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Assessment of drought trends in the Senegal River Basin by a terrestrial water storage index (GRACE)

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Abstract: Droughts lead to significant environmental and economic consequences, especially in arid and semi-arid areas like the Sahel. While site-level assessments of drought in the Sahel are abundant, assessments at the scale of entire hydrological basins are less common. Here, we use a new drought index called the terrestrial water storage index (TWSI) to assess trends in drought throughout the Senegal River Basin. This area covers parts of Guinea, Mali, Senegal, and Mauritania, the study period is between 2003 and 2020. Over the entire period, water storage in the Senegal River Basin is increasing by 0.87 km^3 y^{-1} on the total area of the basin. However, we observed two distinct phases within the time period: an overall water deficit between 2003 and 2012 and a surplus between 2013 and 2020. We also found variations in terrestrial water storage from highly negative at the end of the dry season (-12.47 cm in May 2003) to strongly positive at the end of the rainy season (15.30 cm in September 2020). Our study suggests that the TWSI can be a useful index for regional hydrological drought monitoring, especially for areas where meteo-hydrological observations are insufficient.

Key words: terrestrial water storage, GRACE, drought index, groundwater resources, Senegal River Basin

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1. INTRODUCTION

Groundwater in the Senegal River Basin, an important agricultural production area in Senegal, is of great importance for water resources management, agricultural development and ecosystem health in the region. These water resources are suffering the impacts of climate change and drought, which have become a serious natural disaster in Senegal in recent decades, resulting from low and erratic rainfall and high rates of evapotranspiration [1–7]. Several prolonged and severe droughts have caused severe water shortages, desertification and dust storms in many areas [8]. Monitoring changes and trends in drought in Senegal would generate important information that can be used to improve water resources management and disaster prevention [9].

Due to the increased ability of remote sensing systems to capture large-scale changes in spatio-temporal soil surface conditions, remotely sensed data and products have been incorporated into the monitoring methodology for meteorological, hydrological and agricultural drought, since the 1980s [10]. Among these remote sensing products, the Terrestrial Water Storage (TWS) data extracted from the gravity recovery and climate experiment (GRACE) have been successfully applied to drought monitoring. Numerous drought indices have been developed to quantify complex drought processes and to demonstrate actual hydrological conditions using a single measure from different perspectives on moisture conditions, deficiencies or excess water in a given area [11]. The two most commonly used

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drought indices are the Palmer Drought Index (PDSI) and the Standardized Precipitation Index (SPI) [12,13]. The most recent standardized precipitation-evapotranspiration index (SPEI), which would have been superior to the two previous indices, has been applied in some comparative studies [14]. It is generally accepted that SPIs and SPEIs are more sensitive to drought factors such as precipitation and evapotranspiration and offer improved drought prediction capabilities, particularly with regard to short-term droughts [15].

GRACE data have been used by several authors to characterize and monitor droughts and floods by observing changes in water storage [10,16,17]. Some drought indices have been developed from the changes observed by satellite in terrestrial water storage from GRACE data. From a time series of GRACE, we can quantify the time of occurrence of hydrological drought and its duration and severity [18]. Results suggest that GRACE-generated groundwater storage is strongly correlated with rainfall indices over most areas. Indeed, GRACE-based drought characteristics are consistent with SPI results in some areas [19]. The motivation for including these two indices of climate drought is that the temporal agreement between the hydrological data and these indices using precipitation and evapotranspiration in their formulations is strong, even under different climatic conditions [15].

The strong correlation between the drought indices (based on meteorological data) and GRACE's terrestrial water storage data (independent of meteorological data) can be used for validation and to demonstrate applicability from these datasets to the prediction of drought in some areas [10,20]. We therefore analyzed the interannual variation of terrestrial water storage while indicating the relationships between the variations of the SPI and the SPEI and the variability of the spatiotemporal data of GRACE from 2003 to 2020 in the Senegal River Basin. The objectives of this study were (1) to make a temporal evaluation of the relationship between the GRACE data set and drought indices and (2) to advise on the application of drought indices to detect patterns of drought affected by variations in terrestrial water storage under climatic conditions in Senegal.

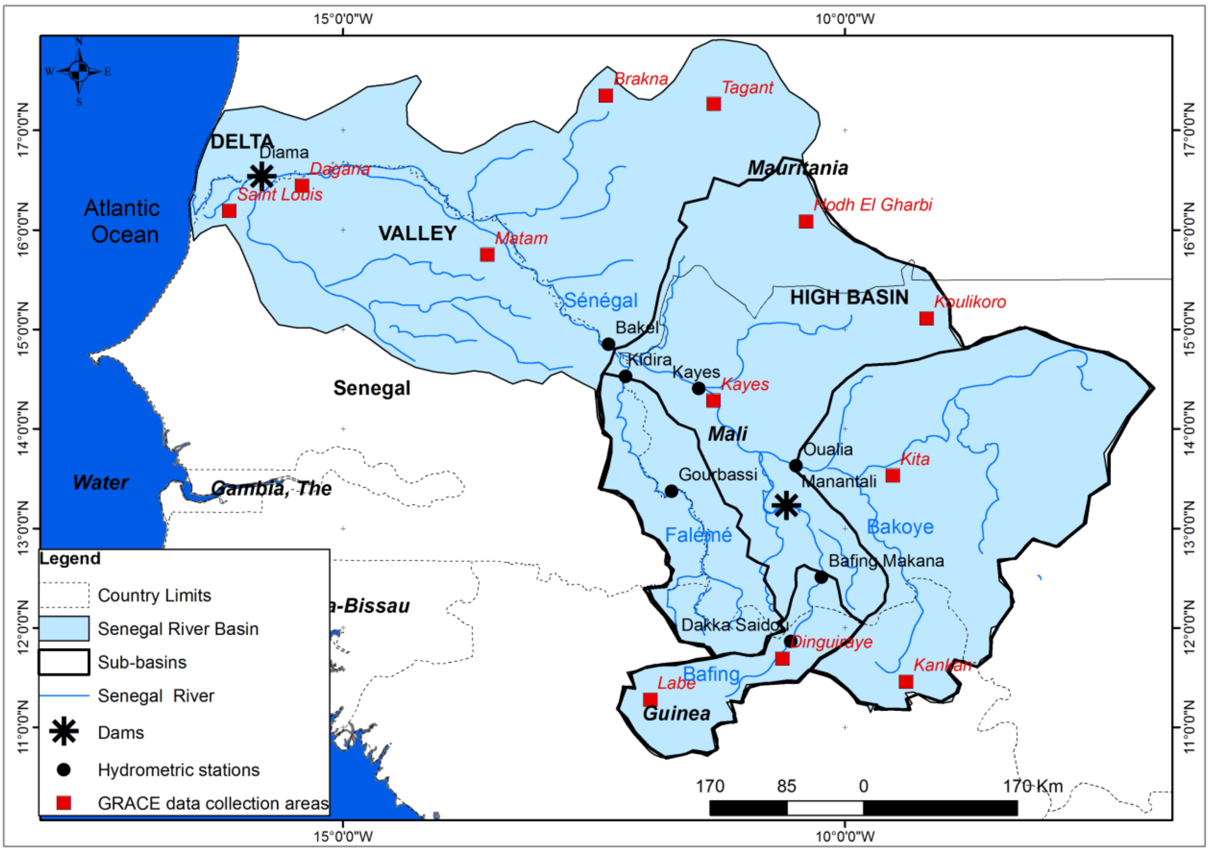


Figure 1. Situation of study stations in the Senegal River Basin.
Source: Senegal River Development Organization (OMVS), 2021

2. STUDY ZONE

The Senegal River covers four countries: Guinea, Mali, Mauritania, and Senegal (Figure 1). The river is 1,700 km long and drains a basin of 300,000 km^2. One of the main tributaries is the Bafing river. The Bakoye and Faleme tributaries, which also have their sources in Guinea, constitute with the Bafing tributary, the "upper basin" of the Senegal River [21] (Figure 1). The Senegal River is formed by the junction of the Bafing and Bakoye tributaries, then is joined by Kolimbiné, then by Karokoro to the west and the Falémé to the east, 50 km upstream of the city of Bakel in Senegal. In the southern part of the basin, the density of the hydrographic network is an indicator that soils are highly impermeable and water runoff into streams is high [22,23].

