# Postprint: Spatiotemporal Variations of Terrestrial Water Storage in the Aral Sea Basin

**Authors:** Lü Ye, Yang Han, Huang Yue

**Date:** 2021-08-01T00:00:00+00:00

## Abstract

Using GRACE (Gravity Recovery and Climate Experiment) gravity satellite JPL-RL06M data from 2002-2016, we analyzed the spatiotemporal variation characteristics of Terrestrial Water Storage Change (TWSC) in the Aral Sea basin, and combined CRU TS4.03 meteorological data, GLDAS-Noah land surface evapotranspiration data, and high-precision land use data to investigate the impacts of climate change and human activities on terrestrial water storage. The results show that: (1) From 2002-2016, terrestrial water storage change in the Aral Sea basin exhibited a declining trend of -3.20 mm · a-1, with surplus states in spring and summer and deficit states in autumn and winter; spatially, the water storage change exhibited surplus in the central and eastern regions and deficit in the surrounding areas. (2) From 2002-2016, precipitation in the Aral Sea basin showed a declining trend of -1.14 mm · a-1, while land surface temperature showed an increasing trend of 0.11 ℃ · a-1; compared with temperature, water storage change had a stronger correlation with precipitation. (3) From 2000-2015, cropland area in the Aral Sea basin increased slightly by 1.65$×104*km*2, *whilewaterareadecreased*; *theincreaseincropwaterconsumptionandirrigationwaterdemande*
m3 · a-1, with the spatial correlation coefficient with terrestrial water storage change reaching up to 0.74, making it one of the main factors affecting terrestrial water storage change.

## Full Text

## Abstract

The Aral Sea, once the largest inland lake in Central Asia, is located far from oceans and features a hydrological system highly sensitive to climate change. Since the 1960s, large-scale water and land resource development and unsustainable irrigation practices in the Amu Darya and Syr Darya basins have caused rapid shrinkage of the Aral Sea and severe ecological degradation, making the "Aral Sea crisis" one of the most serious environmental problems caused by

human activities in the 20th century. Traditional hydrometeorological observations have limitations in comprehensively assessing regional water resource variations due to sparse and discontinuous monitoring stations. The GRACE (Gravity Recovery and Climate Experiment) gravity satellite offers a revolutionary approach by continuously detecting gravity changes caused by mass migration at Earth' s surface and interior, enabling large-scale monitoring of terrestrial water storage and groundwater changes.

This study analyzes spatiotemporal variations of terrestrial water storage change (TWSC) in the Aral Sea Basin using JPL-RL06M GRACE data from 2002 to 2016, combined with CRU TS4.03 meteorological data, GLDAS surface evapotranspiration data, and high-precision land use data to investigate impacts of climate change and human activities. Results show: (1) TWSC in the Aral Sea Basin exhibited a significant declining trend of -3.20 $\mathrm{mm} \cdot \mathrm{a}^{-1}$, with water surplus in spring and summer and deficit in autumn and winter; spatially, central and eastern regions showed surplus while peripheral areas showed deficit. (2) Precipitation decreased at -1.14 $\mathrm{mm} \cdot \mathrm{a}^{-1}$ while temperature increased at 0.11 $^{\circ}\mathrm{C} \cdot \mathrm{a}^{-1}$; TWSC correlated more strongly with precipitation than temperature. (3) Cultivated land area increased by 1.65$×10^{4}$ $\mathrm{km}^2$ while water area decreased; increased crop water consumption and irrigation demand intensified water expenditure. Evapotranspiration increased at 21.63$×10^{8}$ $\mathrm{m}^3 \cdot \mathrm{a}^{-1}$, with correlation coefficients with TWSC reaching up to 0.74, making it a primary factor affecting TWSC.

