A century of groundwater accumulation in Pakistan and northwest India

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Abstract

The groundwater systems of northwest India and central Pakistan are amongst the most heavily exploited in the world. Groundwater has been monitored in the region for more than a century resulting in a unique long-term record of groundwater level change. Here we present an analysis of post-monsoon groundwater levels from 1900 to 2010. We show that for the majority of the last century groundwater levels were rising and calculate net groundwater accumulation of c.350 km^3 (estimated range: 150-450 km^3). Large scale irrigation development via canal construction played a defining role in groundwater accumulation during the early twentieth century. More recent, and well documented, groundwater depletion c.75 km^3(estimate range: 25-100 km^3) occurred during the first decade of the 21st century and was driven by the superimposed effects of low rainfall and large-scale tubewell development. However, between 1970–2000, when large increases in tubewell irrigation began, groundwater levels stabilised as a result of higher than average rainfall. Human activity in the early 20th century increased the total volume of groundwater available prior to large-scale exploitation in the late 20th century.

Main

The transboundary aquifer of central Pakistan and northwest India sits below one of the most intensively irrigated areas in the world. In the first two decades of the 21st century several studies, largely using the Gravity Recovery and Climate Experiment (GRACE) satellites, identified groundwater depletion in the region[1-6]. Declining groundwater levels were attributed to increased groundwater abstraction which began in the late 20th century to supplement surface water irrigation. More recently a number of studies have demonstrated the value of using in-situ measurements of groundwater level to understand the nuance of groundwater level change in the region[4,7,8]. These studies highlight the impact of changes in monsoon precipitation[7] and recharge from the vast canal network[9] as playing an important role in controlling groundwater storage in the region.

Northwest India and central Pakistan are vital agricultural areas and have a long history of major surface and groundwater development. The area represents the largest contiguous tract of irrigated land in the world[10] and the most intensively irrigated[11]. Historically, irrigation was dependent on a vast network of canals. The earliest of these canals date back to the 16th century and were constructed by the Mughals[12]. During British rule the canal network was refurbished and expanded[12,13]. Expansion of the canal network started in the middle of the 19th century, accelerated in the early 20th and continued after Independence in 1947[12-14]. However, in the early 1970s the area irrigated using groundwater surpassed that irrigated by surface water in India for the first time. For a number of reasons, including state policy, the number of irrigation tubewells has increased ever since[15]. Northwest India and central Pakistan have become global hotspots of groundwater exploitation[6,15-17].

To date there has been little consideration of the long-term impact of historical water resource developments on groundwater in the region. Here, for the first time, we investigate groundwater level changes throughout the 20th century in central Pakistan and northwest India (Fig 1a). To do so we have constructed a unique long-term dataset containing 3827 observation well (OW) time-series covering 110 years of groundwater level data from 1900 to 2010 (Fig 1b-c and Supplementary Figs 1-4). Our aim here is to: 1) examine changes in post-monsoon groundwater levels during the 20th century and; 2) unravel the influence of canal construction (using the regions canal command (CC) network shown in Fig 1d), tubewell development (Fig 1e) and precipitation on long-term groundwater storage in northwest India and central Pakistan. While precipitation and groundwater development are important controls on groundwater level, we demonstrate, for the first time on a regional and centennial scale, that groundwater accumulation driven by large increases in canal irrigation was the defining feature of groundwater level change in northwest India and central Pakistan in the 20^{th} century.

