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Impact of high-density managed aquifer recharge implementation on groundwater storage, food production and resilience: A case from Gujarat, India

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A R T I C L E I N F O

Keywords:
Groundwater
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Irrigation
Drought

A B S T R A C T

Study region: The study region is the Kamadhiya catchment (1150 km^2), located in the Saurashtra region of the western state of Gujarat, India. The region has seen intensive development of check dams (CDs) for groundwater recharge with an estimated 27,000 CDs constructed up until 2018.
Study focus: The impact of CDs on groundwater storage, food production and resilience are assessed for Kamadhiya catchment by estimating and comparing changes, across periods of low and high CD development, in potential recharge from CDs, rainfall trends, and irrigation demand. The analysis is carried out for the period from 1983 to 2015.
New hydrological insights for the region: Groundwater storage gains observed following CD development can partly be attributed to an increase in high rainfall years after several drought years. Groundwater demand for irrigation has increased substantially, outweighing increase in groundwater recharge from CDs. This deficit in supply relative to demand is greatest in dry years, and when considered together with the low inter-annual carry-over storage of the region's hardrock aquifers, means that CDs capacity to enhance groundwater storage and mitigate the negative impacts of drought remains limited. Findings suggest that a standalone focus on MAR, unless complemented by greater emphasis on management of water demand and groundwater resources more broadly, may not be sufficient to achieve the long-term goals of sustainable groundwater and concurrently expanding agricultural crop production.

1. Introduction

Reliable and adequate availability of freshwater for irrigation is critical for global food security. With climate change and increasing climate variability leading to more extremes in water availability, expressed as droughts and floods, (United Nations, 2019; IPCC, in press) irrigation is more important than ever (Smit and Skinner, 2002; Ignaciuk and Mason-D′Croz, 2014). Groundwater, being more reliable and more widely available than surface water and largely protected from evaporation losses, plays a critical role in

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providing irrigation water, especially in semi-arid areas (WWAP United Nations World Water Assessment Programme/UN-Water, 2022), and supplies 38% of irrigated areas globally (Siebert et al., 2010). However, in many parts of the world, overdependence on groundwater irrigation has led to unsustainable use and depletion of groundwater resources (Döll et al., 2012; Bierkens and Wada, 2019).

To mitigate groundwater depletion and enhance groundwater security for irrigation, one strategy that is increasingly applied is managed aquifer recharge (MAR) (Zhang et al., 2020; Alam and Pavelic, 2020; Zheng et al., 2021). MAR involves strategically recharging aquifers with excess surface water through infrastructure such as check dams or recharge wells (Dillon et al., 2019; Alam and Pavelic, 2020). The benefits of MAR in these cases include enhanced groundwater storage in dry seasons and drought periods supporting continuous irrigation and/or mitigating depletion (Alam et al., 2020; Dillon et al., 2019; Prathapar et al., 2015; Zhang et al., 2020). MAR is contingent on the availability of harvestable source water for augmenting recharge and storage, like flood waters or treated wastewater, which may be seasonally or perennially available, respectively.

India, as the largest user of groundwater globally, is promoting MAR to mitigate negative impacts of extensive groundwater use through multiple central (CGWB, 2020) and state government programs and policies (Verma and Shah, 2019; CGWB, 2020). One notable example is Gujarat where more than 90,000 MAR structures (in the form of check dams) have been constructed since the year 2000 with the financial support (subsidies) of government and non-government organizations under the government participatory scheme '*Sardar Patel Sahbhagi Jal Sanchay Yojana* (Sardar Patel Participatory Water Conservation Program)' (Shah et al., 2009; NWRWS, 2018; Verma and Shah, 2019; Patel et al., 2020). An extended drought in 1999 – 2002, during which the average rainfall was about 35% less than normal (Pai et al., 2014), greatly accelerated the development of check dams, facilitated by government support

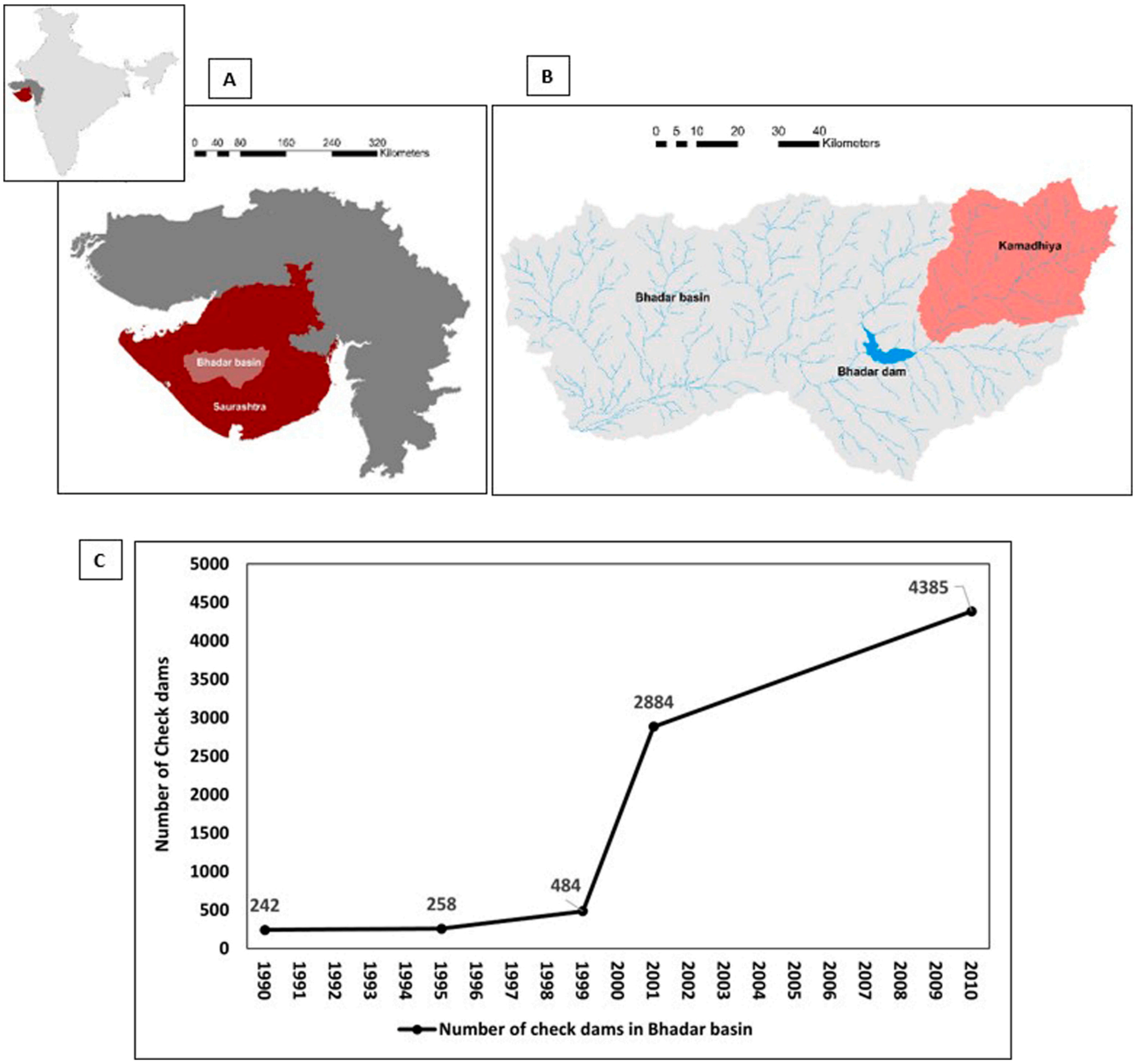

Fig. 1. Location of A) Saurashtra region and Bhadar basin in Gujarat, India; B) Kamadhiya catchment, part of Bhadar basin; and C) timeline of number of check dams in the Bhadar basin.

(Fig. 1c) (Patel, 2007; Patel et al., 2020).

Increased MAR implementation, as a result, has been widely reported as having a positive impact on groundwater storage in the region (Shah et al., 2009; Jain, 2012; Patel et al., 2020). While a number of studies have analyzed the increasing groundwater storage in Gujarat (Shah et al., 2009; Jain, 2012; Bhanja et al., 2017; Kumar and Perry, 2018; Patel et al., 2020), they disagree on the underlying explanation. Improved groundwater storage has been attributed to a number of factors: increased rainfall (Shah et al., 2009; Kumar and Perry, 2018); reduced groundwater abstraction brought about by rationing schemes enabled by separating agriculture and non-agriculture electricity feeders (Shah et al., 2009; Bhanja et al., 2017); inter basin transfer of water (Kumar and Perry, 2018); and enhanced recharge from MAR, mostly through check dams (Shah et al., 2009; Jain, 2012; Patel et al., 2020). The diverging explanations among the studies demonstrate the lack of clarity in attributing the increase in groundwater storage, including the role of MAR. This is because any change in groundwater storage is a result of numerous factors associated with the short- and long-term dynamics of supply (e.g. rainfall amount and intensity, performance of MAR) and demand factors (e.g., changing cropping patterns, irrigated areas, irrigation practices). Previous studies have not systematically accounted for these complexities.