**Keywords:** Aral Sea Basin; terrestrial water storage; climate change; land use change

## 1. Introduction

The Aral Sea Basin is located in the heart of the Eurasian continent between 58°70 -62°20 E and 41°16 -46°52 N, covering approximately 123$×10^{4}$ $\mathrm{km}^2$. The basin features diverse geomorphology with clear patterns, characterized by high elevations in the east and low elevations in the west. The western and northwestern regions consist of the Turan Plain, including the Karakum and Kyzylkum Deserts, while the eastern and southeastern areas comprise the high mountain regions of the Tianshan and Pamir Plateau, which are the primary water source areas. The basin has a typical continental climate with average annual rainfall below 300 mm, though extreme rainfall in the southwestern Fergana region can reach 2000 mm, while areas near the Aral Sea and desert zones receive less than 100 mm.

The water system is primarily composed of the Amu Darya and Syr Darya rivers. The Amu Darya originates from the Vakhsh Glacier on the northern slope of the Hindu Kush Mountains at the Afghanistan-Kashmir border, with the upper reaches extending to the Termez irrigation district. The Syr Darya originates in the Tianshan Mountains of Kyrgyzstan, with its two main tributaries—the Naryn and Kara Darya—converging in the Fergana Basin. Since the 1960s, large-scale expansion of irrigated agriculture in Uzbekistan and Kazakhstan has altered the basin’ s water balance, significantly reducing inflow to the Aral Sea and causing severe ecological problems.

## 2. Data and Methods

### 2.1 Data Sources

**Terrestrial Water Storage Data:** GRACE RL06M Mascon data from 2002 to 2016 were obtained from NASA’ s Jet Propulsion Laboratory (JPL). Due to satellite instrument measurement errors, aliasing errors, and orbital characteristics, direct use of spherical harmonic coefficients produces severe north-south striping errors requiring filtering. The Mascon method, based on point mass models, establishes direct functional relationships between inter-satellite range-rate observations and surface grid mass changes, offering higher signal-to-noise ratios and better correlation with GLDAS hydrological models compared to spherical harmonic methods. The data have a spatial resolution of 0.5°$×$0.5° and monthly temporal resolution, though 20 months of data were missing due to satellite issues. Missing months were left as null values without interpolation.

**Land Surface Assimilation Data:** GLDAS-Noah model simulations of surface evapotranspiration at 1°$×$1° resolution and monthly temporal resolution, covering the same period as GRACE data.

**Meteorological Data:** CRU TS4.03 monthly temperature and precipitation data from the University of East Anglia, covering 2002–2016 at 0.5°$×$0.5° resolution.

**Land Use Data:** High-resolution land use data for Central Asia from the “Earth System Science Data Sharing Platform” of the Chinese Academy of Sciences, covering 2000 and 2015. The dataset was derived from Landsat TM/ETM+ imagery with manual visual interpretation modifications, classifying land into six categories: cultivated land, forest, grassland, urban/industrial/residential land, water bodies, and unused land.

### 2.2 Methods

**2.2.1 GRACE Time-Variable Gravity Field Inversion for Water Storage Change** JPL’ s Mascon solution divides the globe into approximately 4,200 equal-area spherical caps. Using weighted least squares, each cap’ s equivalent water height is determined. This study processed GRACE data through the following steps: (1) Convert Mascon data to raster format; (2) Extract basin water storage change raster maps; (3) Calculate monthly basin water storage change statistics; (4) Perform trend analysis using linear regression.

**2.2.2 Time Series Trend Analysis** Linear trend analysis was applied to TWSC, precipitation, temperature, and evapotranspiration time series. Longterm trend significance was tested using the Mann-Kendall method at 1°$×$1° resolution for spatial trend analysis of interannual variations.

**2.2.3 Spatial Correlation Analysis** Spatial correlation analysis between TWSC and climatic factors (precipitation, temperature) was performed using grid-based methods. Pearson correlation coefficients were calculated pixel-by-pixel:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where $x_i$ and $y_i$ are paired observations, $\bar{x}$ and $\bar{y}$ are means, and $n$ is sample size. Correlation strength was classified as: $|r| = 1.0$ (perfect), $0.8 < |r| \leq 1.0$ (high), $0.5 < |r| \leq 0.8$ (significant), $0.3 < |r| \leq 0.5$ (moderate), $0.0 < |r| \leq 0.3$ (weak), and $|r| = 0.0$ (no correlation).

