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Water budget estimation using remote sensing observations and GLDAS-CLSM for Limpopo River Basin

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Abstract

River Basin Management is heavily reliant on satellite remote sensing technologies. Keeping track of a basin's water supply and demand is essential for efficient and sustainable water resource management. In this study, The Limpopo River Basin's monthly water budget components for the 2019 wet and dry seasons were determined using satellite measurements and the GLDAS-2.1 CLSM model. The water budget components, which include Precipitation, Evapotranspiration, Terrestrial Water Storage, and Runoff, were obtained from several satellite-based sources (GPM-IMERG, MODIS, GRACE & GRACE-FO). Runoff was calculated as a residual from the water balance equation because it could not be directly determined from remote sensing measurements. The datasets were prepared, investigated, and evaluated. The effectiveness of satellite remote sensing for estimating the water budget was assessed. The results showed good stability for the Precipitation and Evapotranspiration, but there were significant ambiguities in the Terrestrial Water Storage and Runoff. The precipitation results for the 2019 wet season were close from GPM-IMERG (~ 108 BCM) and GLDAS (~ 119 BCM). Both MODIS and GLDAS showed similar results for the Evapotranspiration for the 2019 dry season (18 BCM, 15 BCM respectively) The study demonstrated the benefits and drawbacks of GLDAS-2.1 CLSM models with satellite-based remote sensing for calculating water budgets. Since human impact is not considered in remote sensing and modeled data, caution should be used when employing them in ungauged areas. Given the limitations in GLDAS and remote sensing datasets, these data can be extremely helpful, especially in areas with limited data, for assessing seasonal and inter-annual changes in water components and river basin management.

1. Introduction

The availability of water is a significant issue in the twenty-first century [1]. Understanding the hydrologic cycle and how water travels through Earth's atmosphere, land surface, and subsurface is necessary for ensuring sustainable water supplies [2]. Hydrologists and users can quantify the hydrologic cycle by using water budgets [3]. An evaluation of the rates of water flow and the change in water storage in the entire atmosphere, land surface, and subsurface is known as a "water budget" [4]. Water budgets are straightforward in concept, but they could be challenging to calculate precisely. To assess how much water may be available for human and environmental demands, it is critical for the public and decision-makers to understand the uncertainties that exist in water budgets and their relative relevance [5].

A river basin is an area of land that drains water into a river and its tributaries. A river basin collects rain or snow, and it drains into a common outlet such as a stream or a tributary lake or wetland, where it eventually flows into the river. River Basin is major source of fresh water for drinking and agricultural activities, which makes it the lifeblood of the area surrounding it. Moreover, there are 263 trans-boundary river basins covering about half the earth's surface [6]. About 145 states have territory within trans-boundary lakes or river basins, and 30 countries lie entirely within trans-boundary rivers, and it has been noted that since 1948 there have been 37 incidents of acute conflict over water [7,8]. The components of water budget include Precipitation, Evaporation, and transpiration (Evapotranspiration), infiltration, Total water Storage (Soil moisture, reservoirs, and groundwater storage) and Runoff [9].

Surface-based gauges (rain gauges) and remote sensing measurements can be used to measure Precipitation. But since gauge-based observations are dependent on points, the uncertainty in Precipitation values grows as one gets further away from the measuring station [10,11]. Evapotranspiration is the total of all evaporation and transpiration processes that transport water from the ground surface to the atmosphere. When using in situ methods to measure Evapotranspiration at large scales, spatial variability is typically substantial. Numerous factors (such as solar radiation at the surface, air and ground temperatures, surface winds, humidity, soil conditions, and vegetation cover and types) affect Evapotranspiration [12]. Runoff is water that runs off into the stream and eventually out of the watershed or sub-basin. Hydrological stations can be used to monitor Runoff variations, although many basins across the world have a dearth of or a patchy distribution of these stations [13]. A crucial part of the hydrological cycle, which encompasses all types of surface and subsurface water, is Terrestrial Water Storage (TWS). Surface measurements are still very important but point measurements have non-uniform coverage and data void regions. Although point measurements have non-uniform coverage and data empty zones, surface measurements are still very useful [14].

