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Applications of satellite information for rainwater estimation and usage: a comprehensive review

Laura Valeria Avendaño-García, Yeison Alberto Garcés-Gómez
Faculty of Engineering and Architecture, Universidad Católica de Manizales, Manizales, Colombia

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ABSTRACT

Global climate change introduces significant uncertainty in water resource availability, making precipitation studies essential for societal sustainability. Satellite precipitation products (SPPs) have emerged as a vital alternative and complement to traditional meteorological station data for hydrological and climate research. This review examines scientific literature on SPP applications for daily, monthly, and annual rainfall estimations globally. Eleven widely used SPPs were identified, with the tropical rainfall measuring mission (TRMM) and climate hazards group infrared precipitation with station data (CHIRPS) standing out due to their frequent usage, high resolution, and extensive data records. A growing trend in research utilizes SPPs for hydrological studies and validates their estimates by contrasting satellite information with ground station measurements using continuous and categorical statistics. TRMM and CHIRPS, in particular, show precipitation accuracies closer to station data, influenced by local topography and climatology. Furthermore, SPP data, combined with geographic information systems (GIS), proves useful for identifying potential rainwater harvesting sites, offering an alternative information source to address water availability crises in drought-prone areas.

Corresponding Author:

Yeison Alberto Garcés-Gómez
Faculty of Engineering and Architecture, Universidad Católica de Manizales
Cra 23 No 60-63, Manizales, Colombia
Email: ygarces@ucm.edu.co

1. INTRODUCTION

Hydrological resources study has been an important aspect in the development of civilizations, particularly their availability due to aspects related to agriculture, basic sanitation, and urban expansion. Water provision is directly correlated to natural environmental phenomena that varies according to climatic and topographic conditions in an area, watershed, or ecosystem. Among natural phenomena precipitation, evapotranspiration, runoff, and infiltration are found as the most determining factors in the availability of water in a region [1]. Consequently, water resources have been an object of study for several decades due to the emerging climatic change crisis, low liquid availability and unequal distribution, presenting atypical rainfall and droughts events in different parts of the world. Precipitation also known as rainwater or rainfall is a significant indicator of climate dynamics, for this reason is considered an essential variable in hydrological studies, especially in droughts analysis, flow rates and regional water balances estimations [2]. In the last decades, this variable has been estimated using data measurements obtained by meteorological stations, nevertheless this stations also called as “gauge-based observations” or “ground measurements” have limitations related to density (number of stations per unit area), observation frequency and infrastructure [3].

Considering those meteorological networks limitations, satellite observations through remote sensing have emerged as a major tool to study the water cycle in critical climate locations, this in view of it could be a practical alternative to detect and offer rainfall information in areas where there is no data, or the current data is significantly scarce [4]. Inasmuch as remote sensing has presented quick advances in the precipitation estimation field, is nowadays increasingly used as a complementary source of information to meteorological stations and networks, since in some areas it is the only source of information that can be accessed and allow to measure direct and indirect climatic variables [5], [6]. In the same way, its utility has been recognized in topics of international importance such as the global warming in water stress studies, extreme drought events, rainfall and interannual variability; likewise, is valuable in the current challenges that faces water resources management to ensure sustainable development in vulnerable area with on-site monitoring deficit [1].

Climate change has brough to consideration the reformulation of water management. This approach was undertaken due to the future water availability for human activities would be related to the administration of the resource in urban and rural areas. The average annual global precipitation is estimated in 800 mm, however several countries have scenarios with low precipitations in arid regions or intense precipitation events in tropical regions, presenting in both cases problematic relative to water availability and access, for this reason satellite remote sensing has been taking more importance in hydrological studies to allow characterize climatological variables [7]. Prospects of a climate with less predictable pattern has increased warnings regarding water service provisions, hence alternative hydric sources to traditional catchments such as groundwater (aquifers), atmospheric water (mist and moisture) and precipitation (rainwater) has become to be objects of study using remote sensing data and geographic information systems (GIS) tools, being proposed as research means that aim to respond to urban water deficits through water collection infrastructures [8], [9].

2. METHODOLOGY

This study has the objective to research current remote sensing applications in rainwater estimations, particularly satellite information used to estimate precipitations over time as an input in the characterization of rainfall regimes, and its potential as an alternative for human activities use. To carry out this purpose a systematic scientific literature review was conducted, in which publications covering one or both main topics of interest corresponding to i) precipitation estimates and ii) alternative rainwater use through remote sensing were examined independently and in groups to identify different applications and approaches, consequently, two search equations were proposed. In addition, information from various government entities, panels and international was also used to support and corroborate information of interest for subsequent analysis. Among the repositories and tools used for searching and reviewing literature are well known databases such as ResearchGate, Google Scholar, ScienceDirect, Scopus and ProQuest.

