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**Note:**

# Development of a Hydrological Telemetry System in Bago River

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**Hydrological monitoring is one of the key aspects in early warning systems that are vital to flood disaster management in flood-prone areas such as Bago River Basin in Myanmar. Thousands of people are affected due to the perennial flooding. Owing to the increasing pressure of rapid urbanization in the region and future climate change impacts, an early warning system in the basin is urgently required for disaster risk mitigation. This paper introduces the co-establishment of the telemetry system by a group of stakeholders. The co-establishment of the system through intensive consultations, proactive roles in responsibility sharing, and capacity building efforts, is essential in developing a base platform for flood forecasting and an early warning system in the basin. Herein, we identify the key challenges that have been central to the participatory approach in co-establishing the system. We also highlight opportunities as a result of the ongoing process and future impact on the disaster management system in the basin. We also highlight the potential for scientific contributions in understanding the local weather and hydrological characteristics through the establishment of the high-temporal resolution observation network. Using the observation at Zaung Tu Weir, Global Satellite Mapping of Precipitation (GSMaP) and Global Precipitation Measurement (GPM) satellite estimates were assessed. Near real-time and standard versions of both satellite estimates show potential utility over the basin. Hourly aggregation shows slightly higher than 40% probability of detection (POD), on average, for both satellite estimates regardless of the production type. Thus, the hourly aggregation requires correction before usage. The results show useful skills at 60% POD for standard GSMaP (GSMAP-ST), 55% POD for near real-time GSMaP (GSMAP-NR), and 46% POD for GPM, at 3-hourly aggregations. Six-hourly aggregations show maximum benefit for providing useful skill and good correspondence to gauge the observation with GSMAP-ST showing the best true skill score (TSS) at 0.54 and an equitable threat score (ETS) at 0.37. While, both final run GPM and GSMAP-NR show lower POD, TSS, and ETS scores. Considering the latency of near real-time satellite estimates, the GSMAP-NR shows the best potential with a 4-hour latency period for monitoring and forecasting purposes in the basin. The result of the GSMAP-NR does not vary significantly from the GSMAP-ST and all GPM estimates. However, it requires some correction before its usage in any applications, for modeling and forecasting purposes.**

**Keywords:** telemetry, hydrological monitoring, satellite rainfall, Bago River, co-establishment

## 1. Introduction

The increase in flood occurrence is one of the most significant potential consequences of climate change, especially for the Asian Australian monsoon region, which is likely due to the increased intensity in precipitation extremes and lengthening of the monsoon season [1]. Flood occurrences due to the prolonged duration of average rainfall or short-duration intense rainfall [2] necessitate subdaily observations in understanding the long-term changes and flood forecasting. However, hourly to subdaily rainfall observations are limited. Most long-term monitoring over Bago River Basin are daily observation. Previous studies [3–5] on the Bago River basin mentioned that additional gauge stations inside the river basin can help improve the hydrological simulation necessary for flood forecasting and the early warning system. The Bago region is expected to rapidly develop because of the recent socio-political changes in Myanmar. The need for operational monitoring over the river basin is evident for the development of a flood forecasting and early warning system. A partnership between the University of Tokyo (UTokyo) and the Yangon Technological University (YTU) under the Japan Science and Technology Agency (JST)/Japan International Cooperation Agency (JICA), and the Science and Technology Research Partnership for Sustainable Development Program (SATREPS) project was aimed at establishing such a system in the Bago River basin for ultimately contributing to flood risk-reduction efforts in Myanmar. The UTokyo-YTU partnership and local stakeholders co-established the hydrological telemetry system in the basin using a participatory approach framework to satisfy research and operational needs. The river basin covers an approximately 5400 square kilometer area that receives an annual precipitation of 3300 mm [3, 5]. This river network is connected to the Sittaung River through the Bago-Sittaung canal system. The river basin is also connected to a flood diversion channel from the Zaung Tu Weir to the Moe Yin Gyi lake, which serves as a reservoir [3, 5]. The river basin has four dams: the Zaung Tu dam for hydropower generation and three other dams (Salu dam, Shwe Laung dam, and Kodukwe dam) for irrigation purposes [4]. These show the importance of the river basin as a water resource in this region. It also shows the complex system of the canals and river network that require management to deal with floods and droughts in the region. Modeling efforts of recent flood events in the area was performed by Zin et al. [3] for the floods in 2006, 2010, and 2011. While Bhagabati and Kawasaki [4] performed the modeling for floods in 2014 and 2015. The danger level at the Bago station is set at the 910 cm level, where the danger level was reached approximately 50% of the time from 2006 to 2015. The maximum flood peaks from 2006 to 2015 were as follows: 895 cm in 2006, 938 cm in 2007, 946 cm in 2008, 880 cm in 2009, 926 cm in 2010, 960 cm in 2011, 902 cm in 2012, 890 cm in 2013, 936 cm in 2014, and 905 cm in 2015. The monitoring of such annual flooding events in the basin was conducted using two long-term stations in Bago and Zaung Tu within the basin. A clear need to improve the monitoring of the basin to manage the water infrastructure for water and flood management purposes is demonstrated. Owing to this urgent need, the establishment of a hydrological telemetry system in the basin aims to improve and increase the gauged area in the basin. An additional five weather stations and three water level stations along the river helps to increase the coverage of the observation over the river basin. The goal of this paper is to show the current efforts in co-establishing the hydrological telemetry system with various stakeholders in the Bago river basin to support a planned flood-forecasting platform, to support disaster risk reduction activities in the basin. This paper also aims to illustrate the benefits of such a telemetry system not only for disaster risk-reduction efforts but also in providing the understanding of subdaily observations as a validation dataset over the basin.

