



Seasonal and annual hydrologic modeling for water budget estimation of the Ganga River Basin (GRB) by using GLDAS-2.1 products in geospatial environment

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Abstract

Freshwater availability is growing as a global issue and the current situation demands reliable evaluation and quantification of the water regime as this approach is integral to any effective water resource management strategies at the river basin scale. This article evaluates annual and seasonal trends and assesses changes in water balances of the Ganga River Basin (GRB) using Global Land Data Assimilation System (GLDAS-2.1) products, a type of geospatial dataset covering 20 years (2001–2020). The annual trend analyses with state-of-art nonparametric approaches, e.g., Mann–Kendall test statistic (S), Standard normal test statistic (Z_S), Sen's slope estimator (β), and Kendall's τ reveal statistically significant negative trends for hydrometeorological variables such as precipitation (PR, $\beta = -1.690$), surface runoff (RO, $\beta = -3.115$), and base flow-groundwater runoff (BRO, $\beta = -0.170$); where positive trends occur for evapotranspiration (ET, $\beta = 1.410$) and for changes in terrestrial water storage (TWS, $\beta = 0.660$), with distinct drying patterns occurring during other evaluation seasons during the study period. Although the present analysis depicts a negligible water deficit at the annual scale (nearly 0.28 BCM), the basin experiences serious water scarcity in the pre-monsoon (-31.99 BCM) and the post-monsoon (-17.91 BCM) seasons and serious consequences of water surplus conditions in the winter ($+2.59$ BCM) and monsoon ($+43.65$ BCM) seasons. These annual and seasonal outcomes are in agreement with existing studies and point toward potential future challenges in the GRB connected with drought/flood assessments and sustainable water resource management.

Keywords Ganga River Basin (GRB) · GLDAS-2.1 · Water budget · Hydrological model · Statistical tests

Introduction

Freshwater availability and scarcity are growing major global political issues, and all countries are pushing their policies to meet the United Nation's Sustainable Development Goals (SDGs) to address with country-specific water, sanitation and associated water-dependent sustainability problems (Setty et al. 2020; Ge et al. 2018). Many studies

have shown that larger river basins in India are highly sensitive to monsoons and are exposed to the impacts of climate change and other human interventions, which may affect the existing and future water resource management strategies that are beneficial for ensuring sustainable socio-economic development (Jeuland et al. 2013; Nepal and Shrestha 2015). The Ganga River Basin (GRB), the World's most populated region (with more than 550 million people, World Bank 2020), is one of the largest river systems on Earth. The transboundary river basin, GRB lies in India (approximately 79% of the total basin area), Bangladesh, Nepal and China (NMCG 2021). The river and its tributaries have played a significant role in civilizing along the river courses since ancient times and have acted as lifelines for millions of people (Sanghi and Kaushal 2014). Two major economic activities, agriculture (Sadoff et al. 2013) and industrialization (World Bank 2015) are highly influenced by the consistent flow of the Ganga River and its tributaries. This densely populated basin contributes more than 40% of India's GDP

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(PIB-GoI 2020). However, a recent study by the Central Water Commission (CWC) confirmed that different parts of GRB are experiencing freshwater scarcity due to rapidly growing population pressure and various economic activities (Down To Earth 2019). So, water resource management has become a very challenging task in monsoon-dominated GRB because of the seasonal and regional imbalances between water availability in the form of recharge and water loss in the form of discharge (Khan et al. 2014). Analyses based on the various hydrological components, e.g., precipitation (PR), evapotranspiration (ET), surface runoff (RO), base-flow-groundwater runoff (BRO) and terrestrial water storage (TWS), help to understand the present scenario of the water budget across the GRB. To ensure sustainable water management, the quantification of water budget components is necessary (Healy et al. 2007).

A large number of scientific studies dealing with hydrological dynamics have been published at the continental and regional scales (Famiglietti et al. 1995; Sheffield et al. 2009; Gao et al. 2010; Rodell et al. 2011; Sahoo et al. 2011; Wang et al. 2014; Anand et al. 2018). These studies reveal that the implication of remotely sensed satellite images in water budget estimation has made the work easier for researchers over time. Several scholars have contributed to the estimation of basin-level hydrological cycles based on the different types of gridded satellite datasets. In particular, Famiglietti et al. (1995) used the Global ENvironmental and Ecological Simulation of Interactive Systems (GENESIS) and the Regional Climate Model (RegCM) simulation for reprojecting the seasonal and spatial hydrological behaviour of the major drainage basins of the USA with spatial variability in the hydrological cycle. Gao et al. (2010) estimated the water budget components of all major river basins in the USA by using nine different satellite-based products [e.g., precipitation data from the TRMM Multi-Satellite Precipitation Analysis (TMPA), CPC MORPHing (CMORPH) technique, and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN); evaporation data from Princeton University, University of Montana, and University of Washington; and terrestrial water storage data from the Gravity Recovery and Climate Experiment (GRACE), GeoForschungsZentrum (GFZ), and Jet Propulsion Laboratory (JPL)]. In addition, Sheffield et al. (2009) and Wang et al. (2014) have similar results for the Mississippi River basin and the entire Australian continent respectively. However, Rodell et al. (2011) estimated evapotranspiration based on close observations of the water budgets of seven continental-scale river basins (Mackenzie, Fraser, Nelson, Mississippi, Tocantins, Danube, and Ubangi) throughout the world by using various remotely sensed datasets, such as precipitation from the TMPA, runoff from the Global Runoff Data Centre (GRDC), terrestrial water storage from the GRACE, and evapotranspiration from the NLDAS

and GLDAS. Sahoo et al. (2011) included the global terrestrial water budget of 10 river basins (Mackenzie, Yukon, Mississippi, Danube, Lena, Chang Jiang, Mekong, Niger, Murray-Darling, and Amazon) in their study by utilizing the GPCP, TRMM, CMORPH and PERSIANN data for precipitation, the GRDC data for evapotranspiration, and the GRACE satellite products for terrestrial water storage. Furthermore, Anand et al. (2018) developed a basin-scale SWAT model by using gridded IMD data of rainfall and temperature over the GRB for the prediction of the water budget.

However, despite the numerous studies mentioned above, changes in terrestrial water storage (TWS) at annual and seasonal scales in the GRB have not been adequately addressed and discussed in most publications along with other water balance components. Recently, several studies have highlighted the strengths and capabilities of National Aeronautics and Space Administration (NASA)'s Global Land Data Assimilation System (GLDAS) data products for revealing intrinsic regional details of water and energy components at various scales and these data have been used for a wide range of applications (Rzepecka and Birylo 2020; Deliry et al. 2022; Lv et al. 2019; Liu et al. 2020). The GLDAS-2.1 is a rich source of information that integrates both remote sensing and ground-based observations to provide basin-specific quantities (Rui 2020), which are extremely useful in ungauged/poorly gauged regions or transboundary rivers with classified nature of the data like in GRB (Qi et al. 2020; Liu et al. 2020; Hasan et al. 2022). Qi et al. (2020) applied both GLDAS-2.0 and GLDAS-2.1 data for water balance and runoff estimations in ungauged/poorly gauged regions of China. Water budget estimation of the Kizilirmak River Basin was performed using the GLDAS-2.1 Noah and CLSM models by Deliry et al (2022), who highlighted its ability to provide useful information on seasonal and inter-annual changes at the river basin scale. The usefulness of GLDAS land surface models (LSMs) for evapotranspiration reconstruction and water budgeting was elaborately discussed in the Yellow River basin of China by Lv et al (2019) and Liu et al (2020). A previous study of the GRB using GLDAS data SWAT by Anand et al (2018) revealed critical trend changes in streamflow, but a comprehensive assessment of terrestrial water storage variations and other water components is still lacking. The NASA's GLDAS-2 catchment land surface model (CLSM) outputs have been applied for local scale and district-level studies in India to elucidate the changes in soil moisture, terrestrial water storage and groundwater storage (Sahoo et al. 2021). In another study, Lei et al. (2018) explained the strength of CLSM in predicting generally similar patterns to those of other models (for example Noah, VIC) in wet/dry climate zones worldwide. The intercomparative strengths and limitations of the GLDAS-2.1 CLSM and Noah models in water budgeting at the river basin scale are also discussed in Deliry et al.



(2022). Another intercomparison and evaluation study has shown that GLDAS-2.1 CLSM performs better in the north-east and throughout China in comparison to Noah and VIC products when applied for soil moisture budgeting studies (Lei et al. 2018).

The broader aim of this study is to evaluate and discuss changes in the water-cycle components in the GRB over the last two decades using the GLDAS-2.1 data source. In this work, we first estimate the variability in different water budget components (PR, ET, RO, BRO, and TWS) across the GRB. Second, seasonal and annual trend and temporal analysis were conducted using detailed non-parametric tests of the hydroclimatic variables, which helped to understand whether the water balance changed over the period from 2001 to 2020. In addition, we investigated the seasonal (winter, pre-monsoon, monsoon, and post-monsoon) and annual hydrological water budgets of all the sub-basins across the entire GRB. These findings may be useful for the local governments and water and policy managers involved in basin-level water management plans in the GRB.