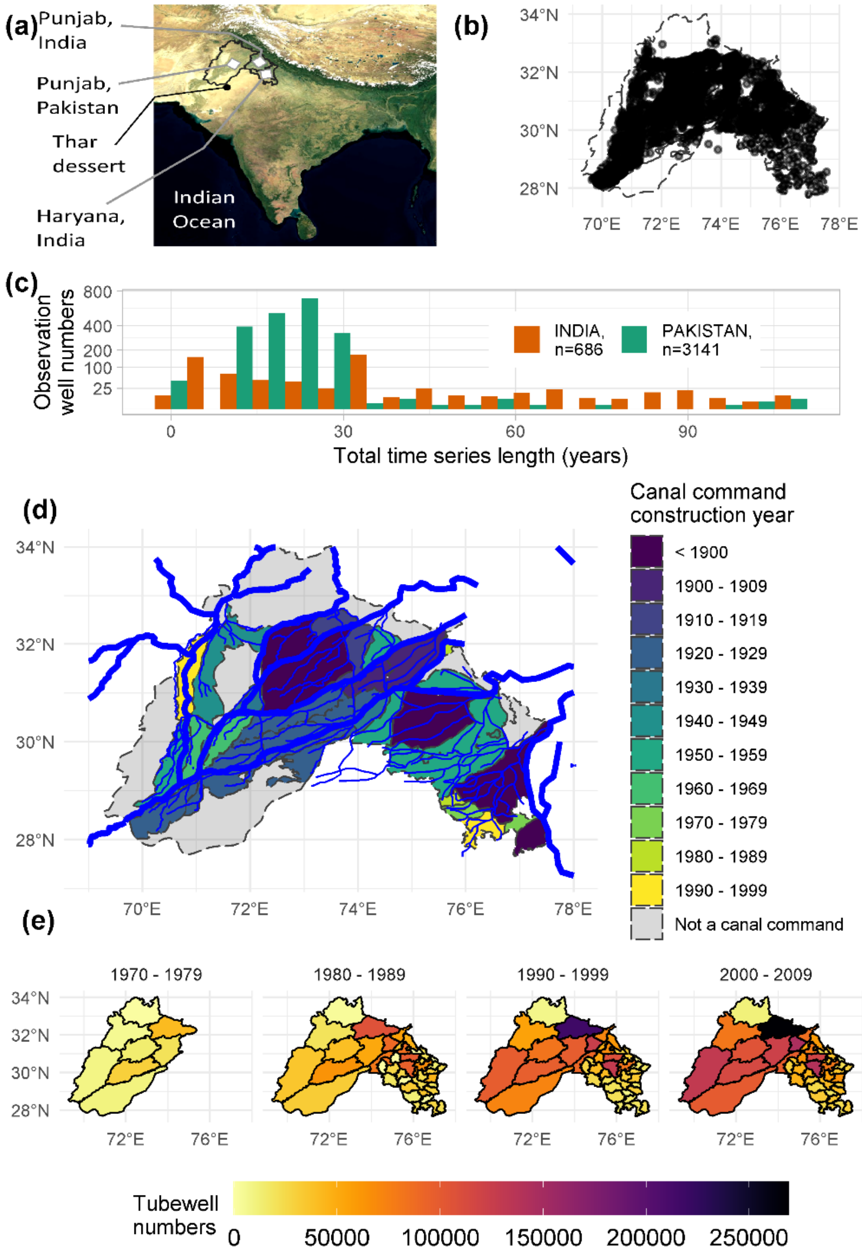

Figure 1 – a) The study area, bounded by the black lines, includes the intensively irrigated areas of northwest India and central Pakistan. Irrigated land is clearly visible running through the centre of the arid areas west of the Thar desert towards the Indian ocean. © MapTiler © OpenStreetMap contributors. b) Location of observation wells (OW) used in the study. c) Histogram showing distribution of OW time-series lengths (see Supplementary Figs. 1-4 for more details of the dataset). d) Canal command (CC) areas and decade of construction and/or refurbishment. Also shown are major rivers (thick blue lines) and canals (thin blue lines) in the study area. e) Distribution of, and increase in, irrigation tubewells across the study area, no data was available prior to 1980 in India or 1970 in Pakistan.

A century of groundwater level change

During 1900–1960 groundwater levels in northwest India and central Pakistan show a consistently rising trend except for some areas in central Indian Punjab (Fig 2a-b) where canals were constructed in the 19th century (Fig 1d). From 1960–2000 groundwater levels stabilised and the trend reversed after 2000, although groundwater levels continued to rise in some areas, most notably southwest Indian Punjab and in parts of Pakistan. In India groundwater level declines began in 1980–1989 but became more significant in 2000–2009. Rises in southwest Punjab in 2000–2009 can be explained by continued dominance of canal irrigation[18,19]. In Pakistan groundwater levels were generally stationary or rising in 2000–2009. Groundwater levels were generally less than 20 m below ground across the region (Fig. 1a). The deepest water levels were in Indian Punjab in 1930–1960 and in Haryana during 1950–1960 (Fig 1a and Supplementary Figs 6-7).

Influence of canals and precipitation

Groundwater level changes from 1900–2010 can be explained by a combination of three factors: canal construction (Fig 1d), tubewell development (Fig 1e) and precipitation (Fig 2c-d). During 1900–1960 rainfall was below the study period mean (Fig 2c-d). Despite this, and with the exception of Indian Punjab during 1910–1940 (Fig 1a-b), the trend across canal command (CC) areas was of rising groundwater levels (Fig 2a-d). The majority of canals were constructed between 1900-1960 (Fig 1d), explaining rising groundwater levels in this period (Fig 2d). Between 1970–2000 canal construction decreased (Fig 1d and 2d), rainfall was above average (Fig 1c) but groundwater levels were stationary (with some spatial and temporal variability) due to increased tubewell development (Fig 1e). However, by 2000–2009 groundwater level decline occurred across the majority of Indian Punjab and Haryana coinciding with below average rainfall. In Pakistan, where rainfall was nearer the long-term average, water levels were stationary with some south-eastern CCs on the Indian border experiencing rising groundwater levels and others in central Pakistan Punjab experiencing declines.