## 2. Co-Establishment of the Hydrologic Telemetry System

The hydrological telemetry system is co-established by the UTokyo-YTU partnership with local stakeholders. The goal of co-establishing the telemetry system is to develop a flood forecasting and early warning system under a disaster risk-reduction management platform. The local stakeholders are defined as the local partner agencies with mandated responsibilities related to water resource utility and navigation in the Bago River basin. The local partner agencies include the Department of Meteorology and Hydrology (DMH), Irrigation and Water Utilization Management Department (IWUMD), Department of Hydropower Planning (DHP), Department of Water Resources and Improvement of River Systems (DWIR), and the Bridge Department under the Ministry of Construction (MoC).

### 2.1. Organizing Participatory Approach

The hydrological telemetry system is aimed at becoming the backbone of the flood forecasting and early warning system in the basin. This will provide valuable data for research and operational needs. The co-establishment of the telemetry system is needed to satisfy both the research needs for UTokyo-YTU and the operational needs for the stakeholders. The idea of the system co-establishment arises from the shared responsibility in proactive roles through collaboration. The academic side provides the equipment and technical knowledge, while the stakeholders provide local knowledge, site preparations, and accountability for long-term maintenance. The group conducts frequent consultations and follow-up meetings in dealing with issues and challenges in co-establishing the system. The group undergoes shared capacity development in installing the equipment on site, preparing the designs of the required site, and maintenance activities. The proactive collaboration among the groups ensures the shared accountability in utilizing the developed system even after project completion.

### 2.2. Telemetry System in Bago River Basin

The hydrological telemetry system in the Bago River basin is shown in **Fig. 1** and described in **Table 1**. The system has a total of 8 stations, which consists of 5 weather stations and 3 water level stations. All of the stations are stand-alone, and equipped with solar panel for energy supply and cellular-network-based communication for data transfer. Four weather stations were already installed in March 2016 (BAGO-01) and March 2017 (BAGO-02, BAGO-03, BAGO-04), whereas one water-level station was installed in May 2017 (BAGO-06). The water-level stations utilize the floating-type sensor that requires a stilling well structure on site before equipment installation. Dr. Aung Than Oo of IWUMD led the design and construction of the water-level stations' stilling well structure at the Tawa Sluicegate. The installation of the last weather station is scheduled for December 2017 and next year for the remaining water level stations. The data from the stations are sent to the UTokyo and YTU data servers and shared among the groups. All of the stations are currently recording at 10-minute intervals and are transmitting recorded data every first 10-minutes of the hour.