The management of water resources is increasingly dependent on satellite remote sensing technologies. When opposed to ground-based nonuniform observations [15], satellite remote sensing offers global coverage and spatially uniform data. One of the key benefits of earth-observing satellites is their ability to give reliable Precipitation estimates on a global scale with high spatial and temporal precision. This capability includes providing Precipitation data over data-restricted regions [16]. Several researchers have recently investigated how well satellite-based rainfall estimates perform. Remotely sensed Precipitation products have been suggested as an alternative in terms of time and space for data-scarce areas because of the encouraging findings that have been reported [17-20]. This paper aim to estimate the Limpopo River Basin terrestrial water budget from GLDAS 2.1-CLSM and remote sensing observations and compare the results to assess how well satellite remote sensing performs in estimating water budgets, and to examine and contrast the spatial patterns between satellite data and earth system model data.

2. Material and Method

In this study, earth system modeling and remote sensing datasets (Table 1) were utilized for evaluating the water budget in the 2019 wet and dry seasons in the Limpopo River basin (December 2015-February2016) and (June2016-August2016) respectively. The Shuttle Radar Topography Mission (SRTM) provided a Digital Elevation Model (DEM) for the research area with a 1 arc-sec (~ 30 m) grid resolution. The basin and its network of streams were defined using the DEM. Due to the GLDAS-2.1 CLSM model's ability to represent groundwater and the high performance of the data assimilation framework, it was chosen to be used with their Level-4 monthly output data for comparative comparison. Datasets from GLDAS 2.1 are accessible at 1° spatial resolution. The model's outputs for Surface Runoff (R), Terrestrial Water Storage (TWS), Evapotranspiration (ET), and Precipitation (P) on a monthly average were retrieved from NASA's Goddard Earth Sciences Data and Information Services Center. To test the water budget estimation utilizing solely remote sensing data, satellite-based hydrological datasets from several sources were acquired.

2.1. Study Area

Southern Africa is home to the Limpopo River basin, which includes parts of Botswana, Mozambique, South Africa, and Zimbabwe. The Limpopo River Basin is situated between the latitudes of 20°S and 26°S and the longitudes of 25°E and 35°E in Southern Africa as shown in Fig. 1. There are several problems in the Limpopo River watershed, but one of the biggest is water scarcity. The Limpopo River basin drains an area of around 408,000 Km^2. The Limpopo River flows from the junction of the Marcio and Crocodile Rivers in South Africa to the Indian Ocean at Xai Xai in Mozambique across more than 1,750 km. Before entering Mozambique at Pafuri, the river forms the border between Botswana and South Africa, then between Zimbabwe and South Africa. The climate of the Limpopo River basin varies along the path of the river from the temperate climate of the Western basin to the subtropical environment at the river mouth in Mozambique. The minimum and maximum summer temperatures within the catchment range from 14°C to 25°C, whereas the minimum and maximum winter temperatures range between 0°C and 17°C, respectively, during the chilly winter months [21]. The basin receives 530 mm of rain on average annually, with rainfall varying from 1200 mm in the Southeast to 200 mm in the central-West [22]. Due to the climate's wildly erratic rainfall patterns, there are both relatively dry years and years with floods. With rates ranging from 1,000 mm/year in the Southern half of the basin to 2 000 mm/yr in the north, Evapotranspiration across the basin is high in comparison to rainfall according to the Food and Agriculture Organization (FAO) [23].

Table 1. List of hydrological variables used in this study.

Variable	Product	Spatial resolution	Temporal resolution	Time Span	Website
Precipitation	GPM IMERG V6	0.1°	Monthly	06/2000-Present	https://giovanni.gsfc.nasa.gov/giovanni/
	GLDAS-2.1 CLSM output	1°	Monthly	01/1981-Present	https://daac.gsfc.nasa.gov/
Evapotranspiration	MOD16A2	500m	8-day	12/1999-Present	https://appeears.earthdatacloud.nasa.gov/
	GLDAS-2.1 CLSM output	1°	Monthly	01/1981-Present	https://daac.gsfc.nasa.gov/
TWS	GRACE	0.1°	Monthly	03/2002-Present	https://grace.jpl.nasa.gov/
	GLDAS-2.1 CLSM output	1°	Monthly	01/1981-Present	https://daac.gsfc.nasa.gov/
Runoff	GLDAS-2.1 CLSM output	1°	Monthly	01/1981-Present	https://daac.gsfc.nasa.gov/

