GRACE-Based Long-Term Terrestrial Water Storage Decline in the Susurluk Basin, Türkiye

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Keywords: Grace, Trend, Drought, Terrestrial Water Storage (TWS)

Abstracts

Climate change is reshaping the global water cycle, causing substantial alterations in precipitation, evaporation, and runoff patterns. These shifts are driving rapid changes in terrestrial water storage (TWS), which includes groundwater, soil moisture, surface water, snow, and ice. Declining TWS threatens freshwater security, increases the vulnerability of ecosystems and communities, and directly impacts sustainable water management—key concerns addressed under SDG 6. In parallel, intensifying climate-driven water losses align with the global challenges highlighted in SDG 13, particularly regarding adaptation and resilience. This study examines long-term TWS variations in the Susurluk Basin of Türkiye's Marmara Region using NASA's GRACE and GRACE-FO satellite missions. By measuring gravity anomalies caused by mass changes, GRACE enables the detection of large-scale water storage shifts. Monthly data from 41 GRACE grid points (2002–2022) were processed using the Mann-Kendall trend test at a 5% significance level. Consistent acceptance of the H1 hypothesis and universally negative Z values confirm a statistically significant and persistent decline in TWS across the basin. Results show that water storage loss accelerated dramatically between 2012 and 2022 compared to 2002–2011. The basin exhibits an overall decreasing coefficient of –0.0561, while sub-basin analyses indicate 20-year average losses ranging from –1.3 cm to –0.1 cm. These findings demonstrate a clear, worsening depletion of water resources, emphasizing the urgent need for climate-adaptive water management. The documented TWS decline underscores the relevance of this work to SDG 6 by highlighting risks to water availability and to SDG 13 through evidence of climate-induced hydrological change.

1. Introduction

Climate change is driving profound changes to the Earth system, including significant disruptions to the global water cycle. As worldwide patterns of precipitation, evaporation, and runoff fluxes shift, terrestrial water storage (TWS)—which encompasses all water stored as ice, snow, surface water, canopy water, soil moisture, and groundwater—continues to change rapidly in response. These changes have critical implications for freshwater sustainability, directly affecting SDG 6 (Clean Water and Sanitation), which emphasizes the need for reliable water resources, efficient water management, and long-term protection of water-related ecosystems (URL 1).

Declining TWS challenges water availability and undermines sustainable resource management for communities, agriculture, and ecosystems. Such reductions can jeopardize livelihoods and food security, intensifying social vulnerability and creating conditions that may contribute to climate-driven migration and cross-border tensions (Chandanpurkar et al., 2025). These risks highlight the urgency of SDG 13 (Climate Action), which calls for adaptive strategies, improved resilience, and strengthened scientific monitoring in response to climate-induced environmental pressures.

TWS is widely recognized as a key indicator of freshwater availability and long-term hydrological stability. Understanding its trends is therefore essential for assessing climate impacts, water scarcity risks, and future resource planning. Planning these resources is possible through watershed management. Watershed management is a sustainable, integrated planning effort aimed at the use and protection of resources within the defined natural environment, and at preventing risks, pollution, and problems. Therefore, it is appropriate to examine TWS values within the watershed boundaries, which are the areas where natural environment conditions are defined. More comprehensive analyses are carried out by determining the boundaries of sub-basins. This study aims to investigate and document the long-term decline in TWS within the Susurluk Basin of the Marmara Region. Using NASA GRACE and GRACE-FO satellite observations, we demonstrate that the basin has undergone an unprecedented and accelerating loss of water storage since 2002. Notably, the decline observed between 2012 and 2022 is substantially greater than that of the previous decade, indicating that the magnitude of water loss continues to intensify with each successive decade.

2. Literature Review

Initial studies focused on determining the usability of the GRACE satellite in terrestrial water storage. A global study conducted in 2004, using TOPEX/Poseidon Radar Altimeter data and Grace data from August 2002 to December 2003 and applying a Gaussian filter, indicated that it could be used to model TWS results in large river basins (Chambers et al., 2004). John W. Crowley and his colleagues calculated the water level in the Congo basin using TOPEX/Poseidon Radar Altimeter and GRACE data from April 2002 to May 2006, with gaps of 4.3 cm. The study showed that the accuracy of GRACE measurements is one cm or less of water. This study is the first in the literature to prove that GRACE can be used alone (Crowley et al., 2006).

