Depleting groundwater – an opportunity for flood storage? A case study from part of the Ganges River basin, India

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ABSTRACT

Storing excess rainwater underground can become key in mitigating the frequency and magnitude of flood events. In this context, assessment of depleted groundwater storage that can be refilled in water surplus periods is imperative. The study uses Gravity Recovery and Climate Experiment (GRACE) data to identify variations in groundwater storage in the monsoonal Ramganga River basin (tributary of the Ganges, with an area of 32,753 km^2) in India, over the 9-year period of 2002–2010. Results indicate that basin groundwater storage is depleting at the rate of 1.6 bill. m^3 yr^{-1}. This depleted aquifer volume can be used to store floodwater effectively – up to 76% of the rainfall on average across the Ramganga with a maximum of 94% in parts of the basin. However, the major management challenge is to find and introduce technical and policy interventions to augment recharge rates to capture excess water, at required scales.

Key words | climate extremes, flood, Ganges basin/India, GRACE, groundwater, water storage

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INTRODUCTION

India ranks second globally in agricultural output, exceeding the combined outputs of the USA and Australia (Shah 2010). Agricultural water resources are tightly linked with food security and economic growth in the country. Of the agricultural land in India, 64% is rainfed while the remaining 36% depends on surface (rivers, canals, lakes, tanks, ponds) or groundwater irrigation. In the past decade, groundwater use for irrigation has increased due to increasing climate variability, expanding crop area, agricultural intensification and associated increasing difficulties in access to surface water resources (Briscoe & Malik 2005). As a result, more than 60% of the irrigated agriculture and 85% of domestic water demands were satisfied from groundwater resources (GoI 2009; World Bank 2010). This high demand on groundwater resources has led to groundwater extraction rates that were faster than that of the natural recharge rate (Shah 2010; CGWB 2014), thus causing groundwater depletion in many parts of the country (ADB 2007; ADBI 2012).

Quantification of the spatial and temporal dynamics of groundwater storage, and how it responds to short-term (e.g., pumping) and long-term (e.g., climate and land use) stresses, is prerequisite for formulation of plans for sustainable groundwater use (Maheshwari *et al.* 2014; Chinnasamy & Agoramoorthy 2016; Varua *et al.* 2016). This knowledge can lead to establishing sustainable groundwater extraction rates by which groundwater can be extracted both in the long-term period and prior to a monsoon season in any particular year. It can also help in knowing the excess water that can be captured and recharged, in principle, by monsoonal floods, thereby creating a balance between groundwater use and flood attenuation. Possibilities for flood attenuation by underground storage of floodwater have not yet been well studied in regions where groundwater is being depleted at alarming rates, while flood damage is occurring annually (Prakash *et al.* 2014).

Many parts of the Ganges basin are highly prone to flooding (Amarnath *et al.* 2012; Chinnasamy *et al.* 2015a), where flood buffering through underground storage could be useful for mitigating damage. The Ramganga River (basin area of 32,753 km^2) – one of the tributaries of the

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Ganges – is used in this study to illustrate the dynamics of groundwater depletion, and implications of this depletion for flood capture. The Ramganga River flows through the Indian states of Uttarakhand (U.T.) and Uttarpradesh (U.P.), through the Jim Corbett National Park and along through famous pilgrimage sites. The southwest monsoon delivers most of Ramganga's rainfall over a period of 5 months (June to October), when most of the basin is affected by floods, and yet the basin is also drought prone in the remaining months. According to the Disaster Management Department (2014), floods cause an annual loss of 69 million USD, while the severe drought in 2004 alone led to a loss of 1.2 billion USD.

For basin-wide studies, indirect satellite remote sensing (RS) data can be useful as they complement ground observations, cover larger areas at regular intervals and are readily available. The Gravity Recovery and Climate Experiment (GRACE) data have been successful in estimating groundwater storage trends in many regions of the globe (Swenson & Wahr 2006; Velicogna & Wahr 2006; Morrow *et al.* 2011; Chinnasamy & Sunde 2015). For India, Rodell *et al.* (2009) used GRACE data to estimate groundwater depletion rates in the northeastern Indian states of Rajasthan, Punjab and Haryana. The estimated groundwater depletion rate was 13.2 km^3 greater than that reported by the Indian Ministry of Water Resources. In another study, Chinnasamy *et al.* (2013) illustrated that GRACE-derived groundwater level trends for Gujarat State were in agreement with the Central Ground Water Board (CGWB) groundwater trends. That study also advocated the need for CGWB and RS data to be used conjunctively more widely for groundwater management in India. Chinnasamy & Agoramoorthy (2015), in a study using GRACE data for Tamil Nadu, India, inferred that the annual average rate of groundwater withdrawal was 8% more than the natural groundwater recharge rate, thus explaining the declining trend in groundwater storage across the state. They further recommended immediate measures to regulate groundwater use to sustain ongoing agricultural practices. The above examples increase confidence in using GRACE data for estimating changes in groundwater storage.