The Sahelian zone, in which the Senegal River is formed, was documented by inter-decadal patterns of drying and rewetting. While there is still debate on what drives these patterns, they are related to well documented ecological change. For example, various studies on the hydrology of the Senegal River Basin have shown changes in its hydrological regime, with the decline in flow rates during the period of the great drought from the 1970s [1–7,24,25]. In addition to changing climate patterns, human-built infrastructure has caused major changes to the hydrological dynamics of the Senegal River basin, specifically the large dams built at Diama and Manantali.

The Senegal River basin is generally divided into three entities: the "upper basin", the valley and the delta, strongly differentiated by their topographical and climatological conditions. For this study, we focus on the entire basin, with selected stations on the Guinean, Malian, Senegalese and Mauritanian parts. On each part, the three stations are randomly selected from those that had data that is derived from the GRACE product. The Guinean and Malian parts of the river basin provide almost all of the water supply (over 80% of the inflow) up to the town of Bakel because of the higher precipitation rates in those areas [21]. In this area, rains fall between April and October in the mountainous part of the extreme south of the basin, especially in the Guinean part of the basin, and cause the annual flood of the river which takes place between July and October. For example, at the Labé station in Guinea (in the extreme south of the basin), the annual rainfall amounts vary between 1500 and 2000 mm for a total recorded annual mean rainfall of 1612 mm during the period 1933-2004 [2].

3. METHODS AND DATA

3.1. Data

3.1.1. GRACE terrestrial water storage data

To analyse the interannual variation of terrestrial water storage in the Senegal River basin, we used GRACE data from a set of water level data from the French Space Center (CNES / GRGS, current version: RL03-v3.monthly, available at: http://www.thegraceplotter.com). The National Aeronautics and Space Administration (NASA) and Deutsches Zentrum für Luft-und Raumfahrt (DLR) joint satellite mission, the Gravity Recovery and Climate Experiment (GRACE) mission launched in March 2002, is designed to measure small mass changes within the Earth over a large spatial scale [26]. The GRACE instrument represents one of newest observational system to improve the estimate of hydrologic, glacier, ice-sheet and oceanic mass changes with unprece-dented accuracy, ~a few cm in the form of water thickness change [27]. GRACE is currently measuring the Earth's mass redistributions with a spatial resolution longer than 300–600 km (half-wavelength) or finer and at monthly temporal resolution. GRACE is capable of observing the total (both surface and subsurface) water thickness change over an entire watershed or basin [28], and although at relatively coarse spatial and temporal resolutions, GRACE represents a revolutionary tool to address contemporary research problems in terrestrial hydrology.

We extracted data at two scales. To characterize the temporal evolution of the TWS data, the data were first selected on the whole Senegal River Basin (for this, the average value of the basin was used in the study). To characterize the spatial variability of the TWS data, data are then selected at the level of the four riparian states (Guinean, Malian, Senegalese and Mauritanian parts of the basin) because of three sites per state: Guinea (Dinguiraye, Kankan and Labé), Mali (Kayes, Kita and Koulikoro), Senegal (Saint Louis, Dagana and Matam) and Mauritania (Brakna, Hodh El Gharbi and Tagant) (Table 1).

Table 1. Characteristics of the stations for which GRACE data were extracted.

Country	**Sites**	**Latitude**	**Longitude**	**Maximum water height (cm)**	**Minimum water height (cm)**	**Annual amplitude (cm)**	**Series trend** (cm y^{-1})
Guinea	Dinguiraye	11.69	-10.62	30.89	-26.75	17.09	0.29
	Kankan	11.46	-9.39	32.52	-27.66	15.85	0.54
	Labé	11.28	-11.94	33.23	-25.55	22.74	0.23
Mali	Kayes	14.28	-11.31	20.84	-22.70	7.25	0.32
	Kita	13.53	-9.52	26.52	-20.52	9.70	0.51
	Koulikoro	15.11	-9.19	47.43	-12.07	6.41	-0.08
Senegal	Saint Louis	16.19	-16.13	15.62	-16.61	4.32	0.28
	Dagana	16.44	-15.40	14.33	-16.54	3.34	0.26
	Matam	15.75	-13.56	19.57	-16.46	5.61	0.68
Mauritania	Brakna	17.35	-12.38	12,17	-8.52	1.26	0.14
	Hodh El Gharbi	16.08	-10.38	12.94	-13.55	3.02	-0.32
	Tagant	17.27	-11.30	13.34	-7.41	0.77	0.07
Total basin				15.30	-12.47	6.87	0.30

Source: CNES / GRGS, 2020

Annual amplitude: 22.741 cm

The values of terrestrial water storage are estimated from GRACE RL03-v3.monthly terrestrial products in the form of anomalies (difference in the value of each month compared to the mean). Monthly terrestrial water storage values were calculated as deviations from the average value of period from January 2003 to December 2020. Missing data were interpolated as the average values of the points before and after the missing data period. The anomalies were expressed in centimetres of equivalent water thickness per year, where 1 cm of variation in water thickness represents a mass change equivalent to a water layer of 1 cm. Positive values meant that there was more water than in the past, while negative values meant less water than in the past.

3.1.2. Climatological data

The 2003-2020 monthly and annual climatological data for the Senegal River Basin used in this study are precipitation and potential evapotranspiration (PET) calculated from climatological data from the Kedougou station. Due to the lack of climatological data on the sites selected to characterize the TWSI, only the Kédougou station, which is also fairly representative of the basin, was used and the data are provided by the National Agency of the Civil Aviation and Meteorology (ANACIM). On the series used, the precipitation is measured, whereas the PET is calculated by the Penman-Monteith method. Monthly precipitation and potential evapotranspiration data are used to calculate the SPI and SPEI indices. The FAO–Penman–Monteith method (FAO-PM) was recommended as the standard PET method based on physiological and aerodynamic criteria [29] by Food and Agriculture Organization (FAO) and World Meteorological Organization (WMO). The FAO–PM method as given by FAO Irrigation and Drainage Paper No. 56 [29] as:

$$PET_{PM} = \frac{0.408\times\Delta\times(R_n-G)+\gamma\times\frac{900}{T_{mean}+273}\times u_2\times(e_s-e_a)}{\Delta+\gamma\times(1+0.34\times u_2)} ,$$

where PET_PM is the potential evapotranspiration (mm/d); Δ is the slope of the saturation vapour pressure function (kPa/°C); R_n is the net radiation ($MJ/m^2/day$) (MJ means megajoule), which was estimated from total incoming solar radiation measurements following the procedure of Allen et al. [29]; G is the soil heat flux density ($MJ/m^2/day$), which was considered as null for daily estimates; γ is the psychometric constant (kPa/°C); T_{mean} is the daily average temperature (°C), which is the average value of the sum of maximum and minimum temperature; u_2 is the wind speed at 2 m height (m/s); e_s is the vapor pressure of the air at saturation (kPa); and e_a is the actual vapor pressure (kPa).

3.1.3. Hydrological data

The hydrological data consist of monthly hydrometric surveys from the hydrometric stations of Kidira (in the Falémé sub-basin) and Bakel (at the outlet of the upper Senegal River basin). The data were made available to us by the Senegal River Development Organization (OMVS). The data are available from 2002 to 2020. The two stations obey criteria of continuity (absence of gaps), duration of the available information and quality of the data (stations well gauged and respecting the relationship between the water levels and past flows). Their choice is also explained by the fact that one (Kidira station) is in a sub-basin with natural flow (Falémé basin) and the other (Bakel station) with artificial and complex flow (cumulative contributions natural flow tributaries and developed tributaries).

