Chapter 4
Water Budget Monitoring of the Ganga River Basin Using Remote Sensing Data and GIS

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4.1 Introduction

River systems across the globe are the lifelines for millions of people residing in their catchments, providing fresh water for drinking and agricultural purposes. Apart from supporting various aquatic and terrestrial ecosystems, rivers also facilitate transportation and hydropower generation. River basin management is crucial for water allocation and sharing between regions and states of a country or in a river basin located across different countries. The Transboundary Freshwater Dispute Database (TFDD, 2018) has identified 263 international transboundary river basins (see Fig. 4.1). These transboundary river basins occupy nearly 47% surface area of the Earth (excluding Antarctica) and carry about 60% of the global river discharge (Baranyai 2020). Almost 40% of the total world population lives in the transboundary basins spread over at least two countries (Wolf et al. 1999).

This map has been adopted from the 'Transboundary Freshwater Dispute Database': Product of the Transboundary Freshwater Dispute Database, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University. Additional information about the TFDD can be found at: http://transboundarywaters.science.oregon state.edu."

However, the water availability per person in Asia and the Pacific region is the lowest globally as it accommodates and suffices 60% of the global population with only 36% of the global water resources (APWF 2009). Monitoring water availability in a basin is a very crucial requirement for efficient river basin management. Factors like basin hydrology, ecology, weather as well as climate govern water availability. Accurate delineation of the watersheds and stream network on the basis of slope and terrain is an essential requirement for effective river basin management. Furthermore,

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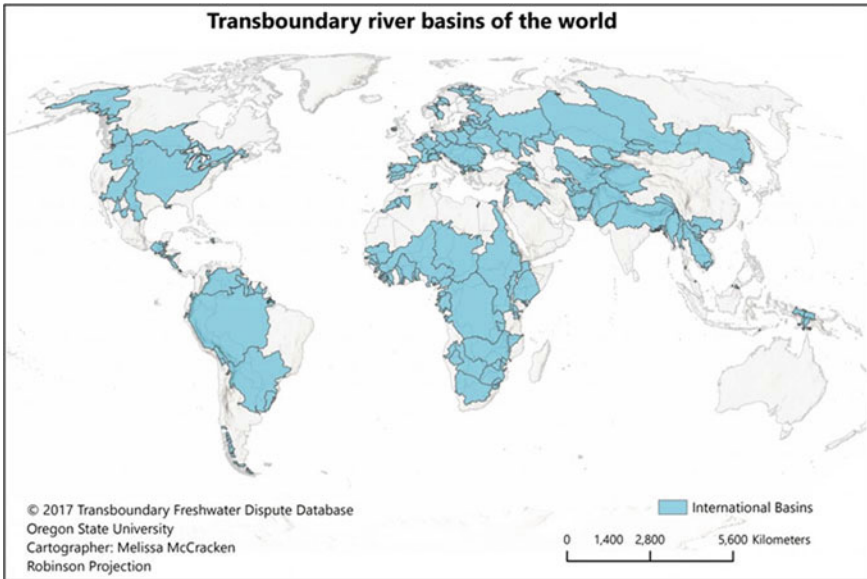
Fig. 4.1 Spatial representation of the transboundary river basins in the world

the prime requirements for monitoring water availability in a river basin are the observation, modeling, and information retrieval of the water budget components. The most significant water budget components contributing to the river flow in a basin are precipitation, evapotranspiration, infiltration, surface water, groundwater storage, and runoff.

