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REVIEW ARTICLE

Assessing the Reliability of Satellite-Derived Evapotranspiration Data Using Numerical Modified Penman Method at Citarum Watershed

Evi Anggraheni[1*], Faris Zulkarnain[2], Pranita Giardini[1], Kintan Maulidina[2], Babag Purbantoro[3], Raisya Afifah[1], Anang Muchlis[4], Siswanto[5], Andry Rustanto[2], Muhammad Dimyati[2], Ahmad Zubair[2], Triarko Nurlambang[2], Ratih Dewanti[3], Iqbal Putut Ash-Shidiq[2], Irma Susanti[6]

[1]Civil and Environmental Engineering, Faculty of Engineering, Universitas Indonesia, Indonesia.
[2]Department of Geography, Faculty of Mathematics and Natural Science, Universitas Indonesia, Indonesia.
[3]Remote Sensing Technology and Data Center, National Research and Innovation Agency, Indonesia.
[4]Citarum River Basin Agency, Ministry of Public Work and Housing, Indonesia.
[5]Meteorological, Climatological, and Geophysical Agency, Indonesia.
[6]Center for Applied Geography Research, Universitas Indonesia, Indonesia

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***Correspondent email:**
evi.anggraheni@eng.ui.ac.id

Abstract. Evapotranspiration (ET) is crucial in the analysis and estimation of water availability and demand for crops. Due to limited discharge measurement stations, assessing water availability becomes a challenge in water management planning. Specifically, Citarum watershed, the biggest watershed in West Java, serves as a primary source of raw water for Jakarta, Indonesia's capital city. Modified Penman method, which was originally developed by the Food and Agriculture Organization (FAO) and subsequently modified for tropical areas, is commonly employed to analyze ET. In water balance equation, ET represents one of its key components, and solving this equation becomes necessary to determine water losses accurately. Accordingly, the standard product of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite, MOD16A2, offers an alternative source of ET data. To address the absence of ground station data, the reliability of satellite data becomes crucial. Therefore, the aim of this study is to compare and analyze the reliability of satellite-derived ET potential images with numerical Modified Penman method specifically within Citarum Watershed. This method is one among several other methods used to calculate ET potential based on climate data. The MOD16A2 and Modified Penman equation were used for the simulation and baseline data respectively. The reliability of the two simulations was analyzed by examining the skewness percentage of each pixel and period. By observing the distribution of percent skewness, it becomes possible to evaluate the performance comparison of two simulations. Lastly, it is important to note that the sensitivity of satellite is significantly affected by local weather conditions.

1. Introduction

Water resource management is being challenged by the rising demand for water in various sectors such as households, food production, energy generation, and agriculture (Tsouni et al., 2008). To effectively manage water resources, it is essential to have access to high-quality information encompassing both the geographical and temporal aspects of watershed (Loucks, 2000). Accordingly, Evapotranspiration (ET) serves as an essential component of water resource data, despite the inherent difficulties associated with its direct measurement and temporal variability (Tsouni et al., 2008). In general, ET process at the ground surface is calculated using method for measuring water loss in the hydrological cycle (Konukcu, 2007). ET plays an important role not only in determining water availability but also in estimating irrigation water supply (Thomas, 2000; Wu et al., 2014). Therefore, the accurate representation of ET is important for rainfall-runoff modeling due to its impact on the hydrological responses (Anggraheni et al., 2018), but unfortunately, many watershed in Indonesia lack sufficient ET measurements. To address this issue, previous study was conducted where ET was calculated using a variety of numerical models, such as Penman-Monteith (Aprialdi et al., 2019; Widyanto et al., 2014), Thornthwaite method (Pramudya et al., 2019), and modified Penman (Batchelor, 1984).