## 3. Results

### 3.1 Spatiotemporal Variation of Terrestrial Water Storage

**3.1.1 Interannual and Intra-annual Variation** From 2002 to 2016, TWSC in the Aral Sea Basin showed a significant declining trend of -3.20 $\text{mm} \cdot \text{a}^{-1}$ ($p < 0.05$). Maximum surplus occurred in March 2005 (81.05 mm), while maximum deficit occurred in November 2010 (-85.93 mm). Seasonally, TWSC was higher in spring (March-May) and autumn (September-November) than in summer (June-August) and winter (December-February), with peaks typically in March and troughs in November.

**3.1.2 Spatial Variation** Spatially, TWSC exhibited surplus in the central hinterland and eastern regions, with deficits in peripheral areas. Northern and western basin areas showed greater deficits than southern regions, particularly in Turkmenistan and the Aral Sea area of Uzbekistan. Surplus areas were concentrated in eastern mountainous regions and irrigation districts in the middle reaches of the Amu Darya.

The basin was divided into Amu Darya and Syr Darya sub-basins, with further upstream, midstream, and downstream subdivisions based on geomorphology, hydrological stations, and irrigation district distribution. Both sub-basins showed significant declining trends: -2.91 $\text{mm} \cdot \text{a}^{-1}$ for Amu Darya ($p < 0.01$) and -5.18 $\text{mm} \cdot \text{a}^{-1}$ for Syr Darya ($p < 0.05$). Except for a slight increase in the Amu Darya midstream (1.79 $\text{mm} \cdot \text{a}^{-1}$), all sub-regions showed decreasing trends. The Amu Darya downstream showed the largest decrease (-7.36 $\text{mm} \cdot \text{a}^{-1}$), followed by upstream (-7.28 $\text{mm} \cdot \text{a}^{-1}$) and midstream (-3.81 $\text{mm} \cdot \text{a}^{-1}$).

### 3.2 Environmental Impacts on Terrestrial Water Storage

**3.2.1 Sensitivity to Climate Factors** Precipitation in the Aral Sea Basin decreased at -1.14 mm · a$^{-1}$ from 2002 to 2016, with reductions most pronounced in the basin’ s east (-8.22 mm · a$^{-1}$). Increases occurred in the lower reaches of both rivers (2.67 mm · a$^{-1}$). Surface temperature increased at 0.11 °C · a$^{-1}$, with maximum increases in the Amu Darya midstream (0.05 °C · a$^{-1}$) and decreases in some downstream areas (-0.03 °C · a$^{-1}$).

TWSC showed positive correlation with precipitation across most of the basin, with high correlations in upstream and central regions. Negative correlations appeared in the Syr Darya lower reaches, Amu Darya midstream, and parts of the Amu Darya downstream. TWSC and surface temperature showed positive correlations in the Syr Darya mid-lower reaches and confluence areas with the Amu Darya, but negative correlations elsewhere. Overall, TWSC correlated more strongly with precipitation than temperature, indicating precipitation is the dominant climatic factor.

**3.2.2 Impacts of Land Use Change** From 2000 to 2015, cultivated land in the Aral Sea Basin increased by 1.65$×10^{4}$ km$^2$ (1.19$×10^{4}$ km$^2$ in Amu Darya basin and 0.45$×10^{4}$ km$^2$ in Syr Darya basin), while grassland and water areas decreased by 1.52$×10^{4}$ km$^2$ and 1.56$×10^{4}$ km$^2$ respectively. The Amu Darya midstream accounted for 63.87% of total cultivated land increase. Water area changes were significant: the Amu Darya basin lost water area due to South Aral Sea shrinkage, while the Syr Darya basin gained water area, particularly in its lower reaches (0.12$×10^{4}$ km$^2$ increase).