Remote sensing and geographical information system (GIS) have tremendous potential and applicability to be a valuable tool for water resources management (Pandey et al. 2022). Precipitation, evapotranspiration, streamflow, and terrestrial water storage change are balanced to represent the terrestrial water budget (Abolafia-Rosenzweig et al. 2021). Researchers have demonstrated effective use of remotely sensed datasets in conjunction with the land surface models (LSMs) for assessing the global historical water budget (Zhang et al. 2018; Pan et al. 2012) and produce a reliable estimate of the water cycle. The remote sensing and modeling data offer some advantages which make these products highly useful in water budget assessment (Himanshu et al. 2017; Dhami et al. 2018). The remotely sensed data provides near-global to global coverage, which is impossible with spatially non-uniform in-situ measurements. Remote sensing technology enables to capture of data at practically inaccessible locations on the earth's surface. The earth system models offer a unique combination of ground-based and remote sensing observations resulting in frequent and repeated observations of water budget components. These models also provide datasets for parameters that are not directly observed by the satellites. The most game-changing advantages are that all these data products are freely downloadable and are available in near-real-time continuously for more

than a decade now. Moreover, these data products can be employed to monitor the water budget for basins that are sparsely gauged or where data access is restricted. Ganga River Basin in India is one such basin where the discharge data is restricted for public use (Singh & Pandey 2021).

This paper focuses on employing remote sensing-based data to obtain river basin networks and consequently assessing surface water budget components in the Ganga River Basin (GRB). The objectives of this study are to estimate seasonal (wet and dry season) water budget components for the entire GRB as well as at the sub-basin level by employing remote sensing datasets and GLDAS 2.1 model data.

4.2 Study Area and Methodology

4.2.1 Study Area

The Ganga River basin (GRB) is a transboundary basin shared by India, Nepal, and Bangladesh, which makes it a very vital resource for Asia. The Ganges originates situated in the Himalayan Mountain state of Uttarakhand in India at Gomukh, the terminus of Gangotri Glacier. It runs for a distance of over 2500 km before joining the ocean at the Bay of Bengal. The catchment area of the river basin constitutes 26% of the entire landmass of India and is thus labeled as the largest river basin in the country. It extends between 73.39°E and 89.75°E longitudes and 21.55°N and 31.46°N latitudes (Fig. 4.2). In India river, Ganga flows across 11 states (Fig. 4.2), namely, Uttarakhand, Himachal Pradesh, Delhi, Haryana, Rajasthan, Uttar Pradesh, Madhya Pradesh, Bihar, Jharkhand, Chhattisgarh, and West Bengal. However, in this study entire GRB with a catchment area of 1,027,095 km^2 is considered for which the basin boundary was downloaded from the HydroSHEDS database. Also, sub-basin boundaries were obtained from the HydroSHEDS level 5 classification scheme, which divides GRB into 14 sub-basins, as shown in Fig. 4.2.

4.2.2 Data Sources

All the datasets used in this study are remote sensing-based data products and downloaded from various sources, as presented in Table 4.1.

GLDAS model operates on a global scale and solves for the interaction of mass, energy, and momentum between the surface and atmosphere by integrating remote sensing and surface-based observations in the land surface models. It provides uniformly gridded ready to use data products on the water budget components.
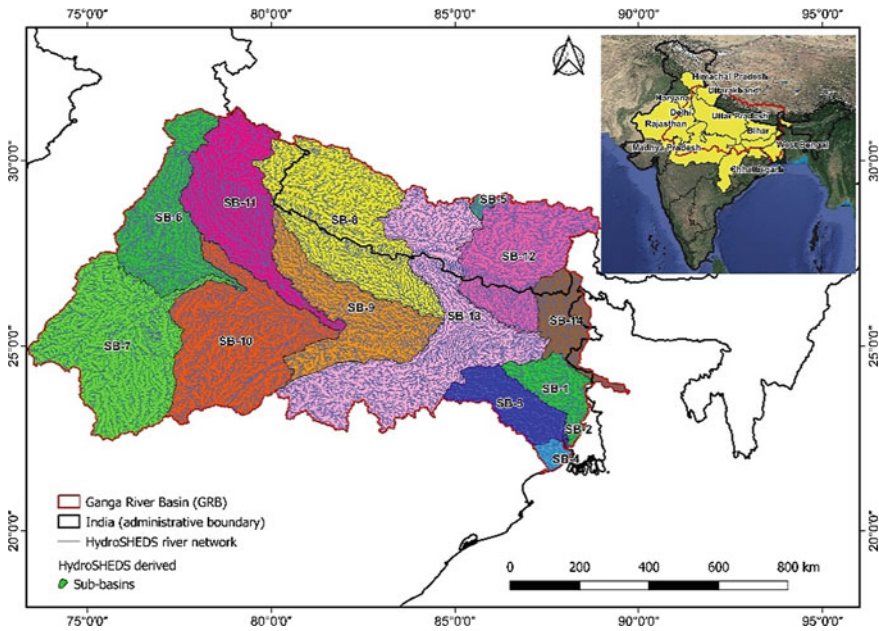
Fig. 4.2 Study area showing the location and extent Ganga River Basin and its sub-basins