2.2. Methods

First, the DEM data was used to delineate the basin and its stream network using Arc Hydro Tools within the ArcGIS environment. The hydrological raster data were then subjected to image pre-processing to prepare them for analysis. The Raster Calculator function was then used to change the variable units to millimeters each month. The values for each variable were then retrieved from the monthly basin averages using Zonal Statistics. The monthly data were compiled for the basin water budget calculation, and calculations were made using the general water balance equation. To produce the overall seasonal quantities, the seasonal accumulated components were finally multiplied by the basin area. Below is provided the general water balance equation.

$$P=ET+R+\Delta S$$

Where P is Precipitation, ET is Evapotranspiration, R is Runoff, and $\Delta S=ds/dt$ is change in surface and subsurface water storage. It is important to note that the water balance calculation does not explicitly account for water quantities used for agriculture or other residential purposes, due to the lack of a mechanism for estimating such values that is universally consistent. Studies are typically carried out to ensure the accuracy and caliber of observations both before and after the launch of earth observation satellites and the introduction of new services. By contrasting the findings with remotely sensed data, and model outputs, validation studies can be carried out. Utilizing in situ research and other techniques, all the data used in this study have undergone comprehensive validation. Many academics have separately assessed remote sensing Precipitation datasets like TRMM and GPM. Various studies have evaluated Evapotranspiration data from MODIS. Multiple studies have validated the forcing data as well as the GLDAS outputs.

3. Results

For each season, the amounts of Precipitation, Evapotranspiration, Runoff, and Change in Terrestrial Water Storage were estimated. In this part, satellite-based water budget elements are assessed by comparing them with model results and measured data.

3.1. Precipitation

The regional distribution of total Precipitation for the wet and dry seasons is depicted in Fig. 2 using data from remote sensing observations (GPM IMERG) and the GLDAS model (CLSM). Due to the limited spatial resolution of GLDAS outputs, extracting raster by mask can result in loss of data; to address this problem, the shape extent coordinates were employed. then the Zonal Statistics tool in ArcGIS was used to get the area average data. IMERG data underestimates Precipitation over the Northeast region in the wet season, While GLDAS showed underestimation only on the East region. GLDAS offered higher Precipitation rates than IMERG. The variations in the datasets may result from the models' use of various forcing data.

