How Has Malaysia Benefited from the High-Resolution Satellite Rainfall? Trends, Gaps and Further Research Opportunities

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This paper presents a scientific review on how Malaysia has benefited from the high-resolution satellite rainfall since its first launch in 1998. As a tropical country in which the environment is highly characterised by rainfall dynamics, public domain access of high-resolution satellite rainfall data could be very useful to support the hydrologic and related environmental studies. The scope of this paper includes achievements, the trend of studies, as well as gaps and future opportunities for scientific research. Examining this element is crucial in determining the present information on the status quo of the applications of space-based technology to Malaysian hydrologic research. Furthermore, this information is critical to charter the future action for the policymakers and revision of respective disciplines, including climate change, environmental sustainability, disaster resilience, food security, and education. Based on the search throughout the largest scientific databases of Web of Science and Scopus, five major trends have been identified. Those trends were ranked based on the number of research, 1) Satellite rainfall data performance and quality evaluation (40%), 2) Satellite rainfall data as input to environmental modelling (27%), 3) Rain fade & telecommunication (16%), 4) Satellite rainfall data quality improvement (7%), and 5) Rainfall studies. These trends were identified about 11 years after the satellite rainfall project started in 1998. The major achievement till now is validating the accuracy of the satellite rainfall and also downscaling it for local application.

Keywords: Tropical Rainfall Measuring Mission (TRMM); Global Precipitation Mission (GPM); hydrology; water

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I. INTRODUCTION

This paper provides a scientific review on how Malaysia had benefited from the high-resolution satellite rainfall since its launch in 1998. The launch of the high-resolution satellite rainfall of Tropical Rainfall Measuring Mission (TRMM) in 1998 remarks a new era of global hydrology, especially for/in the tropical region. With the new datasets that provide rainfall information at the finest spatial (0.25°) and temporal (3-hourly) scale ever, the TRMM data is expected to contribute significant knowledge and help in the advancement of the rainfall and related hydrological studies. Malaysia, as one of the countries in the tropical equatorial region with their climate and livelihood, is directly influenced by high dynamics rainfall and may benefit from these scientific advances to reach sustainable development. Therefore, reviewing the scientific achievements at the local scale is important in charting our way towards the future and what are the elements we should opt.

Although the early development of measuring rainfall from space has started in 1981where rainfall has been estimated using the cloud imageries from the MeteoSAT satellite, it did not reach the operational level until 1998. The limitation of the coarse and temporal resolution has been overcome by the Tropical Rainfall Measuring Mission (TRMM) project; a joint initiative by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (Simpson *et al.*, 1996). The satellite was specifically designed to study the precipitation that occurred within the tropics and sub-tropics region (35°N and 35°S) from low orbit altitude about 237km. Theoretically, the TRMM satellite used an indirect approach to estimate the rainfall. The mechanism of TRMM to estimate the rainfall was driven by the active microwave precipitation radar (PR), TRMM microwave imager (TMI), and the visible, infrared scanner (VIRS) (NASDA, 2001). The reflected signals were empirically related to the rainfall values at the ground known as Z-R relationships (Iguchi *et al.*, 2000).

The initiative by the Precipitation Processing System of NASA has created the much-sought operational data when combined with other meteorological satellites. At present, the TRMM based precipitation products were available at 3-hourly, daily and monthly scale. These datasets have supported significant scientific studies on tropical or sub-

tropical rainfall at various scale and ecosystems (National Research Council of the National Academies, 2006). Before its success and the endeavour to ensure the longevity of their contribution, the project was succeeded by the Global Precipitation Mission satellite in 2014 (Hou *et al.*, 2014). This new version of precipitation data has an improved spatial resolution of 0.1° and half-hourly temporal resolution.

