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RESEARCH ARTICLE

A Preliminary Assessment of the Reliability of a Personal Weather Station for Urban Flood Monitoring in a Tropical Coastal Urban Area: A Case Study from Kendari, Indonesia

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Abstract

This study conducted a preliminary assessment of the PWS reliability compared to the official BMKG reference station in a tropial coastal urban area of Kendari, Indonesia, particularly for urban flood monitoring. Daily rainfall obtained from the PWS and the BMKG station were compared over February to December 2024, using rainy days where both stations recorded rainfall exceeding 10 mm on the same day. For statistical tests, there were statistical metrics implemented in this study including Pearson correlation (r), coefficient of determination (R^2), mean bias error (MBE), percent bias (PBIAS), mean absolute error (MAE), and root mean square error (RMSE). The rainfall data was also compared to flood-confirmed dates. The rainfall data analysis showed that there was moderate agreement between the PWS and the BMKG ($r = 0.66$, $R^2 = 0.40$, MBE = 1.83 mm/day, PBIAS = 4.91%, MAE = 17.12 mm/day, RMSE = 23.87 mm/day). Moreover, the PWS recorded the same rainfall category as BMKG on three flood events, particularly for heavy and very heavy rainfall category. However, the PWS showed moderate rainfall category for two flood events when the BMKG recorded heavy rainfall category. This difference could be attributed to climate backgorund of Kendari and the device environment settings. Moreover, it is suggested that the PWS can be a useful tool for urban flood monitoring, especially during large and spatially widespread rainfall events.

Keywords: urban flooding, rainfall, personal weather station, Kendari, Indonesia

1. Introduction

Urban flooding is one of increased natural hazards that many cities have been experiencing over the last decades, and the impacts will be exarcebated due to ongoing climate change and urbanization (Hirabayashi et al., 2013; Winsemius et al., 2016). Indonesia has more than 60% of its population resides in coastal urban centres that are vulnerable to flood-related disasters (Budiyono et al., 2015; Marfai and King, 2008). Kendari is the capital of Southeast Sulawesi Province of Indonesia that has been experiencing urban flooding in recent years due to several factors that include inappropriate urban drainage system, increased surface runoff volume, and extreme rainfall events, causing property and infrastucture damages, as well as several problems on public health. Therefore, it is important to provide urban flood mitigation and adaptation strategies that require high-resolution precipitation monitoring systems that are able to capture the spatial and temporal rainfall variability, as well as to support urban flood monitoring (Borga et al., 2007; Zanchetta and Coulibaly, 2020). However, most rainfall monitoring systems in Indonesia are maintained by Indonesia's Agency for Meteorology, Climatology, and Geophysics (BMKG), which its coverage is spatially sparsed in some places. This condition is insufficient for appropriate urban flood management requiring the fine-scale precipitation data (Berne et al., 2004; Villarini et al., 2008).

Recent technological developments have quite improved the capacity of rainfall monitoring systems. Among these developments, satellite-derived precipitation products provide broad spatial coverage that are providing valuable information for regions where ground-based measurements are scarce or in ungauged basins or watershed (Almeida et al., 2025; En-nagre et al., 2025). Moreover, the integration of several meteorological data sources into climate reanalysis dataset have supported comprehensive assement of rainfall patterns over time and space (Li et al., 2023; Pelosi, 2023; Ratri et al., 2023). Recently, crowdsourced rainfall observations, such as rainfall data obtained from personal weather stations, have enhanced existing traditional monitoring networks by increasing the density and resolution of available data, for instance providing sub-daily and hourly rainfall data (Chen et al., 2022; Gharesifard and Wehn, 2016; Khaing Kyaw et al., 2024). Collectively, those technology innovations can play an important role in supporting flood monitoring, adaptation and disaster mitigation efforts within vulnerable urban environments (Tedla et al., 2024). The utilization of crowdsourced rainfall and personal weather stations

(PWS) have attracted great interests over the last decade, particularly in the context of flood monitoring and flood-related disaster management. The citizen-operated stations that have high density and spatial resolution of rainfall observations can be a supplement for traditional meteorological networks (de Vos et al., 2019). The utilization and the integration of crowdsouced rainfall measurements and PWS have been recognized as an important aspect, particularly in urban centers facing increasing vulnerability and flood risks due to urbanization and climate change (Bárdossy et al., 2021).