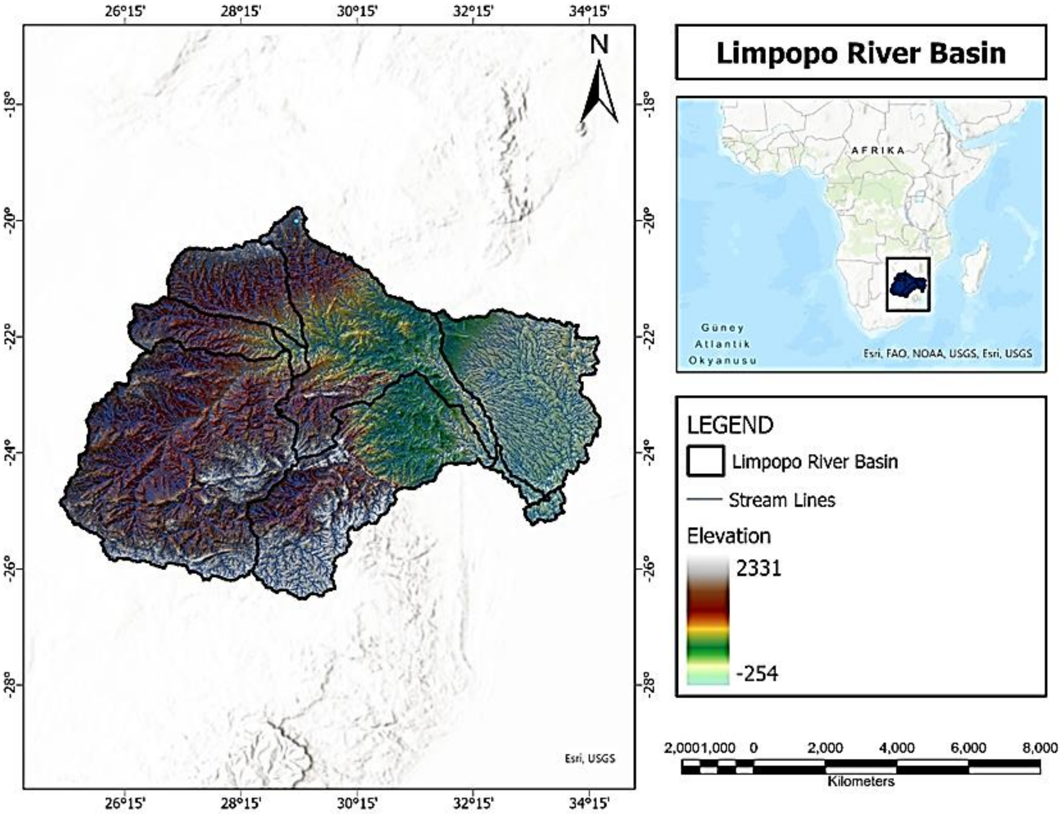

Figure 1. Study Area- Limpopo River Basin

3.2. Evapotranspiration

Using data from remote sensing observations and GLDAS CLSM, Fig. 3shows the seasonal area-averaged total Evapotranspiration for the water in the wet and dry season for the Limpopo River Basin. MODIS and GLDAS data show High rates of Evapotranspiration on the North, South, East regions in the wet season. Even while ET maps produced from GLDAS outputs have relatively low spatial resolutions, certain similarities can be seen in the patterns.

3.3. Terrestrial Water Storage Change

The water cycle relies heavily on Terrestrial Water Storage. The difference of monthly TWS over the study period was used to calculate the values of DTWS derived from the GRACE and GLDAS models. Change in TWS derived from two model outputs and GRACE product are shown in Figure 4. Most of the regions show discrepancies between the GLDAS outputs and GRACE DTWS. The variations could result from a variety of factors such as Spatial signal-leakage from adjacent areas is probable due to GRACE's coarse resolution (330 x 330 km), particularly at the sea boundary. The monthly grids have greater inaccuracies when the orbit is close to an exact repeat, which leads to incorrect gravity field estimations. Additionally, uncertainty in P, ET, and R results in uncertainty in TWSC. Another reason for the differences between the GRACE TWSC and GLDAS models could be that the GLDAS model does not take lake and river modules into account. It is GRACE's and GLDAS's primary drawback.

3.4. Runoff

Figure 5 illustrates the seasonal total Runoff derived using the GLDAS-CLSM model and the residual (P-ET-TWS) from the water balance equation for the 2019 wet and dry seasons. We calculated the residuals to determine if we can interpret those numbers as Runoff in the basin as R cannot be determined directly from satellite data. This study's objective is to evaluate each component's behavior over the Limpopo River basin rather than to resolve the water balance. Figure 5 shows that exact R values cannot be determined, not even from model output residuals.