2.1. Data collection

In the searching process key expressions and words were generated, due to a major availability of scientific materials and documents a great part of the research was carried out in English, and to a lesser extent in Spanish and Portuguese. Some of the keywords related to rain correspond to “rainwater”, “rainfall”, “storm water”, and “precipitation”, these were used in conjunction with “remote sensing”. Other expressions were also used to obtain articles that approach both research topics as “use of precipitation for water supply purposes using remote sensing”. For large databases such as Scopus, the equation “Satellite” AND “Estimate” AND “rainfall” OR “Precipitation” was proposed for a general search, and the equation (“use” OR “utilization”) AND (“rainwater” OR “storm water” OR “precipitation”) AND “remote sensing” AND (“trmm” OR “chirps”) was proposed for a search with a higher degree of specificity.

These equations allowed us to obtain a largen number of research articles, review articles, reports, and book chapters. However, those that did not use satellite information to obtain rainfall or used remote sensing in other areas such as land coverages identification, classification or in interferometry were not considered. Also, those that did not specify satellite mission, source of information or sensor was discarded. Recent scientific literature is prioritized, focusing on studies published between 2007 and 2024, spanning a total of 17 years. The last five years are considered particularly important for identifying current applications of satellite information in estimating precipitation.

2.2. Analysis of literature components

This review presents two main analyses based on the information from databases. The first analysis provides an overview of the object of interest mentioned previously, while the second focuses on the components of literature. The initial analysis is designed to provide a comprehensive overview of studies related to precipitation and satellite information. It examines key indicators such as the trend in the volume of studies, relevant field of expertise and the distribution of research efforts across various countries globally. This examination aims to elucidate the current state of research in this field.

In the second analysis, a detailed examination of the methodologies employed, the satellite products utilized, and the statistical techniques applied to the information analysis are conducted. Additionally, commonly used research locations and the findings present in the literature are also investigated. This approach allows us to assess the usefulness, key variables, frequency, and applicability of satellite information effectively.

3. LITERATURE REVIEW REGARDING SATELLITE PRODUCT WITH HIGH RESOLUTION FOR GLOBAL RAINFALL ESTIMATION

Among the alternative hydrological sources, rainwater is the purest source of water that population can access in many areas, for this reason its catchment and collection is considered one of the most economical and practical methods that contributes significantly to urban sustainable development as the main source of water, or complementary after a proper treatment [10]. Rainwater harvesting (RWH) systems have been widely used to contribute water demand for domestic use and agriculture [9]. In general, RWH systems consist of three main components, those correspond to a catchment, convergence, and storage areas [11], [12]. On the other hand, implementation of those systems requires the estimation of characteristics such as rainfall intensity and distribution, therefore its common the use of meteorological stations information [11]. Nevertheless, different parts of the world where the RWH could be applied lack meteorological data due to low densities of stations networks.

In the last years, remote sensing has provided an opportunity to carry out hydrological studies in areas with low density of stations, where it is necessary to estimate the potential use of rainfall for human activities or purposes. Station density and its contributions as a network is usually scarce along the time or non-existent in different parts of the world, primarily in developing countries and remote areas where stations coverage is limited, and measurements date are insufficient to capture aspect such as the spatial and temporal variability of meteorological variables [13], [14]. According to the World Meteorological Organization (WMO) it is ideal to have a station located every 575 km^2, for temperate and flat tropical regions the range is increased between the 600 to 900 km^2, however, worldwide the number of active stations has decrease, consequently historical data and meteorological information availability has been affected as well [14], [15]. Although station networks allow obtaining climatological information, those still provide punctual and defective records due to their irregular distribution, short-terms records, integrity, consistency, and availability for real-time analysis, hence measurements with rain gauges have limitations [16]. In developing tropical regions for example, high variability makes the correct estimation of precipitation difficult [3].

In view of ground measurements limitation and challenges identified previously, remote sensing has offered an alternative that has evolved in obtaining accurate meteorological data starting in the 1980s with the launch of the tropical rainfall measuring mission (TRMM). Satellite information has proven to be a potential source of rainfall records, principally in region with low meteorological stations density and scarce data, allowing for example, to efficiently carry out hydrological models, water balances of basins, estimates of forecasts and hydrological variables [17]. Studies using satellite-derived products as precipitation inputs are becoming increasingly common around the world, specifically in tropical countries such as Brazil and arid regions like Ethiopia in Africa [15]. In the same way, riparian countries such as Colombia could be benefited using those satellite products to understand climate dynamics and analyze the overall picture of hydrology in various important basins [17]. Precipitation due to its importance in the understanding of water cycle, intensity, duration, and frequency is one of the major variables that could be benefited by satellite observations [1].

Because of its potential, high resolution and almost global coverage, several research have carried out studies to evaluate and validate satellite information performance of satellite-based precipitation products (SPPs) [13], [18]. In addition, SPPs data are currently increasingly available with freely access, appropriate spatial and temporal resolutions that allow to conduct hydrological and climatic studies [19]. Among outstanding datasets missions such as TRMM, Precipitation Estimation from remotely sensed information using artificial neural networks (PERSIANN), the integrated multi-satellite retrievals for GPM (IMERG), climate prediction center morphing method (CMORPH) and climate hazards group infrared precipitation with station data (CHIRPS) are found for their rainfall measurements accuracy [16]. Table 1 summarizes the specifications and characteristics of the most used satellite product identified in the literature review.

