# Evaluating CHIRPS Satellite-Based Rainfall Data for Hydrologic Modeling and Climate Impact Assessment in the Abra River Basin, Philippines

Alibuyog N.R.[1*], Dolores, S.B.F.[2], Utrera R.T.[3] and Mata C.B.[1]

[1]Coastal Engineering Research and Management Center, Mariano Marcos State University, City of Batac, Ilocos Norte, Philippines 2906

[2]College of Computing and Information Sciences, Mariano Marcos State University, City of Batac, Ilocos Norte, Philippines 2906

[3]Research Directorate, Mariano Marcos State University, City of Batac, Ilocos Norte, Philippines 2906

*nralibuyog@mmsu.edu.ph (*Corresponding author)

***Abstract:*** *Reliable rainfall data are essential for hydrologic modeling and water resource planning, particularly in data-scarce and topographically complex regions like the Abra River Basin (ARB) in Northern Luzon, Philippines. This study evaluates the performance of CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data), a satellite-based rainfall product, against ground-observed data from the PAGASA Vigan station for the period 1990 to 2020. Comparative statistical analysis revealed that CHIRPS captured higher mean annual rainfall (2,571.8 mm) with lower variability (CV = 14.53%) than PAGASA (2,190.4 mm, CV = 22.23%). CHIRPS also demonstrated improved spatial representation, particularly in higher elevation areas of the basin and across climatic transitions, as reflected in a lower seasonality index (0.76 vs. 0.99). Hydrologic simulations using the Soil and Water Assessment Tool (SWAT) demonstrated that CHIRPS-based inputs yielded more consistent baseflow and total water yield estimates, validating their reliability for modeling ungauged basins. Furthermore, future climate scenarios (SSP5-8.5 for 2050 and 2070) based on CHIRPS input project increases in rainfall (up to 15%), surface runoff (42%), groundwater recharge (9%), and total water yield (18%), alongside elevated evapotranspiration rates due to warming temperatures. These results emphasize the utility of CHIRPS as a robust alternative to sparse ground observations for hydrologic modeling, climate change impact assessments, and sustainable water resource management. The study highlights how remote sensing technologies contribute to SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action) through data-driven planning in vulnerable watersheds.*

***Keywords:*** *Abra River Basin, CHIRPS precipitation data, Remote sensing for water resources, Satellite-based rainfall estimation, Sustainable Development Goals (SDGs)*

## Introduction

Accurate rainfall data are essential inputs for hydrologic modeling, water resource planning, and climate adaptation strategies. Precipitation directly influences surface runoff, infiltration, groundwater recharge, and evapotranspiration—key elements of the hydrologic cycle and water balance analysis. However, the accuracy and reliability of rainfall data remain a major challenge in data-scarce regions, especially in mountainous and remote basins like the Abra River Basin (ARB) in Northern Luzon, Philippines. Traditional ground-based meteorological stations, such as those operated by the Philippine Atmospheric, Geophysical, and Astronomical

Services Administration (PAGASA), often face limited spatial coverage, data gaps, and maintenance issues (Amadore, 2005). These limitations hinder comprehensive hydrologic modeling and the development of effective water management strategies. For instance, Guiamel and Lee (2020) noted that the SWAT model's poor performance in identifying potential hydropower development sites was due to data quality and scarcity issues.

To address these constraints, satellite-based and blended rainfall datasets have become increasingly popular in hydrological studies. One of the most widely used is the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), which provides quasi-global rainfall estimates from 1981 to the present at a 0.05° (~5 km) spatial resolution (Funk et al., 2015). CHIRPS blends satellite imagery with in-situ station data to capture spatial variability more comprehensively, particularly in regions with complex terrain and sparse weather monitoring networks (Toté et al., 2015). Its growing application in data-scarce basins has shown promise in various studies evaluating flood forecasting, drought monitoring, and climate impact modeling (Dinku et al., 2018; Amorim et al., 2020).

In the Philippines, a country often affected by extreme hydroclimatic events such as typhoons, floods, and droughts, there is an urgent need to improve the availability and quality of rainfall data. The Abra River Basin, which spans parts of the Cordillera and Ilocos regions, highlights a challenging hydrological environment. The basin exhibits distinct rainfall patterns influenced by monsoons and orographic effects from the Cordillera Mountain ranges. PAGASA has limited long-term meteorological records in the area, with the Vigan Station serving as the main ground-based reference. However, this station captures only Type I climate on the western edge of the basin, failing to reflect rainfall variability in the eastern sectors, which are classified as Type III climate (Coronas, 1920; DOST-PAGASA, 2018).

Given these spatial limitations, satellite-derived data such as CHIRPS can serve as a potential alternative or complementary source of rainfall information for hydrologic modeling. Yet, it is critical to evaluate the extent to which CHIRPS captures regional rainfall dynamics relative to ground observations and to understand how the choice of rainfall input affects hydrologic model outputs, such as surface runoff, baseflow, and groundwater recharge.

The Soil and Water Assessment Tool (SWAT), a semi-distributed, process-based model developed by the USDA-ARS (Arnold et al., 1998), has become a widely used tool for simulating the impacts of land use, climate, and management practices on water resources. Its ability to integrate varied spatial and temporal datasets makes it particularly suitable for evaluating the hydrologic implications of different rainfall sources.

**Objectives of the Study**

This paper aims to evaluate CHIRPS rainfall data and its implications for hydrologic modeling in the Abra River Basin. Specifically, it seeks to:

1. Compare the statistical properties and seasonality of CHIRPS and PAGASA (Vigan) rainfall data from 1990 to 2020.
2. Analyze the spatial variability and rainfall regime representation of each dataset.
3. Evaluate the impact of rainfall data selection on the SWAT-simulated water balance components in the ARB.
4. Provide insights into the suitability of data for hydrologic modeling in basins with limited in-situ rainfall observations.

## Literature Review

### Importance of Reliable Rainfall Data in Hydrology

Rainfall is the primary driver of hydrologic processes, influencing surface runoff, infiltration, evapotranspiration, and groundwater recharge. Its spatial and temporal variability affects the timing and magnitude of streamflow, the recharge of aquifers, and the availability of water for agriculture and ecosystems. In river basins with complex terrain, such as those in the Philippines, rainfall distribution is highly variable due to the combined effects of the southwest and northeast monsoons, frequent typhoons, and orographic lifting along mountainous areas (Amadore, 2005; Coronas, 1920). These factors lead to very uneven rainfall patterns seasonally and geographically, which makes water balance modeling and water resources management more challenging.

Accurate and spatially representative rainfall data are crucial for hydrologic applications such as flood forecasting, drought assessment, irrigation scheduling, and climate impact evaluation. Although ground-based rain gauges offer precise point measurements, their usefulness at the basin scale is limited by sparse spatial coverage, temporal gaps, and the logistical challenges of maintaining a dense monitoring network. In the Philippines, where PAGASA manages the national observation system, the number of operational gauges remains inadequate to capture rainfall variability across upland and remote basins (PAGASA, 2018). This limitation is especially significant for large watersheds like the Abra River Basin, where orographic and climatic factors can produce rainfall gradients that single stations cannot adequately represent. To address these challenges, remotely sensed and blended rainfall datasets have been developed, providing spatially continuous coverage, near-real-time updates, and extensive historical records. Among them, the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset has become widely used. By combining satellite infrared Cold Cloud Duration data with station-based observations, CHIRPS offers a 0.05° (~5 km) gridded rainfall product covering from 1981 to the present (Funk et al., 2015). These datasets improve the ability to perform basin-scale hydrologic modeling, especially with process-based models like the Soil and Water Assessment Tool (SWAT), which depend on consistent, spatially distributed rainfall inputs to simulate runoff, streamflow, and water balance components.