The PWS' mechanism is governed by a three-step procedure involving mechanical acquisition, digital signal processing, and cloud-based data integration. In the first step, rainfall is captured by an unheated plastic tipping-bucket assembly and channeled into a calibrated funnel, where each discrete volume of water tips the bucket and generates an electrical pulse (de Vos et al., 2019). Each tip generates an electrical pulse at the station's logic board, which converts the pulse into a discrete cumulative rainfall value (Bárdossy et al., 2021; de Vos et al., 2019). Finally, the processed data are transmitted wirelessly to an indoor base module, which uploads the observations at setup intervals to cloud-based platforms such as the Weather Underground or the Netatmo Weathermap (de Vos et al., 2019).

Furthermore, crowdsourced rainfall measurements from PWS networks have facilitated more detailed and accurate urban flood prediction and analysis. In Oslo, Norway, private weather stations demonstrated an indispensable role in urban flood modeling as it was able to accurately detect rainfall events resulting in more accurate inundation maps (Khaing Kyaw et al., 2024). In Valencia, Spain, a study based on approximately 225 PWS having the network density higher than that of the official network showed a more detailed analysis of spatial and temporal rainfall dynamics of catastrophic floods on October 29, 2024 (Rombeek et al., 2025b). In Sweden, PWS was able to detect and to identify the spatial distribution of a highly localized convective rainfall event (Petersson Wårdh et al., 2026). Furthermore, a study conducted in the Netherlands by Rombeek et al. (2025a) revealed that PWS clusters had good agreement against automatic weather stations, particulary during moderate rainfall events, but it had significantly underestimated high-intensity rainfall events, particularly for accumulation period of one hour.

However, recent research have revealed that rainfall measurements from PWS were subject to data biases that can affect the effectiveness of flood-related disaster mitigation and adaptation initiatives (de Vos et al., 2019; Overeem et al., 2024). A study conducted in Houston, Texas, demonstrated that PWS could provide unreliable data influencing the accuracy of monitored rainfall data (Chen et al., 2021). Additionally, an analysis of PWS adoption across twelve major metropolitan areas in the United States found that increasing number of the PWS networks had strong potential to fill the gap from official local observation, though adoption patterns had spatially biased data (Chen et al., 2022). These biases could be associated with several factors, including the installation environment, the geographical and topographical characteristics of the PWS location, and the local climate background. For instance, nearby buildings, structures, or vegetation might intercept rainfall, leading to an underestimation of recorded rainfall amounts (Bárdossy et al., 2021). Furthermore, measurement bias can also be caused by the geographical and topographical positioning of a PWS. A station located in varied terrain — such as coastal or inland areas — may record different rainfall patterns due to locally specific features including elevation and water body proximity (Pontoppidan et al., 2025). Furthermore, the local climate background of a PWS location can influence the accuracy of rainfall measurements. For instance, dynamics in prevailing weather systems, such as convective storms or monsoonal rainfall, may generate spatial and temporal differences in precipitation that are captured across all stations (Overeem et al., 2024; Pontoppidan et al., 2025). Hence, it is recommended to understand local climate background and influences on PWS data interpretation, especially in the flood-related disaster management context.

To our knowledge, no previous study has carefully evaluated the reliability of the PWS rainfall measurements compared to that of the official observation, particularly in an Indonesia tropical urban area. This study aims to assess the reliability of the PWS compared with the BMKG as a preliminary step to understanding its potential for urban flood monitoring. The objectives of this study are as follows: (1) to evalute the agreement between PWS and BMKG rainfall measurements; and (2) to characterize the spatial and temporal patterns of measurement discrepancies, with particular attention to extreme precipitation episodes associated with urban flooding. It is expected that the result of this study can provide a preliminary information on the applicabilty of PWS rainfall measurements as a supporting and an alternative tool for flood-related disaster mitigation and adaptation initatives.

2. Methodology

2.1 Study Area

Kendari is the capital of Southeast Sulawesi Province in Indonesia, located on the southeastern peninsula of Sulawesi Island. As shown in Fig 1, the city is remarked by its complex topography, comprising coastal lowlands next to elevated hillslopes inland in Northern part of the city, and flat urbanized areas in Southern part of the city. The local climate in Kendari is categorized into a tropical rainforest climate based on the Köppen classification (Af) (Köppen Climate Explorer, n.d.). The city experiences the rainy season from November through March and the dry season from May to September, although considerable rainfall is recorded throughout the year. In recent decades, the urban area has undergone rapid population growth mainly from inland immigration from surrounding areas, and notable spatial expansion in the Western and the Southern part of the city, increasing susceptibility to flood hazards due to land use and land cover changes and modifications.