Although Malaysia has relatively good coverage of rain gauge distribution and effective weather radar monitoring systems provided by the respective agencies primarily the Department of Irrigation and Drainage and Malaysian Meteorological Department (Mahmud *et al.*, 2014), the development of satellite rainfall which provides public access data with sound quality provides the researchers with ample opportunities to strengthen the existing systems. In this context, satellite rainfall data can be used as either substitute or back-up data in case of data conflict situation (DCS) which involved missing data condition, data sharing complexity, unknown quality of rainfall data and unavailable data condition. Hence, it is a known fact that climate change has impacted Malaysia either directly or indirectly via fluctuations in rainfall patterns (Zin *et al.*, 2010; Tangang *et al.*, 2013). Looking at the other tropical countries especially the developing ones which make use of this publicly free access satellite rainfall technology and data to their advantage, it is a wise and progressive action for researchers to emulate them. From a technical perspective, it provides an opportunity to learn the knowledge, science and engineering aspect in space application for weather and climate application in the tropical region. Who knows that in the future, we might be coordinating in those large scale projects or initiating our specific space weather programs that could benefit the regional community and spearheading new economic opportunities in local space sectors?

To address the aforementioned situation, this paper has set up two objectives; 1) search, analysed and systematically categorise the scientific research regarding the use of satellite rainfall in Malaysia and, 2) identify the subsequent gaps and future opportunities. Scholarly articles from the two largest scientific databases, Web of Science and Scopus from 1998 until 2018, were used. Among the primary reason for the selection of these two databases are to ensure the scientific soundness and relevance of the scholarly works. These two databases were strictly peer-reviewed by

experts, and the total combined resources are large. Scopus database itself comprises 64 million articles, 21548 titles from about 5000 journals (Scopus, 2018). Web of Science, on the other hand, comprises nearly 90 million articles (Clarivate analytics, 2018). The output of this review should hopefully be able to track the trend on how Malaysia's benefited from one of the biggest global space science programs and assist the future strategy to optimise it.

II. GENERAL TREND OF SATELLITE RAINFALL UTILISATION & DEVELOPMENT IN MALAYSIA

Based on the statistic shown in Figure 1, there were five major trends in the research and studies related to the use of high-resolution satellite rainfall in Malaysia.
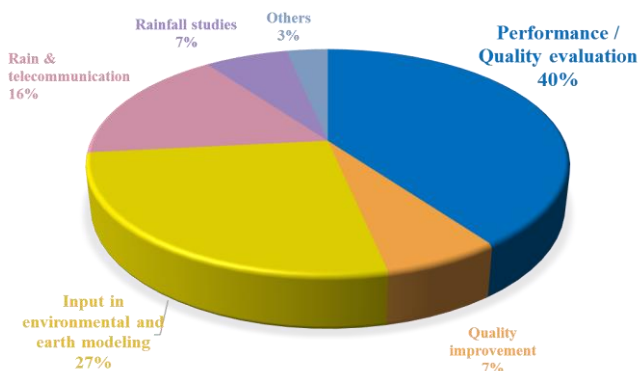

Figure 1. The trend of research and studies related to high-resolution satellite rainfall in Malaysia

The five trends are; 1) performance and quality evaluation (40%), 2) input to environment and earth modelling (27%), 3) rain and telecommunication (16%), 4) quality improvement (7%), 5) rainfall studies (7%) and others (3%). From the temporal perspective, major trends for Malaysia started in 2010, although the earliest was identified in 2002. This means that the significant scientific contribution occurred about ten years after the data was first captured in 1998. Table 1 shows the five scientific trends occurred at a different rate in 20 years (1998-2018).

The first and second trends are more frequent than the others, since 2011. These two trends were more dominant and frequent compared to the other trend because of several factors. The first trend primarily influenced by the nature of

the algorithm used to estimate the rainfall that was based on global datasets. Therefore, using it for the local environment might induce inaccuracy. Also, the lesson learnt from the previous studies related to satellite rainfall tends to highlight the necessity to determine the quality of the datasets at the local scale for better results (Huffman *et al.*, 2005).