Study area

The GRB (lat. ext.: 22°27'00" N to 31°28'12" N; long. ext.: 73°22'12" E to 89°18'36" E) drains through China, Nepal, India and Bangladesh and feeds a total area of approximately 1.03 million km² (CWC-IMD 2015). It is considered the largest river basin in India because the basin covers nearly 26% of the country's landmass (NMCG 2021). The total catchment area of the Ganga River Basin comprises ten states, namely Uttarakhand, Haryana, Rajasthan, Himachal Pradesh, Uttar Pradesh, Madhya Pradesh, Bihar,

Chhattisgarh, Jharkhand and West Bengal with one union territory, i.e., Delhi (Tripathi and Tripathi 2012).

Topographically, the GRB is a very complex region. The basin is bounded by the Himalayas on the north and by the Vindhyas and Chhotanagpur Plateau on the south. It is also surrounded by the Brahmaputra range on the east and the Aravalli Hills, which separate the GRB from the Indus River Basin (IRB) on the west (CWC-IMD 2015; Shukla et al. 2021). The entire basin area is broadly classified into three physiographic divisions, viz.: the Himalayan Mountainous terrain, the Gangetic Plains, and the Central Highlands (Fig. 1a). The Himalayan Mountain belt consists of several high ridges above 7000 m (NMCG 2021). On the other hand, the Gangetic Plain is a vast flat alluvial depositional surface with an elevation less than 250 m.

The entire catchment area of the river Ganga comprises 21 sub-basins. The India Meteorological Department (IMD) has assigned some specified codes from 323 to 325 and 401 to 418 for each sub-basin (Table 1). The sub-basin coded as 408 is divided into three (e.g., 408-Betwa, 408-Ken, and 408-Sind), where another two sub-basins, 401 and 403, are further divided into two (Fig. 1b). Originating from the Gangotri Glacier of Uttarakhand at an elevation of approximately 7000 m above mean sea level (MSL), the Bhagirathi River meets with the Alakananda River at Devprayag and acquire its name as the Ganga River. Several tributaries have joined in its nearly 2500 km long run before falling into the Bay of Bengal (CWC-IMD 2015; NMCG 2021). Some of these are the Ramganga, the Yamuna, the Betwa, the Ken, the Sind, the Gomti, the Ghagra, the Son, the Gandak, the Kosi, the Damodar, the Ajay and the Mayurakshi.

The climatic condition of the entire basin, which is mainly confined by the Himalayas on the north and the Bay of Bengal on the south, is predominantly subtropical

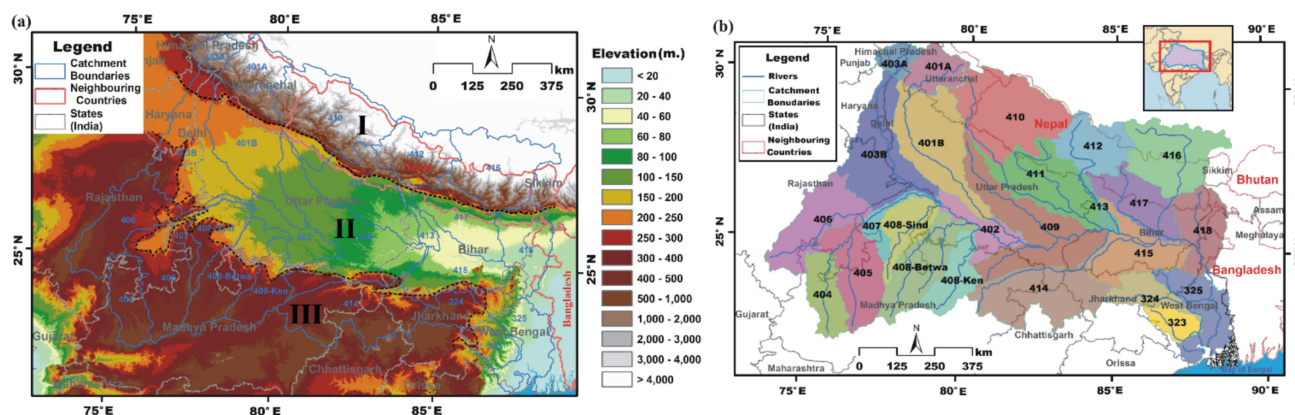


Fig. 1 **a** The altitudinal zones across the entire Ganga River Basin (GRB) with the physiographic divisions (I: Himalayan Mountainous terrain, II: Gangetic Plains, and III: Central Highlands) and **b** the drainage system of the Ganga River with all the major tributaries are shown on the map. (Source: Shuttle Radar Topography Mission data,

2000 has been used for physiographic divisions with altitudinal zones and catchment codes in both segments of this map have been derived from the publication of RMSI (2015) in collaboration with CWC and IMD)

Table 1 Details of all the sub-basins that are under the Ganga River Basin (GRB): major drainage system, areal extension and administrative coverage

Sl. No	Sub-basin Code	Major drainage system	Areal coverage ('000 Sq. km)
1	323	Rivers between Damodar and Subarnarekha catchment area	14.96
2	324	Damodar River	22.04
3	325	Mayurakshi, Ajay and Hoogli River	41.72
4	401 A	Ramganga River (a tributary of the River Ganga)	24.46
	B		69.88
5	402	Ganga River from its confluence of River Yamuna at Allahabad to its confluence with Ramganga (excluding Yamuna River)	23.83
6	403 A	Yamuna upto its confluence with Chambal River at Etawah (excluding River Chambal)	11.46
	B		68.03
7	404	Chambal River upto Kota dam site	28.62
8	405	Kota dam site on Chambal River to confluence with Banas River (excluding River Banas)	49.71
9	406	Banas River	50.90
10	407	Chambal River from its confluence with Banas River near Sawai Madhopur to its confluence with Yamuna River at Etawah	11.46
11	408	Betwa	47.22
	Ken	Yamuna River from its confluence with Chambal River at Etawah to its confluence with Ken River at Fatehpur	27.88
	Sind		27.87
12	409	Ganga River from Allahabad Upto Chhapra including Gomti River and Tons River	82.66
13	410	Trans-Himalayan Rivers	77.06
14	411	Ghagra River	55.44
15	412	Trans-Himalayan region and Gandak River	36.49
16	413	Rest of Gandak River upto its confluence with Ganga River	7.63
17	414	Son River	67.20
18	415	Ganga River between its confluence with Son River and Kosi River (excluding Kosi River)	44.61
19	416	Kosi River upto Barahakshetra dam site	58.04
20	417	Kosi River from Barahakshetra dam site to its confluence with Ganga River at Kursela	39.89
21	418	Ganga River from its confluence with Kosi River at Kursela to Bangladesh border	39.40
Entire Ganga River Basin (GRB)			1028.46

Source: PMP Atlas for Ganga River Basin Including Yamuna (CWC and IMD) and modified by the authors

and tropical in nature (CWC-NRSC 2014; CWC-IMD 2015). The GRB experiences four seasons throughout the year (Subramanya 2013): (i) Winter, (ii) Pre-monsoon, (iii) Monsoon, and (ii) Post-monsoon. More than 80% of the total rainfall occurs due to southwest monsoonal winds from June to September over the basin (CWC-IMD 2015). The average annual temperature ranges between 9 °C and 40 °C across the entire catchment area (CWC-NRSC 2014).

The present study has been carried out over 20 years (2001–20). The GLDAS-2.1 images are catchment land surface model-based remotely sensed datasets. The data are downloaded for several selected hydrological components viz., the PR, ET, RO, BRO and TWS from the National Aeronautics and Space Administration (NASA) for estimating the water budget of the GRB. The extracted datasets also help to understand the long-term trends of the basin and sub-basin levels of various water budget components.

Materials and methods

Datasets used

Two types of datasets (Table 2) have been utilized for two different purposes in the present study. The SRTM DEM images from the USGS website have been used for delineating the altitudinal zones based on the topographical variation (USGS-EROS 2018) throughout the GRB. In addition, NASA's Global Land Data Assimilation System Version 2.1 (GLDAS-2.1) datasets, the satellite-based gridded products, which provide different hydrological data (Rodell et al. 2004; Li et al. 2020), have been used to estimate the water budget over the GRB. Those images also help to obtain continuous information on each selected hydrological component for such a long period (2001–20). The Pearson correlation coefficient (r) scatter plot matrix helps to understand the association among different water budget components



Table 2 Satellite images used for the analysis and visualization of the water budget-related hydrological data across the entire Ganga River Basin (GRB)

Product Name with Product Code		Used in this research	Spatial Resolution	Data source
Shuttle Radar Topography Mission		SRTM	90 m	https://earthexplorer.usgs.gov/
GLDAS-2.1 (GLDAS_CLSM10_M)	Total Precipitation (Rainf_f_tavg)	PR	$1.0^{\circ} \times 1.0^{\circ}$	https://daac.gsfc.nasa.gov/
	Evapotranspiration (Evap_tavg)	ET		
	Storm surface runoff (Qs_acc)	RO		
	Baseflow-groundwater runoff (Qsb_acc)	BRO		
	Terrestrial water storage (TWS_inst)	TWS		

Source: Authors' own creation

(Fig. 2), which have been used for the analysis and visualization of different water budget components over the GRB in the present article.