The subsequent studies focused on comparing terrestrial water storage data obtained from Grace with terrestrial measurements. Data from 5 observation wells were compared with Grace data using the R programming language with ncdf419, nortest, e1071, ralnet package, Python scikit-learn package and Ncview18 software. A high correlation was found between them (Swenson et al., 2006).

Further studies aimed to reassess global water storage trends using the GRACE time series. The study concluded that Alaska experienced glacial mass loss, the Caspian Sea lost water, North India, California, and the High Plains Aquifer experienced groundwater depletion, Argentina, Chile, and the Eastern Amazon suffered from drought in the last decade, and India

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLIX-B4-2026-613-2026

depleted its groundwater resources very rapidly (Ramillien et al., 2008). Another study in India between February 2003 and December 2005 showed agreement between GRACE and GLDAS data and terrestrial data. Water mass change was detected (Mukherjee and Ramachandran, 2018).

A study conducted across 33 different basins claimed and confirmed that at least some of the interannual variability in global average sea level can be attributed to fluctuations in black water storage. An increase in black water storage of +80.6 ± 15.7 km3/year led to a negative sea level trend of ~0.22 ± 0.05 mm/year (Llovel et al., 2010).

Another study conducted in 2012 investigated the accuracy of TWS values. It was found that errors caused by signal attenuation resulted in noise, and that smoothing with a Gaussian filter reduced this noise. It was suggested that applying the filters to the model rather than the raw data increased accuracy (Landerer and Swenson, 2012).

Jiang et al. (2014) states that over the course of a decade of development, GRACE data has been widely applied in terrestrial hydrology monitoring, and the Gravity satellite provides new datasets for hydrology research based on remote sensing technology.

In previous studies, global groundwater storage change and sea level change were inferred for 33 major basins worldwide using GRACE data with a spatial resolution of 1.0° x 1.0°. For this inference, the sum of the differences in continental, oceanic, and atmospheric variations was considered zero, meaning atmospheric variation was ignored; continental variation was interpreted as negative variation in oceanic variation. As a result of the study, it was determined that a portion of the interannual variability in global average sea level can be attributed to groundwater storage fluctuations, with a correlation of 0.6. An increase in groundwater storage of +80.6 ± 15.7 km3/year led to a negative sea level trend of ~0.22 ± 0.05 mm/year (Vishwakarma et al., 2021).

Another study noted that while much of the world's arid regions continue to dry out and wet regions continue to get wetter, dry areas are drying out faster than wet areas. Simultaneously, they stated that as drought-stricken areas increase, wet areas decrease, continental drought is becoming more widespread, extreme droughts are increasing, freshwater resources are diminishing, and sea levels are rising. They added that these effects should be a major cause for concern for the public, resource managers, and decision-makers worldwide (Chandanpurkar et al., 2025).

All these studies have proven the usability of GRACE data for wastewater storage changes. It has also shown that it is possible to make predictions about the future.

This study analyzed the spatial-temporal variation in TSW in the Susurluk Basin, an area of Türkiye suffering rapid population growth, using both classical Mann-Kendall and innovative Sen trend analyses to determine whether a trend exists.

3. Methodology

GRACE's (Gravity Recovery and Climate Experiment) primary mission is to monitor Earth's gravitational anomalies in the k (26 GHz) - ka (32 GHz) band to measure distance changes between two satellites with an accuracy of 10 µm. The satellite is equipped with a dual-frequency GNSS sensor, accelerometer, laser retroreflector, and camera. With a temporal resolution of 30 days and a spatial resolution of 110 km, the satellite has been flying in tandem since March 17, 2002.

GRACE stands for Gravity Recovery and Climate Experiment and is part of the international Earth Observing System (EOS) satellite series (URL 2). Grace's working principle examines the change in the total amount of water. It calculates the change in gravitational acceleration. The change in gravitational acceleration is due to the change in mass. During mass change, continents are assumed to be fixed. People, buildings, etc., do not affect gravity. The change here represents the change in water volume (Figure 1). The delta is used to measure the change. It is considered the difference between two dates. It is more accurate to look at the trend, the delta, rather than the amount of water. By observing changes in the Earth's gravitational field, they can estimate the changes in the amount of water stored in a region, which in turn cause changes in gravity.