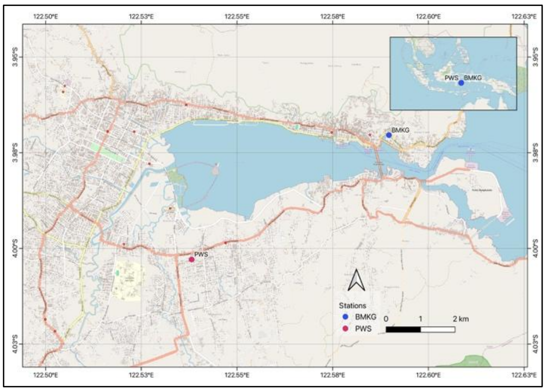

Fig. 1. Map of Kendari and the BMKG stations.

2.2 Data Collection

This study used two different datasets, Personal Weather Station (PWS) and BMKG station, collected and processed in four phases. The rainfall data was systematically collected in four distinct phases to ensure both the accuracy and comparability of meteorological datasets sourced from the two monitoring stations. In the first phase, rainfall data was obtained from the BMKG station as well as from the PWS situated in Kendari. The BMKG rainfall data was obtained directly from its official online database (BMKG, 2025). The BMKG station was situated in a coastal-orographic location at approximately 4.0°S, 122.6°E, near to Kendari Bay and elevated hillslope terrain. Moreover, PWS data was obtained from the Weather Underground platform (Weather Underground, 2025), particularly for the PWS with ID IKENDA8. The specific PWS used in this study was situated within an inland urban area on relatively level terrain at approximately 4.0°S, 122.5°E, separated 5–6 km from the BMKG station. The PWS data collected for this study involved the total daily rainfall for the study period spanning from February to December 2024. The period selection was based on the data availability from the PWS.

The second phase involved a strict data cleaning procedure to ensure that the rainfall data measurements from the two stations were comparable. Data processing was organized by assuming that there was distributed rainfall in the city recorded in both stations. Hence, daily rainfall data was included in the analysis exclusively when both stations reported daily rainfall intensities exceeding 10 mm/day on the same day. The selection of rainfall threshold of 10 mm/day was based on the BMKG rainfall classification: light rain (5-20 mm/day), moderate (20-50 mm/day), heavy rain (50-100 mm/day) and very heavy rain (>100 mm/day) (Limahelu et al., 2020). Having the daily rainfall threshold was important to minimize trace precipitation events due to high measurement uncertainties of both stations, to focus on daily rainfall having relevance for urban flooding, and to minimize the potential of localized rainfall events at one station.

The third phase focused on the evaluation of the statistical reliability and agreement of rainfall measurements between both stations. Some statistical tests were conducted for the evaluation to ensure that the analysis had a strong comparison procedure. Six statistical metrics were used in this study including Pearson coorelation coefficient, the coefficient of determination (R^2), percent bias (PBIAS), mean bias error (MBE), root mean square rrror (RMSE) and mean absolute rrror (MAE). The Pearson correlation was calculated as:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{1}$$

where xi and yi were the ith values of the PWS and the BMKG respectively, x and y are the means, and n was the number of observation data. R^2 was derived from linear regression analysis between PWS and BMKG measurements:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(PWS_i - \widehat{PWS}_i)^2}{\sum_{i=1}^{n}(PWS_i - \overline{PWS})^2} \tag{2}$$

Moreover, the bias analysis was conducted to quantify the relative deviation of rainfall data of the PWS from rainfall data of the BMKG. The Percent Bias (PBIAS) was calculated as:

$$PBIAS = \frac{\sum_{i=1}^{n}(PWS_i - BMKG_i)}{\sum_{i=1}^{n} BMKG_i} \times 100\% \tag{3}$$

where PWSi was rainfall data of the PWS, and BMKGi was rainfall data recorded at the BMKG. PBIAS indicated overall model tendency where values were expected to close to zero. Moreover, mean bias error (MBE) was calculated as:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(PWS_i - BMKG_i) \tag{4}$$

and the RMSE was calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(PWS_i - BMKG_i)^2} \tag{5}$$

