Nonstationarity in global hydrological systems: Evidence-based on GRACE satellite gravimetry missions

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Abstract

Anthropogenic climate change signature has been detected in several Earth’s systems as a manifestation of the warming atmosphere and oceans that led to significant changes in the global water cycle. As a result, the hydrological systems display substantial and intermittent shifts in their natural courses with time-variant intra-annual and interannual variability, i.e., *nonstationarity*. Via GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO satellite gravimetry records, we assessed the regional stationarity across 39 hotspot hydrological systems in a global context. Three main nonstationarity tests were applied around the deterministic and periodic components. Distinctively, 38 percent of the tested hotspot regions are identified as nonstationary systems, where a combination of anthropogenic and climatic forcings is dominant. The nonstationary hydrologic systems would be more susceptible to hydrologic extremes with compromised capacities to timely cope, respond, and mitigate. Continuation of satellite gravity missions is crucial to evaluate the (non)stationary status in global hydrologic systems.

Introduction

Anthropogenic climate change (ACC) influence has been noted unequivocally in many Earth systems\textsuperscript{1,2}, with a growing human imprint from the start of the industrial revolution onward\textsuperscript{14}. Over the past half-century, the ACC signals have been substantiated in various hydroclimatic and heat budget records, e.g., precipitation, global surface temperatures, sea surface temperature (SST), and Ocean Heat Content (OHC)\textsuperscript{3,4}. The significant variations in the SST patterns, accordingly, have led to remarkable alterations in various atmospheric teleconnections phases, e.g., the dramatic intermittent changes of the Pacific Decadal Oscillation (PDO) (see Fig. S1). Modifications in the frequency, duration, and intensity of the warm and cold SST phases have consequently modified the natural hydroclimatic and hydrologic water budget globally\textsuperscript{5–7}. The conventional hydrologic water budget describes the relationship among various inputs (inflows) and outputs (outflows) variables\textsuperscript{8}. The pronounced anthropogenic activities have altered their relative balance and consequently introduced a human factor to the natural water budget components, Eq. 1.

\[
(P + R_I + G_I + H_I) - (ET + R_O + G_O + H_O) = \Delta S
\]  

Where, \((P)\) is precipitation, \((R_I)\) is the runoff, \((G_I)\) is groundwater, \((H_I)\) is a human import of water into the basin, \((ET)\) is evapotranspiration, \((R_O)\) is runoff, \((G_O)\) is groundwater, and \((H_O)\) human-export of water out of the basin or study domain.

ACC has led to shifting natural water flow with a notable variation in the intra-annual and interannual variabilities among various water budget components\textsuperscript{9–11}. Extremes of precipitation, evapotranspiration,
and river discharge became frequent\textsuperscript{3,12}. Recovery time between extreme weather and climate events has inclined, susceptibilities increased, and our capacities to cope, respond, and mitigate to recent hydrological extremes were compromised \textsuperscript{19,20}. In recent decades, human-climate alterations manifested the concurrent shifting patterns in freshwater resources availability and changes across scales\textsuperscript{4}. The uncertain trajectories of water availability and the need for more water to serve the food and energy production requirements have diminished the natural seasonal and interannual storage.

The human-induced modifications in water systems, land cover, and land use have triggered uncontrolled water resources exploitation\textsuperscript{9–11}, and introduced the notion of “\textit{nonstationarity}” in the hydrologic system\textsuperscript{13}. The concept implies significant changes in the hydrologic systems’ intra-annual and interannual variabilities with a time-variant mean, variance, and non-uniform density distribution\textsuperscript{14,15}. Therefore, the assumption that the future projections would be statistically similar to the past trends became irrelevant\textsuperscript{13,16}. The hydrological variability will no longer vary about a relatively constant average with a constant spread (standard deviation). The frequencies, magnitudes, and durations of floods and droughts are outside the historical range. With respect to hydrologic modelling and forecasting, as best practice modellers usually render the stationarity of a time series (TS) using various mathematical transformations, i.e., eliminating the secular trend and deterministic seasonal patterns. Stationary is recommended to ensure that traditional water management practice is successful\textsuperscript{7}. A stationary hydrologic system has an unchanged envelope of variability, invariant intensities, time, and durations. Abrupt changes in various statistical momentums (mean and variance) could indicate nonstationary. Decadal climate patterns, extreme weather events, and anthropogenic shifting manifest the transition of a hydrologic system from stationary to nonstationary. Such a transition has led to the concept that “\textit{stationarity is dead}” \textsuperscript{13}.