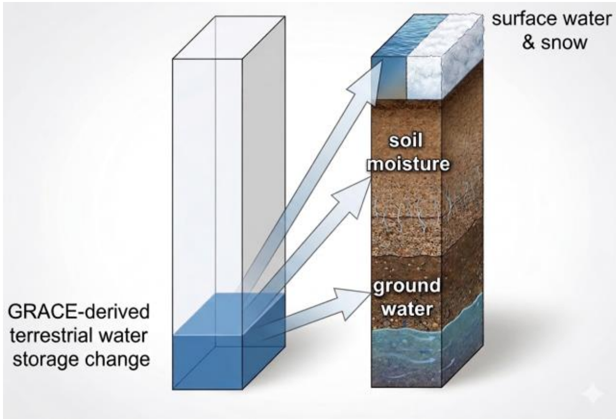

Figure 1. Grace and Grace-Fo TWS Data

The dataset covers image acquisition of descending tracks between January 2019 and October 2022. There are 41 grace points within the study area boundaries (Figure 2). All 20-year data from these points were subjected to the Mann-Kendall trend test. The H1 hypothesis is accepted at the 5% significance level. Acceptance of H1 hypothesis means that there is a trend. All z values were found to be negative. It can be said that there is one data point for each month in the study area. Table 1 shows the Mann Kendall test results by selecting 10 of the 41 points within the study area. The nonparametric Mann-Kendall trend test is very useful because it does not require the data to conform to a specific distribution and allows for the presence of missing data (Hamed and Rao, 1998).

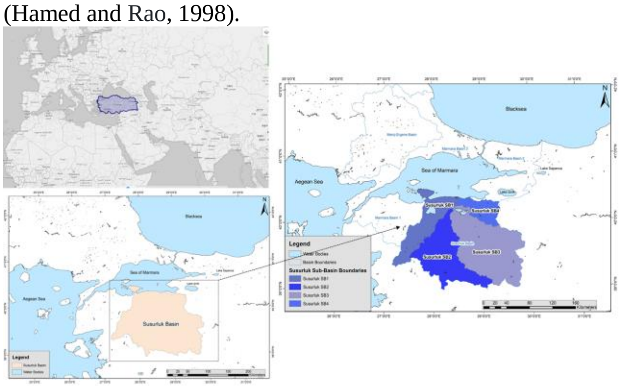

Figure 2. Location of the study area, Susurluk Basin, Türkiye

# Point	z	P value	s	varS	tau
28	-4.804	0.000002	-5102	1127460	-0.21972
37	-4.804	0.000002	-5102	1127460	-0.21972
38	-4.501	0.000007	-4780	1127460	-0.20586
46	-4.804	0.000002	-5102	1127460	-0.21972
47	-5.288	0.000002	-5616	1127460	-0.24186
55	-5.288	0.000002	-5616	1127460	-0.24186
64	-5.288	0.000002	-5616	1127460	-0.24186
73	-5.288	0.000002	-5616	1127460	-0.24186
267	-4.804	0.000002	-5102	1127460	-0.21972
268	-4.804	0.000002	-5102	1127460	-0.21972

Table 1. Mann Kendall test results by selecting 10 of the 41 points within the study area (n=21).

The sub-basin boundaries were generated using the Global Digital Elevation Model (GDEM) Version 3, which is produced from ASTER data (URL 3). Figure 2 shows the production boundaries of sub-basin number 1 from Aster Gdem data. GDEM data is obtained by evaluating stereo-dual satellite images from the ASTER sensor on the Terra satellite. GDEM V3 has a vertical accuracy of 7-14 m and a spatial resolution of 30 m. Version 3 of GDEM was released on August 6, 2019. The data, obtained in geotiff format, is used for analyses in disaster monitoring, hydrology, energy, environmental monitoring, etc. Using the established sub-basin boundaries and basin boundaries as the study area, raster maps were produced using TWS data obtained from the Grace satellite. Inverse Distance Weighted Interpolation (IDW) is a commonly preferred method for producing raster data by interpolation from sample point data. The IDW interpolation technique is based on the principle that points closer to the surface to be interpolated have more weight than points further away. This technique performs a surface interpolation based on the weighted average of the sample points, reducing the weight as the distance from the point to be interpolated increases (Lu and Wong, 2008).

4. Results and Conclusions

The analysis indicates that the rate of terrestrial water storage (TWS) decline accelerated during the second decade of the study period (2012–2022) compared with the first decade (2002–2011). As illustrated in Figures 3 and 4, the magnitude of TWS loss in the latter decade is substantially greater, demonstrating an acceleration of hydrological depletion over time.