Modified Penman equation, also known as the FAO Modified Penman Method, is widely used for calculating ET and was developed by the Food and Agriculture Organization (FAO). A previous study investigated that the FAO Modified Penman is specifically suitable for tropical areas (Batchelor, 1984). However, this method relies on parameters obtained from ground-based climatological stations. Over the past two decades, significant advancements have been made in the field of remote sensing technology and methodologies for acquiring

ET data, coinciding with the launch of the Moderate-Resolution Imaging Spectroradiometer (MODIS) in 1999 (Justice et al., 1997; Zhang et al., 2016). There are several remote sensing ET retrieval method, including surface energy balance for land (SEBAL), Penman-Monteith, Priestley-Taylor, Ts-VI Space, MEP, Water-Carbon Linkage, Water Balance, and Empirical Models (Zhang et al., 2016). Accordingly, SEBAL method, which was initially introduced by Cleugh et al., (2007) and Leuning et al., (2008), has garnered considerable attention in the field of ET study. Mu et al., (2007, 2011) further advanced this method by utilizing data from the MODIS satellite and ground measurements obtained from 7000 Global Modelling and Assimilation Office (GMAO) to develop ET models. The MODIS standard data used was MOD16A2, which provided an 8-Day ET estimate at a spatial resolution of 500 meters, calculated using Penman-Monteith model (Mu et al., 2007, 2011). This dataset has been widely used by various investigators (Degano et al., 2021; He et al., 2019; Marques et al., 2020; Shekar et al., 2021; Sriwongsitanon et al., 2020) to analyze ET patterns across tropical to polar regions.

The availability of satellite-based ET data has facilitated the representation of ET process across watershed, supported by cloud computing platforms such as Google Earth Engine (Gorelick et al., 2017; Laipelt et al., 2021). In Indonesia, ET estimation primarily relies on Penman Modification Equation, which necessitates various climatological data and assumptions. However, due to the limited availability of climatological stations, an alternative approach is to utilize more accessible ET satellite data. The reliability of this data must, however, be analyzed before use. The aim of this study is to analyze the reliability of ET data obtained from the MOD16A2 Satellite by comparing it with numerical modified Penman equation. Statistical method, including standard deviation and Box Whisker Plot, were employed to assess the reliability of the MOD16A2 Satellite-derived ET data in comparison to numerical Modified Penman method. This analysis specifically focuses on Indonesia, offering novel insight and a new approach to accurately measure ET using satellite data. To further advance this study, an attempt should be made to conduct the study in another watershed. This approach can be implemented not only in Indonesia but also in other regions worldwide that have similar characteristics but with more climatological stations. This will enable the correction of data deviations to be conducted.

2. The Study Area

Citarum watershed is located in the West Java Province, Indonesia, and spans an approximate area of 6,867 km2 (Boer et al., 2012). The climatic condition at this watershed is categorized as monsoonal, and it is influenced by the monsoon winds originating from Australia and Asia (Aldrian et al., 2003), making it susceptible to El Niño events (D'Arrigo et al., 2011; Sahu et al., 2012). Furthermore, it is the biggest of its kind in the West Java Province, and it plays an important role in water management (Hengsdijk et al., 2006). Watershed is also surrounded by two major cities, as shown in Figure 1. It encompasses five districts, with the city of Bandung being the largest, alongside several surrounding smaller cities. Within watershed, there are three reservoirs, namely Jatiluhur, Cirata, and Saguling, which serve various purposes such as supplying water for electricity generation, household consumption, irrigation, and flushing (Siswanto et al., 2019; Yulianto et al., 2019). Notably, the Jatiluhur reservoir serves not only as an irrigation water storage for Citarum River basin and the surrounding small cities but also as a source of water supply for Jakarta city (Hengsdijk et al., 2006; LuoID et al., 2019).