Remote sensing SPPs possess advantages over the traditional meteorological measurements, these correspond to spatial variability reduction as the result of the implementation of rain gauges to validate the products, overcome of limitations associated to low density in rain gauges networks, continuous and reliable data guaranteed that could be use in global hydrological studies, and SPPs validation for a specific application in water resource planning instead of a simple rainfall monitoring [3], [20]. Additionally, radar systems characterized by offer higher accuracy in measurements may represent elevated acquisitions costs and maintenance that some countries could not afford, for these reasons SPPs are also an affordable and promising alternative that contributes to the precipitation measure improvement [3].

Nevertheless, estimates derived from satellite products may be influenced by cloud microphysics and the land surface characteristics, specifically high-level clouds with lower temperatures could generate inaccuracies related to precipitation events occurrences [2]. In order to reduce those inaccuracies, satellite products have use bands combinations to improve the accuracy of measurements, to archive that purpose the use of (i) geostationary infrared sensors (IR) characterized by a high revisit time and (ii) microwave sensors in polar orbit passive microwave (PMW,) in low earth orbit (LEO) satellites, which present a lower revisit time than IR, allow to obtain more precise precipitation estimates [20]. By including PMW sensors, precipitation particles are identified by scattering due to large ice particles in the clouds; in this way, clouds that IR could not differentiate are discriminated and both errors derived from cloudy scenes and the sensitivity of the radiative transfer model are corrected [1], [19]. Some missions that have use that bands combination from both sensors are the tropical rainfall measuring mission multi-satellite precipitation analysis (TMPA), PERSIANN and CMORPH as a trial to improve rainfall data consistency, precision, coverage, and punctuality [13].

Table 1. Outstanding satellite precipitation products characteristics

Product	Version	Coverage area	Spatial resolution	Temporal resolution	Information availability	Source
CHIRPS	CHIRPS v2.0	50° N - 50° S	0.05° (5 Km)	Daily	1981- present	CHC, UCB
CMORPH	CMORPH-CDR	60° N - 60° S	0.08° (8 Km)	30 min	1998 – present	NOAA
GLDAS	GLDAS_NOAH025 v2.1	*	0.25° (25 Km)	3 h	2000 – present	NASA
GPCP	GPCPMON v3.0	60° N - 60° S	0.1° (50 Km)	3 h	1983 – present	WCRP
GPM	GPM-IMERG	60° N - 60° S	0.1° (10 Km)	Daily	2015 – present	NASA
GSMAP	GSMaP-MVK	60° N - 60° S	0.1° (10 Km)	1 h	2005 – present	JAXA
MERRA	MERRA-2	*	0.5°x0.625°(50x65Km)	2 h	1979 – 2016	NASA
MSWEP	MSWEP v2	*	0.1° (10 Km)	3 h	1979 – present	GloH20
PERSIANN	PERSIANN-CDR	60° N - 60° S	0.25° (25 Km)	6 h	1983 – present	CHRS, UCI
TRMM	TRMM_3B42 v7	50° N - 50° S	0.25° (25 Km)	3 h	1998 – 2019	NASA, GSFC, PPS
TMPA	TMPA v7	50° N - 50° S	0.25° (25 Km)	3 h	1998 - present	NASA

*Corresponds to information that is not available or that could not be corroborated

4. RESULTS AND DISCUSSION

The set of searches demonstrates a long remote sensing application trajectory and a growing interest in climatic and hydrological studies using satellite information, which have started to investigate since the late 60s and early 70s, registering since the 2010 decade to the present an exponential growth in studies applying remote sensing information from SPPs products. As reference, Figure 1 demonstrates the studies distribution over the years for the general equation proposed in the Scopus search database, where growth trend of this type of study is clear, with nearly 500 studies published each of the last three years (2021 to 2023) and a planned publication schedule for 2025. Furthermore, the Scopus database enabled the identification of diverse areas of expertise that have incorporated satellite information in precipitation studies by applying equation searches. Among the areas earth and planetary science, environmental sciences, engineering, agriculture, multidisciplinary approaches, and mathematics are found; Figure 2 summarizes the studies distribution categorized by outstanding areas of expertise. Although other areas of expertise such as chemical engineering, computational sciences, physics, astronomy, social sciences, medicine, materials sciences, economy, psychology, arts, and humanities were also found, the subjects in question were not of interest even though the use of satellite information is identified.

In addition to the expertise areas, as expected, the number of research in English is dominant for the object of study, representing 97% and 95% of the general and specific search equations respectively, while other languages such as Spanish represent only 0.3% for general search and did not have a significant percentage for the specific search proposed. At a regional level in Latin America, due to Brazil influence Portuguese has a greater number of studies, representing 0.4% for the general search and 0.6 % for the specific, in this way even when it is a language spoken to a lesser extent that Spanish it currently attracts much research. In terms of number of studies per countries, the United States of America (USA) tops the list (25%) followed by China (15%) and India (5.58%) with the highest number of total studies, meanwhile several Latin America countries together account 6.5% of total studies approximately, being Brazil the country that contributes the most, representing 4.1 % of global studies and 63.4% of Latin American studies; Figure 3 summarize proportion of studies conducted in each country for the specific equation search. On the other hand, Colombia contributes to less than a 6% of Latin American studies, although surpassed by

Argentina and Mexico, it has a higher proportion of studies compared to countries such as Peru, Ecuador, Puerto Rico, and Bolivia.