Evaluating stationarity in global hydrological systems requires a uniform, continuous, and frequently updated hydrologic records. The requisite hydrologic observations, therefore, should be dependable, collected using the same standards, and spatially and temporally uniform. The available in-situ observations are uneven spatially, gauged with different norms, and may express unique aspects of temporal details. Unfortunately, more than half of all hydrological gauges are located across and within the river networks and channels\textsuperscript{12}. Moreover, the majority of the available land surface model (LSM), and the reanalysis observations are lacking the representation of various hydrologic and anthropogenic components\textsuperscript{17}, e.g., several hydrologic measurements are notoriously unavailable or hard to measure (e.g., groundwater, surface waters, lake water storage, and ice caps). The status of the in-situ, LSM and the reanalysis observations imposes enormous challenges to understanding and assessing the possible trajectories and the divergent trends in freshwater resources.

To enable a precise overview of the global freshwater availability, change, and evolution in space and time, GRACE (Gravity Recovery and Climate Experiment) and its successor GRACE-FO (Follow-On) satellite gravity missions have a significant record of implementation\textsuperscript{18–20}. GRACE missions monitor the changes in terrestrial water storage (TWS) via precisely recording the changes in the Earth's gravity field
in response to the mass changes in the hydrosphere, cryosphere, and oceans. The data have a monthly temporal coverage and represent a spatial resolution equivalent to approximately $3 \times 3$ degrees at the equator. As opposed to other ancillary hydrological remote sensing, LSM, and reanalysis observations, GRACE encapsulates the changes in the hydrologic water systems as a lumped sum of the changes in all water storage from the surface to the deepest groundwater aquifer. Thus, GRACE observations have allowed -- for the first time -- consistent measurements of the equivalent water height (EWH) at monthly temporal intervals. GRACE TWS measurements integrate the effects of natural and anthropogenic processes at locations undergoing rapid climatic and environmental changes. GRACE datasets have been utilized to study the climate-anthropogenic interactions on surface and groundwater resources among several hydrological applications. GRACE data provide a consistently sampled view of the water storage cycle and complement the sparse in-situ data, and lack of several hydrologic and anthropogenic components from LSM and reanalysis observations. Given appropriate caveats related to latency and footprint, GRACE produces a single lumped parameter, $\Delta\text{TWS}$, which is considered analogous to the storage changes, $\Delta S$, in classical water budget hydrology (Eq. 1). GRACE gravity missions provide valuable measurements of the water storage changes globally, and in locations and instances where the data paucity leads to inconclusive and counterintuitive results using conventional methods.

While hydrological nonstationarity is widely debated, the question remains, why is it important to recognize whether a hydrologic system is stationary or not? Understanding whether a hydrologic system is stationary or not is crucial to assessing the trajectories of freshwater availability and changes in space and time. Accounting for the nonstationarity in hydrologic systems became among the greatest challenges to making accurate hydrologic predictions. The nonstationarity makes it exceptionally difficult to predict the next floods or droughts with confidence. A stationary hydrologic system, however, depicts great tendencies toward normal conditions, even under considerable variations. The system will display a strong memory that allows for better prediction of future variability, i.e., the ability to perform future forecasts will be more achievable. Therefore, a crucial assessment of the present-day stationarity status in a global hydrologic water system is critical to depict a holistic overview of freshwater availability and will allow an understanding of how human activities affect water resources availability globally.

