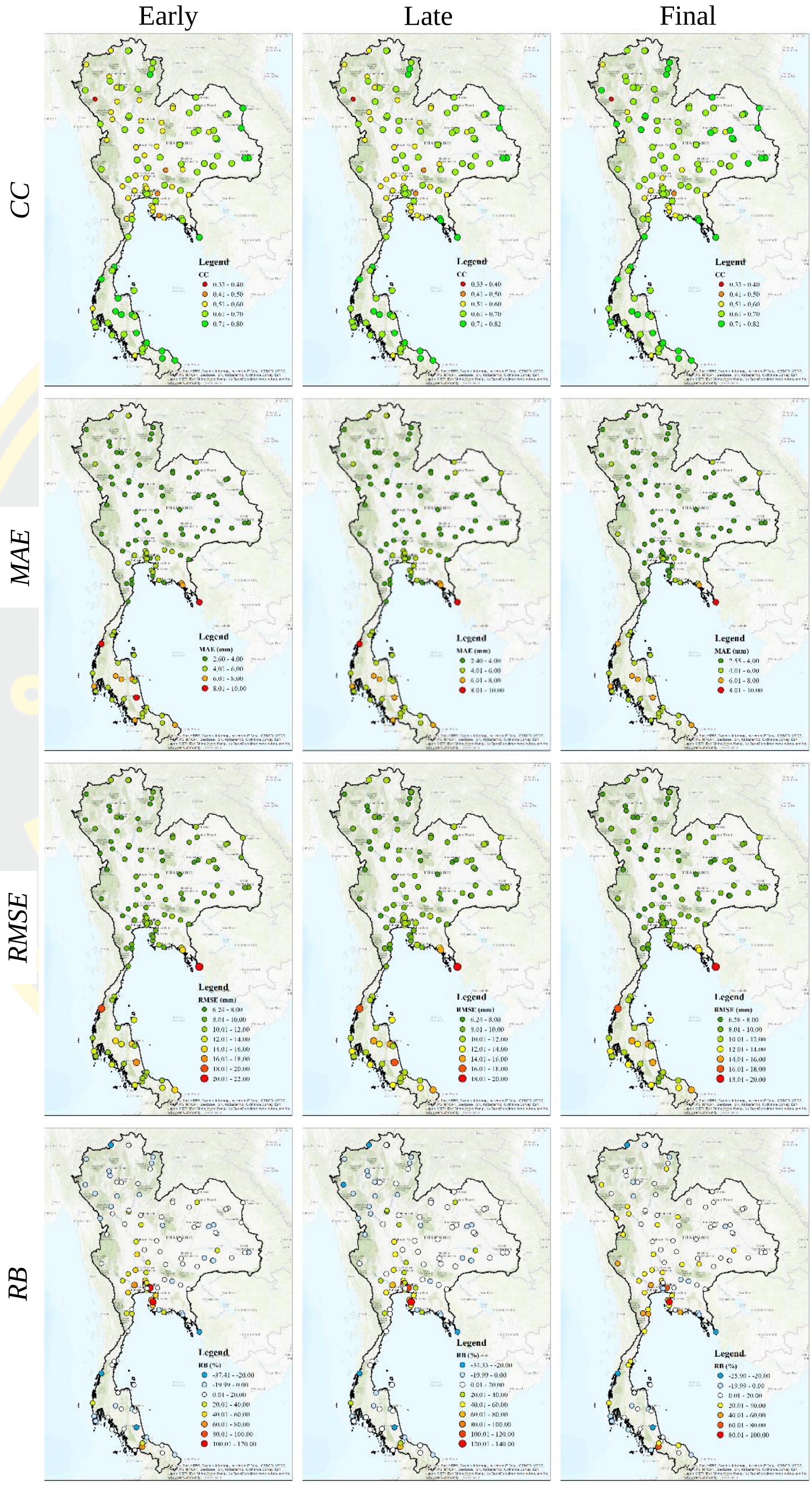
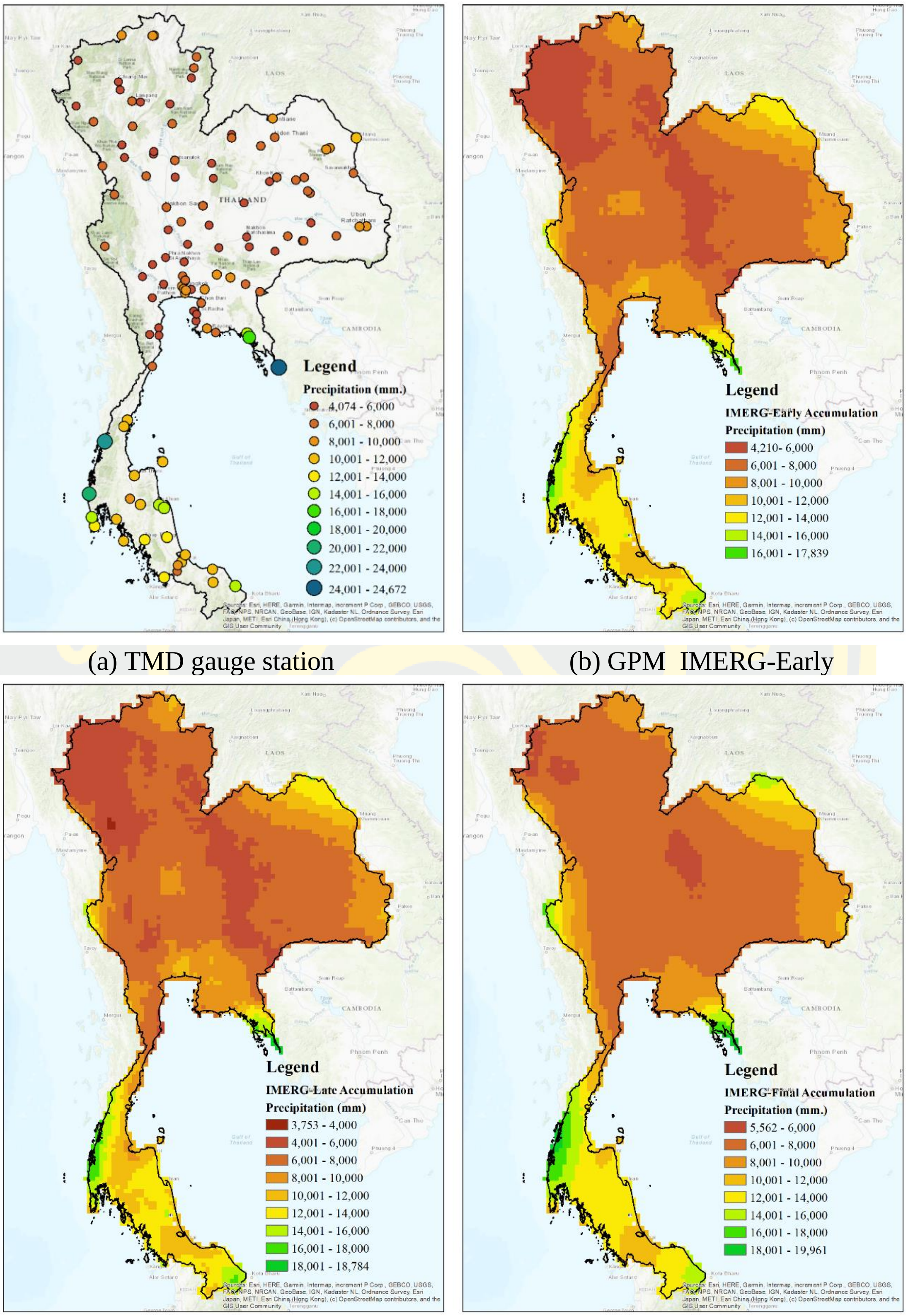


Figure 27: Spatial distribution of assessment indices at the ground-based station.



(a) TMD gauge station
(b) GPM IMERG-Early
(c) GPM IMERG-Late
(d) GPM IMERG-Final

Figure 28: Spatial distribution of Accumulated rainfall from TMD ground-based station and GPM IMERG precipitation product on study period over Thailand.

4.1.2 Data Assessment at Annual scale

Figure 29 presents the scatter plot for IMERG precipitation products at an annual scale. The IMERG has a high correlation with the ground-based observation from TMD in post-real-time products and near-real-time products. For the assessment metrics result, Table 11 shows that CC has the most precise estimate in the post-real-time product. IMERG-Final has a CC value of 0.936, followed by the near-real-time product, IMERG-Late has a CC value of 0.915, and IMERG-Early has a CC value of 0.906. The MAE values of IMERG precipitation products ranged from 239.129 to 258.782 mm/year, and The RMSE ranged from 346.066 to 400.696 mm/year. All IMERG precipitation overestimates in annual scale with RB values ranging from 7.304% to 9.118%. Average annual precipitation from TMD and IMERG precipitation products more than 1,300 mm/year (except 2019 that collected data until 15 February 2019) shown as Figure 30. Compared with TMD rainfall data, all IMERG precipitation products overestimated the average annual precipitation on the studied period.