Overall methodology

The data related to the water budget estimation also help to understand the distribution of various hydrological components (viz., PR, ET, RO, BRO and TWS) over the GRB. The GLDAS-2.1 datasets, which are simulated with the Catchment-F2.5 Land Surface Model (CLSM), provide those hydrological products since 2000 with 1° spatial resolution (Li et al. 2020). The total precipitation (Rainf_f_tavg) data includes both the rainfall (the liquid precipitation) and snowfall (the frozen precipitation) rates. It also acts as the primary source of all freshwater in the terrestrial hydrologic cycle (Winter et al. 1998). On the contrary, evapotranspiration (Evap_tavg) returns water to the atmosphere as the combined activity of the evaporation from the earth's surface and the transpiration from the plants (Winter et al. 1998). The surface and subsurface runoff (Qs_acc and Qsb_acc) also contribute significantly to the water budget estimation over the entire GRB because these parameters help to keep the water cycle active. As CLSM simulates both the water storage on the Earth's surface and in the subsurface, the terrestrial water storage (TWS_inst) consists the groundwater, soil water, snow water equivalent, and canopy water (NASA-GES DISC 2021). The selected GLDAS CLSM hydrological products contain the datasets of different temporal resolutions ($\text{kg m}^{-2} \text{s}^{-1}$ in case of PR and ET data, kg m^{-2} per 3-h in case of RO and BRO data, and mm/month in case of TWS data). So unit conversion is a very necessary task for obtaining the monthly accumulated rates of the hydrological parameters, excluding the TWS. In the present study, Q-GIS 3.14 version helped to perform the task through the raster calculator. The expressions for the unit conversion

have been given in Table 3. Further analyses have been done in the Q-GIS environment for obtaining the seasonal and annual variations of the water budget components over the GRB based on the suggested seasonal classification by IMD as stated in Table 4 (CWC-IMD 2015; IMD 2021; IMD Pune 2021). The adopted methodology is directed in Fig. 3 and this approach helps get new knowledge on the annual and seasonal water budget over the GRB and associated trend changes of the hydrological components for the selected twenty years (2001–20).

Methods used in water budget estimation

The water budget is a process of accounting for various hydrological components of the water cycle, based on the inputs (gains) and outputs (losses) of water within the hydrological system (Thornthwaite and Mather 1957; Schicht and Walton 1961; Arnold and Allen 1996). Many scholars expressed the relationship among various water budget components through several unique equations. Those water-budget equations are as follows,

Schicht and Walton (1961) stated the water budget equation (Eq. 1) as,

$$P = R + ET + U + \Delta S_s + \Delta S_g \quad (1)$$

where, P = Total precipitation, R = Surface runoff, ET = Evapotranspiration, U = Groundwater flow, ΔS_s = Change in soil moisture, and ΔS_g = Change in groundwater storage.

Hordon (1998) noted the water budget equation (Eq. 2) as,

$$P = R + ET + U + S_s + S_g + I \quad (2)$$

where, P = Total precipitation, R = Surface runoff, ET = Evapotranspiration, U = Groundwater flow, S_s = Change

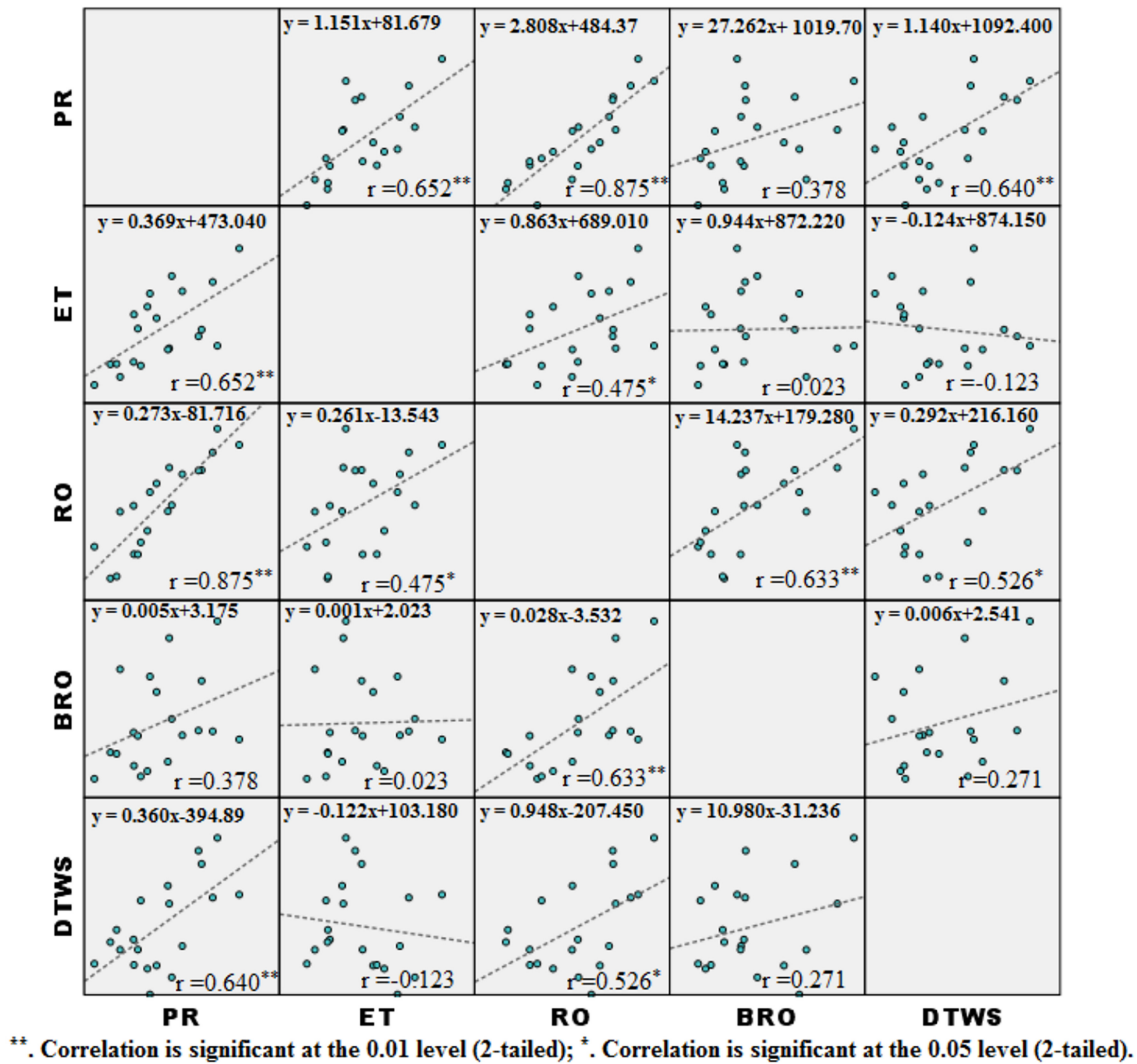


Fig. 2 Scatter plot matrix showing the relationships among various water budget elements [Total Precipitation (PR), Evapotranspiration (ET), Storm surface runoff (RO), Baseflow-groundwater runoff (BRO) and Change in Terrestrial water storage (DTWS) in Billion

Cubic Meters (BCM)] with the Pearson correlation coefficient (r) across the Ganga River Basin (GRB) from 2001 to 2020. (Source: Based on the authors' calculations)

in soil moisture, S_g = Change in groundwater storage, and I = Interception.

Healy et al. (2007) mentioned the water budget equation (Eq. 3) in the USGS Circular 1308 as,

$$P = ET + \Delta S + RO + Q^{bf} \quad (3)$$

where, P = Total precipitation, ET = Evapotranspiration, ΔS = Change in water storage, RO = Surface runoff, and Q^{bf} = Base flow or groundwater flow.

Besides, the water budget equation (Eq. 4) as proposed by Stanton et al. (2011):

$$P + Q_{in} = ET + Q_{out} + \Delta S \quad (4)$$

where, P = Total precipitation, Q_{in} = Inflow into the system, ET = Evapotranspiration, Q_{out} = Outflow into the system, and ΔS = Change in water storage.