The main limitations associated with the previous studies include: 1) focusing on recharge enhancement while not accounting for increased groundwater irrigation demand for agriculture (Bhanja et al., 2017; Kumar and Perry, 2018; Patel et al., 2020); 2) neglecting the long-term change in rainfall and inter-annual variability in rainfall (Shah et al., 2009; Bhanja et al., 2017); 3) focusing on small scale assessments of MAR structures or micro-catchments (Patel et al., 2002; Sharda et al., 2006) leading to high uncertainty when attempting to extrapolate results to large scale; and 4) focusing on state level impacts (Shah et al., 2009; Bhanja et al., 2017) and thus discounting spatial variability and heterogeneity in biophysical factors (hydrogeology, soil, water demand) (Kumar and Perry, 2018) and the interconnectedness of MAR structures within a hydrologic unit (Mozzi et al., 2021).

With the progressive priority and increased investment being made in MAR in Gujarat and other states in India (Verma and Shah, 2019), there is clear and urgent need to assess the effectiveness of MAR at an appropriate intermediary scale and for relevant contexts. This requires a long-term integrated analysis, accounting for the dynamics of both supply and demand on a catchment scale, which this study aims to carry out. In this study, we analyze the dynamics of groundwater storage in conjunction with changes in rainfall, irrigation demand and increase in supply through MAR in Gujarat. With this, we aim to establish the contribution of MAR to groundwater storage and agricultural production relative to other key factors.

2. Study area

The analysis is carried out for Kamadhiya catchment (1150 km^2), located in the Saurashtra region (~6600 km^2) of the western state of Gujarat, India (Fig. 1). Kamadhiya catchment is an upstream catchment of the Bhadar basin, one of the larger river basins in the region. Kamadhiya catchment drains to Bhadar dam (~240 million cubic meters (MCM) (Fig. 1), the largest dam supplying both irrigation and drinking water in the Bhadar basin (NWRWS, 2010). While the catchment scale considered here provides a closed hydrologic unit for assessment and accounts for the limitation of the small spatial scales of earlier studies focusing on specific MAR structures or micro-watersheds, it still falls short of a basin-scale assessment as it represents only 17% of the entire basin area. Therefore, attempts to extrapolate these findings to the basin scale would require further investigation.

Saurashtra region has been the focus of development of MAR in India (mostly in the form of check dams, hereafter referred to as CD) (Shah et al., 2009; Patel et al., 2020). An estimated 27,000 CDs were constructed across Saurashtra before 2018 (NWRWS, 2018). Within Bhadar basin, the number of CDs increased from 484 (24.0 MCM storage) in 1999 to 4385 (103.3 MCM storage) by the end of 2010 (Fig. 1c) (Kamboj et al., 2011) with more than 90 % of CDs constructed after 2000, primarily during 2001–2002, in response to the extended 2000 – 2002 drought (Patel, 2007; Patel et al., 2020).

In the Kamadhiya catchment, the total number of CDs in 2006 was estimated to be 576 with total storage capacity of 12.7 MCM (Patel, 2007). With lack of time series data for Kamadhiya catchment, we assume the same development curve as in Bhadar basin with ~90 % of CDs (at the end of 2006) constructed post 2000 during 2001–2002. Also, we further assume that the rate of development of new CDs post 2006 will be approximately matched by the rate of attrition of existing CDs, as they lose functionality from lack of maintenance (e.g., siltation, collapse) (Kumar and Perry, 2018; Mozzi et al., 2021). Thus, based on the density of CDs in the catchment, we term the period until 2002 as pre-CD, during which CD density was relatively low (10 % of CDs in 2006 = 58 CDs ~ 1 CD per 20 km^2), and the period after 2002 as post-CD, during which CD density had increased ten-fold (100 % of CDs in 2006 = 576 CDs ~ 10 CDs per 20 km^2).

2.1. Climate

The climate of the Kamadhiya catchment is semi-arid with an average annual rainfall of 638 mm yr^{-1} (1983–2015) (Pai et al., 2014). More than 90 % of the rainfall is concentrated in the four monsoon months from June to September. Rainfall is also associated with high inter-annual variability with a coefficient of variation of 46 %, estimated for the period 1983–2015 from the India Meteorological Department (IMD) gridded rainfall dataset (Pai et al., 2014). Average annual mean temperature is 27°C with minimum temperature observed in January with a mean of 20.6°C and the maximum temperature observed in May with a mean of 30.7°C (Srivastava et al., 2009).

2.2. Agriculture and irrigation

Agriculture and irrigation data were available only on an administrative level. Thus, we report and use data from Rajkot district and absolute values for the catchment are derived using the proportion of catchment area which lies within the district (86 %). The kharif (monsoon) is the main cropping season where groundnut and cotton are the main crops occupying 48 % and 41 % of total sown area, respectively (DoA Gujarat, 2021). Other minor crops in the kharif season include bajra (pearl millet) and sesame. Rabi (post-monsoon) season has limited cropping area, which is reflected by low annual cropping intensity of 113 % (DoES Gujarat, 2018). Wheat is the main rabi crop (DoA Gujarat, 2021). Of the total net cropped and gross cropped area, 39 % and 42 % is equipped for irrigation, respectively (DoES Gujarat, 2018). During the kharif season, cotton requires supplemental irrigation whereas groundnut is rainfed. Rabi crops rely entirely on irrigation (DoA Gujarat, 2021). Groundwater is the main source of irrigation in the district, accounting for 82 % of the irrigated area (DoES Gujarat, 2018). The main source of surface water in the district is from Aji and Bhadar dams (GGRC, 2015). Irrigation and domestic water supply represent about 95 % and 5 % of the overall water demand, respectively (GGRC, 2015).

2.3. *Hydrogeology*

The groundwater in the Saurashtra region is found at shallow depths under unconfined conditions in aquifers characterized by parent basalt rock of the Deccan trap formation with little primary porosity (Mohapatra, 2013; Patel, 2007). In the region, deccan trap basalt has weathered upper parts to a depth of 20–30 m, forming good aquifers, which are tapped for irrigation mostly by large diameter open dugwells (Fig. 2a) (Mohapatra, 2013; MoWR, RD and GR, 2017a). The groundwater well yields are seasonally variable and highest after monsoonal recharge (Pavelic et al., 2012). The weathered aquifer is underlain by consolidated basalt rocks generally forms a poor aquifer with groundwater present in fractured and vesicular zones (secondary porosity) in successive basalt flows and tapped by deeper borewells of depth > 150 m (Mohapatra, 2013; Patel et al., 2020; MoWR, RD and GR, 2017a).

3. Methods and data

The analysis is carried out for the period from 1983 to 2015 (33 years). This period is divided into the pre-CD (1983–2002) and post-CD (2003–2015) period, where the post-CD period indicates the period after the 2000–2002 extended drought and after 90% of the CDs were constructed. We assess the impact of CDs by estimating and comparing changes, from the pre-CD to the post-CD period (Δ = post-CD – pre-CD), specifically in groundwater recharge (ΔGWR) and groundwater abstraction (ΔGWA). Since both groundwater recharge and groundwater abstraction for irrigation depend on rainfall, which is associated with high inter-annual variability, we only compare pre-CD and post-CD periods in similar rainfall years classified using standard precipitation index (SPI) (WMO and GWP, 2016). We define a year in terms of the hydrological year (June to May) and classify years as either dry, normal or wet. Years reported in the subsequent analysis refer to the hydrological year (e.g., the year 2001 covers Nune 2001 to May 2002).

We assume that positive difference in groundwater recharge (ΔGWR), between pre-CD and post-CD periods for years under the same SPI classification, will primarily come from increase in groundwater recharge from new CDs (i.e., $\Delta GWR = \Delta GWR_{CD}$). Balance of ΔGWR_{CD} (Section 3.1) and ΔGWA (Section 3.2) between the pre-CD and post-CD periods is used to estimate the change in groundwater storage (ΔGWS_E) between the two periods (Eq. 1).

$$\Delta GWS_{E(SPI)} = \Delta GWR_{CD(SPI)} - \Delta GWA_{(SPI)} \tag{1}$$

ΔGWS_E, where *E* stands for estimated, will be positive if the increase in groundwater abstraction (ΔGWA) is less than the increase in recharge (ΔGWR_{CD}) and vice-versa. Estimated ΔGWS_E is compared with observed groundwater storage change (ΔGWS_O, Section 3.3).