Simply, a hydrologic TS is a combination of deterministic (which might be due to an anthropogenic forcing) and stochastic (a result of chaotic nonlinear dynamics and unpredictable natural forcing) components. A nonstationary system of a time-variant mean and/or variance components displays significant deterministic patterns with long periodicity, runs, and tendency to breakpoints (inhomogeneity). Thus, we applied the nonstationarity tests around the level (change in the mean), the presence of the secular trend, and the variation in the periodic component (i.e., variance) in each tested hydrologic system. To delineate the areas with significant hydrologic variability (hotspot regions) and strong variation in the mean and/or variance, we used a ratio between the mean and standard deviation (white noise), $\left(\frac{\mu}{\sigma}\right)$, of all GRACE data. The ratio $\left(\frac{\mu}{\sigma}\right)$ has illustrated a number of notable positive (increasing trends in blue), and negative (decreasing trends in red) hotspot areas. A total of 39 locations...
were identified using this \( \left( \frac{\mu}{\sigma} \right) \) ratio. The corresponding time series of the GRACE-based EWH for each hotspot location is provided in Fig. 1. The figure indicates significant secular trend components, with a number of breakpoints (dashed vertical lines) due to the significant abrupt changes in the TS levels (mean). Most of these positive and negative trends around similar hotspot regions were previously outlined by various research, e.g.,\(^{32-37}\). The attributions include different anthropogenic and climatic dynamics, e.g., groundwater exploitation \(^{38}\), agricultural activity \(^{39}\), frequent droughts, and flooding \(^{37}\). The full discussion of the chaotic drivers for these trends is beyond the scope of this research. For more information about these hotspot areas please refer to Table S1 in the supplementary information that summarizes several statistical measures across these areas.

Distinct from available literature, this study aims to extend the satellite gravity mission applications to evaluate the hydrologic nonstationarity that corresponds to the influence of various anthropogenic and climatic forcings. Specifically, this research evaluates the stationarity status across major hydrologic hotspot regions using uniform, continuous, and frequently updated gravity measurements. To achieve our goal, we make use of the most recent GRACE and GRACE-FO mascons (mass concentration blocks) products of release (RL06). The datasets are available from the Center for Space Research (CSR) at the University of Texas at Austin\(^{40}\). The acquired GRACE (-FO) records cover the period from April 2002 to June 2017, and from July 2018 to May 2021, respectively. We do not perform any gap-filling or interpolation of the missing months in GRACE or (-FO) records. Noteworthy, other mascon products are available from JPL (Jet Propulsion Laboratory) and GSFC (Goddard Space Flight Center) at NASA that can be used to in a similar context.

**Results**

Using the extracted TWS TS records for the selected locations, we applied three stationarity tests around the level, trend, and the time-variant periodicity, i.e., variance\(^{41,42}\) for each hotspot location. Please, see the methods section for more details about the applied stationarity tests. The statistical analysis was performed using the CARN.R-project. We provide the summary statistics of each TWS TS record (see supplementary info Fig. S2, also Table S2 summarizes the tests for the nonstationarity around the level, trend, and periodicity across the studied regions. The figure shows that the majority of the studied hotspot regions display significant declining trends as indicated by the contribution of the statistical minimum (Min) values with strong variability as indicated by the contribution of the standard deviation (Stdev). Figures 2a&2b illustrate regions of nonstationary TS as assessed by the stationarity test around the level and trend, respectively. The results indicate that 92 percent of the tested hotspots are nonstationary around the TWS level. For the trend component, 66 percent showed a nonstationarity status around the TWS trend. These nonstationary areas around the level and trend components are concentrated within arid or semi-arid climate climates and across the high latitudes. Fewer hotspot locations are within tropical and sub-tropical regions. As noted earlier, the secular trend in these locations is attributed, generally, to anthropogenic forcing. For instance, in the Northern Sahara region, where a number of major sandstone aquifers are located, a pronounced declining trend is expected in response to
significant groundwater withdrawals to meet the human needs in the region\textsuperscript{37}. Similarly, the Arabian Peninsula, Iran, and the Southern High Plain Aquifer (HPA) in the United States, among other locations, were identified as nonstationary systems with significant negative trends. Conversely, additional hotspot regions are attributed to a significant positive trend, e.g., the East African Lake system, Okavango River Delta, Northern HPA, and Eastern Australia. Some of these locations have recovered from an extensive drought, e.g., the Eastern Australia region has recovered from a prolonged recent Millennium drought between 1997 to 2009\textsuperscript{37}. The test for stationarity around periodic signals showed that 43 percent of the hotspot regions are nonstationary (Fig. 2c). Distinctively, 38 percent of the hotspot regions mark nonstationary systems around all tested components, e.g., level, trend, and periodicity. These areas represent regions where a combination of anthropogenic and climatic factors is dominant.