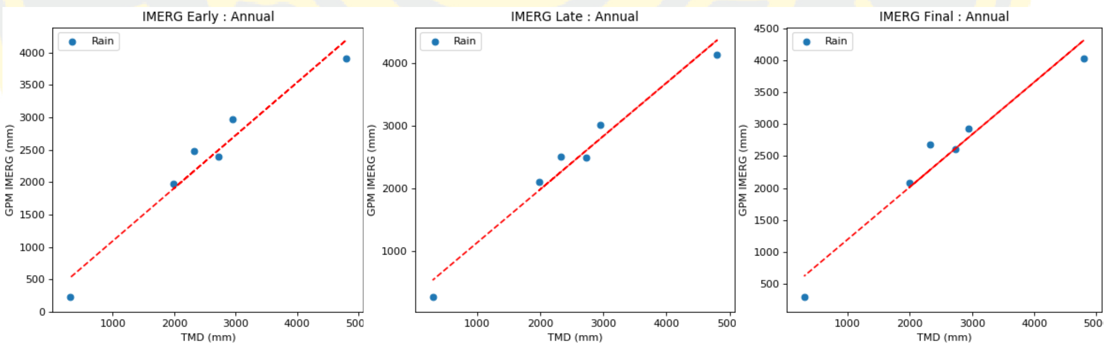


Figure 29: The assessment results of the GPM IMERG Annual scale.

Table 11: The assessment results of GPM IMERG products at the Annual scale.

SPPs	IMERG-Early	IMERG-Late	IMERG-Final
CC	0.906	0.915	0.936
MAE (mm)	258.782	251.824	239.126
RMSE (mm)	400.696	383.089	346.066
RB (%)	7.304	7.340	9.118

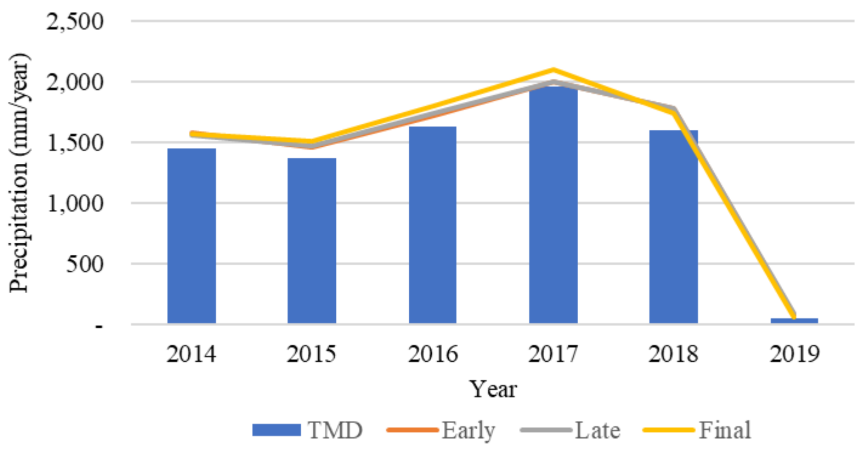


Figure 30: Average annual precipitation from TMD and IMERG precipitation products.

To investigate the annual precipitation, we also assess the performance of all IMERG precipitation products each year, as shown in Table 12. All IMERG has a good correlation with ground-based observation but still performed overestimated precipitation at all year. For the precipitation detection ability, all IMERG shows a good detection ability with the POD more than 0.98. However, the FAR and CSI are moderate detection ability for all IMERG at an annual scale, while POFD is a lower value 0.792 in 2015 of IMERG near-real-time products.

Table 12: Assessment indexes of IMERG products in each annual scale.

SPPs	Month	CC	MAE (mm)	RMSE (mm)	RB (%)	POD	FAR	POFD	CSI
IMERG-Early	2014	0.859	275.387	397.908	9.531	0.992	0.534	0.812	0.465
	2015	0.844	241.589	349.088	7.243	1.000	0.534	0.792	0.466
	2016	0.833	323.615	489.871	6.073	0.986	0.552	0.826	0.445
	2017	0.850	317.627	465.994	1.862	1.000	0.510	0.938	0.490
	2018	0.789	347.146	470.784	11.590	0.987	0.555	0.887	0.443
	2019	0.698	47.331	66.255	64.562	1.000	0.610	0.833	0.390
IMERG-Late	2014	0.873	261.634	371.020	7.935	0.992	0.532	0.806	0.466
	2015	0.865	230.503	326.953	7.683	1.000	0.534	0.792	0.466
	2016	0.855	309.003	456.993	6.766	0.993	0.549	0.821	0.450
	2017	0.854	320.868	457.800	2.148	1.000	0.511	0.943	0.489
	2018	0.799	339.210	461.216	11.492	0.987	0.557	0.896	0.440
	2019	0.711	49.727	69.619	74.420	1.000	0.619	0.867	0.381

IMERG-Final	2014	0.913	246.183	328.750	8.493	0.992	0.530	0.801	0.468
	2015	0.895	248.388	316.491	10.295	0.993	0.549	0.833	0.450
	2016	0.893	325.710	449.603	10.898	1.000	0.550	0.830	0.450
	2017	0.902	310.708	414.541	7.037	1.000	0.509	0.932	0.491
	2018	0.885	281.472	367.310	9.219	0.987	0.558	0.901	0.439
	2019	0.891	22.297	37.742	16.077	1.000	0.619	0.867	0.381

4.1.3 Data Assessment at Monthly scale

Figure 31 and Table 13 show the scatter plot and assessment metrics of IMERG precipitation products against ground-based observation from TMD on a monthly scale on the whole studied period. All IMERG precipitation products have a high correlation with precipitation from TMD ground-based observation. The IMERG Final has the best CC value of 0.928, followed by the IMERG-Late has a CC value of 0.908, and IMERG-Early has a CC value of 0.896. The MAE values of IMERG precipitation products ranged from 157.210 to 186.929 mm/month, and The RMSE ranged from 248.675 to 293.653 mm/month. The values of RB did not change from daily scale to monthly scale with a similar pattern of monthly precipitation that was recorded by ground-based observation.

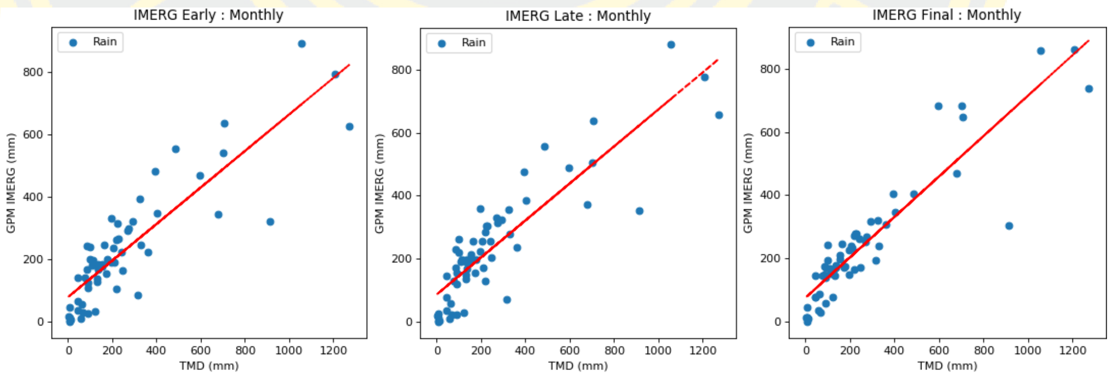


Figure 31: The assessment results of the GPM IMERG Monthly scale.

Table 13: The assessment results of GPM IMERG products at the Monthly scale.

SPPs	IMERG-Early	IMERG-Late	IMERG-Final
CC	0.896	0.908	0.928
MAE (mm)	186.929	179.690	157.210
RMSE (mm)	293.653	277.822	248.675
RB (%)	7.304	7.340	9.118

For an average of precipitation on a monthly scale, as shown in Figure 32, all precipitation products captured with the same pattern of TMD precipitation. A high monthly average precipitation of more than 800 mm/month is found during July until September with a good correlation between IMERG and ground-based precipitation data. The lowest monthly average precipitation is found in February with CC value lower than 0.3 in IMERG near-real-time products but a good correlation in IMERG-Final with a CC value of 0.751, as shown in Table 14. For the precipitation detection ability, all IMERG shows a good POD (0.921-1.000) and high POFD on each month. However, the FAR is moderated value, and CSI shows a lower value for all IMERG each monthly scale.