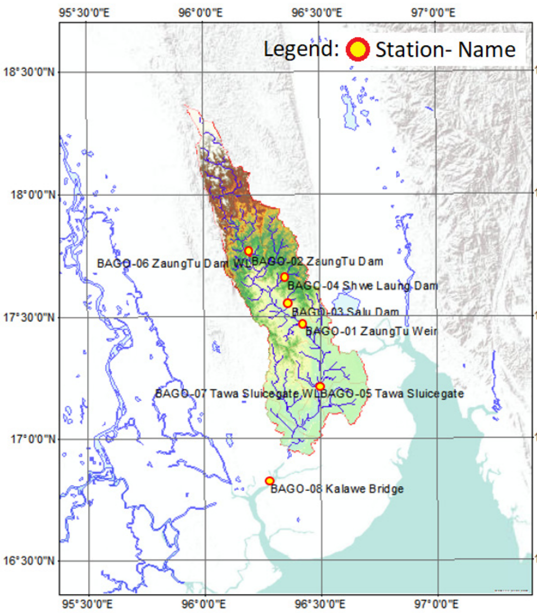


**Fig. 1.** Stations of the telemetry observation.

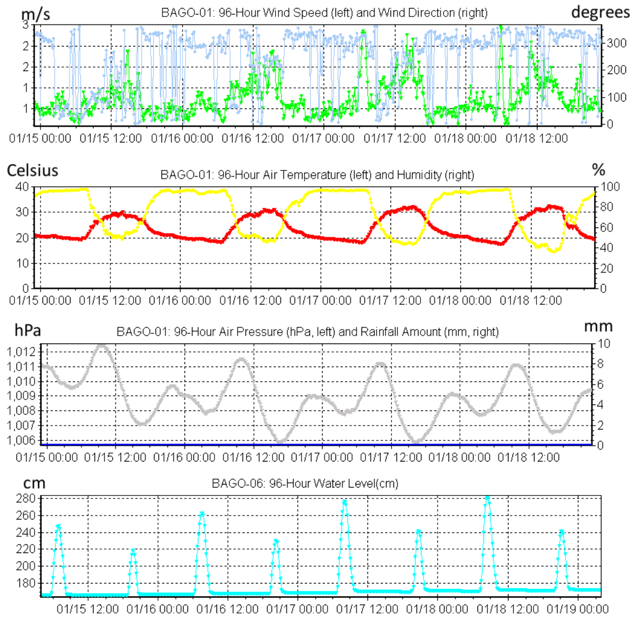


**Fig. 2.** Realtime 96-hr time series of BAGO-01 and BAGO-06.

**Table 1.** Overview of the observation stations (Note: W=Weather, WL=Water Level).

| Station | Name | Stakeholder |
|---|---|---|
| BAGO-01 | ZaungTuWeir-W | IWUMD |
| BAGO-02 | ZaungTuDam-W | DHP |
| BAGO-03 | SaluDam-W | IWUMD |
| BAGO-04 | ShweLaungDam-W | IWUMD |
| BAGO-05 | TawaSluicegate-W | IWUMD |
| BAGO-06 | TawaSluicegate-WL | IWUMD |
| BAGO-07 | ZaungTuDam-WL | - |
| BAGO-08 | Kalawe-WL | DWIR |

### 2.2.1. Description of Telemetry System Dataset

The weather stations can observe 6 weather parameters (rainfall, air temperature, humidity, air pressure, wind speed, and wind direction), while the water level stations only observe 1 parameter (water level).

**Figure 2** shows a near real-time visualization of the collected weather parameters from the Zaung Tu Weir Station (BAGO-01). It includes three panels of the recent 96-hour time-series plot and near real-time readings of wind speed, wind direction, air temperature, humidity, air pressure, and rainfall amount. The uppermost panel shows the time series of wind speed (green line with left side *y*-axis in m/s) and wind direction (light-blue line with right side *y*-axis in degrees). The next panel shows the time series of air temperature (red line with left side *y*-axis in Celsius) and humidity (yellow line with right side *y*-axis in percentage). The second lowest panel shows the 10-min rainfall on the right and air pressure on the left. The lowermost panel shows the water level measurements from BAGO-06. **Fig. 2** shows a near real-time visualization of the water level measurements from the Tawa Sluicegate Station (BAGO-06). It shows the time-series of the most recent 96-hour collected data and the 10-minute intervals that can reveal the influence of tidal fluctuations in greater detail. This potentially allows the decomposition of the different temporal components of tidal fluctuations. It has been observed to have tidal impacts on the water level up until the Bago Station at approximately 0.70 m fluctuation; therefore, the tidal impact at Tawa station is possibly higher than 0.70 m since it is located on the more downstream part of the Bago River. One ongoing study uses the observations at Tawa station to understand the impact of tidal fluctuations on the discharge and inundation in the Bago River.

### 2.2.2. Key Challenges in Co-Establishing Telemetry System

The co-establishment of a hydrological telemetry system is essential for providing a base platform for monitoring, early warning, and the flood forecasting system in the Bago River basin. Three main challenges include: (1) equipment handling and maintenance; (2) data transfer and access by stakeholders; and (3) gaps in the observation network. Equipment handling and maintenance necessitate knowledge transfer and continual capacity development. Specific conditions arise in equipment handling; therefore, constant updates of the protocol manual are essential for the operational longevity of the stations. The protocol manual serves as the compilation of all the equipment handling and troubleshooting procedures based on the combination of technical knowledge from experts and the shared accumulated experience of stakeholders. This manual is key for long-term maintenance and ensured the longevity of the equipment in stations and the entire telemetry system. Data transfer and access by stakeholders are central to the establishment of the telemetry system. The goal for making such automatic measurements and data receiving are such that the stakeholders can access the data for the needs of the stakeholders. The telemetry system is a sim-based mobile communication data transfer, which was chosen for a low-budget stand-alone system. However, some information technology (IT) knowledge is essential for the operation of the telemetry system. The steep learning curve in IT is one of the obstacles encountered, unless employing a consultant or IT company can provide IT expertise. Finally, the entire network owing to budgetary limitations and/or access limitations cannot cover the river basin. The Bago River basins' upper catchment is mountainous terrain, limiting both access and cellular communication coverage. Therefore, the observation network cannot entirely cover the basin. Because of these limitations, some spatial gaps in the coverage exist. This is where the satellite data estimates can augment the observation network. The study herein attempts to fulfill this need. The preliminary assessments of the satellite dataset are essential in augmenting the observation gap of the ungauged areas of the catchment, and in demonstrating the benefits of establishing a telemetry system in providing subdaily measurements.