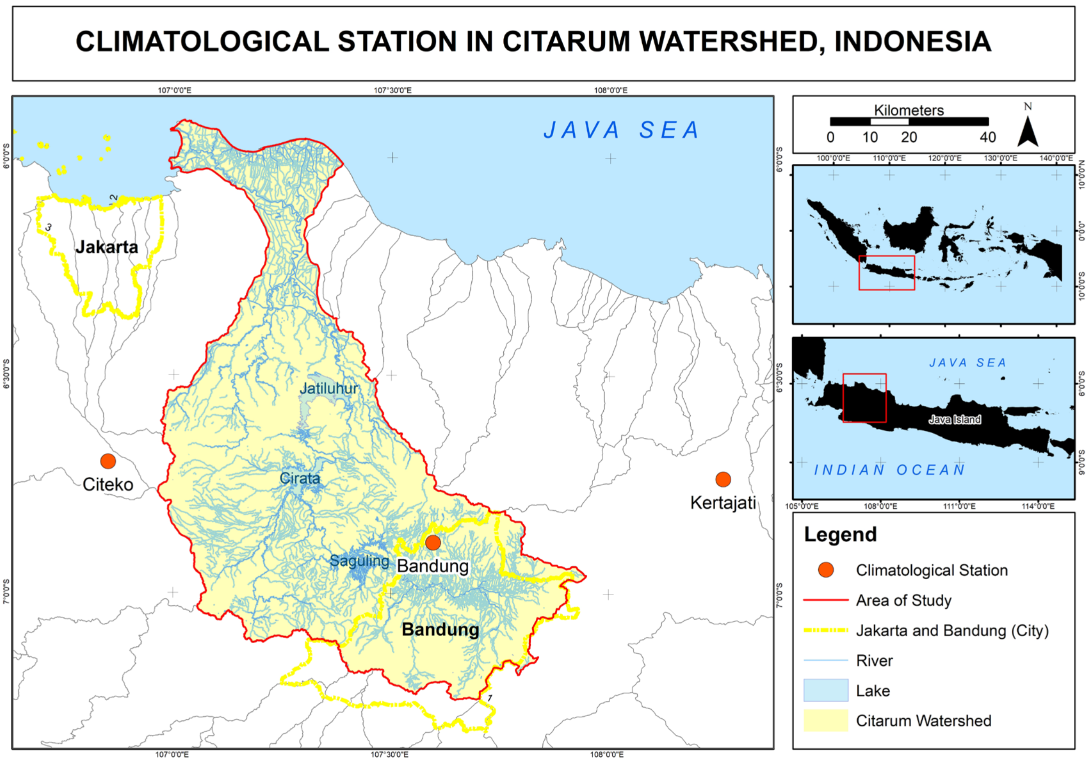

Figure 1. Citarum Watershed location of interest. It is surrounded by Jakarta-the Indonesian capital city and Bandung, the second-largest city in West Java
Analysis of ET using Modified Penman was provided by 3 climatological stations such as Bandung, Citeko, and Kertajati.

2. Methods

MOD16 Satellite-Derived ET Data Processing

The MOD16 data used in this study was obtained from the United States Geological Survey (USGS) and it comprises an 8-day composite dataset with a resolution of 500 meters. Furthermore, its product algorithm is based on Penman-Monteith equation generated from the MODIS data. The MOD16 dataset offers valuable information into the dynamics of vegetation properties, albedo, and land cover (Mu et al., 2013). There are two types of the MOD16 dataset available, namely the 8-day composite and the annual composite of MOD16A2. In this study, the MOD16A2 8-day composite dataset was used. This dataset comprises data points from all 8-day periods in the years 2009, 2010, 2014, and 2015, and was obtained from USGS through their website (https://earthexplorer.usgs.gov/). The MOD16A2 products have a 500 meters spatial resolution pixel size and the obtained data points from satellite that are covered in clouds (noise) are discarded. To compensate for the missing values, interpolation techniques utilizing surrounding values were applied. This is necessary because cloud-covered areas lack valid data, and performing calculations on such areas would yield significantly divergent results.

Modified Penman ET Method

As numerical Model of ET, Modified Penman equation relies on four climatological parameters, sourced from data provided by the Meteorology, Climatology, and Geophysical Agency (BMKG) (dataonline.bmkg.go.id). These parameters include average temperature, average wind speed, sunshine duration, and saturation vapor pressure. Following this, Modified Penman equation is applied using the 8-day composite data, aligning with the periodicity of satellite-based ET measurements. In Indonesia, the utilization of Modified Penman equation follows the recommendation of the FAO, which affirms its effectiveness based on its successful application in Sri Lanka (Batchelor, 1984). However, Nusantara & Nadiar, (2020) mentioned that although Penman Modified equation yields satisfactory evaporation values, it requires extensive and intricate data inputs.