For the second trend, the stimulus was highly depending on the characteristics of the satellite rainfall which capable in providing the measurement of remote areas, at extensive coverage and reliable temporal scale (3 hourly to monthly). Because of this, the satellite rainfall data was significantly used as a substitute or supporting the in-situ measurement for regional analysis and areas which experienced in-situ data conflict situation (DCS) (Mahmud *et al.*, 2018).

The third trend, which was more towards the application of satellite rainfall data to telecommunication engineering, was only active from 2011 to 2014. It was an obvious scientific fact that the frequency used in telecommunication, especially involving the K band was highly sensitive to water droplets. Because the satellite rainfall estimation was depending on the empirical relationship between the precipitable water and signal backscatter (Iguchi *et al.*, 2000b), it does make sense that it was useful in telecommunication application. It provides information in knowing how severe the effects of the rain fade effects to telecommunication signals (ITU, 2015).

Following the gap identified by the first two trends, the fourth scientific research niche was focusing on quality improvement. The earliest works were identified in 2015, which focuses on reducing the quantitative rainfall estimation error during the heavy monsoon thunderstorm (Mahmud *et al.*, 2015). Subsequent research then emphasised on the improvement of the spatial resolution where smaller gridded rainfall (~5km) was created (Mahmud *et al.*, 2018). The downscaling was required because the catchment size in the humid tropics of Southeast Asia is relatively small, and its rainfall variation is highly dynamic.

Table 1. Scientific research utilising the high-resolution precipitation in Malaysia

Topics / Year	2002	2010	2011	2012	2013	2014	2015	2016	2017	2018
Performance / Quality evaluation		Daily TRMM rainfall (Varikoden *et al.*)	Monthly TRMM rainfall (Abiola *et al.*)	Monthly TRMM rainfall (Semire *et al.*)	Monthly TRMM rainfall (Nadzri *et al.*)	Minute TRMM rainfall (Omotosho *et al.*)	Monthly TRMM rainfall (Semire *et al.*)		Daily rainfall TRMM (Paska *et al.*)	Daily rainfall (Zad *et al.*)
				Monthly rainfall (Huey and Ibrahim)			Seasonal TRMM rainfall (Mahmud *et al.*)		Multi-temporal TRMM (Rauniyar *et al.*)	
									Daily GPM (Mahmud *et al.*)	
Quality improvement							Temporal downscaling (Mahmud *et al.*)			Spatial downscaling (Mahmud *et al.*)
Input in environmental modelling		Water balance analysis (Sani *et al.*)	Forest water yield (Mahmud and Hashim)			Surface water (Ali *et al.*)		Forest ecology assessment (Azmy *et al.*)		Hydrology modelling (Ramli and Ibrahim)
		Forest water yield (Mahmud and Hashim)						Climatological assessment (Ibrahim *et al.*)		
								Surface run-off (Hashim *et al.*)		
Rain & communication			Rain fade in tropics (*Azlan et al.; Aris and Din; Yusuff et al.; Omotosho et al.*)							
Rainfall studies	Diurnal rainfall characterisation at synoptic regional scale (Soroshian *et al.*)						Seasonal and diurnal variability of rain height (Isiaka and Khamis)		Characterisation of Sarawak daily rainfall (Patrick *et al.*)	
Others						Review for hilly catchment (Mahmud *et al.*)				

Finally, the fifth trend, which involved studying the rainfall from space, had occurred occasionally in two periods, in 2002 and 2015-2017. Using the satellite rainfall data for rainfall or hydrometeorology analysis require less complex processing rather than modelling or calibrating, we hypothesised that this trend is getting greater attention just recently by the scientists and the community due to the availability of the data and advancement of the processing software. ESRI, for instance, evolved drastically in 2004 before the integration with ERDAS Imagine module (Smith, 2004). Furthermore, the open-source of cloud-based GIS system may also contribute to these trends (Sutton, 2009).