## 3. Benefits of Telemetry System in the Provision of Subdaily Rainfall Observation

An alternative approach to obtaining subdaily observations is by using satellite rainfall estimates. Extensive studies have applied satellite rainfall estimates for various applications such as water resource management, hydrological simulations, and early warning systems. However, satellite rainfall estimates contain uncertainties related to complex terrains, coastlines, inland water bodies, light precipitation, etc [6]. The use of satellite rainfall estimates necessitates the assessment of its quality over the catchment and the investigation of correction methods to improve the product. The goal of the section is to conduct a preliminary assessment of subdaily satellite rainfall estimates from GPM and GSMaP in comparison to gauge stations of the telemetry system, as the benefit of establishing a hydrological telemetry system in the basin. This highlights the necessity of the subdaily observation network and also explores the use of the satellite estimates for monitoring and other operational needs. This can help in combining the satellite dataset with the telemetry observation network to improve the monitoring coverage for rainfall estimates. A combination of descriptive statistical metrics and categorical statistics were used to investigate the difference between satellite rainfall and gauge rainfall. The mean bias (BIAS), root-mean-square error (RMSE), and the Pearson correlation coefficient (CC) were used in describing the difference between the two datasets as shown by the equations below:

$$\mathrm{BIAS} = \frac{1}{N}\sum_{i=1}^{N}(S_i - G_i) \quad \dots\dots\dots \quad (1)$$

**Table 2.** Contingency table.

| Category | G>=Threshold | G<Threshold |
|---|---|---|
| S>=Threshold | a (Hits) | c (False Alarm) |
| S<Threshold | b (Miss) | d (correct negative) |

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - G_i)^2} \quad \dots\dots\dots \quad (2)$$

$$\mathrm{CC} = \frac{\sum_{i=1}^{N}\left(S_i - \overline{S}\right)\left(G_i - \overline{G}\right)}{\sqrt{\sum_{i=1}^{N}\left(S_i - \overline{S}\right)^2}\sqrt{\sum_{i=1}^{N}\left(G_i - \overline{G}\right)^2}} \quad \dots\dots \quad (3)$$

The ability of the satellite data products to detect rain or no-rain events were assessed using a contingency table (**Table 2**). Categorical statistics were utilized as shown by the equations below.

$$\mathrm{POD} = \frac{a}{a+b} \quad \dots\dots\dots \quad (4)$$

$$\mathrm{FAR} = \frac{c}{a+c} \quad \dots\dots\dots \quad (5)$$

$$\mathrm{CSI} = \frac{a}{a+b+c} \quad \dots\dots\dots \quad (6)$$

$$\mathrm{ETS} = \frac{(a-ar)}{(a+b+c-ar)}; ar = \frac{(a+b)(a+c)}{n} \quad . \quad (7)$$

$$\mathrm{HSS} = \frac{2(ad-bc)}{(a+b)(b+d)+(a+c)(c+d)} \quad \dots \quad (8)$$

$$\mathrm{TSS} = \frac{(ad-bc)}{(a+c)(b+d)} \quad \dots\dots\dots \quad (9)$$

The POD assesses the percentage of correctly detected rain occurrences. The false alarm rate (FAR) describes the percentage of false positive detection of rain occurrence. The critical success index (CSI) shows the percentage of correctly detected rain occurrences for all events except the correctly detected no-rain days. The equitable threat score (ETS) is slightly similar to the CSI but includes the impact of random events. The Heidke skill score (HSS) and true skill score (TSS) are both single-value performance scores in different formulations for evaluating the ability of predicting rain events.

## 4. Zaung Tu Weir Station as a Pilot Validation Dataset for Subdaily Rainfall Measurement in the Basin

This study investigates two satellite-based rainfall estimates from GPM and GSMaP. The GPM dataset is called the integrated multisatellite retrievals for GPM (IMERG), but will be referred to as GPM in this paper. The GPM satellite was launched in February 2014 and succeeded the tropical rainfall measuring mission (TRMM), which aims

**Table 3.** Statistical scores for NRT products.

| Scores | GSMAPNR | GPME | GPML |
|---|---|---|---|
| CC | 0.40 | 0.41 | 0.42 |
| RMSE | 2.86 | 2.86 | 2.86 |
| BIAS | -0.21 | -0.18 | -0.17 |
| CC (JUN) | 0.60 | 0.51 | 0.48 |
| RMSE (JUN) | 2.62 | 3.03 | 3.17 |
| BIAS (JUN) | -0.06 | 0.02 | 0.04 |
| CC (JUL) | 0.40 | 0.39 | 0.44 |
| RMSE (JUL) | 3.67 | 3.47 | 3.37 |
| BIAS (JUL) | -0.52 | -0.41 | -0.41 |

**Table 4.** Statistical scores for research products.

| Scores | GSMAPST | GPMF |
|---|---|---|
| CC | 0.41 | 0.42 |
| RMSE | 2.72 | 3.07 |
| BIAS | -0.26 | 0.04 |
| CC (JUN) | 0.60 | 0.48 |
| RMSE (JUN) | 2.36 | 3.51 |
| BIAS (JUN) | -0.18 | 0.16 |
| CC (JUL) | 0.32 | 0.44 |
| RMSE (JUL) | 3.58 | 3.44 |
| BIAS (JUL) | -0.52 | -0.21 |

to improve the spatiotemporal resolution, spatial coverage, and precipitation measurement accuracy [7, 8]. The GPM dataset is a half-hourly 0.10-degree global rainfall dataset that includes several release types such as research products and near real-time products (Final Run is the research product with 4-months latency – referred to here as GPM, Early Run with 6-hour latency – GPME, and Late Run with 18-hour latency – GPML). In contrast, the GSMaP [9, 10] is a multisatellite dataset focused on blending microwave radiometer data and infrared dataset to produce hourly 0.10-degree global precipitation maps. The GSMaP also utilizes the estimates from GPM satellite observations. Similar to GPM, GSMaP also has research products (standard version with 3-day latency from March 2014 – referred to here as GSMAPST) and near real-time products (NRT with 4-hour latency – GSMAPNR).