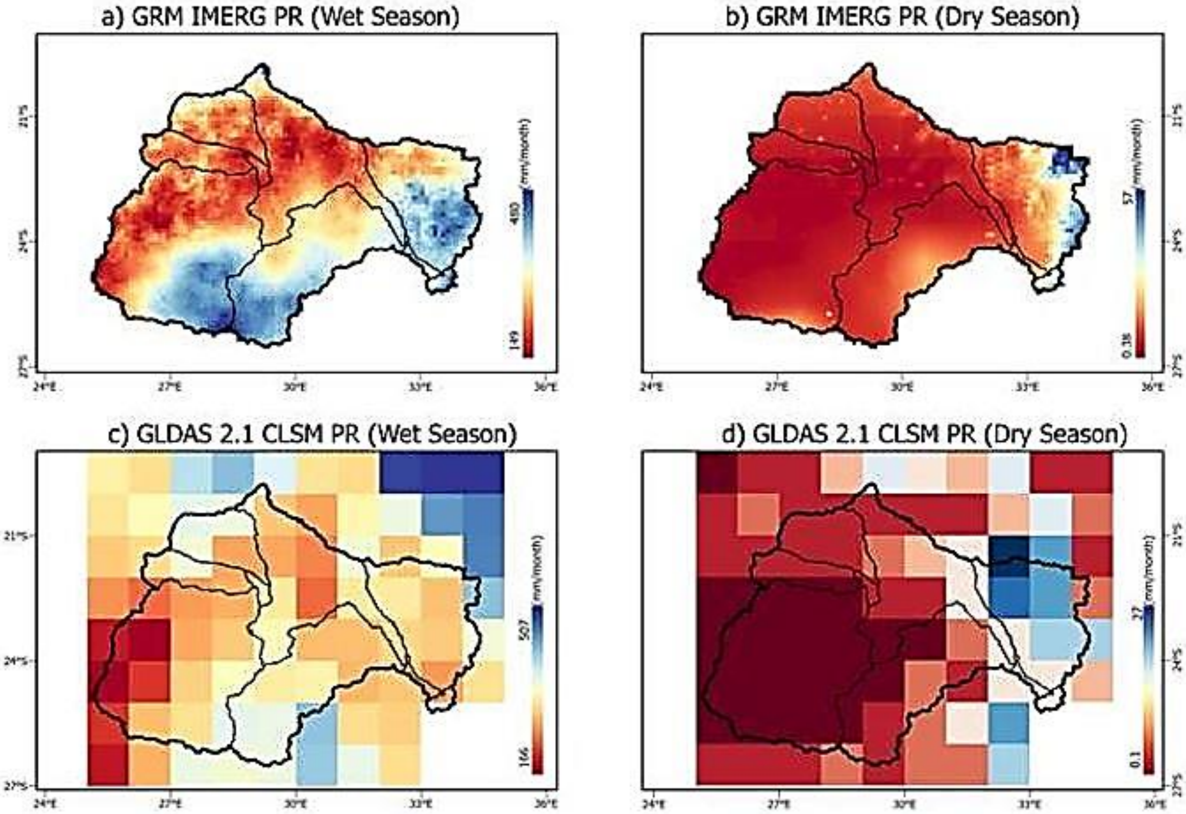

Figure 2. Average total Precipitation for the Wet and Dry season in 2019 a and b GPM IMERG (remote sensing observation), c and d GLDAS CLSM