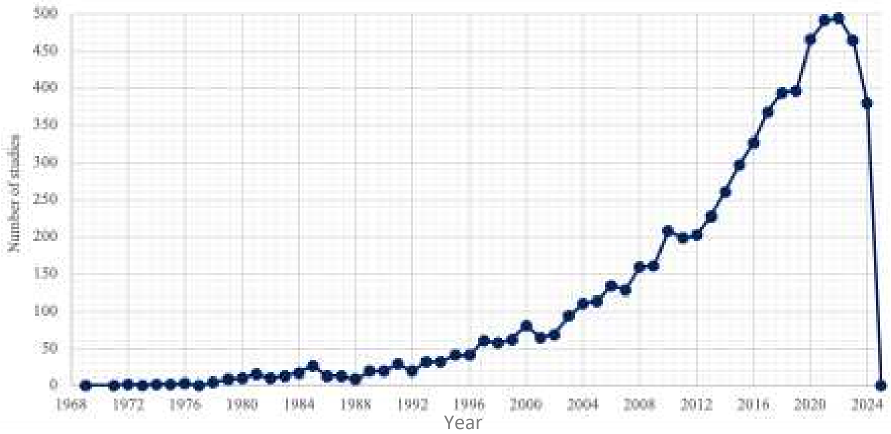

Figure 1. Studies distribution by general equation search in Scopus database

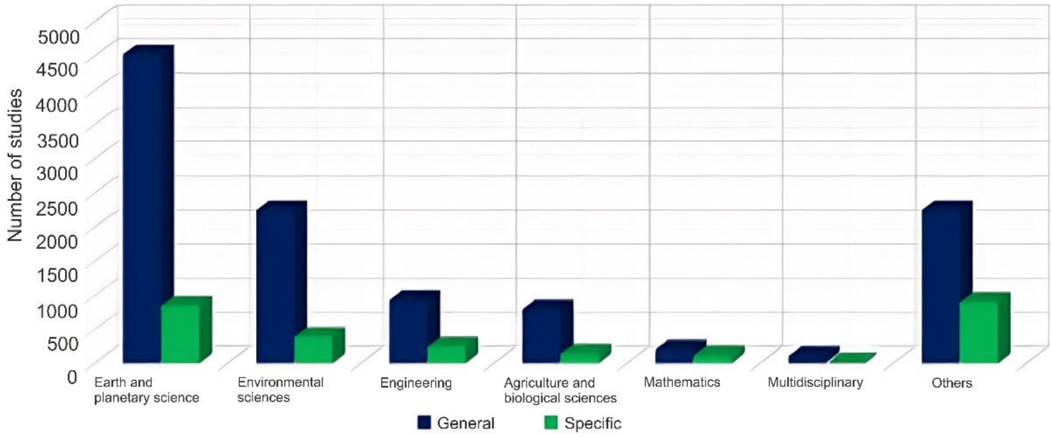

Figure 2. Studies distribution by equation search and expertise area in Scopus database

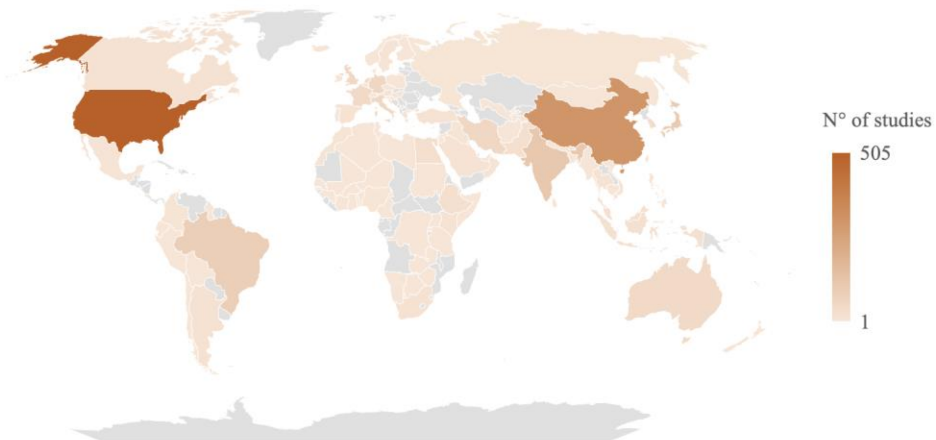

Figure 3. Studies proportion for specific equation search per country. The five countries with the highest number of studies are as follows: USA (505), China (303), India (112), Japan (106) and Brazil (83)

Several satellite precipitation products have been used in recent years to study rainfall regimes in different parts of the world, particularly many of these studies have integrated information from various SPPs in their research as those carry out by [13]–[15], [18], [19], [21], in which a comparation of the best products performance was evaluated in different study areas. Precipitation estimates from products were usually contrasted with historical records obtained from stations, rainfall networks or closer ground measurements. During the literature review process, Table 1 identifies SPPs used in several research mainly investigating characteristics associated with the products, while Figure 4 relates the frequency of use of these products in the highlighted studies, as a result CHIRPS and TRMM are identified as the most used SPPs. Such preference could be related to three principal aspects such as i) amount of historical data available, ii) smooth access to information, and iii) high spatial and temporal resolutions. Other products such as PERSIANN, CMORPH and TMPA are also widely used for their outstanding performances, being TMPA a result of TRMM mission and its continuation in the GPM mission.