### 4.1. Assessment of Hourly Satellite Rainfall

The reference dataset used here is the 10-minute gauge rainfall located in the Zaung Tu Weir (will be denoted as ZTW or BAGO-01). The period for assessment is selected to include Universal Time Coordinate or UTC 5:00 25-MAY-2016 to 10:00 22-AUG-2016. The satellite dataset was extracted from the pixel covering the station location. Research products (GSMAPST and GPM) and near real-time products (GSMAPNR, GPME, GPML) were compared with the gauge rainfall. For comparing the hourly rainfall, the threshold used to construct the contingency table was 1/24 mm/hour. The threshold used for longer time aggregations were scaled against the hourly rainfall threshold.

The NRT satellite rainfall products have generally similar performances, as summarized in **Table 3**. The GSMAPNR performs slightly better in terms of correlation, and the RMSE score is better than the GPME and GPML estimates. The GSMAPNR tends to show an underestimation compared with the gauge station. The scores show very similar performances between the satellite products. In terms of the research products, the correlation coefficients for both satellite datasets were not improved. However, the RMSE of the research products are slightly decreased compared to the near real-time products. Further, the scatter plots in **Fig. 3** were checked for linear correspondence and for significance. All of the satellite dataset show the similar correlation coefficient and indicated significance when the p-value is almost zero.

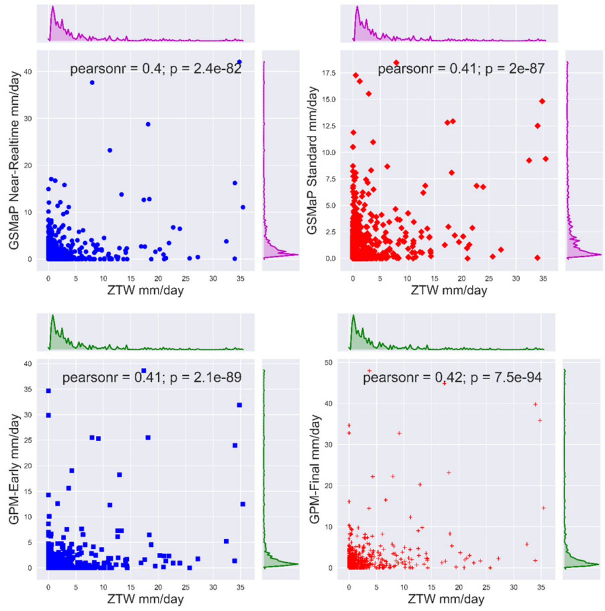


**Fig. 3.** Scatterplots of the satellite dataset with CC and p-value.

The results of the categorical statistics show an averaged detection rate of 0.52 for GSMAPNR, and 0.47 for both GPME and GPML. The CSI scores are 0.39 for GSMAPNR, 0.39 for GPME, and 0.42 for GPML. A slight increase occurred for the CSI score in the late release as compared to the early release GPM. This increase is due to the improvement of the lower FAR score. The NRT products do not show significant monthly variation in the scores. In terms of the standard products, the GSMAP has better detection capability at 0.50 while the GPMF scored 0.47 but with an opposite trend for the FAR. Both satellite products have 0.47 CSI. These scores also do not change for June and July. The results do not vary significantly from each of the satellite dataset as summarized in **Tables 5** and **6**. However, the GPM dataset tends to show lower FAR scores than the GSMaP dataset for both studies (**Table 6**) and near real-time products (slightly lower FAR for GPML than GPME, **Table 5**).

In general, the satellite estimates show similar characteristics, as revealed by typical statistical metrics. The

**Table 5.** Categorical scores for NRT products.

| Scores | GSMAPNR | GPME | GPML |
|---|---|---|---|
| POD | 0.52 | 0.47 | 0.47 |
| FAR | 0.31 | 0.29 | 0.22 |
| CSI | 0.39 | 0.39 | 0.42 |
| POD(JUN) | 0.54 | 0.47 | 0.47 |
| FAR(JUN) | 0.41 | 0.33 | 0.25 |
| CSI(JUN) | 0.40 | 0.37 | 0.41 |
| POD(JUL) | 0.56 | 0.54 | 0.52 |
| FAR(JUL) | 0.36 | 0.20 | 0.15 |
| CSI(JUL) | 0.43 | 0.47 | 0.47 |

**Table 6.** Categorical scores for research products.

| Scores | GSMAPST | GPMF |
|---|---|---|
| POD | 0.50 | 0.47 |
| FAR | 0.31 | 0.21 |
| CSI | 0.41 | 0.42 |
| POD (JUN) | 0.50 | 0.47 |
| FAR (JUN) | 0.38 | 0.25 |
| CSI (JUN) | 0.38 | 0.41 |
| POD (JUL) | 0.52 | 0.52 |
| FAR (JUL) | 0.25 | 0.15 |
| CSI(JUL) | 0.45 | 0.47 |

satellite dataset also does not vary significantly in detecting rain and no-rain events, as revealed by the categorical statistics. The research and near real-time products have similar performance characteristics. The assessment of hourly satellite datasets show some potential usage based on the correlation coefficient of close to 0.40 with the p-value (<0.05). The p-value describes the rejection of the null hypothesis that the coefficient is almost zero. Therefore, a low p-value indicates the non-rejection of the null hypothesis. This means that the linear correspondence indicated by the coefficient is statistically significant to a certain alpha level of 0.05 that translates to 95% confidence interval.