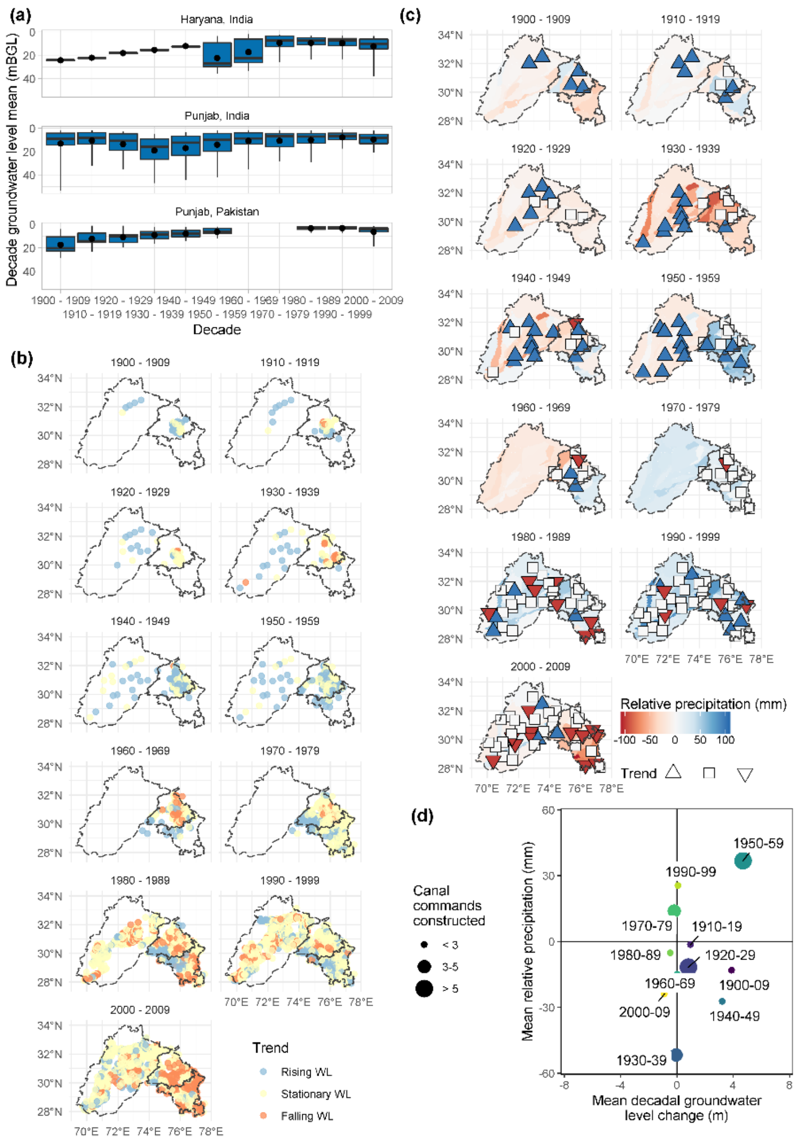

Figure 2 – a) Mean groundwater level (metres below ground level – mBGL) in each state and decade. The black line is the median, the black dot the mean, the 75th and 25th percentiles are shown by the upper and lower bounds of the blue box respectively and the whiskers represent the 95th and 5th percentiles respectively. Supplementary Fig. 5. shows outliers. Supplementary Figs 6-7 show maps of mean decadal OW and CC groundwater levels. b) Mann-Kendall groundwater level trend based on a minimum of 6 observations from each OW in a decade. Supplementary Figs 8-10 show trend results using 4, 6, and 8 observations in a decade. c) Map shading shows deviation from mean precipitation and symbols show mode (>50% OWs) Mann-Kendall groundwater level trend for each CC area (including prior to CC construction). No symbols mean missing data. Symbol infills are red for falling groundwater level, blue for rising groundwater level and white for stationary groundwater level. Supplementary Fig 11 is larger version. d) Mean decadal relative precipitation versus mean decadal groundwater level change. Individual OWs are coloured to match the scale in Fig 1d. Supplementary Fig 12 shows individual decadal observations. In decades when rainfall was below mean, i.e. 1970–1980 and 2000–2009, water levels were lower at the end of the decade than they were at the start. Points in the lower right, which represent decades 1900–1960, show rising groundwater levels but below mean precipitation, demonstrating the influence of canal construction on groundwater levels.