In the same way, several studies using SPPs data carrying out validation methodologies for precipitation estimates obtained respect to those recorded by meteorological or pluviometric stations are identified. Entire studies that used a validation methodology applied continuous and/or categorical statistical metrics, which allowed determining the performance and similarity that the satellite information presented in relation to ground measurements, some studies that used these statistics are those carried out by [2], [4], [13], [15], [16], [18], [19], [22]. The most widely used continuous statistics correspond to the root mean square error (RMSE), bias percentage (PBIAS), nash-sutcliffe efficiency (NSE), coefficient of determination (R2) and Pearson correlation coefficient (usually referred as r, cc, or PCC). Other statistics such as mean absolute error (MAE), mean error (ME), concordance index (d) and standard deviation (SD) were also frequent, although to a lesser extent. Regarding categorical statistics, probability of detection (POD) and false alarm ratio (FAR) were those that were used the most, while others such as critical success index (CSI), BIAS and frequency bias index (FBI), were used by a smaller number of investigations. It is noteworthy that major part of studies reviewed as those carry out by [3], [6], [14], [23]–[26] did not employ categorical statistics, resulting in a significant emphasis on continuous statistics within the applications of SPSs. Table 2 (in Appendix) specifies the continuous and categorical indices used by some of the reviewed studies in the methods section column.

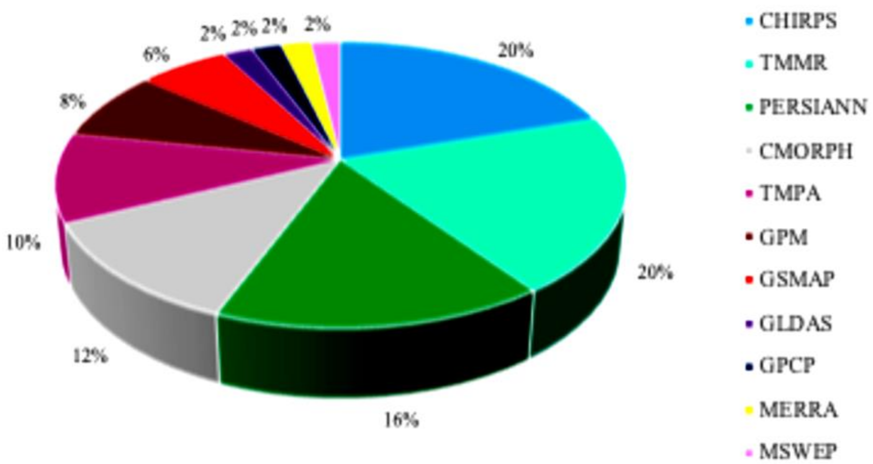

Figure 4. Satellite precipitation products often used in studies during literature review process

In contrast, different structures that were usually proposed for the storage and subsequent use of rainwater such as dams, percolation tanks and terraces were identified in studies that used both offered and validated estimates from SPPs and in those that made exclusive use of ground measurements; other systems such as aquifers, cisterns and contour ridges were implemented to a lesser extent, most of these systems were designed for agricultural purposes rather than for human activities [11], [24]. Several researchers and RWH studies in conjunction with GIS tools have been carried out in various parts of the world and have concluded about benefits offered by these systems such as the assessment of rainfall potential volumes for utilization, as inputs in the planning of catchment or collection sites, evaluation of feasibility and economic efficiency and administrative aspects associated with water resource management [27].

The combination of data provided by ground measurements and remote sensing is increasingly used to achieve greater depth, especially hydrological and meteorological studies use these two types of data, allowing the characterization of precipitation events and reducing errors related to sampling distribution in time and space [1]. Radar technology has significantly improved the accuracy of precipitation measurements over time, studies such as those referenced in [28], have demonstrated the potential of SPPs for the rainfall events mapping and distribution. Additionally, estimations from SPPs have been utilized in risk management, such is the case of the [29] research, where satellite data was useful in studying landslides; this research also indicated that in some regions SPPs could be even more accurate than on-site measurements, highlighting the wide range of applications that precipitation products could offer.

5. CONCLUSION

The overall analysis indicates a significant increase in the use of satellite information, particularly over the past decade, during which the number of studies conducted each year has surpassed 200; exceptionally, environmental science along with earth and planetary sciences are found as the major fields dedicated to the exploration of innovative applications in satellite information. Additionally, research indicates that studies conducted in English tend to exhibit a broader scope, even in regions where other languages such as Spanish, are prevalent. While Latin American countries have not produced as many studies compared to first-world nations like the United States or China, there is a growing recognition of the value of satellite information. It is noted that this topic is gradually gaining traction and is being explored by developing countries, although the pace of this progress remains comparatively slow. Greater growth is anticipated as satellite precipitation products enhance their estimation capabilities.