## 4.2. Dependence of Performance Metrics to Temporal Aggregation

The satellite rainfall was temporally aggregated from hourly to 3-hourly, 6-hourly, 12-hourly, and daily aggregations. The aggregation was performed to understand the scale at which the satellite rainfall demonstrates some useful skills under the subdaily scales, which is typically defined by a linear correlation score of 0.5 and above. Owing to the similar characteristics of the GPM datasets, only the GPM Final run was compared with the GSMAPST and GSMAPNR. Daily and 72-hour aggregations were also performed to check if the increase in temporal aggregation should increase the correlation coefficient.

**Figure 4** shows the impact of temporal aggregation to CC and BIAS scores. The satellite dataset shows an almost linear increase in CC scores as temporal aggregation increases. The 3-hour aggregation seems to mark the start of the useful skill for the satellite estimates. However, it seems that the increase in the CC scores remains constant for the GSMAP rainfall estimates. Both satellite products exhibit an increase in the CC scores as a function of increasing temporal aggregation, with the GSMAP products showing slightly better performance from the 3-hourly aggregation and higher. Although the results show that temporal aggregation causes an increase in the CC scores, it also increases the RMSE, as well as larger errors indicated by the RMSE values. Both GPM and GSMAP satellite products exhibit such a tendency. Using the linear trends plotted for the CC versus ln(RMSE) followed by a slope comparison, the GPM product shows a larger tendency to increase the RMSE with the increase in the CC score, compared to the GSMAP products. The increase in the RMSE as a function of temporal aggregation is shown to be a general increase in the underestimation for GSMAP estimates, while an increase in the overestimation is shown for the GPM estimates. To further understand the potential useful skill, additional regression plots were shown in **Fig. 5**. All of the satellite estimates show a CC score greater than 0.5 and are shown to be statistically significant by the almost zero p-value. A similar trend is shown for the 6-hourly aggregated satellite estimates. Focusing on the scatter plots in the same figure, the outliers from the GPM estimates show a significantly larger magnitude compared to the GSMAP estimates. The standard version of the GSMAP estimates shows a decrease in the magnitude of the outliers as compared to the near real-time version.

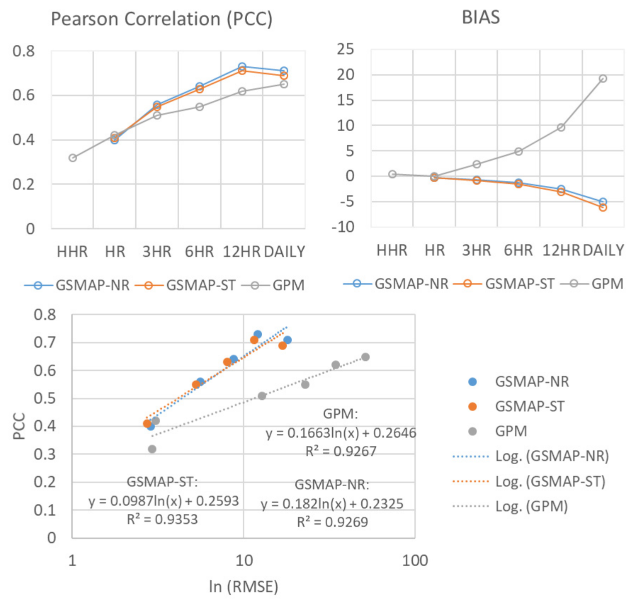

**Fig. 4.** Impact of temporal aggregation to statistical metrics(CC, BIAS, RMSE).

## 4.3. Impact of Temporal Aggregation to Categorical Statistics

The categorical statistics were calculated for half-hourly aggregations up to daily aggregations. **Fig. 6** shows the plot for POD, FAR, TSS, and ETS. The gen-