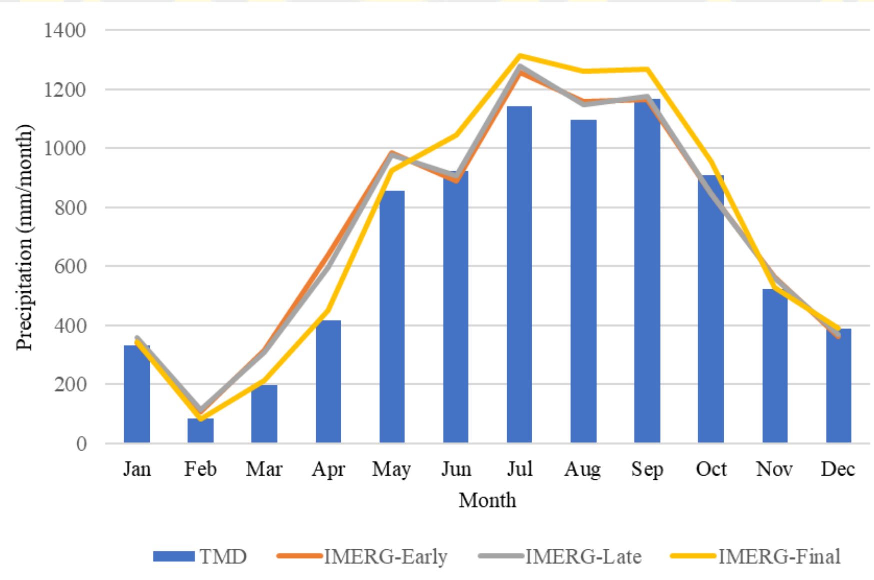


Figure 32: The average monthly precipitation from TMD and IMERG precipitation products.

Table 14: Assessment indexes of GPM IMERG products on each monthly scale.

	Month	CC	MAE (mm)	RMSE (mm)	RB (%)	POD	FAR	POFD	CSI
IMERG-Early	Jan	0.902	231.747	123.047	3.083	0.986	0.490	0.864	0.507
	Feb	0.298	82.874	59.821	25.532	0.947	0.647	0.641	0.346
	Mar	0.717	154.521	129.261	59.444	1.000	0.742	0.500	0.258
	Apr	0.655	267.371	228.093	52.824	0.929	0.772	0.721	0.224
	May	0.684	290.896	228.652	15.123	1.000	0.680	0.981	0.320
	Jun	0.885	331.631	210.668	-3.637	1.000	0.633	1.000	0.367
	Jul	0.863	424.995	297.842	9.858	1.000	0.610	0.989	0.390
	Aug	0.809	397.601	271.376	5.661	1.000	0.587	1.000	0.413
	Sep	0.772	393.764	246.455	-0.238	1.000	0.514	0.949	0.486
	Oct	0.823	266.090	200.979	-6.839	1.000	0.416	0.985	0.584
	Nov	0.963	189.700	116.157	7.909	1.000	0.228	0.971	0.772
	Dec	0.946	289.309	130.801	-7.684	1.000	0.314	0.960	0.686
IMERG-Late	Jan	0.910	220.772	124.389	7.748	0.986	0.493	0.877	0.503
	Feb	0.264	93.159	67.209	34.781	0.947	0.647	0.641	0.346
	Mar	0.731	145.313	118.626	54.191	1.000	0.744	0.508	0.256
	Apr	0.643	232.374	191.144	43.290	0.964	0.765	0.721	0.233
	May	0.702	283.255	223.353	13.973	1.000	0.680	0.981	0.320
	Jun	0.895	301.165	199.862	-1.842	1.000	0.633	1.000	0.367
	Jul	0.874	408.228	294.641	11.897	1.000	0.610	0.989	0.390
	Aug	0.840	362.938	247.292	4.559	1.000	0.587	1.000	0.413
	Sep	0.792	373.125	241.257	0.611	1.000	0.514	0.949	0.486
	Oct	0.830	259.621	194.073	-6.994	1.000	0.416	0.985	0.584
	Nov	0.964	186.942	116.832	6.796	1.000	0.228	0.971	0.772
	Dec	0.945	287.759	137.598	-5.329	1.000	0.314	0.960	0.686
IMERG-Final	Jan	0.930	180.319	88.488	3.606	1.000	0.493	0.889	0.507
	Feb	0.751	47.927	34.820	-1.461	0.921	0.670	0.689	0.321
	Mar	0.807	71.483	57.171	6.937	1.000	0.750	0.523	0.250
	Apr	0.758	111.659	83.318	8.187	0.964	0.767	0.730	0.231
	May	0.854	213.015	159.046	7.919	1.000	0.680	0.981	0.320
	Jun	0.913	306.726	234.904	12.893	1.000	0.631	0.989	0.369
	Jul	0.905	385.396	300.379	14.778	1.000	0.605	0.968	0.395
	Aug	0.870	382.334	294.797	14.974	1.000	0.587	1.000	0.413
	Sep	0.899	330.323	238.409	8.632	1.000	0.523	0.987	0.477
	Oct	0.860	230.475	172.237	5.256	1.000	0.416	0.985	0.584
	Nov	0.962	196.486	111.044	1.045	1.000	0.228	0.971	0.772
	Dec	0.954	233.835	111.911	0.148	1.000	0.314	0.960	0.686

4.1.4 Data Assessment at Seasonal scale

Figure 33 and Table 15 shows the scatter plot and assessment metrics of IMERG precipitation products against ground-based observation from TMD on a seasonal scale. All IMERG precipitation products have a high correlation with ground-based precipitation from TMD. The IMERG Final has the best CC value of 0.938, followed by the IMERG-Late has a CC value of 0.926, and IMERG-Early has a CC value of 0.917. The MAE values of IMERG precipitation products ranged from 210.671 to 243.209 mm/season, and The RMSE ranged from 126.074 to 146.835 mm/season. The RB values also overestimated ranging from 7.304% to 9.118%.

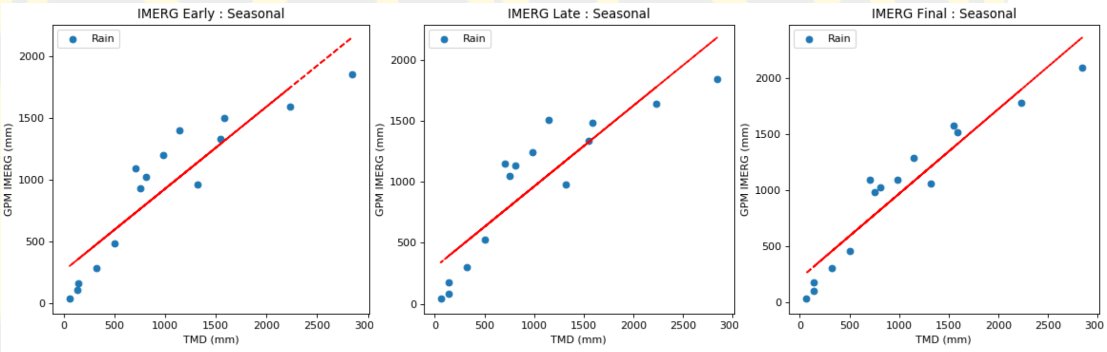


Figure 33: The assessment results of the GPM IMERG Seasonal scale.

Table 15: The assessment results of IMERG products at the Seasonal scale.

SPPs	IMERG-Early	IMERG-Late	IMERG-Final
CC	0.917	0.926	0.938
MAE (mm)	243.209	228.829	210.671
RMSE (mm)	146.835	141.693	126.074
RB (%)	7.084	7.119	8.844

For an average of precipitation in seasonal scale, as shown in Figure 34, the IMERG precipitation products are overestimated in all-season over Thailand. IMERG-Final has accurately captured precipitation than the near-real-time product in summer but inaccurate in the rainy season. All IMERG precipitation has similarly average value with a ground-based observation from TMD in the summer season.

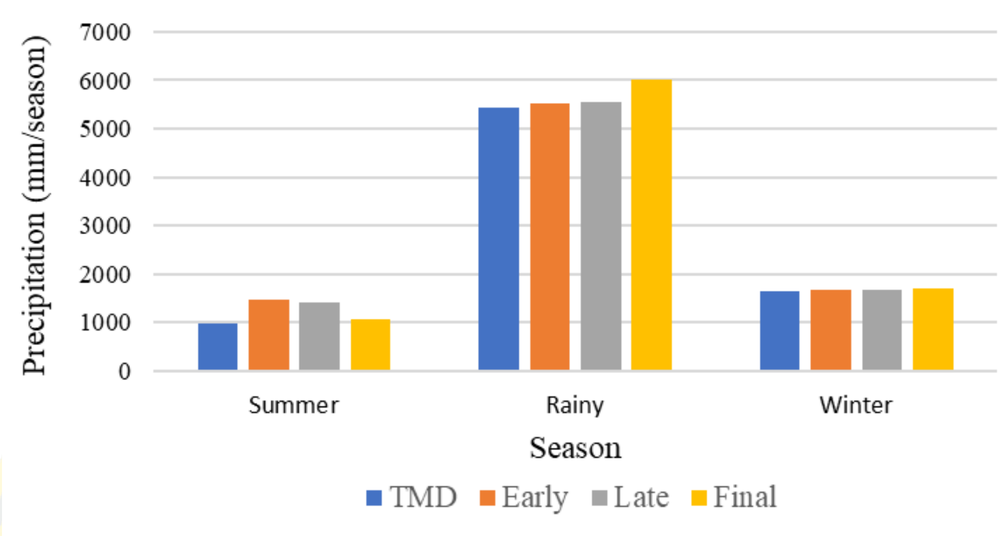


Figure 34: The average seasonal precipitation from TMD and IMERG precipitation products.