Furthermore, the analysis of literature has revealed two significant components related to literature methodology. Firstly, it highlighted continuous and categorical statics used as precision indicators, especially continuous statics were widely applied. Secondly, it emphasized the validation process, which is essential for determining the effectiveness of the SPPs under specific environmental conditions. This insight is particularly valuable for countries seeking to assess the most effective SPPs as reliable sources of information.

Additionally, satellite precipitation products perform differently based on climatic and topographic conditions; therefore, the specific characteristics of each product, such as temporal and spatial resolutions, along with the validation phases, are crucial for selecting the most suitable SPP. These innovations offer significant potential for conducting studies in regions where meteorological networks and stations are limited, their utility is notably pronounced in poorer and developing countries, which often face budget constraints that limit the implementation of new detection technologies or the expansion of ground measurement coverage. Satellite information can be viewed as a viable alternative to traditional meteorological measurements; however, many studies suggest that the best approach is to combine satellite data with information from ground stations, this combination enhances the capabilities of current monitoring networks, serving as a valuable complementary tool for accurate weather assessment.

Regarding rainwater collection and use, the review allowed to identify that African countries, such as Ethiopia, Egypt, and Kenya, which have arid, semi-arid, and desert regions, are more inclined to implement RWH systems, as a result, these countries account for a significant portion of the studies that explore the use of these technologies in conjunction with GIS. In the same way, highly populated countries such as Indonesia are exploring rainwater harvesting as an alternative method to meet urban water demands. In contrast, western countries such as the United States (USA), Brazil and Colombia with higher rainfall, are utilizing satellite data to analyze rainy periods in important basins, study precipitation phenomena and estimate flow rates.

This review emphasizes the significant role of satellite precipitation products (SPPs) in estimating rainfall, demonstrating their value as essential alternative and complementary source of information for conducting climatic and meteorological studies on a global scale. This growing technology serves as a crucial resource for various research areas, such as climate change research, climate patterns understanding and water management. At the same time, it serves as a vital source of information for initiatives focused on enhancing water accessibility. It facilitates the identification and selection of appropriate sites for rainwater collection, where understanding the frequency, intensity, and nature of precipitation events is essential. In this regard, it can be considered a significant and impactful tool for both research and the development of solutions that effectively respond to the current environmental crisis.

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APPENDIX

Table 2. Specifies the continuous and categorical indices used by some of the reviewed studies

