ABSTRACT

Climate and Anthropogenic Contribution to Groundwater Storage Variability in India

A significant fraction of the Indian population is directly or indirectly involved in agriculture. Over 70% of food grain production in India comes from the irrigated agriculture in which groundwater plays a considerable role. Groundwater has been one of the major driving forces in the irrigated agriculture growth over the last three decades in India, and now about 60% of total irrigated crop production is dependent on groundwater resources. Moreover, groundwater is considered as stored water to meet the requirements during extreme drought conditions and to supplement surface water resources. In the initial stages of the green revolution, surface water was the primary source of irrigation in Indian agriculture. Irrigation using the groundwater resources expanded exponentially from the 1970s due to the availability of mechanical pumps and subsidized electricity supply. This rapid expansion in irrigated areas and resources to pump groundwater caused a noticeable decline in groundwater in many parts of India. Therefore, sustainable management of groundwater resources is essential to meet the requirements of the growing population and for food production. However, our understanding of the relative contribution of groundwater pumping and climate variability on groundwater and terrestrial water storage in India remains limited.

Groundwater plays a major role in food and freshwater security in India that could be compromised in some regions by groundwater depletion primarily due to abstraction for irrigation. Another coincident and generally unacknowledged threat to groundwater resources is the increasingly erratic Indian summer monsoon that has decreased precipitation in many parts of north India and is influenced by sea surface temperature anomalies in the Indian Ocean. However, it remains unclear how the groundwater storage variability in India is driven by abstraction for irrigation or the monsoon season precipitation. To assess the relative influence of pumping and climate variability on groundwater storage in India, we use the groundwater observations from Gravity Recovery and Climate Experiment (GRACE) satellite and well level observations. Our results show that long-term change in the monsoon season rainfall is a major driver of groundwater resource variability in most parts of India either directly by changing recharge or indirectly by changing abstraction. We observed a decline in groundwater storage in northern India at the rate

of 2 cm yr^{-1} and an increase in south India at the rate of 1 to 2 cm yr^{-1} between 2002 and 2013. The changes in precipitation can explain a large fraction of the total variability in groundwater storage in north-central and southern India. Groundwater storage variability in north-western India can be explained predominantly by variability in abstraction for irrigation, which is, in turn, influenced by changes in precipitation. Declining precipitation in northern India is linked to Indian Ocean warming, suggesting a previously unrecognized teleconnection between ocean temperatures and groundwater storage.

Precipitation intensity has changed in the observed climate and likely to change under the future climate in India. However, the crucial impact of precipitation intensity on groundwater recharge in India remains unknown. We evaluate the role of year to year variability of precipitation amount and characteristics (low and high intensity) on groundwater storage variability in India. Using groundwater well level observations, we show the strong linkage between precipitation intensity and groundwater recharge in India. In the northwest and north-central India, the low-intensity precipitation is strongly linked with groundwater recharge, whereas in South India, the major driver is high-intensity precipitation. We observed a decline in the low-intensity precipitation in the northwest and north-central India that are strongly driven by sea surface temperature over the Pacific Ocean. Increases in the high-intensity precipitation in South India are linked with the sea surface temperatures in the Atlantic Ocean. Our results highlight the importance of precipitation intensity for the monsoon season groundwater recharge in India, which can provide insights to manage rapidly declining groundwater resources in India sustainably.

The role of vegetation growth on groundwater storage variability is quantified at annual and seasonal scale using Gravity recovery climate experiment (GRACE) groundwater storage anomaly (GWSA) and Solar-induced chlorophyll fluorescence (SIF). At an annual time scale, precipitation is positively correlated with groundwater storage variability in north-central (NCI), and south India (SI). Whereas in northwest India, precipitation is negatively correlated with GRACE groundwater storage anomaly. The negative correlation between GRACE groundwater storage variability and precipitation in northwest India is attributed to groundwater depletion due to anthropogenic pumping from deep aquifers. We show that crop growth is negatively correlated with groundwater storage variability at annual time scales in north India. Analysis of the two main crop growing seasons (Rabi and Kharif) showed that crop growth is negatively related to groundwater storage in both Kharif (June-September) and Rabi seasons in north India (NWI and NCI). Groundwater contributes more than precipitation in NCI during the Kharif season and in NWI and SI during the Rabi season. We observed an increase in soil moisture and evapotranspiration in Rabi season during 2002-2016, attributed to irrigation for growing crops. Our findings based on three regions (NWI, NCI and SI) and two crop growing seasons (Kharif and Rabi) highlight the need for effective management of groundwater resources by introducing efficient water management practices in India.

To quantify the change in groundwater and terrestrial water storage due to climate variability and anthropogenic pumping, we use Variable Infiltration Capacity Simple Groundwater Model (VIC-SIMGM) and GRACE datasets for the major Indian river basins. The GRACE and well level observations have limitations in their spatial and temporal resolutions. The GRACE observations can be effectively utilized for the regional planning but limited in real-time monitoring of groundwater at high spatial resolution. Moreover, GRACE and well level observations are influenced by the anthropogenic factors, especially in the irrigated regions. We address these critical challenges by establishing a hydrologic modeling framework that integrates satellite observations and high-resolution meteorological forcing. The model was calibrated and evaluated against observed streamflow, well observations, and GRACE terrestrial water storage anomaly. We observed that under anthropogenic influence, groundwater storage anomaly explains the majority of the variability in terrestrial water storage. However, under natural conditions, soil moisture is the major contributor to terrestrial water storage in the majority of India. Moreover, we observed a considerable difference in groundwater drought characteristics under anthropogenic influence compared to natural conditions. Hence, the groundwater droughts can be intensified under the anthropogenic influence, which emphasizes the need for sustainable groundwater management in India.