In this context, reliable rainfall information is more than just a requirement; it is essential for effective water resources planning and climate adaptation. For the Philippines, where climate variability and extreme events continually present risks, enhancing rainfall measurement through satellite-based tools has great potential to improve hydrologic assessments and support sustainable watershed management.

**Satellite-Based and Blended Precipitation Products**

The limitations of ground-based rainfall observations have led to the growing use of satellite-based and blended precipitation datasets in hydrologic and climate research. These products provide spatially continuous estimates of rainfall, often at fine temporal resolutions and across large spatial extents, making them valuable for monitoring and modeling in data-scarce regions. Among the most widely used products are the Tropical Rainfall Measuring Mission (TRMM) (Jamandre and Narisma, 2013; Fensterseifer et al., 2016), the Global Precipitation Measurement (GPM) (Veloria et al., 2021; Bagtasa, 2022), the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) (Ramos et al. 2016; Hsu et al., 2022), and CHIRPS (Alejo and Alejandro, 2021; Du et al., 2023). Each of these datasets uses different retrieval algorithms, sensors, and data-merging strategies, resulting in varying performance across regions and timescales (Toté et al., 2015; Ramos et al., 2016; Dinku et al., 2018).

CHIRPS has emerged as a particularly valuable dataset due to its unique design that combines satellite infrared Cold Cloud Duration (CCD) data with in-situ station records. This blending approach improves rainfall estimate accuracy while maintaining long-term temporal consistency (Funk et al., 2015). CHIRPS provides a quasi-global dataset at a 0.05° (~5 km) spatial resolution, with a record spanning from 1981 to the present (Funk et al., 2015). These characteristics make it suitable for both near-real-time monitoring and retrospective climate studies.

One of CHIRPS' key strengths lies in its ability to fill observational gaps in regions with sparse or uneven station networks. Validation studies conducted across different geographic settings have demonstrated that CHIRPS can reasonably capture seasonal rainfall patterns and is particularly effective for drought monitoring and agricultural applications (Toté et al., 2015; Dinku et al., 2018; Alejo and Alejandro, 2021). However, its performance is not uniform: while monthly and seasonal totals are generally reliable, daily estimates may underrepresent short-lived convective storms, and performance tends to vary with topography and climatic regime (Bai et al., 2018; Cavalcante et al., 2020).

For the Philippines, where rainfall variability is driven by monsoons, typhoons, and complex terrain, CHIRPS offers clear advantages over relying solely on sparse ground stations. By providing spatially distributed rainfall inputs, CHIRPS can enhance the accuracy of basin-scale hydrologic modeling and climate impact assessments, making it a promising tool for research and operational water management in the country.

**Validation of CHIRPS Across Regions**

The performance of CHIRPS has been extensively evaluated across various climatic and geographic regions, generally highlighting its strengths at seasonal to monthly timescales and its limitations in capturing short-term rainfall extremes. For example, Toté et al. (2015) assessed CHIRPS in Mozambique and found it effective for drought and flood monitoring, especially in capturing seasonal variability, although it was less accurate for daily rainfall extremes. Similarly, Dinku et al. (2018) validated CHIRPS over Eastern Africa and reported good agreement with ground observations at monthly and seasonal scales, noting that biases tend to increase in highland areas and during convective events.

Beyond Africa, CHIRPS has also been tested in Asia and Latin America, where studies have demonstrated its utility for hydrological modeling, agricultural monitoring, and climate analysis. In India, Dhanesh et al. (2020) demonstrated that CHIRPS-driven hydrologic simulations produced accurate streamflow estimates, especially in basins with limited ground data. In Brazil, Amorim et al. (2020) found that CHIRPS outperformed several other satellite products when evaluated against gauge observations, particularly for analyzing long-term rainfall variability.

A consistent finding across these studies is that CHIRPS provides reliable estimates for basin-scale applications but tends to underestimate extreme rainfall events and localized convective storms. This underestimation is partly due to the spatial averaging inherent in satellite-derived datasets and the limited density of gauge data available for blending in certain regions. As a result, CHIRPS is often recommended for use in combination with bias correction techniques or supplemental gauge data when accurately simulating extremes is necessary.

Validation studies in the Philippines are still limited but are increasing. Alejo and Alejandro (2021), for example, compared CHIRPS with station data across the country and found that the dataset accurately captured rainfall occurrence and amounts in many areas, although biases changed with the season and location. These results highlight the need for basin-specific evaluations to assess whether CHIRPS is suitable for local hydrologic modeling and water resource management.

**CHIRPS as Input to Hydrologic Models**

Hydrologic models mainly depend on rainfall data as a key input for simulating streamflow, water balance, and watershed processes. The SWAT model has become one of the most popular process-based tools for assessing the impacts of land use, climate change, and management practices on hydrologic systems (Arnold et al., 1998). The accuracy of SWAT results largely relies on the quality and representativeness of rainfall data. Incomplete or biased rainfall data can cause substantial errors in streamflow estimation, baseflow representation, and runoff partitioning.

The gridded nature of CHIRPS makes it particularly suitable for large basins where rainfall exhibits substantial spatial variability. By providing continuous spatial coverage, CHIRPS reduces the reliance on single-point gauges, which often fail to capture orographic and localized rainfall events. Several studies have demonstrated the potential of CHIRPS for driving hydrologic models. For example, Dhanesh et al. (2020) showed that CHIRPS-driven SWAT simulations provided reliable streamflow estimates in Indian catchments with limited station data. Similarly, Amorim et al. (2020) reported that CHIRPS improved rainfall-runoff simulations in Brazilian basins compared to other satellite products.

Recent work also emphasizes the importance of calibration and uncertainty analysis when utilizing satellite rainfall data in hydrological modeling. Tools such as the SWAT-CUP platform, particularly the Sequential Uncertainty Fitting Algorithm (SUFI-2), have been widely applied to optimize parameter sets and quantify predictive uncertainty (Abbaspour et al., 2007). By accounting for uncertainties in both rainfall inputs and hydrologic processes, SUFI-2 enhances the reliability of CHIRPS-driven simulations.

Nevertheless, studies consistently show that CHIRPS tends to underestimate peak flows because it smooths out short-duration rainfall extremes. This issue can impact flood modeling and the analysis of extreme events unless it is addressed through bias correction or combined with local gauge data. Despite these issues, CHIRPS remains a useful rainfall data source for hydrologic modeling, especially in areas like the Philippines, where station coverage is sparse and basin-level water resource evaluations are critically needed.

**Rainfall Seasonality and Hydrologic Implications**

Beyond total rainfall amounts, the seasonality of rainfall is crucial in shaping hydrologic processes and water availability. Seasonal concentration affects the timing of streamflow, groundwater recharge, soil moisture dynamics, and irrigation needs. In monsoon-dominated countries like the Philippines, rainfall is not evenly spread throughout the year but occurs in distinct wet and dry seasons. This variability is further influenced by topography and the passage of tropical cyclones, resulting in strong intra-annual differences in rainfall distribution (Amadore, 2005; Coronas, 1920).

The Seasonality Index (SI) introduced by Walsh and Lawler (1981) remains one of the most widely used measures for quantifying rainfall concentration across months. An SI close to zero indicates evenly distributed rainfall throughout the year, while higher values reflect strong seasonal clustering of precipitation. Using the SI has proven valuable in identifying climate regimes, characterizing drought and flood risks, and guiding agricultural water management.

