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RESEARCH ARTICLE Open Access

Flood inundation simulations based on GSMaP satellite rainfall data in Jakarta, Indonesia

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Abstract

Jakarta is the capital of Indonesia and is considered one of the most vulnerable cities to climate-related disasters, including flooding, sea-level rise, and storm surges. Therefore, the development of a flood-forecasting system for Jakarta is crucial. However, the accurate prediction of flooding in Jakarta is challenging because of the short flood concentration time in highly urbanized basins and the shortage of rainfall data in poorly gauged areas. The aim of this study is to simulate recent flood inundation using global satellite mapping of precipitation (GSMaP) products. The GSMaP products (NRT and Gauge V7) were evaluated and compared with hourly observation data from five ground stations in the Ciliwung River Basin. In addition, a rainfall-runoff and flood inundation model was applied to the target basin. The results of the analysis showed that the GSMaP Gauge data were more accurate than the GSMaP NRT data. However, the GSMaP Gauge cannot be used to provide real-time rainfall data and is, therefore, inadequate for real-time flood forecasting. We conclude that the GSMaP Gauge is suitable for replicating past flood events, but it is challenging to use the GSMaP NRT for real-time flood forecasting in Jakarta.

Keywords: GSMaP, Flood inundation simulation, Rainfall-runoff simulation, Jakarta, Indonesia, Chiliwung River

1 Introduction

Jakarta is considered to be one of the most vulnerable cities in the world to climate-related disasters, such as flooding, sea-level rise, and storm surges (Firman et al. 2011). Jakarta has experienced several flood disasters in the past, including in 1996, 2002, 2007, 2013, and 2020. These floods not only led to severe economic damage but also human casualties (Kure et al. 2014).

Several studies related to flood problems in Jakarta have been conducted. Moe et al. (2016) applied a rainfall-runoff and flood inundation model to the 2013 flood event and concluded that a shortage of capacity in the lower Ciliwung and other rivers accounted for 79.6% of the total flood inundation volume in Jakarta, with urbanization and land subsidence accounting for the remaining 20.4%. According to Bricker et al. (2014), the reduced capacity of the drainage system generated by trash-clogging flood gates is a factor that causes flooding. Budiyono et al. (2016) and Januriyadi et al. (2018) reported that climate change in the future would increase flood risk in Jakarta.

In these flood-prone situations, several countermeasures have been implemented in Jakarta to mitigate flood damages, such as dredging and diversion tunnels. However, flood risk in Jakarta is still high, and more than 60 people were killed in Jakarta during the most recent flood event that occurred in January 2020 (Berlinger and Yee 2020). Thus, a flood-forecasting system is required in Jakarta to ensure early evacuation and prevent traffic jams during flood disasters. Nevertheless, the development of a flood-forecasting system in Jakarta is a challenging task because the rapid flooding of rivers and canals will not provide sufficient lead time for a prediction based on the water levels in the upstream regions

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(Miyamoto et al. 2012). In addition, the shortage of rainfall data, such as radar rainfall and ground gauge data, results in uncertainty and low accuracy in predicting flood hydrographs and inundations based on hydrologic models owing to insufficient rainfall input accuracy, model calibrations, and data assimilation opportunities (Kure et al. 2013).

In this study, we analyzed whether satellite rainfall data can be used as an input for real-time flood forecasting in Jakarta because of the discontinuation of rainfall radars in 2013 owing to high maintenance costs. Various satellite rainfall products can be accessed and downloaded freely, and the data are provided in near real-time worldwide. We used global satellite mapping of precipitation (GSMaP) products as the satellite rainfall data in this study because of their high spatial and temporal resolutions suitable for flood simulations in highly urbanized areas. GSMaP products have been evaluated and verified through comparison with observational data from several previous studies.

Based on a verification study of hourly GSMaP rainfall conducted by Setiawati and Miura (2016), GSMaP-MVK data can potentially be used to replace rain gauge data, particularly for lowland areas in the Kyusyu region, Japan, if inconsistencies and errors are resolved. However, without bias correction, significant underestimation or overestimation of heavy rainfall events will be observed. Moreover, the former algorithm of the GSMaP microwave radiometer does not consider topographical effects (Setiawati and Miura 2016). Other researchers have also reported an underestimation via the GSMaP (Fu et al. 2011; Admojo et al. 2018; Pakoksung and Takagi 2016). Fu et al. (2011) evaluated the accuracy of the GSMaP using a gauge station in a basin in China and found that GSMaP products generally underestimated the precipitation amount. Additionally, GSMaP rainfall data are less accurate when used for mountainous regions than flat areas owing to the occurrence of topographical rainfall (Fu et al. 2011). Conversely, Tian et al. (2010) reported that satellite products (e.g., GSMaP) overestimate rainfall in the summer based on the estimations over the contiguous United States.

Hence, GSMaP rainfall products provide less accurate results compared with gauge-based rainfall networks or radar rainfall information systems. Nevertheless, GSMaP rainfall products are often used as inputs for hydrological models in simulating flood events. Admojo et al. (2018) and Pakoksung and Takagi (2016) statistically evaluated satellite rainfall products, including the GSMaP, and applied hydrological simulations to a large river basin in Thailand using satellite data. They showed acceptable model results (high correlation coefficient: 0.85) to simulate the observed discharge in a river basin, but underestimations (NSE = 0.37) of simulated runoff were reported in a previous study (Admojo et al. 2018). To improve the flood simulation results based on satellite data, bias correction (Sayama et al. 2012) of satellite rainfall products, and ensemble flood simulation methods (Jiang et al. 2014) have been successfully used for flood simulations in large-scale basins. Sayama et al. (2012) applied a hydrological model with a bias-corrected GSMaP for flood inundation simulation in Pakistan to provide additional information for flood relief operations. The simulated flood inundation area reasonably matched well (the fit index: 0.61, peak discharge ratio: 1.0, and inundated area ratio: 1.0) with the actual area, even though the satellite rainfall products were used as the input for the simulation.

These literature reviews indicate that the accuracy of GSMaP data should be verified for several cities and regions before being used in practice. In several studies, hydrological models were applied with satellite rainfall data to large basins, where the flood travel time is relatively slow (Sayama et al. 2012). However, GSMaP evaluation investigations of highly urbanized cities prone to rapid flooding in rivers and subjected to local convective rainfall owing to urban heat environments or humid tropical climates have not been conducted in detail.

The main objective of this study is to investigate a satellite-based rainfall product for flood inundation modeling of a flood event in Jakarta, a mega Asian city located in a humid tropical region. Satellite-based rainfall can be used to reconstruct historical flood events. A problem faced by developing countries is the evaluation of historical flood events with insufficient survey and hydrological observation data. Thus, GSMaP data were also evaluated in this study as input rainfall data to simulate the historical flood events in Jakarta, including the most recent large-flood event that occurred in January 2020.

2 Study area

Jakarta is the capital of Indonesia and is located on the northwest coast of Java island. Jakarta is the largest metropolitan city in Indonesia, and its development is progressing rapidly.

The rainy season in Jakarta begins in November and ends in March, and peak rainfall intensity often occurs in January and February. Thirteen main rivers flow through the region, with the Ciliwung River being the longest. The area selected for this study included Jakarta and the surrounding river basins, which cover a total of 1346.6 km^2 (Fig. 1). It should be emphasized that Jakarta is a highly urbanized area with complex urban systems of river channels and canals, buildings, and roads. Thus, the flood concentration time is relatively short (approximately 12–16 h), which creates problems regarding the use of warning systems, evacuation, and the prevention of traffic congestion.