Ref.	Study area	Objectives and methods	Findings
Africa			
[19]	Burkina Faso (West of Africa)	Objective: evaluate the daily, monthly, and annual estimates obtained by 7 satellite reception products from 2001 to 2014. Methods: satellite precipitation information was compared from ARC 2.0, CHIRPS, PERSIANN, RFE 2.0, TAMSAT, TARCAT and TMPA with historical records from nine meteorological stations using continuous (r, ME, PBIAS, RMSE, NSE) and categorical (POD, FAR) statistics.	SPPs were weakly related to station records, showing a contribution of ± 10% to rainfall. CHIRPS performed better overall, TRMM determined occurrences better than quantities. TARCAT was recommended for droughts and CHIRPS for floods.
[6]	Burkina Faso (West of Africa)	Objective: evaluate the daily, monthly, and annual estimates obtained by 7 satellite reception products from 2001 to 2014. Methods: satellite precipitation information was compared from ARC 2.0, CHIRPS, PERSIANN, RFE 2.0, TAMSAT, TARCAT and TMPA with historical records from nine meteorological stations using continuous (r, ME, PBIAS, RMSE, NSE) and categorical (POD, FAR) statistics.	SPPs were weakly related to station records, showing a contribution of ± 10% to rainfall. CHIRPS performed better overall, TRMM determined occurrences better than quantities. TARCAT was recommended for droughts and CHIRPS for floods.
[30]	Burkina Faso (West of Africa)	Objective: evaluate the daily, monthly, and annual estimates obtained by 7 satellite reception products from 2001 to 2014. Methods: satellite precipitation information was compared from ARC 2.0, CHIRPS, PERSIANN, RFE 2.0, TAMSAT, TARCAT and TMPA with historical records from nine meteorological stations using continuous (r, ME, PBIAS, RMSE, NSE) and categorical (POD, FAR) statistics.	SPPs were weakly related to station records, showing a contribution of ± 10% to rainfall. CHIRPS performed better overall, TRMM determined occurrences better than quantities. TARCAT was recommended for droughts and CHIRPS for floods.
[23]	Burkina Faso (West of Africa)	Objective: evaluate the daily, monthly, and annual estimates obtained by 7 satellite reception products from 2001 to 2014. Methods: satellite precipitation information was compared from ARC 2.0, CHIRPS, PERSIANN, RFE 2.0, TAMSAT, TARCAT and TMPA with historical records from nine meteorological stations using continuous (r, ME, PBIAS, RMSE, NSE) and categorical (POD, FAR) statistics.	SPPs were weakly related to station records, showing a contribution of ± 10% to rainfall. CHIRPS performed better overall, TRMM determined occurrences better than quantities. TARCAT was recommended for droughts and CHIRPS for floods.
[14]	Burkina Faso (West of Africa)	Objective: evaluate the daily, monthly, and annual estimates obtained by 7 satellite reception products from 2001 to 2014. Methods: satellite precipitation information was compared from ARC 2.0, CHIRPS, PERSIANN, RFE 2.0, TAMSAT, TARCAT and TMPA with historical records from nine meteorological stations using continuous (r, ME, PBIAS, RMSE, NSE) and categorical (POD, FAR) statistics.	SPPs were weakly related to station records, showing a contribution of ± 10% to rainfall. CHIRPS performed better overall, TRMM determined occurrences better than quantities. TARCAT was recommended for droughts and CHIRPS for floods.
[24]	Burkina Faso (West of Africa)	Objective: evaluate the daily, monthly, and annual estimates obtained by 7 satellite reception products from 2001 to 2014. Methods: satellite precipitation information was compared from ARC 2.0, CHIRPS, PERSIANN, RFE 2.0, TAMSAT, TARCAT and TMPA with historical records from nine meteorological stations using continuous (r, ME, PBIAS, RMSE, NSE) and categorical (POD, FAR) statistics.	SPPs were weakly related to station records, showing a contribution of ± 10% to rainfall. CHIRPS performed better overall, TRMM determined occurrences better than quantities. TARCAT was recommended for droughts and CHIRPS for floods.
America			
[16]	Río Grande Basin (Brazil)	Objective: evaluate the estimates made by a satellite precipitation product on a monthly scale for the period 1981-2020. Methods: CHIRPS SPP was used for precipitation estimation, also performs validation with 11 meteorological stations using continuous statistics (EM, RMSE, PBIAS, NES, R2, r), and categorical statistics (PC, POD, FBI, FAR, and α).	The product presented a better result in the numerical variables (continuous) during the dry season, however, it had a better performance in the categorical variables for the rainy season. The correlation between the data sets (R2>0.81) was excellent.
[2]	Mato Grosso State (Brazil)	Objective: compare precipitation estimates from five satellite products on a daily, monthly and annual scale for the period 2000-2018. Methods: satellite precipitation information from GLDAS, MERRA, TRMM, GPM and GPCP is compared with records from 11 meteorological stations using continuous (d, RMSE, r) and categorical (POD, FAR, BIAS, CSI) statistics.	TRMM and GPCP overestimate precipitation at daily and annual scales respectively, MERRA underestimates at all scales, GLDAS and GPM do not differ significantly at the three scales with respect to ground measurements. GPM was the best, obtaining a low error and a high correlation.
[3]	Tocantins-Araguaia River Basin (Brazil)	Objective: study the applicability of three satellite precipitation products for hydrological modeling in the basin during the period 2000-2018. Methods: data from three SPPs TMPA and GPM-IMERG are used for hydrological modeling in the SWAT tool and were compared with information from 30 meteorological stations using continuous statistics (RMSE, r, PBIAS, KGE, NSE).	MERG and TMPA presented similar results on both time scales and low correlation for daily precipitation. The recession periods in the simulations performed with TMPA were better represented than those of IMERG and rain gauges.

Table 2. Specifies the continuous and categorical indices used by some of the reviewed studies *(Continues)*