Fig. 2. a) Open dugwell commonly used for irrigation in the Bhadar basin; b) and c) check dam in the area in dry and wet season, respectively (images taken from downstream side).

Subscript SPI denotes classified years of dry ($SPI \leq -0.49$), normal ($-0.49 < SPI < 0.49$) and wet years ($SPI \geq 0.49$).

3.1. Change in groundwater abstraction (ΔGWA)

To estimate change in groundwater abstraction from pre-CD to post-CD, we focus our analysis on two main irrigated crops of the region: cotton and wheat. Cotton is supplementarily irrigated during the kharif season and wheat is fully irrigated during the rabi season. We assume the irrigation water volume derived from groundwater is proportional to the fraction of groundwater irrigated area in the area. Groundwater irrigated area data was taken from annual agricultural statistics as reported by the government (DoES Gujarat, 2018; ICRISAT, 2021) and was assumed to be the same for both crops (in the absence of crop-specific information). Also, we disregard groundwater abstraction for non-irrigation purposes, which is less than 5% in the district (CGWB, 2019). Fig. 3 gives the conceptual flow diagram showing the approach taken to arrive at groundwater abstraction (GWA).

To estimate groundwater abstraction for hydrological year *i*, we first estimate the annual net irrigation water applied (Irrigation) for crops. In the case of cotton, applied Irrigation volume (mm) is estimated as the difference between actual evapotranspiration (AET) of rainfed ($AET_{rainfed}$) and irrigated ($AET_{irrigated}$) cotton (Eq. 2a). For wheat, grown with 100% cultivated area under irrigation, we assume all crop water demand is met through irrigation, and Irrigation volume (mm) is equal to $AET_{irrigated}$ (Eq. 2b). We neglect any post-monsoon rainfall during the wheat growing season as for the period 1983–2015, this averaged only ~ 5 mm. $AET_{rainfed}$ and $AET_{irrigated}$ is calculated using FAO crop yield response to water (Eqs. 3a and 3b) (Steduto et al., 2012).

$$Irrigation_{(c)(i)} = AET_{irrigated(c)(i)} - AET_{rainfed(c)(i)} \quad \{for \quad cotton\} \tag{2a}$$

$$Irrigation_{(c)(i)} = AET_{irrigated(c)(i)} \quad \{\text{for } wheat\} \tag{2b}$$

$$AET_{rainfed(c)(i)} = ET_{c(i)} \times (1 - \frac{1}{K_{Y(c)}}(1\text{-}\frac{Yield_{rainfed(c)(i)}}{Yield_{Potential(c)}}) \tag{3a}$$

$$AET_{irrigated(c)(i)} = ET_{c(i)} \times (1 - \frac{1}{K_Y}(1\text{-}\frac{Yield_{irrigated(c)(i)}}{Yield_{Potential(c)}}) \tag{3b}$$

$$ET_{c(i)} = \sum\nolimits_{s=1}^{4} ET_{o(i)} \times K_{c(s)} \tag{4}$$

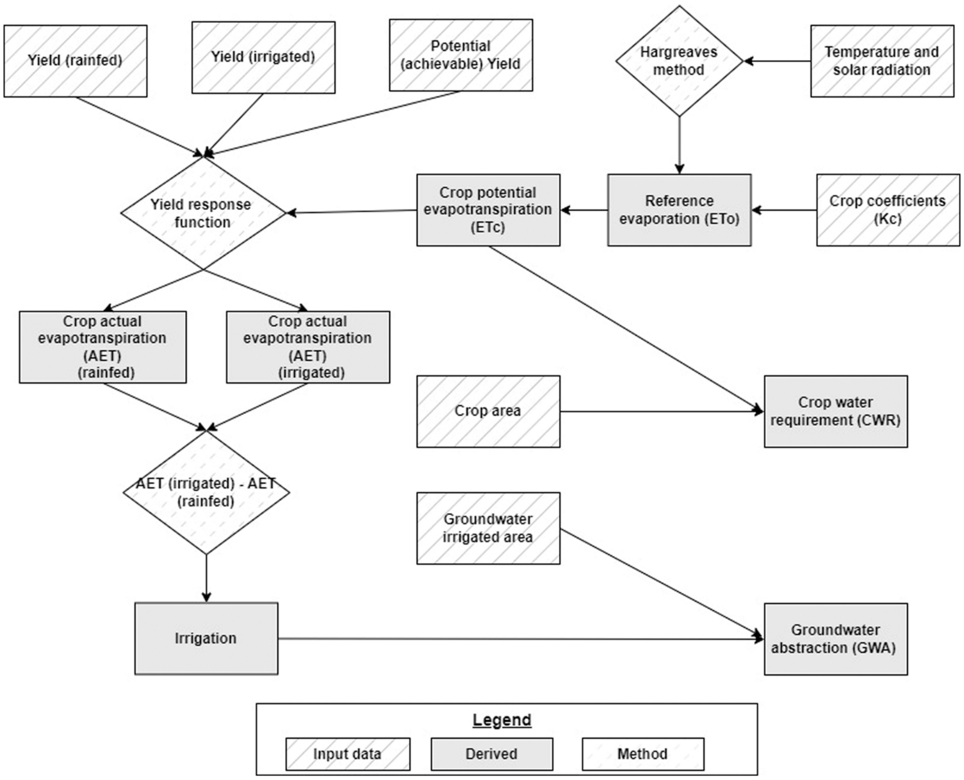

Fig. 3. Conceptual flow diagram showing the approach taken to derive groundwater abstraction.

Where, subscript *i* denotes year and *c* denotes crop (cotton and wheat). ET_c (Eq. 4) is the crop potential evapotranspiration demand and is estimated using FAO four stage (s) crop coefficient approach (Allen et al., 1998), and ET_o is reference evaporation estimated using Hargreaves method (Hargreaves and Samani, 1985). The Hargreaves method was chosen due to its simplicity, reliability and minimal data requirements as it requires only monthly average, minimum and maximum temperature along with solar radiation data. $K_{c(s)}$ is the crop coefficient for stage *s*; $Yield_{rainfed(c)}$ and $Yield_{irrigated(c)}$ is the observed rainfed and irrigated crop yield and $Yield_{Potential(c)}$ is the potential (achievable) yield. $Yield_{Potential(c)}$ is estimated as the five-year moving average of observed irrigated yield. Observed annual yield data, used to estimate rainfed $Yield_{rainfed(c)}$) and irrigated$Yield_{irrigated(c)}$) yield pertains to Rajkot district and were taken from annually reported government statistics (DoA, 2021; ICRISAT, 2021). $K_{y(c)}$ is the crop yield response factor representing the effect of a reduction in water use (relative to potential demand) on yield losses (Steduto et al., 2012). Values of K_Y for cotton (0.85) and wheat (1.15) were taken from the literature and are based on extensive analysis of data on crop yield, water relationships and deficit irrigation (Doorenbos and Kassam, 1979; Steduto et al., 2012).

Data on overall yield (average of rainfed and irrigated yield) for cotton was available for the whole time (1983–2015), whereas segregated data on rainfed and irrigated yield were only available starting 1995. Thus, for the time period of 1983–1994, segregated rainfed and irrigated cotton yield was derived based on the developed relationship between the ratio of overall yield to irrigated yield and irrigated area to the overall area (R^2 of 0.79, see Figure A1) in the 1995–2015 period.

Derived irrigation volume is multiplied with annual groundwater irrigated area of a crop (Eq. 5) to get a volumetric estimate (million cubic meter, MCM) of groundwater abstraction (GWA_c). Annual groundwater irrigated area was taken from annually reported government statistics (DoES Gujarat, 2018; ICRISAT, 2021). Crop potential evapotranspiration demand (ET_c) is multiplied by annual crop area, taken from annually reported government statistics (DoES Gujarat, 2018; ICRISAT, 2021), to get a volumetric estimate (MCM) of total crop water requirement (CWR) (Eq. 6).

$$GWA_{c(i)} = Irrigation_{(c)(i)} \times Annual \quad groundwater \quad irrigated \quad area \tag{5}$$

$$CWR_{c(i)} = ET_{c(i)} \times Annual \quad crop \quad area \tag{6}$$

Values for duration and crop coefficient for each crop stage were taken for Indian conditions (Kar et al., 2014; Allen et al., 1998; Table A1). The sowing dates for cotton and wheat were taken as 15th June and 15th November, respectively (DoA Gujarat, 2020). Thereafter, change in groundwater abstraction (ΔGWA_c) between the pre- and post-CD periods is estimated for years in the same SPI class by determining the mean GWA_c of each class for pre-CD and post-CD and taking the difference (Eq. 7).

$$\Delta GWA_{c(spi)} = \frac{1}{n_{postCD(spi)}}\left(\sum\nolimits_{i=1}^{n_{postCD(spi)}} GWA_{(c)(i)}\right) - \frac{1}{n_{preCD(spi)}}\left(\sum\nolimits_{i=1}^{n_{preCD(spi)}} GWA_{(c)(i)}\right) \tag{7}$$

Where, *spi* denotes the SPI class (dry, normal and wet) and $n_{pre-CD(spi)}$ and $n_{postCD(spi)}$ is the number of years in each SPI class in pre-CD and post-CD periods, respectively.