Differences in rainfall seasonality between point gauges and gridded products such as CHIRPS can significantly impact hydrologic modeling. Gauge data, being highly localized, may overstate seasonality if located in areas with orographic enhancement or convective rainfall. In contrast, gridded datasets depict spatially averaged rainfall conditions, which can reduce extremes but offer a more balanced representation at the basin level. These differences affect hydrologic outputs, especially the estimation of baseflow, groundwater recharge, and streamflow seasonal patterns.

For the Philippines, accurately characterizing rainfall seasonality is essential because it underpins water resource planning for irrigation, hydropower generation, and flood control. Misrepresentation of seasonality may lead to underestimation of dry-season water stress or overestimation of wet-season runoff. Therefore, evaluating how CHIRPS represents rainfall concentration compared to PAGASA station data is crucial for assessing its suitability in basin-scale hydrologic and climate studies.

**Strengths and Limitations of CHIRPS**

The CHIRPS dataset offers several advantages that make it highly suitable for hydrologic and climate studies, particularly in data-scarce regions. Its high spatial resolution (0.05°, ~5 km) and long temporal coverage (1981–present) offer consistent rainfall data suitable for both retrospective studies and near-real-time monitoring (Funk et al., 2015). Combining infrared satellite estimates with ground-based observations improves spatial coverage while calibrating rainfall estimates to in situ data. These features have made CHIRPS valuable for applications like drought tracking, crop modeling, and hydrologic simulations (Toté et al., 2015; Dinku et al., 2018).

Despite its advantages, CHIRPS also has limitations. A common issue is its tendency to smooth out short-term rainfall events, which can cause underestimation of peak intensities and convective storms. This smoothing happens due to the spatial averaging inherent in gridded products and the limitations of infrared-based retrieval algorithms. As a result, CHIRPS may perform well for monthly and seasonal totals but is less accurate for daily or sub-daily rainfall extremes. Another limitation is the variable density and quality of ground stations used for blending, which can influence performance in different regions. In areas with sparse gauges, such as mountainous regions in the Philippines, CHIRPS estimates may have biases that need correction.

To overcome these limitations, several studies recommend the application of bias-correction methods like quantile mapping or combining CHIRPS with additional data sources (e.g., PAGASA station data, radar, or reanalysis products). These strategies can improve CHIRPS's reliability for hydrologic applications that need precise representation of extremes, including flood forecasting and climate change impact assessments.

**Methodology**

**Study Area**

The Abra River Basin (ARB) is one of the most important and ecologically vital watersheds in Northern Luzon, Philippines. It covers approximately 4,909 square kilometers, and spans six provinces: Abra, Ilocos Sur, Ilocos Norte, Apayao, Benguet, Kalinga, and Mountain Province, which are part of the Cordillera Administrative Region (CAR) and Region I (Ilocos Region). Of these, the province of Abra accounts for 77% of the basin's land area, with the remaining area spread across neighboring provinces (Figure 1).

The Abra River, the main stem of the basin, originates from the rugged eastern mountains in the municipalities of Tineg and Tubo in Abra, flows generally westward for about 206 kilometers, and drains into the West Philippine Sea at the coast of Ilocos Sur. Along its course, it is fed by numerous tributaries, notably the Tineg River, Sinalang River, and Lagut River, creating a complex hydrologic network that nourishes upland and lowland ecosystems. Using high-resolution Interferometric Synthetic Aperture Radar (IFSAR) digital elevation data at 5-meter resolution, the basin was divided into 71 sub-watersheds and 5,247 hydrologic response units (HRUs) for hydrologic simulation, capturing spatial differences in terrain, soil, and land cover.

The climatic pattern of the ARB follows the Coronas classification, where the basin lies within two distinct climate zones: Type I in the western and lowland areas and Type III in the eastern and mountainous interior (Figure 2). Type I zones, particularly in Ilocos Sur, experience a pronounced dry season from November to April and a wet season from May to October, primarily influenced by the Southwest Monsoon (Habagat). In contrast, the Type III areas, which encompass much of the interior Abra and the eastern highlands, exhibit no pronounced dry season. However, they may experience short, unpredictable dry spells. This transition across climate types contributes to significant spatial variability in rainfall and seasonality, as further confirmed by the analysis of satellite and station data in this study.

Topographically, the ARB is mainly characterized by mountainous terrain, especially in the northern, eastern, and southern areas, with elevations from sea level to over 2,500 meters above sea level (masl) (Figure 3). The central Cordillera ridges in the east create strong orographic effects, intensifying rainfall in upland regions, while the western basin slopes gently toward the Ilocos lowlands. Elevation analysis shows that about 38.36% of the basin falls within the 501–1,000 masl range, and 25.45% is above 1,000 masl, highlighting the basin's steep and diverse topography. The slope classification map (Figure 4) also indicates that more than 64% of the basin has slopes over 18%, categorized as undulating to severely steep terrain, which directly affects runoff, erosion risk, and flooding potential.

The ARB plays a critical role in supporting agriculture and water security in Northern Luzon. It supplies irrigation water through national and community irrigation systems, private pumping stations, and small reservoirs. According to records from the National Water Resources Board (NWRB), about 80% of total water use in the basin goes to irrigation, mainly for rice, corn, vegetables, and tobacco farming in lowland areas. Municipalities in the midstream and downstream parts also rely on surface water for domestic and municipal use, while upland communities depend heavily on springs and shallow groundwater sources. Additionally, the basin enables small hydropower projects in Benguet and Mountain Province and offers key ecosystem services such as aquifer recharge and sediment management transport.