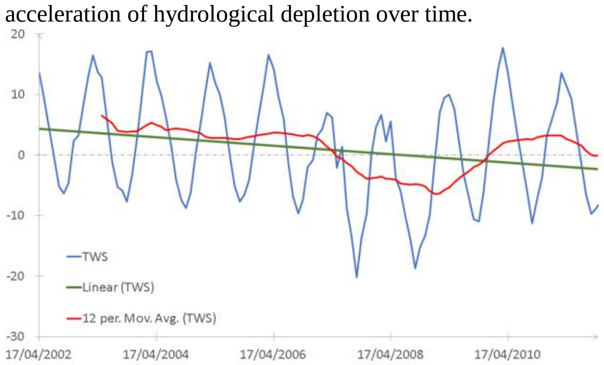

Figure 3. Temporal trend of total water storage (TWS in cm) in the Susurluk Basin for the period 2002–2011.

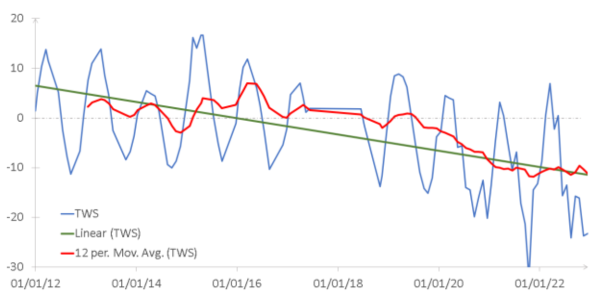

Figure 4. Temporal trend of total water storage (TWS in cm) in the Susurluk Basin for the period 2012–2022.

4.1 Temporal Trend for TWS

As summarized in Table 1, the Susurluk Basin exhibits an overall decreasing trend, with a long-term trend coefficient of –0.0561 for the full 20-year period using Mann-Kendall test. Table 2 presents the individual trend coefficients for the four sub-basins within the study area, each of which displays a statistically significant negative trend based on the Mann–Kendall test results.

Sub-Basin	First decade		Second decade		All time	
	Trend	R^2	Trend	R^2	Trend	R^2
SB 1	Y=-0.535x+4.0098	0.036	Y=-0.1693x+6.5269	0.286	Y=-0.0507x+4.8333	0.112
SB 2	Y=-0.0611x+4.3811	0.047	Y=-0.1771x+6.9615	0.291	Y=-0.0521x+4.9699	0.113
SB 3	Y=-0.0585x+4.1757	0.043	Y=-0.1938x+7.0672	0.319	Y=-0.0587x+5.2719	0.136
SB 4	Y=-0.0476x+3.648	0.030	Y=-0.1857x+6.3984	0.311	Y=-0.0585x+5.1766	0.140
Susurluk	Y=-0.059x+4.2366	0.044	Y=-0.1876x+7.0451	0.310	Y=-0.0561x+5.1612	0.127

Table 2. 1st decade, 2nd decade and all-time trend graph equations for the Susurluk Basin and its’ sub-basins.

4.2 Temporal Trend for TWS for 10 years period

The trend graphs are shown separately for the first 10 years and the second 10 years for the 4 different sub-basin boundaries that were produced. Figure 5 shows the 1st 10-year trend graph of the average GRACE values for sub-basin number 1 in Susurluk, and Figure 6 shows the 2nd 10-year trend graph of the average GRACE values for sub-basin number 1 in Susurluk.

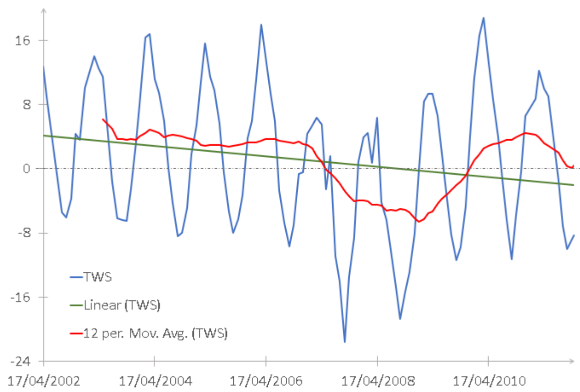

Figure 5. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 1 for the period 2002–2011.