ET is a term that refers to the process of water being released into the atmosphere through the evaporation and transpiration processes (Hamon, 1961; Katul et al., 2012). Accordingly, the calculation of ET value is carried out using modified Penman method, which was recommended by the FAO, utilizing climatic data inputs such as latitude, air temperature, relative air humidity, wind speed, and the duration of solar irradiation. According to (Batchelor, 1984), modified Penman formula is a rearrangement of Penman equation to improve its performance. The enhanced performance has been demonstrated in Sri Lanka (Batchelor, 1984).

It is also important to note that among the preexisting approaches, Modified Penman method requires the most extensive set of parameters. ET formula is expressed as follows (Batchelor, 1984);

$$ET=C[W.Ra+(1-W)f(u)(ea-ed)], \quad (1)$$

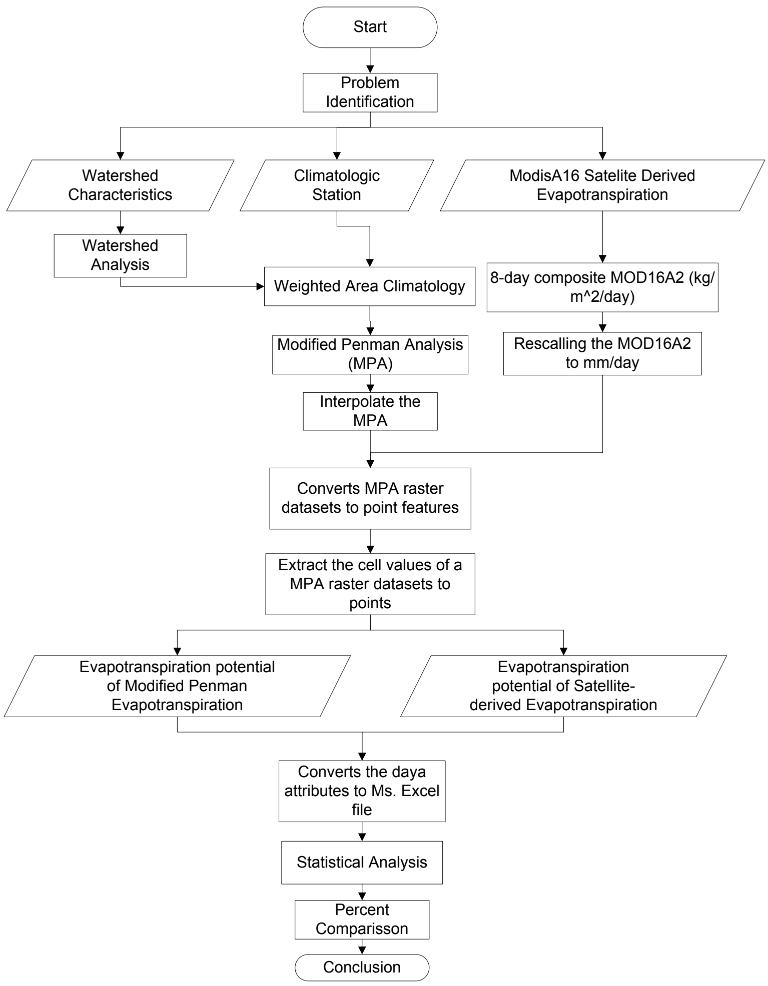

Figure 2. The Study Flowchart

where ET represents ET in mm/day, C is the weighting factor that depends on the air temperature and the altitude, Ra is the extra-terrestrial sun radiation, W represents the temperature-related weighting factor, f(u) is wind speed function, ea and ed are the saturated and actual vapor pressure at the average temperature of the air respectively. While f(u) is defined as;

$$f(u)=0.27(1-U2/100), \qquad (2)$$

where U2 is the wind speed in km/day

Data Selection and Processing

The MOD16A2 products have a 500 m spatial resolution pixel size, which was rescaled from 0.1 kg.m2/8-day to mm/day to represent the real potential average ET value. To achieve this, the MOD16A2 dataset was rescaled for each 8-day period by multiplying all pixels by 0.1 to get the mm/8-day values (Miranda et al., 2017). Subsequently, these values were divided by 8 to obtain the mm/day measurement.