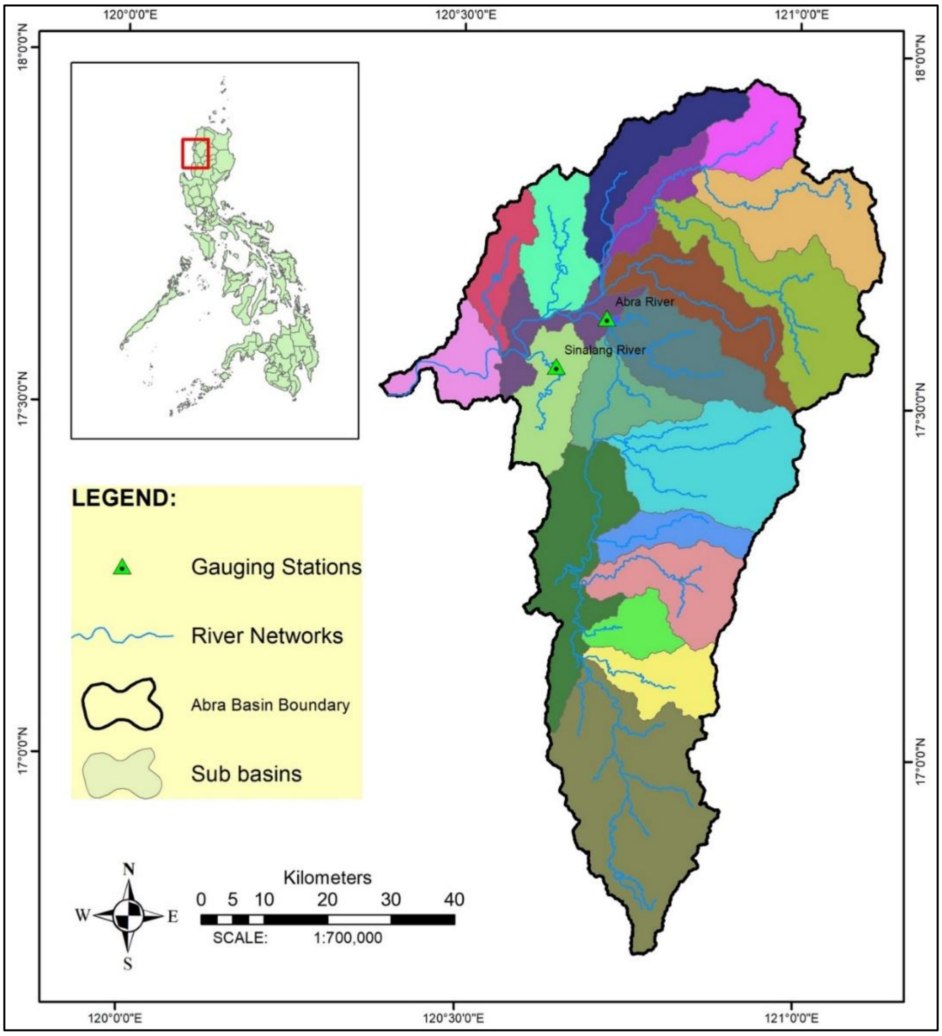


Figure 1: Location and administrative map of the Abra River Basin, indicating provincial boundaries, municipalities, river networks, and the extent of the basin across Region I and CAR.

**Rainfall Data**

Two rainfall datasets were utilized in this study for comparative analysis and hydrologic modeling in the Abra River Basin (ARB). The first dataset comes from the PAGASA synoptic station in Vigan City, which supplied ground-observed daily rainfall data for 1990–2020. This station, located on the western side of the basin, represents a Type I climate but has limited spatial coverage to reflect the diverse rainfall patterns across the basin.

The second dataset is the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), a nearly global rainfall product with a spatial resolution of about 0.05° (~5 km), providing data from 1981 to the present. For this study, CHIRPS rainfall records from 1983 to

2020 were extracted and clipped to the spatial extent of the ARB to represent the basin-wide precipitation patterns.

To ensure a valid comparison, the common period from 1990 to 2020 was selected for statistical analysis. Both datasets underwent harmonization steps, including quality control, unit standardization (mm/day), temporal alignment, and formatting to meet the input requirements of the Soil and Water Assessment Tool (SWAT). The CHIRPS dataset was processed in raster format using ArcGIS and Python scripts and then converted into text-based weather generator files via the ArcSWAT V10.4 interface.

**Rainfall Data Analysis**

The rainfall data were evaluated using descriptive statistical measures, including mean, maximum, minimum, standard deviation, and coefficient of variation (CV), to characterize temporal rainfall patterns. The seasonal distribution of rainfall was also analyzed by segregating values into Northeast Monsoon (NE: November–March) and Southwest Monsoon (SW: June–October) periods, consistent with PAGASA's climatic designations.

To assess rainfall concentration and seasonality, the Seasonality Index (SI) proposed by Walsh and Lawler (1981) was calculated using the formula:

$$SI = \frac{1}{R}\sum_{n=1}^{n=12}\left|X_n - \frac{R}{12}\right|$$

where $R$ is the mean annual rainfall, and $X$ is the mean monthly rainfall. The SI results were used to classify the rainfall regime into standard categories (e.g., equable, seasonal, markedly seasonal, extreme).

Additionally, spatial variability was analyzed using CHIRPS gridded data aggregated across the basin. Mean annual rainfall maps were generated using GIS to visualize spatial distribution and highlight areas with high orographic influence. This spatial analysis provides insights into the limitations of single-station data for representing the full climatic variability of the basin.

**SWAT Hydrologic Modeling Framework**

To simulate the hydrologic processes of the Abra River Basin, this study employed the Soil and Water Assessment Tool (SWAT), a process-based, semi-distributed watershed model developed by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS). The SWAT model is widely recognized for its ability to simulate the impact of land use, soil, topography, and climate on water resources over long periods. It operates by subdividing the basin into smaller units called sub-watersheds, which are further partitioned into hydrologic response units (HRUs), unique combinations of land cover, soil type, and slope class that enable the spatial representation of watershed heterogeneity.

For the topographic input, the study used a high-resolution Interferometric Synthetic Aperture Radar (IFSAR) digital elevation model with a five-meter spatial resolution. This DEM served as the basis for delineating watershed boundaries, generating stream networks, and calculating slope classes within the modeling framework. Land use and land cover data were extracted from the 2020 land cover map developed by the National Mapping and Resource Information Authority (NAMRIA). This dataset was reclassified to match the SWAT land cover coding scheme. Soil data, on the other hand, were obtained from the Bureau of Soils and Water Management (BSWM, 2013) and supplemented with literature-based values for soil physical properties, including bulk density, texture, hydraulic conductivity, and available water capacity.

The climatic inputs required by the model included daily precipitation, minimum and maximum air temperature, solar radiation, relative humidity, and wind speed. However, due to limited long-term weather data from PAGASA within the basin, only rainfall and temperature were used, with the CHIRPS satellite-derived rainfall dataset serving as the primary input from 1983 to 2020. These datasets were converted into weather input files using the ArcSWAT V10.4 interface within ArcGIS.

After data preparation, the watershed was discretized into 71 sub-watersheds and 5,247 HRUs, representing variations in terrain, land use, and soil characteristics across the basin. The model was first run using historical weather data to simulate daily hydrologic processes. Calibration and validation of the model were then conducted to ensure its predictive accuracy. Monthly streamflow data from two gauging stations —Sinalang River (1984–2020) and Abra River (2005–2008) — were used for model calibration and validation.

To enhance calibration quality, baseflow separation was performed using the digital filter method of Arnold et al. (1995), enabling a more detailed adjustment of surface runoff and groundwater contributions to streamflow. Model calibration was performed using SWAT-CUP, a model-independent interface that supports uncertainty and sensitivity analysis. Specifically, the Sequential Uncertainty Fitting algorithm (SUFI-2) was used to identify the most sensitive parameters and optimize them by minimizing the difference between observed and simulated streamflow.

The model's performance was assessed using the Nash–Sutcliffe Efficiency (NSE) to evaluate how well the simulated data reproduced the observed values, and the Percent Bias (PBIAS) to measure the average tendency of the simulated data to overestimate or underestimate the observations. Despite limitations in simulating high-peak flows, likely due to localized rainfall events not captured by the available data, the calibration results indicated that the model sufficiently replicated the overall temporal variability of streamflow at both gauging stations. This provided confidence in using the SWAT model to analyze the hydrologic behavior of the Abra River Basin, especially for long-term simulations and climate impact assessments.

**Water Balance Simulation**

The water balance in SWAT was computed using the model's internal routines, which simulate the movement of water through surface and subsurface pathways, including precipitation interception, surface runoff, evapotranspiration (ET), lateral flow, percolation, baseflow, and groundwater recharge. The water balance equation is as follows:

$$SW_t = SW_o + \sum_{i=1}^{t}\left(P_{day} - Q_s - E_a - W_{seep} - Q_{gw}\right)$$

where $SW_t$ is the soil water content at time t, $SW_0$ is the initial soil water content, $P_{day}$ is the daily precipitation, $Q_s$ is surface runoff, ET is evapotranspiration, $W_{seep}$ is the amount of percolation into the vadose zone, and $Q_{gw}$ is return flow or baseflow from shallow aquifers.

In this study, the historical water balance simulation was conducted for the period 1986–2020, with the first three years (1983–1985) used as a warm-up period to stabilize soil moisture and groundwater reservoirs. The rainfall input for the simulation was exclusively derived from the CHIRPS dataset, selected for its spatial comprehensiveness and continuity. The model outputs included the following water balance components: surface runoff, baseflow, shallow and deep aquifer recharge, total water yield, and potential evapotranspiration (PET).

