APPLICATION OF THE SATELLITE RAINFALL PRODUCTS IN FLOOD INUNDATION MODELING USING RRI MODEL – A CASE STUDY IN MUNDENI ARU RIVER BASIN, SRI LANKA

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ABSTRACT: Applicability of satellite rainfall products to a flood inundation modelling was tested for the Mundeni Aru River Basin in the eastern part of Sri Lanka. The RRI (Rainfall-Runoff-Inundation) model developed by the International Center for Water Hazard and Risk Management (ICHARM) for the flood simulation was used as a flood inundation model, and the satellite rainfall products (PERSIANN, TRMM and GSMaP) were applied to the model. The model employed USGS-HydroSHEDS DEM with 30-second resolution, and was calibrated with the gauged rainfall and runoff data in January-February 2011. The results of calculation with the PERSIANN, TRMM and GSMaP data were compared with those calculated with the gauged rainfall data. From the simulation results, all of the satellite rainfall products seemed to be able to be applied to the RRI model and offer overall proper simulations, although some of peaks in the hydrographs calculated with the satellite rainfall products did not match well with those observed; this might be due to the difference in the total rainfall amount between satellite rainfall estimations (SREs) and the corresponding gauged stations. Bias adjustment using scale factors could make the estimation of runoff discharge improved. Hence, the satellite rainfall products could be potentially applied for flood inundation simulation studies using the RRI model, but aids from ground level observations of rainfall and runoff could contribute improvement of the simulation.

1. INTRODUCTION

Extreme weather events associated with climate change is considered to be getting more severe worldwide. Water-related hazards such as floods are expected to increase and that in particular people in poverty in developing countries are likely to be exposed to extreme weather events. According to the Emergency Events Database (EM-DAT; Guha-Sapir et al., 2016), about 3 billion people were affected by floods and droughts between 1995 and 2014 globally. Damages on human livelihood and food production by water-related disasters are concerned to be intensified by further changes in climate.

Remote sensing techniques such as satellite image analyses have been utilized for capturing extent of damaged areas by floods and droughts, but there are some limitations that for instance satellite images are not always available due to satellite's orbital period and cloud cover. Recently, application of data of remotely-sensed rainfall information and hydrological numerical modelling have been applied to simulate flood inundation extent which can complement results of satellite images taken at discrete time. The models are also likely to be applicable to early flood prediction with application of near-real-time satellite rainfall maps, even in poorly gauged basins.

The RRI (Rainfall-Runoff-Inundation) model (Sayama, 2015) is one of the numerical models for simulation of two-dimensional flood inundation distribution which was developed by the International Center for Water Hazard and Risk Management (ICHARM). The RRI model has the following merits; able to simulate flood inundation in areas with both floodplain zone and mountainous zone; applicable to calculation for multiple basins where the downstream floodplain can be affected by multiple rivers. Another advantage of the RRI model is free of charge which makes us provide tools such as early flood forecast system with application of satellite rainfall data and this charge-free modelling software, which could help decision making on water-related disasters in developing countries.

In this study, a procedure for setting up the RRI model and evaluating performance of reservoirs was developed. An area in the eastern part of Sri Lanka was picked up as the study area, where information for determining parameters of the model is less. Hence the procedure proposed in this study would be useful in areas in developing regions which is poorly equipped for hydrological observation. In addition, satellite rainfall data were also examined as input of the model instead of gauged rainfall data, and its applicability and issues to be addressed were discussed. The RRI model was also employed to evaluate impact of reservoir installation on river discharge and water storage, which would support decision making in flood and drought management.

2. MATERIALS AND METHODS

2.1 Study Area

The study area was located in the eastern part of Sri Lanka, including the Mundeni Aru River Basin (hereafter, MRB) (Figure 1). The catchment area of MRB is approximately 1,300 km^2, and elevation of the highest point is 873 m above the sea level. A large part of the catchment area is covered by forest and grassland, and most of the rest is composed of paddy fields.