3.1.1. Potential groundwater demand met

We also estimate how much of crop annual potential groundwater demand (GWA_{Pot}) could be met through groundwater abstraction (GWA_c) (%met $= \frac{GWA}{GWA_{Pot}} \times 100$). For cotton, GWA_{Pot} is estimated as the difference between crop potential evapotranspiration demand (ET_c) and $AET_{rainfed}$ multiplied with cotton groundwater irrigated area (Eq. 8). As wheat is completely irrigated, wheat GWA_{Pot} estimated is equal to the crop potential evapotranspiration demand (ET_c) multiplied with wheat groundwater irrigated area (Eq. 9).

$$GWA_{pot(c)} = \left(ET_c - AET_{rainfed(c)}\right) \times groundwater \quad irrigated \quad area \quad \{\text{for } cotton\} \tag{8}$$

$$GWA_{pot(c)} = ET_c \times groundwater \quad irrigated \quad area \quad \{\text{for } wheat\} \tag{9}$$

Thereafter, the change in potential groundwater demand (ΔGWA_{Pot}) is estimated for each SPI class by obtaining the mean of GWA_{Pot} of each SPI category for pre-CD and post-CD period and taking the difference (Eq. 10).

$$GWA_{pot(c)(SPI)} = \frac{1}{n_{postCD(spi)}}\left(\sum\nolimits_{i=1}^{n_{postCD(spi)}} GWA_{pot(c)(i)}\right) - \frac{1}{n_{preCD(spi)}}\left(\sum\nolimits_{i=1}^{n_{preCD(spi)}} GWA_{pot(c)(i)}\right) \tag{10}$$

Where, SPI denotes the SPI classification (dry, normal and wet) and $n_{preCD(spi)}$ and $n_{postCD(spi)}$ is the number of years under each SPI classification in pre-CD and post-CD, respectively.

3.2. Change in recharge from check dams (ΔGWR_{CD})

Groundwater recharge from CDs (GWR_{CD}) is simulated using an analytical dynamic tool (Mozzi et al., 2021). The tool integrates a daily water balance of individual CDs with a set of analytical infiltration equations (Bouwer, 1969, 2002) giving daily dynamics of storage, infiltration, and evaporation. The tool was previously applied to four structures in the Bhadar basin and validated at sites in Rajasthan where more extensive data were available (Mozzi et al., 2021). Application of the tool has shown good performance with validation results giving an average R^2 of 0.93 between the simulated and measured water levels in individual CDs. The tool requires input data on CD geometrical parameters, catchment area hydrogeology characteristics, daily inflow to CD and potential evaporation. Representative values of CDs in Kamadhiya catchment were applied (Table A2).

To estimate GWR_{CD}, the tool is used to simulate recharge from a representative CD ($GWR_{CD(r)}$) with a storage capacity ($V_{CD(r)}$) of 21,486 m^3 (Table A2). A simulation is carried out for the pre-CD period 1983–2002 where runoff is assumed to be representing the baseline conditions with low CD development. Annual recharge values are then averaged for each SPI class. Thereafter, to get relative CD recharge for pre-CD and post-CD periods at the catchment scale (GWR_{CD}) for each SPI classified year, the ratio of representative CD recharge ($GWR_{CD(r)}$) to its storage capacity ($V_{CD(r)}$) is multiplied with catchment cumulative CD storage capacity ($V_{CD(pre)} = 1.3$ MCM and $V_{CD(post)} = 11.4$ MCM) (Eqs. 11a and 11b).

$$GWR_{CD(spi)(pre)} = \left(\frac{GWR_{CD(r)(spi)}}{V_{CD(r)}}\right) \times V_{CD(pre)} \tag{11a}$$

$$GWR_{CD(spi)(post)} = \left(\frac{GWR_{CD(r)(spi)}}{V_{CD(r)}}\right) \times V_{CD(post)} \tag{11b}$$

Thereafter, change in groundwater recharge (ΔGWR_{CD}) is estimated for each SPI class from the mean GWR_{CD} of each SPI category for pre-CD and post-CD and taking the difference (Eq. 12).

$$\Delta GWR_{CD(SPI)} = \frac{1}{n_{postCD(spi)}}\left(\sum_{i=1}^{n_{postCD(spi)}} GWR_{CD\quad(post)(i)}\right) - \frac{1}{n_{preCD(spi)}}\left(\sum_{i=1}^{n_{preCD(spi)}} GWR_{CD\quad(pre)(i)}\right) \tag{12}$$

Where, *spi* denotes the SPI classification (dry, normal and wet) and $n_{preCD(spi)}$ and $n_{postCD(spi)}$ is the number of years under each SPI classification in pre-CD and post-CD periods, respectively. All GWR figures are calculated on daily time scales and thereafter aggregated to annual scale. We assume that all CDs are functioning, behave similarly, and do not interact.

3.3. Observed change in groundwater storage (ΔGWS_O)

The observed change in groundwater storage is the annual net balance of groundwater recharge and abstraction in the catchment. This is estimated using the water table fluctuation method (MoWR, RD & GR, 2017b; Pavelic et al., 2012). The water table fluctuation method has been used extensively and found suitable for climatic and hydrogeological conditions of unconfined weathered hardrock aquifers (Pavelic et al., 2012; Dewandel et al., 2010; Machiwal et al., 2017). The water table fluctuation method derives groundwater storage change (GWS_O) from the rise in monsoonal groundwater levels (GWL_r) estimated as the difference between pre (GWL_{PrM}) and post monsoon (GWL_{PM}) groundwater levels (Eqs. 14–15).

$$GWS_{o(i)} = GWL_{r(i)} \times S_y \times catchment \quad area \tag{14}$$

$$GWL_{r(i)} = GWL_{PM(i)} - \quad GWL_{PrM(i-1)} \tag{15}$$

Where $GWL_{PM(i)}$ is the post monsoon of GWL of hydrological year *i* (taken in November), $GWL_{PrM(i-1)}$ is the pre monsoon GWL of previous hydrological year *i* (taken in May). Hence, pre monsoon GWL of previous hydrological year is the groundwater level/storage at the start of year i. S_y is the specific yield, which is taken as 0.02 as the recommended value for the region (MoWR, RD & GR, 2017b; Patel et al., 2020).

Annual catchment averaged pre (GWL_{PrM}) and post monsoon (GWL_{PM}) groundwater levels are derived using observed data from monitored wells for the time period 1983–2015 from the Central Groundwater Board (CGWB, 2015). A total of 15 observation wells located within the catchment and up to a 10 km distance beyond the catchment boundary were used for the analysis. The data were filtered for outliers using interquartile range method with data outside an interquartile range of 1.5 removed. Only monitoring wells with observation records containing more than 2/3 of the years of pre and post GWL data points were used. GWL_{PM} and GWL_{PrM} for each year were then derived from spatially interpolating observation wells using inverse distance weighing (Li and Heap, 2008). Thereafter, GWL_r is calculated according to Eq. 15. Finally, the change in groundwater storage (ΔGWR_O) is estimated for each SPI classified category by getting mean of GWS_O of each SPI category for pre-CD and post-CD and taking the difference (Eq. 16).

$$\Delta GWS_{O(SPI)} = \frac{1}{n_{postCD(spi)}}\left(\sum_{i=1}^{n_{postCD(spi)}} GWS_{O(i)}\right) - \frac{1}{n_{preCD(i)}}\left(\sum_{i=1}^{n_{preCD(i)}} GWS_{O(i)}\right) \tag{16}$$

Where, *spi* denotes the SPI classification (dry, normal and wet) and $n_{preCD(spi)}$ and $n_{postCD(spi)}$ is the number of years under each SPI classification in pre-CD and post-CD, respectively.