Evapotranspiration increased at 21.63$×10^{8}$ m$^3$ · a$^{-1}$ across the basin: 11.02$×10^{8}$ m$^3$ · a$^{-1}$ in Amu Darya basin and 8.36$×10^{8}$ m$^3$ · a$^{-1}$ in Syr Darya basin. All sub-regions except the Amu Darya downstream (-0.26$×10^{8}$ m$^3$ · a$^{-1}$) showed increasing evapotranspiration. The correlation coefficient between evapotranspiration and TWSC reached 0.74, indicating evapotranspiration is a primary factor affecting TWSC. High positive correlations occurred in irrigation districts at the Amu Darya mid-lower reaches junction, while negative correlations appeared in the southwestern Amu Darya downstream and Syr Darya mid-lower reaches confluence area.

## 4. Discussion and Conclusions

This study extracted TWSC time series from GRACE data and analyzed impacts of climate change and human activities. Key findings include:

1. **TWSC Decline:** From 2002 to 2016, the Aral Sea Basin experienced overall TWSC decline, most severe in the northwestern Aral Sea region. Following the Soviet Union’ s dissolution, Uzbekistan intensified agricultural economics, expanding irrigation areas in the Amu Darya mid-lower reaches. Combined with warming temperatures, increased evapotranspiration exacerbated water depletion.

2. **Climate Factor Dominance:** TWSC showed stronger correlation with precipitation than surface temperature, with temperature correlations being non-significant across most of the basin, indicating temperature is not the dominant factor.
3. **Land Use Impacts:** Cultivated land expansion and increased irrigation water demand intensified water expenditure. Basin-wide evapotranspiration increased at 21.63$×10^{8}$ $\mathrm{m}^3 \cdot \mathrm{a}^{-1}$, strongly correlating with TWSC (maximum r = 0.74), making it a primary influencing factor. However, evapotranspiration is driven by complex interactions of meteorological factors (temperature, wind speed, humidity) and land surface characteristics (crops, vegetation, water bodies), making quantitative attribution challenging with current data.
4. **Regional Variations:** The South Aral Sea's persistent shrinkage reduced lake water storage, with groundwater depletion for irrigation causing significant TWSC decline in the Amu Darya downstream. In the North Aral Sea, while lake area and volume increased slightly, expanded water surface evaporation, combined with increased evapotranspiration from farmland and vegetation, caused TWSC decline in the Syr Darya downstream, though less severe than in the Amu Darya downstream.

While this study used the latest GRACE Mascon data, uncertainties remain in TWSC retrieval for the Aral Sea Basin. Future research should integrate multiple GRACE data versions and GLDAS multi-model evapotranspiration simulations for comparative analysis to reduce uncertainties.

[Figure 1: see original paper] The Aral Sea Basin
[Figure 2: see original paper] Interannual and intra-annual changes of TWSC in the Aral Sea Basin from 2002 to 2016
[Figure 3: see original paper] Spatial distribution of TWSC in the Aral Sea Basin from 2002 to 2016
[Figure 4: see original paper] Interannual change of TWSC in the Aral Sea Basin and its sub-region
[Figure 5: see original paper] The variation of meteorological elements and the correlation with TWSC in Aral Sea Basin
[Figure 6: see original paper] Changes of land use cover in the Aral Sea Basin from 2000 to 2015
[Figure 7: see original paper] Change percentage of land use and change of evapotranspiration in the Aral Sea Basin
[Figure 8: see original paper] Change of evapotranspiration in the Aral Sea Basin and its relationship with TWS
Changes in land use areas in the Aral Sea Basin and its sub-basin in 2000 and 2015 ($10^4$ $\mathrm{km}^2$)
Change rates of various elements from 2000 to 2016 ($\mathrm{mm} \cdot \mathrm{a}^{-1}$)

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv —Machine translation. Verify with original.*