To determine the average value of ET for each 8 days, Modified Penman calculation was performed using data from three meteorological stations namely Kertajati, Citeko, and Bandung Stations, and linear interpolation, specifically the spline method. The oscillation index was used to pick the study cases for this study, and it identified that droughts occurred in the years 2009, 2010, 2014, and 2015. Moreover, these years were selected due to the presence of El Nino events (Glantz & et al., 2020), which indicated greater fluctuations in drought conditions compared to other years (Tait et al.2007). The interpolation process was executed to obtain the estimated ET value at locations surrounding each metrological station. These values were then compared with ET value from the MOD16A2 dataset. The study flowchart illustrating this process is shown in Figure 2.

3. Result and Discussion

Comparison Result

Statistical analysis was conducted to assess the reliability of satellite images obtained using numerical Modified Penman method by comparing them with ET data from the MOD16A2 satellite. The gradient value from the standard deviation and box Whisker Plot indicated the reliability of the two simulations.

Furthermore, the reliability between satellite data and numerical method involved calculating the percentage difference in ET values obtained from the two method for the 8-day averaged period. Figure 3-6 shows the percentage similarity between satellite and numerical method for the selected years. In these figures, the labels I, II, III, and IV represent the four sets of 8-day accumulated data within each month.

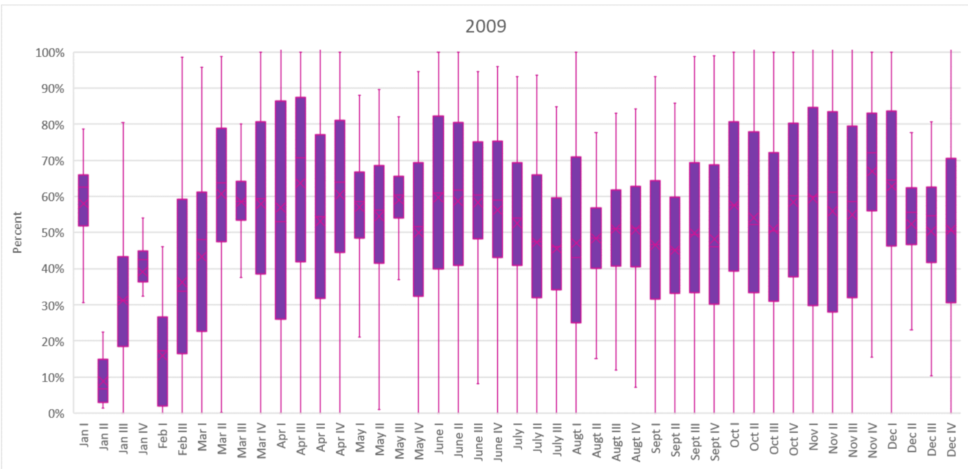

Figure 3. Percentage similarity between satellite and numerical method for the year 2009 at Citarum Watershed