The major objective of this paper is to assess the potential of RS data to estimate groundwater storage depletion in a data scarce region of the Ramganga basin. The specific objectives of this paper are to quantify trends in groundwater storage in the Ramganga basin during a 9-year period (January 2002 to December 2010) for which GRACE data are available, and to examine the extent to which (if at all) the excess flood water can be stored underground. Such an objective will support the need to increase groundwater management activities to increase groundwater recharge leading to sustainable groundwater use. Comparing the depleted volume against flood water volume, at annual scales, will aid in understanding the source of water for groundwater recharge activities.

DATA AND METHODS

Terrestrial water storage, soil moisture and groundwater storage

GRACE data were used in the study to estimate spatial and temporal dynamics in groundwater storage across the basin. The GRACE satellite mission was launched on 17 March 2002, as a combined effort between the National Aeronautics and Space Administration (NASA) and the Deutschen Zentrum für Luft- und Raumfahrt from the German Aerospace Agency. GRACE is the first RS mission that can estimate global water storage (both surface and groundwater) on a monthly time scale. GRACE records changes in mass that affect the gravitational pull on the satellite, which is later converted to changes in water storage mass. These were in turn converted to net changes in terrestrial water storage (TWS) in units of equivalent water thickness in centimetres (Swenson & Wahr 2006; Landerer & Swenson 2012). A scaled version of the GRACE data – processed and archived by Landerer & Swenson (2012), were used in this study, which enabled the estimation of TWS at 1° by 1° resolution (approximately 100 by 100 km at the study site). Monthly TWS data, in 1° by 1° grid-cells format (version RL05), available from the NASA Jet Propulsion Laboratory (GRCTellus Land grids), were accessed online at the NASA website (ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/). The corresponding scaling factors (Landerer & Swenson 2012) were also accessed from the same website. The scaling factors also accounted for the GRACE data errors, i.e., leakage errors (caused by

GRACE signal leakage from neighbouring land and ocean grids) and measurement errors (caused by errors in processing the raw GRACE data). The GRCTellus Land grids were then multiplied by the scaling grids to arrive at TWS estimates for the study site. The newly released RL05 GRACE data alleviated leakage and measurement errors and improved spatial resolution (1° by 1°), which were limited in past GRACE data versions (Landerer & Swenson 2012). This enabled GRACE-derived water storage analysis for regional, district (Tiwari *et al.* 2011) and even watershed scale (e.g., as in Billah *et al.* (2015), whose study areas were from 30 to 7,000 km^2) water resources assessments. In addition, GRACE data are only available as monthly anomalies with a baseline average (from January 2004 to December 2009) removed, to understand long-term trends in TWS. The GRACE data processing team defines the baseline period (i.e., January 2004 to December 2009). The overall data are available from 2002 April onwards, and can be used as an anomaly in TWS. For the study, data from 2002 April to 2010 December were used.

TWS includes snow, soil moisture (SM), surface water (e.g., dams) and groundwater (both deep and shallow). However, since snow is not present in Ramganga and there have not been any new dams constructed in the basin over the study period, the TWS changes can be attributed only to groundwater storage changes (Rodell *et al.* 2009). Groundwater storage (GW) in Ramganga is therefore the difference between TWS and SM. In addition, since the study aims to quantify maximum groundwater storage depletion during the study period, the data from the summer and pre-monsoon seasons were most important. During these seasons, the surface water storage is low (and mostly negligible as it cancels out with the baseline average) and thus farmers of the Ramganga rely on groundwater resources, which explains the overuse of groundwater in the region. Hence, dynamics of surface water storage during other seasons (mostly monsoon and post-monsoon) should not affect the overall maximum groundwater depletion results sought by the study (Rizvi *et al.* 2013; Dasgupta *et al.* 2014).