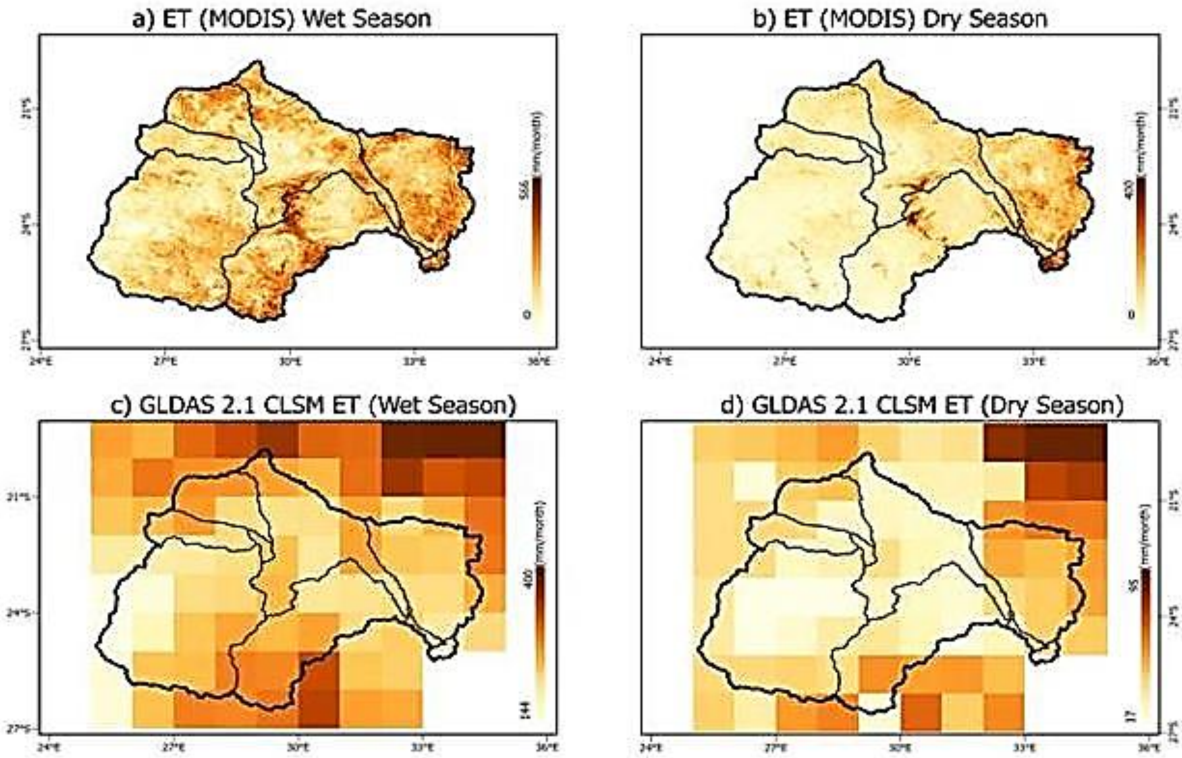

Figure 3. Average total Evapotranspiration for the Wet and Dry season in 2019 a and b GPM IMERG (remote sensing observation), c and d GLDAS CLSM