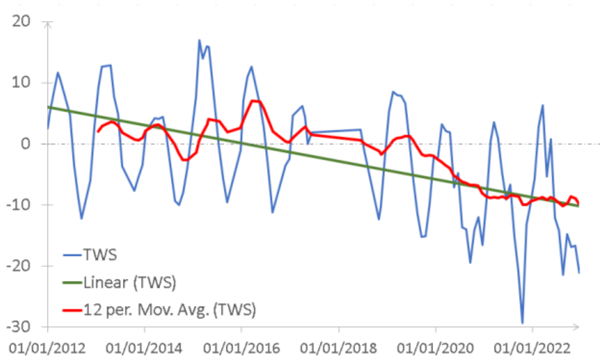

Figure 6. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 1 for the period 2012–2022.

For the second sub-basin boundary, Figure 7 shows the trend graph of the average Grace values first decades, and Figure 8 shows the trend graph of the average Grace values second decades for sub basin 2.

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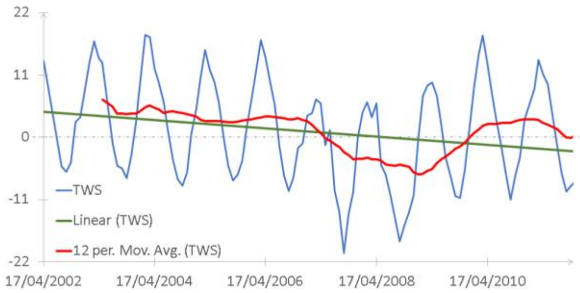

Figure 7. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 2 for the period 2002–2011.

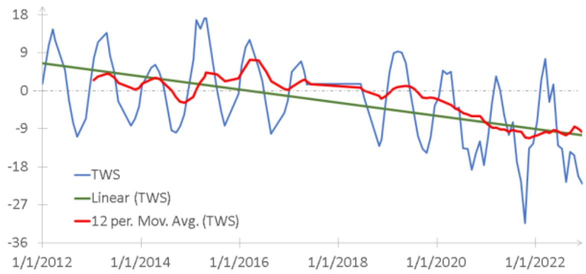

Figure 8. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 2 for the period 2012–2022.

Figure 9 represents the first 10-year trend graph of the Susurluk sub-basin number 3, generated from Grace values; Figure 10 represents the second 10-year trend graph of the Susurluk sub-basin number 3, also generated from Grace values.

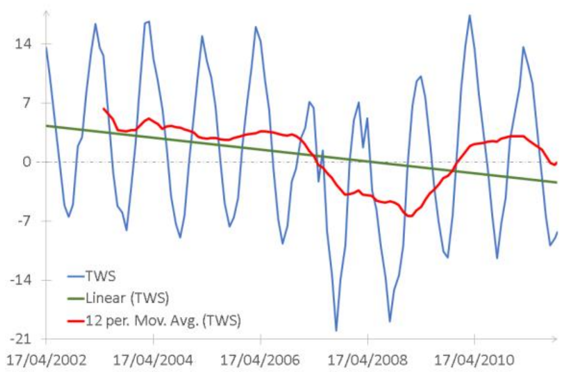

Figure 9. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 3 for the period 2002–2011.

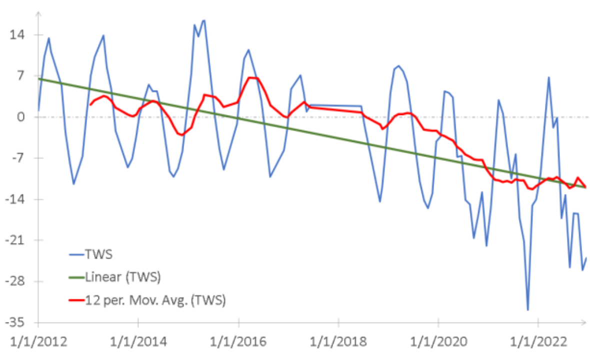

Figure 10. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 3 for the period 2012–2022.

For the final sub-basin boundary, Figure 11 shows the trend graph generated from the average of the first 10 years of GRACE data, and Figure 12 shows the trend graph generated from the average of the second 10 years of GRACE data for sub-basin 4.

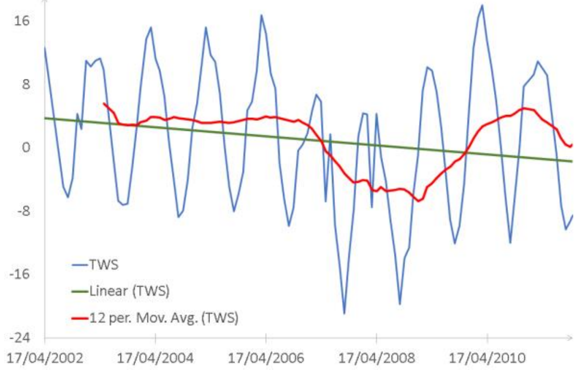

Figure 11. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 4 for the period 2002–2011.