For assessment results of IMERG products at the seasonal scale in each IMERG precipitation products shown as Table 16, The IMERG-Final have the best performance at all seasonal scale with CC value of 0.961 in winter, following by 0.907 in rainy and 0.754 in summer. While the near-real-time product has similar performance, The CC values of 0.957 (Winter), 0.868 (Rainy), and 0.647 (Summer) in IMERG Late. And CC values of 0.954 (Winter), 0.851 (Rainy), and 0.647 (Summer) in IMERG Early. The MAE values of IMERG-Final ranged from 169.784 (Summer) to 1,101.422 (Rainy) mm/season, IMERG-Late ranged from 355.120 (winter) to 944.063 (Rainy) mm/season and IMERG-Early ranged from 363.191 (winter) to 989.294 (Rainy) mm/season. The RMSE ranged from 227.521 (Summer) to 1,478.988 (Rainy) mm/season, IMERG-Late ranged from 507.871 (Summer) to 1,483.999 (Rainy) mm/season and IMERG-Early ranged from 561.313 (Summer) to 1,616.212 (Rainy) mm/season. Overall, IMERG precipitation product overestimated in seasonal scale. The IMERG-Final have the best performance comparing with TMD ground-based observation for all season in Thailand, and the rainy season has high MAE and RMSE in all IMERG precipitation products. While IMERG-Early and IMERG-Late have high relative bias value in summer. For the precipitation detection ability, all IMERG precipitation product performs high POD at seasonal scale ranged from 0.952 to 1.0. A good capability FAR and CSI can be found in the winter season, while POFD is lower capability with a high score in all IMERG products.

Table 16: The assessment results of IMERG products at the Seasonal scale in each IMERG precipitation products.

SPPs	Seasonal	CC	MAE (mm)	RMSE (mm)	RB (%)	POD	FAR	POFD	CSI
IMERG-Early	Summer	0.647	493.064	561.313	48.694	0.952	0.755	0.669	0.242
	Rainy	0.851	989.294	1614.212	1.576	1.000	0.567	0.986	0.433
	Winter	0.954	363.191	657.312	1.480	0.997	0.382	0.871	0.617
IMERG-Late	Summer	0.647	437.772	507.871	42.739	0.964	0.753	0.672	0.245
	Rainy	0.868	944.063	1483.999	2.416	1.000	0.567	0.986	0.433
	Winter	0.957	355.120	643.686	2.443	0.997	0.383	0.875	0.616
IMERG-Final	Summer	0.754	169.784	227.521	9.123	0.952	0.759	0.686	0.238
	Rainy	0.907	1101.422	1478.988	10.755	1.000	0.567	0.986	0.433
	Winter	0.961	323.756	591.509	3.693	1.000	0.387	0.890	0.613

4.2 Evaluation of the hydrological utility

The assessment results of the IMERG precipitation products in hydrological simulation using the NAM model simulation at grid value on daily precipitation data over the upper catchment area of the Vajiralongkorn reservoir are shown in Table 17. The IMERG precipitation products perform a high correlation of inflow rate in NAM model simulation comparing with inflow data over the Vajiralongkorn reservoir than ground-based precipitation data from EGAT Telemetering stations. The IMERG-Final has a CC value of 0.913, followed by the near-real-time product, IMERG-Late has a CC value of 0.892, and IMERG-Early has a CC value of 0.887. while EGAT-Tele data are the lowest CC value of 0.777. The MAE values of IMERG precipitation products ranged from 69.937 to 109.719 (m3/s), and the RMSE ranged from 9.673 to 10.169 (m3/s). While the MAE values of EGAT-Tele have 90.634 (m3/s), and the

RMSE has 175.331(m3/s). Overall, in NAM model simulation the IMERG-Final performs better than the near-real-time product (IMERG-Early, IMERG-Late) and EGAT-Telemetering data. Both of precipitation source from IMERG and EGAT telemetering are underestimated compared with observed inflow with RB ranging from 37.624% to 68.597%.

Figure 35-39 shown the hydrograph of inflow value from NAM model simulation of EGAT Telemetering station, IMERG-Early, IMERG-Late, and IMERG-Final compared with observation inflow from EGAT. Related with monsoon and seasonal of Thailand, The inflow value pack in the rainy season and low in summer and winter season. The inflow rate of EGAT telemetering are lower than observed inflow and missing data in 2017 because EGAT telemetering out of operated in this period. For the IMERG near-real-time products, the inflow rate of IMERG-Early and IMERG-Late are similarly pattern with lower than observed inflow. The inflow rate of IMERG-Final is lower than observed inflow but still better than other precipitation products.

Table 17: Assessment of inflow value in the NAM Model of IMERG products in with a Daily scale.

Product	EGAT-Tele	IMERG-Early	IMERG-Late	IMERG-Final
CC	0.777	0.887	0.892	0.913
MAE (m3/s)	90.634	109.719	106.623	69.937
RMSE (m3/s)	175.331	212.142	202.478	137.588
RB (%)	-44.648	-68.597	-66.592	-37.624

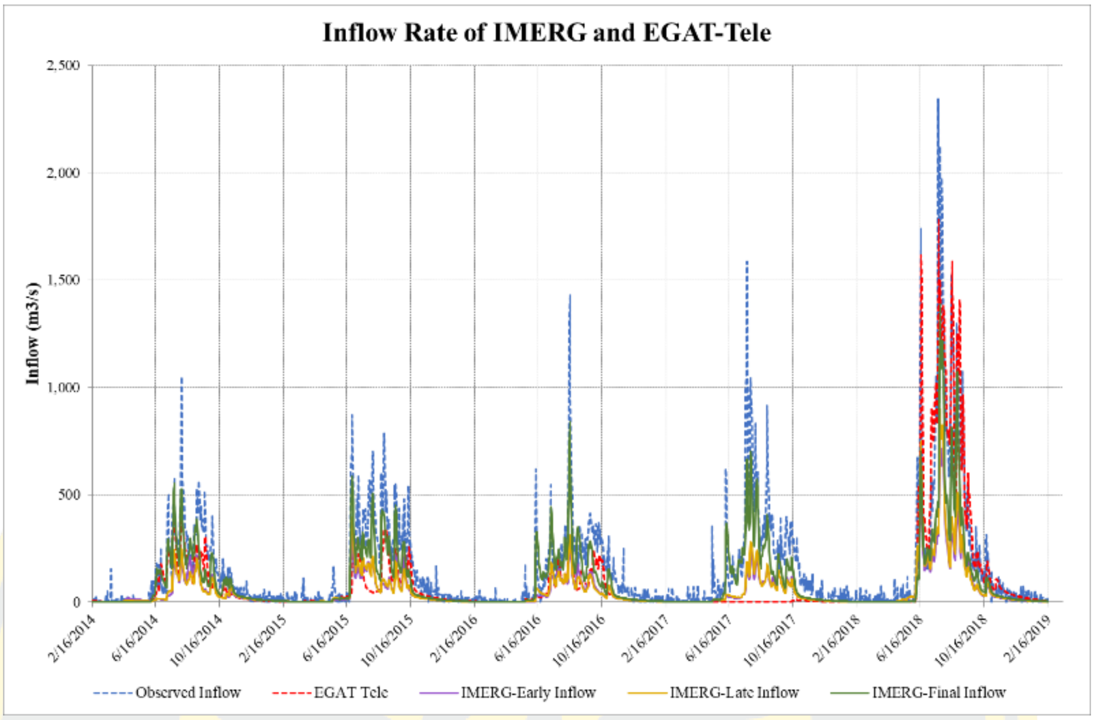


Figure 35: Simulated daily hydrograph of inflow rate from IMERG-Early, IMERG-Late, IMERG-Final and EGAT Telemetering stations compared with the observation inflow data.