3.2. Methods

3.2.1. Terrestrial water storage with GRACE (TWSA)

The GRACE Space Mission is a joint project of NASA (the US Aeronautics and Space Administration) and DLR (German Aerospace Center) to provide monthly solutions to spherical harmonic coefficients describing the Earth's gravity field and to monitor spatio-temporal variations. In the gravity field with unprecedented bi-satellite resolution and precision on spatial scales ranging from 400 to 40,000 km and time scales ranging from a few months to several years from March 2002 [26]. The main objective of the GRACE project is to quantify the terrestrial hydrological cycle by vertically integrated measures of water mass evolution from aquifers, soils, surficial reservoirs and snowpack, with an accuracy of a few millimetres in terms of high and low spatial (>500 km) and temporal (>10 days) resolutions [30]. There is currently no global observing network with the temporal and spatial resolutions needed to properly characterize the water balance at regional and continental scales; GRACE satellite data are therefore used to monitor groundwater storage anomalies, including soil moisture content, groundwater, snow and ice, biomass and unsaturated soils, and surface water in rivers, wetlands, natural lakes and artificial reservoirs. These measurements represent the total amount of water stored at the soil surface and in the subsoil in response to the frequency and severity of large-scale, extreme climate changes [10,31,32]. In addition, the GRACE-based water storage deficit (TWS) is defined as the difference between the time series values of the terrestrial water storage with GRACE (TWSA) and the monthly average of the TWS values [17], and given as follows:

$$TWS_{i,j} = TWSA_{i,j} - \overline{TWSA} \quad ,$$

where TWSAi,j is the GRACE-inferred TWSA time series for the jth month in year i, and $\overline{TWSA}$ is the long-term mean (from January 2003 to December 2020) of TWSA for the same month (the jth month in a year). Negative WSD represents deficits in land water storage compared to its monthly mean values, while a positive value signifies a surplus water storage. TWS lasting for three or more consecutive months are designated as drought events, according to Thomas et al. [17]. To better characterise droughts based on TWS, and to compare TWS with other drought indices, we normalised this parameter using the zero mean normalisation method into the TWSI as follows:

$$TWSI = \frac{TWS - \mu}{\sigma} \quad ,$$

where μ and σ are the mean and standard deviation of the TWS timeseries, respectively. The TWSI time series represents the average seasonal deviation from the average conditions, and its magnitude indicates the drought intensity.

3.2.2. Standardised drought indices

Drought phenomena are generally expressed and characterised using standardised indices. In this study, we used three types of drought indices, namely the SPI (Standardised Precipitation Index), SPEI (Standardised Precipitation and Evaporation Index) and SFI (Standardised Flow Rates Index), to characterize droughts, in the Senegal River Basin and compare them to the Terrestrial Water Storage indices (TWSI) obtained using GRACE data.

The SPI [33] is primarily a meteorological drought index based on long-term precipitation records adjusted to a probability distribution. This calculates SPI, the precipitation record is first adjusted to a gamma distribution, and then converted to a normal distribution using an equiprobability function.

Positive SPI values indicate that the wet conditions are more pronounced than the median precipitation levels, while negative values indicate that the dry conditions are more pronounced than the median precipitation levels [10]. The drawbacks of SPI come from the fact that only rainfall is taken into account, while the other meteorological factors are neglected. The main advantages of the SPI relate to its simple calculation and its multi-scale characteristics (for example, 1, 3, 6, 12 or 24 months) [34]. For example, time scales of 3 to 6 months are appropriate for drought analysis in agriculture, 1 to 2 month scales for weather drought analysis and 12 to 24 month scales for analysis hydrological drought. Numerous studies have shown that SPI can be used to characterise drought trends in the Senegal River Basin and serve as a reference for drought mitigation, local management of water resources and agricultural decision-making, taking into account its flexibility, its simplicity and its wide application in real observations [35].

SPEI [14]) represents an extension of SPI, which considers precipitation in combination with potential evapotranspiration. SPEI uses monthly precipitation and temperature levels for calculations [36]. Precipitation and temperatures calculated for potential evapotranspiration (PET) are obtained from data from the Kedougou station. It should be noted that the PET values are estimated using the Penman-Monteith method [37], which is more accurate than the Thornthwaite method [38], that is, commonly used in most research studies on SPEI. PET allows SPEI to perform better in monitoring drought, flow and soil moisture in the Senegal River Basin [39]. SPEI is often used to assess and monitor water resource management, climate change adaptation, sustainable agricultural development, and variability and trends in drought [10,35].

The SFI [40] uses past flows from the Kidira and Bakel hydrological stations. The IFS has a calculation procedure similar to that described for the SPI, that is, a distribution is fitted to the data and then transformed into a normal distribution. The IFS was developed to quantify the water deficit for multiple time scales that will reflect the impact of drought on the availability of different types of water resources for a given period of time [41]. Studying this index also makes it possible to distinguish dry months and years (deficits) from wet (surplus) months and years. A drought occurs when the SFI is consecutively negative and its value reaches an intensity of -1 or less and ends when the SFI becomes positive.

The three drought indices can be calculated on different time scales (1 month, 3 months, 6 months, 9 months, 12 months, 24 months). In this work, the 1-month time scale was used to show the storage deficit of earth water monitored by GRACE satellites [10].

4. RESULTS

4.1. Analysis of GRACE data on the various selected sites in the Senegal River Basin

Figure 2 shows the spatio-temporal configuration of the water depth trends (in cm) estimated from the GRACE data on sites located in the riparian states of the Senegal River Basin from 2003 to 2020.

These heights of water are a great variability in the basin, at the level of the different riparian states. In addition, there is a latitudinal gradient of land water storage in the basin that increases from north to south, in accordance with the rain which also increases from north to south of the basin.

In the Guinean part of the Senegal River Basin, the three selected sites all show the greatest variability of water levels throughout the basin. Thus the annual amplitudes are very high and of the order of 22.74 cm at Labé (for a maximum height of 33.23 cm and minimum of -25.55 cm), 17.09 cm at Dinguiraye (for a maximum height 30.89 cm and a minimum of -26.75 cm) and 15.85 cm at Kankan (for a maximum height 32.52 cm and a minimum of -27.66 cm). Next come the sites located in the Malian part of the Senegal River basin with annual amplitudes that are two to three times less than those noted on the Guinean sites. These annual amplitudes are of the order of 9.70 cm at Kita (for a maximum height of 26.52 cm and a minimum of -20.52 cm), 7.25 cm at Kayes (for a maximum height of 20.84 cm and minimum of -22.70 cm) and 6.41 cm at Koulikoro (for a maximum height of 47.43 cm and a minimum of -12.07 cm).

The fall in annual amplitudes is largely noted in the Senegalese and Mauritanian parts of the Senegal River basin, which records the lowest water level values in the whole basin. In the Senegalese part of the Senegal River basin, the annual amplitudes are only around 5.61 cm in Matam (for a maximum height of 19.57 cm and a minimum of -16.46 cm), 4.32 cm in Saint Louis (for a maximum height of 15.62 cm and a minimum of -16.61 cm) and 3.34 cm in Dagana (for a maximum height of 14.33 cm and a minimum of -16.54 cm). In the Mauritanian part of the Senegal River basin, the annual amplitudes are the lowest in the basin with only 3.02 cm at Hodh El Gharbi (for a maximum height of 12.94 cm and a minimum of -13.55 cm), 1.26 cm at Brakna (for a maximum height of 12.17 cm and a minimum of -8.52 cm) and 0.77 cm at Tagant (for a maximum height of 13.34 cm and a minimum of -7.41 cm).