To further investigate the dynamics of groundwater level change in the region we examined the relationship between the standardised precipitation index (SPI) and standardised groundwater levels (SGWL) in a number of CCs (Fig 3). We consider four broad categories of groundwater level change. The first group show consistently rising groundwater levels throughout the 1900s, then steady or slightly falling groundwater levels and more significant declines in the 2000s. CCs in this first group include the Lower Jhelum (Fig 3a), Central Bari Doab (Fig 3d) and Mailsi CCs (Fig 3e) in Pakistan. Many canals were constructed in Pakistan between 1890–1930 (Fig 3) leading to rising groundwater levels. In Central Bari Doab, groundwater levels were stable until 1940 after which rises occurred. Groundwater level decline occurred in the 2000s coinciding with declines in precipitation and increased tubewell development (Fig 1e). Groundwater levels increased in the latter part of the 2000s due to rising precipitation.

The second group display consistently rising water levels throughout the 20th century followed by stable groundwater levels in the 2000s. CCs in this group include Shahnehar (Fig3b) and Bist Doab (Fig 3c) in north Indian Punjab and the Sirhind feeder system (Fig 3h) in southwest Indian Punjab, all were constructed between 1950–1990. Shahnehar and Bist Doab display similar behaviour with clear changes in gradient around the time of canal construction. Shahnehar is a small CC that was likely influenced by surrounding CCs prior to construction, explaining rising groundwater levels in the 1930s despite low average rainfall. Sirhind feeder in southwest Punjab experiences the most consistent rises in groundwater level in the 20th century, likely influenced by the higher use of surface water irrigation in this region[20].

The third group of groundwater level behaviour begins with stable groundwater levels, followed by declines in the 1930s, stables water levels until the 1950s, rises in the 1950s, stable or declining levels in the 1960s and then stable groundwater levels after 1970. Significant declines occur after 1990. This category includes the Bharka (Fig 3g), Sirhind CCs (Fig 3i) and non-CC areas in Punjab (Fig 3f). These areas are strongly influenced by rainfall in the 20th century and groundwater abstraction in the 21st. The fourth category is areas with less extensive canal networks in Haryana (Fig 3j) which display the largest groundwater level fluctuations driven by changing rainfall and increased abstraction after 1990 (Fig 1e).

The contrast between the Bist Doab and Bharka CCs illustrates the relative importance of canals and rainfall on groundwater level change. In Bist Doab (Fig 3b) groundwater levels increased fastest immediately after CC commissioning in the 1950s but rainfall appears more important thereafter (i.e. lower rainfall in 1970s, 1990s and 2000s). In the Bharka CC, groundwater levels were stable between 1960–2000 despite lower rainfall in the 1970s and 1990s illustrating a less immediate but more sustained response to commissioning. Canals appear to have a stronger influence on groundwater levels in the south[21] than the north where rainfall is higher[18,22].