To assess the potential impacts of climate change, future climate scenarios were generated using projected rainfall and temperature anomalies from the SSP5-8.5 scenario under CMIP6 for the mid-century (2040–2059) and late-century (2060–2079) periods. The projections were derived from the World Bank's Climate Change Knowledge Portal and downscaled to monthly deltas applied to the historical baseline.

These projected weather inputs were used to simulate the basin's future water balance, enabling comparison of changes in hydrologic parameters under baseline and future climate scenarios. The results inform on likely shifts in water availability, seasonality, and runoff extremes in response to increasing temperatures and rainfall variability.

## Discussion of Results

### Statistical Comparison

The comparison between rainfall records from the PAGASA Vigan Station and the CHIRPS satellite-based dataset for the period 1990–2020 reveals notable differences in annual rainfall characteristics within the Abra River Basin. Table 1 presents the statistical summary of annual rainfall derived from both datasets, including mean, minimum, maximum, standard deviation, and coefficient of variation (CV).

Table 1: Annual Rainfall Statistics (1990–2020): CHIRPS vs. PAGASA Vigan Station.

| Parameter | Units | VIGAN STATION | | | CHIRPS | | |
|---|---|---|---|---|---|---|---|
| | | Annual | Monsoon | | Annual | Monsoon | |
| | | | NE | SW | | NE | SW |
| Mean | mm | 2,190.4 | 58.9 | 1,787.9 | 2,571.8 | 213.6 | 2,571.8 |
| Std Deviation | mm | 487.0 | 77.0 | 396.2 | 373.8 | 104.0 | 373.8 |
| Maximum | mm | 3,558.1 | 271.6 | 2,503.1 | 3,568.1 | 426.7 | 3568.1 |
| Minimum | mm | 1,135.4 | 3.2 | 856.2 | 2,056.8 | 55.2 | 2,056.8 |
| Median | mm | 2,153.4 | 28.0 | 1,740.0 | 2,469.0 | 198.8 | 2,469.0 |
| Coefficient of Variation | % | 22.23 | 130.75 | 22.16 | 14.53 | 48.70 | 14.53 |

The CHIRPS dataset recorded a higher mean annual rainfall of 2,571.8 mm, compared to 2,190.4 mm at Vigan Station. CHIRPS also showed a lower coefficient of variation (14.53%), suggesting more consistent rainfall estimates over time, whereas the Vigan Station exhibited higher variability (CV = 22.23%), reflecting the influence of localized rainfall patterns and dry spells, particularly in areas exposed to Type I climate.

Notably, the minimum annual rainfall from the Vigan Station was 1,135.4 mm, which is significantly lower than the CHIRPS minimum of 2,056.8 mm. This disparity indicates that CHIRPS does not capture the extremely low rainfall events observed at the Vigan Station, likely because of its spatial averaging and smoothing algorithms. While ground-based stations can reflect sharp localized rainfall deficits, CHIRPS offers a basin-wide perspective that reduces such extremes. These differences have significant implications when selecting rainfall inputs for hydrologic modeling, particularly in representing drought periods or low-flow conditions.

### Seasonal Rainfall Patterns

The monthly rainfall distributions from both datasets are shown in Figures 2 and 3. The Vigan Station data (Figure 5.1) presents a rainfall pattern typical of Type I climate, with a pronounced wet season from June to September, peaking in August, and a distinct dry season from November to April, reaching a minimum in February. Monthly rainfall in the driest months drops below 10 mm, with February registering only 3.05 mm.

In contrast, the CHIRPS dataset (Figure 3) exhibits a smoother and more balanced seasonal profile, with significant rainfall even during the drier months. While it still shows peaks in the wet season, it does not capture the same depth of the dry season as recorded in Vigan. For instance, the lowest CHIRPS monthly rainfall is 10.21 mm in January, compared to only 6.49 mm at Vigan.

CHIRPS integrates rainfall signals from both the western and eastern portions of the basin, effectively capturing the dual influence of Type I (wet-dry monsoonal) and Type III (evenly distributed) climates. The eastern sub-watersheds, situated in the Cordillera highlands, experience more persistent rainfall due to orographic lifting, which CHIRPS accounts for through its spatial coverage and blended station-satellite retrievals. This attribute makes CHIRPS particularly valuable for basin-scale hydrologic modeling, where a single ground station may not adequately reflect the full spatial diversity of precipitation regimes.

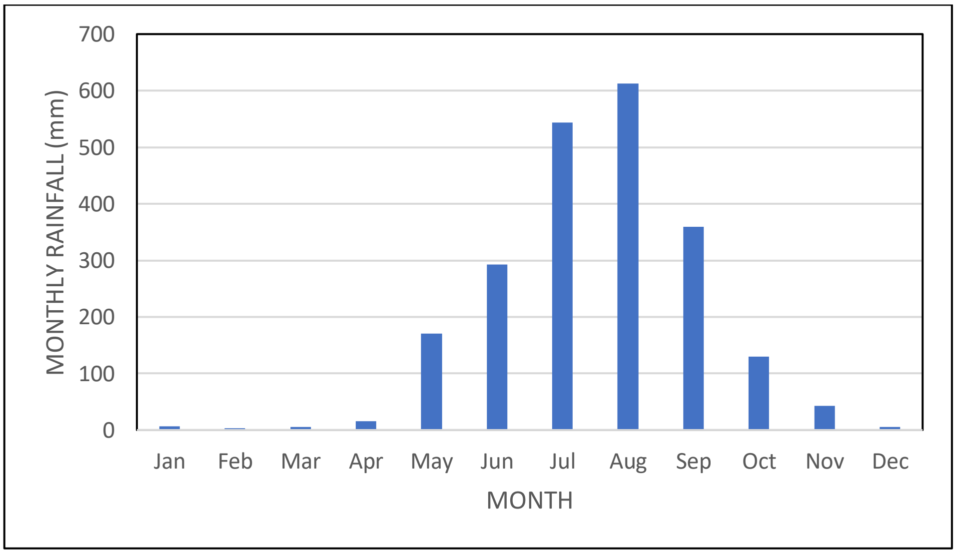


Figure 2: Monthly Rainfall Distribution – Vigan Station (1990–2020)

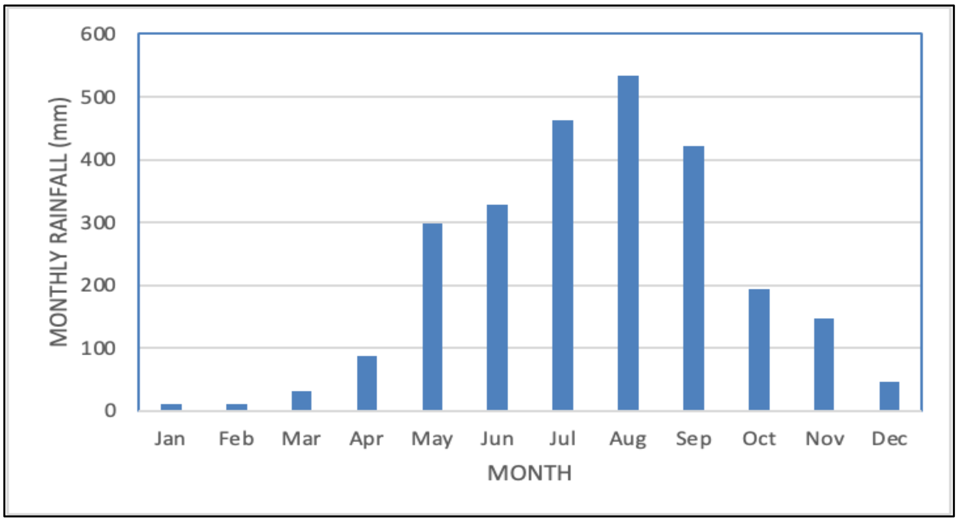


Figure 3: Monthly Rainfall Distribution – CHIRPS (1990–2020)

**Seasonality Index Analysis**

To quantify rainfall seasonality, the Seasonality Index (SI) was computed for both datasets using the 30-year monthly average. The index measures the concentration of annual rainfall within specific months and is widely used in hydrologic studies to evaluate the implications of rainfall distribution on water availability.