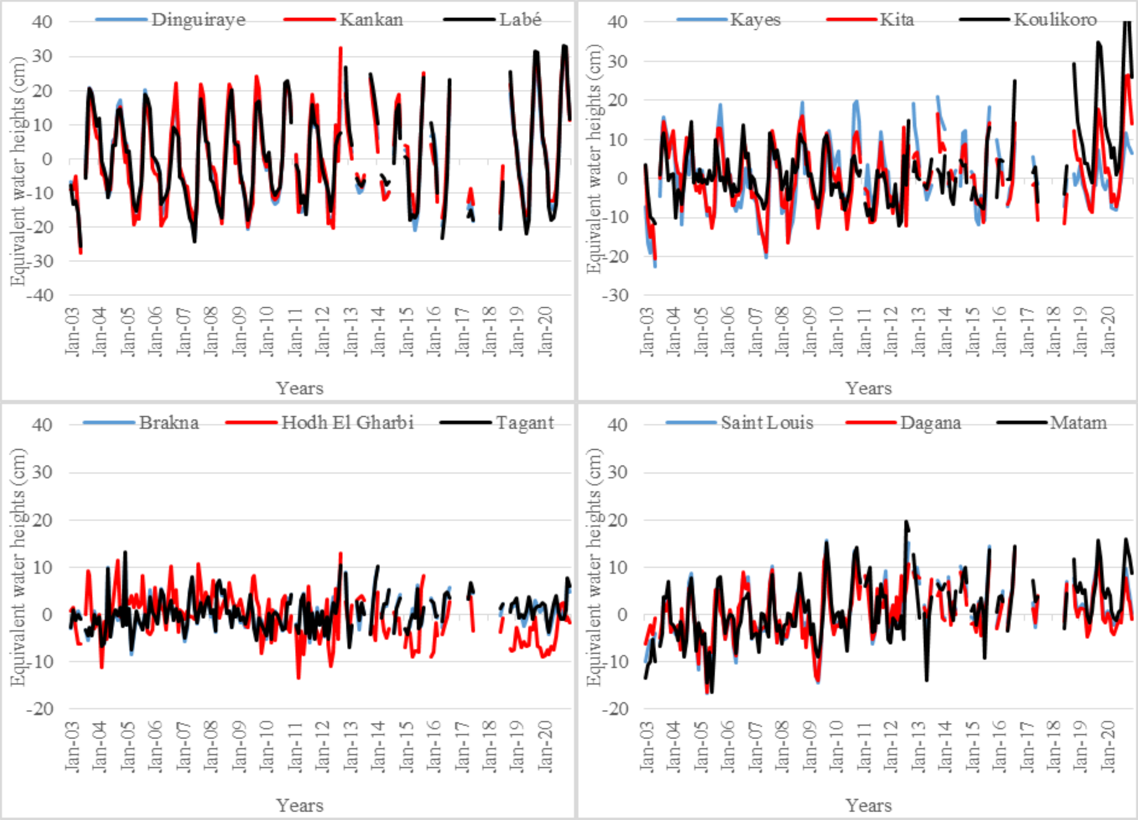


Figure 2. Monthly evolution of water depths (in cm) estimated from GRACE data on sites located in the riparian states of the Senegal River basin from 2003 to 2020.
Source: CNES / GRGS, 2020

In the Senegal River basin, a slight increase in stored water levels is noted in its various parts (upper, middle and lower basins and deltaic zone) and in the four riparian states (with the exception of Koulikoro in Mali with a trend of -0.08 cm/year and Hodh El Gharbi in Mauritania with a trend of -0.32). This upward trend is related to the improvement of rainfall and hydrological conditions in the basin since the 2000s in the West African zone [42–44], as indicated by the drought indices. The most obvious positive trends are found in different parts of the basin (0.68 cm/year in Matam, Senegal; 0.51 cm/year in Kita, Mali; 0.54 cm/year in Kankan, Guinea) as well as the weakest ones, although positive (0.28/year at Saint Louis and 0.26/year at Dagana in Senegal; 0.29 cm/year at Dinguiraye and 0.23 cm/year at Labé in Guinea; 0.32 cm/year at Kayes in Mali; 0.14 cm/year in Brakna and 0.07 cm/year in Tagant in Mauritania).

Figure 3, which also shows the annual evolution of the terrestrial water storage indices estimated from the GRACE data on sites located in the riparian states of the Senegal River Basin from 2003 to 2020, makes it possible to distinguish the different phases of the twelve selected sites and better highlight the obvious seasonal and interannual variations of terrestrial water storage in the basin.

On an annual scale, the analysis of land water storage indices from 2003 to 2020 allows two main phases to be distinguished on virtually all sites. The first phase runs from 2003 to 2012 with generally average annual water shortfall and therefore a negative index on the sites of the four states. Although the situation is more variable between 2003 and 2005 (down on some sites and up on others), on the other hand, from 2007 to 2009, the water level deficit is almost homogeneous at the different sites. In this phase, the deficit knows its largest magnitude over the period 2005-2012, despite the presence of years with positive indices such as 2003 (0.02 in Guinea), 2004 (0.2 in Guinea, 0.22 in Mali and 0.05 in Mauritania) and 2008 (0.1 in Mali and 0.47 in Mauritania). 2007 remains the year with most deficit (-0.28

in Guinea, -0.25 in Mali and -0.18 in Senegal). Over this year, the largest deficits are recorded at the Kayes (-0.53) and Kita (-0.34) stations in Mali and Labé (-0.39) in Guinea.

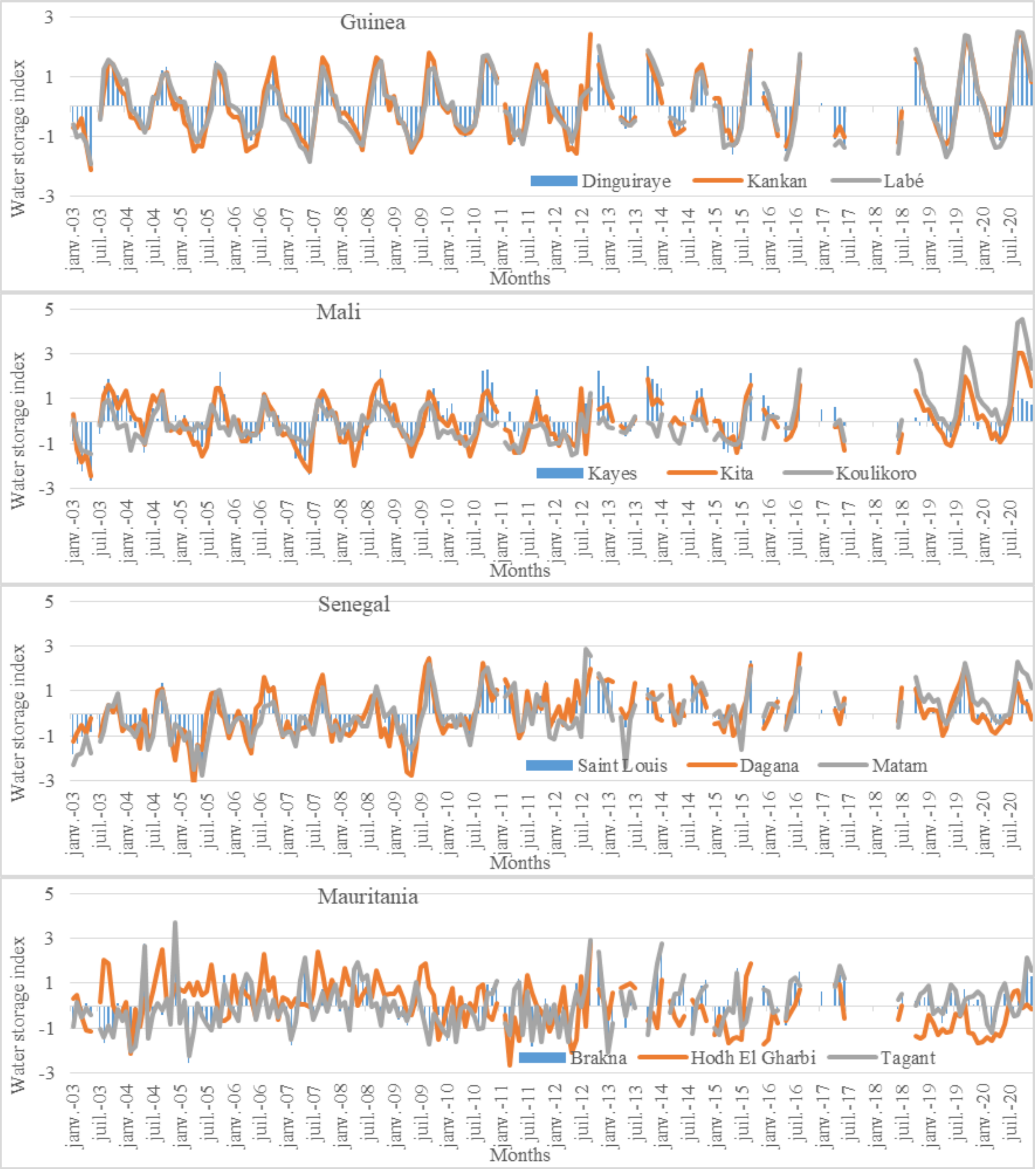


Figure 3. Annual evolution of terrestrial water storage indices estimated from GRACE data on sites located in the riparian states of the Senegal River basin from 2003 to 2020.
Source: CNES / GRGS, 2020