GLDAS also hosts data not directly observed by the satellites viz. runoff, evapotranspiration, and snow water equivalent. In this study, satellite-based precipitation data product from Integrated Multi-satellitE Retrievals for GPM (IMERG) was employed. Evapotranspiration dataset based on MODIS vegetation index, thermal infrared (TIR) bands of MODIS, Landsat-8, and global geostationary satellites was used.

4.2.3 Methodology

The water-budget equation is simple and universally adaptable. The basis of the equation rests on a few assumptions on mechanisms of movement of water and its storage (Healy et al. 2007). A basic water budget for a watershed can be expressed as:

$$PR + Q_{in} = ET + \Delta S + Q_{out}$$

where PR is precipitation, Q_{in} is the discharge flowing into the watershed, ET is the evapotranspiration, ΔS is the change in water storage, and Q_{out} is the discharge flowing out of the watershed. All these components derived from remote sensing

**Table 4.1** Details of the data products and their sources

Dataset	Spatial resolution	Temporal resolution	Data source
IMERG precipitation	0.1° × 0.1°	30-min, daily, monthly	Giovanni https://giovanni.gsfc.nasa.gov/giovanni/
MODIS ET	500 m	8-daily, annual	Application for extracting and exploring analysis ready samples (AρρEEARS) https://lpdaacsvc.cr.usgs.gov/appeears/
GRACE-FO	1.0° × 1.0°	Monthly	JPL GRACE Tellus https://grace.jpl.nasa.gov/
GLDAS 2.1 Precipitation, evapotranspiration, runoff, terrestrial water storage	1.0° × 1.0°	3-hourly, monthly	GES DISC https://daac.gsfc.nasa.gov/
stream network, watershed, and sub-basin boundaries	–	–	**Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales (HydroSHEDS) https://hydrosheds.org/downloads

observations as well as GLDAS 2.1 model were freely downloaded from the data sources listed in Table 4.1.

In this study, two different approaches have been employed to examine and compare dry and wet season water budget components of GRB in 2019. Figure 4.3a shows the detailed methodology adopted using remote sensing-based datasets of IMERG precipitation, MODIS Evapotranspiration (ET), and GRACE Terrestrial Water Storage (TWS) anomalies to derive sub-basin wise and overall seasonal water balance for GRB. Figure 4.3b shows the detailed methodology adopted to obtain water balance using the water budget components extracted from GLDAS 2.1 model. In the northern part of India, the dry season spans between March and May, while the wet season stretches from June to September.