Table 2: Seasonality Index and Classification

| Dataset | SI Value | Classification |
| --- | --- | --- |
| Vigan Station | 0.99 | Markedly seasonal with a long dry season |
| CHIRPS | 0.76 | Seasonal |

The Vigan Station recorded an SI of 0.99, placing it at the upper end of the "markedly seasonal" classification. This confirms that rainfall is highly concentrated within a few months, leaving the rest of the year extremely dry. In contrast, the CHIRPS dataset yielded a lower SI value of 0.76, categorized as simply "seasonal", indicating a more balanced rainfall distribution.

These differences have important implications for hydrologic modeling and water resource planning. A highly seasonal rainfall regime, as captured by the Vigan Station, can lead to pronounced streamflow fluctuations, extended dry spells, and water supply stress during planting seasons. On the other hand, the more moderate seasonality suggested by CHIRPS could translate into more consistent recharge, higher baseflow maintenance, and greater reliability in modeling groundwater contributions and dry season flows.

Thus, while station data like Vigan's can represent localized extremes critical for short-term drought assessments, CHIRPS is more suitable for basin-wide water balance simulations and long-term planning scenarios. Its ability to reflect both monsoonal and orographic influences improves its reliability for integrated hydrologic studies, especially in a complex terrain like the Abra River Basin.

**Water Balance Results**

The results of the hydrologic simulation using the SWAT model provide a detailed view of the water balance in the Abra River Basin under both historical and projected climate scenarios (Figure 4). For the baseline period from 1986 to 2020, the model estimated an average annual rainfall of 2,558.5 mm, serving as the main driver of the basin's hydrological processes. The simulation showed that baseflow contributes the largest portion of the rainfall budget, with an average of 1,328.93 mm per year, which is about 51.94% of the total rainfall. Surface runoff was computed at 518.77 mm per year or 20.28% of rainfall, indicating that a significant portion of precipitation infiltrates the soil and contributes to subsurface flows. Shallow aquifer recharge was 859.49 mm per year, while deep aquifer recharge was much smaller at 45.24 mm, for a total aquifer recharge of 904.73 mm or 35.36% of the rainfall. Potential evapotranspiration reached 1,295.20 mm annually, representing around 50.62% of the precipitation, and the total water yield—including both surface runoff and baseflow—amounted to 1,892.94 mm, or 73.99% of the total rainfall.

Future projections under the SSP5-8.5 climate scenario indicate significant changes in water balance components. In the 2050 scenario (2040–2059), rainfall is expected to increase to 2,845.2 mm annually, an 11.21% rise over the historical baseline. This leads to a corresponding increase in surface runoff to 677.87 mm (a 30.67% increase) and baseflow to 1,429.57 mm (a 7.57% increase). Similarly, total aquifer recharge is projected to rise to 971.89 mm (a 7.42% increase), while potential evapotranspiration increases moderately to 1,352.0 mm (a 4.39% increase). The total water yield during this period is predicted to grow to 2,156.03 mm, a 13.90% increase from the baseline.

The 2070 scenario (2060–2079) projects a further increase in rainfall to 2,942.1 mm per year, a total rise of 14.99% from historical levels. Surface runoff under this scenario is estimated at 734.66 mm, an increase of 41.62%, while baseflow rises to 1,457.72 mm, up by 9.69%. Recharge to shallow and deep aquifers also continues to rise, leading to a combined recharge total of 990.09 mm. Meanwhile, potential evapotranspiration is expected to increase to 1,384.6 mm, or 6.90% above the historical level. The total water yield reaches 2,241.88 mm annually, a rise of 18.43%, indicating an overall improvement in streamflow and groundwater contributions.

These projected changes in the water balance suggest significant hydrological responses to climate change in the basin. Increased rainfall leads to higher runoff and streamflow, which could improve water availability but also increase flood risks during peak months. Similarly, better recharge and baseflow contributions indicate a positive trend in groundwater replenishment, although the rise in evapotranspiration could partially counteract these benefits, especially in months with less rainfall. These dynamics highlight the need for adaptive water resource management strategies to address both increased water availability and greater hydrologic extremes in the future.

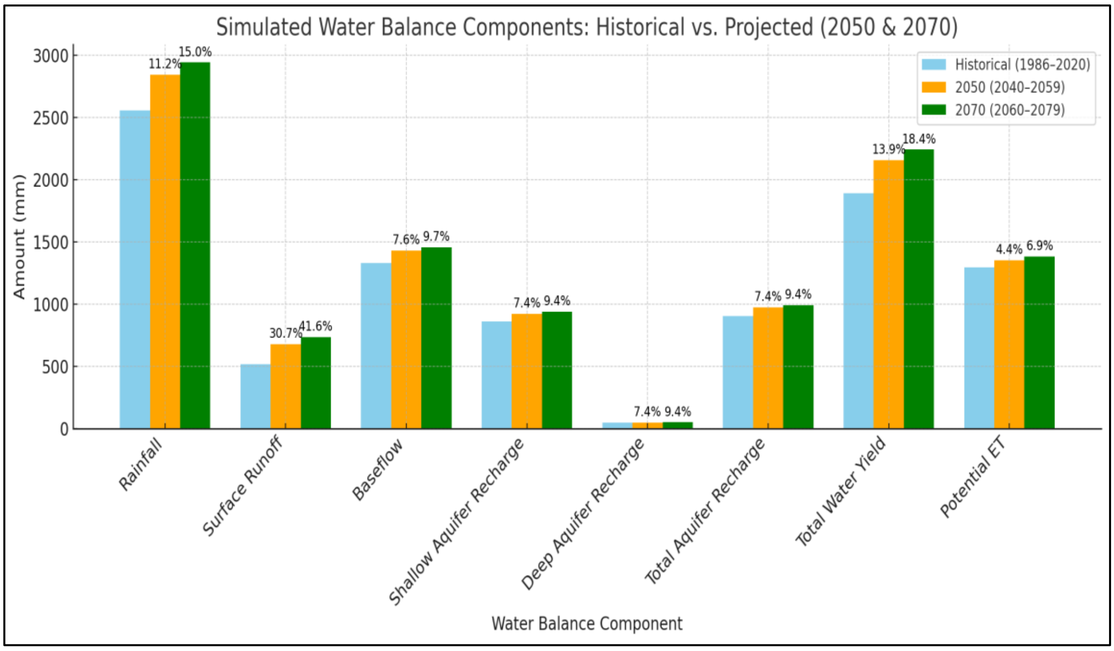


Figure 4: Simulated Water Balance Components in the Abra River Basin under Historical and Projected Climate Scenarios (2050 and 2070)

**Interpretation of Results**

The results of this study highlight the importance of selecting suitable rainfall datasets when conducting hydrological modeling in physiographically and climatically diverse basins, such as the Abra River Basin (ARB). The comparison between CHIRPS and PAGASA Vigan station data revealed substantial differences in rainfall representation, spatial variability, and seasonality, all of which directly affect model inputs and outputs.