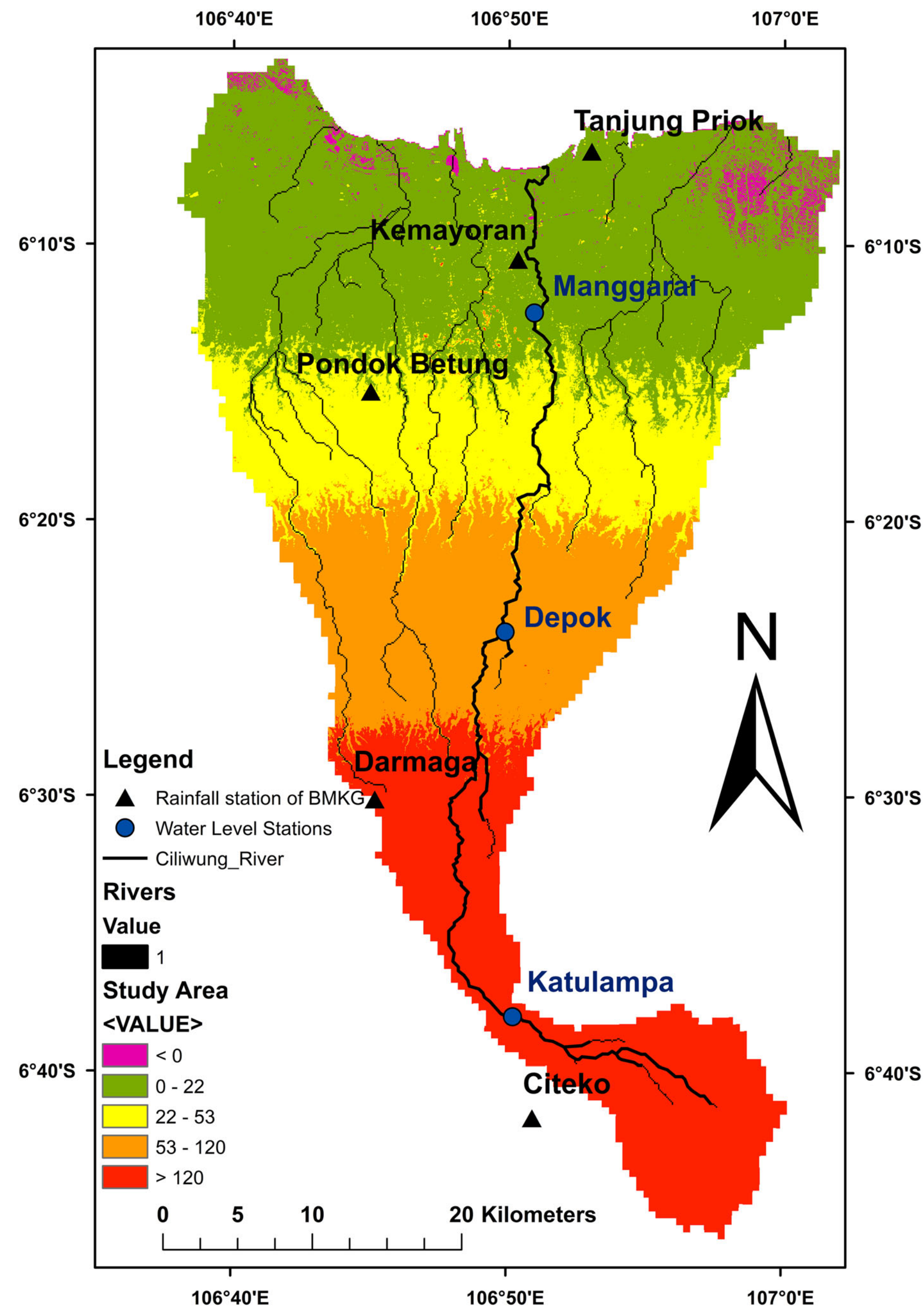

Fig. 1 Study area

Almost every year, Jakarta experiences flooding in January, February, or both, owing to high rainfall with insufficient capacity flows in the drainage system. The details of the floods and damage are listed in Table 1. In Table 1, the damage cost and main damages were obtained from several sources, such as web online news and several reports, and the values of the rainfall, water level, and flooded area were obtained from the observed data. In the 2013 flood event, the failure of an embankment on the west drainage canal at Laturharhari occurred, and the city's financial core, including the president's palace, was inundated, which led to the death of 41 people. In 2020, at least 67 people were killed, and 60,000 were displaced in the worst flooding that has occurred in the area since 2007.

3 Methods

3.1 Dataset

For the rainfall-runoff and flood inundation simulation, the following data were used. A digital elevation model

Table 1 Summary of historical flood events

Year	Averaged rainfall (mm)	Maximum water level (cm) at Manggarai	Flood area (km^2)	Death person	Main damage	Damage Cost (IDR)
1996	421	970	-	10	529 houses were highly damaged	6.4 Trillion
2002	464	1050	160	32	Electrical System Shutdown	9.9 Trillion
2007	340	1060	397	80	Electrical System Shutdown	8.8 Trillion
2013	168	1020	132	41	Embankment failure	1.5 Trillion
2014	581	830	201	26	134,662 persons were affected	5 Trillion
2015	310	890	196	5	Electrical System Shutdown	1.5 Trillion
2016	275	580	152	2	-	3 Trillion
2017	322	700	139	6	1,178 houses were inundated	147 Billion
2018	346	775	79	1	42 houses were highly damaged	150 Billion
2019	154	890	84	2	-	100 Billion
2020	196	965	150	67	Electical System Shutdown	1 Trillion

data set of the Shuttle Radar Topography Mission having a 30 m resolution was used in this study. The river cross-sectional and drainage system data for the Ciliwung River recorded in 2011 were obtained from the project authority of the Japan International Cooperation Agency. Water level and river flow discharge data for the Ciliwung River and a flood inundation map of Jakarta were provided by Badan Penanganan Bencana Daerah (Jakarta Disaster Management Agency).

3.2 Satellite rainfall products

The GSMaP project was implemented in 2002 to develop retrieval algorithms for rainfall rates and to produce high-resolution global precipitation maps based on satellite data (Ushio et al. 2009; Aonashi and Liu 2000). GSMaP products are distributed by the Japan Aerospace Exploration Agency (JAXA) Global Rainfall Watch. GSMaP Now, GSMaP NRT, and GSMaP MVK are provided by JAXA.

GSMaP Now only allows the extrapolation of rainfall maps every 30 min; therefore, the accuracy of the data may be relatively low. Moreover, it only provides data for 2017, 2018, and 2019. GSMaP MVK is a reanalysis version of GSMaP NRT and has a resolution of 0.1°/h with a domain coverage from 60° N to 60° S. It was available from March 2000 until December 2010. GSMaP NRT uses the same algorithm as GSMaP MVK, and it has been available since October 2008. GSMaP NRT is released every hour (4 h latency), and a Kalman filter algorithm is applied to the data (Ushio et al. 2009). GSMaP Gauge V7 is a calibrated version based on the ground gauge data and yields high accuracy. Its data have been available since March 2014.

In this study, we evaluated the data using GSMaP NRT and GSMaP Gauge V7. GSMaP NRT can be used as the input for a real-time flood-forecasting system, and the GSMaP Gauge can be used for reconstructing past flood events. The simulated data were compared with ground observation data.

3.3 Ground observation rainfall data

Hourly rainfall data were obtained for the target area from Badan Meteorologi, Klimatologi dan Geofisika (Indonesian Agency for Meteorology, Climatology, and Geophysics). We evaluated the uncertainties in the hourly satellite rainfall data from the Citeko, Darmaga, Pondok Betung, Kemayoran, and Tanjung Priok stations. The locations of the stations are shown in Fig. 1. Table 1 shows the total rainfall values at the stations during flood events. Then, the satellite product rainfall data for January and February of 2015–2020 were obtained from both GSMaP NRT and GSMaP Gauge data.

3.4 Flood inundation model

As mentioned earlier, we modeled the flood inundation in Jakarta based on rainfall-runoff (Kure and Yamada 2004; Kure et al. 2008) and flood inundation modeling (Moe et al. 2017). The flood inundation model comprised a rainfall-runoff module for each sub-basin, a hydrodynamic module for the rivers and canal networks, and a flood inundation module for the flood plains.

For the rainfall-runoff simulation, the lumped rainfall-runoff model used by Kure and Yamada (2004) and Kure et al. (2008) was applied to each sub-basin because this model can be used to simulate the Horton overland flow in urban areas, as well as subsurface and saturation overland flow in mountainous areas. These flows depend on the relationship between the soil and geological characteristics and the intensity of rainfall on hill slopes.