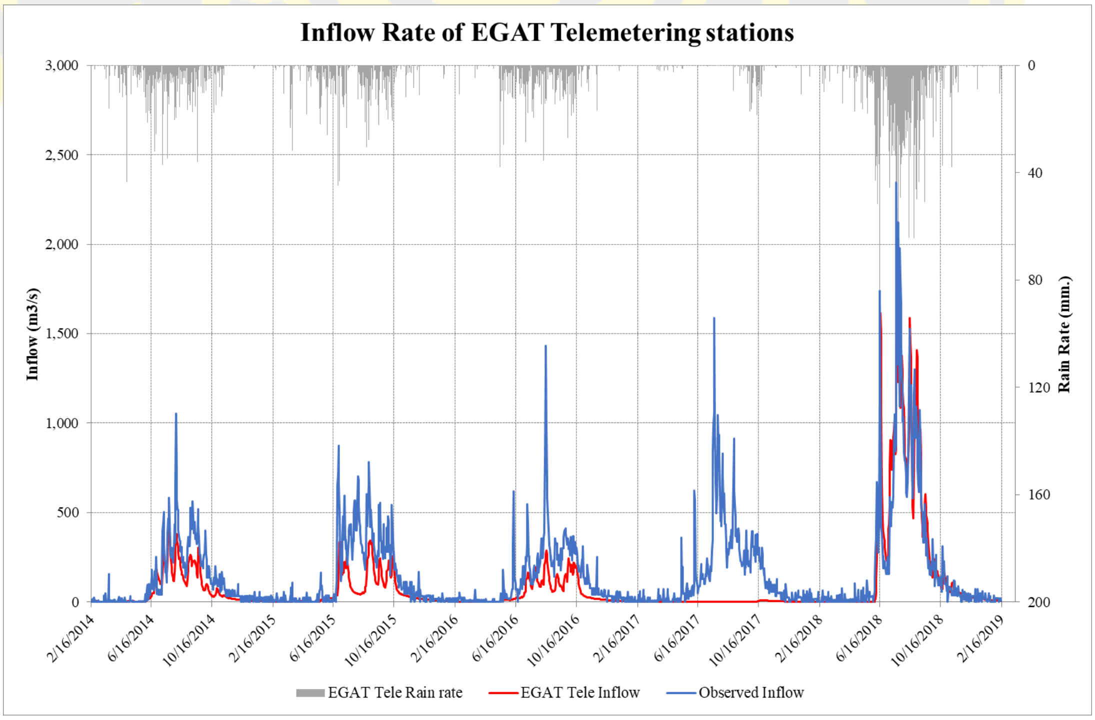


Figure 36: Simulated daily hydrograph of inflow rate from EGAT Telemetering stations compared with the observation inflow data

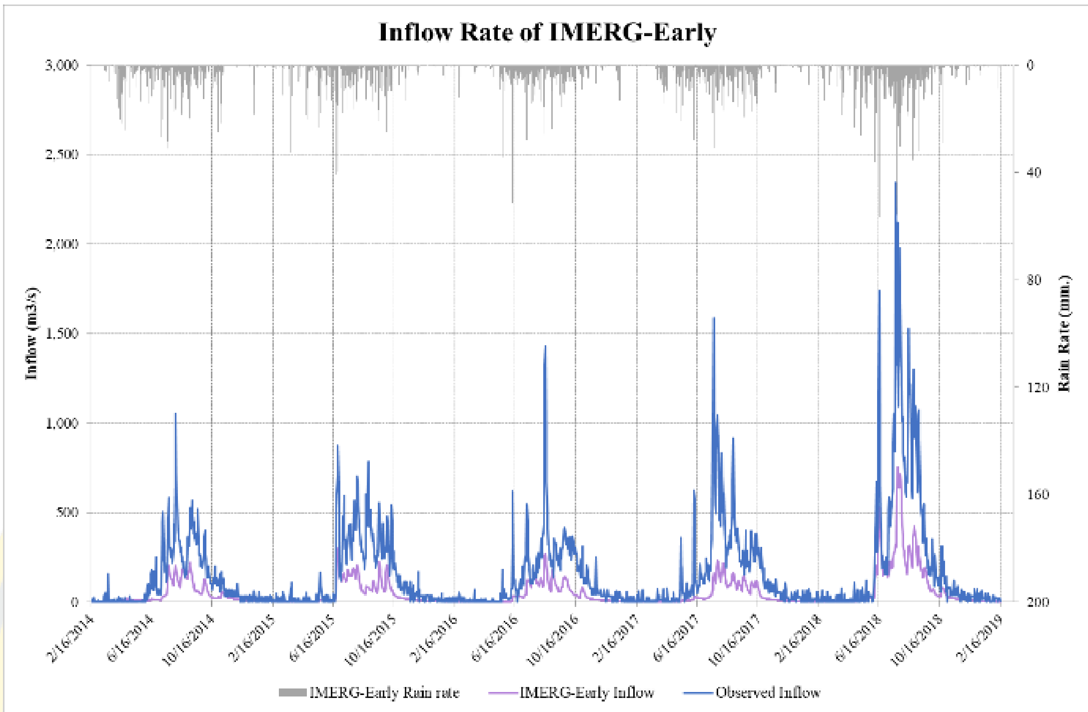


Figure 37: Simulated daily hydrograph of inflow rate from IMERG-Early compared with the observation inflow data

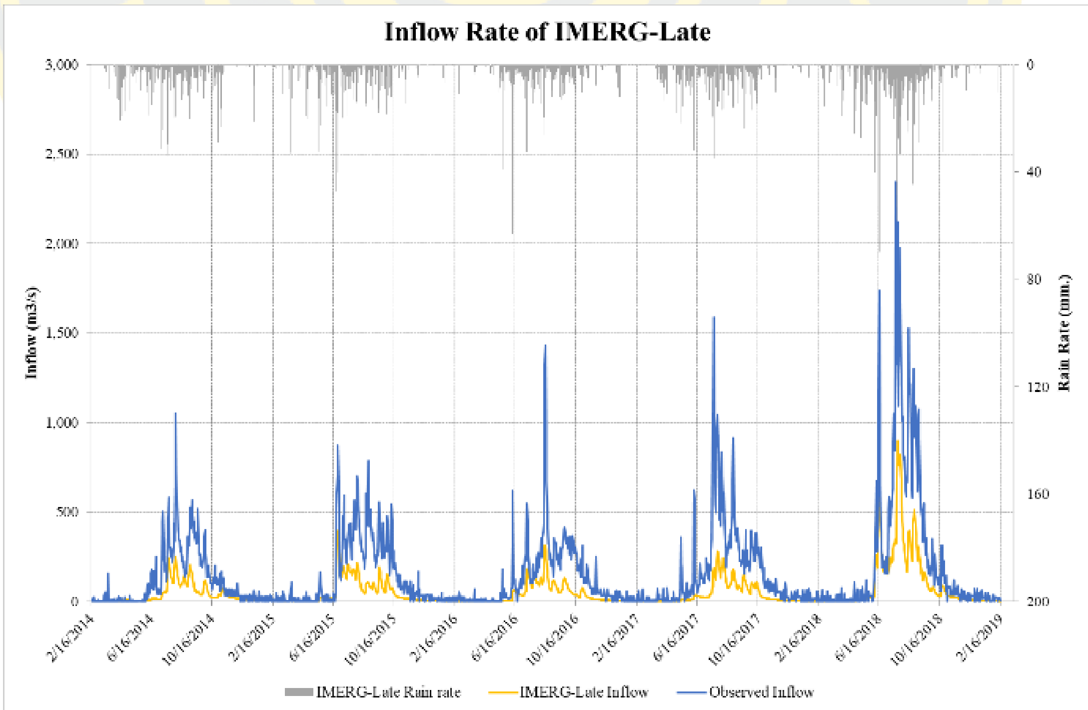


Figure 38: Simulated daily hydrograph of inflow rate from IMERG-Late compared with the observation inflow data

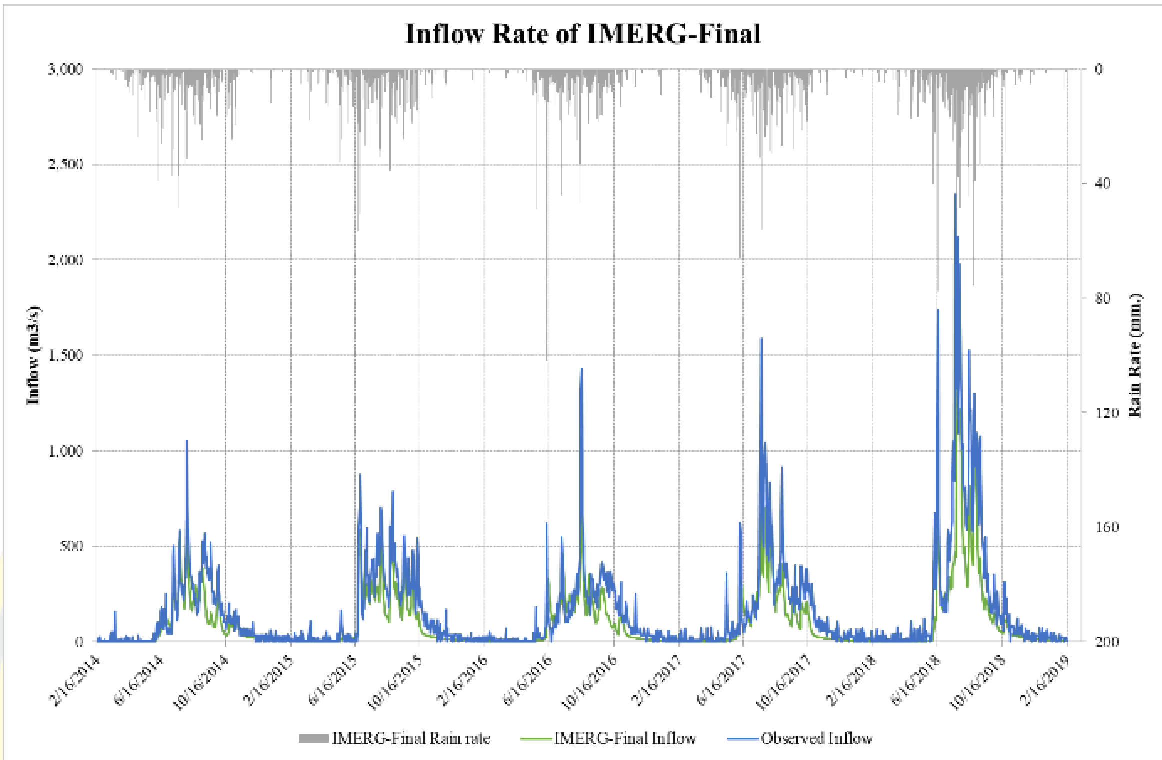


Figure 39: Simulated daily hydrograph of inflow rate from IMERG-Final compared with the observation inflow data.