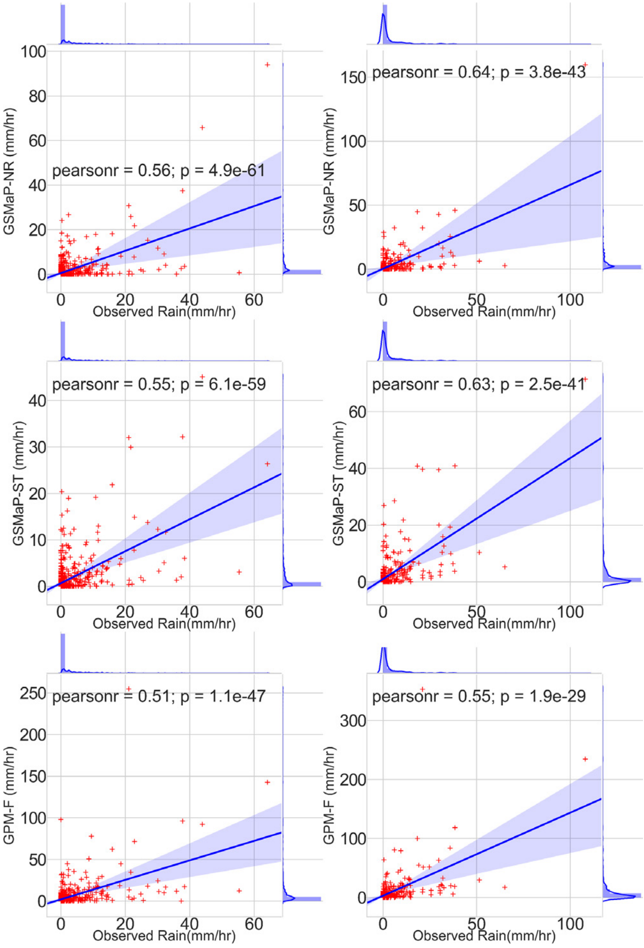


**Fig. 5.** Increase of CC due to temporal aggregation from 3 hourly (left) and 6 hourly plots (right).

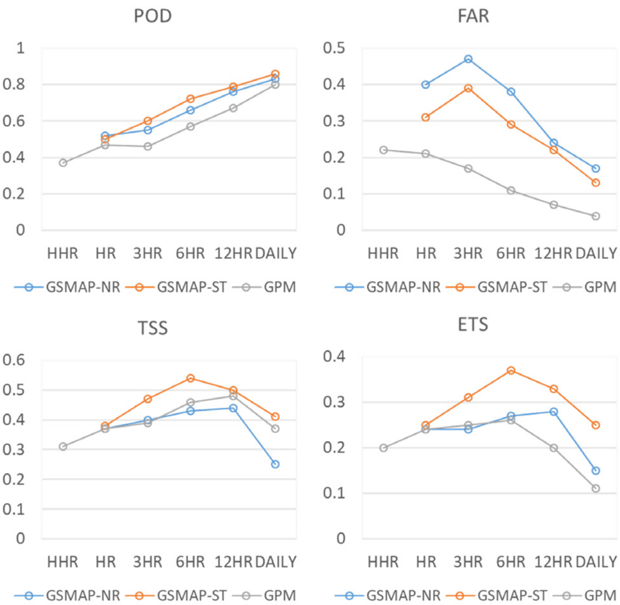


**Fig. 6.** Dependence of categorical statistics to temporal aggregation.

eral trend of increasing statistical performance, showing dependence on temporal aggregation is also seen for the POD and CSI. The detection capability of the satellite estimates increases as the aggregation increases. The GSMAP satellite estimate shows better POD than that of the GPM estimates. As shown by the increase in the statistical scores and POD, the FAR decreased in general by comparing the hourly and daily aggregation scale. The GPM satellite estimates show lower FAR than the GSMAP estimates. The GSMAP standard version indicates a better accuracy compared to the near real-time products. The GSMAP estimates show almost constant FAR scores, indicating no improvement in the false alarms even with increased temporal aggregation. In comparison, the trends on the POD are not similarly shown in the TSS, HSS (not included in the figure), and ETS. The skill scores do not increase as the POD and CC scores increase. The TSS measures the ability to separate rain events from no-rain events, which indicates that it does not monotonically increase with increasing temporal aggregation. Instead, it shows the maximum temporal aggregation that reaches its maximum value. This can be a good indicator for the temporal aggregation that is necessary in providing useful skills for satellite estimates. The GSMAPST shows improvement in the TSS as compared to the near real-time GSMAPNR. A similar trend is shown for the ETS, which accounts for random events. The GSMAPST shows considerably better skills than the GSMAPNR and GPM that peaked at the 6-hour aggregation. Both TSS and ETS plots show that the 3-hourly to 12-hourly aggregations improve the ability of the satellite estimates. The six-hourly aggregation almost satisfies the maximum skill scores and also maximizes the increase in statistical metrics such as the CC and POD.

## 5. Conclusion and Future Work

The work presented shows the efforts in developing a hydrological telemetry system in the Bago River basin, through the proactive collaboration of all the stakeholders. Some key challenges were identified in developing the hydrological telemetry system in the basin. The establishment of the hydrological telemetry system greatly contributes to the backbone of monitoring and observation in the basin since the data can be obtained in almost real time. The provision of such data can impact the operational needs of the local stakeholders that have a specific mandate related to water. In addition, the research needs for the forecasting modeling applications in the basin are also satisfied. To illustrate such benefits, the Zaung Tu Weir station was used as a pilot validation station for sub-daily rainfall estimates from two satellite estimates such as GPM and GSMAP for the investigation of the use of both the standard and near real-time satellite estimates. A combination of descriptive and categorical metrics was used to preliminarily assess the potential use of the satellite estimates. Three main points on the use of the satellite rainfall estimates were drawn, as follows:

(1) Hourly aggregations for both satellite rainfall products show potential use but may need some form of correction. Useful skill was found at 3-hourly aggregations and higher but 6-hourly aggregation shows the maximum useful skill based on the combination of typical statistical metrics (CC, RMSE) and categorical skill metrics (POD, FAR, TSS, and ETS).