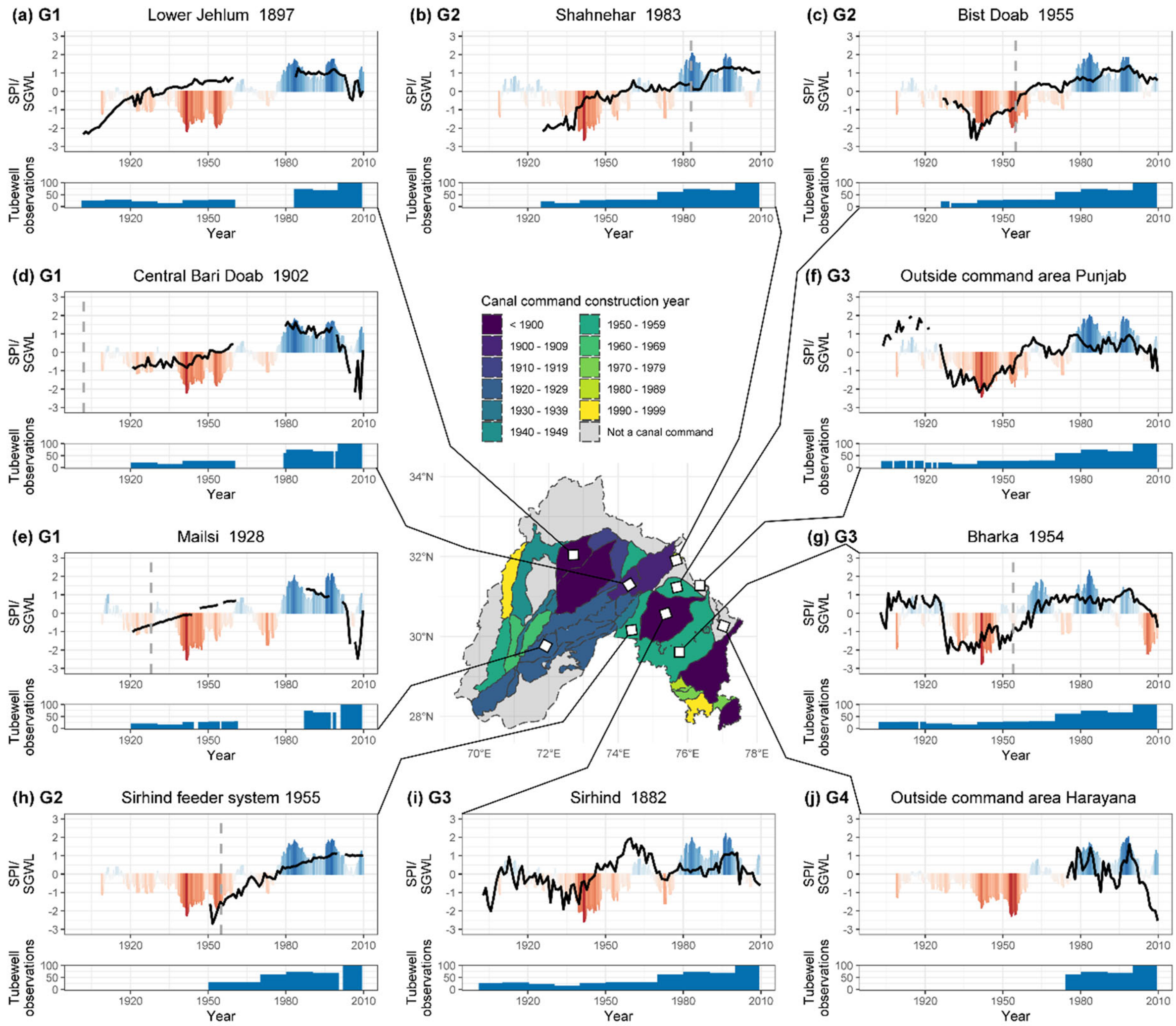

Figure 3 – Mean standardised groundwater level (SGWL), shown by the black line, and standardised precipitation index (SPI), shown by the coloured histogram (darker colours show higher SPI and vice-versa), in selected CC and non-CC areas. The date that each CC is constructed is shown in the subplot title, as is the hydrograph grouping discussed in the text (G1–G4). In cases where the CC was constructed during the study period the commissioning date is shown by a grey dashed line in the main plot. The map shows the location of each CC and decade of CC commissioning. The subplot in each figure shows the mean number of OWs that were used to calculate mean CC SGWL.

A century of groundwater level accumulation

We estimate net groundwater accumulation in northwest India and central Pakistan between 1900 and 2010 was c.350 km^3 (with an estimated range of 150-450 km^3) (Fig 4b, also Supplementary Figs 14-15 for slope estimates and Supplementary Figs 15-17 for state estimates of accumulation). Our estimates are conservative as there is also evidence that groundwater levels were rising in the latter part of the 19th century[23,24]. Groundwater storage peaked in the 1970s. Depletion of groundwater in the 2000s was c.25-100 km^3, similar to previous estimates[9] and approximately a fifth of net groundwater accumulation between 1900–2000. The majority of groundwater accumulation occurred between 1900–1960 which coincided with lower average rainfall (Fig 4a) and significant increases in total CC area (Fig 4c). Approximately 150,000 km^2 of CC area was constructed between 1900–1960 which resulted in groundwater level increases despite lower average rainfall (Fig 4a). The highest rate of groundwater accumulation occurred after construction of CCs in 1920–1940. A second period of canal construction in the 1950s was followed by lower average rainfall in the 1960s resulting in a lower rate of accumulation. After 1960 only about 20 km^2 of CC was constructed but almost six million tubewells were drilled between 1970–2010. However, because rainfall was higher than average between 1970–1990 groundwater levels stabilised. In 2000–2009 lower average rainfall and continued tubewell development led to groundwater depletion. Tubewell development was concentrated in central Indian Punjab and in a north-south band in central Pakistan Punjab (Fig 1e) which corresponds to areas of declining and deep groundwater levels in 2000–2009 (Fig 2b and Supplementary Figs. 6-7).