CHAPTER 5
CONCLUSION

In this study, the daily precipitation from the IMERG-Early, IMERG-Late, and IMERG-Final are assessed with 121 ground-based measurements from TMD over Thailand in multiple time scales on period 16 February 2014 to 15 February 2019. The daily IMERG precipitation product was used reliability assessment (CC, MAE, RMSE, RB) and quality assessment (POD, FAR, POFD, CSI) method to assessed IMERG precipitation products with ground-based measurement. The assessment focused on the performance of IMERG precipitation products against ground-based observation and the performance of IMERG precipitation products in the hydrological model. The conclusions from this study are summarized as follows:

(1) The IMERG performed a good correlated with a ground-based observation from TMD in the annual, monthly, seasonal scales with CC value ranging from 0.896 to 0.938, but moderate correlated in daily scales with CC value ranging from 0.642 to 0.684. While the post-real-time product (IMERG-Final) have better correlated than the near-real-time product (IMERG-Early and IMERG-Late) at all time scale.

(2) There were no statistically significant differences in the performance of the IMERG near-real-time products at all time scales, but IMERG-Late slightly better performance than IMERG-Early.

(3) All IMERG are overestimated precipitation over Thailand at all time scales with Relative Bias ranging from 7% to 9%.

(4) The IMERG showed excellent performance in precipitation detection capability over Thailand at all time scale.

(5) In the hydrological model, the IMERG performed a high correlation with the inflow rate in the Vajiralongkorn reservoir (CC value ranging from 0.887-0.913) than ground-based precipitation data from EGAT Telemetering (CC = 0.777). IMERG-Final performs better than the near-real-time product and EGAT-Tele rainfall data.

(6) The inflow rate from all IMERG and EGAT telemetering precipitation data underestimated the inflow rate compared with observed inflow with Relative

Bias ranging from -44.648% to -37.624%. The IMERG-Final better performance than other data sources.

Overall, the correlation between IMERG precipitation products and ground-based observation is an excellent performance in daily precipitation estimates over Thailand, which is consistent with findings in the Mun-Chi river basin in Thailand (Li et al., 2019). While, the nearby countries in South-East Asia was found a moderate correlation of IMERG precipitation products with ground-based measurements such as in Singapore (Mou Leong & Zheng, 2017), Malaysia (Tan & Santo, 2018), and excellent performance in precipitation detection capability over a study area.

The among of precipitation of Thailand occurred under the influence of the South-west monsoon and north-east monsoon, which is mainly factored to bring the moisture to Thailand and cause of high precipitation in the rainy season. All IMERG have a high MAE and RMSE in the rainy season with good correlation in seasonal scale but a moderate correlation in summer. In terms of precipitation data source, IMERG slightly underestimated the inflow rate at the local scale in the NAM model that operating model of Electricity generating authority of Thailand (EGAT) over the Vajiralongkorn reservoir, Thailand.

In future research should be considering the performance of both IMERG near-real-time products (IMERG-Early and IMERG-Late) for flood events and more studies about IMERG precipitation products for hydrological modelling on a local scale. Moreover, in this studied was used daily for temporal resolution but there are many temporal resolutions for IMERG precipitation products. The performance of IMERG Half-hourly precipitation products needs to study in future work in a different region of Thailand for water resources management and hydrological model.

REFERENCES

Asong, Z. E., Razavi, S., Wheater, H. S., & Wong, J. S. (2017). Evaluation of Integrated Multisatellite Retrievals for GPM (IMERG) over Southern Canada against Ground Precipitation Observations: A Preliminary Assessment. Journal of Hydrometeorology, 18(4), 1033-1050. doi:10.1175/JHM-D-16-0187.1

Brown, R. A. (2013). Doppler Weather Radar. In P. T. Bobrowsky (Ed.), Encyclopedia of Natural Hazards (pp. 188-188). Dordrecht: Springer Netherlands.

CIMSS. (2019). Satellite Meteorology For Grade 7-12, Weather Satellites and Orbits. Retrieved from http://cimss.ssec.wisc.edu/satmet/modules/

2_weather_satellites/ws-1.html

Chen, C., Chen, Q., Duan, Z., Zhang, J., Mo, K., Li, Z., & Tang, G. (2018). Multiscale Comparative Evaluation of the GPM IMERG v5 and TRMM 3B42 v7 Precipitation Products from 2015 to 2017 over a Climate Transition Area of China. *Remote Sensing*, *10*(6), N.PAG-N.PAG. https://doi.org/10.3390/rs10060944

Chokngamwong, R., & Chiu, L. S. (2008). Thailand Daily Rainfall and Comparison with TRMM Products. *Journal of Hydrometeorology*, *9*(2), 256–266. https://doi.org/10.1175/2007jhm876.1

Danish Hydraulic Institute. (2003) MIKE BASIN: Rainfall-runoff modeling reference manual. DHI, Denmark.

Danish Hydraulic Institute. (2009) MIKE 11: A modelling system for Rivers and channels User Guide. DHI, Denmark.

Electricity Generating Authority of Thailand. (2019). Vajiralongkorn Dam. Retrieved 5, 2019 from https://www.egat.co.th/en/information/power-plants-and-dams?view=article&id=61

Fei, Y., Limin, Z., Khin Wah Wah, W., Liliang, R., Chongxu, Z., Yonghua, Z., … Yi, L. (2017). Assessment of GPM and TRMM Multi-Satellite Precipitation Products in Streamflow Simulations in a Data-Sparse Mountainous Watershed in Myanmar. *Remote Sensing*, *9*(3), 1–23. https://doi.org/10.3390/rs9030302

Fengrui, C., & and Xi, L. (2016). Evaluation of IMERG and TRMM 3B43 Monthly Precipitation Products over Mainland China. *Remote Sensing*, *8*(6), 1–18. https://doi.org/10.3390/rs8060472

Global Precipitation Measurement (GPM) Mission Overview. (n.d.). Retrieved December 5, 2019, from https://gpm.nasa.gov/GPM

He, Z., Yang, L., Tian, F., Ni, G., Hou, A., & Lu, H. (2017). Intercomparisons of Rainfall Estimates from TRMM and GPM Multisatellite Products over the Upper Mekong River Basin. *Journal of Hydrometeorology*, *18*(2), 413–430. https://doi.org/10.1175/JHM-D-16-0198.1

Hou, A. Y., Kakar, R. K., Neeck, S., Azarbarzin, A. A., Kummerow, C. D., Kojima, M., … Iguchi, T. (2013). The Global Precipitation Measurement Mission. *Bulletin of the American Meteorological Society*, *95*(5), 701–722. https://doi.org/10.1175/BAMS-D-13-00164.1

Huffman, G., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., … Wolff, D. (2007). The TRMM multi-satellite precipitation analysis: Quasi-global, multi-year, combined-sensor precipitation estimates at fine scale. *J. Hydrometeor.*, *8*, 28–55.

Hur, J., Raghavan, S. V, Nguyen, N. S., & Liong, S.-Y. (2016). Evaluation of High-resolution Satellite Rainfall Data over Singapore. *Procedia Engineering*, *154*, 158–167. https://doi.org/10.1016/j.proeng.2016.07.437

Joyce, R. J., Janowiak, J. E., Arkin, P. A., & Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology*, *5*(3), 487–503. https://doi.org/10.1175/1525-7541(2004)005<0487:CAMTPG>2.0.CO;2

Li, R., Shi, J., Ji, D., Zhao, T., Plermkamon, V., Moukomla, S., … Kruasilp, J. (2019). Evaluation and Hydrological Application of TRMM and GPM Precipitation Products in a Tropical Monsoon Basin of Thailand. *Water*, *11*(4). https://doi.org/10.3390/w11040818

Mason, I. (1989). *Dependence of the Critical Success Index on sample climate and threshold probability* (Vol. 37).