III. ACHIEVEMENTS, GAPS & OPPORTUNITIES

A. Trend 1 - Performance and Quality Evaluation

The performance and quality evaluation primarily involved the quantitative accuracy of the rainfall estimates over local areas. Generally, a comparison against the rain gauges was conducted. It was quite difficult to define the consensus because the validation strategy and methodology were different from each other. These differences include the scale of rainfall, region of interest, the number of samples and techniques, however, were varied. In summary, all types of rainfall from minutes to annual scale have been conducted (Table 2).

Table 2. Summary of the performance and quality evaluation studies on satellite rainfall in Malaysia

Source	Data product	Technique	No. of stations	Rainfall scale	Average error	Ratio (%)	Correlation	NSE
Varikoden *et al.*, 2010	TRMM 3B42	Discrete comparison	4	3-hourly	-	18	0.710	-
Abiola *et al.*, 2011	TRMM 3B43	Discrete comparison	-	Monthly	-	15	0.834	-
Semire *et al.*, 2012	TRMM 3B43	Discrete comparison	4	Monthly	-	15	0.871	-
Huey and Ibrahim 2012	TRMM 3B43	Discrete comparison	24	Annual	-	-	0.623	-
Nadzri *et al.*, 2013	TRMM 3B43	Discrete comparison	26	Monthly	90mm/mth	-	-	0.5
Omotosho *et al.*, 2014	TRMM 3B42	Discrete comparison	57	Minute	50mm/min	-	0.700	-
Mahmud *et al.*, 2015	TRMM 3B43	Interpolated surface	984	Seasonal	100mm/mth	50	0.7	0.5
Semire *et al.*, 2016	TRMM 3B43	Discrete comparison	5	Monthly	-	-	0.800	-
Paska *et al.*, 2017	TRMM 3B42	Discrete comparison	20	Daily	-	-	0.500	-
Rauniyar *et al.*, 2017	TRMM 3B42	Discrete comparison	49	Daily	5mm/d	6	0.800	-
Patrick *et al.*, 2017	TRMM 3B42	Discrete comparison	25	Daily	140mm/mth	17	0.800	-
Mahmud *et al.*, 2017	GPM Imerge	Interpolated surface	843	Daily	20mm/d	-	0.6	-
Zad *et al.*, 2018	TRMM 3B42	Discrete comparison	30	Daily	-	27	0.3	-

It was proven that the satellite rainfall estimates were having different accuracy and performance via season and locations. Some consensuses that can be identified were the quantitative measurement during the heavy rainfall (Mahmud *et al.*, 2015; Zad *et al.*, 2018; Paska *et al.*, 2017). Other significant information was that the correlation was better during the wet seasons (Semire *et al.*, 2016; Mahmud *et al.*, 2017; Patrick *et al.*, 2017). It was indicated, however,

that different evaluation method yields different results (e.g., Rauniyar *et al.*, 2017).

Almost all of the validation works were conducted by referring to the ground rain gauges. Performing this famous methodology possesses limitation as mentioned by Mahmud *et al.* (2015); the different mechanism of rainfall measurement between those rain gauge and satellite precipitation radar. While rain gauge was measuring the

amount of water trapped inside the gauge, the satellite precipitation radar estimates the rainfall based on the probable precipitable water in the atmosphere. The horizontal wind might cause the changes of rainfall pattern on the ground; hence commit uncertainties in the validation.

It was suggested that the alternative validation on satellite rainfall could be done with other devices which had a similar mechanism such as ground precipitation radar. If it is conducted simultaneously and using exact frequency, theoretically it could provide a more accurate justification on the performance and limitation of the satellite data performance at a local scale. For information, Malaysia did have their precipitation radar which operated by the Malaysian Meteorological Department. The biggest challenge could be dealing with the processing of the data, especially in term of adjusting the angle of propagation and projecting the images.

B. Trend 2 - Input for Environmental Modelling

The development for satellite rainfall utilisation in environmental modelling comprises two major spheres, 1) hydrological modelling and 2) ecological assessment. The exploitation of satellite rainfall data in hydrological modelling was intended in conducting a large scale or regional scale modelling (Ramli and Ibrahim, 2016; Ali *et al.*, 2014; Sani *et al.*, 2010; Hashim *et al.*, 2016) and remote catchment (Mahmud and Hashim, 2010, 2011).