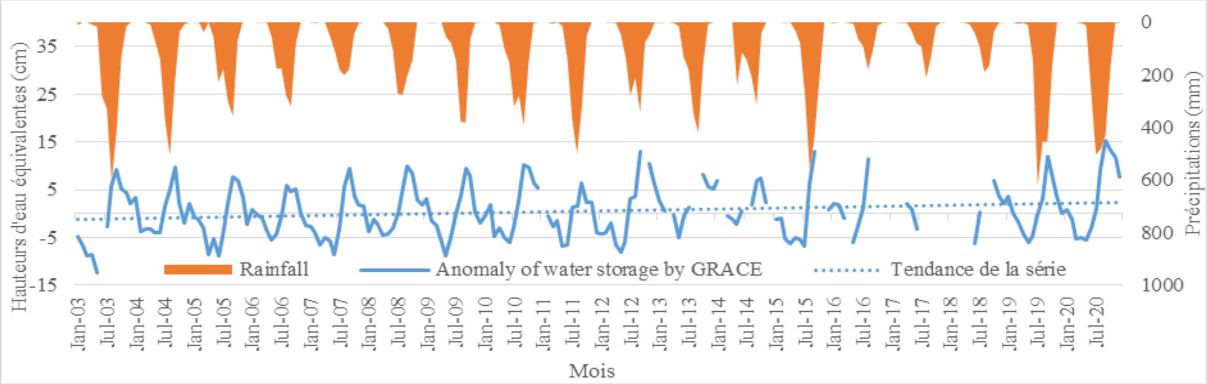
The second phase, which has a large surplus in land water storage, starts in 2012 and continues until 2020. Here, only a few years like 2015 (which recorded a negative index of -0.2 in Guinea, -0.16 in Mali and -0.36 in Mauritania), 2011 (-0.04 in Guinea, -0.35 in Mali and -0.44 in Mauritania) and 2012 (-0.15 in Mali) had deficits on average. Beyond this, all the years recorded an excess of water storage and that at the sites retained on the four residents of the basin. In this second phase, the year 2013 recorded the largest surpluses with 0.34 in Guinea, 0.38 in Mali and 0.5 in Senegal. Between 2012 and 2014, surpluses are the largest in the series. In 2012, indices can reach record highs in Senegal (0.75 in Dagana, 0.63 in Saint Louis and 0.54 in Matam). In Guinea and Mali, the highest positive indices are noted in 2013 with values that can exceed 0.3 (0.3 in Kankan and 0.45 in Labé in Guinea, 0.51 in Kita and 0.61 in Kayes in Mali). In the same year 2013, the indices are also very important in Senegal (0.65 in Saint Louis and 0.69 in Dagana) as well as in Senegal in 2014 (0.46 in Dagana, 0.58 in Saint Louis and 0.62 at Matam), Mauritania (0.54 at Tagant and 0.58 at Brakna) and Mali (0.38 at Kayes). This evolution reflects fairly well the rainfall anomalies during the period studied.

At the monthly scale, the analysis of the land water storage indices from 2003 to 2020 also makes it possible to distinguish two main seasons on practically all sites. The first season concerns the months of February to July marked by negative indices (although some positive) on the sites of the four states bordering the Senegal River basin. The month of April (-1 in Guinea, -0.82 in Mali and -0.55 in Senegal), May (-1.23 in Guinea, -1.08 in Mali and -0.7 in Senegal) and June (-1.04 in Guinea, -0.69 in Mali and -0.49 in Senegal) record the largest negative indices. The rest of the year (from August to January) concerns the second season during which the indices remain overall positive. The most important values are noted in August (0.42 in Guinea, 0.61 in Mali and 0.72 in Senegal), September (1.41 in Guinea, 1.27 in Mali, 0.38 in Mauritania and 0.34 in Senegal) and October (1.23 in Guinea, 0.86 in Mali and 0.58 in Senegal).

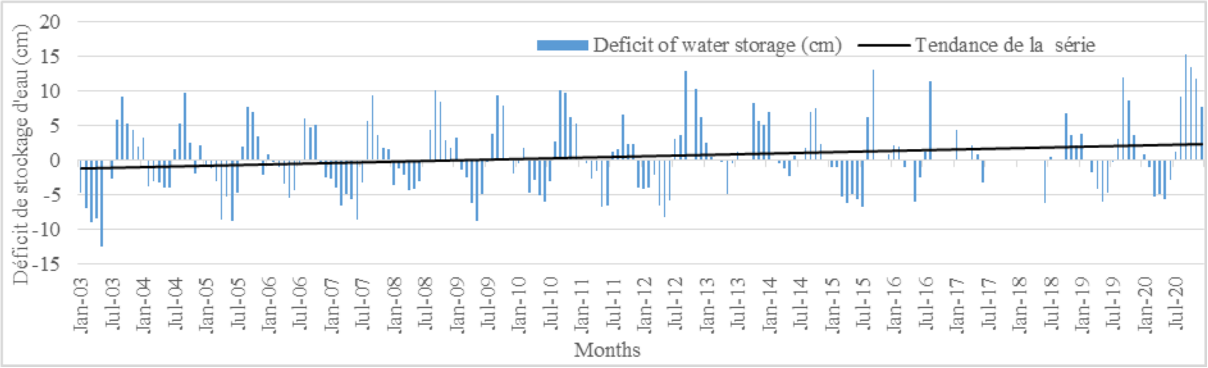
4.2. Analysis of the relationship between GRACE data and drought indices in the Senegal River Basin

To analyse the relationship between the GRACE data and the standardized drought indices in the Senegal River Basin, the average values of the GRACE data for the whole basin are used, from which the deficits and the storage indices are calculated of land water. The deficit of terrestrial water storage (TWS) is an important feature of the occurrence of drought. Figure 4a shows the temporal variations in average land water storage and associated precipitation from 2003 to 2020. In general, precipitation is well correlated with water storage anomalies from 2003 to 2020. The data were clearly revealed that the most significant precipitation occurred during the rainy seasons of 2012 and 2020, and that these periods corresponded to peaks in the TWS time series. At the annual scale, water storage increased at a rate of 3 mm/year between 2003 and 2020, while precipitation increased a little less strongly, at a rate of 0.25 mm/year. The same is true for flows that increased by 0.38 m^3/s/year in Kidira on the Falémé and 0.21 m^3/s/year in Bakel at the outlet of the “upper basin”. Thus the annual amplitude is of the order of 6.87 cm in the basin for a maximum height of 15.30 cm and a minimum height of -12.47 cm, significant deficits in water storage were recorded between 2003 and 2012 (Figure 3b). More specifically, deficits of -12.47 cm and -8.75 mm were detected in May 2003 and June 2005, respectively.