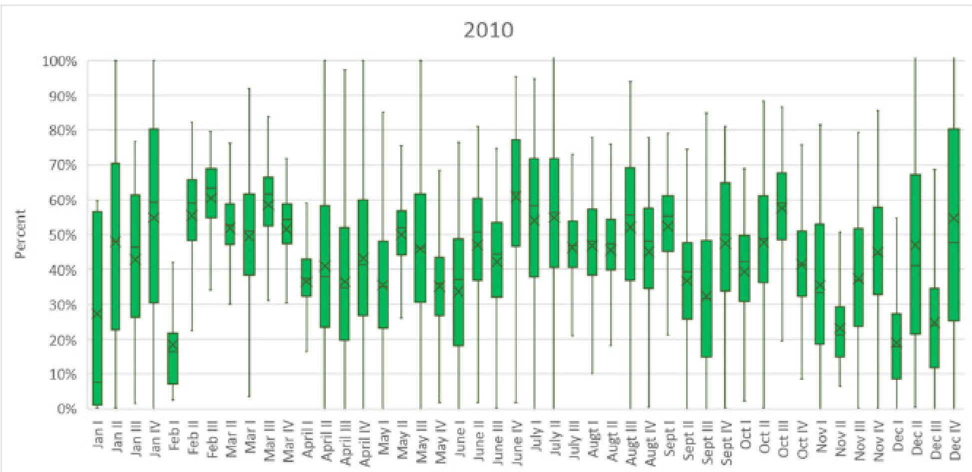

Figure 4. Percentage similarity between satellite and numerical method for the year 2010 at Citarum Watershed

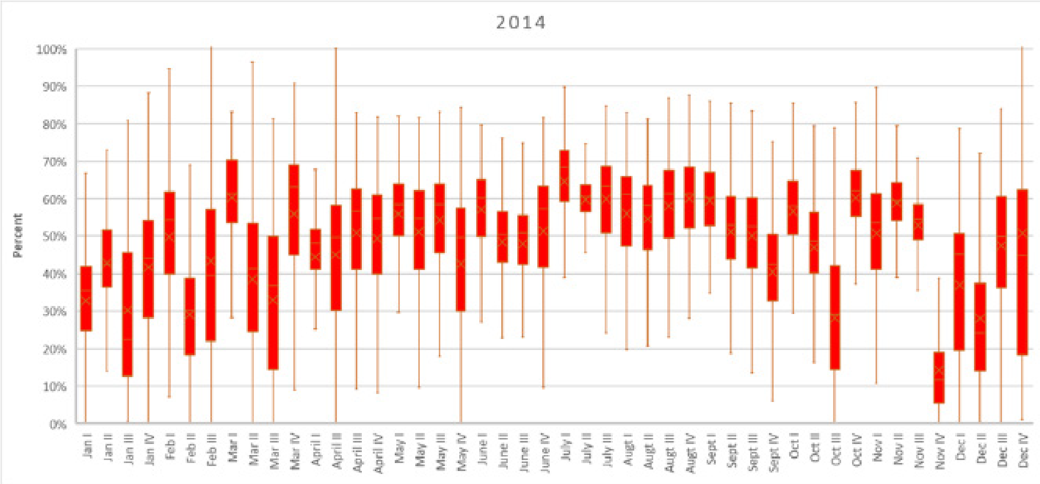

Figure 5. Percentage similarity between satellite and numerical method for the year 2014 at Citarum Watershed

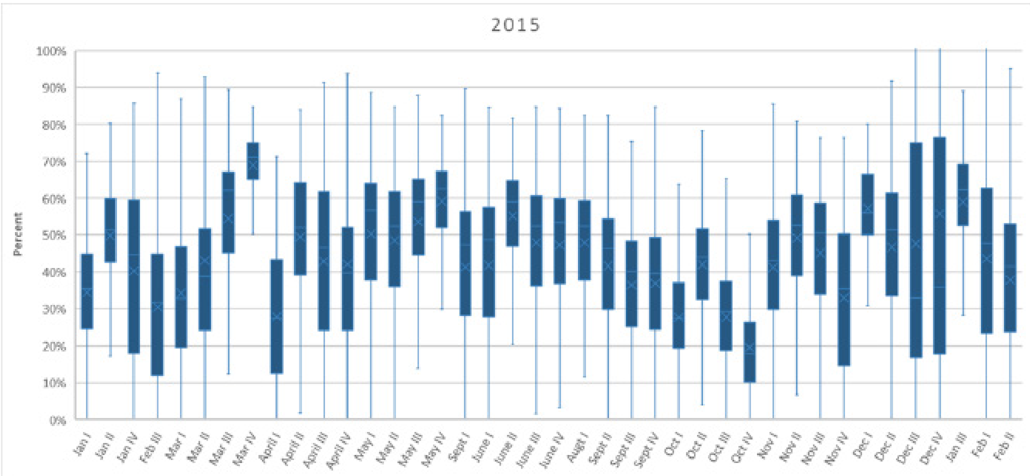

Figure 6. Percentage similarity between satellite and numerical method for the year 2015 at Citarum Watershed