Saint-Venant equations for the conservation of continuity and momentum were applied to connect runoffs from each sub-basin and conduct river flood routing as the distributed model in the river channels and drainage

Table 2 Evaluation index of rainfall comparisons

Period	Location/ coverage area	Observed Rainfall (mm)	Altitude (m)	GSMaP NRT						GSMaP Gauge					
				Volume Bias	Total Rainfall	Hourly Rainfall		Daily Rainfall		Volume Bias	Total Rainfall	Hourly Rainfall		Daily Rainfall	
						Correlation	RMSE	Correlation	RMSE			Correlation	RMSE	Correlation	RMSE
				(%)	(mm)	coefficients (CCs)	(mm)	coefficients (CCs)	(mm)	(%)	(mm)	coefficients (CCs)	(mm)	coefficients (CCs)	(mm)
Event 2015	Citeko	160	920	-34	107	0.07	4	0.04	24	81	290	0.10	5	0.28	49
	Darmaga	206	190	-52	98	0.05	5	-0.45	42	17	240	-0.08	5	-0.34	58
	Pondok Betung	156	50	24	193	-0.03	10	-0.28	60	127	353	-0.03	11	-0.18	84
	Kemayoran	505	4	-61	196	0.47	9	0.92	66	-44	282	0.44	8	0.91	55
	Tanjung Priok	425	2	-54	196	0.45	9	0.82	74	-41	250	0.40	9	0.90	63
	Basin Averaged	283		-46	150	0.53	4	0.69	34	12	310	0.55	4	0.79	28
Event 2016	Citeko	176	920	8	189	0.01	3	-0.12	22	52	268	0.01	3	-0.25	31
	Darmaga	126	190	31	165	-0.01	6	-0.30	36	114	270	-0.04	6	-0.34	43
	Pondok Betung	104	50	90	198	-0.02	3	0.15	29	180	292	-0.05	4	-0.01	41
	Kemayoran	178	4	94	346	0.35	5	0.81	28	53	273	0.43	4	0.43	33
	Tanjung Priok	256	2	37	350	0.20	5	0.84	22	-3	248	0.39	4	0.96	14
	Basin Averaged	172		83	316	0.16	3	0.49	30	59	275	0.15	2	0.47	24
Event 2017	Citeko	361	920	-24	273	0.02	4	-0.34	34	-6	338	-0.06	4	-0.19	32
	Darmaga	146	190	-100	282	-0.03	4	-0.17	34	129	333	-0.03	4	-0.25	31
	Pondok Betung	111	50	121	246	0.00	3	0.04	20	203	336	-0.02	3	0.03	27
	Kemayoran	233	4	-9	212	0.09	3	-0.08	20	27	295	0.17	3	0.27	19
	Tanjung Priok	543	2	-53	253	0.04	6	0.19	45	-46	292	0.01	6	-0.32	52
	Basin Averaged	228		14	260	-0.02	3	-0.37	28	41	322	0.005	3	-0.21	33
Event 2018	Citeko	497	920	-84	80	-0.01	6	0.09	60	-46	268	0.00	6	0.29	53
	Darmaga	258	190	-73	69	-0.04	4	-0.37	28	71	440	0.05	4	0.17	41
	Pondok Betung	143	50	-39	87	0.02	3	0.07	12	101	290	0.00	3	0.07	19
	Kemayoran	213	4	-53	100	0.18	1	0.30	7	19	253	0.21	2	0.53	19
	Tanjung Priok	213	2	-28	154	-0.04	3	0.61	11	17	250	-0.04	3	0.29	15
	Basin Averaged	188		-49	96	-0.03	2	-0.02	15	74	325	0.07	2	0.35	23

Table 2 Evaluation index of rainfall comparisons *(Continued)*

Period	Location/ coverage area	Observed Rainfall (mm)	Altitude (m)	GSMaP NRT						GSMaP Gauge					
				Volume Bias	Total Rainfall	Hourly Rainfall		Daily Rainfall		Volume Bias	Total Rainfall	Hourly Rainfall		Daily Rainfall	
						Correlation	RMSE	Correlation	RMSE			Correlation	RMSE	Correlation	RMSE
				(%)	(mm)	coefficients (CCs)	(mm)	coefficients (CCs)	(mm)	(%)	(mm)	coefficients (CCs)	(mm)	coefficients (CCs)	(mm)
Event 2019	Citeko	1141	920	-81	217	-0.09	12	-0.10	122	-82	204	-0.10	12	0.46	116
	Darmaga	174	190	28	222	-0.01	5	-0.14	26	25	216	0.00	4	-0.29	26
	Pondok Betung	21	50	508	128	0.18	1	0.29	12	520	130	0.08	1	0.14	12
	Kemayoran	151	4	-43	86	0.06	2	0.50	13	-13	132	0.08	2	0.50	16
	Tanjung Priok	186	2	-56	82	0.15	4	0.41	22	-32	126	0.29	3	0.44	20
	Basin Averaged	215		-41	128	0.22	2	-0.05	15	-29	154	0.46	2	0.65	13
Event 2020	Citeko	563	920	-68	181	0.12	10	0.52	80	-68	181	0.13	10	0.60	78
	Darmaga	230	190	-26	170	0.10	4	0.91	16	-20	183	-0.01	4	0.90	16
	Pondok Betung	343	50	-23	265	0.23	9	0.98	23	-41	203	0.03	9	0.98	43
	Kemayoran	445	4	-46	240	0.48	7	0.91	61	-62	169	0.50	7	0.99	68
	Tanjung Priok	424	2	-29	301	0.35	7	0.79	59	-63	156	0.51	7	0.92	69
	Basin Averaged	310		-19	244	-0.03	6	0.91	27	-36	196	0.11	6	0.99	24

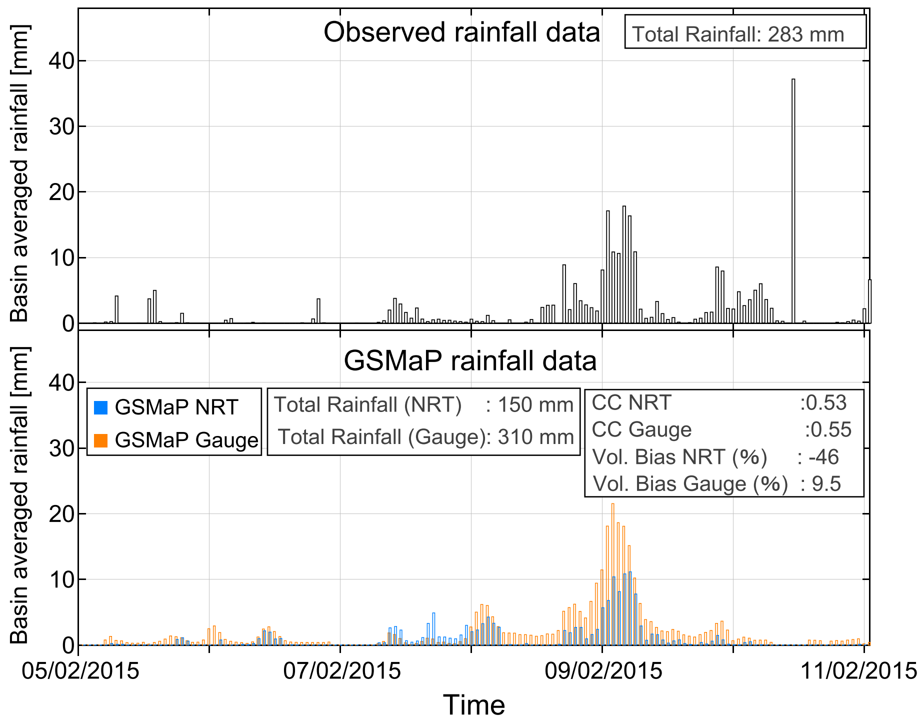

Fig. 2 Comparisons of hourly rainfall between GSMaP products (NRT & Gauge V7) and observation for flood event of 2015

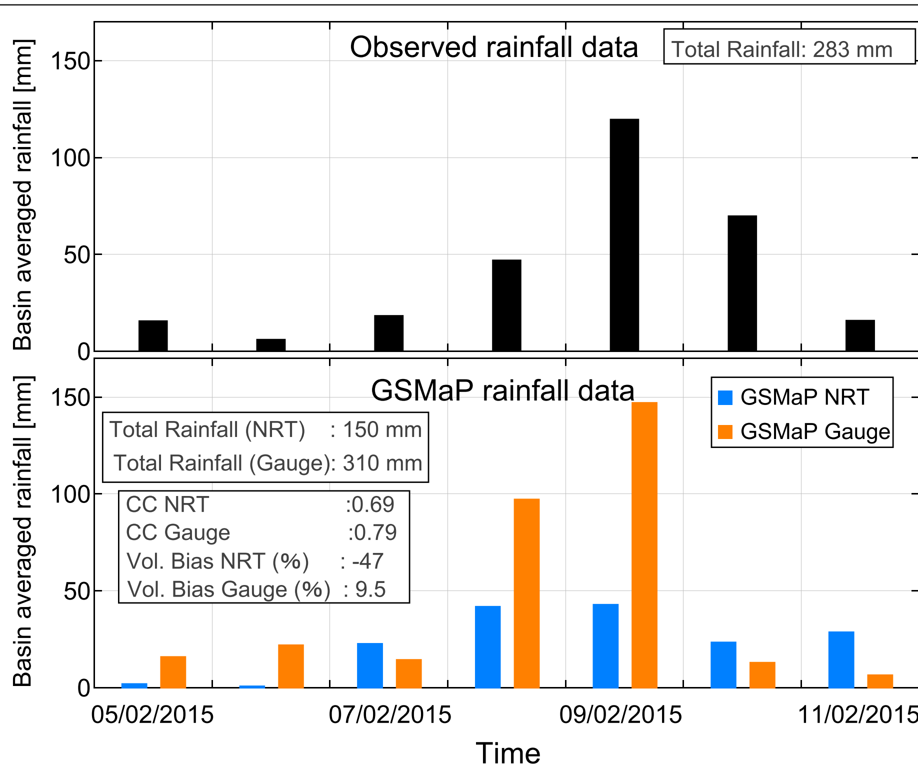

Fig. 3 Comparisons of daily rainfall between GSMaP products (NRT & Gauge V7) and observation for flood event in 2015