In general, despite reliable results given in all studies, it shared common problems; uncertainties during low rainfall season and large errors during heavy rain. Perhaps the next step in refining the modelling result is to carefully localise the satellite rainfall data especially when it involved quantitative hydrology such as run-off estimation and yield estimation.

In ecological assessment, satellite rainfall data is useful in studying the forest species adaptation towards the changing environment. Azmy *et al.* (2016) had successfully utilised the long-term rainfall and other meteorological data in identifying the early signals of dipterocarp reproductivity. On the other hand, Ibrahim *et al.* (2016) had investigated the relationship between rainfall, temperature and the El-Nino Southern Oscillation. This shows that the satellite rainfall could be optimised to study the gap left by the limitation of rain gauges.

However, such studies were only reported in 2016. The TRMM has released the data in 2002. This means that the development of research areas that irrelevant to hydrology and water take longer time to advance in Malaysia. To encourage this multi-disciplinary trend to continue to evolve in the future, the gap of knowledge between the data scientist and the environmental scientist must be narrowed. Perhaps, the most effective ways to encourage such multi-disciplinary studies is to establish an open-access satellite rainfall geodatabase with a user-friendly format; purposely to reduce data processing, retrieval and bureaucracy.

C. Trend 3 - Quality Improvement

This trend was the most recent to occur, plausibly due to the performance limitation found in the quality performance trend and during the direct forcing of satellite rainfall data for environmental modelling. There were two major types of quality improvement found, one is tackling the temporal deficiencies, and second is to improve the coarse grid of the satellite rainfall data. Since Malaysia is relatively a small region, improvement of spatial resolution is crucial, especially for catchment hydrology. The initial 0.25° resolution of TRMM data tends to generalise the local scale rainfall pattern. The effort of using the seasonal monsoon co-efficient has successfully generated TRMM data with the highest resolution of 0.05° (Mahmud *et al.*, 2018).

The large quantitative error during heavy rainfall & thunderstorm must be addressed in order to achieve accurate quantitative hydrologic modelling. Temporal downscaling algorithm using the PCA initiated by Mahmud *et al.* (2015) is effective during low rainfall (<25mm/d) and drought. Several innovative ideas that might be useful for quality improvement is to utilise topographic and orographic effect for mountainous catchment downscaling. It proved to be an effective method in sub-tropic and temperate climate condition (Jian *et al.*, 2013; Chen *et al.*, 2014). Another approach is to take advantage of the big

geodata and advanced computer processing. With the aid of heavy computing, utilising the advanced computer learning algorithm such as support machine vector, machine learning and artificial network should be possible.

D. Trend 4 - Rainfall Studies

Despite the importance of rainfall studies for Malaysia and the novelty of satellite rainfall data to be used in hydrologic studies, the development in this area is relatively slow. The existing niche of studies involved utilisation of satellite rainfall data for rainfall analysis at synoptic scale (Sorooshian *et al.*, 2002), the vertical profile of tropical rainfall (Isiaka and Khamis, 2015) and tropical storm in Sarawak (Patrick *et al.*, 2017). This could be because of several factors, 1) data handling and processing, 2) satellite rainfall data theory and sciences, 3) restricted data access and 4) quality of research.

These challenges must be addressed in order to encourage the progress of hydrologic research utilising satellite rainfall data. The first and second challenges can be tackled by providing specific training by experts or experienced users. NASA currently offers satellite rainfall data in an open-access database, which may address the third challenge. Challenge number four could be the hardest one. Identifying the scientific gaps that the conventional rain gauge or in-situ based measurement could not provide can be the key to improve the quality of research. If the strength of satellite rainfall and the missing elements in our understanding of local hydrology is carefully analysed, the focus should be put around the dynamic Spatio-temporal of tropical thunderstorm modelling.