SM data are obtained from Global Land Data Assimilations System (GLDAS), developed by the USA NASA Goddard Space Flight Center and the National Oceanic and Atmospheric Administration. GLDAS investigates SM changes using land surface models (LSMs). Rodell *et al.* (2009) compared five GLDAS models for India and chose Noah estimates for their better performance than the other models. Hence, of the various LSMs used by GLDAS, Noah 2.7.1 is used in the current study given its successful application in the Indian sub-continent, particularly in northern India (e.g., Rodell *et al.* 2009; Chinnasamy *et al.* 2015b, 2015c). Noah estimates of SM were accessed in gridded format similar to that of the GRACE data, at monthly averages with a spatial and temporal scale (1° grid-cells/monthly resolution) from the GLDAS website (http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings/parameters). All storage components, i.e., TWS, SM and GW, are reported as equivalent water thickness measured in cm.

Observed groundwater level

The CGWB monitors groundwater levels throughout the country. In the Ramganga basin, CGWB monitors 152 wells (Figure 1). Measurements at each well were taken four times annually, and correspond to pre-monsoon Rabi (January), pre-monsoon (May), monsoon (August) and post-monsoon Kharif seasons (November). The groundwater data were available at the CGWB website (http://www.india-wris.nrsc.gov.in/). The average of all wells was used to estimate the average groundwater status for the basin. For this study, depth to groundwater level from CGWB monitoring wells (from January 2002 to December 2010) was compared against groundwater storage anomaly trends from GRACE data. The data on the depth of the CGWB wells were not readily available; however, CGWB (2014) indicates that 99% of the wells only monitor shallow (unconfined) aquifers in the study region. Therefore, the use of GRACE (which can estimate total groundwater storage change) along with CGWB estimates can indicate differences in shallow and total groundwater depletion. Long-term comparisons were made between GRACE data (observed at monthly intervals) with CGWB well data (measured at quarterly intervals).

Rainfall and runoff

Monthly precipitation data for the Ramganga basin were collected from the India Meteorological Department (IMD). The IMD daily records were also aggregated into monthly values for each climate station. The average