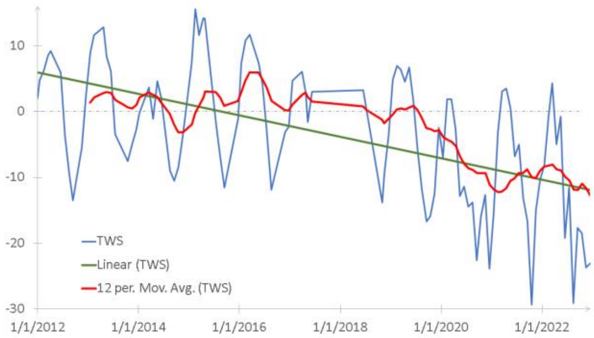

Figure 12. Temporal trend of total water storage (TWS in cm) in the Susurluk SB 4 for the period 2012–2022.

4.3 Spatial Trend for TWS

Data from the Grace satellite was obtained as a .nc file, covering the days the satellite acquired data. This data includes latitude and longitude information and TWS values. TWS values were obtained over a 20-year period according to the latitudes and longitudes within the study area. The points were imported into the GIS program to create table data. Raster maps were generated by performing a join operation. Using the IDW method, raster maps of average grace values for 4 separate sub-basins and the entire basin were produced for the 1st and 2nd 10-year periods.
Figure 13 (a) shows the thematic map of the Susurluk sub-basin number 1, produced using the IDW method from 20-year average grace values. The average values for the 20-year period are between -0.59 cm and -1.17 cm. Figure 13 (b) shows the thematic map of the Susurluk sub-basin number 2, produced using the IDW method from 20-year average grace values. The average values for the 20-year period are between -0.1 cm and -1.33 cm. The thematic map of the Susurluk sub-basin number 3, produced using the IDW method from the 20-year average grace values, is shown in Figure 13 (c). The average values for the 20-year period are between -0.48 cm and -1.33 cm. Figure 13 (d) shows the thematic map of the Susurluk sub-basin number 4, produced using the IDW method from the average of 20-year GRACE values. The average of the values in this thematic map is the same for the sub-basin boundary and is -1.17 cm. For this reason, the generated thematic map is presented in a single color.

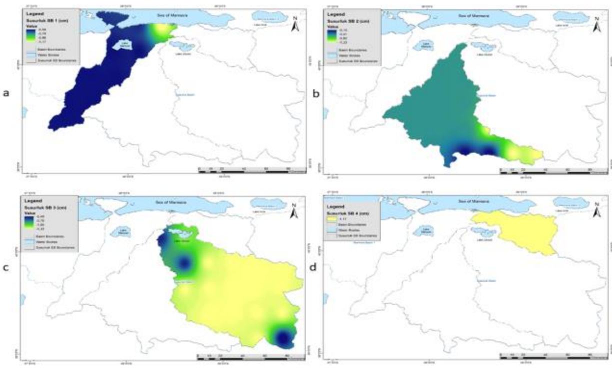

Figure 13. (a) Thematic map of average value over many years for Susurluk SB 1, (b) Thematic map of average value over many years for Susurluk SB 2, (c) Thematic map of average value over many years for Susurluk SB 3, (d) Thematic map of average value over many years for Susurluk SB 4

Figure 14 shows the thematic map of the Susurluk basin produced using the IDW method from the average of the first 10-year grace values; Figure 15 shows the thematic map of the Susurluk basin produced using the IDW method from the average of the second 10-year grace values. The average values for the first 10 years are between 0.83 cm and 1.14 cm. The average values for the second 10 years are between -1.26 cm and -3.60 cm.