According to EM-DAT (Guha-Sapir et al., 2016), there had been nine major riverine-flood events which occurred in Sri Lanka in 2011-2015, and total deaths in these events exceeded 300. Among them, heavy rain events in the beginning of 2011 seriously damaged on residents and agricultural productions in areas throughout the northeastern part of Sri Lanka. In the MRB, a major flood event on February 3rd, 2011 induced broad-spread inundation mostly in the downstream part of the basin and the water depth reached to approximately 2 m (Amarnath et al., 2015). In addition, another flood event occurred in December 2012 and affected residents in the eastern part of Sri Lanka.

Discharge of Mundeni Aru River was observed at a gauging stations in Tampitiya (the catchment area is around 90 km^2), and rainfall was also observed at three stations in Rugam, Kolaneyaya and Kongaspenvila (Figure 1), by the Department of Irrigation in Sri Lanka. These data were available from October 1st, 2010 to September 30th, 2014. The rainfall observation was daily. The data of runoff amount at Tampitiya was averaged values of observation that was made several times a day.

2.2 Satellite Rainfall Products

Three products of satellite rainfall observation (PERSIANN, TRMM, GSMaP[1]) were employed in this study. PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks; Sorooshian et al., 2000) is an algorism providing information of rainfall distribution. TRMM (Tropical Rainfall Measuring Mission; NASA, 2014) data was a project to provide distributional rainfall information in the tropical zone from a satellite. GSMaP (Global Satellite Mapping of Precipitation; JAXA, 2016) provides information of global rainfall distribution generated from multiple-satellite data. Resolution and available period of each of the products are shown in Table 1.

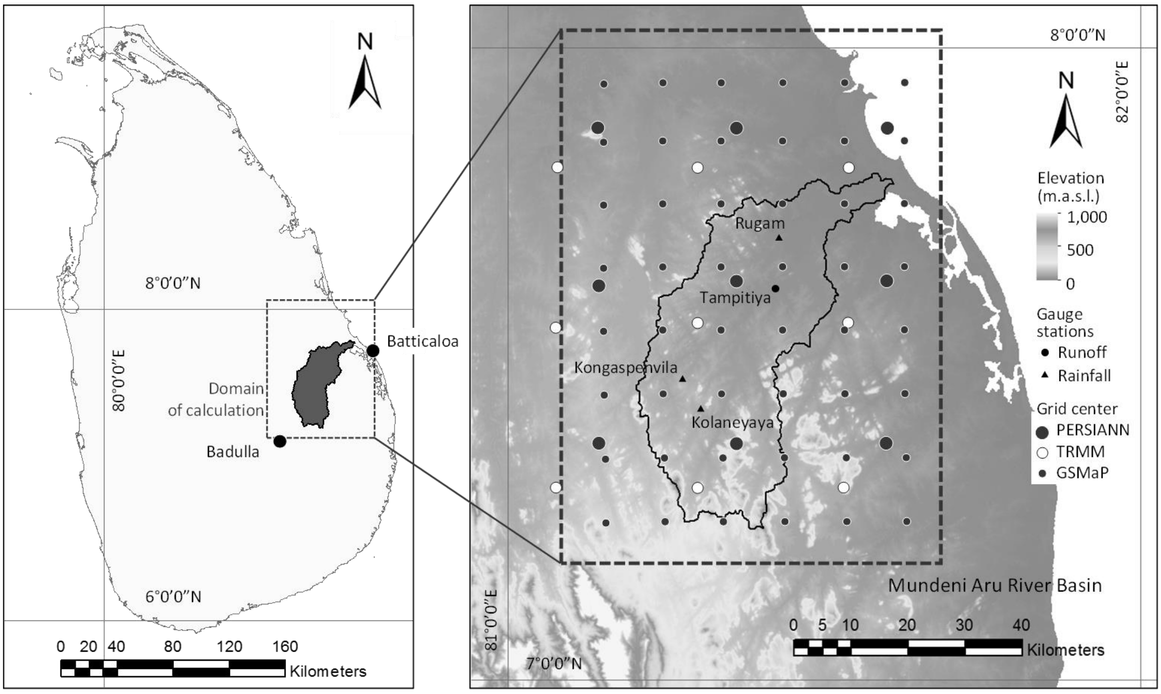

Figure 1. Domain of the calculation of the study area and gridded points of the satellite rainfall products

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[1] Data of GSMaP can be downloaded through the website <http://sharaku.eorc.jaxa.jp/GSMaP/>; user registration is required.