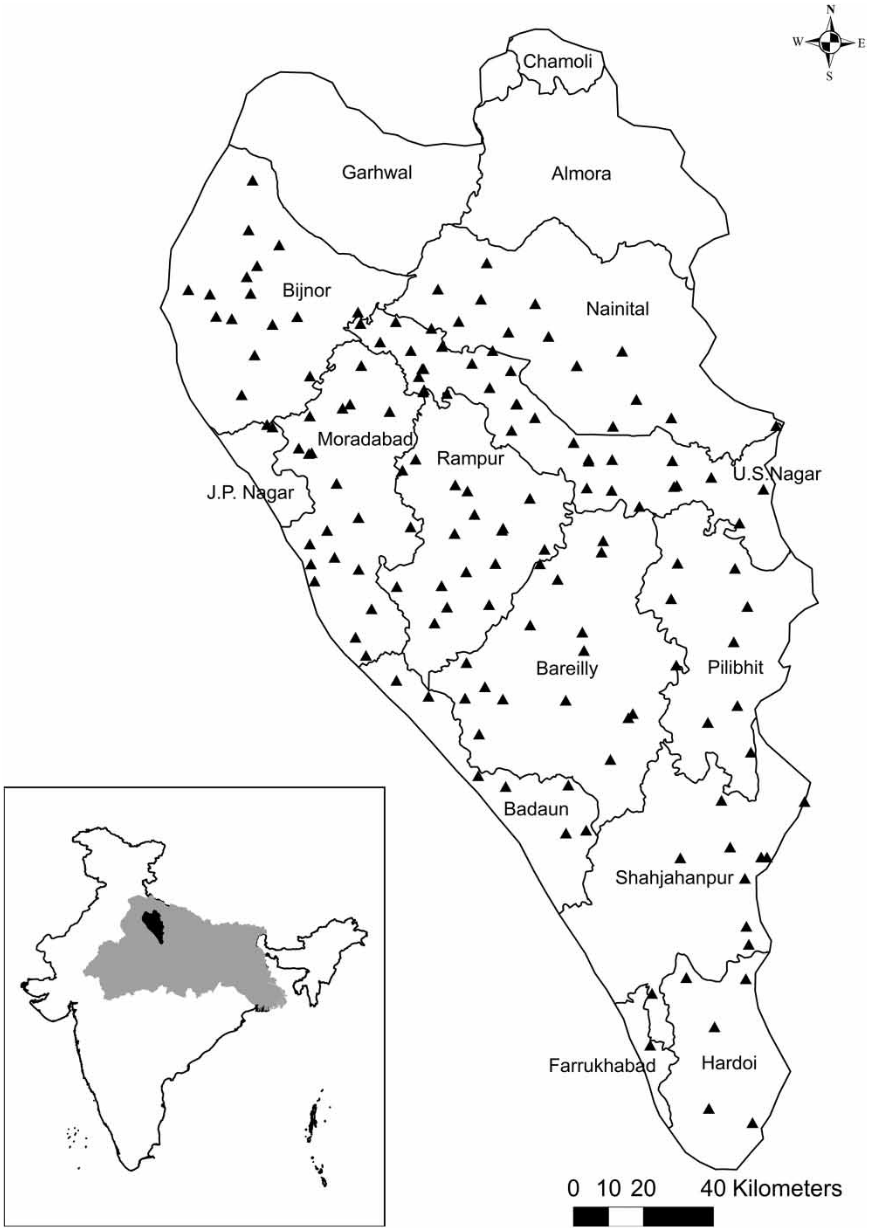

Figure 1 | Location of the Ramganga sub-basin (black) in the Ganges basin, district boundaries and names within Ramganga, and CGWB well locations ($n = 151$ wells – triangles).

monthly rainfall of stations in each district that falls within the Ramganga basin was used in the current study. Runoff is computed using the available published runoff coefficients for the basin (e.g., Chaturvedi 1976; Zade *et al.* 2005).

The above data sets were used to estimate maximum percentage of rainfall and runoff that can be stored in basin aquifers, and therefore, the extent to which groundwater store can reduce flood volumes.

RESULTS AND DISCUSSION

GRACE-derived ground water storage trend

Estimated groundwater storage anomaly values above zero indicate a higher groundwater level than baseline situation (i.e., average groundwater storage from 2004 to 2009), whereas groundwater storage anomaly values below zero indicate a groundwater depletion trend when compared to the baseline scenario. The district level groundwater storage anomalies, estimated for the monsoon month of June, are shown in Figure 2, while the basin averages of monthly groundwater storage anomalies are shown in Figure 3. Groundwater storage anomalies (Figure 2) in the basin indicate that the groundwater storage is decreasing (with respect to the baseline). In addition, the GRACE data for the districts in the Ramganga basin also showed a depleting trend.

The basin-level GRACE analysis (Figure 3) indicated that the groundwater storage was being depleted at the rate of 5 cm yr^{-1}. This rate translates to an annual volume of 1.6 billion cubic metres (BCM). Assuming a specific yield of 0.18 (GEC 2009) for the Ramganga basin, the basin level mean rate of water table decline was estimated to be 0.27 m yr^{-1}. The groundwater storage trend further indicates that the bandwidth of resilience (maximum storage level – minimum storage level) of the Ramganga aquifer is