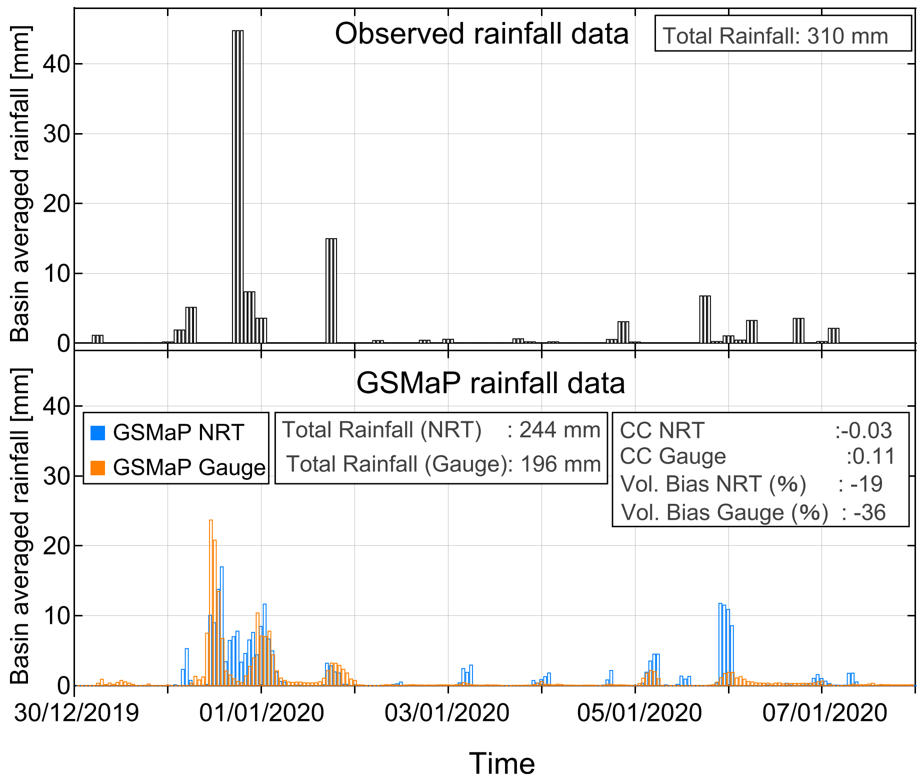

Fig. 4 Comparisons of hourly rainfall between GSMaP products (NRT & gauge.v7) and observation for flood event of 2020

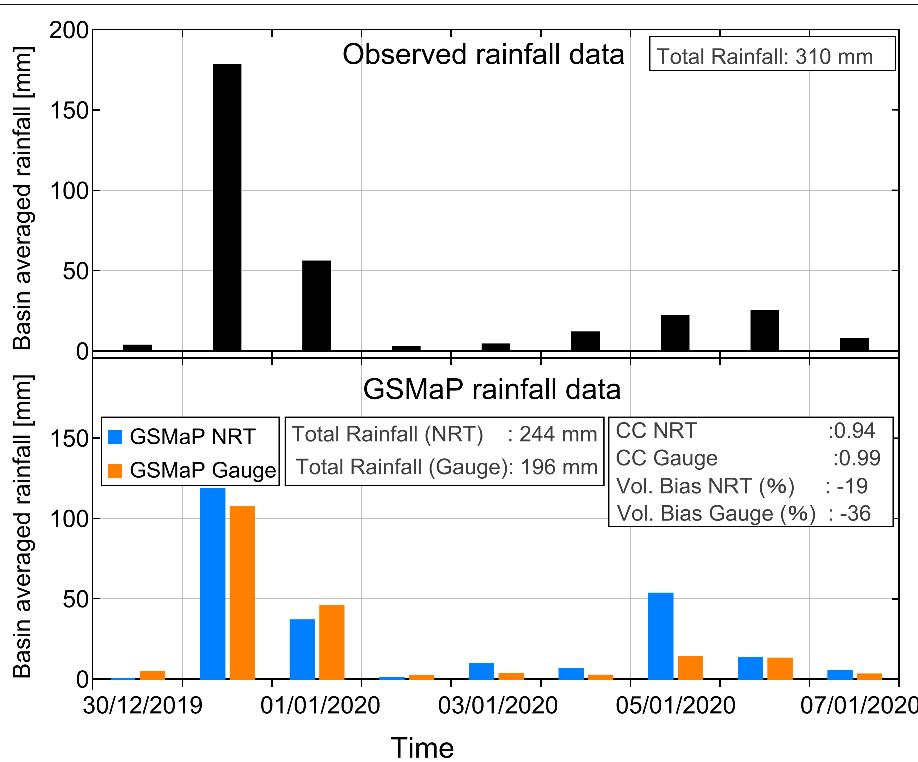

Fig. 5 Comparisons of daily rainfall between the GSMaP products (NRT & Gauge V7) and observation for flood event of 2020

systems. Unsteady two-dimensional flow equations, i.e., the continuity and momentum equations, were numerically solved for the flood inundation simulation of the flood plain.

The rainfall-runoff and flood inundation model were applied to the 2013 flood event based on the radar rainfall data and were validated against the observations (see Moe et al. 2016, 2017) for the calibrated parameters and details of the simulations.

In this study, flood observation data and flood inundation simulations modeled using the GSMaP rainfall input were compared.

3.5 Target flood events

Six yearly largest flood events from 2015 to 2020 were selected as the target in this study because both GSMaP NRT and GSMaP Gauge data are available for these flood events. These events produced the highest water levels at the stations in the Chiliwung river during these years. The event periods lasted for approximately a week in January or February.

3.6 Evaluation index

We compared the agreement of the GSMaP products and examined the rainfall data of the study area. Statistical validation methods, such as the root mean square error (RMSE), correlation coefficients (CCs), and volume bias, were used as evaluation indexes; these were employed to evaluate the relationship between the GSMaP and observed rainfall data. The RMSE was used to compare the magnitude of the error between the GSMaP and observation data sets. CC represented the correlation between the data sets; its value ranged between zero and one. The volume bias (%) is the difference in the percentages of the total rainfall volume between the GSMaP and ground rainfall observation. It is calculated using the following equation: (100 × ((GSMaP − Observation)/Observation)). For the flood hydrograph comparisons, the Nash–Sutcliffe efficiency index (NSE) was computed. The NSE values ranged from minus infinity to 1, and an efficiency index of 1 indicated a perfect match.

4 Results

4.1 Rainfall comparison

Good performances on a daily scale with respect to the CCs and volume bias were observed for the 2015, 2019, and 2020 events, as listed in Table 2. Figures 2 and 3 show the hourly and daily comparisons, respectively, between the basin-averaged GSMaP and rainfall