Keeping in view all the above water budget equations as expressed by various authors, a generalized equation has been made for use in the present article during the water budget estimation over the entire GRB. It has been stated as follows in Eq. 5:

$$PR = ET + RO + BRO + DTWS \quad (5)$$

where, PR = Total Precipitation, ET = Evapotranspiration, RO = Storm surface runoff, BRO = Baseflow-groundwater runoff, and $DTWS$ = Change in terrestrial water storage,



Table 3 Unit conversion through Raster Calculator in QGIS to extract the monthly data of various hydrological cycle parameters

Hydrological parameters or variables	used in this article	used for those particular variables in GES DISC website for GLDAS-2.1 data	Unit Conversion		Expression for conversion
			From	To	
Total Precipitation	PR	Rainf_f_tavg	kg m ⁻² s ⁻¹	mm/month	Need to multiply by 3600 (s/hr) × 24(hr/day) × (No. of days in that particular month)
Evapotranspiration	ET	Evap_tavg	kg m ⁻² s ⁻¹	mm/month	Need to multiply by 3600 (s/hr) × 24(hr/day) × (No. of days in that particular month)
Storm surface runoff	RO	Qs_acc	kg m ⁻² per 3-h	mm/month	Need to multiply by 8 (3 h/day) × (No. of days in that particular month)
Baseflow-groundwater runoff	BRO	Qsb_acc	kg m ⁻² per 3-h	mm/month	Need to multiply by 8 (3 h/day) × (No. of days in that particular month)
Terrestrial water storage	TWS	TWS_inst	mm/month		No need of unit conversion

Source: Authors' own creation

Table 4 Temporal parameters with monthly extension for understanding meteorological seasons across the GRB

Temporal parameters	Monthly extension
Meteorological seasons	
Winter (W)	January–February
Pre-monsoon (PM)	March–May
Monsoon (M)	June–September
Post-monsoon (PoM)	October–December
Annual (A)	January–December

Source: India Meteorological Department (IMD)

which includes snow water equivalent, soil moisture, root zone moisture, and also groundwater component.

Methods used in trend analysis

Several nonparametric statistical tests, e.g., Mann–Kendall test statistic (S) in the IBM SPSS Statistics 23 environment, Standard normal test statistic (Z_S), Sen's slope estimator (β), and Kendall's τ correlation coefficient have been used to get the seasonal and annual trends of each selected hydrological parameters over the GRB from 2001 to 2020. Besides, linear regression slope (b) has also been used for understanding the nature of datasets.

The Mann–Kendall test (Mann 1945; Kendall 1975) is used in detecting the twenty years (2001–20) trend as denoted by the test statistic S in Eq. 6:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (6)$$

When,

$$\text{sgn}(x_j - x_k) = \begin{cases} +1, & \text{if } (x_j - x_k) > 0 \\ 0, & \text{if } (x_j - x_k) = 0 \\ -1, & \text{if } (x_j - x_k) < 0 \end{cases} \quad (6a)$$

where, n is the number of observation, x_j and x_k are the data values in time series from $j = k + 1, \dots, n$ and $k = 1, 2, \dots, n-1$ respectively.

Standard normal test statistic (Z_S) can be computed for understanding the seasonal and annual trends of different hydrological elements by the following equation (Eq. 7):

$$z_s = \begin{cases} \frac{S-1}{\sqrt{\text{var}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{var}(S)}}, & \text{if } S < 0 \end{cases} \quad (7)$$

When, the variance of S or

$$\sqrt{\text{var}(S)} = \frac{n(n-1)(2n+5)}{18} \quad (7a)$$

where, positive value of Z_S indicates an increasing trend of the variable, and vice versa.

Sen (1968) also developed a nonparametric statistical test by estimating the slope to observe the trend of the sample. That has also been calculated in the present article for different hydrological elements with the help of Eq. 8:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad (8)$$

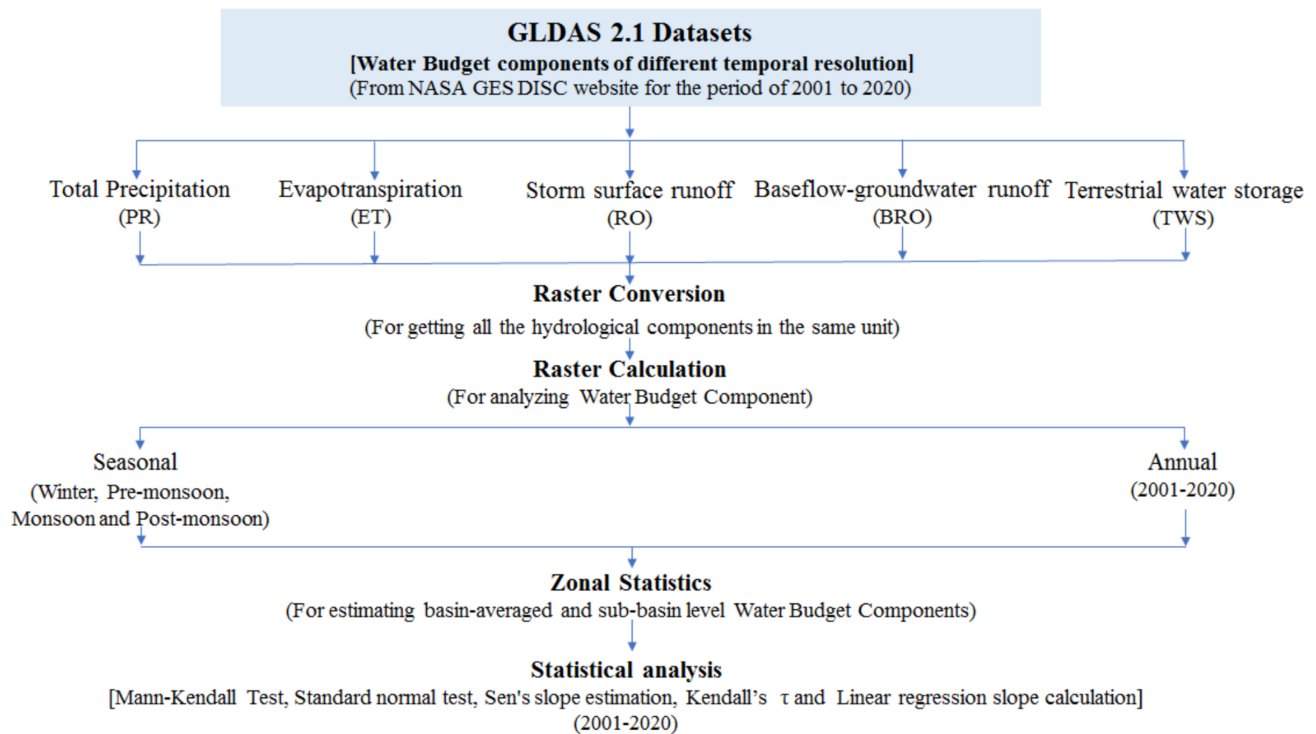


Fig. 3 Workflow for the basin-average and sub-basin level estimation of seasonal and average annual water budget components with several statistical analyses over the Ganga River Basin (GRB) in the present study. (Source: Authors' own creation)

where, β is the Sen's slope estimator which indicates the upward trend when $\beta > 0$, j and i refers the years ($j > i$ for always), and x_j and x_i are the observations for the year j and i respectively.

According to Berg (2021), SPSS runs the following equation (Eq. 9) in the background based on the numbers of concordant (n_c) and discordant pairs (n_d) for calculating Kendall's τ , which has been used for hydrological trend analysis:

$$\tau = \frac{n_c - n_d}{\frac{1}{2}n(n-1)} \quad (9)$$

Besides, the linear regression slopes (b) have also been acquired for observing the seasonal and annual trends of all the selected water budget components over the GRB for twenty years (2001–20).

Results and discussion

The following parts under this section help to understand the spatiotemporal variability of different hydrological components with the estimated seasonal and annual water budgets across the entire GRB.

Spatial variability of hydrological components

Here in this part, we first examine how water budget components and their variations that occur seasonally and annually have evolved over the study period at the sub-basin level. As the catchment area of each sub-basin in GRB varies from one another in terms of area, they contribute differently to the hydrological system dynamics. The study shows that the annual quantities of the accumulated PR, ET, RO, and subsurface runoff or BRO are very high for the large sub-basins (e.g., 325, 401B, 409, 410, 414, 418 etc. coded sub-basins) than any other sub-basins under the GRB (Fig. 4a). Besides, the amount of water loss from the terrestrial water storage is also very high in case of those sub-basins, e.g., (–) 0.3676 BCM for sub-basin code 325, (–) 0.2027 BCM for sub-basin code 401B, (–) 0.3569 BCM for sub-basin code 409, and (–) 0.9446 BCM for sub-basin code 410 etc. That is the reason why the change or difference in TWS (DTWS) values show highly negative for the large sub-basins than the smaller ones (Fig. 4a). Normally, these sub-basins contribute much to the hydrological cycle of the GRB. Irrespective of the seasons, all the water budget components behave almost similarly throughout the year, except during the monsoon season. The amount of ET is higher (highest in pre-monsoon season) than the total amount of PR in winter (Fig. 4b), pre-monsoon (Fig. 4c), and post-monsoon season