Where PWS_i indicated the rainfall measurement recorded by the PWS for the ith observation, and $BMKG_i$ denoted the corresponding rainfall measurement from the BMKG station for the same observation. The mean absolute error (MAE) was calculated as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|PWS_i - BMKG_i| \tag{6}$$

The fourth and final phase of the methodology aimed to synchronize daily rainfall records from both stations with documented flood events occurred during 2024 in Kendari. Data regarding flood evets were carefully compiled from a range of sources such as online news media and disaster management agency (BPBD) records. This synchronization allowed a direct comparison between rainfall patterns and flood event times, thereby enabling a more rigorous examination of the correlation between precipitation intensity and flood onset in Kendari's urban area.

3. Results

3.1 Statistical Analysis

The statistical test to assess the correlation of rainfall data between the PWS and BMKG showed a Pearson correlation coefficient of r = 0.66 (R^2 = 0.40). Moreover, the errorr metrics of rainfall data of the PWS and the BMKG was 17.12 mm/day and 23.87 mm/day for MAE and RMSE, respectively. Another statistical test conducted was PBIAS showing that rainfall data of the PWS had an average tendency of 4.91%, while the MBE was about 1.83 mm/day. Fig. 2 shows the linear regression and the scatter plot from both rainfall data of the PWS and the BMKG.

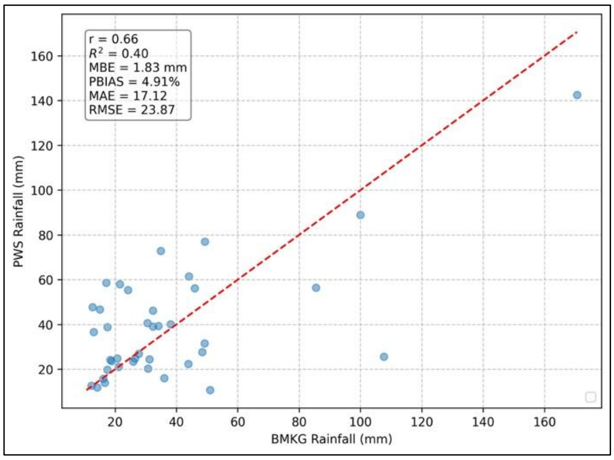

Fig. 2. Statistical correlation between PWS and BMKG.

Furthermore, the descriptive statistics of rainfall data from the PWS and the BMKG are given Fig. 3. Based on the statistic test results, it was found that the PWS had a mean daily rainfall of 39.08 mm/day and a median value of 31.50 mm/day, whereas the rainfall data of BMKG has a mean value of 37.25 mm/day and a median of 30.50 mm/day. Moreover, the interquartile range (IQR) between the PWS and the BMKG had great discrepancies. For instance, the IQR of the PWS ranged approximately from 23 to 52 mm/day lower than the IQR of the BMKG approximately from 18 to 44 mm/day.

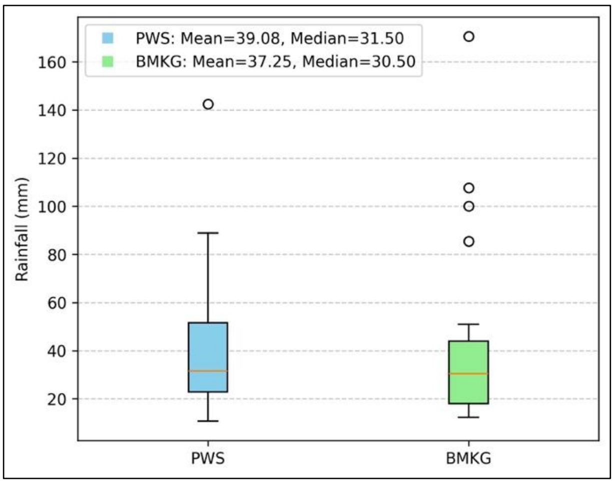

Fig. 3. Rainfall distribution of the PWS dan the BMKG.

3.2. Flood Events and Daily Rainfall

Daily rainfall (>10 mm) from both stations along with flood events are shown in Fig. 4. It was found that rainfall events higher than 10 mm were mainly observed between January and June, and between November and December, while rainfall events less than 10 mm/day or no rainfall events were mainly observed between July and October at both the PWS and the BMKG.