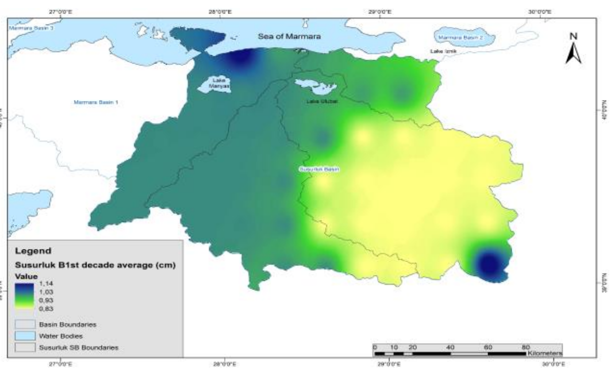

Figure 14. Thematic map of average value for first decade for Susurluk Basin

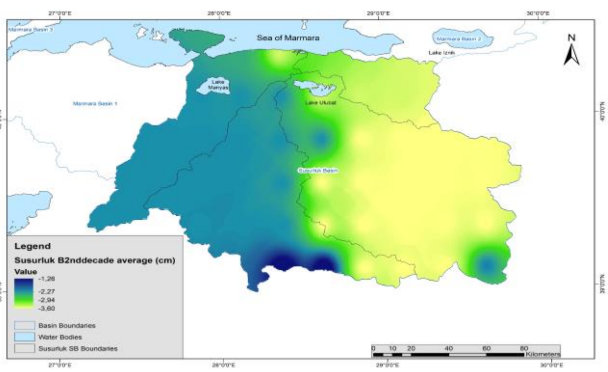

Figure 15. Thematic map of average value for second decade for Susurluk Basin

Figure 16 shows the thematic map of the Susurluk basin, produced using the IDW method from the average of all grace values. The average values range from -1.40 cm to 0.75 cm.

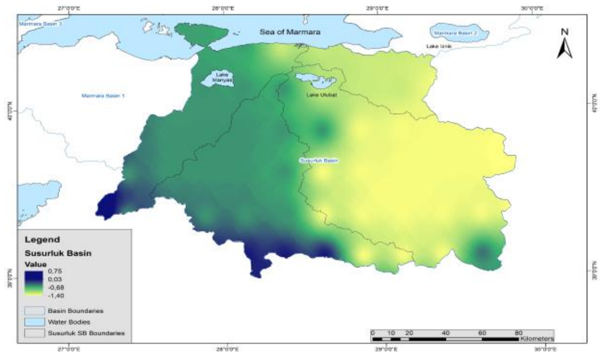

Figure 16. Thematic map of average value over many years for Susurluk Basin

4.4 Innovative Sen Trend for TWS

Figure 17 shows innovative Sen slope for TWS in the two periods (2002-2011 and 2012-2022). The second period (2012-2022) has lower values because of decreasing the TWS.

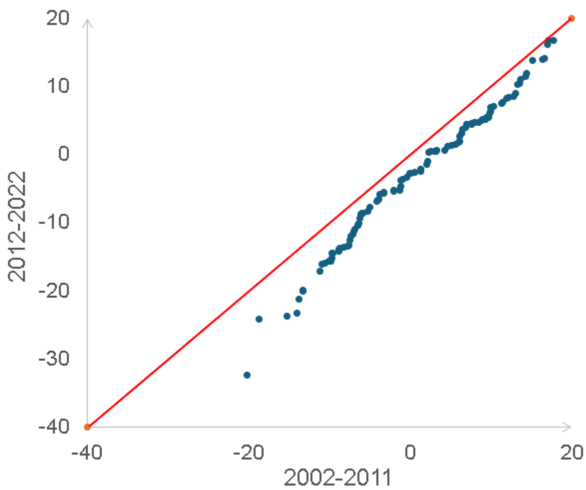

Figure 17. Innovative Sen trend scatter graphs for TWS (in cm) in Susurluk Basin for 2002-2011 and 2012–2022 periods.

The all results show TWS is decreasing with accelerating in Susurluk Basin, Türkiye. It should be noted that the basin is at higher risk of drought, so more accurate water management is needed.

In this study, it was clearly observed that the TWS values decreased according to the data covering a 20-year period in the Susurluk Basin. The decrease in each region is visualized with maps and values are expressed. TWS changes are a critical indicator of freshwater availability. This study also shows that continents have experienced TWS loss since 2002 using NASA GRACE/GRACE-FO data. Changing TWS patterns threaten water availability and sustainable water management for people and the environment, risk livelihoods and food security, and act as a trigger for climate migration and cross-border conflict both domestically and internationally. Here, using twenty years of data from the GRACE and GRACE-FO missions for the Susurluk basin and Susurluk sub-basins, the changes in TWS since 2002 are examined by showing trends and maps.

Acknowledgments
This study was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under grant number 2224-A.

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