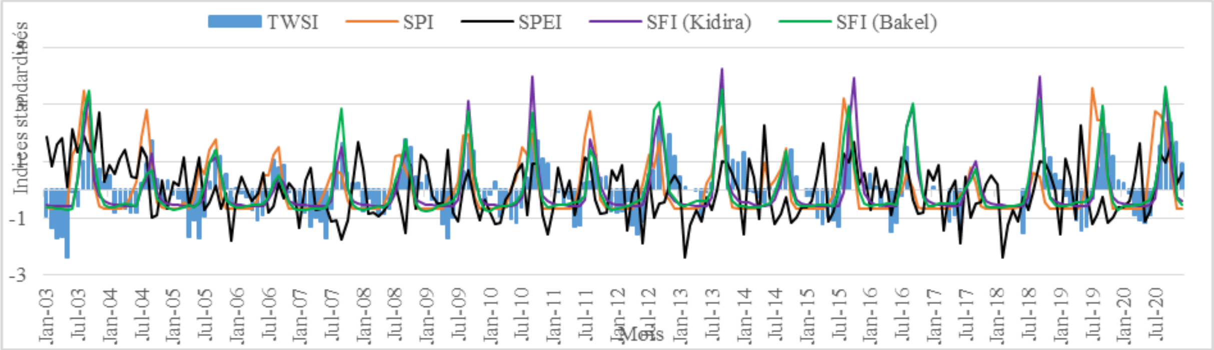
As of 2010, the annual water storage was mainly in surplus, with one obvious exception of water storage deficit detected in 2011 (with an average deficit of -0.72 cm and a total of 7 months all deficit) and 2020 (with an average deficit of -3.94 cm and a total of 5 months, ranging from February to June, all in deficit). On the other hand, the years 2010, 2012, 2013 and 2014, 2018 recorded excess water storage, with an average surplus of the order of 1.14 cm, 0.48 cm, 1.14 cm and 2.46 cm respectively. According to the definition of a drought episode [17], seven droughts were confirmed on the basis of land-water storage during the period 2003-2020 in the Senegal River Basin (Table 2). The number of deficit months in the driest years is between 6 and 8 months. The 2005 and 2006 periods were the two most important drought periods in the basin, with respective durations of 8 months. The peak deficits recorded in May 2003, June 2005 and May 2009 (referred to as the most severe drought events) were -124.7 mm, -87.2 mm and -86.9 mm, respectively. Beyond these years, others like 2007, 2012 and 2020 had a respective average deficit of -50.9 mm, 51.2 mm and 55.6 mm.



(a)



(b)



(c)

Figure 4. Time series from 2003 to 2020: (**a**) Evolution of precipitation and anomaly of GRACE-inferred terrestrial water storage (TWSA); (**b**) Evolution of the water storage deficit (TWS), and (**c**) Evolution of standardized indices (TWSI, SPI, SFI).
Source: CNES / GRGS and OMVS, 2020

Table 2. Summary of drought episodes identified by GRACE in the Senegal River basin from 2003 to 2020.

Years	Duration (number of months)	Average deficit (mm)	Peak deficit		Total gravity (mm)
			Values (mm)	Dates	
2003	6	-73.4	-124.7	May	-440
2004	6	-33.2	-40.0	June	-199
2005	8	-43.0	-87.2	June	-344
2006	8	-21.7	-54.2	May	-174
2007	7	-50.9	-86.7	June	-356
2008	6	-31.3	-44.0	A vril	-188
2009	7	-36.9	-86.9	May	-258
2010	6	-36.9	-59.4	June	-221
2011	6	-36.3	-67.0	May	-218
2012	6	-51.2	-81.5	May	-307
2013	3	-18.7	-49.4	May	-56.2
2014	3	-17.8	-23.0	May	-40.1
2015	7	-43.9	-66.9	June	-307
2016	-	-	-59.7	May	-
2017	-	-	-	-	-
2018	-	-	-62.5	June	-
2019	5	-33.4	-60.6	May	-130
2020	5	-39.4	-55.6	May	-178

Source: CNES / GRGS, 2020

Figure 4c shows the comparison between the Terrestrial Water Storage Index (TWSI) and the three most commonly used drought indices, namely SPI, SPEI and SFI in the Senegal River basin from 2003 to

2020. An analysis of the relationship between the GRACE dataset, the SPI, the SPEI and the SFI showed good agreement on certain years and seasons. However, because these indices are formulated using different variables and methodologies, some behavioural differences have also been observed. Thus, for certain months, seasons and years, the storage values do not really reflect the evolution observed on climate indices. For example, the TWSI index was lower than other indices in some years such as 2003, 2007, 2012 and 2015 and generally higher than the three indices of other years. As for the SPI, SPEI and SFI indices, they are marked by great variability and have a nearly identical evolution over the period of study in the basin. They record some negative values over the periods 2005-2012 and 2013-2020 (which reflects drought conditions), sometimes positive over the years 2003, 2004, 2010, 2011, 2015, 2019, 2020 (which reflects humidity conditions). The year 2013 remains exceptionally the only one of the series of which the SPI is positive (0.05) and the SPEI is negative (-0.54).

Table 3. Correlation matrix of drought indices in the Senegal River basin from 2003 to 2020.

	TWSI	**SPI**	**SPEI**	**SFI (Kidira)**	**SFI (Bakel)**
TWSI	1.00				
SPI	0,40	1.00			
SPEI	0,02	0,17	1.00		
SFI (Kidira)	0,69	0,66	0,12	1.00	
SFI (Bakel)	0,66	0,73	0,10	0,95	1.00

Source: CNES / GRGS and OMVS, 2020

Although the water storage deficit can be used to quantify the extent of a water deficit, it does not reveal the differences in the intensity of a water deficit. In general, the behaviour observed for the water storage index and its response to climate anomalies were reasonably consistent with the other indices examined in this study. Table 3 shows the estimates of correlations between the four drought indices. The correlation coefficients show a significant correlation between the TWSI and other drought indices, including SPI and SFI (at a 95% confidence interval), as well as a similar associated internnual trends. The most important TWSI correlation coefficients are with SFI at Kidira station at 0.69 and SFI at Bakel station at 0.66. SFI is therefore better correlated with TWSI than with other indices, suggesting that droughts are more dependent on runoff production and soil moisture characteristics. Between the SPI and the SFI, the correlation is also relatively important and of the order of 0.73 at Bakel and 0.66 at Kidira. The SPI and the SPEI showed the lowest correlation coefficients, but positive with 0.17. Evapotranspiration is the only difference between SPEI and SPI, and the stronger correlation between TWSI and SPI (0.40) than between TWSI and SPEI (0.02) suggests that precipitation is more responsible for soil release than the difference between rainfall and evapotranspiration in the Senegal River Basin between 2003 and 2020. Overall, strong correlations were determined between the three standardised drought indices, which were also reliably correlated with the TWSI.

4.3. Spatial distribution of GRACE data in the Senegal River Basin

4.3.1. Inter-annual distribution of GRACE data

To better understand the interannual spatial variations of GRACE-based terrestrial water storage in the Senegal River Basin, we have spatialised the average values of water storage over a three-year period (Figure 5).

As shown in Figure 5, changes in groundwater levels based on GRACE indicate rapid depletion of groundwater over the period 2003-2005 (7 out of 12 sites have negative values), 2006-2008 (8 sites out of 12 record negative values) and 2009-2011 (6 sites out of 12 record negative values). This decrease in values is consistent with the decrease in precipitation over the same year. On the other hand, the period 2012-2014, considering the increase of the rain, generally registered positive values, with the exception of Koulikore (-0,87 cm) and Hodh El Gharbi (-1,64). In addition to go further into the analysis, we can split the series into two parts, From 2003 to 2009, water storage anomalies are negative (only Koulikore with 1.08 cm and Hodh El Gharbi with -0.09 cm recorded positive values), which is quite consistent with the relatively low rainfall over this period. After that, the groundwater level showed a substantial increase from 2013 to 2020 with the increase in annual rainfall totals (only Koulikore with -1.46 cm and Hodh El Gharbi with -1.77 cm recorded negative values).