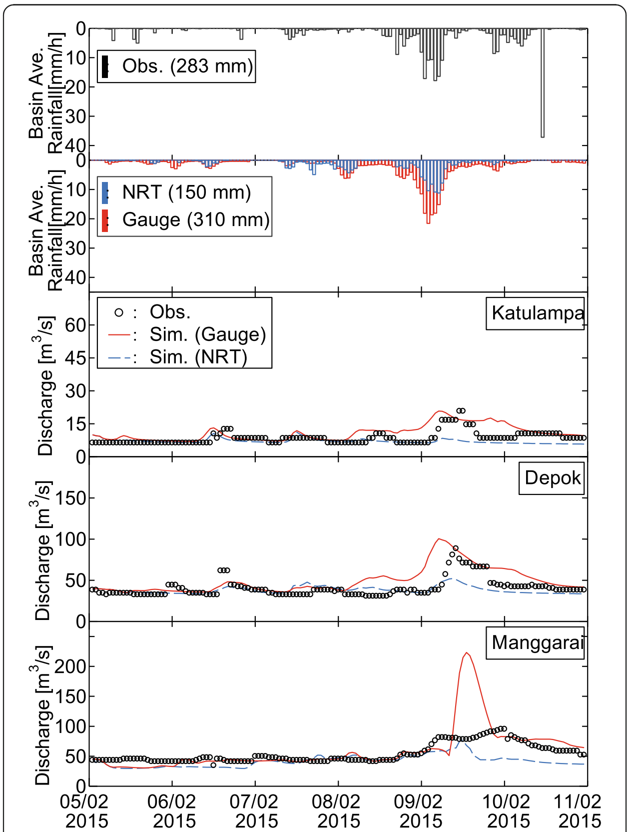

Fig. 6 Hydrograph comparisons for flood event of 2015

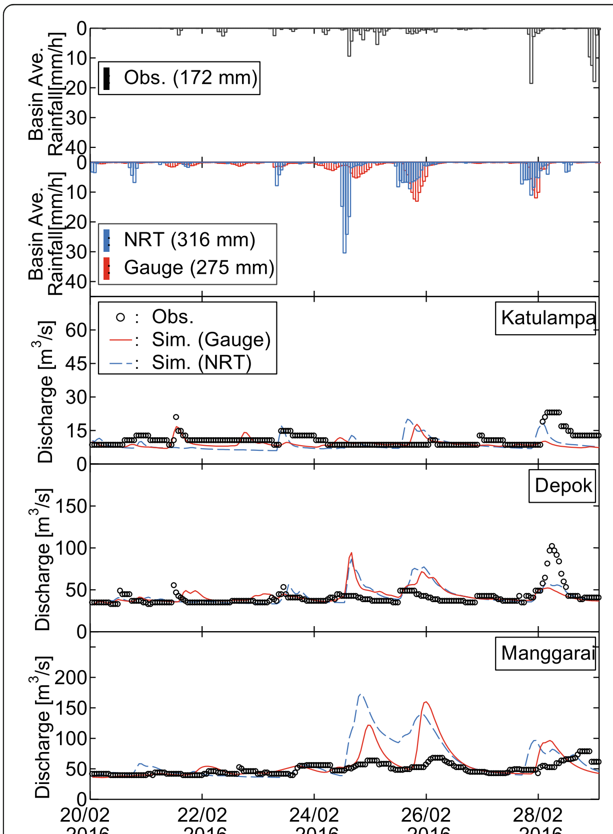

Fig. 7 Hydrograph comparisons for flood event of 2016

observation data for the 2015 flood event. In this case, we confirmed relatively strong correlations for the daily basin-averaged gauge rainfall, particularly for the GSMaP Gauge and observation data (0.79 for the daily basin-averaged gauge rainfall). Figures 4 and 5 show the hourly and daily comparisons, respectively, between the average basin observation and GSMaP data for the 2020 flood event. It is noted that the observed rainfall in 2020 only provides the data at 3 h intervals, so that hourly data was made from these 3 h intervals assuming uniform time distributions at each hour. In this case, the best correlation existed (0.99, for the daily basin-averaged rainfall), but weak correlations could be confirmed on an hourly time scale. Table 2 summarizes the evaluation index data. The values for the other years are listed in Table 2. The agreement of the GSMaP data was not very high (Table 2). Only weak correlations were found for the flood events from 2016 to 2018, both hourly and daily. Overestimation of the GSMaP was observed for the 2016, 2017, and 2018 events except for the GSMaP NRT in 2018, whereas slight underestimation was observed for the 2019 and 2020 events. It should be noted that the volume bias in the Pondok Betung station in 2019 showed an extremely large overestimation for both hourly and daily scales. This is because the observed rainfall in the Pondok Betung station in the 2019 event was 21 mm, which is too small compared with the values at other stations. The data quality of the rainfall stations during heavy rainfall events should be checked in Jakarta.

4.2 Flood hydrograph

We performed rainfall-runoff and flood inundation simulations at an hourly time step using the GSMaP rainfall data as the input and compared the observed and simulated results.

Figures 6, 7, 8, 9, 10, and 11 show the hydrographs for the observations at the Katulampa, Depok, and Manggarai stations and the corresponding simulations for the 2015–2020 flood events. The locations of the stations are shown in Fig. 1. The simulated hydrographs showed relatively good agreement with the observations on an hourly time scale with respect to CCs (the average CCs of the Gauge simulation is 0.53), but some underestimations and/or overestimations with respect to the peak discharge bias (from 62 % to 134 % in the Gauge simulations) occurred. For the Nash index, generally low performance was confirmed, except for the 2019 and 2020 events.