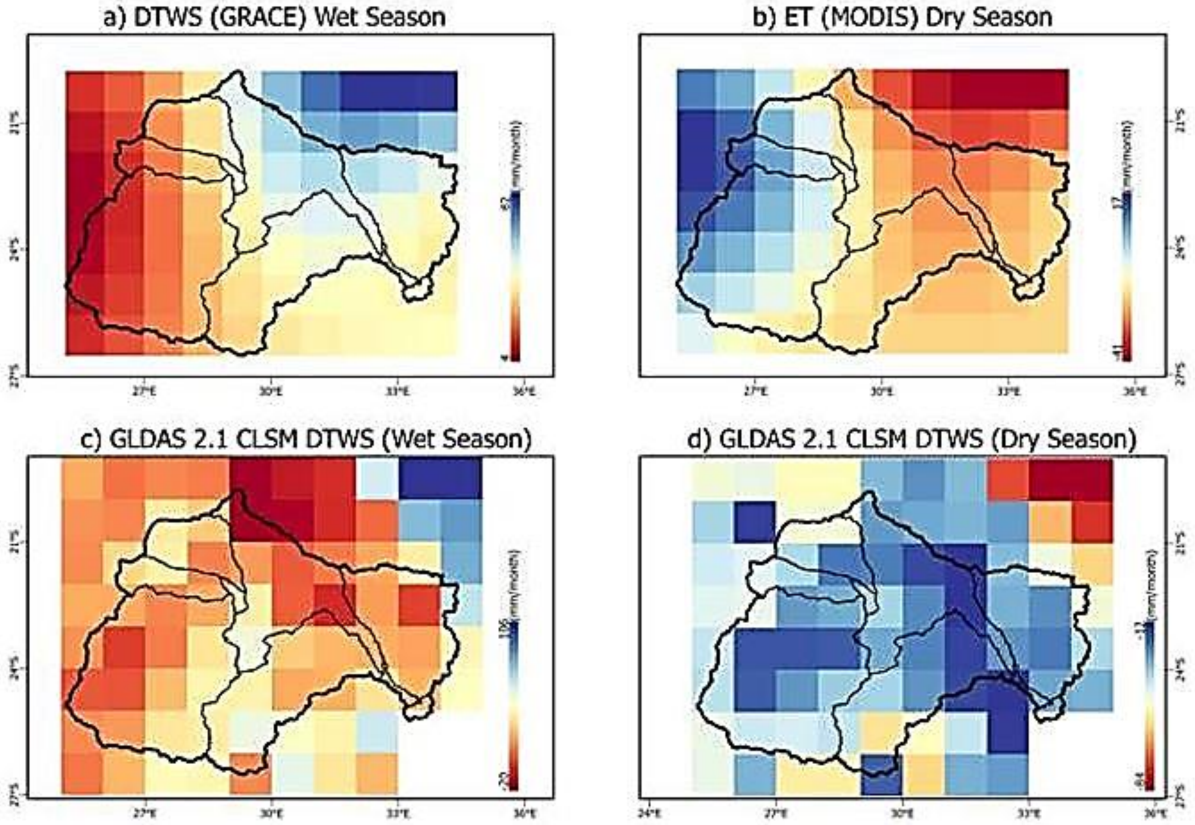

Figure 4. Total Difference Terrestrial Water Storage (DTWS) for the Wet and Dry season in 2019 a and b GPM IMERG (remote sensing observation), c and d GLDAS CLSM

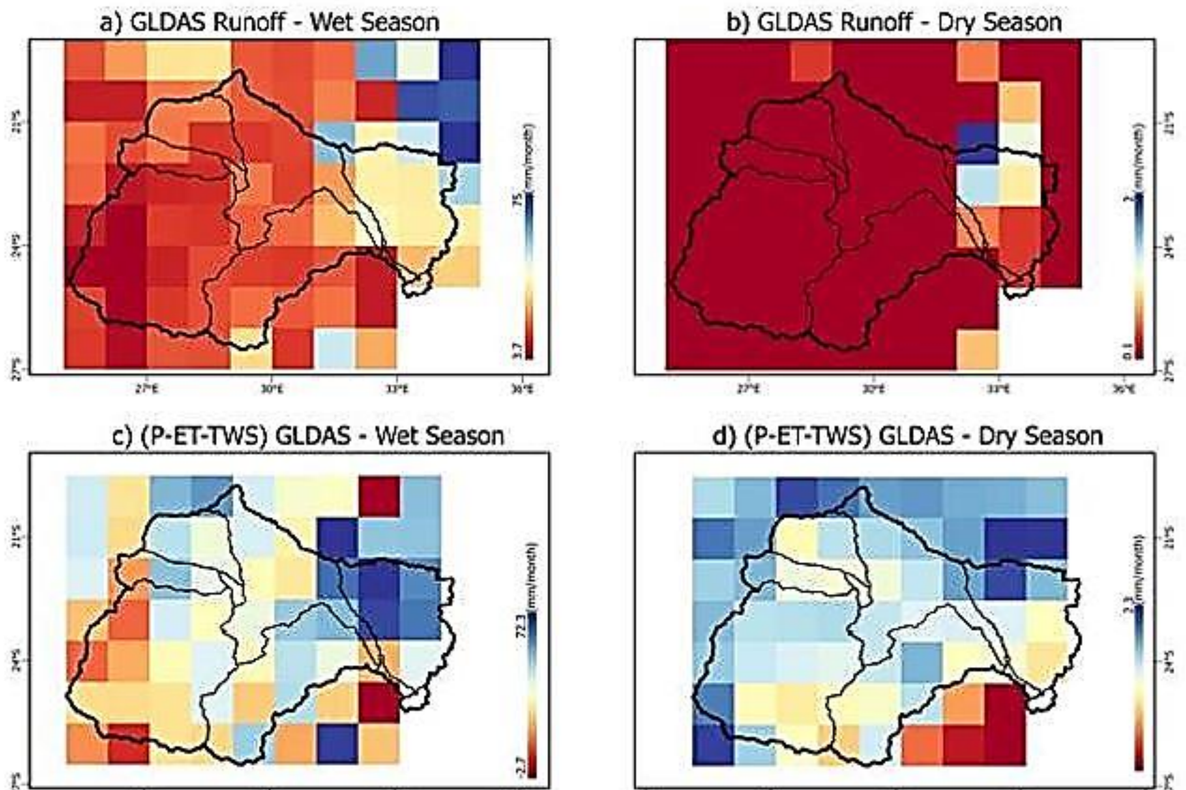

Figure 5. Total Runoff (R) for the Wet and Dry season in 2019 a and b GLDAS-CSLM for 2019 wet and dry Season, c and d water residual calculated from using water balance equation (P-ET-TWS) for 2019 wet and Dry Season