We compared observed (ΔGWS_O, Eq. 16) with estimated (ΔGWS_E, Eq. 1) change in groundwater storage to validate our results. Storage change derived from the water table fluctuation method incorporates all sources and sinks, including diffuse rainfall recharge, recharge from CDs, subsurface irrigation returns flows, groundwater evaporation, and any net lateral groundwater flow (Pavelic et al., 2012, MoWR, RD & GR, 2017b). It is assumed that net groundwater inflow/outflow is negligible as hardrock areas have limited lateral subsurface hydraulic connectivity at the regional scale (Bouma et al., 2011; Dewandel et al., 2010; Pavelic et al., 2012). Table 1 summarizes the datasets used in the analysis.

4. Results

4.1. Rainfall

Fig. 4 shows the annual rainfall time series, with individual years categorized as either 'wet', 'normal' or 'dry' based on SPI. For the overall period, average rainfall is 638.6 mm yr^{-1} Average post-CD rainfall (809.8 mm yr^{-1}) is ~27% higher than the overall average, whilst the pre-CD rainfall (511.9 mm yr^{-1}) is ~25% lower than the average. Also, there is a high inter-annual variability characterized by a high coefficient of variation of ~45% across the whole time series. Wet rainfall years are concentrated in the post-CD (8 in post-CD vs 3 in pre-CD), whereas dry years are disproportionately occurring in the pre-CD period (8 in pre-CD vs 1 in post-CD) (Table 2).

4.2. Groundwater abstraction (GWA)

4.2.1. Cotton

Area under cotton cultivation has steeply risen, especially during the post-CD (Fig. 4b). The average post-CD cotton area (30,670 ha) is ~124 % higher than the pre-CD period (13,670 ha) (Table 2). At the same time, average irrigated cotton area has increased in post-CD (to an average of 85.4 % of cropped area) compared to 64.2 % in pre-CD (Fig. 4b and Table 2). Results show that this increase in area and irrigation from pre- to post-CD is consistent for all SPI classified years (Table 2).

Increase in cotton area (Fig. 4b) translates to more than two-fold increase in crop water requirement (CWR) in post-CD for both overall and SPI classified years (Table 2). With ~85 % of crop area irrigated with groundwater, this translates into an increase in potential groundwater demand (GWA_{pot}) of 96.4 MCM (increase of 188 %), 62.9 MCM (increase of 168 %) and 56.6 MCM (increase of 203 %) in dry, normal, and wet years, respectively (Table 2).

In normal and wet years, with practically all GWA_{pot} being met (%met between 86.2 % and 100 %) (Table 2), GWA increases by 40.1 MCM (increase of 125 %) and 54.6 MCM (increase of 200 %), respectively. However, for dry years most of GWA_{pot} remains unmet in post-CD (%met ~ 30 %) reflecting that irrigation in dry years is limited by available groundwater storage. Thus, GWA increases by only 9.8 MCM in dry years between the two periods (Table 2).

4.2.2. Wheat

The wheat area in post-CD period (7770 ha) is 112 % higher than in the pre-CD (3660 ha) (Table 2). In contrast to cotton, there is no or limited change in wheat area when compared across similar SPI classified years (Table 2), with area increasing only in wet years (~21 %). However, across SPI years, wheat shows a large increase from dry (700–1000 ha) to wet (8500–10,300 ha) years. This shows that large overall increase (~118 %) in wheat area in post-CD is largely due to higher number of wet years (Table 2). Wheat is completely irrigated (~99 % area under irrigation) in both periods for all years (Fig. 4c and Table 2).

Wheat CWR and GWA, similar to wheat area, show an increase of 115 % for overall period in post-CD relative to pre-CD (Table 2). However, across SPI classified years, there is no or limited change in CWR and GWA. Only wet years show moderate increase in GWA by 7.8 MCM (~26 % increase). Wheat yield does not show decrease across SPI years reflecting that 100 % of demand is met (GWA_{pot} = GWA). Summing up cotton and wheat irrigation, overall GWA_{Pot} and GWA post-CD increases by 67.5 MCM (~124 %) and 63.4 MCM (~162 %) as compared to pre-CD.

4.3. Change in recharge from check dams (ΔGWR_{CD})

The average recharge from CDs (GWR_{CD}) increases from 2.4 MCM in pre-CD to 34.0 MCM in post-CD (Table 3). Overall, this means a 14-fold increase in recharge from CDs (ΔGWR_{CD}). Also, GWR_{CD} increases from dry to wet years with ΔGWR_{CD} (post-CD -pre-CD) increasing from dry (10.7 MCM) to normal (21.2 MCM) to wet years (37.2 MCM) (Table 3). Monthly recharge estimates (Table A3) show that, on average, highest recharge takes place in July and August when sufficient runoff is available and groundwater tables are deeper. Table 3 shows that GWR_{CD} is constrained by inflow capture of the CDs, calculated as the difference between flow entering and leaving a check dam, which decreases from dry to wet years. On average, 67 % of inflow is captured by CD with highest capture in dry years (94 %), followed by normal years (85 %) and wet years (55 %). Besides rainfall, recharge and inflow capture are sensitive to CD

Table 1
Summary of data used in the analysis.

Parameter	Temporal period	Temporal resolution	Source
Daily rainfall and temperature	1983–2015	Daily	India Meteorological Department gridded rainfall data (Pai et al., 2014)
Groundwater levels	1983–2015	Pre (May) and post (Nov) monsoon	Central Ground Water Board (CGWB, 2015)
Crop area and yield	1983–2015	Annual	Government reported annual agriculture statistics (DoA, 2021; ICRISAT, 2021)
Irrigated area and irrigation water source	1983–2015	Annual	Government reported annual agriculture statistics (DoA, 2021; ICRISAT, 2021; DoES Gujarat, 2018)
Number and storage capacity of check dams	Pre-CD (1983–2002) Post-CD (2003–2015)		Patel (2007);NWRWS (2018)

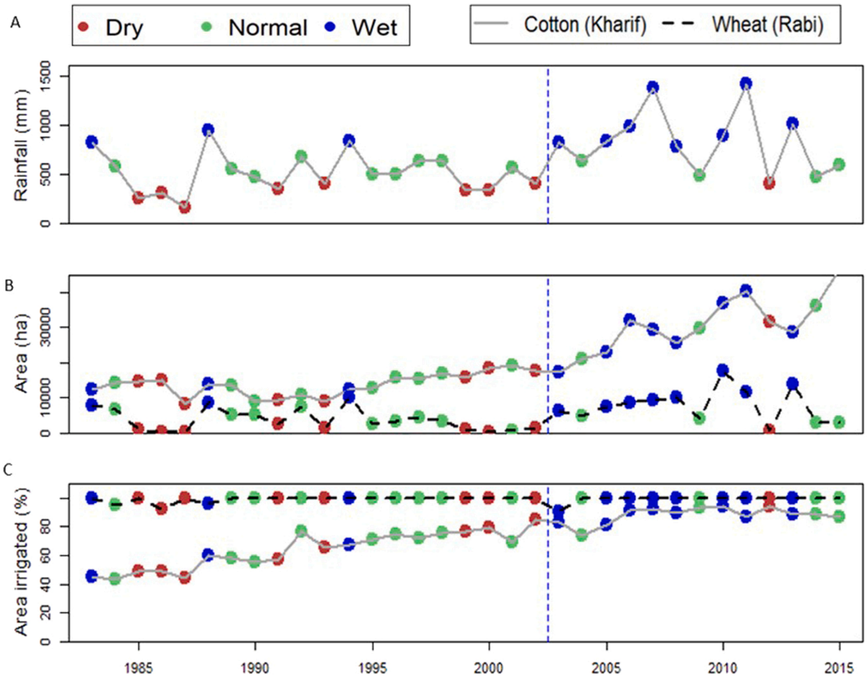

Fig. 4. A) Annual rainfall (mm/year) for the time period 1983–2015; B) Cultivated area (ha) of cotton (kharif crop) and wheat (rabi crop); and C) Cotton and wheat irrigated area (given as percentage of total cultivated area of crop) Note: Years are indicated according to rainfall class (dry, normal and wet).

Table 2
Average values of key water and crop variables for all years and for SPI classified years, split into pre-CD and post-CD period.