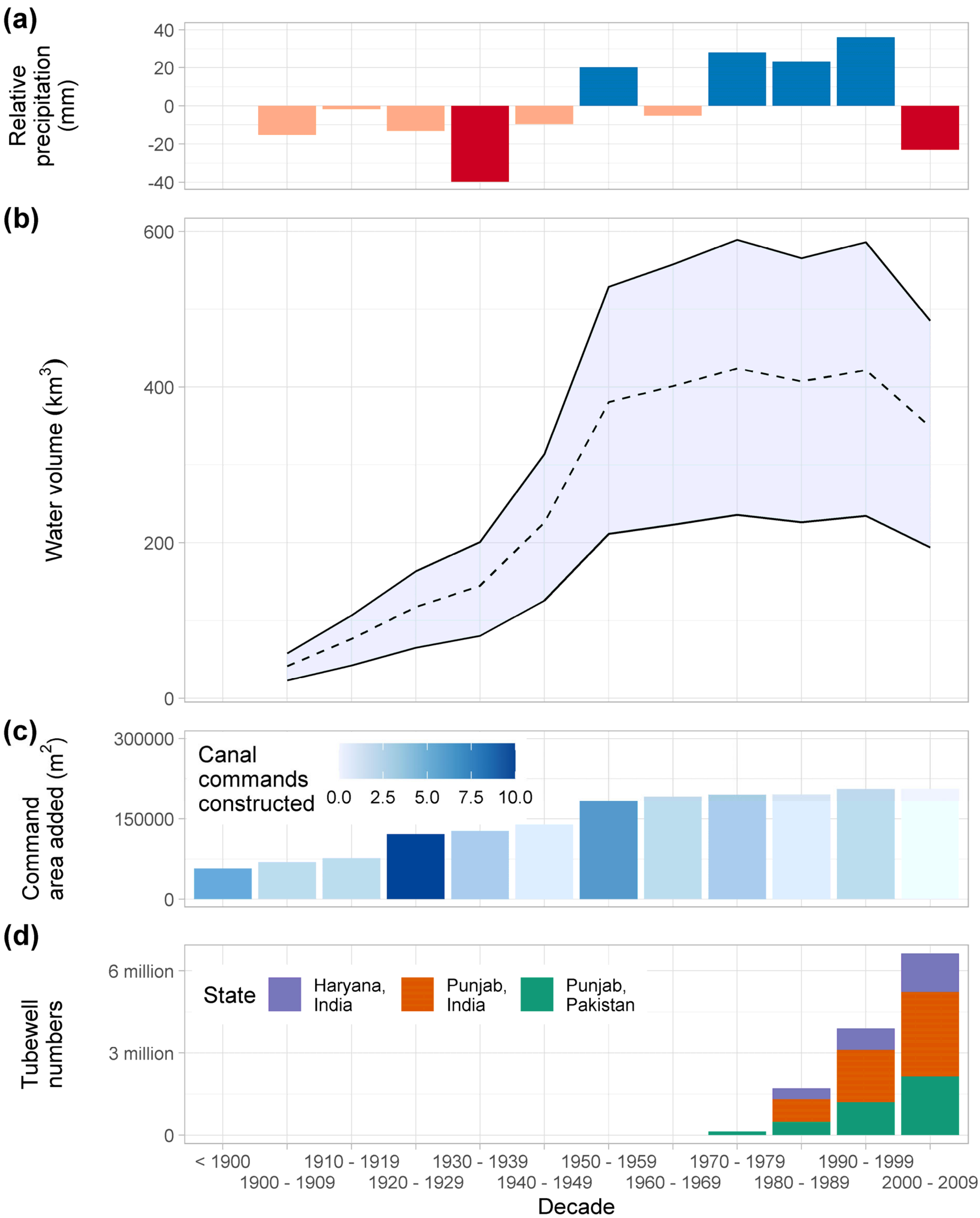

Figure 4 – a) Precipitation relative to long-term mean rainfall in the study area for each decade. b) Estimated groundwater accumulation in the study area. The blue envelope shows the estimated range of accumulation, the dashed line shows the best estimate, the porosity values used to calculate groundwater accumulation were based on previous work in the study area. See Supplementary Figs. 15-17 for estimates of accumulation within Haryana and Indian and Pakistan Punjab. Note that slope estimates were not possible for Pakistan between 1960–1980 so accumulation was not calculated for this period in Pakistan. c) Number of CCs constructed and area added in each decade. d) Increase in tubewell numbers in the study area.