4.3 Results and Discussion

The remote sensing data sets were pre-processed in a GIS environment using open source QGIS 3.18 software. Figure 4.4 shows maps depicting the spatial variation of
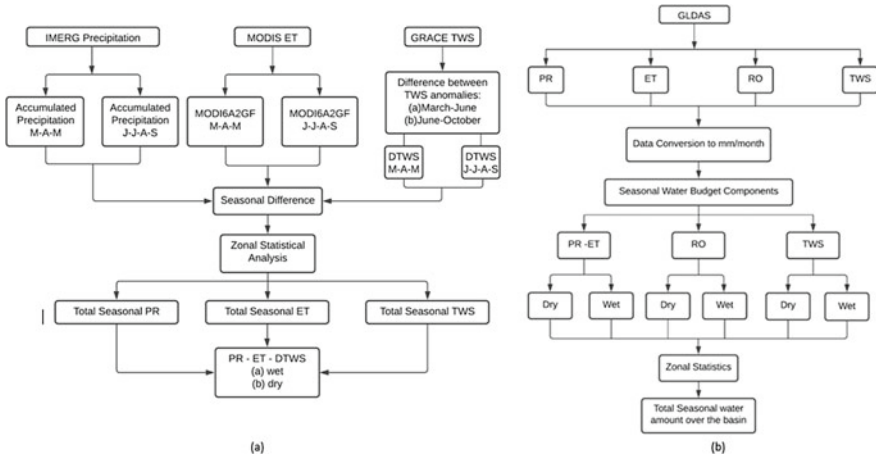
Fig. 4.3 Methodology flowchart **a** water budget assessment using remote sensing-based datasets; **b** water budget assessment using GLDAS 2.1 model data (PR = Precipitation; ET = Evapotranspiration; RO = Runoff; TWS = Terrestrial Water Storage; M-A-M = March–April-May; J-J-A-S = June-July–August-September; MOD16A2GF = Gap Filled MODIS ET data product)

water budget components over Ganga River Basin for dry (top row) and wet (bottom row) seasons of 2019. The seasonal (wet and dry seasons of 2019) spatial variation of monthly accumulated IMERG rainfall data is shown in Fig. 4.4a, b. It is visibly evident from the maximum and minimum values that there is a considerable variation in the rainfall in the dry and wet seasons of 2019. Similarly, the seasonal variation in Evapotranspiration (ET) is presented in Fig. 4.4c, d. Also, the change in water storage for wet and dry seasons is illustrated in Fig. 4.4e, f.

The precipitation and ET maps presented in Fig. 4.4 were further used to obtain the difference between wet and dry seasons by subtracting the dry season raster from the wet season raster, as shown in Fig. 4.5. Figure 4.5a shows that the northern part of GRB experienced lesser rainfall in the wet season and therefore shows the lower range of change significantly in the region of Nepal and the northwestern region of India. The remaining part of the basin shows medium to high variation in the difference of rainfall observed between the dry and wet seasons of 2019. However, the ET difference map presented in Fig. 4.5b shows a contrasting spatial variation over the basin. Almost the entire basin features low to very low (negative) difference in the ET with a minimal area featuring high difference.

These maps were further used to calculate zonal statistics for each of the 14 sub-basins of GRB. Table 4.2 presents the basin-averaged water budget components viz. precipitation, evapotranspiration, and terrestrial water storage for the entire GRB and at the sub-basin level for the year 2019. The residuals obtained after subtracting TWS from (PR-ET) for wet and dry seasons can be attributed as seasonal discharge.