One of the key advantages of the CHIRPS dataset lies in its spatial continuity and capacity to reflect basin-scale variability. CHIRPS integrates satellite observations with ground station data using advanced interpolation techniques to produce rainfall estimates at approximately 5 km spatial resolution. This granularity allows it to capture the influence of orographic effects and the dual climatic regimes present in ARB—Type I in the west and Type III in the east. As demonstrated by the rainfall distribution and seasonality index results, CHIRPS captures rainfall that is more balanced and persistent in the eastern and high-elevation portions of the basin, which are underrepresented in single-station data.

In contrast, the PAGASA Vigan station, while accurate at its location, reflects only the western lowland climatic conditions, characterized by a sharply defined wet and dry season typical of Type I climate. Its low minimum rainfall values and higher seasonality index highlight its sensitivity to localized dry spells. Still, it fails to account for rainfall contributions from upland watersheds, particularly those that feed tributaries such as the Tineg and Sinalang Rivers. This spatial limitation is critical because it introduces bias when such data are used as sole inputs for basin-wide hydrologic assessments.

Furthermore, the analysis of rainfall statistics revealed that CHIRPS records a higher annual mean rainfall with lower interannual variability (CV = 14.53%) than the Vigan station (CV = 22.23%), suggesting a more stable and smoothed depiction of rainfall conditions. While this may underestimate extreme dry or wet events, it improves model consistency over long periods. It reduces the potential for misrepresenting baseflow or recharge dynamics in long-term water balance simulations.

Meanwhile, the simulated water balance results revealed a nuanced hydrologic behavior of the Abra River Basin (ARB) under both historical and future climate conditions. The historical simulation showed that a substantial portion of the annual rainfall is converted into streamflow, with baseflow and groundwater recharge accounting for more than half of the total rainfall. This indicates that the basin has a strong subsurface flow regime, consistent with its mountainous terrain, permeable soils at upper elevations, and forested land cover that facilitates infiltration and delays runoff.

The projected increases in rainfall under the SSP5-8.5 scenario—11.21% by 2050 and 14.99% by 2070—result in proportional increases in the components of the water balance. Notably, surface runoff is expected to rise by over 30% by 2050 and 40% by 2070, raising concerns about flash floods, sedimentation, and downstream erosion, especially during the intensified wet season. The increase in baseflow and aquifer recharge, although more modest, suggests that groundwater systems could benefit from climate-related rainfall increases, provided infiltration pathways remain intact and land cover remains preserved.

On the other hand, the increase in potential evapotranspiration (PET) due to rising temperatures—estimated at 4.39% and 6.90% for 2050 and 2070, respectively—could impose greater pressure on water resources during the dry season. This is particularly critical in April and May, when rainfall is projected to decline or remain stagnant. These shifts underscore the basin's sensitivity to climatic extremes, where increased water supply during the rainy season must be balanced against prolonged dry spells with elevated atmospheric demand.

**Suitability for Hydrologic Modeling**

The application of CHIRPS as the primary rainfall input in the SWAT model yielded significantly improved simulation of streamflow dynamics, as evidenced by the model calibration results and water balance outputs. The SWAT simulations using CHIRPS captured the timing, magnitude, and seasonality of streamflow at both the Sinalang and Abra gauging stations, though it has some limitations in simulating extreme peaks. The model revealed that the majority of streamflow is derived from baseflow, reflecting the basin's infiltration-dominated hydrology and the importance of groundwater contributions, which are closely tied to accurate rainfall representation in upper watersheds.

The strong alignment of simulated streamflow with observed baseflow trends confirms that CHIRPS can effectively inform basin-scale modeling, particularly in environments where rainfall exhibits spatial heterogeneity and/or orographic modulation. In regions with sparse rain gauge coverage—such as most upland and interior river basins in the Philippines—the use of CHIRPS overcomes the limitations imposed by logistical and financial constraints on ground monitoring networks.

Moreover, the water balance simulations under climate change scenarios demonstrate that CHIRPS can be successfully extended for climate impact modeling, capturing shifts in hydrologic response such as increased runoff and evapotranspiration. The spatial uniformity and completeness of the CHIRPS dataset make it well-suited for simulating both current and future hydrologic processes across various scenarios without the need for additional data interpolation or infilling, which are often required when using incomplete ground station datasets.

**Broader Applications**

The insights from this study establish a strong case for the broader use of CHIRPS in other Philippine River basins, particularly those facing similar challenges in data availability and topographic complexity. Watersheds in the Cordillera, Sierra Madre, and Mindanao regions, where gauge stations are limited and rainfall is influenced by elevation and monsoonal interactions, stand to benefit from CHIRPS as a reliable and consistent rainfall source.

Beyond hydrologic modeling, CHIRPS also shows potential for drought monitoring, flood risk evaluations, and climate change adaptation planning. Its extensive historical archive (dating back to 1981) and near-real-time updates make it an excellent resource for tracking long-term rainfall patterns and anomalies. Specifically, CHIRPS can support the development of early warning systems, help inform agricultural water management, and guide the creation of climate-resilient infrastructure by providing reliable input for hazard modeling.

In the face of increasing climate variability, the ability of CHIRPS to accurately reflect spatial and temporal rainfall patterns across the entire watershed is vital for enhancing water governance and adaptive resource management. It fills the data gaps in areas with limited monitoring, supporting evidence-based decisions aligned with national goals for sustainable water use, disaster resilience, and climate-smart development.

**Conclusion**

This study evaluated and compared rainfall data from the CHIRPS satellite-derived product and the PAGASA ground station in Vigan to assess their suitability for hydrologic modeling using the SWAT model in the Abra River Basin (ARB), Philippines. Results showed that CHIRPS provides significant advantages over single-station data in capturing the spatial and temporal variability of rainfall in a topographically and climatically complex watershed.

The statistical comparison showed that CHIRPS consistently produced higher mean annual rainfall, lower interannual variability, and more spatially distributed precipitation estimates than the Vigan station, which only represents the western lowland (Type I climate) and does not capture rainfall in the upland and eastern parts of the basin (Type III climate). The seasonality analysis further emphasized this disparity, with the Vigan station indicating a markedly seasonal regime (SI = 0.99) and CHIRPS showing a less extreme seasonal pattern (SI = 0.76), which aligns more closely with basin-wide conditions.

SWAT simulations using CHIRPS data resulted in more realistic streamflow results, showing good agreement in the magnitude and timing of baseflow and runoff. This demonstrates its value for hydrologic modeling in areas with limited data. The climate change projections for 2050 and 2070 under SSP5-8.5 forecast increases in rainfall, surface runoff, recharge, and total water yield—highlighting the importance of using spatially representative datasets like CHIRPS for long-term water resource planning and climate resilience efforts.

Given its basin-wide applicability, extensive historical data, and compatibility with climate projections, CHIRPS is recommended as a dependable alternative or addition to ground station data for hydrologic assessments in the Philippines. Its use can enhance modeling accuracy, especially in upland, mountainous, and poorly monitored basins, and support wider applications such as drought and flood forecasting, climate impact research, and integrated water resource management.