Human and climate influence on groundwater storage

Recent anthropogenic drivers of groundwater depletion in northwest India and central Pakistan are well documented[1-6]. However, by taking a long term view we show that human activity had substantial influence on groundwater prior to large scale exploitation. Human activity has, to a greater extent over a longer period of time, led to increases in the total volume of groundwater available in the region. We demonstrate that, for the greater part of the 20th century, canal construction led to groundwater accumulation. While other studies have identified the importance of canals for groundwater recharge on a smaller spatial and temporal scale[21,25], our study is the first to quantify the effect of canals on a regional and centennial scale. The CCs of northwest India and central Pakistan may represent the world's largest, if unintended, aquifer recharge system.

The underlying reasons for increased groundwater abstraction in areas historically associated with surface water irrigation are complex[17,26-28] but include drought[28], climatic change[7] and evolving agricultural and energy policy[15]. We demonstrate that the superimposed effects of groundwater abstraction and low precipitation explains groundwater depletion in the 21^{st} century and that higher precipitation from the 1950s to the 1990s offset the effects of increased groundwater abstraction until the 21^{st} century. While canal development was the primary control on groundwater accumulation in the early 20^{th} century, rainfall was important for recharging the aquifer and maintaining elevated groundwater levels later in the century. Recent evidence suggests that monsoon precipitation is decreasing[729] which has implications for groundwater recharge in the region. Nevertheless, the north-westward shift of late season monsoon precipitation[30] may offset the effects of overall decreases in monsoon precipitation. In addition to direct recharge from rainfall, increased glacier melt will also affect recharge from canals and rivers[31,32]. Given the uncertainties associated with these important processes the depletion that occurred in the 2000s illustrates the dangers of continued unmanaged abstraction. Recent studies have shown that modest decreases in abstraction (c.20%)[33] have the potential to decrease rates of groundwater depletion by c.36-67%[20]. The largest impacts are likely to be in the most heavily exploited areas. In some areas in India groundwater levels have risen in the decade following our study period (2010–2019)[20]. In other areas increasing salinity may be forcing farmers to use canal water for irrigation resulting in rising groundwater levels[20]. Where groundwater depletion is high the increased cost of abstraction may moderate demand and slow rates of decline[34].

Using a unique long-term dataset of post-monsoon groundwater level observations, we demonstrate that throughout the first half of the 20th century groundwater levels were rising across central Pakistan and northwest India, despite lower average rainfall in this period. We identify four categories of long-term groundwater level behaviour and demonstrate that groundwater accumulation can be explained by the interplay of rainfall, canal construction and tubewell development. From 1900–1960 approximately 125,000 km^2 of CC area was constructed. The construction of these canals led to total net groundwater accumulation of c.350 km^3 (with an estimated range of 150-450 km^3). Much of this accumulation happened when rainfall was below the 20^{th} century average during 1900-1960. Only in the first decade of the 21^{st} century did this trend reverse when approximately a fifth (or c.75 km^3, with an estimated range of c.25-100 km^3) of accumulated groundwater was lost due to the superimposed, and linked[7], effects of below mean rainfall and increased groundwater abstraction. The substantial loss of stored groundwater in 2000–2009 serves as a warning about the consequences of over abstraction of groundwater in the region, particularly when severe drought occurs[29] inducing increased abstraction[7] and further groundwater depletion. However, distribution of surface water via canals continues to occur on a vast scale across the region and canal leakage (up to 50%[35]) will continue to provide a source of recharge[18,21] counteracting the effects of over abstraction. Small decreases in groundwater abstraction, irrigation efficiency improvements, conjunctive use of surface water and groundwater and, appropriate electricity and agricultural policy have the potential to reverse groundwater depletion in northwest India and central Pakistan[10,15,17,20,26-28,31,36,37].