Parameter		Overall		Dry		Normal		Wet	
		Pre-CD	**Post-CD**	**Pre-CD**	**Post-CD**	**Pre-CD**	**Post-CD**	**Pre-CD**	**Post-CD**
Number of years		20	13	8	1	9	4	3	8
Annual rainfall (mm/year)		516.8	825.9	326.2	403.9	570.1	552.6	864.9	1015.3
Cotton	Cotton area ('00 ha)	136.7	306.7	135.5	317.8	140.7	334.6	128.4	291.4
	Cotton average irrigated area (%)	64.2	85.4	63.1	93.8	67.3	83.6	57.8	85.3
	CWR (MCM)	84.6	183.6	85.7	196.2	86.1	199.7	76.6	173.9
	GWA_{pot} (MCM)	41.5	94.2	51.2	147.6	37.4	100.3	27.9	84.5
	GWA (MCM)	26.3	74.9	19.4	29.2	32.1	72.2	27.3	81.9
	%met	79.1	90.2	53.6	30.0	94.9	86.2	100	100
Wheat	Wheat area ('00 ha)	36.7	77.7	10.7	7.5	42.5	37.0	88.2	106.9
	Wheat average irrigated area (%)	99.1	99.2	99.1	100.0	99.4	100.0	98.6	98.8
	CWR (MCM)	12.8	27.6	4.2	2.7	14.6	13.4	30.0	37.8
	GWA_{Pot} (MCM)	12.8	27.6	4.2	2.7	14.6	13.4	30.0	37.8
	GWA (MCM)	12.8	27.6	4.2	2.7	14.6	13.4	30.0	37.8
	%met	100	100	100	100	100	100	100	100

geometry catchment area (Mozzi et al., 2021), and results reflect the first order average potential recharge from existing CD storage in the catchment (Table A3).

4.4. *Observed change in groundwater storage (ΔGWS_O)*

GWLs show no statistically significant long-term declining or rising trend over the whole study period ($p > 0.05$), but high inter annual variability (Fig. 5). Averaged over pre-CD and post-CD, post monsoon groundwater level (GWL_{PM}) below ground level (bgl) and average annual groundwater storage increase (GWS_o) are higher (GWLs closer to ground level) during the post-CD period (GWL_{PM} = 6.8 m bgl, GWL_{PrM} = 11.4 m bgl and GWS_O = 107.0 MCM) than in the pre-CD period (GWL_{PM} = 8.7 m bgl, GWL_{PrM} = 11.8 m bgl and GWS_O = 70.4 MCM) (Table 3). However, when compared across similar SPI classified years to account for the influence of rainfall, GWLs and GWS_O are lower in post-CD as compared to pre-CD (Table 3). For example, GWS_o in post-CD decreases by 2.5 MCM (pre-CD=17.7 MCM and post-CD= 15.2 MCM), 19.4 MCM (pre-CD=83.9 MCM and post-CD= 64.5 MCM) and 31.1 MCM (pre-CD=170.8 MCM and post-CD= 139.7 MCM) for dry, normal, and wet years, respectively. This shows that overall higher GWLs and GWS_O in post-

Table 3
Average value of check dam groundwater recharge (GWR_{CD}), groundwater level monsoon rise (GWL_r), corresponding monsoon groundwater storage change (GWS_O) and pre (GWL_{PrM}) and post (GWL_{PM}) monsoon groundwater levels for all years and for SPI classified years, split into pre-CD and post-CD period.

	Overall		Dry		Normal		Wet	
	Pre-CD	Post-CD	Pre-CD	Post-CD	Pre-CD	Post-CD	Pre-CD	Post-CD
GWR_{CD} (MCM)	2.4	34.0	1.3	12.0	2.6	23.8	4.7	41.9
Inflow capture (%)[a]	67.1		93.7		84.7		55.0	
GWL_r[b] (m)	3.1	4.7	0.8	0.7	3.6	2.8	7.4	6.1
GWS_O (MCM)	70.4	107.0	17.7	15.2	83.9	64.5	170.8	139.7
GWL_{PM} (m bgl[c])	8.7	6.8	11.2	11.2	7.8	8.5	4.9	5.3
GWL_{PrM} (m bgl)	11.8	11.4	12.6	13.5	11.8	12.8	9.4	10.5

[a] Calculated as the difference between flow entering and leaving a check dam.
[b] $GWL_{r(i)} = GWL_{PM(i)} - GWL_{PrM(i-1)}$
[c] bgl = below ground level

CD is the result of disproportionally higher number of wet years in post-CD period (Table 3) and not due to the increased number of MAR interventions.

Dynamics of GWLs show that GWL_{PM} are sensitive to the magnitude of monsoon seasonal rainfall with average GWL_{PM} highest during wet years (~5 m bgl) and much deeper in dry years (~11 m bgl). On the other hand, pre monsoon groundwater levels (GWL_{PrM}) are relatively less sensitive to monsoonal rainfall with average GWL_{PrM} fluctuating from ~9.4–10.5 m bgl in wet years to ~ 12.6–13.5 m bgl in dry years (Fig. 5 and Table 3). This reflects the properties of low storage aquifer systems where storage is filled during monsoon months (to an extent depending on rainfall and storage capacity of the aquifer) and irrigation leads to desaturation at the end of hydrological year (Pavelic et al., 2012). The lower GWL_{PrM} and their low sensitivity to annual rainfall shows that there is limited inter-annual groundwater storage carry-over from the dry season to the wet season in the catchment.

5. Discussion

5.1. Dynamics of groundwater balance changes

Table 4 compares changes in observed (ΔGWS_o) and estimated (ΔGWS_E) groundwater storage, increase in recharge (ΔGWR_{CD}), changes in potential groundwater demand (ΔGWA_{Pot}) and actual groundwater abstraction (ΔGWA) for the Kamadhiya catchment between pre- and post-CD periods. The latter two are aggregated sums of cotton and wheat (Table 2). Results show that both ΔGWA_{Pot} and supply via increased recharge (ΔGWR_{CD}) has increased in post-CD but the increase in GWA_{pot} has outpaced the increase in GWR_{CD}. Additionally, the increase is not uniform across the SPI classified years. ΔGWR_{CD} is highest in the wet years, whereas ΔGWA_{pot} is highest in the dry years and vice-versa. Thus, the deficit (demand-supply) is highest for dry years followed by normal and wet years, with ΔGWR_{CD} representing only 11% of the increased groundwater demand (ΔGWA_{Pot}) for dry years. With limited natural recharge in dry years combined with low groundwater storage at the start of the year (i.e., GWL_{PrM} of previous year) (Fig. 5, Table 3) and low additional CD recharge (ΔGWR_{CD}) (Table 4), only ~30% of cotton GWA_{pot} is met in the post-CD period, whereas wheat cultivated area is significantly reduced (~10% of average wheat area in post-CD) (Table 2). Limited abstraction and recharge also mean that there is very limited change in estimated groundwater storage ($\Delta GWS_E = -2.5$ MCM) from pre-CD to post-CD (Table 4). This matches with limited change observed in groundwater storage ($\Delta GWS_o = 2.4$ MCM). This shows that groundwater storage remains low in dry years for both periods (Table 3) and is unable to meet irrigation demands. The high unmet demand reflects the limited efficacy of CDs in semi-arid regions with low storage aquifers for mitigating impact of droughts, which supports the findings of earlier studies (Boisson

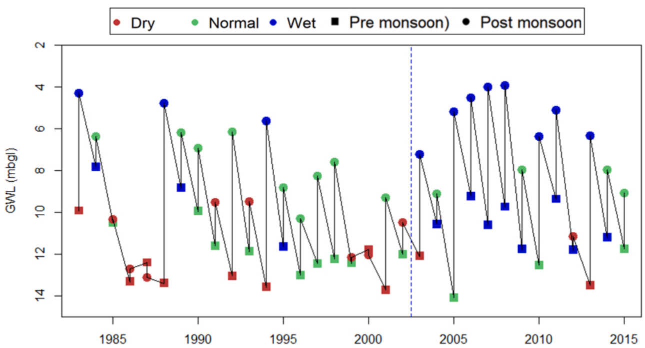

Fig. 5. Catchment-averaged pre- and post-monsoon GWLs (GWL_{PrM} and GWL_{PM}). Number of observation wells, n = 15. Color denotes SPI classified years. Symbols denote pre- (circle) [May] and post- monsoon (square) [November] levels. Blue vertical line divides the pre-and post-CD. Hydrological year in June-May.

Table 4
Average values of change in potential groundwater demand (ΔGWA_{pot}), groundwater abstraction (ΔGWA) [cotton + wheat], CD recharge (ΔGWR_{CD}), estimated (ΔGWS_E) and observed (ΔGWS_O) groundwater storage change for SPI classified years between pre-CD and post-CD period. All values are in MCM.

	Dry	Normal	Wet
ΔGWA_{pot} (MCM)	94.9	61.7	64.4
ΔGWA (MCM)	8.3	38.9	62.4
ΔGWR_{CD} (MCM)	10.7	21.2	37.2
ΔGWS_E (MCM)[a]	2.4	-17.7	-25.2
ΔGWS_O (MCM)	-2.5	-19.4	-31.1

[a] $\Delta GWR_{CD} - \Delta GWA$

et al., 2015; Enfors and Gordon, 2008; Kumar et al., 2008; Kumar and Perry, 2018; Ogilvie et al., 2016, 2019). For example, Ogilvie et al., (2016, 2019), in assessing rainwater storage structures in Tunisia, showed that their low storage capacity limits their ability to recharge groundwater sufficiently, thus having a limited impact on farmers' drought coping capacity. A similar conclusion was reached by Enfors and Gordon (2008) assessing MAR in Tanzania (locally termed Ndiva system). Thus, the hypothesis that sufficient runoff is available and remains available for planning recharge interventions may not hold in semi-arid areas, especially in dry years (Boisson et al., 2014, 2015).