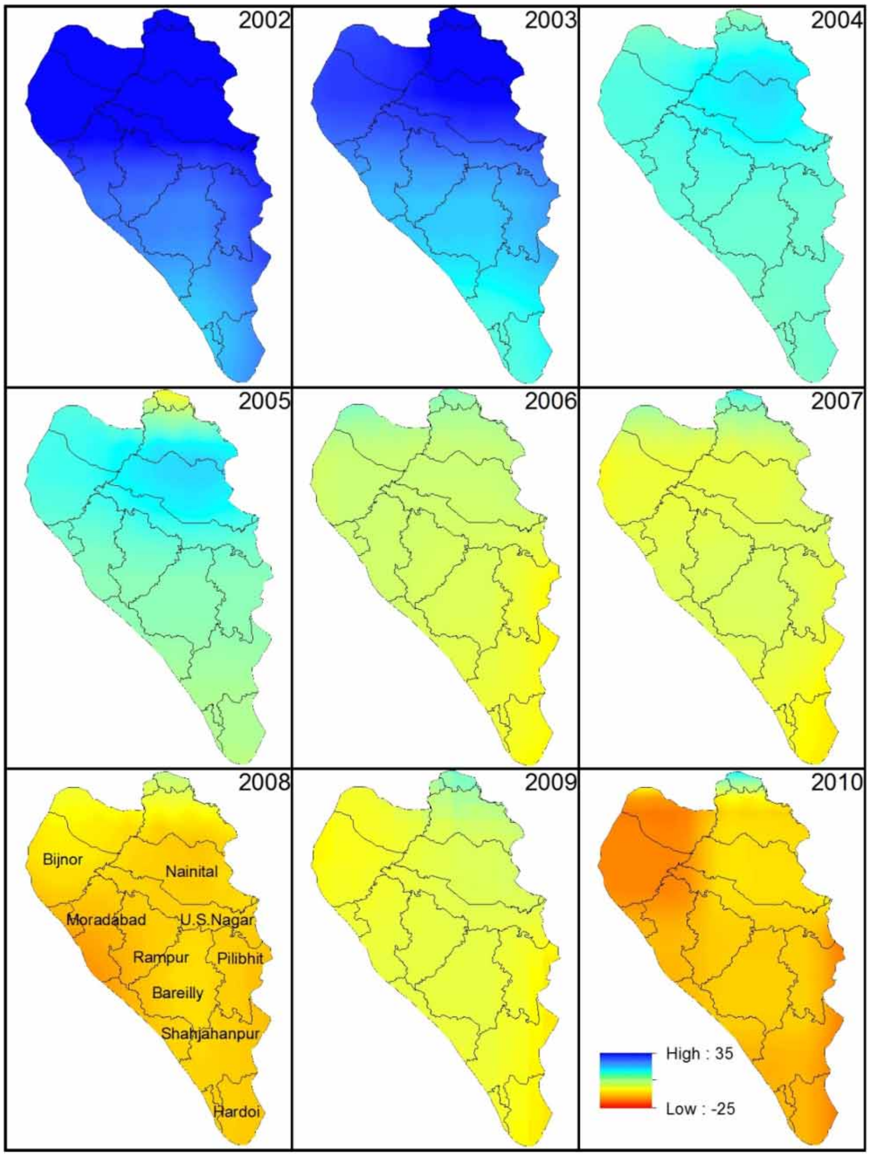

Figure 2 | Ramganga groundwater storage anomaly (cm) from GRACE for the monsoon month of June from 2002 to 2010.

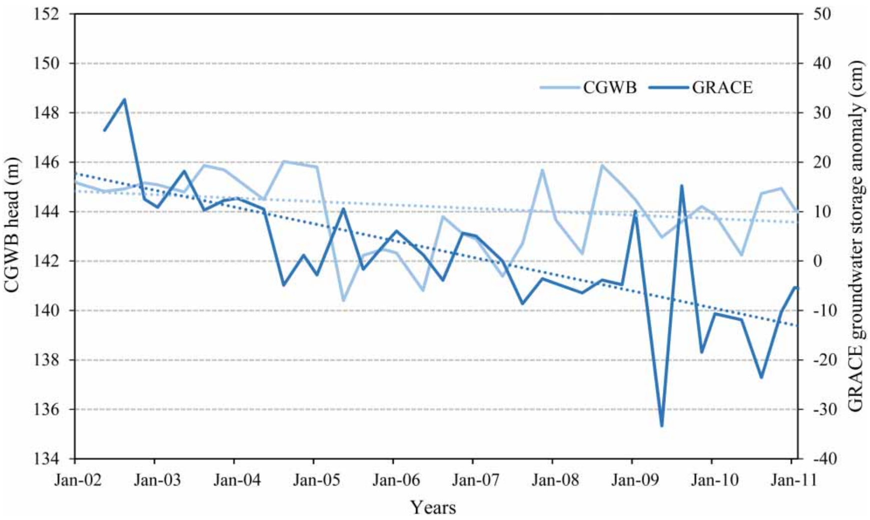

Figure 3 | Comparison between CGWB-derived groundwater head and GRACE-derived groundwater storage anomaly for the Ramganga basin.

73 cm for the study period. However, the aquifer was not able to return to the baseline scenario due to extraction being higher than groundwater recharge. Therefore, the aquifer resilience was breached and the depletion trend continued. These findings were in agreement with Dasgupta *et al.* (2014), who used RS (GRACE) and field measurement data (CGWB well data) and inferred that the groundwater storage depletion in the Gangetic plain was occurring at 4 cm yr^{-1}. The study also indicated that groundwater storage decline at this magnitude will have serious effects on baseflow during dry seasons and on sustainable agriculture. The result also indicates that the groundwater depletion is occurring at a faster rate in the later part of the study period, i.e., 2009 to 2010.

Groundwater head trend

A comparison between GRACE-derived groundwater storage and CGWB groundwater head shows a net depleting trend (Figure 3). However, certain periods in the CGWB groundwater observation do not agree well with the GRACE groundwater storage anomaly. For example, in 2005, both CGWB and GRACE show a declining trend in groundwater. However, the CGWB data reveal an increasing trend after 2006, while the GRACE data continue to decline. This could be due to the fact that the CGWB data mostly monitor shallow aquifers (99% of the wells in the study area monitor shallow aquifer) that were recharged annually (as shown in Figure 3), while GRACE estimates the shallow and deep aquifer, of which the latter may not be recharged annually (CGWB 2014; Dasgupta *et al.* 2014). The CGWB data suggest basin-level mean rate of water table decline of 0.23 m yr^{-1} for the study period. However, the limitation of the CGWB estimate is that it mostly considers unconfined aquifer depletion, while the presence of deep bore wells in the region should also be considered (Shah 2010; Rizvi *et al.* 2013).