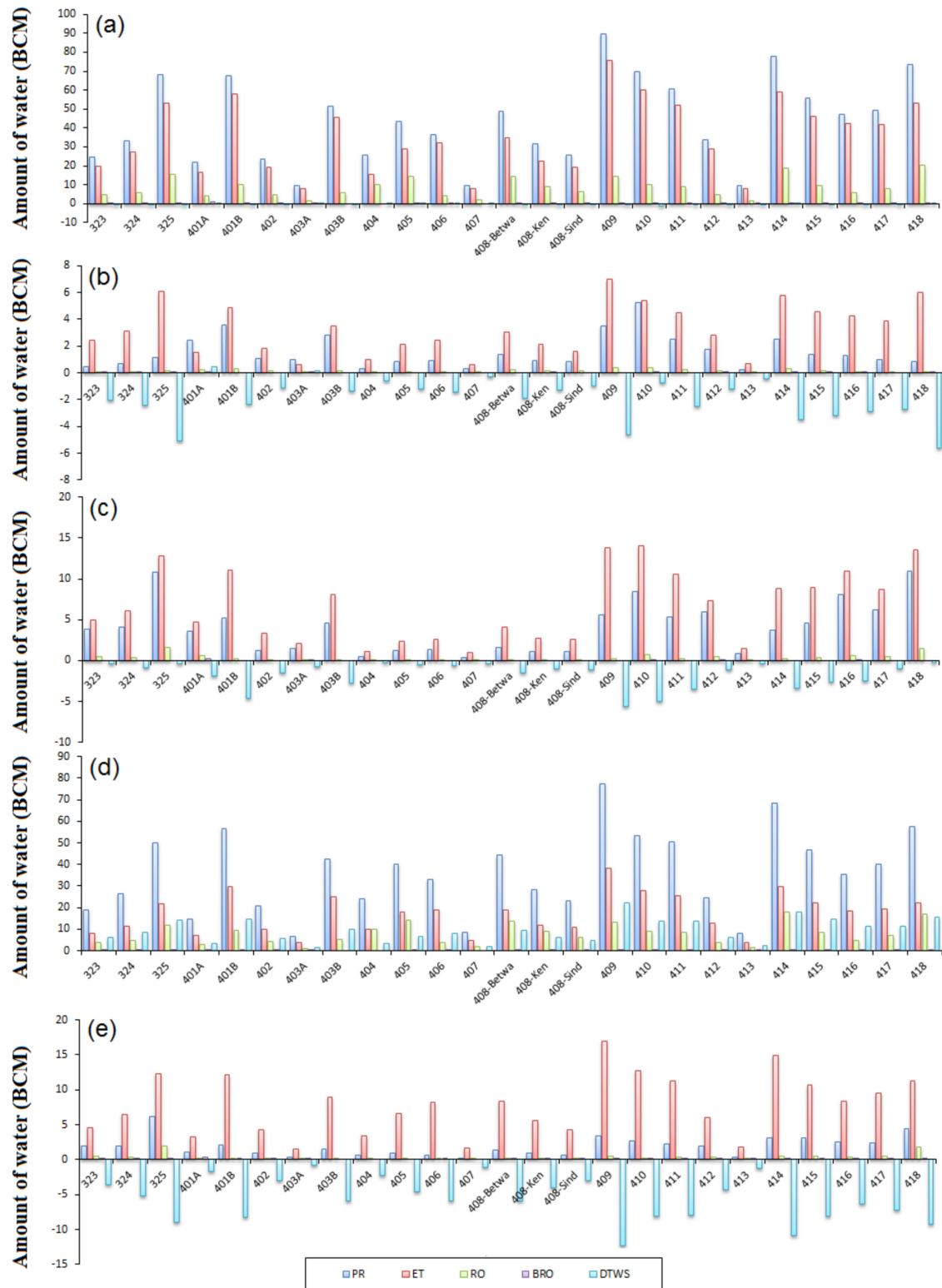


Fig. 4 Bar diagrams showing major hydrological parameters across the Ganga River Basin (GRB) for making comparison among the sub-basins and seasonal variations based on the GLDAS-2 1 data-

set (2001–20): **a** Annual, **b** Winter season, **c** Pre-monsoon season, **d** Monsoon season, and **e** Post-monsoon season. (Source: Based on the authors' calculations)

(Fig. 4e). But in the case of the monsoon season (Fig. 4d), all the basins over the GRB experience much higher PR than ET because of the southwest monsoon-winds from June to September (CWC-IMD 2015; IMD 2021; IMD Pune 2021). For example, sub-basin 325 experiences 49.8637 BCM PR and 21.8379 BCM ET, sub-basin 401B experiences 56.7593 BCM PR and 29.5474 BCM ET, sub-basin 409 experiences 77.3198 BCM PR and 38.1199 BCM ET, and sub-basin 410 experiences 53.3239 BCM PR and 28.0739 BCM ET etc. So, ET causes the loss of only 47.74% of precipitated water in the monsoon season over the GRB. More interestingly, this is the only season when the change in TWS is less due to the recharge of water during monsoon. That is the reason why the changes in TWS amounts show positive values in the monsoon season throughout the basin. In addition, the gridded annual and seasonal distribution maps (Fig. 5) of different hydrological components, e.g., the PR, the ET, the RO, the BRO, and the changes in TWS, also help to visualize the spatial variations throughout the entire GRB. One can also see from Fig. 5 that the annual average TWS changes in

spatial patterns with the variance (σ^2) value of 7.9089, and the seasonal trends of σ^2 in the GRB region is also showing 5.2965, 5.2943, 7.9277, and 4.8831 respectively for winter, pre-monsoon, monsoon and post-monsoon during our study period. We could see interesting magnitude changes in TWS signals of the GRB basin with a maximum in the western and south-western region (nearer to Alwar, Bharatpur, Bhilwara, Bundi, Chittorgarh, Rajsamand, Jhalawar, Tonk, Jaipur, Sawai Madhopur, Dausa, Kota, and western part of Dholpur districts in Rajasthan; Mandsaur, Ratlam, Ujjain, Indore, Dewas, Sehore, Rajgarh, Sheopur, the western part of Shivpuri, Guna, the western part of Ashoknagar and Sagar district in Madhya Pradesh; Rewari, Mahendragarh, Jhajjar, Rohtak, Yamunanagar, Gurugram, the western portion of Sonapat, Panipat and Karnal district in Haryana; and Mathura and western part of Agra in Uttar Pradesh) that ranges 0 to 100 mm/yr, and the minimum magnitude is observed throughout the middle and eastern part of the GRB region with a magnitude of 0 to -100 mm/yr in amount. The variance (σ^2) values of other annual average hydrological