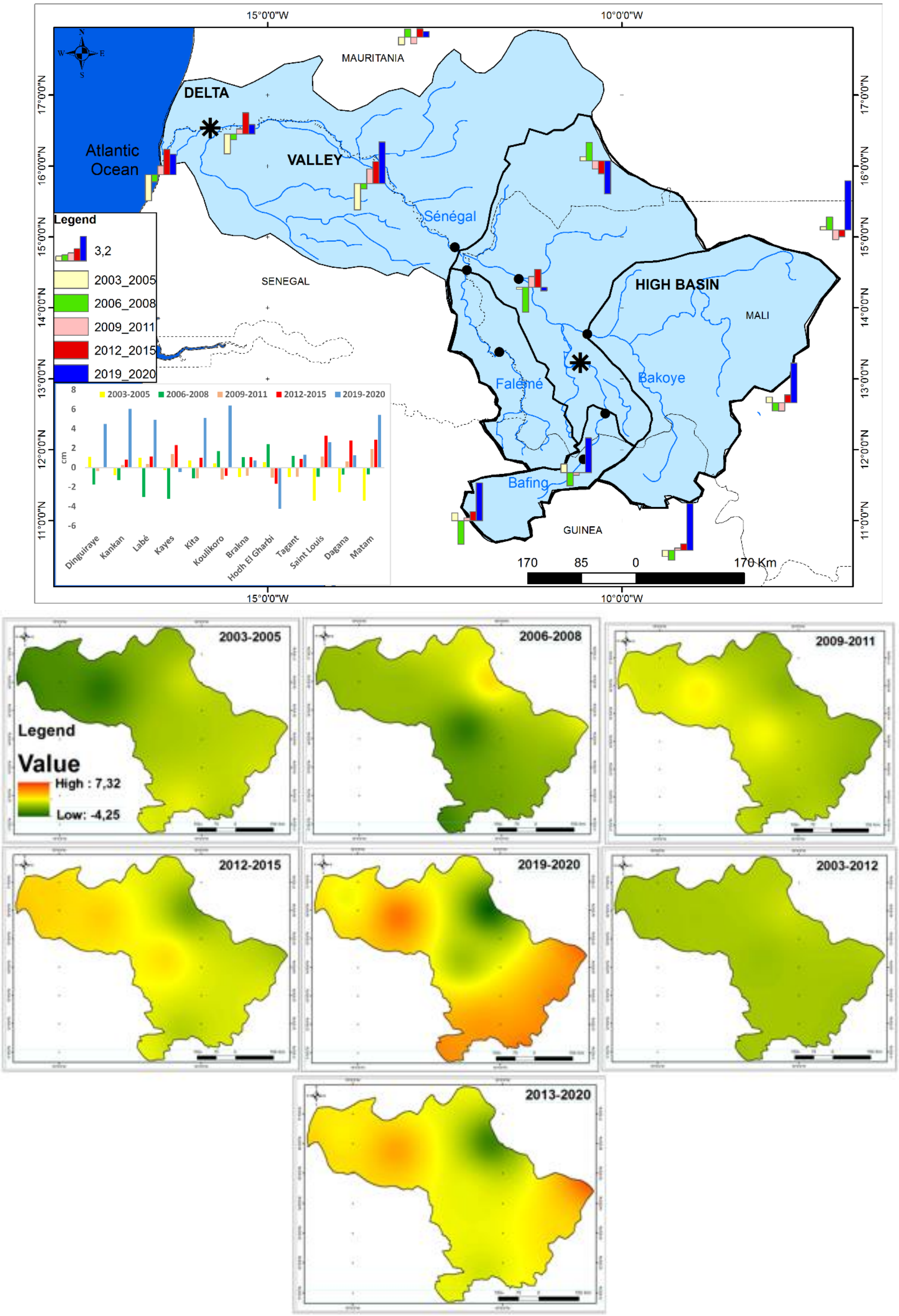


Figure 5. Interannual spatial variations in water depth (in cm) estimated from GRACE data for the entire Senegal River Basin by periods from 2003 to 2020.
Source: CNES / GRGS and OMVS, 2020

There is therefore a fairly good agreement between the inter-annual variations of water storage based on GRACE and those of rain in the basin. In general, when the annual precipitation anomaly is negative, the annual depletion of groundwater is also negative; and vice versa. However, in the basin, observed year-to-year variations in groundwater levels are not always consistent with rainfall data (such as the case of 2003 and 2004 where water level anomalies are negative for water storage) and positive for precipitation). This concordance of anomalies is more noticeable between 2005 and 2012 (with negative values on both parameters) and between 2010 and 2011 (with positive values on both parameters).

4.3.2. Seasonal and monthly distribution of GRACE data

Figure 6 shows the monthly distribution of spatial variations of GRACE-based terrestrial water storage in the Senegal River Basin.

At the different sites, the months that record negative storage anomalies are generally the months of February to July (coinciding with the dry season) and those whose anomalies are positive are the months of August to January (coinciding with the seasonal rains).

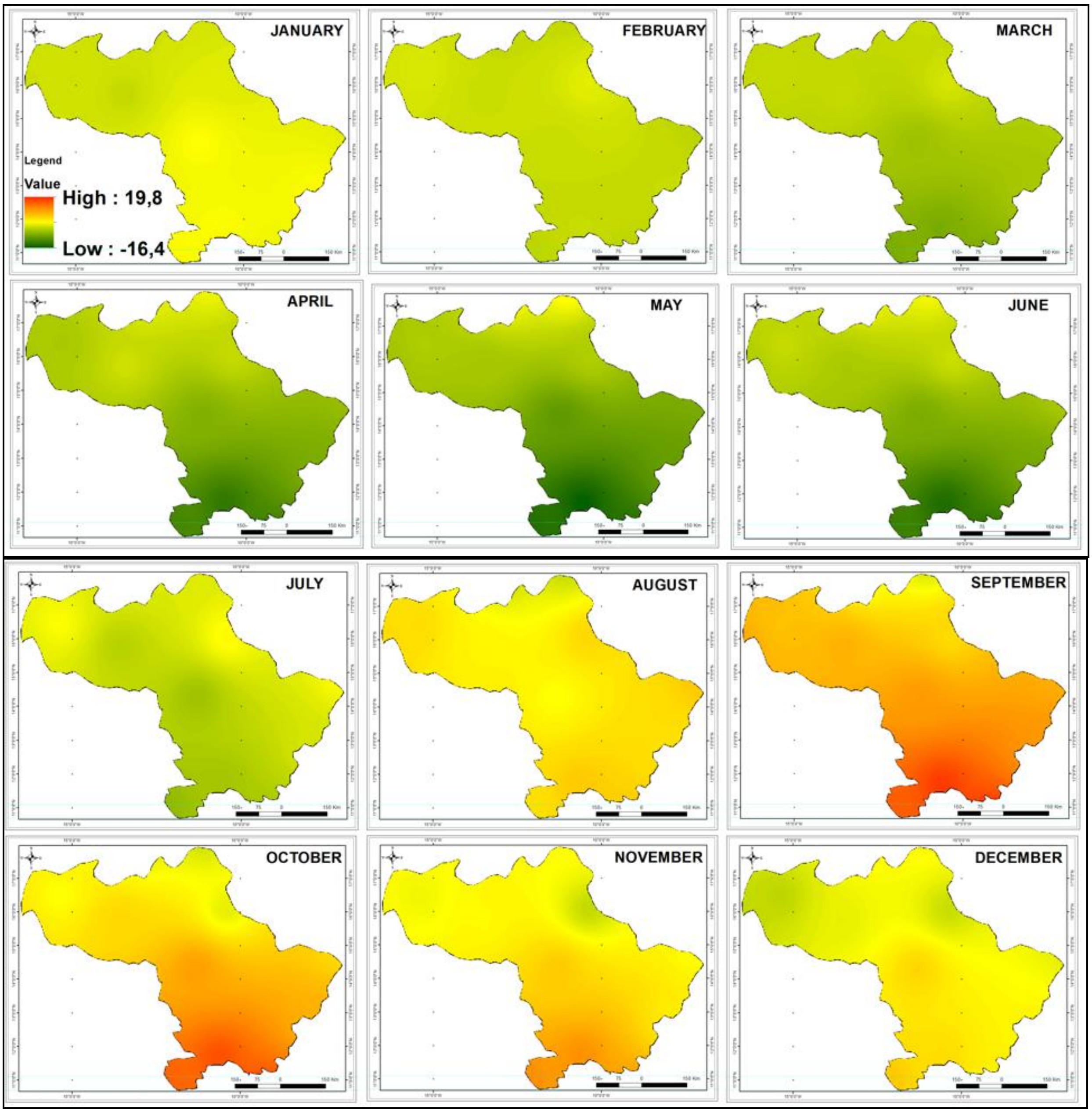


Figure 6. Monthly spatial variations of water depths (in cm) estimated from GRACE data for the entire Senegal River Basin by periods from 2003 to 2020.
Source: CNES / GRGS and OMVS, 2020

Nevertheless, some sites record unusual anomalies in the dry phase as was the case of the sites of Brakna in the months of April (1.00 cm), May (2.20 cm) and June (1,14 cm), of Hodh El Gharbi in the months of February (0.04 cm) and July (2.15 cm), of Saint Louis (0.13) and Dagana (1.59) in the month of July. Similarly, sites record negative anomalies on the wet phase as was the case of Brakna sites in August (-1.86 cm), September (-0.31 cm), October (-0, 60 cm) and January (-1.43 cm), of Hodh El Gharbi in the months of November (-2.10 cm), December (-1.77 cm) and January (-0.24 cm), of Tagant in the months of August (-1.73 cm), September (-0.49 cm) and October (-1.02 cm), Koulikore for the months of December (0.35 cm) and January (-0.25 cm).