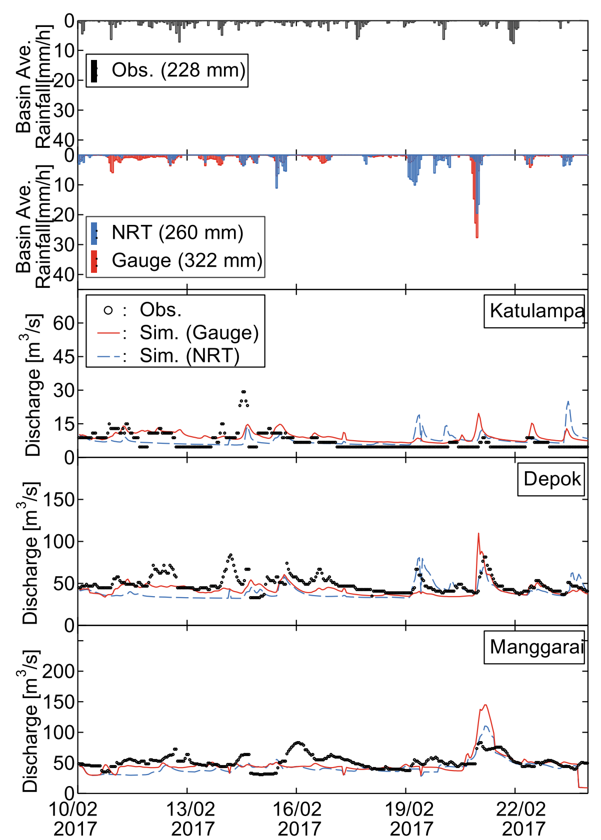

Fig. 8 Hydrograph comparisons for flood event of 2017

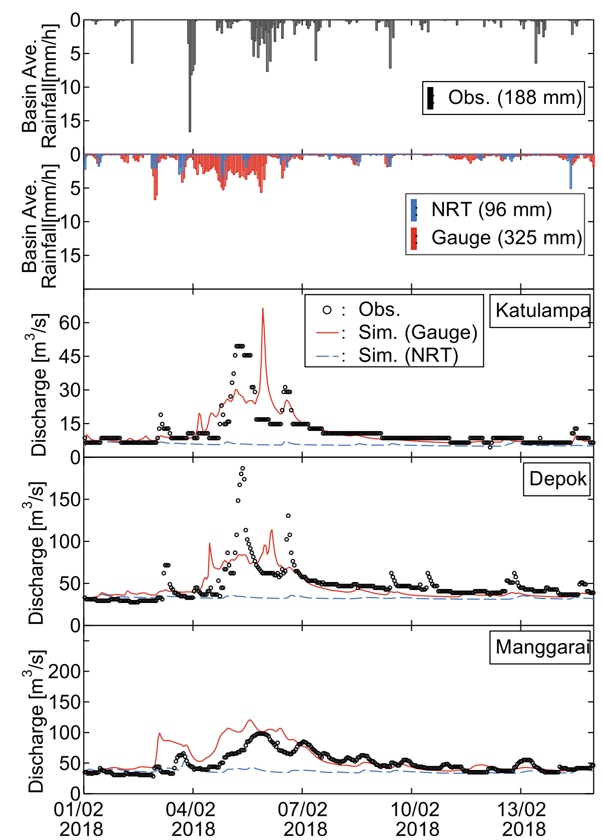

Fig. 9 Hydrograph comparisons for flood event of 2018

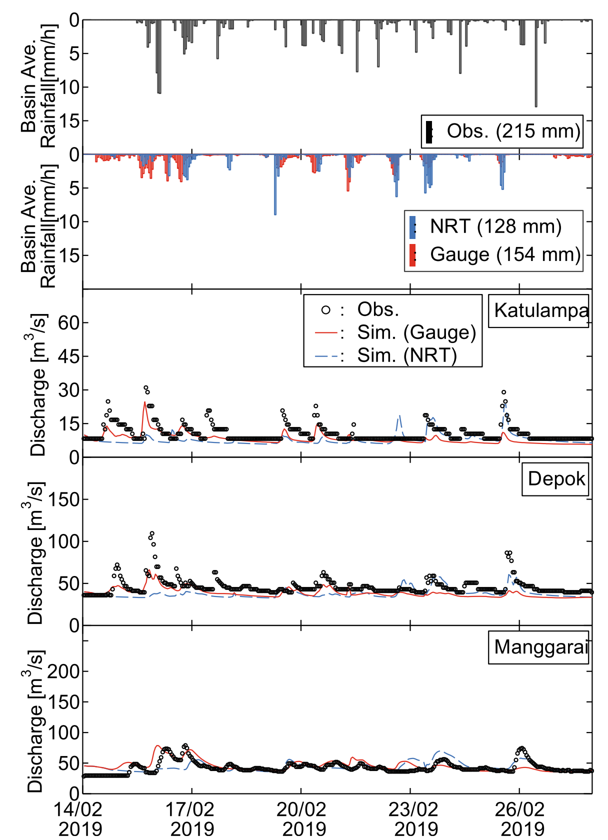

Fig. 10 Hydrograph comparisons for flood event of 2019

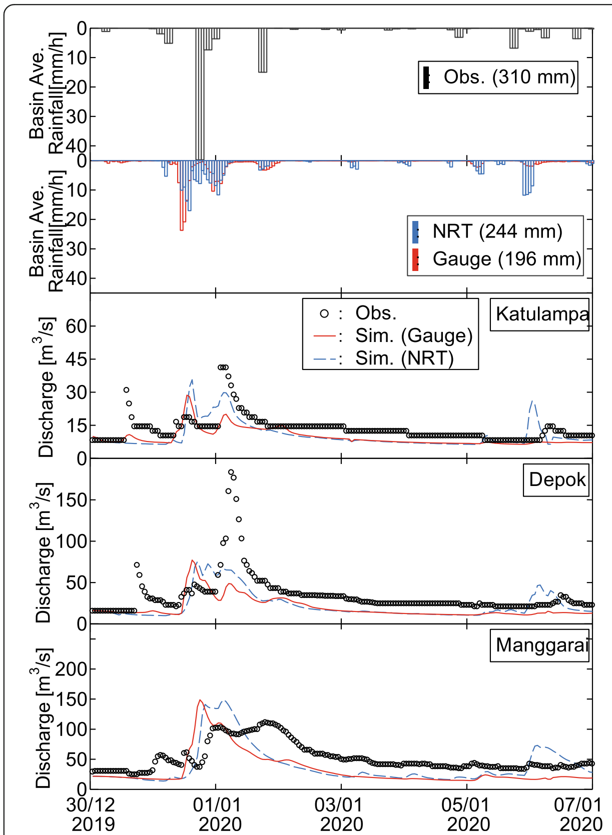

Fig. 11 Hydrograph comparisons for flood event of 2020

For the 2015 flood event (Fig. 6), flood peak discharges were captured through GSMaP Gauge simulations at the Katulanmpa and Depok stations, but apparent peak time and volume differences were observed. These differences in the flood event resulted in the worst Nash index values of all events, although the hourly rainfall correlations in Fig. 2 performed well, as discussed in the previous sentences. At the Manggarai station, the GSMaP Gauge simulation was overestimated in the peak discharge compared with the observation. For 2016 and 2017 flood events (Figs. 7 and 8), several high flood-flow fluctuations were observed and simulated, but the simulated flood hydrograph occasionally overestimated and underestimated the observations. The simulation results of the GSMaP Gauge simulations for the 2018 event showed good correlations (Fig. 9) in CCs (0.64–0.73), good peak discharge biases (– 39–35%), and relatively acceptable Nash index values (0.38 and 0.39). The flood peak timing and values of the 2018 flood event were accurately simulated, but the GSMaP NRT simulations did not show any floods in the event. This is because significant underestimations of the rainfall of the GSMaP NRT during the event were found at all stations (Table 2 and Fig. 9), even though GSMaP NRT captured the rainfall well in the 2018 rainy season, except during this flood event. One possibility of this underestimation might be due to shallow orographic rainfall, because large rainfall observation values at high elevations can clearly be observed in this event, as shown in Table 2. This type of rainfall may still be difficult to capture by the satellite after a new orographic/non-orographic rainfall classification scheme was installed (Kubota et al. 2020). This will be discussed further in the discussion section.

For the 2019 flood event (Fig. 10), good CCs and Nash index values were observed in the gauge simulation. The best Nash index values were confirmed for the 2019 flood event. For the 2020 flood event (Fig. 11), CCs show more than 0.6 in all stations for both the GSMaP NRT and gauge simulations. The relatively acceptable Nash index values (0.15–0.54) were observed, except at the Manggarai station. As such, the 2019 and 2020 events show good flood simulation results because these events show good daily rainfall correlations and volume bias of the GSMaP Gauge data compared with the observations. The simulation results for the hourly time scales are presented in Table 3. The peak bias (%), CCs, RMSE, and NSE

Table 3 Summary of discharge hydrograph comparison

Period	Water Level station	GSMaP NRT				GSMaP Gauge			
		Peak Discharge Bias (%)	Correlation coefficients (CCs)	Nash Index	RMSE (m^3/s)	Peak Discharge Bias (%)	Correlation coefficients (CCs)	Nash Index	RMSE (m^3/s)
Event 2015	Katulampa	-46	0.03	-0.36	3.15	0	0.52	-1.15	3.97
	Depok	-41	0.50	0.20	10.02	13	0.63	-0.80	15.02
	Manggarai	-19	0.53	-0.31	17.99	134	0.72	-2.39	28.92
Event 2016	Katulampa	-13	0.14	0.31	4.30	-23	0.03	0.44	3.86
	Depok	-15	0.35	-0.36	11.74	-7	0.24	-0.40	11.92
	Manggarai	122	0.49	-10.39	30.31	104	0.52	-5.18	22.32
Event 2017	Katulampa	190	-0.03	0.59	4.52	128	0.42	0.67	4.04
	Depok	0	0.16	-1.35	14.65	36	0.39	-0.44	11.48
	Manggarai	33	0.38	-0.78	16.85	76	0.39	-0.94	17.61
Event 2018	Katulampa	-80	0.13	-0.45	9.83	35	0.69	0.39	6.41
	Depok	-80	0.21	-0.46	25.75	-39	0.64	0.38	16.75
	Manggarai	-42	0.20	-0.53	20.19	24	0.73	-0.18	17.76
Event 2019	Katulampa	-19	0.35	0.57	4.71	-62	0.60	0.69	3.96
	Depok	-30	0.25	0.19	12.48	-52	0.60	0.43	10.49
	Manggarai	-5	0.36	-0.08	9.75	-28	0.49	-0.06	9.67
Event 2020	Katulampa	80	0.60	0.51	5.65	2	0.68	0.54	4.37
	Depok	22	0.64	0.32	17.22	-19	0.60	0.15	19.25
	Manggarai	-25	0.64	-0.43	21.77	-50	0.62	-0.61	23.11

were computed (Table 3). From Table 3, it can be observed that the gauge simulations are better than the NRT simulation, especially for the 2018 event. The gauge simulation results in Table 3 show that stations at higher altitudes show good RMSE and NSE values because of the small catchment size and sub-basin numbers and few opportunities to have uncertainty (Moriasi et al. 2007). Several NRT simulations yielded negative NSE values, which signified that these simulations were not useful for flood prediction.

Based on the comparison, GSMaP Gauge simulations were found to be significantly better than GSMaP NRT-based simulations. Significant underestimation of the GSMaP NRT simulation occurred compared with the observation. GSMaP NRT data were designed as input for the flood-forecasting simulations because these data sets provided near real-time rainfall data. However, in terms of agreement, the GSMaP NRT data were unsuitable for the real-time forecasting of flooding in Jakarta, and significant bias corrections or modifications are required to obtain more accurate simulation results. Finally, it should be emphasized that GSMaP Gauge simulations showed relatively good performance. These results encourage us to use satellite-driven rainfall data to reconstruct historical flood events in poorly gauged basins and developing countries, even when the target areas are highly urbanized.

4.3 Flood inundation

The flood inundation conditions were also compared. Figures 12, 13, 14, 15, 16, and 17 show flood inundation maps based on the simulation and observation data for 2015–2020 flood events. The observed flood inundation maps were provided by the National Disaster Management Agency. These observation maps were based on eyewitness reports of government officers during the flood events and interviews with residents after the event. The observation maps tended to overestimate the inundation area because the entire district in the map was treated as the entire inundation when the flooding of a part of a district was reported. The simulation of the flood inundation results using the GSMaP Gauge showed relatively good consistency with the observations, particularly for 2017, 2018, 2019, and 2020. A slight overestimation of the flood inundation in some districts can be confirmed in 2015 and 2016 due to overestimation of the flood hydrograph at some stations. The GSMaP NRT captured the flood inundation for 2015, 2016, and 2020 events but could not capture the inundation for 2018 due to significant underestimations of the rainfall during the event. It is noted that these comparisons were made by visual-graph comparisons because the observation maps were not appropriate for use as a statistical test because of the overestimation of the inundation area, as explained in the above sentences.