Figure 3 shows four distinctive hotspots that have been identified as nonstationary in all applied tests, i.e., level, trend, and periodicity. The hotspot locations include regions across the Southern HPA in the United States, Eastern Australia, and Northeast China that display strong periodicities (runs) with non-uniform and unexpected variabilities are prevailing. The TWS TS in these areas displays significant abrupt changes (breakpoints) in the mean with different periodicities. Further research is needed to identify the sources for such distinctive features across the presented TWS TS. We provided the lag autocorrelation plots of these series in Fig. S2 in the supplementary information. Fig. S2 indicates significant autocorrelation at various lags with time.

**Discussion**

By definition, the ongoing nonstationary conditions make the magnitudes, durations, and frequencies of extreme weather and climate outside the historical range of observations. A nonstationary hydrologic system will be vulnerable to more extreme events with less ability to retain its normal conditions. The nonstationary system as well will display volatile memory that hinders any attempts for a reliable forecast of future variability, compromising future forecasts. Via GRACE and GRACE-FO gravity observations, we identified the nonstationarity in global hydrological systems. The nonstationarity across these systems manifests various anthropogenic and climatic forcings, such as groundwater withdrawals, and/or triggers of frequent extreme climates. In general, returning to normal conditions under such significant nonstationarity influence would generate a number of changing points and abrupt changes in the series. In addition, the hotspot regions that displayed joint nonstationarity around the level, trend, and periodic components represent a joint effect from both anthropogenic and climatic processes. The inhomogeneity variability around these hotspot areas will increase the susceptibility to more hydrologic extremes and compromise the capacity to timely cope, respond, and mitigate. Understanding and accounting for such nonstationary patterns in the hydrologic water budget will enhance our awareness and preparedness to make informed decisions about hydrological extremes. Gravity measurements from the GRACE and -FO satellite missions provide the first step toward detecting and attributing the nonstationarity in global hydrologic systems at various scales of interest due to extensive climate-anthropogenic processes. GRACE missions have eased several technical issues related to the availability
and accessibility of quality-controlled in-situ data. Future developments of frequent updates to a long-records of gravity measurements with the ability to produce high-frequency, low-latency, and near-real-time measurements will enhance our capabilities to monitor various hydrologic extremes across scales and at shorter seasonal and sub-seasonal intervals. Continuation of satellite gravity missions is crucial in depicting a holistic overview of the hydrological (non)stationary status in global hydrologic systems.

**Methods**

**GRACE Datasets**

We utilized GRACE data using the mascons (mass concentration blocks) solutions, release 06 (RL06), version 02 (short name CSR-M RL06 V02) produced by the Center for Space Research (CSR), the University of Texas at Austin. The data cover the period from April 2002 through June 2017 for GRACE and from July 2018 to May 2021 for GRACE-FO records. The derived TWS anomalies are relative to the baseline average between 2004–2009. Standard corrections of the CSR-M include the replacement of the C20 and C30 coefficients with satellite laser-ranging estimates, optimizing geocenter motions, and correcting glacial isostatic adjustment (GIA) using the ICE6G-D model. The CRS mascons are represented by a grid with a spatial resolution of 0.25°x0.25°. The native spatial representation, however, is hexagonal titles with an equivalent spatial resolution of 1°x1° at the equator.

To delineate the hotspot areas of significant variabilities, we used the ratio between the mean and standard deviation of all CSR-M records. The calculation is done at each pixel. Using the delineated areas, we extracted the corresponding GRACE TWS anomalies across each hotspot area. Then, we tested the stationarity around the level, trend, and periodic components in each series.

