EGU23-14106, updated on 17 Nov 2023
https://doi.org/10.5194/egusphere-egu23-14106
EGU General Assembly 2023


# Reinvestigating Groundwater Drought Using In Situ and GRACE Data

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Groundwater plays a unique role in the terrestrial water cycle. It is one of the prime sources of water during periods of severe drought. Depletion of groundwater reaching certain thresholds substantially lead to the degradation of water quality. Among all the hydrological variables, it has a characteristics behavior due to its lagged response to precipitation, evapotranspiration, soil water content variations, and surface water variation due to anthropogenic activities. Groundwater drought has been studied in various regions in the world, which revealed significant correlation among hydrological factors, including precipitation, soil water content, and various terrestrial water storage. Terrestrial water storage variables used for monitoring groundwater drought are total water storage change (TWSC) and groundwater storage change (GWSC). While the TWSC can be estimated from the Gravity Recovery and Climate Experiment (GRACE), GWSC can be estimated from in situ groundwater level within the network of well records using relevant hydrogeological information. Previous studies showed the ability and reliability of GRACE data in groundwater monitoring in the regions under extreme drought. Hydrological model outputs, e.g., the Global Land Data Assimilation System (GLDAS), have been used to derive groundwater drought indicators that reached certain reliability. The present study conducts a systematic investigation on the ability of the GRACE data to reflect the groundwater drought conditions, by comparing in situ groundwater data, TWSC estimated from GRACE ($TWSC^{GRACE}$), GWSC estimated from the conjuncture of GRACE and GLDAS ($GWSC^{GLDAS}$), Standardized Precipitation Index (SPI), and satellite land surface temperature. Further, by estimating the vadose zone water storage change (VZWC) using TWSC and in situ groundwater data ($VZWC^{in\ situ}$), as well as using TWSC and GLDAS ($VZWC^{GLDAS}$), we investigate the ability of GRACE and in situ data to monitor the vadose zone water content. Our results show that $TWSC^{GRACE}$ correlates better with in situ groundwater data as compared to $GWSC^{GLDAS}$ in all three study areas located in India, Australia, and Belgium, which are some of the hotspots suffering from intensive flash drought in the recent decade. $TWSC^{GRACE}$ shows stronger correlation and better consistency with SPI and land surface temperature as compared to in situ groundwater data. $VZWC^{in\ situ}$ correlates well with $VZWC^{GLDAS}$ but is limited to data availability from the well network. Results from $GWSC^{GLDAS}$ and $VZWC^{GLDAS}$ show that hydrological model outputs can serve as replacement or supplement to estimate GWSC and VZWC when in situ groundwater data is significantly missing.