Groundwater storage recharge and discharge

The net groundwater discharge for the X^{th} year was estimated by subtracting the GRACE groundwater storage anomaly in the post-monsoon month of the previous year (November of the $(X-1)^{th}$ year) from the groundwater storage anomaly in the monsoon month of the X^{th} year (June of the X^{th} year). Similarly, the net groundwater recharge of the X^{th} year was estimated by subtracting the groundwater storage anomaly in the post-monsoon (November of the X^{th} year) from the groundwater storage anomaly in the monsoon month (June of the X^{th} year). The estimated groundwater discharge included water withdrawal for all sectors (e.g., irrigation, domestic, industry, etc.). In addition, due to the above calculation, the anomalies cancel out resulting in the estimation of net recharge or net discharge thickness. Estimated average recharge, over the study period (2002 to 2010), for the basin was 0.8 BCM per year, while the discharge was 1.6 BCM per year. Thus, the discharge occurred at approximately double the rate of the recharge. It can be hypothesized that if the groundwater recharge rates are increased, the 0.8 BCM per year deficit can be replenished.

Groundwater storage potential for flood control in the Ramganga basin

For district level analysis, CGWB well data were used along with the GRACE estimates (only for those districts greater than 1° by 1° resolution). The district level aquifer bandwidth (i.e., the range between maximum and minimum in GRACE groundwater storage or CGWB groundwater head levels) indicated the potential for flood storage. For the analysis using GRACE, of all the districts, Nainital showed the highest underground storage potential with 2.9 BCM, while Hardoi had the lowest storage of 0.5 BCM (Figure 4). The results of flood storage were similar while using the GEC (2009) water table fluctuation methods with a specific yield of 18% (GEC 2009) for the Ramganga region (Figure 4). Nainital showed the highest underground storage potential with 5.8 BCM, while Hardoi had the lowest with 0.7 BCM. The underground storage volumes were different between GRACE and CGWB, mostly due to the fact that CGWB is a point representation, while GRACE is averaged across the region. An aquifer depleted due to intensive pumping during pre-monsoon months is ideal for the storage of excess flood water during monsoon. Such a decentralized approach in underground storage of floods can also help sharing stored water during dry periods between districts, while surface structures (e.g., dams or canals) only largely benefit areas located immediately near such structures.

Of all administrative districts that fall into Ramganga basin, Nainital had the highest rainfall of 1,603 mm yr^{-1}, while Bareilly had the lowest with 682 mm yr^{-1}. On average, the northern part of the basin receives more rainfall than the southern part. The variation could be due to the topographic gradient changes within the basin, as the northern region has a higher elevation compared to the southern part. From a purely hydrological perspective, a district with an underground storage potential that is close to rainfall volume can be an ideal location to pursue underground storage of floodwater. For example, Bijnor district, with an average annual underground storage of 2.3 BCM, can accommodate 96% of mean annual rainfall volume. Thus, if Bijnor can store most of the rainfall, downstream flooding can be reduced. The result for Bijnor, while using CGWB well data, indicated