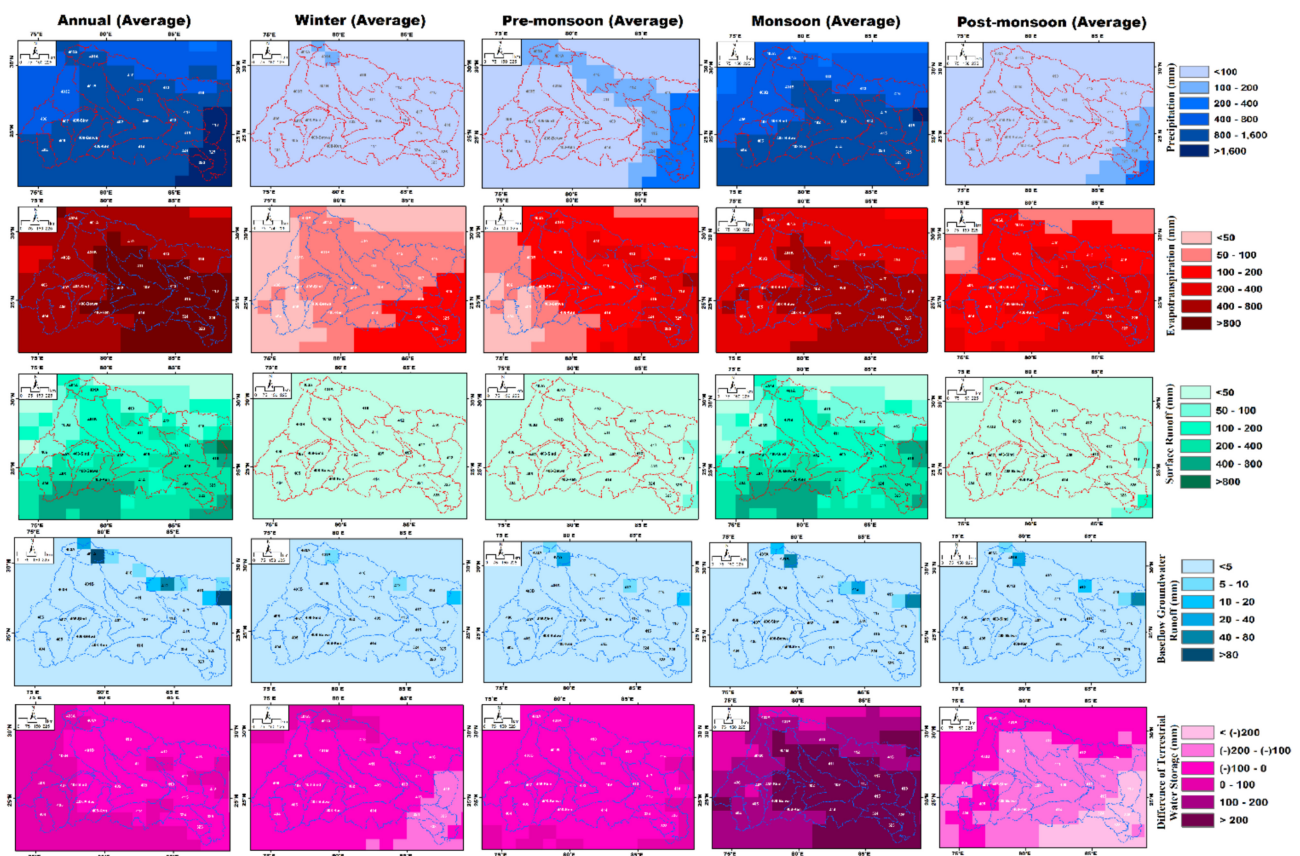


Fig. 5 Pixel-based annual and seasonal distributions of different hydrological components [Total Precipitation (PR), Evapotranspiration (ET), Storm surface runoff (RO), Baseflow-groundwater runoff (BRO) and Change in Terrestrial water storage (DTWS)] are derived

directly by analyzing the GLDAS-2.1 datasets for 2001–20 in the GIS environment over the Ganga River Basin (GRB). (Source: Based on the authors' calculations)



elements, i.e., PR, ET, RO, and BRO are 10.5543, 7.9415, 5.8921, and 1.2420, respectively.

Temporal variability of hydrological components

The twenty years (2001–20) average annual values of selected water budget components have been shown by the line graph (Fig. 6a) for getting the idea about temporal fluctuations over the GRB. The linear regression slopes (b) of those hydrological components have also been estimated for understanding the nature of datasets and the trends for twenty years (2001–20) in Fig. 6b. The results derived from the several nonparametric statistical tests have identified similar annual and seasonal behavioural trends of each selected hydrological parameters for the twenty years (Table 5). The analyses infer the negative trends annually for the PR, the RO, and the BRO, whereas the annual accumulated ET and the changes in TWS show positive trends with time. The behavioural patterns of all the water budget components are similar in the winter and the pre-monsoon season, i.e., the negative trends in the case of the ET, the RO and the BRO, while the positive trends in the case of the PR and the changes in TWS. In the Monsoon season, all the hydrological components (except the ET) show a negative trend over time. Apart from that, only the changes in TWS show a positive trend among all the water budget elements in the Post-monsoon season.

Seasonal and annual water budget estimation

The estimated quantities of water in different forms within the complex riverian system and its associated hydrological cycle help to understand the water budget or balance condition over the GRB. As mentioned in the methodology, a generalized equation (Eq. 5) was applied for the water budget estimation in all the sub-basins of GRB (Table 6) for twenty years (2001–20). The results derived in Table 6 help to observe six distinct types of changes in a water year which reflects a strong spatial heterogeneity in TWS and other water balance components across the GRB. These are: *Firstly*, water surplus condition in winter, monsoon and post-monsoon season, but water deficit in pre-monsoon season: leads the sub-basin towards water deficit condition annually (Sub-basin code: 323 and 325); *Secondly*, seasonal water budget condition is same like the first one, but ultimately the annual water budget condition leads towards water surplus state (Sub-basin code: only 418); *Thirdly*, water surplus condition in monsoon and post-monsoon season, but water deficit in winter and pre-monsoon season: leads the sub-basin towards water deficit condition annually (Sub-basin code: only 324); *Fourthly*, water surplus condition in winter and monsoon season, but water deficit in pre-monsoon and post-monsoon season: leads the sub-basin towards water deficit condition annually (Sub-basin code: 401, 402, 403, 407, 408- Betwa, 408- Sind, 409, 410, 411 and 413); *Fifthly*, water surplus condition only in monsoon season, but water

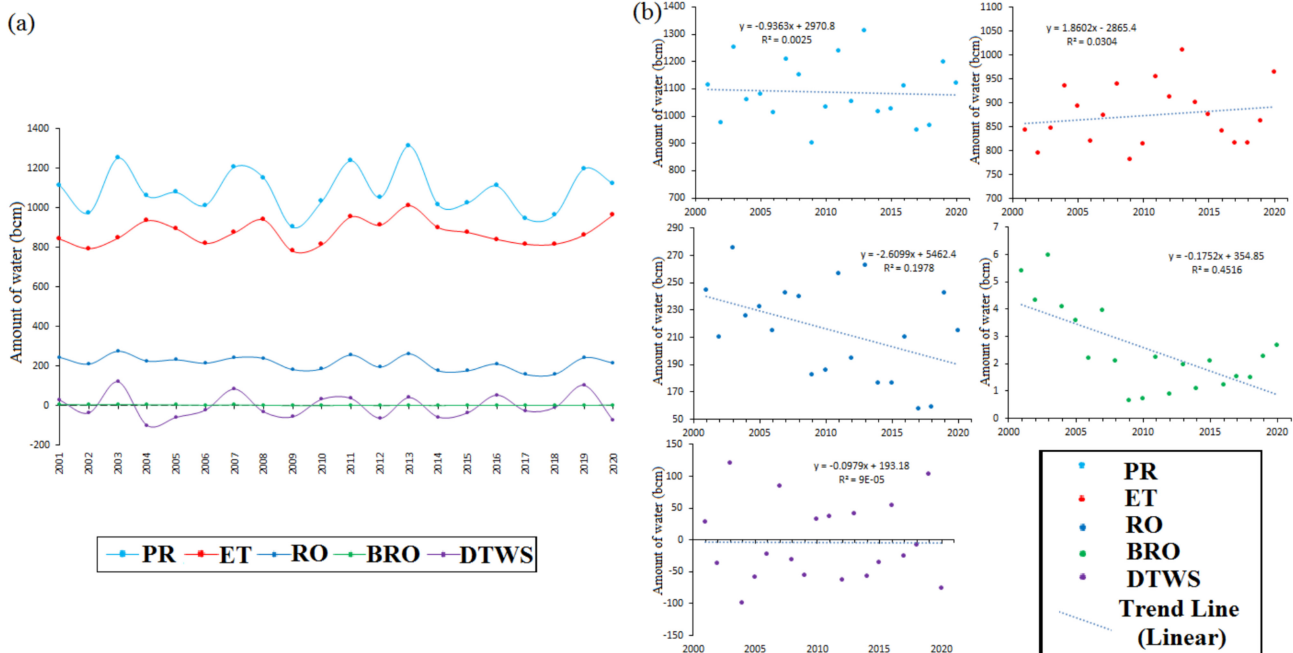


Fig. 6 a Temporal variations of different hydrological parameters with b the twenty years trend (2001–20) over the entire Ganga River Basin (GRB). (Source: Based on the authors' calculations)

Table 5 Results of the statistical tests for seasonal and annual trend analyses of different hydrological parameters for the entire GRB for the period 2001–2020. Abbreviations of hydrological parameters: Total Precipitation (PR), Evapotranspiration (ET), Storm surface runoff (RO), Baseflow-groundwater runoff (BRO), and Change in Terrestrial water storage (DTWS). Abbreviations of temporal parameters: Winter (W), Pre-monsoon (PM), Monsoon (M), Post-monsoon (PoM), and Annual (A)

Statistical tests	PR					ET				
	W	PM	M	PoM	A	W	PM	M	PoM	A
Mann–Kendall test statistic (S)	8	2	– 4	– 38	– 10	– 64	– 52	100	– 34	20
Standard normal test statistic (Z_0)	0.227	0.032	– 0.097	– 1.200	– 0.292	– 2.044	– 1.655	3.212	– 1.071	0.616
Sen's slope estimator (β)	0.280	0.075	– 0.670	– 1.225	– 1.690	– 0.945	– 2.250	4.990	– 1.035	1.410
Kendall's τ	0.042	0.011	– 0.021	– 0.200	– 0.053	– 0.337	– 0.274	0.526	– 0.179	0.105
Linear regression slope (b)	0.183	0.576	– 0.890	– 0.804	– 0.936	– 1.132	– 1.562	5.921	– 1.367	1.860
Statistical tests	BRO					DTWS				
	W	PM	M	PoM	A	W	PM	M	PoM	A
Mann–Kendall test statistic (S)	– 6	– 10	– 46	– 44	– 56	– 98	– 84	– 68	– 42	10
Standard normal test statistic (Z_0)	– 0.162	– 0.292	– 1.460	– 1.395	– 1.784	– 3.147	– 2.693	– 2.174	– 1.330	0.292
Sen's slope estimator (β)	– 0.020	– 0.040	– 2.370	– 0.400	– 3.115	– 0.010	– 0.060	– 0.170	– 3.530	0.660
Kendall's τ	– 0.032	– 0.053	– 0.242	– 0.232	– 0.295	– 0.516	– 0.442	– 0.358	– 0.221	0.053
Linear regression slope (b)	– 0.042	0.088	– 2.200	– 0.455	– 2.610	– 0.018	– 0.082	– 0.175	– 4.191	– 0.098