IV. NEW NICHES OF INNOVATION AND DEVELOPMENT

Based on the identified trend and scientific contributions above, we suggest that the new niche of research related to the utilisation of satellite rainfall data should emphasise in these four spheres of sciences, 1) strengthening the national hydrological framework, 2) social, culture, & humanities, 3) tourism, and 4) environmental safety.

This public domain satellite rainfall data could play a significant role in strengthening the national hydrological framework. Firstly, it can be used as secondary data to evaluate the integrity of the existing rain gauge network data. Since the distribution of rain gauge is a laborious and tedious task, satellite data can be used as alternatives. It saves cost, time and tedious physical works. Secondly, it is useful for the source of rainfall data over sparse, ungauged and missing information areas or known as HDCS (hydrological data conflict situation) (Mahmud *et al.*, 2018). Mountainous and high elevation, wetland and remote areas such as forest and large-scale plantations are mostly facing those constraints. Thirdly, satellite rainfall data could serve as useful data in creating a national high-resolution rainfall gridded network. Merging between rain gauge, satellite rainfall and ground precipitation radar is technically practical to be done in many developed countries, and the requirement for Malaysia is to have one particularly concerning a higher temporal scale framework, mainly hourly and daily. Availability of this data would benefit strategic economic and infrastructure planning, development and maintenance, as well as national safety towards environmental disasters, meteorological and environmental scientific research advancement and education.

Increasing the use of satellite rainfall data to study the impact of rainfall and its pattern, changes and evolution towards the social, culture and humanities are the next way forward to improve the adaptation of human to the environment. Rainfall played a significant role in the livelihood of the people. Therefore, by having effective spatial information of the rainfall over a substantial amount of time at various temporal scales, we could understand and further study our own social, culture and humanities evolution through time. Hence, it was considered as a crucial aspect in human development, capacity building and adaptation (Tait and Hanna, 2015). Climate change has been a prominent subject since a few decades, and since then, human adaptation to changing environment has been a priority for many countries (Frankhauser, 2016; Orlove, 2005).

Malaysia's ecotourism sites were mainly a rainfall-based environment or indirectly depending on rainfall to sustain its ecosystems. These include islands, waterfall, streams,

rivers, and forest. Although substantial research can be found about the tourism potential of those ecosystems and its sustainability (Lee, 2013; Abdurahman *et al.*, 2016), most are focusing at selected national parks with limited samples, and the covering was not spatially extensive. It leaves a big gap for the areas which do not have any in-situ rainfall measurement to be at least be supported by the satellite rainfall data.

The increased rainfall intensity, especially in urban areas of Malaysia, has increased the risk of safety. In the densely populated urban areas with complex road networks, heavy rain and thunderstorm could cause traffic congestions, slippery road, flash flood, and reduced visibility. Backcasting studies are important to determine the causal relationship and effective understanding of the past disaster for better future prevention. The new generation of satellite rainfall data product such as Global Precipitation Mission (GPM) and GsMAP provide high spatial resolution gridded rainfall up to 0.1° (~10km) could enable effective depiction of rainfall variation in urban areas. This is useful for the scientist to study the causal relationship between rainfall and the prospective disasters; and potentially identify risky areas for prevention, mitigation and assessment.

V. FUTURE WORKS

The trade-off of only considering the scientific papers from Web of Science and SCOPUS, which is lower in quantity and the covered niche was also limited. The main reason is to ensure that only significant scientific contribution was accounted for in the review. Studies published outside of WoS and SCOPUS including one that conducted at the undergraduate level, the non-indexed research publications, and the non-indexed conference proceedings provides merit in term of efforts by the scientific community; but pertaining issues of quality of the scientific works must be dealt with. It is also recommended that for the future work, scientific report by the local authorities or non-governmental organisation (NGO) should be included. A better report on the satellite rainfall data usage and its peripherals issues can be chartered with the increased samples and careful evaluation of the novelty and scientific soundness of the scientific materials.

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