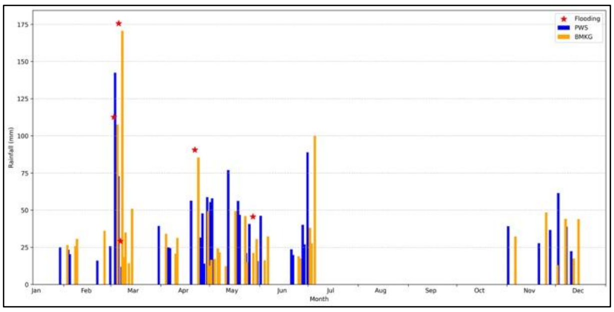

Fig. 4. Temporal distribution of daily rainfall at the PWS and the BMKG along with indicated flood events.

Furthermore, there were 5 flood events observed during the study period, particularly between March and May 2024, as given in Table 1.

Table 1. Daily rainfall intensity and flood events.

Flood event	Daily Rainfall Intensity (mm/day)		Source
	PWS	BMKG	
03-03-2024	25.65	107.6	(Tempo, 2024)
06-03-2024	142.50	170.60	(Suara Sulsel, 2024)
07-03-2024	24.13	18.40	(BNPB, 2024; Tempo, 2024)
22-04-2024	56.39	85.50	(Radar Kendari, 2024)
28-05-2024	40.64	30.50	(Kompas, 2024)

On the first flood event of March 3, 2024, the PWS recorded daily rainfall intensity of 25.65 mm/day, while the daily rainfall at the BMKG was 107.66 mm/day. During the second flood event on March 6, 2024, the daily rainfall intensity at the PWS was 142.50 mm/day, whereas the BMKG recorded daily rainfall intensity of 170.60 mm/day. Those recorded daily rainfall were the highest daily rainfall in the study period. The third flood event was on March 7, 2024, when the PWS recorded daily rainfall of 24.13 mm/day, while the BMKG recorded 18.4 mm. The fourth flood event was observed on April 22, 2024, when daily rainfall intensity was 56.39 mm at the PWS and 58.5 mm/day at the BMKG. The fifth flood event was on May 28, 2024, when the PWS recorded daily rainfall intensity of 40.64 mm/day and the BMKG recorded daily rainfall of 30.5 mm/day.

Furthermore, daily rainfall of flood events was categorized following the rainfall category of BMKG as given in Table 2.

Table 2. Rainfall intensity categories (L=Light, M=Moderater, H=Heavy, VH=Very Heavy.

Date	PWS (mm/day)	PWS Category	BMKG (mm/day)	BMKG Category	Category Match
03-03-2024	25.65	M	107.6	VH	No
06-03-2024	142.50	VH	170.6	VH	Yes
07-03-2024	24.13	M	18.4	L	No
22-04-2024	56.39	H	85.5	H	Yes
28-05-2024	40.64	M	30.5	M	Yes

6. Discussion

As a preliminary study, this study provided an early information of the reliability of the PWS for urban flood monitoring. The Pearson correlation value of 0.66 and R^2 value of 0.40 indicated a moderate correlation between the PWS and the BMKG. Moreover, the bias analysis showed a small number and percentage of 1.83 mm/day and 4.91% for MBE and PBIAS, respectively. Those values indicated that the PWS had possibilty to have the same rainfall pattern as the official measurement of the BMKG. However, the result of RMSE (23.87 mm/day) and MAE (17.12 mm/day) indicated big differences between both stations, which could be associated with a few extreme events. The extreme event is important to be considered for urban flood monitoring because it can cause urban flooding along with another factor such as inapprorpriate urban drainage conditions. Hence, a station that cannot well-performed during the extreme event would be less useful for urban flood monitoring.