Table 1. Specification of available rainfall datasets.

Datasets	Resolution	Available period
Gauged	(3 stations)	October 1st, 2010 to September 30th, 2014
PERSIANN	0.25 degree	January 1st, 1983 to December 30th, 2014
TRMM	0.25 degree	January 1st, 1998 to December 30th, 2014, but not available in November and December in 2013
GSMaP	0.10 degree	January 1st, 2001 to February 18th, 2014

Here, the data in nine cells of the product of PERSIANN and TRMM, respectively, were picked up and then applied to the model (Figure 1). Similarly, the data in 48 cells of the GSMaP product were picked up and applied (Figure 1). The data were available from 1st January 1983 to 31st December 2014, but there were several missing data in the PERSIANN product. All of the satellite rainfall products have a tendency that the total amount of rainfall is likely to be underestimated in comparison with that of the gauged data. In this study, scale factors were determined from comparisons between the gauged and the satellite products from October 1st, 2010 to September 30th, 2014, and employed to correct the tendency.

2.3 The RRI Model

The RRI model (Sayama 2015) was employed for calculating flood inundation extent and depth in heavy rainfall events in this study. The model considers water movement in both slopes and river channels. The governing equations of lateral flow on slopes considered in the model are composed of the following mass balance equation (1) and momentum equations (2) and (3):

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=r \qquad (1)$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial u q_x}{\partial x}+\frac{\partial v q_x}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho_w} \qquad (2)$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial u q_y}{\partial x}+\frac{\partial v q_y}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho_w} \qquad (3)$$

where suffixes x and y indicate directions in the x-y coordinate system, h is height of water from the local surface, q_x and q_y are the unit width discharges, u and v are flow velocities, r is rainfall intensity, H is height of water from the datum, ρ_w is the density of water, g is the gravitational acceleration, τ_x and τ_y are shear stresses, and t is time. The spatial differentiation in the momentum equations (2) and (3) are converted to functions of H with application of the Mannning's law. The model can also consider percolation and groundwater flow governed by the Darcy's law. Then, the spatial differentiation in the mass balance equations (1) is discretized by the first-order finite deference method, and the time differentiation is solved by the fifth-order Runge-Kutta formula.

The model requires topographic information as a digital elevation model. In this study, HydroSHEDS with 30-second resolution provided by U.S. Geological Survey (Lehner et al., 2008) was employed.

The RRI model requires to set the parameters for the calculation. In this study, at first the degree of freedom of the model was reduced by the following ways: (1) Values of the parameters related to cross-sectional shape of channels and capacity of soil were set to the default values shown in the manual (Sayama, 2015); (2) Every cell is considered to have a channel, which is reasonable assumption because in rural areas there are drainage canals for farmlands. Then, the parameters to be calibrated were limited to parameters for Manning's roughness and groundwater permeability. Calibration has been done in the period from January 1st to February 28th, 2011, and then verification has been done in the other periods.

3. RESULTS AND DISCUSSION

3.1 Characteristics of the satellite rainfall products

Comparison of yearly total amounts of the satellite rainfall products to those of the gauged datasets is shown in Table 2. In addition, ratios of the total amounts of the satellite rainfall products from October 2010 to September 2014 to that of the gauged dataset are shown as scale factors in Table 2. All of yearly amounts of the satellite rainfall products are smaller than those gauged, and hence the scale factors are more than 1.

Table 2. Summation of yearly total amount and scale factors of the rainfall datasets.