(2) Standard and near real-time products of the GSMAP and GPM show comparable statistical performance metrics and categorical statistics, which indicates that near real-time satellite estimates can be used for the basin. However, the GSMAPST showed improvement in categorical skill scores as compared to the GSMAPNR. The aggregation of rainfall estimates increases uncertainty as indicated by the RMSE values, where the GSMAP tends to underestimate, as shown by the negative bias, and the GPM generally overestimates.

(3) Statistical metrics show some dependence on temporal aggregation. It is possible that the aggregation reduces the intermittency of the rainfall, which is dependent on the temporal scale. Future work includes preliminary assessment using additional stations. Confirmation of the results is needed. The combination of the satellite rainfall products, especially of the near real-time to the gauge station observations, should be also investigated in future work.

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**References:**

[1] IPCC, "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," IPCC, Geneva, Switzerland, 2014.

[2] S. Blenkinsop, E. Lewis, S. C. Chan, and H. J. Fowler, "Quality-control of an hourly rainfall dataset and climatology of extremes for the UK," International Journal of Climatology, Vol.37, No.2, pp. 722–740, 2017.

[3] W. W. Zin, A. Kawasaki, and S. Win, "River flood inundation mapping in the Bago River Basin, Myanmar," Hydrological Research Letters, Vol.9, No.4, pp. 97–102, 2015.

[4] S. S. Bhagabati and A. Kawasaki, "Consideration of the rainfall-runoff-inundation (RRI) model for flood mapping in a deltaic area of Myanmar," Hydrological Research Letters, Vol.11, No.3, pp. 155–160, 2017.

[5] A. Kawasaki, N. Ichihara, Y. Ochii, R. A. Acierto, A. Kodaka, and W. W. Zin, "Disaster response and river infrastructure management during the 2015 Myanmar floods: A case in the Bago River Basin," International Journal of Disaster Risk Reduction, Vol.24 (Supplement C), pp. 151 – 159, 2017.

[6] Y. Tian and C. D. Peters-Lidard, "A global map of uncertainties in satellite-based precipitation measurements," Geophysical Research Letters, Vol.37, No.24, 2010. L24407.

[7] Z. Liu, D. Ostrenga, B. Vollmer, B. Deshong, K. Macritchie, M. Greene, and S. Kempler, "Global Precipitation Measurement Mission Products and Services at the NASA GES DISC," Bulletin of the American Meteorological Society, Vol.98, No.3, pp. 437–444, 2017.

[8] G. Huffman, D. Bolvin, D. Braithwaite, K. Hsu, and R. Joyce, "Algorithm Theoretical Basis Document (ATBD) NASA Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG)," Nasa, December 29, 2013.

[9] T. Kubota, S. Shige, H. Hashizume, T. Ushio, K. Aonashi, M. Kachi, and K. Okamoto, "Global Precipitation Map using Satelliteborne Microwave Radiometers by the GSMaP Project : Production and Validation," In 2006 IEEE MicroRad, pp. 290–295, 2006.

[10] T. Ushio, K. Sasashige, T. Kubota, S. Shige, K. Okamoto, K. Aonashi, T. Inoue, N. Takahashi, T. Iguchi, M. Kachi, R. Oki, T. Morimoto, and Z.-I. Kawasaki, "A Kalman Filter Approach to the Global Satellite Mapping of Precipitation (GSMaP) from Combined Passive Microwave and Infrared Radiometric Data," Journal of the Meteorological Society of Japan. Ser. II, Vol.87A, pp. 137–151, 2009.

[11] W. McKinney and P. D. Team, "Pandas – Powerful Python Data Analysis Toolkit," Pandas – Powerful Python Data Analysis Toolkit, p. 1625, 2015.

[12] J. D. Hunter, "Matplotlib: A 2D graphics environment," Computing in Science and Engineering, Vol.9, No.3, pp. 99–104, 2007.

[13] M. Waskom, O. Botvinnik, P. Hobson, J. B. Cole, Y. Halchenko, S. Hoyer, A. Miles, T. Augspurger, T. Yarkoni, T. Megies, L. P. Coelho, D. Wehner, cynddl, E. Ziegler, diego0020, Y. V. Zaytsev, T. Hoppe, S. Seabold, P. Cloud, M. Koskinen, K. Meyer, A. Qalieh, and D. Allan, "seaborn: v0.5.0 (November 2014)," November 2014.

[14] E. Jones, T. Oliphant, P. Peterson et al. "SciPy: Open source scientific tools for Python," 2001 – [online; accessed Jan. 19, 2018]

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• "Data Generation of Daily Rainfall Time Series for Myanmar's Water Resources Planning," International Agricultural Engineering Journal, Vol.14, No.1, pp. 29-34, 2005.
• "Land Cover Mapping for Agricultural Water Management of Rice-based Irrigation Systems in Myanmar Using GIS and Remote Sensing," Journal of Rainwater Catchment Systems, Japan Rainwater Catchment Systems Association (JRCSA), Vol.12, No.2, pp.1-15, 2007, doi.org/10.7132/jrcsa.KJ00004557609.

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