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Emerging trends in global freshwater availability

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Freshwater availability is changing worldwide. Here we quantify 34 trends in terrestrial water storage observed by the Gravity Recovery and Climate Experiment (GRACE) satellites during 2002–2016 and categorize their drivers as natural interannual variability, unsustainable groundwater consumption, climate change or combinations thereof. Several of these trends had been lacking thorough investigation and attribution, including massive changes in northwestern China and the Okavango Delta. Others are consistent with climate model predictions. This observation-based assessment of how the world's water landscape is responding to human impacts and climate variations provides a blueprint for evaluating and predicting emerging threats to water and food security.

Groundwater, soil moisture, surface waters, snow and ice are dynamic components of the terrestrial water cycle[1–3]. Although they are not static on an annual basis (as early water-budget analyses supposed), in the absence of hydroclimatic shifts or substantial anthropogenic stresses they typically remain range-bound. Recent studies have identified locations where terrestrial water storage (TWS; the sum of these five components) appears to be trending below previous ranges, notably where ice sheets or glaciers are diminishing in response to climate change[4,5] and where groundwater is being withdrawn at an unsustainable rate[6–8].

Accurate accounting of changes in freshwater availability is essential for predicting regional food supplies, human and ecosystem health, energy generation and social unrest. Groundwater is particularly difficult to monitor and manage because aquifers are vast and unseen, yet groundwater meets the domestic needs of roughly half of the world's population[9] and boosts food supply by providing for 38% of global consumptive irrigation water demand[10]. Nearly two-thirds of terrestrial aquatic habitats are being increasingly threatened[11], while the precipitation and river discharge that support them are becoming more variable[12]. A recent study[11] estimates that almost 5 billion people live in areas where threats to water security are likely—a situation that will only be exacerbated by climate change, population growth and human activities. Therefore, the key environmental challenge of the 21st century may be the globally sustainable management of water resources.

Much of our knowledge of past and current freshwater availability comes from a limited set of ground-based, point observations. Assessing changes in hydrologic conditions at the global scale is exceedingly difficult using in situ measurements alone, owing to the cost of installing and maintaining instrument networks, the presence of gaps in those networks and the lack of digitization and sharing of existing data[13]. Satellite remote sensing has proven crucial to monitoring water storage and fluxes in a changing world, enabling a truly global perspective that spans political boundaries[14]. In particular, since its launch in 2002, the GRACE mission[15] has tracked ice-sheet and glacier ablation, groundwater depletion and other TWS changes[16–19]. On a monthly basis GRACE can resolve TWS changes with sufficient accuracy over scales that range from approximately 200,000 km^2 at low latitudes to about 90,000 km^2 near the poles[1]. However, owing to GRACE's coarse spatial resolution, the inability to partition component mass changes and the brevity of the time series, proper attribution of the TWS changes requires comprehensive examination of all available auxiliary information and data, which has never before been performed at the global scale.

Here we map TWS change rates around the globe based on 14 years (April 2002 – March 2016) of GRACE observations (Fig. 1). The GRACE data were processed using an advanced mass concentration[20] ('mascon') approach that enables improved signal resolution relative to the standard spherical-harmonic technique[21]. Best-fit linear rates of change after removing the seasonal cycle (referred to herein as 'apparent trends') are presented in Table 1 for 34 study regions. For context, the largest man-made reservoir in the USA, Lake Mead, has a capacity of about 32 Gt; during the study period, all but one of the 34 regions lost or gained more water than that, and eleven of them lost or gained more than ten times that amount. The reported uncertainty bounds are typically low because the process of removing glacial isostatic adjustment (GIA) signals is the only major source of error in the secular signal. Therefore, low uncertainty does not, on its own, imply that the apparent trends existed before the GRACE period or will continue into the future. The coefficient of determination (r^2), which represents the 'goodness of fit' of the regressed linear trends, is included in Table 1 to quantify the strength of the apparent trends relative to non-secular interannual variability. It is hence a useful, but by no means conclusive, piece of evidence that can be used to predict whether the trend will be fleeting or enduring, reflecting the cohesiveness of the TWS time series tendencies, as shown in Extended Data Fig. 1–4. We attribute the trends to natural variability, direct human impacts or climate change and forecast the likelihood that they will continue on the basis of 1979–2016 precipitation data from the Global Precipitation Climatology Project version 2.3 (GPCP)[22] (see Extended Data Figs. 5–8), an irrigated area map[23], satellite-based lake-level altimetry time series[24], Landsat imagery and published reports of human activities including agriculture, mining, reservoir operations and inter-basin water transfers. Further, for each region we provide the median climate model prediction of precipitation changes between 1986–2005 and 2081–2100 using the Representative Concentration Pathways 8.5 W m^{-2} (RCP8.5; 8.5 W m^{-2} radiative forcing in 2100 relative to pre-industrial levels) greenhouse gas emissions scenario from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[25]. We chose the high-end ('business as usual')

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