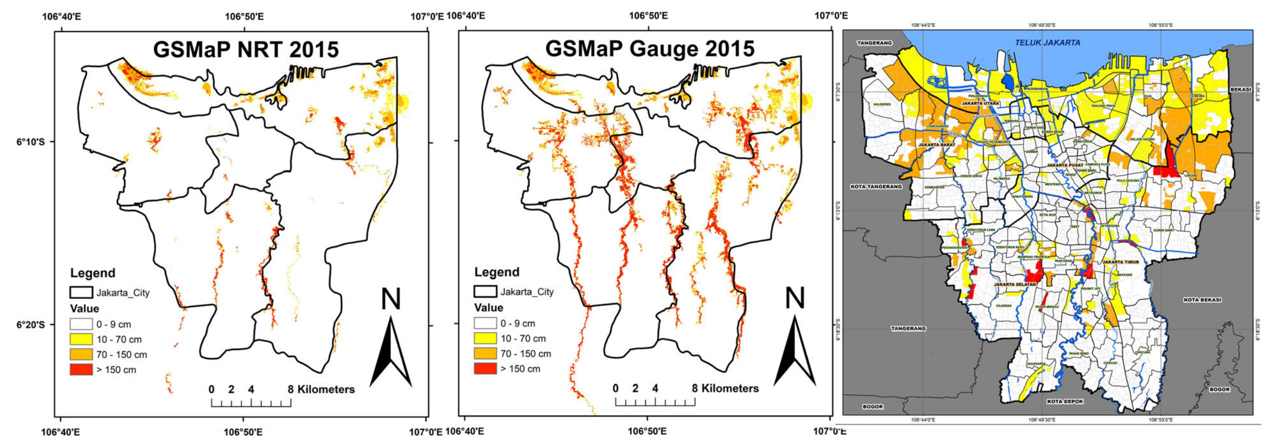

Fig. 12 Flood Inundation comparisons for flood event of 2015

From these results, we concluded that the GSMaP Gauge data could be used to reproduce previous flood inundation events in Jakarta. However, it is challenging to use GSMaP NRT data as the input in a real-time flood-forecasting system owing to its low accuracy.

5 Discussion

Based on the comparison between gauge-based observations and satellite-based GSMaP rainfall data, we found that the GSMaP NRT is not useful as an input for the real-time flood-forecasting system in Jakarta. Several previous studies have shown that the GSMaP products can capture the overall rainfall pattern (Kubota et al. 2009; Pakoksung and Takagi 2016) and could be useful as inputs to hydrologic models to reproduce past flood events (Sayama et al. 2012). However, several studies (Fu et al. 2011; Admojo et al. 2018; Pakoksung and Takagi 2016) have pointed out that the GSMaP products tended to be underestimated, and this underestimation was due to orographic effects (Kubota et al. 2009, 2020). Over coastal mountain ranges, heavy rainfall can be caused by shallow orographic rainfall, which is inconsistent with the assumption in the PMW algorithm that heavy rainfall results from deep clouds with significant ice (Kubota et al. 2020). Therefore, a new orographic/non-orographic rainfall classification scheme was installed in the PMW algorithm in V6 for the TMI and V7 for all sensors (Kubota et al. 2020). From the analysis of the paper in Jakarta, we observed both the underestimation and overestimation of the GSMaP rainfall, and only the 2018 rainfall event showed difficulty in capturing the rainfall in the high-altitude zones. Therefore, it might be inferred that the orographic effects on the quality of the GSMaP products in Jakarta are negligible. It should be noted that it is difficult to capture the 2018 rainfall event that showed clear orographic effects even after the new scheme was installed. However, it is difficult to draw any conclusions from only one case,

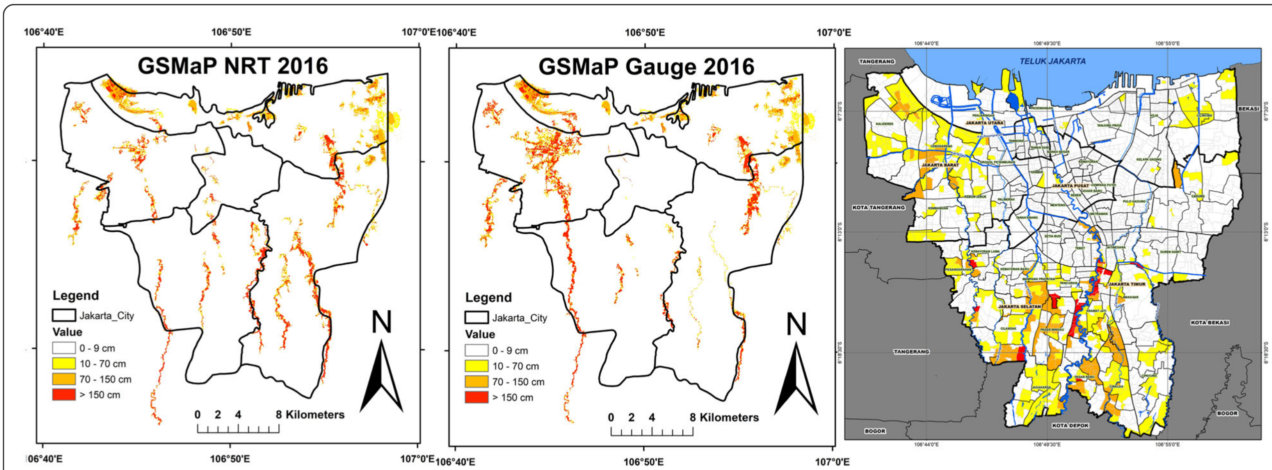

Fig. 13 Flood inundation comparisons for flood event of 2016

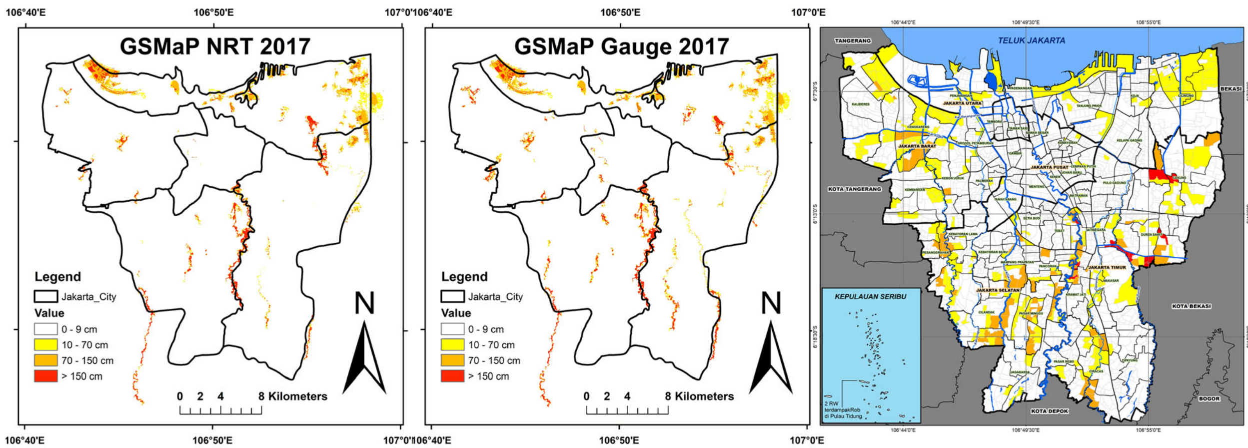

Fig. 14 Flood inundation comparisons for flood event of 2017

and other atmospheric conditions, such as wind fields, should be analyzed to understand the orographic rainfall effects in Jakarta.

Many reasons are attributed to the general difficulties in capturing heavy rainfall in Jakarta. First, Jakarta and its surroundings are highly urbanized areas, and convectional rainfall typically occurs in urban areas of humid tropical regions. Additionally, the heat island phenomenon is significantly progressing in Jakarta, and there exists the urban thermal influence on the background environment of convective rainfall (Sugawara et al. 2018). The rain retrieval algorithms may have errors when applied to "warm rain" processes that are typical of convectional rainfall in tropical regions (Chang et al. 2013). Thus, it might be difficult to predict and capture convectional rainfall in urban areas using satellite information. This convection-type rainfall in an urban area may be a challenge for the accurate prediction of rainfall in Jakarta. Furthermore, the timing of microwave observation from the satellite might be related to the low quality of GSMaP because the local heavy rains regularly fall for short periods in Jakarta.

Second, the flood travel time in Jakarta is short. Jakarta and its surrounding areas are highly urbanized, and the flood travel time in rivers and canals is approximately 12–16 h. Local heavy rainfall should be captured hourly using the satellite to predict rapid floods. In previous studies, the GSMaP was evaluated at large-scale basins daily and monthly. This rapid flood response to rainfall is another challenge for GSMaP prediction in Jakarta.