**Recommendations**

Based on the results of this study, the following recommendations are proposed:

- Adoption of CHIRPS in Hydrologic Studies: Encourage wider use of CHIRPS satellite-derived rainfall data as a reliable alternative or supplement to PAGASA station data in river basin assessments, especially in data-scarce and mountainous regions.
- Integration into Planning and Policy: Institutionalize CHIRPS-based hydrologic modeling in water resource planning, watershed management, irrigation scheduling, and climate change adaptation strategies at both local and national levels.
- Strengthening Ground-Satellite Data Synergy: Promote the combined use of PAGASA ground data and CHIRPS to improve calibration, capture extreme events, and refine water balance simulations.
- Capacity Development: Provide training for LGUs, river basin authorities, and national agencies on the use of CHIRPS, GIS, and SWAT modeling tools to enhance local technical capacity for evidence-based decision-making.
- Expansion to Early Warning Systems: Integrate CHIRPS rainfall monitoring into drought and flood early warning systems to support disaster preparedness and community resilience.
- Long-Term Research and Climate Impact Studies: Continue research using CHIRPS to inform long-term hydrologic projections under climate change scenarios, guiding sustainable water allocation, agricultural planning, and infrastructure development.

**Acknowledgment**

The authors express their sincere gratitude to the Department of Science and Technology, through the NICHE Centers in the Region for R&D program, for funding this study, and to the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) for providing essential rainfall data. They also thank the Mariano Marcos State University (MMSU), particularly the Research Directorate and the Coastal Engineering Research and Management Center (COASTER), for their institutional and technical support, as well as colleagues, staff, and all who provided guidance and encouragement toward the successful completion of this work.

## References


Abbaspour, K. C., Vejdani, M., & Haghighat, S. (2007). SWAT-CUP calibration and uncertainty programs for SWAT. In *Proceedings of the International Congress on Modelling and Simulation (MODSIM 2007)* (pp. 1603–1609). Modelling and Simulation Society of Australia and New Zealand.

Alejo, L. A., & Alejandro, G. J. D. (2021). Validation of CHIRPS satellite-based rainfall data in the Philippines. *Philippine Journal of Science, 150*(S1), 121–133.

Amadore, L.A. 2005. Crisis or Opportunity: Climate Change Impacts and the Philippines. Greenpeace Southeast Asia in the Philippines. Quezon City, Philippines. 58pp. www.greenpeace.org. Retrieved on September 19, 2007.

Amorim, J. d. S., Viola, M. R., Junqueira, R., Oliveira, V. A. d., & Mello, C. R. d. (2020). Evaluation of Satellite Precipitation Products for Hydrological Modeling in the Brazilian Cerrado Biome. *Water*, *12*(9), 2571. https://doi.org/10.3390/w12092571.

Arnold, J. G., Allen, P. M., & Bernhardt, G. (1995). Automated base flow separation and recession analysis techniques. *Groundwater, 33*(6), 1010–1018. https://doi.org/10.1111/j.1745-6584.1995.tb00046.x

Arnold, J.G., Srinivasan, R., Muttiah, R.S., & Williams, J.R. (1998). Large area hydrologic modeling and assessment: Part I. Model development. *Journal of the American Water Resources Association*, 34(1), 73–89.

Bagtasa, G. (2022). Assessment of Tropical Cyclone Rainfall from GSMaP and GPM Products and Their Application to Analog Forecasting in the Philippines. *Atmosphere, 13*(9). https://doi.org/10.3390/atmos13091398

Bai, L., Shi, C., Li, L., Yang, Y., & Wu, J. (2018). Accuracy of CHIRPS satellite-rainfall products over mainland China. *Remote Sensing, 10*(3). https://doi.org/10.3390/rs10030362

Cavalcante, R. B. L., Ferreira, D. B. da S., Pontes, P. R. M., Tedeschi, R. G., da Costa, C. P. W., & de Souza, E. B. (2020). Evaluation of extreme rainfall indices from CHIRPS precipitation estimates over the Brazilian Amazonia. *Atmospheric Research, 238*. https://doi.org/10.1016/j.atmosres.2020.104879

Coronas, J.V. (1920). *The climate and weather of the Philippines*. Manila: Bureau of Printing. https://quod.lib.umich.edu/p/philamer/agh9000.0001.001/1

Dhanesh, Y., Singh, A., & Mishra, A. (2020). Assessment of CHIRPS rainfall data for hydrological simulations in India. *Hydrological Sciences Journal, 65*(12), 2036–2049. https://doi.org/10.1080/02626667.2020.1776479

Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S. J., & Ropelewski, C. F. (2018). Validation of satellite rainfall products over East Africa's complex topography. *International Journal of Remote Sensing*, 28(7), 1503-1526, *DOI: 10.1080/01431160600954688*.

Du, H., Tan, M. L., Zhang, F., Chun, K. P., Li, L., & Kabir, M. H. (2024). Evaluating the effectiveness of CHIRPS data for hydroclimatic studies. In *Theoretical and Applied Climatology 155*(3), 1519–1539. https://doi.org/10.1007/s00704-023-04721-9

Fensterseifer, C., Allasia, D. G., & Paz, A. R. (2016). Assessment of the TRMM 3B42 Precipitation Product in Southern Brazil. *Journal of the American Water Resources Association, 52*(2), 367–375. https://doi.org/10.1111/1752-1688.12398

Funk, C., Peterson, P., Landsfeld, M., et al. (2015). The Climate Hazards Infrared Precipitation with Stations—A new environmental record for monitoring extremes. *Scientific Data*, 2, 150066.

Gampe, D., & Ludwig, R. (2017). Evaluation of Gridded Precipitation Data Products for Hydrological Applications in Complex Topography. *Hydrology*, *4*(4), 53. https://doi.org/10.3390/hydrology4040053

Guiamel, I. A., & Lee, H. S. (2020). Watershed modelling of the mindanao river basin in the philippines using the SWAT for water resource management. *Civil Engineering Journal (Iran), 6*(4), 626–648. https://doi.org/10.28991/cej-2020-03091496

Hsu, J., Huang, W. R., & Liu, P. Y. (2022). Comprehensive Analysis of PERSIANN Products in Studying the Precipitation Variations over Luzon. *Remote Sensing, 14*(22). https://doi.org/10.3390/rs14225900

Jamandre, C. A., & Narisma, G. T. (2013). Spatio-temporal validation of satellite-based rainfall estimates in the Philippines. *Atmospheric Research, 122*, 599–608. https://doi.org/10.1016/j.atmosres.2012.06.024

PAGASA. (2018). Observed and Projected *Climate Change in the Philippines*. Philippine Atmospheric Geophysical and Astronomical Services Administration, Quezon City, Philippines, 36 pp.

Ray, R. L., Sishodia, R. P., & Tefera, G. W. (2022). Evaluation of Gridded Precipitation Data for Hydrologic Modeling in North-Central Texas. *Remote Sensing*, *14*(16), 3860. https://doi.org/10.3390/rs14163860

Toté, C., Patricio, D., Boogaard, H., Van der Wijngaart, R., Tarnavsky, E., & Funk, C. (2015). Evaluation of Satellite Rainfall Estimates for Drought and Flood Monitoring in Mozambique. *Remote Sensing*, *7*(2), 1758-1776. https://doi.org/10.3390/rs70201758

Veloria, A., Perez, G. J., Tapang, G., & Comiso, J. (2021). Improved rainfall data in the Philippines through concurrent use of GPM IMERG and ground-based measurements. *Remote Sensing, 13*(15). https://doi.org/10.3390/rs13152859

Walsh, R. P. D., & Lawler, D. M. (1981). Rainfall seasonality: Description, spatial patterns and change through time. *Weather, 36*(7), 201–208. https://doi.org/10.1002/j.1477-8696.1981.tb05400.x