Datasets	Sum in 2011	Sum in 2012	Sum in 2013	Scale factor
Gauged	3,559 mm	2,068 mm	2,164 mm	—
PERSIANN	2,199 mm	1,643 mm	1,584 mm	1.34
TRMM	2,632 mm	1,697 mm	†	1.23
GSMaP	2,891 mm	1,802 mm	1,567 mm	1.24

† TRMM data are not available in November and December in 2013

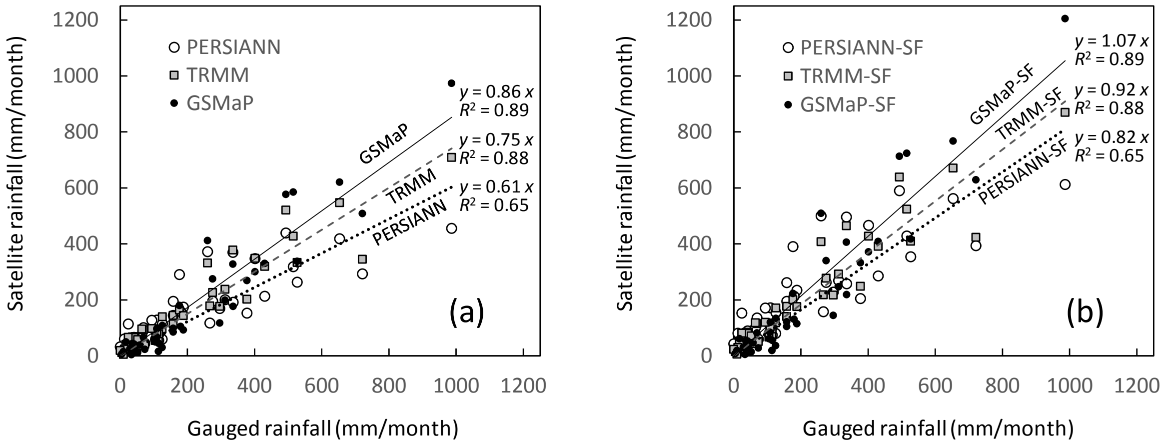

Figure 2. Comparison of monthly amounts of the satellite rainfall products to those of the gauged dataset; (a) raw data; (b) corrected by the scale factors.

Comparison of monthly total amounts of them are shown in Figure 2 (a); in terms of coefficients of determination (R^2) for fitting to proportional relationships, magnitude of the monthly total amounts of TRMM and GSMaP is likely to be consistent with that of the gauged, rather than that of PERSIANN. The corrected satellite rainfall data by the scale factors (shown as a postfix “SF” in the figures; their values are shown in Table 2) were also tested as shown in Figure 2 (b); the coefficients of proportionality for the corrected database became closer to 1, which means correspondence of the satellite rainfall data to the gauged got improved.

3.2 Applicability of the satellite rainfall products to the RRI model

Calculation results of discharge at Tampitiya by the RRI model with the satellite rainfall products are shown in Figure 3. It could be said that all of the satellite rainfall products were able to be applied to the RRI model.

The results of the calibration period (Figure 3 (a-1, a-2, a-3)) show that the peak discharge calculated with PERSIANN was much smaller than the observed even though the scale factor was considered, but in contrast the peak discharge simulated with GSMaP was closer to the observed; this would be because the relationship between PERSIANN and the gauged rainfall dataset was less linear and therefore there might be a difficulty that PERSIANN could not illustrate extreme rainfall events.

On the other hand, the results of another flooding period (Figure 3 (b-1, b-2, b-3)) show that the peak discharge calculated with GSMaP tended to be more overestimated than with PERSIANN and TRMM, and in addition, in the hydrographs calculated by all of the satellite rainfall products there were several large peaks which did not appear in the observed hydrograph. These mismatch would be because of excessive amount of rainfall in the satellite rainfall products which was much greater than the gauged.