Michaelides, S., Levizzani, V., Anagnostou, E., Bauer, P., Kasparis, T., & Lane, J. E. (2009). Precipitation: Measurement, remote sensing, climatology and modeling. *Atmospheric Research*, *94*(4), 512–533. https://doi.org/10.1016/j.atmosres.2009.08.017

Mou Leong, T., & Zheng, D. (2017). Assessment of GPM and TRMM Precipitation Products over Singapore. *Remote Sensing*, *9*(7), 1–16. https://doi.org/10.3390/rs9070720

National Hydroinformatics and Climate Data Center (2019). Thailand Water Situation in 2018. Retrieved from http://www.thaiwater.net/current/YearlyReport2018/rain.html

Northern Meteorological Center. (2014). Instrument. Retrieved from http://www.cmmet.tmd.go.th/instrument/instruments.php

Okamoto, K. i, Ushio, T., Iguchi, T., Takahashi, N., & Iwanami, K. (2005). *The Global Satellite Mapping of Precipitation (GSMaP) project* (Vol. 5). https://doi.org/10.1109/IGARSS.2005.1526575

Promasakha na Sakolnakhon, K. (2013). Comparison the Estimate Rainfall from Global Satellite Mapping of Precipitation (GSMaP) to Ground-based Precipitation data over Thailand. *1st Joint Project Team Meeting for Sentinel Asia STEP3 (JPTM2013)*.

Sorooshian, S., Hsu, K. L., Gao, X., Gupta, H. V., Imam, B., & Braithwaite, D. (2000). Evaluation of PERSIANN system satellite-based estimates of tropical rainfall. *Bulletin of the American Meteorological Society*, *81*(9), 2035–2046. https://doi.org/10.1175/1520-0477(2000)081<2035:EOPSSE>2.3.CO;2

Sultana, R., & Nasrollahi, N. (2018). Evaluation of remote sensing precipitation estimates over Saudi Arabia. *Journal of Arid Environments*, *151*, 90–103. https://doi.org/10.1016/j.jaridenv.2017.11.002

Tan, M. L., & Santo, H. (2018). Comparison of GPM IMERG, TMPA 3B42 and PERSIANN-CDR satellite precipitation products over Malaysia. *Atmospheric Research*, *202*, 63–76. https://doi.org/10.1016/j.atmosres.2017.11.006

Tang, G., Zeng, Z., Long, D., Guo, X., Yong, B., Zhang, W., & Hong, Y. (2016). Statistical and Hydrological Comparisons between TRMM and GPM Level-3 Products over a Midlatitude Basin: Is Day-1 IMERG a Good Successor for TMPA 3B42V7? *Journal of Hydrometeorology*, *17*(1), 121–137. https://doi.org/10.1175/JHM-D-15-0059.1

Wang, Z., Zhong, R., Lai, C., & Chen, J. (2017). Evaluation of the GPM IMERG satellite-based precipitation products and the hydrological utility. *Atmospheric Research*, *196*, 151–163. https://doi.org/10.1016/j.atmosres.2017.06.020

Yang, X., Yong, B., Hong, Y., Chen, S., & Zhang, X. (2016). Error analysis of multi-satellite precipitation estimates with an independent raingauge observation network over a medium-sized humid basin. *Hydrological Sciences Journal*, *61*(10), 1813–1830. https://doi.org/10.1080/02626667.2015.1040020

Chen, C., Chen, Q., Duan, Z., Zhang, J., Mo, K., Li, Z., & Tang, G. (2018). Multiscale Comparative Evaluation of the GPM IMERG v5 and TRMM 3B42 v7

Precipitation Products from 2015 to 2017 over a Climate Transition Area of China. *Remote Sensing*, *10*(6), N.PAG-N.PAG. https://doi.org/10.3390/rs10060944

Chokngamwong, R., & Chiu, L. S. (2008). Thailand Daily Rainfall and Comparison with TRMM Products. *Journal of Hydrometeorology*, *9*(2), 256–266. https://doi.org/10.1175/2007jhm876.1

Fei, Y., Limin, Z., Khin Wah Wah, W., Liliang, R., Chongxu, Z., Yonghua, Z., … Yi, L. (2017). Assessment of GPM and TRMM Multi-Satellite Precipitation Products in Streamflow Simulations in a Data-Sparse Mountainous Watershed in Myanmar. *Remote Sensing*, *9*(3), 1–23. https://doi.org/10.3390/rs9030302

Fengrui, C., & and Xi, L. (2016). Evaluation of IMERG and TRMM 3B43 Monthly Precipitation Products over Mainland China. *Remote Sensing*, *8*(6), 1–18. https://doi.org/10.3390/rs8060472

He, Z., Yang, L., Tian, F., Ni, G., Hou, A., & Lu, H. (2017). Intercomparisons of Rainfall Estimates from TRMM and GPM Multisatellite Products over the Upper Mekong River Basin. *Journal of Hydrometeorology*, *18*(2), 413–430. https://doi.org/10.1175/JHM-D-16-0198.1

Hou, A. Y., Kakar, R. K., Neeck, S., Azarbarzin, A. A., Kummerow, C. D., Kojima, M., … Iguchi, T. (2013). The Global Precipitation Measurement Mission. *Bulletin of the American Meteorological Society*, *95*(5), 701–722. https://doi.org/10.1175/BAMS-D-13-00164.1

Huffman, G., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., … Wolff, D. (2007). The TRMM multi-satellite precipitation analysis: Quasi-global, multi-year, combined-sensor precipitation estimates at fine scale. *J. Hydrometeor.*, *8*, 28–55.

Hur, J., Raghavan, S. V, Nguyen, N. S., & Liong, S.-Y. (2016). Evaluation of High-resolution Satellite Rainfall Data over Singapore. *Procedia Engineering*, *154*, 158–167. https://doi.org/10.1016/j.proeng.2016.07.437

Joyce, R. J., Janowiak, J. E., Arkin, P. A., & Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology*, *5*(3), 487–503. https://doi.org/10.1175/1525-7541(2004)005<0487:CAMTPG>2.0.CO;2

Li, R., Shi, J., Ji, D., Zhao, T., Plermkamon, V., Moukomla, S., … Kruasilp, J. (2019). Evaluation and Hydrological Application of TRMM and GPM Precipitation Products in a Tropical Monsoon Basin of Thailand. *Water*, *11*(4).

https://doi.org/10.3390/w11040818

Mason, I. (1989). *Dependence of the Critical Success Index on sample climate and threshold probability* (Vol. 37).

Michaelides, S., Levizzani, V., Anagnostou, E., Bauer, P., Kasparis, T., & Lane, J. E. (2009). Precipitation: Measurement, remote sensing, climatology and modeling. *Atmospheric Research*, *94*(4), 512–533. https://doi.org/10.1016/j.atmosres.2009.08.017

Mou Leong, T., & Zheng, D. (2017). Assessment of GPM and TRMM Precipitation Products over Singapore. *Remote Sensing*, *9*(7), 1–16. https://doi.org/10.3390/rs9070720

Okamoto, K. i, Ushio, T., Iguchi, T., Takahashi, N., & Iwanami, K. (2005). *The Global Satellite Mapping of Precipitation (GSMaP) project* (Vol. 5). https://doi.org/10.1109/IGARSS.2005.1526575

Promasakha na Sakolnakhon, K. (2013). Comparison the Estimate Rainfall from Global Satellite Mapping of Precipitation (GSMaP) to Ground-based Precipitation data over Thailand. *1st Joint Project Team Meeting for Sentinel Asia STEP3 (JPTM2013)*.

Sorooshian, S., Hsu, K. L., Gao, X., Gupta, H. V., Imam, B., & Braithwaite, D. (2000). Evaluation of PERSIANN system satellite-based estimates of tropical rainfall. *Bulletin of the American Meteorological Society*, *81*(9), 2035–2046. https://doi.org/10.1175/1520-0477(2000)081<2035:EOPSSE>2.3.CO;2

Sultana, R., & Nasrollahi, N. (2018). Evaluation of remote sensing precipitation estimates over Saudi Arabia. *Journal of Arid Environments*, *151*, 90–103. https://doi.org/10.1016/j.jaridenv.2017.11.002

Tan, M. L., & Santo, H. (2018). Comparison of GPM IMERG, TMPA 3B42 and PERSIANN-CDR satellite precipitation products over Malaysia. *Atmospheric Research*, *202*, 63–76. https://doi.org/10.1016/j.atmosres.2017.11.006

Tang, G., Zeng, Z., Long, D., Guo, X., Yong, B., Zhang, W., & Hong, Y. (2016). Statistical and Hydrological Comparisons between TRMM and GPM Level-3 Products over a Midlatitude Basin: Is Day-1 IMERG a Good Successor for TMPA 3B42V7? *Journal of Hydrometeorology*, *17*(1), 121–137. https://doi.org/10.1175/JHM-D-15-0059.1

Thai Meteorological Department. (2019). The climate of Thailand. Retrieved from https://www.tmd.go.th/en/archive/thailand_climate.pdf

Tourism Authority of Thailand. (2019). Geography. Retrieved from https://www.tourismthailand.org/Articles/plan-your-trip-history-and-geography-geology

Wang, Z., Zhong, R., Lai, C., & Chen, J. (2017). Evaluation of the GPM IMERG satellite-based precipitation products and the hydrological utility. *Atmospheric Research*, *196*, 151–163. https://doi.org/10.1016/j.atmosres.2017.06.020

Yang, X., Yong, B., Hong, Y., Chen, S., & Zhang, X. (2016). Error analysis of multi-satellite precipitation estimates with an independent raingauge observation network over a medium-sized humid basin. *Hydrological Sciences Journal*, *61*(10), 1813–1830. https://doi.org/10.1080/02626667.2015.1040020

World Meteorological Organization. (2018). Chapter 6 Measurement of precipitation Retrieved from https://www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide /Prelim_2018_ed/8_I_6_en_MR_tc.pdf

APPENDIX

Detail of rain gauge stations from the Thai Meteorology Department.