The most significant negative monthly anomalies are noted at the sites in Guinea and Mali (which are the most watered parts of the basin), while the weakest are noted in the Senegalese and Mauritanian parts of the basin (the less devoid of rain). On seasonal time scales, GRACE-based groundwater storage troughs occur during the dry season, from January to July. However, precipitation peaks in August (358.3 mm), slightly out of phase with changes in groundwater. Groundwater storage is at its peak, one month after rainfall, in September (18.37 cm at Dinguiraye, 19.83 cm at Kankan, 15.75 cm at Labé, 10.49 cm at Kayes, 10, 74 cm in Kita, 8.90 cm in Saint Louis). The storage, although surplus from August to December, decreases rapidly from October to May and recovers continuously from June, with the beginning of rain (142 mm) to the maximum. Recovery of water storage usually begins in August, when precipitation peaks, resulting in a delayed response of groundwater to precipitation [45].

5. DISCUSSION

The remote sensing approach for detecting, assessing and quantifying groundwater variability presented here provides a framework for identifying regional groundwater storage anomalies. The lack of in situ water observations hampers understanding of the cascading changes in storage caused by moisture changes that traverse the hydrological cycle and affect groundwater resources. On the other hand, remote sensing techniques are very promising for understanding hydrological changes [46] and allow for an assessment of groundwater variation, as shown by the results presented here. Our results document a correlation between GRACE-based storage anomalies and in situ drought indices, suggesting that our approach can effectively characterise groundwater drought.

Globally, inconsistent estimates and different estimates of use and availability are hindering previous global estimates of groundwater stress [47,48] assessment of the sustainability of groundwater. Although groundwater is the main source of water for agriculture [49], the importance of groundwater is increasing rapidly as storage serves as a source of water supply, and surface water becomes less reliable and unpredictable [50].

The results of this study, based on the evolution of the average water depths estimated from the GRACE data, highlight the obvious seasonal and interannual variations of the storage of terrestrial water in the Senegal River basin and show two phases: the first phase, from 2003 to 2009, marked by a decline in groundwater storage, the second phase, from 2013 to 2020, largely surplus in land water storage. Thus, the GRACE-based water storage trend shows a slight improvement in groundwater in the Senegal River Basin, which contradicts the work of Döll [47], Reager et al. [1] and Zhang et al. [10] who reported changes in terrestrial water storage marked by a decline. Our results also incorporate changes in groundwater resources as a function of human pressures and changes in groundwater storage related to climate and natural variability, as captured by GRACE, thus responding to challenges in assessing development objectives to achieve sustainability proposed by the United Nations [52].

In general, the GRACE data set could contribute to the characterisation of regional droughts by measuring water storage deficits and the size of drought-stricken areas; the duration and magnitude of these deficits may be new measures to quantify and monitor the severity of drought [17]. On the basis of this theory, the results of the comparison between the GRACE system and the SPI, SPEI and SFI indices in the Senegal River Basin also provided methods for monitoring the evolution of drought in Senegal. GRACE data can now be used as an appropriate indicator for analysing changes in groundwater levels and for monitoring drought patterns in most watersheds in Senegal. Our results capture integrated assessments of aquifer dynamics, providing a framework for future assessments of aquifer sustainability. All differences in behaviour between indices are noted and are related to the fact that these different drought indices are formulated using different algorithms and principles. The differences and inconsistencies observed in the results could also be attributed to the fundamental differences in the type of data used to calculate the various indices, as well as the different time scales used.

Although GRACE demonstrates the great potential for monitoring groundwater storage variations in many parts of the world, especially in large-scale regions and regions with rare hydro-meteorological sites, where it is impossible to support the traditional methods, based on rich site observations [10], the uncertainties associated with GRACE results are still very high and need to be carefully assessed [45]. First, given the polar orbit design of GRACE satellites and GRACE payload observational errors, there are systematic errors and random noise in GRACE resolutions. In itself, GRACE cannot dissociate the contributions of various hydrological repositories from monthly water storage estimates [53]. In addition, the average monthly water storage is not accurate enough for the short time series, which prompted Thomas et al. [17] to indicate that it is preferable to use time series of at least 30 years, making it difficult to estimate and evaluate droughts using water storage indices. In the space domain, the systematic error is represented by so-called "north-south bands". The greatest uncertainty concerns the storage of soil moisture. The errors mainly result from the SMS error, the GRACE measurement error, the processing error and the leak error. The GRACE observation error and the uncertainty of GRACE data processing related to different smoothing methods must be taken into account. In order to reduce these scratches, researchers have developed methods of detachment [54,55].

GRACE-based inland water storage anomalies are effective indicators of extreme hydrologic events. Compared to traditional methods of drought monitoring, GRACE data provide a new approach to characterise droughts. By providing a single source of information in ungauged basins for which there is no reliable observation of rainfall and flow, GRACE data provide spatially distributed information on drought-related parameters quickly and easily [10]. In addition, the GRACE satellite detects vertically integrated changes in water storage between the Earth's surface and the deepest aquifers, and can monitor groundwater and groundwater loss [56]. However, for light / moderate droughts, such as meteorological droughts caused by a lack of precipitation, GRACE satellites are generally less useful because the storage of surface water remains in normal conditions [57]. Zhangli et al. [58] therefore recommend that GRACE data be used to characterize large-scale droughts, prolonged and severe droughts. It is encouraging that the next generation GRACE monitoring mission, scheduled for launch in 2018, is underway and should increase the spatial resolution to 50,000 km^2 and the temporal resolution to the week or two weeks [59].

Higher resolutions are at the root of wider applications in terrestrial hydrological monitoring. In addition, the combination of GRACE data with associated hydrological models, using methods such as GRACE data assimilation [60], would be an ideal solution to improve hydrological assessment and lead to significant improvements in our understanding of droughts and their development [10].

6. CONCLUSIONS

GRACE satellites have provided considerable information for the field of hydrology, revealing information on large-scale depletion of groundwater. GRACE Satellite Gravimetry provides an important approach for estimating changes in land water storage in the Senegal River Basin. In this study, the regional depletion of groundwater between 2003 and 2012 and its enhancement between 2013 and 2020 was estimated from GRACE-derived groundwater storage data from 2003 to 2020. The estimate was compared to drought indices. On seasonal time scales, variations in groundwater respond to the combined effect of groundwater discharge in the dry season and recharge during the rainy season. On interannual time scales, changes in groundwater correspond to changes in precipitation. Based on GRACE-derived groundwater storage estimates, groundwater recharge is now noted as rainfall increases in the basin. Thus, the annual groundwater amplitude in the Senegal River basin is 6.87 cm with an increasing trend of around 0.3 mm/year from 2003 to 2020, which equates to a volume of 0,09 km^3/year on the total surface of the basin. This increase is related to the improvement of rainfall conditions in the area since the 2000s as indicated by the drought indices. Given GRACE's deepening of groundwater in the Senegal River Basin, more effective measures should be taken to quantify them, and new water-related activities, in addition to those already present, should be more widely introduced and developed respectively.

Overall, as the methodology described in this work reliably captured major drought events occurring over a large spatial area; thus, it can be an ideal substitute for large-scale regions and regions with rare hydro-meteorological sites, where traditional methods based on rich site observations are impossible to apply. In the future, research should focus on improving the methodology of terrestrial water storage indices and identifying drought severity levels to increase the accuracy and scope of this approach.

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