For normal and wet years, the deficit is less pronounced relative to dry years (Table 4). However, ΔGWR_{CD} can only meet 34% and 58% of increased groundwater demand (ΔGWA_{Pot}) in normal and wet years, respectively (Table 4). In normal and wet years, in contrast to dry years, groundwater storage is recharged by rainfall (Fig. 5, GWL_r in Table 3) and meets the irrigation demand in excess of increased recharge from CDs (ΔGWR_{CD}). This is reflected in the results indicating that most of the potential groundwater demand is met in normal and wet years for both major crops (Table 2). Thus, higher groundwater abstraction translates to decrease in ΔGWS_E in post period (Table 4) for both normal (−17.7 MCM) and wet years (−25.2 MCM). This matches well with ΔGWS_O of − 19.3 MCM and − 31.1 MCM in normal and wet years, respectively. This implies that increase in recharge by CDs can only partly support increased kharif irrigation and positive impact of GWR_{CD} on groundwater storage is overshadowed by the increase in demand.

The findings from this study related to no long-term increase in groundwater storage are contrary to findings of other studies (Patel et al., 2020; Shah et al., 2009; Bhanja et al., 2017) and we find that higher overall average storage in the post-CD period is primarily due to an increased number of wet years. The divergence between the findings could be attributed to differences in the temporal period considered and/or the spatial scale of analysis. For example, Shah et al. (2009) only compared two distinct years (2000 and 2008) but did not fully account for the variability of rainfall. Similarly, both Asoka et al. (2017) and Bhanja et al. (2017) have a different temporal period for analysis with data starting from 1996, thus having very limited data for the pre-CD period which may accentuate low groundwater levels during the 2000–2002 drought relative to post-CD period. Their analysis was also focused at the national scale thus discerning regional differences is more difficult. While Patel et al. (2020) do account for longer time series (starting from 1975), they only compare wet year periods during the pre-CD (1975–1984) and post-CD (2004–2009), and the analysis focuses on the larger spatial region (whole of Saurashtra), thus again making a direct comparison difficult. It is important to note that none of the above studies accounted for changes in water demand, without which dynamics of groundwater storage cannot be reliably derived.

5.2. *Implication of MAR on kharif and rabi season cropping*

Overall, our findings of increased cropping and irrigation water demand of mainly kharif cotton and additional recharge from CDs partly support the hypothesis of Shah et al. (2009) that kharif production has increased, with GWR_{CD} making good rainfall years (i.e., normal, and wet years) better. However, even in normal and wet years, increased recharge can only partially meet increased demand (Table 4) translating to lower groundwater storage in post-CD when compared with pre-CD across similar SPI years (Tables 3 and 4). This further builds on the argument that CDs can only provide supplemental irrigation during good (normal or wet) rainfall years and cannot be expected to sustain intensive irrigation in dry years, as also evidenced in other regions (e.g. Ogilvie et al., 2016, 2019).

Our results do not show any consistent and significant increase in wheat area which was also hypothesized by Shah et al. (2009), except in wet years (Table 2). In this respect, our findings also contrast with findings by Garg et al. (2020) carried out in Bundelkhand region of Uttar Pradesh state of India. Their results show that the impact of recharge interventions in terms of increasing area and production was more tangible during the rabi season.

The low impact on rabi area and production in our study could be attributed to extensive irrigated cotton area in the study catchment (Table 2), which utilizes much of recharge during the monsoon season thus leaving limited storage for rabi cultivation dependent on irrigation. This is supported by the observation that post-monsoon GWLs (GWL_{PM}) have been similar or slightly lower in post-CD relative to pre-CD (Fig. 4 and Table 3). With no increases in groundwater storage at the end of the monsoon, (indicated by GWL_{PM}), there is limited increase in wheat area (Table 2) as it is highly dependent on GWL_{PM} signified by good correlation (R^2 of 0.64) of wheat area and GWL_{PM} (Fig. 6a). This also suggests that farmers across the catchment consistently plan their wheat crop areas cognizant of the irrigation demand that the post monsoon storage can support. The correlation of pre-monsoon levels with cotton area is much less pronounced (R^2 of 0.01) (Fig. 6b). This could be attributed to kharif cropping dependence on expected monsoon rainfall. The increase in wheat area for wet years (~21% increase in post-CD) couldn't be explained just from dynamics of GWLs, as GWL_{PM} are high and similar in both periods (Table 3). Thus, further research is needed to ascertain whether the increase in wheat area in wet years is a result of CD recharge or other dynamics.

5.3. Inter-annual groundwater storage

A commonly stated benefit of recharge interventions is that they create storage for dry years by recharging in years of good rainfall (Alam et al., 2020; Garg et al., 2020; Megdal et al., 2014; Singh et al., 2021). This may happen in situations where structures have larger storage capacity and are thus able to capture more and recharge over longer durations (Ogilvie et al., 2016, 2019) or in areas where there is low demand due to low cropping and irrigation intensity thus recharged water in wet years is in excess to demand and remains available for irrigation in dry years (Garg et al., 2020; Singh et al., 2021).

The study catchment, underlain by hardrock aquifers (low porosity, limited thickness) with limited aquifer storage capacity, shows no clear evidence of this. As compared to post-monsoon GWLs (GWL_{PM}), pre-monsoon GWLs (GWL_{PrM}, representing end of year storage) are much less sensitive to yearly rainfall and is in the range of ~10–12 m for all years (Section 4.4 and Table 3). We hypothesize that because of the wheat area's (post monsoon crop) strong dependence on GWL_{PM} (Fig. 5a) and limited post monsoon storage due to high demand by the monsoon cotton crop, limited storage is available by the end of hydrological year (Fig. 5). Very low wheat cultivated area in years with GWL_{PM} lower than 10 m bgl (Fig. 6a) suggests that groundwater storage below 10 m bgl offers limited utility to support irrigation due to the low porosity and limited thickness of the underlying hardrock aquifers.

Direct evidence of limited impact of carry-over storage is indicated by the severe impact on crop area and production in the drought year of 2012, which followed a wet year of 2011 (Figure A2). During 2011, wheat sown area was very high, resulting in limited storage at the end of the season (GWL of 11.8 m bgl) (Fig. 4). Thus, without significant carry-over storage and low rainfall (thus low recharge and high demand), the impact of drought was severe in the catchment with cotton and wheat production in 2012 being only 27% and 6% of their respective production in 2011.

5.4. Vulnerability versus benefits and tradeoffs of MAR

Supply-demand dynamics in the catchment points to the case of Jevons paradox (Alcott, 2005) where increased water demand from increased production outweighs water savings (Scott et al., 2014; Glendenning et al., 2012), in this case the increased recharge from CDs. In the absence of any policy or quota on irrigation, irrigation expansion, and higher irrigation efficiency can aggravate scarcity, and reduce resilience (Scott et al., 2014). However, more research is required to ascertain if the increase in demand (increased crop area and irrigation water use) is resulting from perceived increase in supply through GWR_{CD}, increase in rainfall years or other market-related factors. A counter argument to this is that these small storage aquifers are self-regulating, because they cannot be continuously depleted over many years (Taylor et al., 2019). The silver lining to this is that the system will likely not collapse, and whenever there is a good rainfall, the aquifers will be filled up. In turn, irrigated areas will not expand continuously, and likely they will vary more in tune with rainfall but exhaust the groundwater storage every year.

The argument can be made that this increase in demand outpacing supply has increased agricultural vulnerability to drought in the catchment. For example, the percent of demand met was only ~30% in dry years for the post-CD period, whereas this was ~54% in pre-CD period dry years (Table 2). This is evident in the 2012 drought where reduction in cotton production is much higher (relative decrease of 300%) in post-CD compared to 2000 in pre-CD (relative decrease of 61%) (Figure A2). This reiterates that CDs are not effective in a catchment with very low rainfall in dry years, little runoff to capture and low storage aquifers meaning limited carry-over storage.