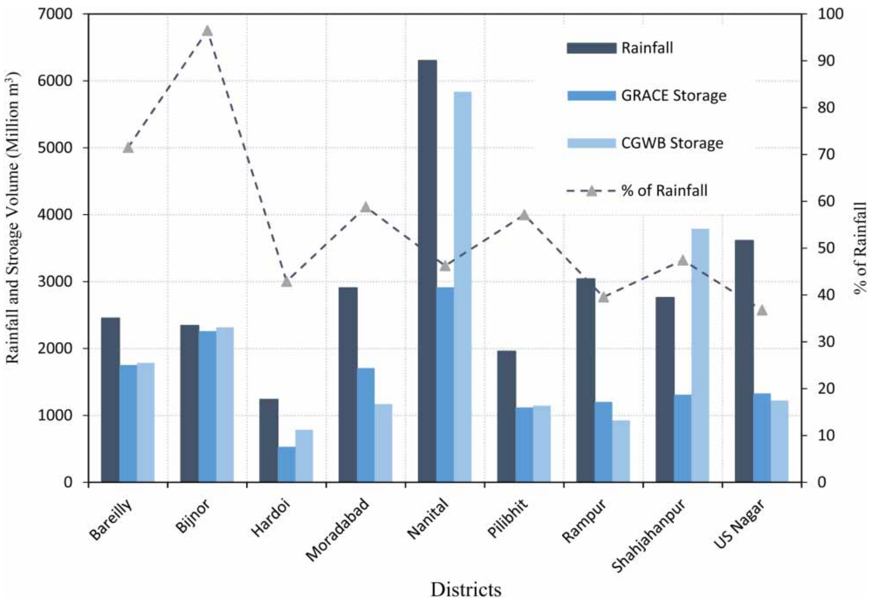

Figure 4 | Comparison between rainfall volume, groundwater storage volume and potential of storage at a district level inferred from GRACE and CGWB data.

that 99% of mean annual rainfall can be stored in the underground storage, thus also indicating that GRACE (with an estimation of 96% storage) and CGWB data (with an estimation of 99% storage) captured similar underground storage volumes. Similarly, underground storage volume is high in most northern regions. Therefore, there is a prerequisite for storing flood water underground more in the northern districts – so that downstream southern districts can be less affected by floods. Specifically, both GRACE and CGWB estimates indicate that the northern Nainital, Moradabad and Rampur districts can store, in principle, at least 50% of their rainfall volume, thus preventing significant amounts of water going downstream and causing flood damage. With the same method using GRACE data, the Ramganga basin, on average, can store up to 76% of the incident rainfall in groundwater storage annually.

It is important to understand flood storage potential at annual intervals. Mutuwatte *et al.* (2015) estimate that the sub-basins in Ramganga have a mean annual surface runoff of 0.1 to 2 BCM, with around 12 BCM total monsoon surface runoff at the Ramganga confluence with the Ganges. From the current study, the current annual groundwater depletion storage volume of 1.6 BCM can store up to 14% of this total basin runoff (12 BCM). Naturally, part of the stored water will contribute to baseflow, increasing streamflow discharge; however, the timing and magnitude of peak flooding can be moderated. Thus, groundwater stores have high potential in reducing long-term and annual flood damage. However, artificial methods are needed to augment natural recharge rates in order to use the groundwater stores in this way and to create extra storage.

Approaches for accelerated groundwater recharge with floodwater

Many methods for flood reduction by storage of surplus surface runoff/flood water have been documented across the globe (Dillon 2005; Gale 2005; Dillon *et al.* 2009; Pavelic *et al.* 2012; Li *et al.* 2015). Pavelic *et al.* (2012) note that these approaches fall into two categories: (1) surface storage of surplus water (e.g., dams, rainwater harvesting, etc.) and (2) aquifer storage (including subsurface and deep aquifers) of surplus water (e.g., check dams, managed aquifer). The latter method has a lesser need for acquiring land and relocation, when compared with surface water storage structures, and is more widely practised (Dillon 2005). In recent years, there has been an increase in groundwater storage of surplus flood water through managed aquifer recharge (MAR) methods (Gale 2005; Pavelic *et al.* 2012; Khan *et al.* 2014; Maheshwari *et al.* 2014; Varua *et al.* 2016).

A comprehensive inventory of devices and methods available for MARs can be found in Gale (2005) and Escalante & Sauto (2012). MAR methods can be broadly classified into six systems: (1) disperse (e.g., infiltration ponds, infiltration fields, irrigation channels); (2) channels (e.g., dykes, diversions); (3) wells (e.g., open infiltration wells, deep wells, mini-probes, dolines); (4) filtration (e.g., filtration banks, inter-dune filtration, subterranean irrigation); (5) rain (e.g., rainwater capture); and (6) sustainable drainage urban systems (e.g., sewerage recharge, urban drainage systems). Methods are selected considering the recharge needs, limitations due to hydrogeological setting and costs for installation and maintenance.

In a case study in the Chao Phraya River basin (Thailand), Pavelic *et al.* (2012) indicated that dedicating 200 km^2 of land to MAR-based groundwater recharge can result in substantial reduction of floods (of up to 5 BCM per year) and flood-related damage (up to 250 million dollars per year). Infiltration ponds and basin plans were used in Israel to reduce peak river floods (Gale 2005). Rain gardens, as a form of decentralized flood water control, were used to manage urban storm runoff and increase groundwater recharge in the Shepherd Creek watershed, Cincinnati, Ohio (Shuster *et al.* 2007). Their study results indicated a recharge of up to 6 cm in some regions in the watershed, which was three times more than in regions without such infrastructure.