Ref.	Study area	Objectives and methods	Findings
[15]	Mearim River Drainage Basin (Brazil)	Objective: evaluate three satellite products and compare them with griBR on a daily, monthly and seasonal scale in the basin for the period 1983-2013. Methods: validate the information of the CHIRPS, MSWEP and PERSIANN-CDR precipitation products with the griBR database (resulting from measurements from meteorological stations) using continuous (PBIAS, RMSE, d) and categorical (PO, FAR) statistics.	PERSIANN-CDR was the best dataset for the period 1983 to 2013 in performance of the metrics, while MSWEP overestimated the mean values. For the RMSE, CHIRPS was the best product overall, both for wet and dry months. All SPPs have difficulties estimating mean precipitation in drier periods.
[25]	Antioquia Department (Colombia)	Objective: validate the performance of a satellite product through rainfall calculation in different areas of the department for the period 1981-2018. Methods: use CHIRPS information, performs validation using both national and private meteorological stations and applies statistical metrics (r, d, bias, RMSE).	The correlation between rainfall data and CHIRPS data is low for the daily scale. However, for the monthly scale it presents a high correlation ranging from +0.75 to +0.92. In general, CHIRPS reproduces precipitation information well even considering the temporal variability and the tendency to overestimate data.
[22]	Guajira Department (Colombia)	Objective: validate the performance of a satellite product through rainfall calculation in a coastal area with complex topography for the period 1981-2020. Methods: use CHIRPS information, performs validation using 37 meteorological stations and applies continuous (PBIAS, MAE, NSE, RMSE, r) and categorical (POD, FAR, HK, FBI) statistics.	Overall, CHIRPS performed well in representing monthly precipitation. However, in coastal areas, SPP underestimated annual precipitation in 64% of the data. Detection performed better in mountainous areas than in plains and on the coast.
[13]	Illinois River Basin (United States of America, USA)	Objective: evaluate the estimates obtained by five satellite precipitation products on a six-hourly (6 h) and monthly scale for the period 2003-2008. Methods: use data from TMPA, PERSIANN and CMORPH and performs validation with information from NEXRAD due to the scarcity of meteorological stations applying continuous (CC, RMSE, PBIAS) and categorical statistics (POD, FAR, BIAS, ETS).	The BIAS adjustment is highlighted by correcting overestimates of heavy precipitation. CMORPH demonstrates high skills in detecting precipitation events. CMORPH and TMPA significantly overestimate areas with heavy rainfall. On both time scales CMORPH better delineates the area of precipitation.
Asia			
[21]	Mailand (China)	Objective: Propose a new method for combining diverse satellite data and validating it across nine major basins in China for the period 19181-2020. Methods: Use satellite information from GPM-IMERG, PERSIANN, GSMAP, CHIRPS and ERA5 as inputs to be combined and compares the results of its model with others such as MBG, MBC, MUI (which do not consider ground measurements), IDW and RBF (which do use these measurements).	The proposed combination method enhanced the performance of SPPs by 4.67% in terms of the correlation coefficient and by 8.75% in reducing the mean error compared to the original data. Additionally, it outperformed other methods, such as inverse distance weighting (IDW) and radial basis function (RBF), for merging satellite data from SPPs.
[4]	Diaoyutai Islands (Japan, China and Taiwan).	Objective: Detect precipitation characteristics of the Islands area focusing on typhoon contributions for a period of 2001-2009. Methods: Compares satellite precipitation information from TMPA, CMORPH, PERSIANN-CDR, and GSMAP with data obtained from 12 stations distributed in different neighboring countries, using both continuous (CC, RMSE, ME, MAE, PBIAS), and categorical (POD, FAR, CSI) statistic.	TMPA, CMORPH, and GSMAP obtain similar distribution patterns, while PERSIANN presents broken bands. TMPA tends to overestimate rainfall while PERSIANN tends to underestimate it. CMORPH and GSMAP obtained rainfall values closer to those of the meteorological stations.
[27]	Semarang City (Indonesia)	Objective: Examine a satellite product coverage to be used in estimating the rainwater storage potential according to the 2007-2016 precipitation regime. Methods: Use CHIRPS reception information, performs the population projection (Pn) and estimates the roof area in the city to obtain the PWH (water storage potential) calculation.	CHIRPS presented values underestimating precipitation for wet months, while for dry months the values were overestimated. However, the information from this SPP can be used in the construction of isohyets for the water storage planning model due to the low mean precipitation error.
[18]	United Arab Emirates (UAE)	Objective: Assess the consistency, variability and concentration of precipitation using four satellite products for the period 2004-2020. Methods: Satellite precipitation information from GPM-IMERG, CHIRPS, PERSIANN-CDR and CMORPH is compared with records from 50 meteorological stations using continuous (RMSE, SD, CC) and categorical (POD, FAR, CSI) statistics.	CHIRPS provided a spatial distribution much closer to the gauge data and at seasonal scales, while PERSIANN-CDR had the lowest performance.

* Other continuous indices and statistics used in lesser proportion correspond to Kiling-Gupta efficiency (KGE), mean bias error (MBE), standard deviation ratio (RSR) and SYTEX which returns the standard error of the value for each regression in X and Y. For categorical statistics, there is alpha level (α), correct proportion (PC), probability of occurrence (PO), equal threat score (ETS) and Hanssen-Kuipers discrimination (HK).

BIOGRAPHIES OF AUTHORS

Laura Valeria Avendaño-García environmental engineer from the Universidad Santo Tomás, and candidate for a master's degree in remote sensing from the Universidad Católica de Manizales. Expertise in natural and environmental sciences, with an emphasis on water resources management and river basins. Professional experience in developing environmental management studies and plans, with a particular emphasis on geographic information systems. Her areas of interest include using remote sensing data for hydrological modeling, environmental and climatic studies. She can be contacted at email: laura.avendano@ucm.edu.co.

Yeison Alberto Garces-Gómez received bachelor's degree in electronic engineering, and master's degrees and Ph.D. in Engineering from electrical, electronic and computer engineering department, Universidad Nacional de Colombia, Manizales, Colombia, in 2009, 2011 and 2015, respectively. He is full professor at the academic unit for training in natural sciences and mathematics, Universidad Católica de Manizales, and teaches several courses such as experimental design, statistics, and physics. His main research focus is on applied technologies, embedded system, power electronics, power quality, but also many other areas of electronics, signal processing and didactics. He published more than 30 scientific and research publications, among them more than 10 journal papers. He worked as principal researcher on commercial projects and projects by the Ministry of Science, Tech and Innovation, Republic of Colombia. He can be contacted at ygarces@ucm.edu.co.