**Stationarity Testing**

For any TS, $Y_t$, the series can be decomposed into deterministic (include periodic) and stochastic (random) components as,

$$Y_t = D_t + Z_t + \epsilon_t$$

where, $D_t$ is the deterministic component, the $Z_t$ is the stochastic or random component, and $\epsilon_t$ is the stationary error process. Because of the $Z_t$, then $Y_t$ is considered a stochastic series. In general, the $Z_t$ can be expressed using an AR(1) process as,

$$Z_t = \varphi Z_{t-1} + \epsilon_t, \epsilon_t \sim WN (0, \sigma^2).$$

2
When $|\varphi| < 1$ then $Yt$ of $I(0)$, and if $\varphi = 1$ then $Yt$ of $I(1)$. Generally, to satisfy the stationarity in $Yt$, the mean, variance, and covariance should not change over time (time-invariant).

were applied: the KPSS (Kwiatkowski-Phillips-Schmidt-Shin)\(^{46}\), which tests the nonstationarity around the levels and the secular trend of the time series across the studied hotspot areas. We also make use of the ADF (Augmented Dickey-Fuller)\(^{47}\) test for nonstationarity around the periodic component. The ADF determines the nonstationarity in TS using the stochastic component. Because the error term, $\epsilon_t$, is unlikely to be white noise, the ADF, therefore, includes extra lag in a term in order to eliminate the autocorrelation problem in the series. It can be illustrated as:

$$Yt = c + \delta t + \varphi Y_{t-1} + \beta_1 \Delta Y_{t-1} + \cdots + \beta_p \Delta Y_{t-p} + \epsilon_t$$

where $\Delta$ is the differencing operator, such that $\Delta Yt = Yt - Y_{t-1}$, $p$ is the number of lagged differences, and $\epsilon_t$ is the error term.

The null hypothesis ($H0$) for the KPSS test is that the series is stationary around the level and trend, while the alternative hypothesis ($Ha$) is not stationary. For the ADF test, the H0: There is a unit root for the series when $\varphi = 1$, and Ha: There is no unit root for the series when $\varphi < 1$. The model with $\delta = 0$ has no trend component, while the model with $c = 0$ and $\delta = 1$ has no shift (abrupt change) or trend. The KPSS and ADF are available via tseries package\(^{48}\) in CRAN.R-project. We further tested the TWS series for the abrupt changes, where several significant change points in the time-variant levels in each series are indicated.

**Declarations**

**Data availability:** All GRACE CSR-M dataset is publicly available from the Center for Space Research (CSR), the University of Texas at Austin (http://www2.csr.utexas.edu/grace/RL06_mascons.html).

**Code availability:** The analysis was done using the open-source R-CRAN software. All packages utilized in this research are cited in the Methods section.

**Author contributions:** E. Hasan. designed the study. H. Save provided key datasets. E. Hasan analyzed the data. E. Hasan, M. Tamisiea and H. Save discussion of the results. H. Save and S. Bettadpur funding acquisition. E. Hasan. wrote the first draft of the paper, and all authors contributed to writing and revising the manuscript.

**Competing interests:** The authors declare no competing interests.

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**References**


**Figures**

![Image of hotspot areas delineation](image.png)

**Figure 1**

Delineation of hotspot areas using a ratio between the mean and standard deviation of GRACE record between April 2002 to June 2017 (GRACE), and from July 2018 to May 2021 (GRACE-FO). The shaded grey area represents the gap between GRACE and GRACE-FO. Time series of equivalent water height (EWH) for each of the hot spots are shown in units of centimeters.
Figure 2

The KPSS stationarity testing around the level (a), trend (b), and the ADF tests stationarity around mean and variance (c). The nonstationary systems showed in red, and the stationary systems (in blue) are indicated in each plot.
**Figure 3**

Changes in TWS (in red) and fitted TWS local mean trends (in grey) across four hotspot locations. The areas show various nonstationarity statuses due to the presence of abrupt changes (vertical dashed lines) and significant periodicities. The shaded colour around each series represents a 1-standard deviation. The vertical shaded period represents the gap between GRACE and GRACE-FO missions.

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- SuppinfoXLS.xls
- SuppinfoStationarityornotmetfin.docx