The differences in rainfall measurement of the PWS and the BMKG could be influenced by several factors, including the local climate background and the environment setting of both stations. Located in the tropics, Kendari is mostly affected by the local climate backgorund characteristics of the tropics in which rainfall development is mainly driven by the convection. Convection is a process in which strong surface heating causes warm, moist air to rise, cool and condense, generating small, short-duration rain cells (Wallace and

Hobbs, 2006). In the tropics, the rain cells are normally formed in a few kilometres wide and exist for about one or two hours (Mandapaka and Qin, 2013; Wallace and Hobbs, 2006). In this study, both stations were set apart of about 5 to 6 kilometres where the PWS might be under the rain cell while the BMKG might be outside the rain cell. The relative station location to the rain cell made the PWS and the BMKG could have different rainfall measurement that was indicated by the results of statistical metrics. Furthermore, the PWS and the BMKG were situated in two different environments. The PWS was in on flat urban development areas where rainfall development could be dominated by convective process from land. On the other hand, rainfall intensity in the BMKG could be infuenced by land-sea breeze circulation that affected rainfall patterns through a complex mechanism of updraft dynamics and atmospheric processes within urban boundary layer (Handayani et al., 2023; Wallace and Hobbs, 2006). As a result, the BMKG might record more rainfall compared to the PWS. This condition is shown in the boxplot analysis in which the BMKG recorded more extreme events compared to the PWS during the study period.

The assessment of reliability of the PWS for urban flood monitoring was also conducted against five recorded flood events in Kendari during the study period. On three flood events, it was found that rainfall data from both stations was in the same rainfall categories: moderate, heavy, and very heavy. These findings revealed that the PWS could provide a reasonable indication for urban flood monitoring. However, there were two flood events on which rainfall data from the PWS and the BMKG were not in the same rainfall categories. For instance, on the recorded flooding event of March 3, 2024, the PWS recorded moderate rainfall whereas the BMKG recorded very heavy rainfall. Almost similar condition was observed on flooding event of March 7, 2024, when the PWS recorded moderate rainfall, while the BMKG recorded heavy rainfall. These differences indicated that the PWS tended to have a measurement bias for moderate rainfall. The differences was relevant to local climate background of Kendari and the different environment settings of both stations where the BMKG probably would like to have more rainfall caused by land-sea breeze circulation as discussed above. Moreover, it was indicated that the PWS could be an alternative for urban flood monitoring particularly during large and spatially extensive extremen events, but it would be less useful during localized extreme rainfall events.

6.1 Limitations of This Study and Future Perspectives

This study was an exploratory step that is important to understand the reliability of the PWS for urban flood monitoring. Hence, the findings from this study should be seen as a preliminary information for further research, since there were some limitations observed in this study.

The first limitation observed in this study was the small number of data station. This study used only one personal weather station (PWS) to be compared with the calibrated official station of the BMKG. Having only two stations, it was hard to precisely define the main cause of the differences in rainfall data measurement at both stations, since rainfall data measurement could be influenced by various factors including the instrument quality of the PWS, the distance between both stations, the geographical and topographical settings, or combination of all factors. Hence, denser rainfall measurement networks are suggested for further research that can separate those effects and later providing a clear insight of rainfall development and mechanism across the study area.

Furthermore, the second limitatios observed in this study was the limited number of flood events during the study period as well as the limited rainy days since the study used only the data when both stations recorded daily rainfall more than 10 mm/day. Consequently, the study could not capture all rainfall pattern dynamics in the study area where flooding event was observed but daily rainfall was not recorded at all stations. Therefore, a longer study period of more than 1 year is suggested for further research so it will allow more detailed analysis to understand the reliability of the PWS in measuring rainfall intensity that can be associated with urban flooding.

7. Conclusion

This study was conducted as a preliminary assessment of the PWS reliability compared to the BMKG as the official reference station in Kendari, particularly focusing on urban flood monitoring. It was found that the PWS showed moderate agreement with the BMKG ($r = 0.66$, $R^2 = 0.40$, MBE = 1.83 mm/day, PBIAS = 4.91%) during the study period. However, there were high differencies found on a small number of extreme rainfall events that were related to flood events. The PWS performance for urban flood monitoring was not consistent since there were two of five flood events in which the rainfall category between the PWS and the BMKG was different. It was observed especially when the PWS recorded moderate rainfall intensity. Moreover, the PWS recorded the same rainfall category with the BMKG, particularly for the heavy and very heavy rainfall category. These differencies could be associated with various factors including the local climate background of Kendari, and the device environment settings of the PWS and the BMKG. Findings from this study suggest that the PWS can be a useful tool for urban flood monitoring, especially during large and spatially widespread rainfall events. For further research, it is recommended to expand the PWS network across the city, to use a longer study period, and to compare the rainfall data with more flooding events reports.

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