Another attempt to estimate the seasonal water budget of GRB was made using the gridded datasets from the GLDAS 2.1 model. The spatial maps of the water budget components for dry and wet seasons are presented in Fig. 4.6. The maps show spatial
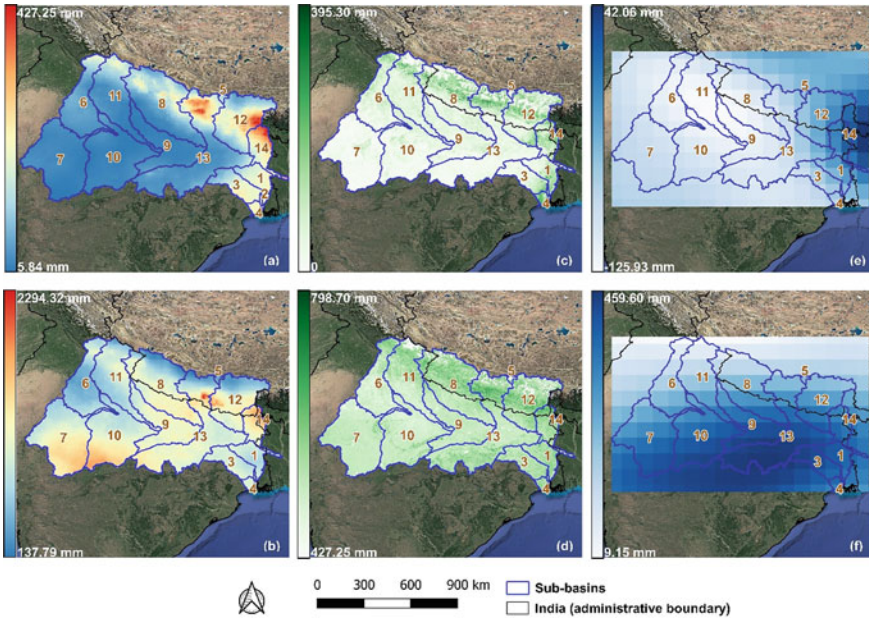
Fig. 4.4 a Accumulated precipitation map (MAM); **b** accumulated precipitation map (JJAS); **c** evapotranspiration map (MAM); **d** evapotranspiration map (JJAS); **e** change in water storage map (MAM); **f** change in water storage map (JJAS) (MAM: March–April–May; JJAS: June–July–August-September)
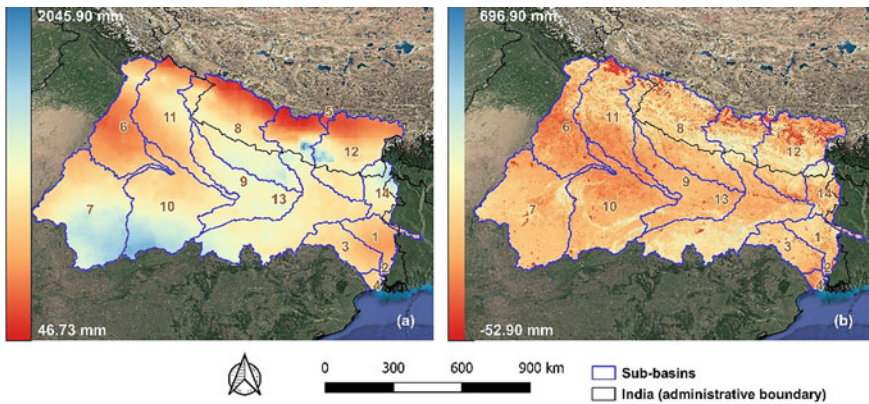
**Fig. 4.5 a** Seasonal precipitation difference map, **b** seasonal ET difference map

Table 4.2 Estimates of seasonal, basin-averaged, and sub-basin level water budget components

Sub-basin	Area (km^2)	PRD (m^3)	PRW (m^3)	ETD (m^3)	ETW (m^3)	TWSD (m^3)	TWSW (m^3)
1	35,180.07	9.05E + 09	4.69E + 10	3.94E + 09	1.13E + 10	1.39E + 07	1.24E + 10
2	89,105.43	1.53E + 10	8.35E + 10	7.82E + 09	2.42E + 10	−3.10E + 09	2.52E + 10
3	166,323.00	1.59E + 10	1.72E + 11	7.76E + 09	4.35E + 10	−1.39E + 10	6.40E + 10
4	131,757.00	1.20E + 10	1.23E + 11	9.64E + 09	3.57E + 10	−1.36E + 10	2.94E + 10
5	82,063.27	1.63E + 09	8.90E + 10	3.54E + 09	1.73E + 10	−9.12E + 09	3.19E + 10
6	93,726.94	5.36E + 09	7.45E + 10	5.90E + 09	2.05E + 10	−1.08E + 10	1.63E + 10
7	130,508.00	2.48E + 09	1.43E + 11	4.07E + 09	2.53E + 10	−1.33E + 10	4.97E + 10
8	142,043.00	2.85E + 09	1.61E + 11	2.48E + 09	2.89E + 10	−1.22E + 10	4.77E + 10
9	79,415.98	4.87E + 09	4.80E + 10	4.43E + 09	1.47E + 10	−8.68E + 09	1.38E + 10
10	29,716.42	5.41E + 09	2.50E + 10	2.47E + 09	8.48E + 09	−9.97E + 08	1.17E + 10
11	977.25	2.02E + 08	9.27E + 08	1.51E + 08	3.01E + 08	−5.82E + 07	3.59E + 08
12	37,698.61	5.91E + 09	3.53E + 10	2.15E + 09	9.66E + 09	−2.56E + 09	1.58E + 10
13	6202.99	1.34E + 09	6.16E + 09	1.03E + 09	1.84E + 09	−4.28E + 08	2.24E + 09
14	2377.78	3.00E + 08	9.02E + 08	1.07E + 08	3.46E + 08	−1.34E + 08	4.96E + 08
	Total volume	8.26E + 10	1.01E + 12	5.55E + 10	2.42E + 11	−8.89E + 10	3.21E + 11
	Billion m^3	82.60	1009.46	55.49	242.01	−88.85	320.93
PR-ET (wet) BCM		767.45	Wet season discharge BCM			446.52	
PR-ET (dry) BCM		27.17	Dry season discharge BCM			115.96	