However, on the other hand, an argument can be made that increased production in normal and wet years supported by CDs outweighs the losses in dry years. This suggest that rather than looking at productivity in individual years, the benefits of CDs or recharge interventions in the area should be assessed by combining good years with bad years. Good rainfall years allow farmers to make higher profits from increased capture of rainfall and address tide-over losses from dry years which remain as bad or worse as the

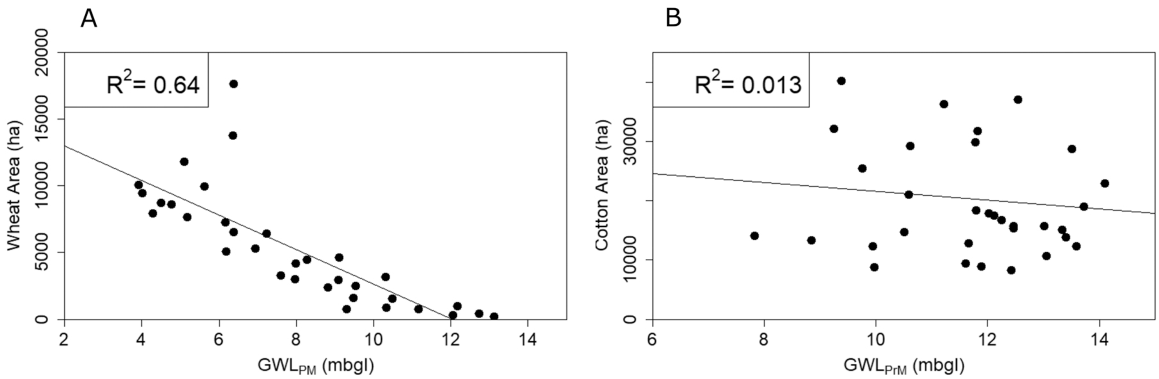

Fig. 6. Relationship between A) wheat area (Y-axis) and spatially averaged post-monsoon groundwater levels (GWL_{PM}) (X-axis); and B) cotton area (Y-axis) and spatially averaged pre-monsoon groundwater levels (GWL_{PrM}) (X-axis).

pre-MAR situation. More research and analysis are needed to ascertain these aspects. The narrative also points towards the need for better understanding the benefits and tradeoffs of MAR in these environments. Our results suggests that though CD came up in response to a drought, they are not necessarily efficient in drought proofing.

5.5. Uncertainties in this analysis and future research needs

The simple method applied in this study, with clearly defined assumptions and accounting for major factors, is able to progress the assessment of the impact of high-density CD development on climate resilience of agriculture in Saurashtra with implications for similar regions elsewhere. There are two major sources of uncertainty in the analysis: (a) reliability and inherent errors in the data used, and (b) methodological assumptions and simplifications made.

Agricultural data (crop area, irrigated area, and irrigation source) in Gujarat (and in India more broadly) is primarily derived from government reported annual agricultural statistics which are collected bottom-up from the village scale (and then aggregated to higher administrative levels) through random sample surveys of 20% of the villages during each crop season in a state and is then further cross-checked through random sampling (Ministry of Statistics and Programme Implementation, 2018; Planning Commission, 2001). Similarly, crop yield data are collected through crop cutting experiments in randomly selected fields and then cross-checked. However, being a manual survey process errors can result from: (1) non-reporting of crops sown (predominant error); (2) incorrect area entered for the crop; or (3) non-reporting of the crop actually sown in the field (Ministry of Statistics and Programme Implementation, 2018). Data for 2015–16 at the national scale in India shows that the error (mismatch of information identified in cross-checking) was 9–25% in different seasons for crop area, 9% for irrigation data (annual) and 5–10% for yields (cotton and groundnut) (Ministry of Statistics and Programme Implementation, 2018). Despite these errors, the absence of other annually available and long-term collected data makes this the primary source of data used extensively in agricultural and water resources research (Sidhu et al., 2022) and contributes to data for many global datasets (e.g. Siebert et al., 2010).

Similarly, data on groundwater levels is collected by the Central Ground Water Board (CGWB) four times each year (January, May, August, and November) by field personnel covering an extensive national monitoring well network (CGWB, 2015). The CGWB data has again been used extensively by researchers over many years as this represents the main source of groundwater data in India (e.g. Hora et al., 2019; Asoka et al., 2017; Bhanja et al., 2017). However, this data has gaps, and outliers, and is often sparse. These issues are usually addressed by removing outliers and monitoring wells with missing data above a threshold (as was done in this study) (Asoka et al., 2017; Bhanja et al., 2017). However, Hora et al. (2019) found that this may lead to bias (so-called survivor bias) where dried wells (often missing data) may lead to better picture of the aquifer than is actually the case. Other sources of data such as GRACE satellite data couldn't be used due to the small spatial scale of the catchment. Daily rainfall is taken from IMD gridded datasets and again has been used extensively (Asoka et al., 2017; Kumar Singh et al., 2019). IMD gridded data is derived from using records of ~ 7000 rain gauge stations (Pai et al., 2014). Multiple studies evaluating the performance of available rainfall products have shown that the IMD data performs satisfactorily over Indian monsoon conditions (Pai et al., 2014; Kumar Singh et al., 2019). Thus, while we have used the best available data (in some cases the only source) and published data sources (Table 1) which have been used extensively, they come with inherent uncertainties which have a bearing on the results.

This analysis required making certain methodological assumptions and simplifications as have been documented in Section 3. One limitation is that the method applied assumes that changes in annual yields primarily results from changes in (ground)water availability, whereas moving average of yields captures changes resulting from improvement in inputs (e.g., better seeds, fertilizers, better wells and pumps, etc.). However, the other factors (e.g., heat waves, cold waves, pest attacks) can still add to yield variability and couldn't be accounted for. Also, we donot consider irrigation efficiency with the assumption that irrigation return flows are completely recyclable. Additionally, while we have considered potential recharge by check dams, there is a need for further research to ascertain plausible upstream-downstream tradeoffs due to the same, as effects of flows captured in upstream areas potentially negatively impacts downstream communities (Calder et al., 2008; Ribeiro Neto et al., 2022; Nune et al., 2014). Similarly, lumped catchment assessment ignores the distribution, both spatial and social, of impacts and there is a need to assess how socially equitable the benefits have been. For example, there are concerns that CD impacts are concentrated near structures in low lying areas (Shah et al., 2021) and that farmers with more financial and social capital benefit the most (Bouma et al., 2011; Calder et al., 2008). This requires setting up more comprehensive hydrological assessments capturing catchment water balance and more explicit inclusion of surface-groundwater dynamics along with socioeconomic field data. The latter is also critical to determine the drivers and impacts of increase in demand. Further research is also needed to assess how these structures will work under the realities of climate change where extreme events are expected to increase (Mukherjee et al., 2018).

6. Conclusions

Managed aquifer recharge (MAR) through various interventions (including CDs) is increasingly being promoted and adopted for sustainable groundwater use and resilience building to dry periods and droughts. Our study analyzed the case of high-density CD development in the Saurashtra region of Gujarat, India. Results considering rainfall variability and crop irrigation water demand show that counter to assumptions of CDs being a strong measure to alleviate the impacts of droughts, their capability is highly restricted in dry years, and especially under scenarios of, possibly accompanying, increasing water demand. This is because there is limited runoff to capture and recharge and the underlying aquifer has low storage capacity that is replenished and depleted annually with limited carry-over storage. The study shows that irrigation water demand has increased significantly and outstripped the increase in recharge from CDs. Thus, with limited runoff in dry years, low groundwater storage, and increasing demand, these interventions may not be very effective in securing irrigation water supplies and may not necessarily lead to long-term climate resilience. For good rainfall years, increased recharge via CDs does increase supply but can only partially compensate for the increased demand of the kharif season, indicating that overall reduction of irrigated areas and flexible annual adjustment to rainfall in the wet season and adjustment to groundwater storage in the dry season are required. These findings suggest that MAR, unless complemented by greater emphasis on water demand management and groundwater governance, may not suffice as a standalone solution to achieving sustainable groundwater and concurrently expanding food production in hydrogeological and climatic settings like in Gujarat, India. Additionally, Irrigated agriculture needs to be flexible and adaptable to prevailing climate and groundwater storage conditions. There is a need for clear communication and realistic assessment and expectation of the potential benefits of recharge interventions in regions with limited aquifer storage and highly variable runoff, while also ensuring that basic water needs are not sacrificed in the quest for increased food production.

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CRediT authorship contribution statement

Mohammad Faiz Alam: Writing – original draft, Methodology, Formal analysis, Data curation. **Paul Pavelic**: Supervision, Formal analysis, Result interpretation, Writing – review & editing, Funding acquisition. **Karen G. Villholth**: Conceptualization, Result interpretation, Writing – review & editing. **Alok K. Sikka**: Supervision, Writing – review & editing. **Saket Pande**: Result interpretation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data generated or analysed during this study are included or referenced in this published article (and its supplementary information files).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101224.

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