Source: Based on Authors' own analyses

Table 6 Seasonal and annual water budget conditions of all the sub-basins in the GRB. Various colours have been used for representing different water budget states: Blue indicates water surplus conditions, and Red indicates water deficit conditions

Sl. No.	Sub-basin Codes		Water budget conditions in Billion Cubic Meter (BCM)				
			Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
1	323		0.0147	-1.2603	0.7952	0.3250	-0.0085
2	324		-0.0926	-1.5793	1.3134	0.1568	-0.0037
3	325		0.0409	-3.2778	1.9380	1.1007	-0.0241
4	401	A	0.1492	-0.0856	0.6279	-0.7110	-0.0146
		B	0.7570	-1.4925	2.9872	-2.1471	-0.0592
5	402		0.2682	-0.6311	0.9646	-0.5657	-0.0088
6	403	A	0.0486	-0.0071	0.3435	-0.3737	-0.0069
		B	0.4858	-0.8142	2.2248	-1.7693	-0.0365
7	404		-0.1008	-0.3994	1.0818	-0.5977	0.0044
8	405		-0.1552	-0.7277	2.0277	-1.1961	-0.0023
9	406		-0.1247	-0.7511	2.4577	-1.6041	-0.0083
10	407		0.0249	-0.1954	0.4811	-0.3110	-0.0022
11	408	Betwa	0.0291	-1.1020	2.2843	-1.2592	-0.0082
		Ken	-0.0087	-0.7197	1.4781	-0.7951	-0.0015
		Sind	0.1122	-0.5423	1.1395	-0.6905	-0.0068
12	409		0.8011	-2.7999	3.6021	-1.7561	-0.0351
13	410		0.1911	-1.4116	2.8157	-2.1885	-0.0213
14	411		0.3112	-2.0493	2.7770	-1.3869	-0.0310
15	412		-0.0111	-0.8427	1.0623	-0.4203	-0.0088
16	413		0.0147	-0.3494	0.4138	-0.1478	-0.0018
17	414		-0.0455	-1.9907	3.2938	-1.4603	0.0083
18	415		-0.1628	-2.0217	1.7884	-0.0905	0.0044
19	416		-0.0873	-1.0986	0.8455	-0.0307	-0.0063
20	417		-0.2012	-2.0118	2.0761	-0.3807	-0.0081
21	418		0.3289	-3.8302	2.8342	0.3867	0.0076

Source: Based on Authors' own analyses

deficit in winter, pre-monsoon and post-monsoon season: leads the sub-basin towards water surplus condition annually (Sub-basin code: 404, 414 and 417); and *Sixthly*, seasonal water budget condition is same like the fifth one, but ultimately the annual water budget condition leads towards water deficit state (Sub-basin code: 405, 406, 408- Ken, 412, 416 and 415). Overall, Fig. 6 shows the linear negative trend of TWS changes (-0.0093) with a spatial mean over the entire region of -3.6054 BCM or km^3/yr , despite having some positive fluctuations for the sub-periods of 2001, 2003, 2007, 2010, 2011, 2013, 2016, and 2019. It is also interesting to note that, a long-term annual hydrological dry condition existing in the GRB basin corresponds to a persistent negative trend of RO (-0.4447) and the BRO (-0.6720) anomalies, and positive trends of ET values (0.1745) and this is in line with finding by Rai et al. (2012) and Anand et al. (2018), indicating how monsoon and annual precipitation values contribute to overall water balance in south Asian river basins and associated TWS variations and volumes. The TWS trend is showing a negative change only in the monsoon season with a Z statistic value of -1.330 ,

and Sen's slope of -3.530 BCM or km^3/yr . Whereas the winter, pre-monsoon and post-monsoon seasons show positive change of TWS with Z statistic values of 1.265, 0.487, and 2.044, respectively and Sen's slopes 1.185, 0.750, and 1.820 BCM or km^3/yr , respectively. Generally, one can see the compensation effect of monsoon seasonal TWS values, on the long-term annual trend analysis. Though the annual change in TWS shows a non-significant linear negative correlation (with a value of -0.0092) and several nonparametric tests show non-significant positive trends (Table 5), the effect became negligible because of positive cross correlation between PR and TWS change with a value of 0.6402 at the 99% confidence level.

This study investigated the GLDAS-2.1 CLSM products informed spatio-temporal variations of TWS and other water budget components in GRB and associated trend perspectives of water storage and fluxes during the 2000–20 period. The analysis confirms that the GRB receives significantly lower precipitation during the winter season compared to other seasons, accounting for only 3.58% of the total annual rainfall, whereas the pre-monsoon, monsoon,

and post-monsoon seasons contribute 9.36%, 82.68%, and 4.38%, respectively. Having low temperatures, the winter season also experiences less ET than other seasons, but the quantity of ET is comparatively higher than the PR in most of the sub-basins (except the sub-basins coded as 401A and 403A). In addition, moderately negative (-1 to -2 BCM) and highly negative (more than -2 BCM) changes in TWS can be found in almost 72% of the sub-basins, whereas 92% of sub-basins are showing negative changes in TWS cumulatively during winter. As a result, 60% of sub-basins experience the water surplus condition, whereas the other 40% of sub-basins experience water deficit conditions in the sub-basin level hydrological budget during winter. In pre-monsoon season, the ET values largely influence the surface and subsurface components of GRB hydrological cycles and all the sub-basins over the GRB react almost similarly. The numerical values (volume) of ET naturally exceed other hydrological components (PR, RO, BRO, and the changes in TWS) and all the sub-basins (including the entire GRB) face severe water deficit conditions. So, the value is higher in the pre-monsoon season with 31.9914 BCM water deficit than in the post-monsoon season with 17.9132 BCM water deficit. In consequence, annual water deficit in the hydrological cycle is observed throughout the sub-basins of the GRB (except the sub-basins coded as 404,

414, 415, and 418), despite having strong PR dominance over all the water budget components (ET, RO, BRO, and the changes in TWS) during monsoon season. Furthermore, during the post-monsoon season, long-term seasonal TWS tends to show high negative changes (more than -3 BCM) across the sub-basins (all except the sub-basins coded as 401A, 403A, 404, 407, 408-Sind, and 413), but its numerical value is higher than other hydrological elements (PR, RO, and BRO) excluding ET. Thus 84% of the sub-basins over the GRB experienced a water deficit situation and it is more significant in 401B and 410 coded sub-basins nearer to Muzaffarnagar, Bijnor, Rampur, Moradabad, Amroha (J.P. Nagar), Bareilly, Budaun, Aligarh, Bulandshahr, Etah, Mainpuri, Farrukhabad, the western portion of Hardoi, Kanpur, the southern and western part of Unnao, and the western portion of Shahjahanpur districts of Uttar Pradesh and Udham Singh Nagar, Bageshwar, Almora, Nainital, and Champawat districts of Uttarakhand (2.1471 and 2.1885 BCM water deficit, respectively), but moderate in 403B, 405, 406, 408-Betwa, 409, and 411 coded sub-basins (1.7693, 1.1961, 1.6041, 1.2592, 1.7561, and 1.3869 BCM water deficit, respectively). A strong long-term water surplus trend was found in 4 sub-basins (coded as 404, 414, 415, and 418), whereas the rest of the sub-basins experience annual