No.	Station ID	Station Name	Latitude	Longitude
1	300201	MAE HONG SON	19.2998	97.9733
2	300202	MAE SARIANG	18.1764	97.9307
3	303201	CHIANG RAI	19.9056	99.8357
4	303301	CHIANG RAI	19.8984	99.7999
5	310201	THUNG CHANG	19.3848	100.88
6	327202	DOI ANG KANG	19.9105	99.0435
7	327501	CHIANG MAI	18.7714	98.9693
8	328201	LAMPANG	18.2783	99.5066
9	328202	THOEN	17.6797	99.316
10	328301	LAMPANG AMS.	18.2985	99.2999
11	329201	LAMPHUN	18.5757	99.0094
12	330201	PHRAE	18.2282	100.224
13	331201	NAN	18.8652	100.75
14	331301	NAN AMS.	18.8652	100.75
15	331401	THA WANG PHA	19.1163	100.813
16	331402	THUNG CHANG	19.3848	100.88
17	351201	UTTARADIT	17.7486	100.283
18	352201	NONG KHAI	17.8764	102.741
19	353201	LOEI	17.4814	101.733
20	353301	LOEI AMS.	17.3986	101.733
21	354201	UDON THANI	17.4125	102.79
22	356201	SAKON NAKHON	17.1486	104.133
23	356301	SAKON NAKHON AMS.	17.1153	104.05
24	357201	NAKHON PHANOM	17.4083	104.783
25	357301	NAKHON PHANOM AMS.	17.401	104.791
26	360201	NONG BUA LAMPHU	17.2014	102.449
27	373201	SUKHOTHAI	17.0044	99.8266
28	373301	SI SAMRONG	17.0653	99.8332
29	376201	TAK	16.9153	99.1166
30	376202	MAE SOT	16.7106	98.579
31	376203	BHUMIBOL DAM	17.2319	99.053
32	376301	DOI MU SOR AMS.	17.7944	98.3601
33	376401	UM PHANG	16.0148	98.8666
34	378201	PHITSANULOK	16.8486	100.35
35	379201	PHETCHABUN	16.4098	101.292
36	379401	LOM SAK	16.777	101.246
37	379402	WICHIAN BURI	15.7376	101.036

Detail of rain gauge stations from the Thai Meteorology Department (cont).

No.	Station ID	Station Name	Latitude	Longitude
38	380201	KAMPHAENG PHET	16.4654	99.6499
39	381201	KHON KAEN	16.4265	102.838
40	381301	THA PHRA AMS.	16.3276	102.661
41	383201	MUKDAHAN	16.5345	104.717
42	386301	PHICHIT	16.4354	100.354
43	387401	MAHA SARAKHAM	16.3648	103.305
44	388401	KALASIN	16.4301	103.51
45	400201	NAKHON SAWAN	15.7017	100.141
46	400301	TAK FA AMS.	15.3488	100.5
47	402301	CHAI NAT AMS.	15.1488	100.183
48	403201	CHAIYAPHUM	15.8048	102.039
49	405201	ROI ET	16.0504	103.658
50	405301	ROI ET AMS.	16.0987	103.6
51	407301	UBON RATCHATHANI	15.2321	105.033
52	407501	UBON RATCHATHANI AMS.	15.2252	104.862
53	409301	SI SA KET	14.9988	104.3
54	410201	UTHAI THANI	15.0757	99.5109
55	415301	PHRA NAKHON SI AYUTTHAYA	14.3625	100.576
56	419301	PATHUM THANI AMS.	14.017	100.537
57	423301	CHACHOENGSAO	13.6867	101.08
58	424301	RATCHABURI	13.4861	99.7974
59	425201	SUPHAN BURI	14.4682	100.121
60	425301	U THONG AMS.	14.2989	99.7999
61	426201	LOP BURI	14.7946	100.656
62	426401	BUA CHUM	15.2627	101.183
63	429201	NAM RONG	13.8569	100.574
64	429301	SAMUT PRAKAN AMS.	13.5981	100.599
65	429601	SUVARNABHUMI AIRPORT	13.6902	100.75
66	430201	PRACHIN BURI	14.0489	101.373
67	430401	KABIN BURI	13.9825	101.709
68	431201	NAKHON RATCHASIMA	14.9682	102.104
69	431301	PAK CHONG AMS.	14.7121	101.421
70	431401	CHOK CHAI	14.7294	102.167
71	432201	SURIN	14.8821	103.467
72	432301	SURIN AMS.	14.8796	103.499
73	432401	THA TUM	15.3166	103.679
74	436201	BURI RAM	14.991	103.108
75	436401	NANG RONG	14.6263	102.797

Detail of rain gauge stations from the Thai Meteorology Department (cont).

No.	Station ID	Station Name	Latitude	Longitude
76	438201	SAMUT SONGKHRAM	13.408	100.032
77	440201	ARANYA PRATHET	13.6322	102.433
78	440401	SA KAEO	13.8181	102.076
79	450201	KANCHANABURI	14.0011	99.5532
80	450401	THONG PHA PHUM	14.741	98.6365
81	451301	NAKHON PATHOM	13.8161	100.071
82	455201	BANGKOK	13.7644	100.522
83	455203	BANGKOK KHLONG TOEI PORT	13.7058	100.568
84	455301	BANGKOK BANG NA AMS.	13.6656	100.617
85	455601	DON MUEANG AIRPORT	13.9156	100.6
86	459201	CHON BURI	13.3589	100.989
87	459202	KO SI CHANG	13.1612	100.81
88	459203	PATTAYA	12.9157	100.867
89	459204	SATTAHIP	12.6601	100.911
90	459205	LAEM CHABANG	13.0818	100.881
91	465,201	PHETCHABURI	12.749	99.9499
92	478201	RAYONG	12.6323	101.346
93	478301	HUAI PONG AMS.	12.7323	101.133
94	480201	CHANTHABURI	12.6073	102.116
95	480301	PHLIO AMS.	12.5157	102.167
96	500201	PRACHUAP KHIRI KHAN	11.806	99.7985
97	500202	HUA HIN	12.564	99.9567
98	500301	NONG PHLAP AMS.	12.5823	99.7332
99	501201	TRAT	11.7744	102.889
100	517201	CHUMPHON	10.4909	99.1844
101	517301	SAWI AMS.	10.3325	99.1
102	532201	RANONG	9.96449	98.6367
103	551201	SURAT THANI	9.13011	99.3577
104	551203	KO SAMUI	9.46592	100.05
105	551301	SURAT THANI AMS.	9.13011	99.3577
106	551401	PHRA SAENG	8.56377	99.2513
107	552201	NAKHON SI THAMMARAT	8.41489	99.9657
108	552301	NAKHON SI THAMMARAT AMS.	8.33267	100.083
109	552401	CHAWANG	8.42378	99.5073
110	560301	PHATTHALUNG AMS.	7.62348	100.155
111	561201	TAKUA PA	8.68264	98.2501
112	564201	PHUKET	7.88771	98.3873
113	564202	PHUKET (Center)	8.10908	98.3126

Detail of rain gauge stations from the Thai Meteorology Department (cont).

No.	Station ID	Station Name	Latitude	Longitude
114	566201	KO LANTA	7.52717	99.0936
115	566202	KRABI	8.0613	98.9208
116	567201	TRANG	7.55552	99.6137
117	568301	KHO HONG AMS.	7.01334	100.509
118	568401	SADAO	6.78722	100.407
119	568501	SONGKHLA	7.19172	100.604
120	568502	HAT YAI	6.93278	100.417
121	570201	SATUN	6.63281	100.083
122	580201	PATTANI	6.8328	101.267
123	581301	YALA AMS.	6.51616	101.283
124	583201	NARATHIWAT	6.42339	101.826

Detail of rain gauge stations from EGAT Telemetering.

No.	Station ID	Station Name	Latitude	Longitude
1	AU01	Ban Vergadi	15.1844	98.32833
2	AU02	Sangkhla Buri	15.1547	98.45306
3	AU03	Ban Chong Awo	14.9667	98.62611
4	AU04	Pilok Mine	14.6786	98.38722
5	AU05	Vajiralongkorn Dam	14.7975	98.60139

BIOGRAPHY

NAME	Tiwakorn Wuttipan
DATE OF BIRTH	18 April 1987
PLACE OF BIRTH	Nonthaburi, Thailand
PRESENT ADDRESS	300/45 Tambon Changpuek, Amphoe Mueang Chiang mai, Chiang mai, Thailand.
POSITION HELD	Administrative Officer Level 6, Electricity Generating Authority of Thailand.
EDUCATION	M.Eng. (Photogrammetry and Remote Sensing) M.Sc. (Geoinformatics)