variation of (PR-ET), total runoff (TRO), and change in terrestrial water storage derived from GLDAS 2.1 model over Ganga River Basin for dry (top row) and wet (bottom row) seasons of 2019.

These maps were further used to calculate zonal statistics for each of the 14 sub-basins of GRB. Table 4.3 presents the seasonal, basin-averaged, and sub-basin level water budget components viz. precipitation, evapotranspiration, terrestrial water storage, and total runoff for the dry and wet seasons of 2019 in GRB.
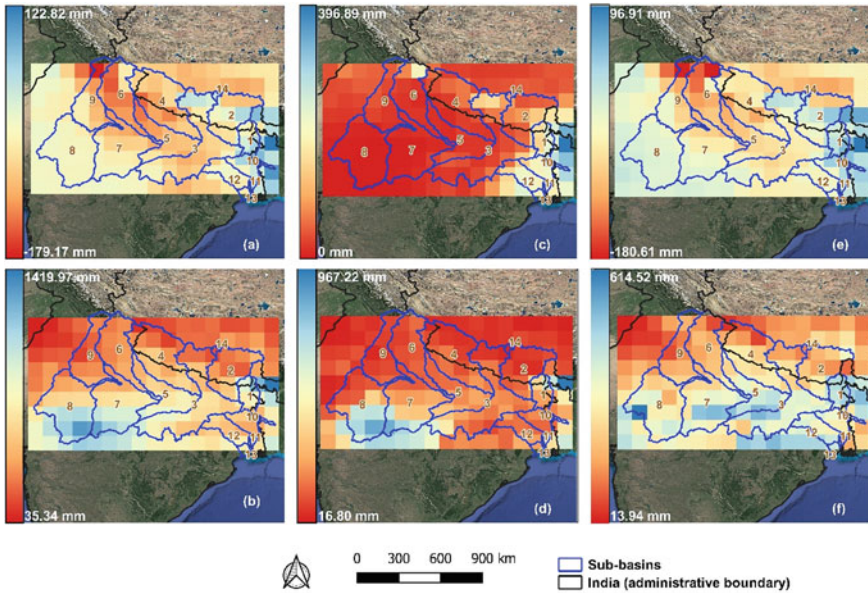
Fig. 4.6 **a** P-ET map (MAM), **b** P-ET map (JJAS), **c** runoff map (MAM), **d** runoff map (JJAS), **e** change in terrestrial water storage map (MAM), **f** change in terrestrial water storage map (JJAS)

Tables 4.2 and 4.3 have summarized the water balance of GRB using remote sensing-based datasets. However, it can be seen that there is variation/mismatch in the water budget components estimated by the two approaches. This can be attributed to the uncertainties associated with the water budget estimation using satellite-based datasets and GLDAS 2.1 model data due to limitations in capturing and modeling the water components and other essential factors which were not taken into account like the actual river discharge, irrigation water application, groundwater extraction, and distribution. The terrestrial water storage (TWS) anomalies from GRACE & its follow-on missions have a coarse spatial resolution of 3×3 degrees. They thus can't provide accurate estimates for watersheds smaller than $\sim 150{,}000 \mathrm{km}^2$. Other remote sensing products viz. MODIS ET and IMERG precipitation used in the assessment may also have significant uncertainties affecting overall water budget estimation accuracy.