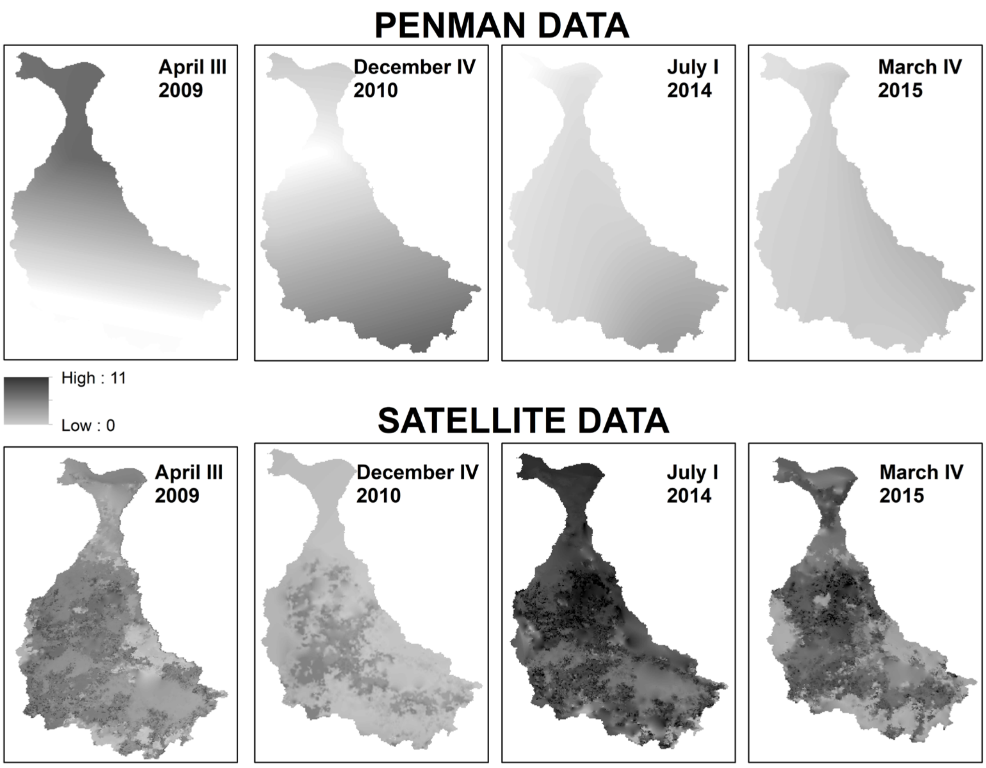

Figure 7. The Best Reliability of Satellite and Modified Penman Results

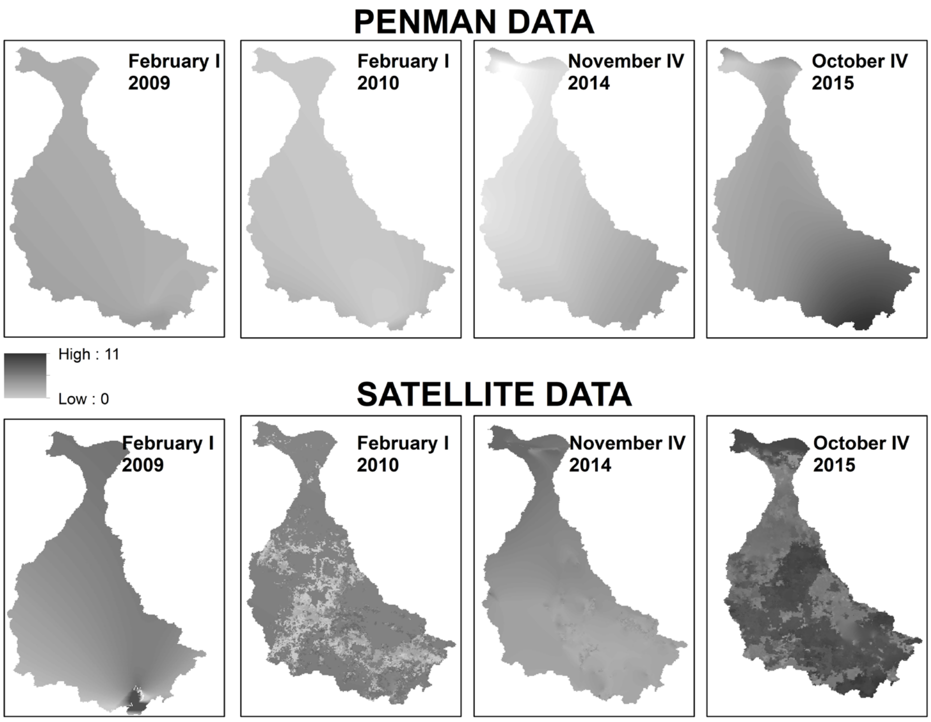

Figure 8. The Worst Reliability of Satellite and Modified Penman Results

From the 4 selected years, it was found that satellite imagery exhibited the best visualization during the dry season. Figures 3 to 6 demonstrate a notably high degree of similarity during the months characterized by dry conditions. The percent similarity during this season reaches up to 80%. This condition occurred because of the minimum atmospheric noise during the dry season, as satellite observations are inevitably affected by cloud cover (Li et al., 2022).

The Reliability of ET Satellite

Based on the results of the percentage similarity between ET satellite and Modified Penman method, specific periods have been identified as the best for satellite visualization using numerical method for each selected year. These periods are as follows, April III, December IV, July I, and March IV. Figures 7 and 8 show the visual representation of ET based on satellite and numerical data.

The average percentage similarity during the most reliable event ranges between 53% and 80%, indicating a strong agreement between satellite-derived ET and numerical results obtained through Modified Penman method. However, during periods of the low reliability, the average percentage difference ranged between 14% and 20%. This variation was influenced by high cloud cover, which tends to occur during the rainy season.

The representation of ET data through imagery is significantly influenced by cloud conditions. It is also important to note that several previous studies conducted in Thailand have confirmed a strong correlation between ET image data obtained from Landsat 8 and numerical models during the dry season in the country (Suwanlertcharoen et al., 2023).