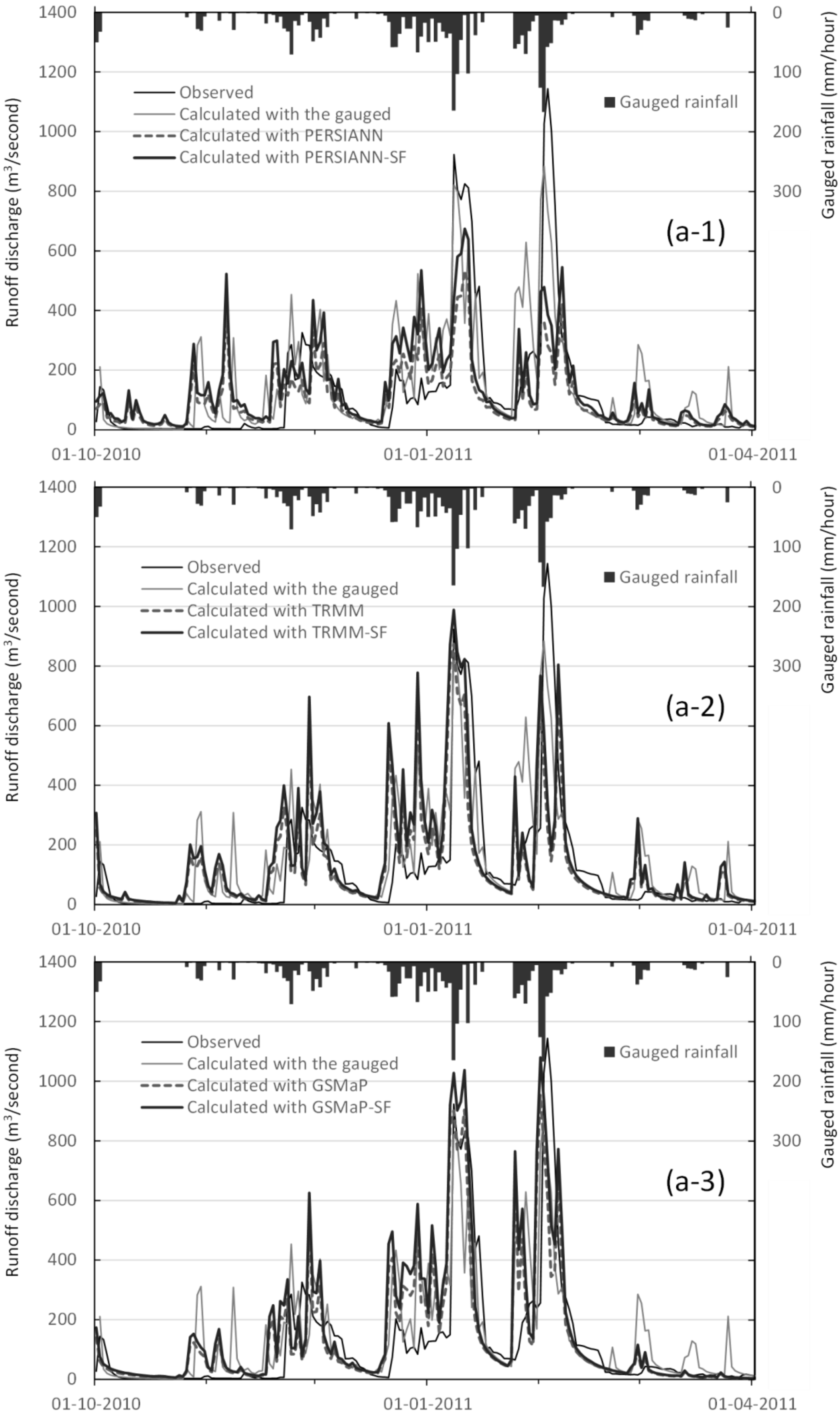

Figure 3. Hydrographs at Tampitiya calculated with the gauged and the satellite rainfall products; (a-1, a-2, a-3) in the calibration period (from October 2010 to March 2011); (b-1, b-2, b-3) in a part of the verification period (from October 2012 to March 2013)