4.4 Conclusions

This study was conducted with a prime focus on exploring the potential of remote sensing data products and GIS-based analysis to estimate water budget components over the Ganga River Basin. Two different approaches were employed (a) using remote sensing products and (b) using GLDAS 2.1 model outputs. The total volumes

Table 4.3 Estimates of seasonal, basin-averaged, and sub-basin level water budget components using GLDAS 2.1 model derived datasets

Sub-basin	Area (km^2)	(PR-ET) W (m^3)	(PR-ET) D (m^3)	TWSW (m^3)	TWSD (m^3)	TROW (m^3)	TROD (m^3)
1	35,180.07	2.67E + 10	4.73E + 08	1.57E + 10	7.75E + 08	9.92E + 09	6.17E + 09
2	89,105.43	2.95E + 10	−3.88E + 09	1.95E + 10	−3.25E + 09	7.87E + 09	5.62E + 09
3	166,323.00	8.91E + 10	−8.02E + 09	5.08E + 10	−6.34E + 09	3.35E + 10	9.15E + 09
4	131,757.00	5.32E + 10	−1.20E + 10	3.05E + 10	−9.43E + 09	1.71E + 10	4.46E + 09
5	82,063.27	5.44E + 10	−6.78E + 09	3.20E + 10	−5.51E + 09	1.91E + 10	1.85E + 09
6	93,726.94	3.17E + 10	−1.01E + 10	1.68E + 10	−1.06E + 10	1.13E + 10	4.39E + 09
7	130,508.00	9.65E + 10	−7.56E + 09	4.36E + 10	−5.95E + 09	4.74E + 10	1.11E + 09
8	142,043.00	1.05E + 11	−3.44E + 09	4.52E + 10	−2.24E + 09	5.24E + 10	7.92E + 08
9	79,415.98	2.14E + 10	−7.07E + 09	1.23E + 10	−6.42E + 09	6.97E + 09	2.30E + 09
10	29,716.42	1.35E + 10	1.36E + 08	9.78E + 09	−8.45E + 06	4.74E + 09	5.47E + 09
11	977.25	6.29E + 08	−1.69E + 07	3.04E + 08	−1.19E + 07	3.01E + 08	1.87E + 08
12	37,698.61	2.14E + 10	−1.18E + 09	1.39E + 10	−1.24E + 09	7.54E + 09	7.60E + 09
13	6202.99	4.11E + 09	−2.59E + 08	2.43E + 09	−1.52E + 08	1.56E + 09	1.20E + 09
14	2377.78	4.09E + 08	−1.26E + 06	3.02E + 08	−2.49E + 07	9.20E + 07	2.06E + 08
	Total volume	5.47E + 11	−5.97E + 10	2.93E + 11	−5.04E + 10	2.20E + 11	5.05E + 10
	Billion m^3	547.49	−59.66	293.14	−50.42	219.86	50.50

of precipitation, evapotranspiration and terrestrial water storage change in the basin for dry and wet seasons were estimated from (a) GPM IMERG, MODIS, and GRACE data and (b) GLDAS 2.1 model for the year 2019.

Despite the uncertainties associated with the satellite-based remotely sensed datasets and GLDAS 2.1 model data could be employed to assess seasonal and inter-annual water budget components to get overall indications of water availability for relatively large river basins. The increase or decrease in water availability can be judiciously acted upon by the stakeholders and government agencies for efficient

water resources management in the basin and sub-basins. This study demonstrates the potential of satellite-based data and GIS analysis for an overall situational assessment of the water budget in the Ganga River Basin, and a similar approach can be replicated elsewhere for other large river basins across the globe. Validation of the remote sensing-based data and GLDAS model data with in-situ measurements of precipitation, discharge, and soil moisture will surely provide more profound insights regarding the accuracy of these datasets.

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