Groundwater irrigation countries like India have started investing in intensive decentralized groundwater management activities (Shah 2008). According to the Indian Government's Groundwater Recharge Master Plan (GoI 2005), intensive groundwater management plans can aid in increasing dry season water availability and reducing flood damage. In addition, Shah (2008) recommends the government to operate surface water systems to augment natural groundwater recharge rates, e.g., by linking canals to divert surplus floodwaters to a network of MARs (recharge ponds and dug wells) for a year-round recharge. The Ghed Canal in

Saurashtra and Sujalam Sufalam transport system in north Gujarat (India) are examples of successful implementation of this plan. Shah (2008) indicates that investments in groundwater management can increase groundwater recharge rates up to 41 BCM per year for some agriculturally intensive states in India, which is nearly 50% of their total annual groundwater draft.

Khan *et al.* (2014) evaluated three conjunctive use management strategies that aimed at reducing flooding by storage of monsoonal discharge in the Ganges basin: the Ganges Water Machine (GWM), Pumping Along Canals (PAC) and Distributed Pumping and Recharge (DPR). Their results indicated that 6 to 37% of the flood water in Uttar Pradesh state (in the Ganges basin) can be stored in the subsurface, and thus flood damage can be highly reduced. To reduce the floods, the pumping costs were estimated to be 1.5, 0.8 and 0.4 billion USD per year for GWM, PAC and DPR, respectively. This is much less compared to the annual flood damage in the basin, e.g., Dewan (2013) estimates that the flooding in Bangladesh (in the Ganges basin) alone caused a loss of 2.3 and 1.4 billion USD due to the 2004 and 2007 floods, respectively. Khan *et al.* (2014) further indicate that considerable public investments and management are needed for successful implications of these strategies. The authors argue that the DPR is less costly than other methods due to a decentralized approach via adoption of existing water use practices across the basin. Khan *et al.* (2014), similar to the current study, recommend the need for pilot projects to provide information on improving design, assumptions of hydrogeologic parameters and for improving models to reflect site-specific conditions. The aforementioned examples show the potential of MAR structures to store surplus flood water in a seasonally flooded basin like the Ramganga.

Chaturvedi (1976) and Zade *et al.* (2005) reported that 44 and 49% of the annual rainfall (1,165 and 1,116 mm, respectively) contributed to runoff in the Ganges basin. Hence, underground storage estimated in this study has the potential to store all of the runoff generated within the basin. However, surface water and groundwater resources in India are still managed separately. This compartmentalization may partially explain why less groundwater management activities use flood water even though risks due to flood and groundwater depletion are high.

LIMITATIONS

GRACE data, with a resolution of 100 km radius, may have errors due to signal leakages from other geophysical features near the Ramganga basin. However, over the past years, GRACE data have been effective in analysing groundwater levels in small-scale regions. It is assumed that signal leakage errors (if present) in this study would be homogenous across the entire study area, and therefore the errors will cancel out when estimating differences (as done in the current study). In addition, completely isolating the exact contributions from variations in the amount of surface water (e.g., irrigation, lakes and rivers) was not possible for the current study as surface water data were not available for this region in India. Future studies should therefore develop tools that incorporate RS data with limited observation data to aid in surface water and groundwater storage assessments.

CONCLUSIONS

This study analysed the potential of underground stores to capture annual floods, using the Ramganga basin as an example. Results indicate that 76% of the incident annual rainfall can be stored in the basin. With reference to the start of the study period (2002), the maximum net storage emptied in the basin by the end of 2010 was 29.5% more than average annual basin runoff. Most of the northern districts can store 50% of the rainfall and can thus reduce downstream flood impacts. Increasing groundwater volume, due to such storage, can be a vital irrigation source during non-monsoon months.

The underlying and implicit assumption of this study is that the underground store can be rapidly filled in the wet season and used in the following dry season. However, the major challenge is to identify cost-effective methods that can accelerate infiltration of flood water into underground storage. In the Ramganga basin, low natural groundwater recharge rates, coupled with increasing pumping, leads to continuing groundwater depletion. There is an urgent need to test and implement artificial recharge technologies that can increase recharge of floodwater into the progressively emptying groundwater storage. Consideration of existing and increasing ‘free’ underground stores in river basins may be seen as an opportunity to diversify options used in planning flood prevention and water supply augmentation measures.

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