Some researchers applied a bias correction method for rainfall simulation using the GSMaP algorithm to reduce the underestimation of rainfall intensity and amount (e.g. Sayama et al. 2012). However, for Jakarta, the difficulties mentioned above complicate the application of bias correction because GSMaP simulations occasionally overestimated and/or

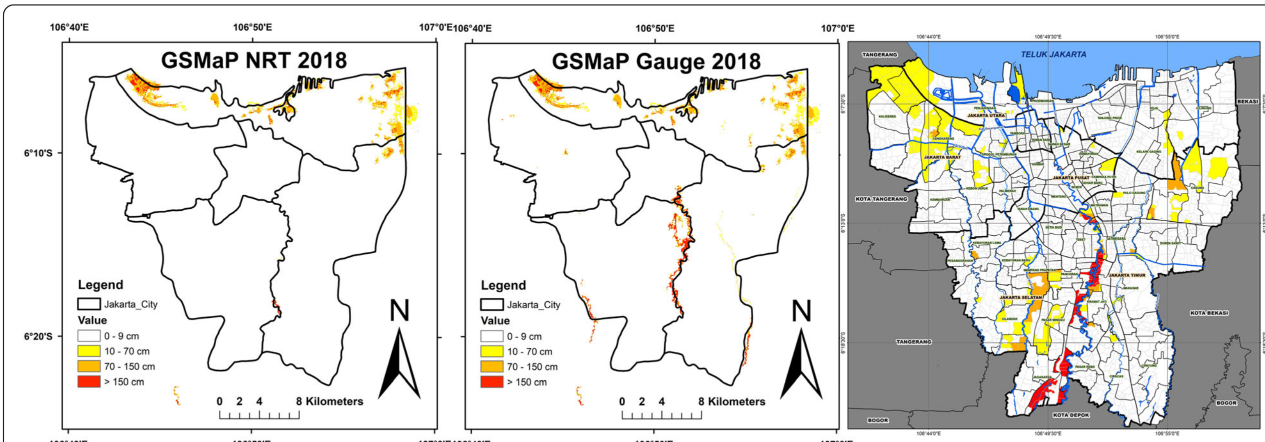

Fig. 15 Flood inundation comparisons for flood event of 2018

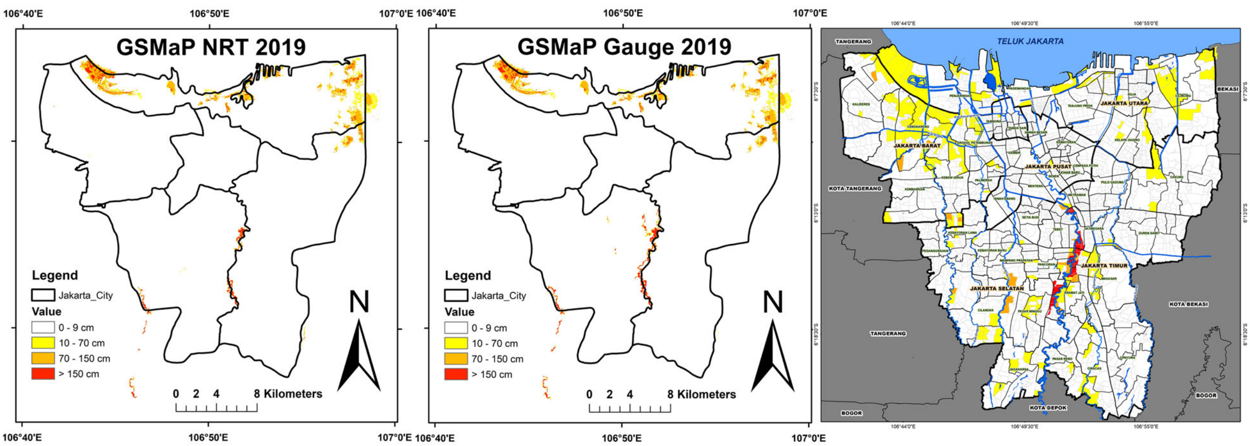

Fig. 16 Flood inundation comparisons for flood event of 2019

underestimated the flood-flow discharge of the 2016 and 2017 flood events. Moreover, the GSMaP NRT simulations did not show any flood responses for the 2018 event. In these situations, it is difficult to apply bias correction to the GSMaP NRT data. If we could find any clear underestimation or overestimation trend of the GSMaP against the ground observation, a bias correction method would work well to improve the simulation results (Saber and Yilmaz 2018).

Multi-ensemble forecasting using several satellite rainfall products has been performed in previous studies (Jiang et al. 2014). Other satellite rainfall products such as TRMM(3B42RT) might be used as the input for flood modeling in Jakarta as a multi-ensemble forecasting. However, the temporal and spatial resolutions of other satellite products are inadequate for capturing local heavy rainfall in Jakarta. Therefore, it is currently challenging to use GSMaP as the input for real-time forecasting systems. Radar information adjusted with ground gauge-based rainfall data is a more viable option for forecasting systems. It should be noted that the five rain gauge stations might be insufficient for capturing rainfall fields in Jakarta. Hence, radar observation systems should be installed and operated properly to predict rainfall and flood events in Jakarta in real time, and denser rain gauge station networks would be required to calibrate and assimilate the radar rainfall values based on the ground true observation rainfall data.

GSMaP Gauge data might be useful for reconstructing and simulating historical flood events to evaluate and compare past floods in poorly gauged basins. This is because the GSMaP Gauge can be used to observe the heavy rainfall that occurred in the past.

6 Conclusions

This study was conducted to examine the possibility of using GSMaP rainfall data as the input for real-time flood forecasting in Jakarta, Indonesia. The NRT and Gauge V7 products of the GSMaP were compared with

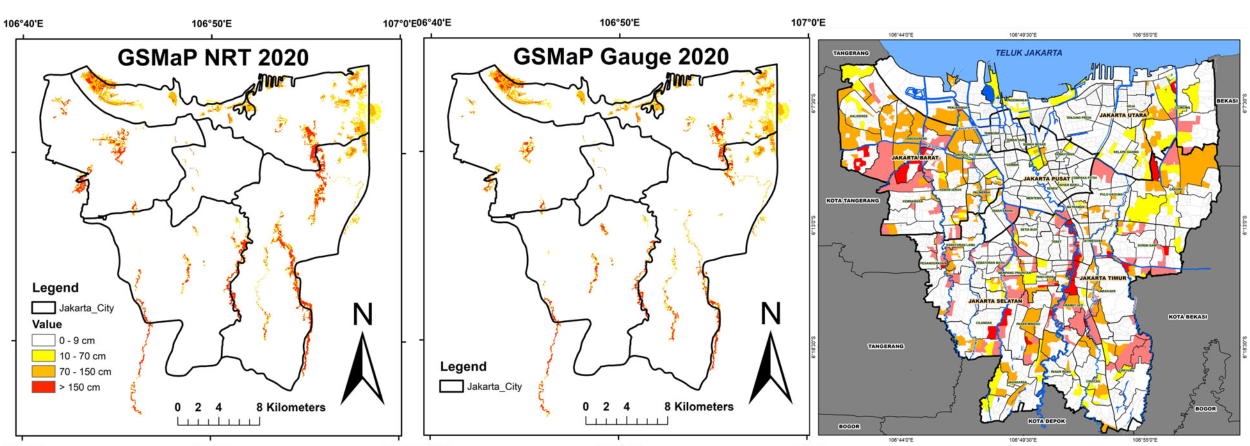

Fig. 17 Flood inundation comparisons for flood event of 2020

ground observation rainfall data at several stations and basin averages formed around Jakarta. The results indicated that the GSMaP Gauge data showed acceptable agreement in simulating the flood hydrograph and inundation of Jakarta. However, the gauge data were unavailable in real time and thus could not be used for real-time forecasting. The gauge data are suitable for replicating historical flood events that occur even in highly urbanized areas.

The GSMaP NRT product, which provided near real-time rainfall data, was suitable for real-time flood forecasting. However, it is necessary to develop a significant bias correction method or change the algorithm of the NRT data set adjusted for urban areas to improve the accuracy of the simulation results.

Abbreviations
GSMaP: Global satellite mapping of precipitation; RMSE: Root mean square error; CCs: Correlation coefficients; NSE: Nash–Sutcliffe efficiency index

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Authors' contributions
BP analyzed the data and conducted numerical experiments. SK designed the study and leads the project. RY supported the numerical experiments. NJ supported the fieldwork and data collections. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets supporting the conclusions of this article are currently not available in any repository. But the authors are willing to share the data based on the requests. Please contact the corresponding author for data requests.

Declarations

Competing interests
The authors declare that they have no competing interests.

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