4. Conclusion

In conclusion, the primary objective of this study was to analyze the reliability of MOD16A2 satellite-derived ET data using numerical Modified Penman method across Citarum Watershed. To achieve this, two distinct sources of ET input data were considered, which are satellite and three climatological stations. The obtained results revealed a high degree of similarity between the two method, indicating their reliability, with an average value of 80% for the selected events. However, lower similarity percentages were observed when cloud cover affected ET values, especially during the rainy season.

Table 1. Statistical Analysis of Satellite Reliability

Year	*Month*	*Modus*	*Average*	*Median*	*Information*
2009	April III	61%	53%	54%	Best
	February I	27%	16%	17%	Worst
2010	December IV	9%	55%	48%	Best
	February I	22%	18%	16%	Worst
2014	July I	76%	65%	68%	Best
	November IV	9%	14%	12%	Worst
2015	March IV	72%	80%	71%	Best
	October IV	12%	20%	18%	Worst

Source: secondary data processing

Based on these findings, it was concluded that modified Penman method using MOD16A2 satellite data is deemed acceptable for further study purposes. However, it is important to conduct further studies in other watershed to establish a correlation equation that can accurately represent the relationship between satellite-derived ET and Modified Penman Method under similar hydrological conditions around the world. This will enhance the applicability of method beyond the confines of the current study area.

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