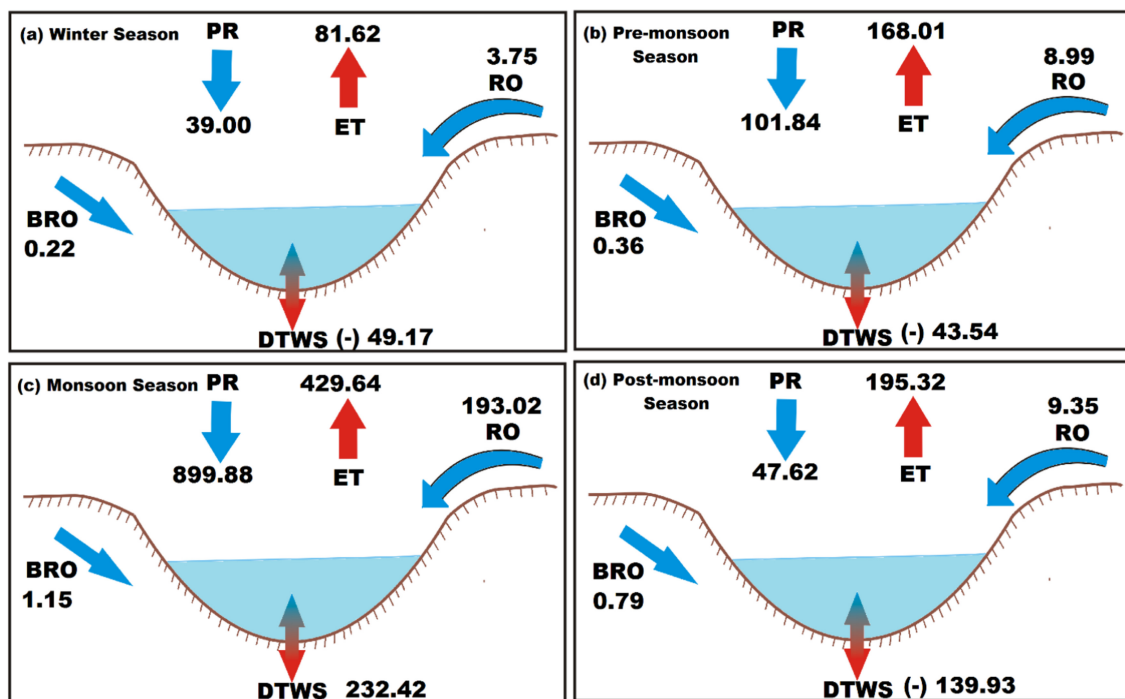
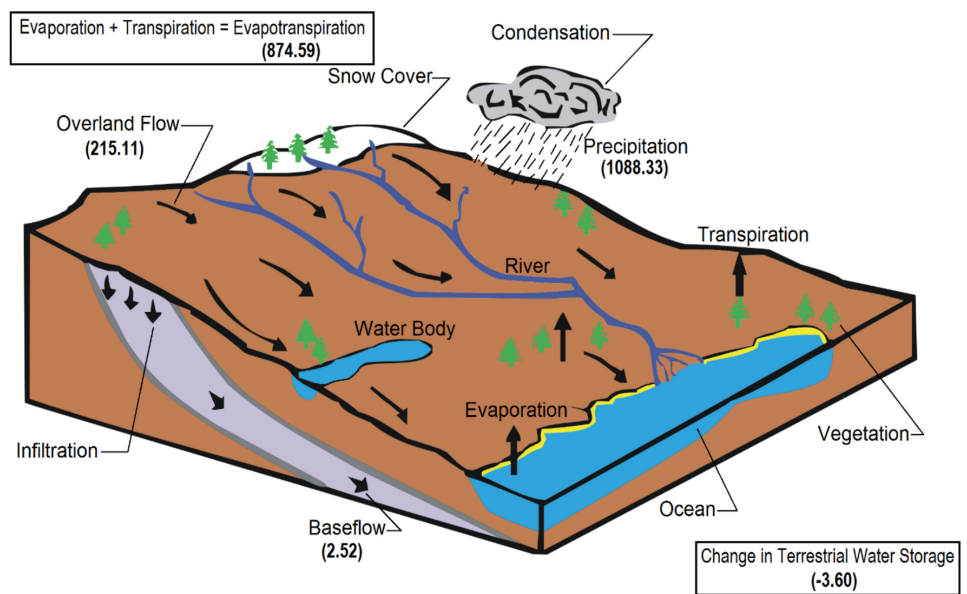


Fig. 7 Average seasonal basin water budget for the years 2001–20: **a** Winter, **b** Pre-monsoon, **c** Monsoon and **d** Post-monsoon. The values are given in Billion Cubic Meters (BCM). Abbreviations have been used: PR, ET, RO, BRO, and the changes in TWS for Total Precipita-

tion, Evapotranspiration, Storm surface runoff, Baseflow-groundwater runoff, and Change in Terrestrial water storage respectively. (Source: Based on the authors' calculations)



Fig. 8 Model showing average annual water budget elements in Billion Cubic Meters (BCM) over the entire Ganga River Basin (GRB) for water years 2001–20. (Source: Based on the authors' creation and calculations)



water deficit conditions, indirectly indicative of droughts and floods over the basin.

The overall results reported in this study can provide information beneficial for local administrations and water managers through the quick overview of the two-decadal average seasonal (Fig. 7) and annual (Fig. 8) water budget in GRB for evaluating water resources potentials and controlling measures, such as identification of those sub-basins across the GRB which are under water stress condition and prioritize water conservation efforts for those sub-basins, seasonal water availability estimation for helping to plan irrigation schedules, and for understanding the ground water regimes to facilitate policy formulation for sustaining ground water extraction. Besides, the measurement of interannual variability might assist in drought and flood preparedness planning. The results show that scarcity is more intense in the pre-monsoon season (31.9914 BCM) than the post-monsoon season (17.9132 BCM) and it has strong links to high evapotranspiration and low precipitation trends during pre and post-monsoon seasons. On the contrary, surplus water can be found during the winter (2.5878 BCM) and monsoon (43.6539 BCM) seasons within the GRB hydrological system. The decreasing trends of PR, RO, and BRO were correlated well to GLDAS-2.1 CLSM-based changes in TWS estimates with the positive cross-correlation of 0.6402, 0.5259, and 0.2708 respectively in the GRB, but a negative cross-correlation of -0.1231 with ET, despite having increasing trend in 20 years (2001–20). Besides, PR has a positive cross-correlation with ET (0.6516), RO (0.8751), and BRO (0.3775). The annual hydrological budget analyses also help to reveal that the precipitated water moves back into the atmosphere in the form of ET (80.36% for the entire GRB) and acts as a dominant component in some cases, e.g.,

85.30% for 401B, 88.81% for 403B, 88.69% for 406, 86.36% for 410, 85.56% for 411, 85.16% for 412, and 88.82% for 416 coded sub-basins. These sub-basins are mainly confined within: (a) the western semi-arid region for 403B and 406 coded sub-basins (nearer to the western part of Rajasthan); (b) the northern mountainous belt region for 410, 412, and 416 coded sub-basins; and (c) the agriculture dominated Gangetic Plain for 401B and 411 coded sub-basins. Moreover, the sub-basins coded as 325 (Mayurakshi, Ajay and Hoogli River system), 404 (Chambal River system up to Kota dam site), 405 (Kota dam site on Chambal River to the confluence with Banas River), 408-Betwa, 408-Ken, 408-Sind, 414 (Son River system), and 418 (Ganga River from its confluence with Kosi River at Kursela to Bangladesh border) are the RO dominated segments and contribute effectively in the hydrological system by transferring 22.67, 40.09, 33.33, 29.14, 29.02, 25.33, 24.18, and 27.85 per cent of annual rainwater and also 23.74, 41.79, 34.99, 30.81, 30.78, 27.01, 25.90, and 29.71 per cent of monsoon time rainwater, respectively. These hydrological statistics are also indicative to determine the flood-prone regions over the GRB. The present analysis also claims that a very negligible annual amount of water (0.2794 BCM) deficit can be found over the entire GRB, and this is because of the compensation effects of the monsoon water budget.

Despite the robustness of our analysis, certain limitations must be acknowledged. As GLDAS 2.1 is model-based (CLSM) products, it inherently possess some uncertainties, which may influence the accuracy of water budget components. Constraints in spatial resolution of hydrological datasets may affect the accuracy of water budget components, especially at the sub-basin scale. Besides, a major challenge is the absence of direct groundwater withdrawal data,

making it difficult to fully quantify anthropogenic influences on water storage and availability.

Conclusion

This study has illustrated the ability of GLDAS-2.1 datasets for explaining hydrological dynamics and spatio-temporal variability in GRB. Though some studies have cautioned about the uncertainties in GLDAS and strengths of remote sensing data, this study has explained well the seasonal and interannual changes in water components in a large river basin like GRB (Deliry et al. 2022; Sahoo et al. 2011). In spite of having a low spatial resolution, this kind of analysis using GLDAS-2.1 CLSM helps to estimate the terrestrial water budget and differences in average seasonal and annual hydrological components. These outcomes would also help to understand the behavioural nature as well as inter-seasonal variations of various hydrological components over 21 sub-basins of the GRB. The GLDAS data was compared and established its strengths to quantify TWS in comparison with many similar data sources like GRACE (Wang et al. 2016; Yang and Chen 2015). Though some studies have highlighted the error propagation of GLDAS precipitation (Seyyedi et al. 2015) data to TWS, the gridded datasets like GLDAS-2.1 CLSM are beneficial for water budgeting in large transboundary rivers like the Ganga having flow data restrictions and data-scarcity. Further analysis with a much longer temporal span also helps to trace the climate variability over time (Stagl et al. 2014) and the changes in water resources related to human interventions in the hydrological cycle (Yan-Nian et al. 1988; Winter et al. 1998; Healy et al. 2007) to get more enhanced knowledge to tackle issues related to flood measurement, design of hydraulic structures, erosion and sediment control, irrigation, and groundwater management etc. over the GRB. It is also believed that a comparative analysis with other data sources can reinforce the authenticity of these reported estimates and merging GLDAS-2.1 CLSM data products with other high-resolution satellite products can significantly amount the refined information about the water cycle in GRB.

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Declarations

Conflict of interest The authors declared that they have no conflict of interest.

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