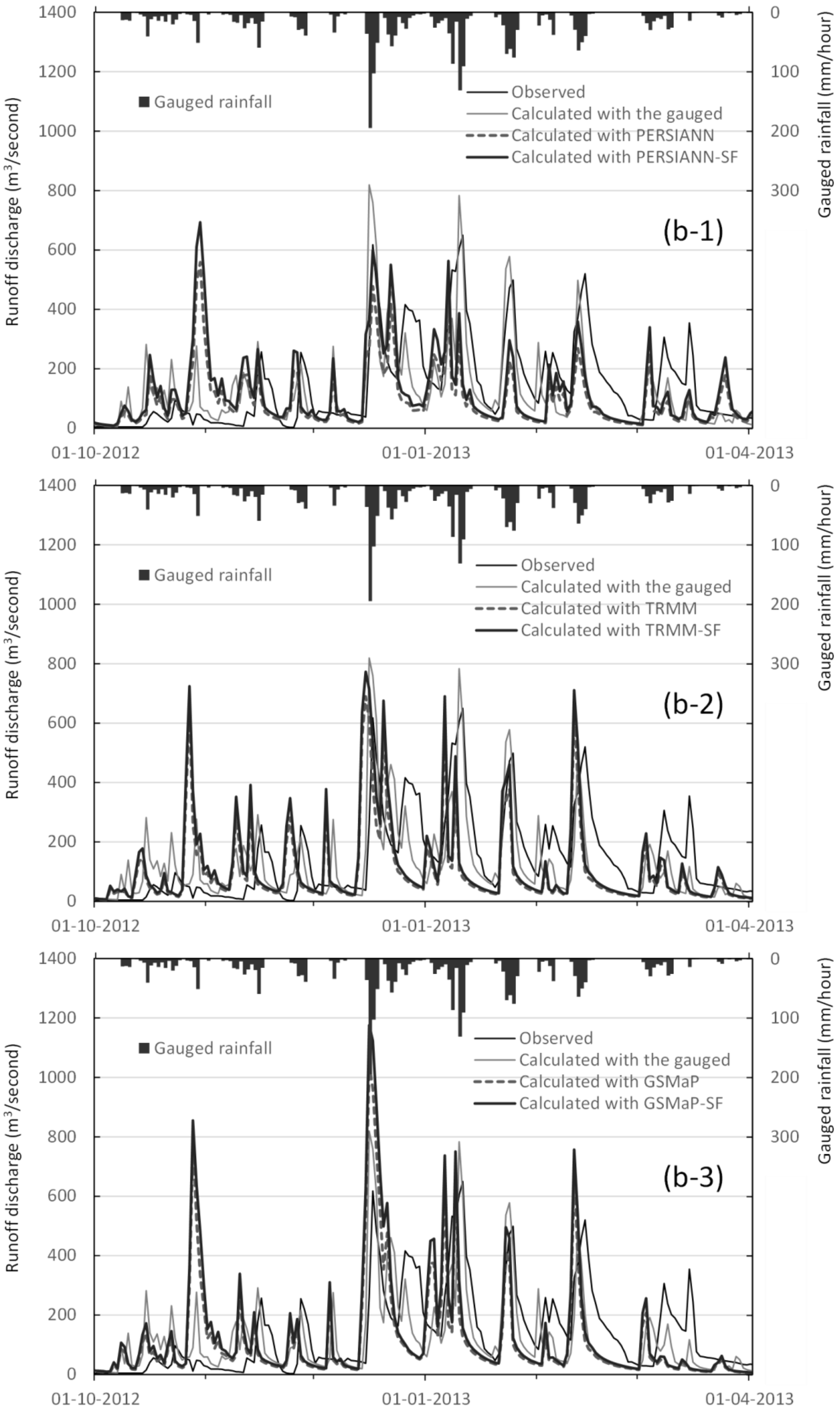

Figure 3. Hydrographs at Tampitiya calculated with the gauged and the satellite rainfall products (*cont.*)

4. CONCLUSION

Applicability of satellite rainfall products (PERSIANN, TRMM and GSMaP) to a flood inundation modelling with using the RRI model was tested with targeting a basin in the eastern part of Sri Lanka. The results of calculation with the PERSIANN, TRMM and GSMaP data were compared with those calculated with the gauged rainfall data.

From the results, it could be said that all of the satellite rainfall products were able to be applied to the RRI model and offer overall proper simulations, although some of the peaks in hydrographs calculated with the satellite rainfall products did not match well with those observed. Hence, aids from ground level observations of rainfall and runoff could contribute improvement of early flood simulation.

Especially, in area where in-situ observation are limited or poorly measured, satellite rainfall products would provide opportunity to quickly predict flood situation for better decision making.

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