Methodology

Development of long-term groundwater level dataset

To construct the long-term groundwater level dataset, data were collated from a number of different sources. Firstly, groundwater level data were digitised from two historic reports. The first of these reported groundwater levels from the early 1900s to the early 1960s in the Punjab in Pakistan[24]. The second reported groundwater levels between the early 1900s and mid-1970s in northern Haryana and southern Punjab in India[23]. Secondly, digital records of groundwater level representing periods from 1895–1960 and 1980–2010 were provided by the Pakistan Water and Power Development Authority for Punjab in Pakistan. Thirdly, long-term hydrographs were digitised from original paper records provided by the Agricultural Department of the Government of Punjab, these represented data from pre-1900 to the early 2000s. Separate, digital records of groundwater level, covering the period from 1975–2016 were provided by the Agricultural Departments of Punjab and Haryana. Finally, a dataset containing groundwater levels from both India and Pakistan for the period from 2000–2012 were added to the dataset[9]. The collated dataset, which contains 3827 individual OW records, represents a range of different time-series length and observation frequencies (see Fig 1c and Supplementary Figs 1-4). In order to create the maximum possible number of individual continuous time-series records for the study period (1900–2010) historic and recent data were combined. The criteria for combining historic and recent data were, 1) the same OW name or identification number, 2) the same coordinates or, 3) if historic and recent data were within 5 km.

Water resource development dataset

Tubewell numbers for Pakistan were obtained from the annual statistical abstracts of the Bureau of Statistics Planning & Development Board of the Government of the Punjab. Data prior to 1980 were obtained from the 2003 report[38] and more recent data from the 2019 report[39]. In India tubewell numbers were obtained from the Punjab[40] and Haryana[41] annual statistical abstracts and the fifth minor irrigation survey[42]. The spatial extent of CCs was obtained from the Indian statistical association and the Pakistan Water and Power Development Authority. Information on the year of CC construction was obtained from two reports available online[12,14].

Precipitation dataset

Precipitation data was taken from Version 4 of the Climatic Research Unit gridded Time Series (CRUTS) dataset[43], which has resolution of 0.5°, and covers the whole study area. The CRUTS precipitation data covers a time period from 1901–2018 in the form of monthly precipitation.

Data analysis

Decadal analysis: groundwater level trend and precipitation

Only post-monsoon data was used in the analysis, for three reasons; firstly, to avoid seasonal effects obscuring long-term trends in the Mann-Kendall trend analysis (more details below). Secondly, in some cases observations wells with data prior to 1950 only had post-monsoon groundwater observations, so in order to maximise the amount of historic data in the analysis these wells were included. Thus, for consistency only post-monsoon data was used across the dataset. Thirdly, the process of digitising hydrographs was often ineffective at capturing seasonal groundwater level variations due to deterioration over time, and the general low quality, of many of the paper records.

To maximise the number of individual OW time-series used and to ensure the data included in the analysis was optimised to cover the maximum possible temporal and spatial scales represented by the dataset, the analysis was conducted by decade. For calculations of mean water level in each decade, any OW with any data in any decade, was included. Groundwater level trend was calculated using a bootstrapped version of the non-parametric Mann-Kendal trend test (see more details in Supplementary Note 1). By using post-monsoon groundwater level observations seasonal trends did not affect the trend results or slope estimates. When calculating trends, a minimum of six data points within each decade was used which represents 60% of the maximum possible number of data points within each decade for each OW. A basic sensitivity analysis was conducted to understand how the minimum number of observations affected the number of wells included within the bootstrapped Mann-Kendall analysis (see Supplementary Figs. 8 and 9). We tested the effect of using a minimum of 4 (Supplementary Fig. 8) and a maximum of 8 (Supplementary Fig. 9) data points within a decade for each OW.

Using CRUTS precipitation data we calculated the annual precipitation for each CC. We then estimated the average annual rainfall deviation within CC and each decade relative to the long-term annual precipitation mean for the period from 1901–2009. We also calculated the 96-month standardised precipitation index (SPI)[44] for each CC, the 96-month period was selected to be consistent with our decadal groundwater level analysis. We compared the 96-month SPI to standardised groundwater levels (SGWL), which was calculated by subtracting the mean and dividing by the standard deviation of groundwater levels within a canal command.

Groundwater accumulation and depletion

Groundwater accumulation and depletion was calculated for each decade for the period 1900–2000 using Sen's slope method. The average slope, CC area and the porosity range for the study area (0.1 to 0.25[45]) was used to calculate accumulation in each CC during each decade. Decadal accumulation was then summed to estimate overall groundwater accumulation and depletion. We used a mean porosity of 0.18 for our best estimate of groundwater accumulation which was based on previous work in the study area[9].

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Author contributions

DJM conducted the analysis and wrote the manuscript with inputs from AMM, GK and MB. DJM and AMM designed the research. DJM led digitisation of the data, he also collated and cleaned the data. GK and MB collected the data. DC conducted the Mann-Kendall analysis.

Data availability

The Mann-Kendall trend and Sen slope data for each canal command will be made publicly available.

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