3.5. Evaluation of Water Budget Estimation

Figure 6 depicts the Limpopo Basin's basin-averaged water budget components in billion cubic meters for both the wet and dry seasons in 2019. It shows the total Seasonal P, ET, R, and TWSC calculated using the GLDAS models and observations from remote sensing. For R, ET and TWS, the results between IMERG and GLDAS were close to each other for both seasons. However, there was a noticeable difference in the Runoff observation. GLDAS Seems to underestimate the runoff values. The GLDAS-2.1 simulations do not incorporate stream flow routing; hence the modeled R has significant inaccuracies relative to the observed values.

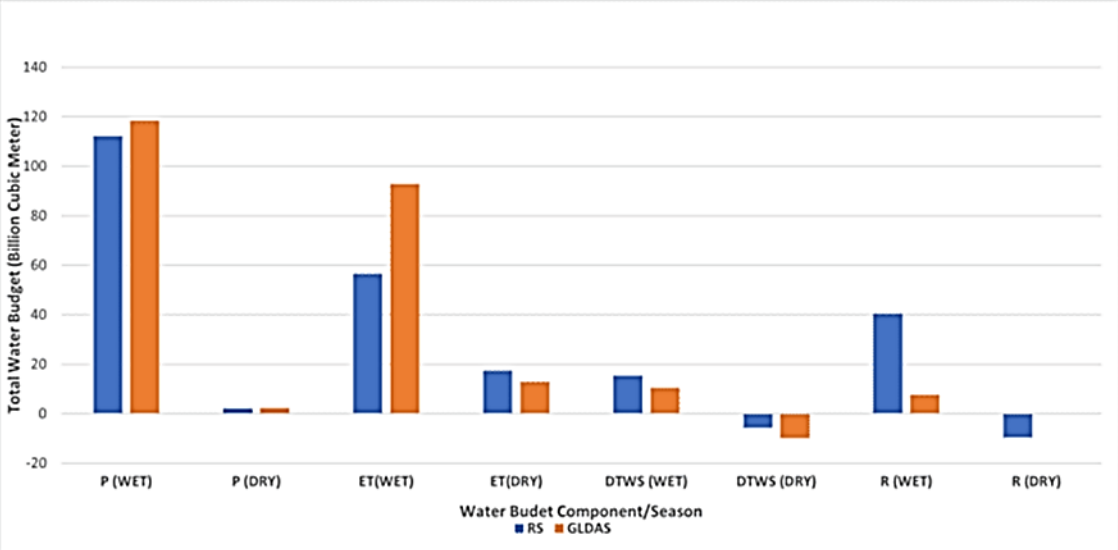

Figure 6. Seasonal water budget components of the Limpopo River Basin for the 2019 wet and dry seasons

4. Conclusion

This study used publicly available monthly satellite data and GLDAS model output products for the wet and dry seasons of 2019 to analyze GIS data over the Limpopo River Basin and assess the primary water balance components (P, ET, R, and TWSC). GPM-IMERG, MODIS, GRACE, and GLDAS-2.1 CLSM products were used to determine the amounts of Precipitation, Evapotranspiration, Runoff, and change in Terrestrial Water Storage. The findings showed how the basin's overall water budget components changed on a seasonal basis. The results showed some similarities especially for the Precipitation and Evapotranspiration. The change in Terrestrial Water Storage was estimated with the greatest degree of uncertainty. The modeled Runoff products varied greatly from one another. The residual from the water balance equation (P-ET-TWSC) was interpreted as Runoff in order to investigate the indirect approach because precise Runoff cannot be determined using remote sensing. When the residual quantities were compared to the Runoff levels predicted by the model, the findings revealed sizable disparities. Due to numerous uncertainties, including the limited resolution of GRACE & GRACE-FO and large mistakes in MODIS Evapotranspiration, closing water balance continues to be difficult. Due to the difficulty of modeling/observing all the water components in a basin, there are limits in determining the overall water budget utilizing the outputs of the GLDAS model and satellite-based remote sensing data. For instance, groundwater pumping, irrigation, and stream flow.

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Conflicts of interest

The authors declare no conflicts of interest.

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