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RESEARCH ARTICLE

Chasing the water table: The impact of groundwater depletion on rural drinking water supply in peninsular India

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Abstract

Groundwater overexploitation has been cited as one of the biggest threats to rural drinking water in India, but there is very little quantitative evidence on the risks to source sustainability. In this paper, we aim to understand (1) the extent of actual groundwater depletion and its impact on rural water supply systems, (2) the primary driver of groundwater depletion and (3) the additional financial burden in finding new sources for water supply, relying on temporal data from two *Gram Panchayats* (local administrative unit) in the Upper Arkavathy watershed near Bengaluru, in south India. Study results confirm that groundwater depletion, in this hard rock aquifer region, is a severe problem, driven largely by agricultural water abstraction. Rural water supply systems have had to catch up continuously with the falling water table, abandoning non-functional wells and drilling new borewells to replace them. This has resulted in a major financial burden to the *Gram Panchayats*. Hitherto, state and central government grants have paid for rural well installation in India, but the increased pumping costs associated with declining groundwater levels impose a major burden on the *Gram Panchayat*, many of which are severely in "electricity debt".

1. Introduction

Sustainable access to safe drinking water is a problem in rural areas. Even where functional infrastructure producing adequate levels of drinking water quality have been put in place, maintaining the performance of these facilities over time remains extremely difficult in the face of financing, local capacity, and governance challenges. Roughly one in four hand pumps in sub-Saharan Africa are non-functional at any given point in time, while estimates vary more widely for Asia-Pacific countries [1].

The global discourse on "sustainability of water, sanitation, and hygiene (WASH)" is largely focused on technical and financial aspects. In India, though, inadequate water resource management (WRM) can arguably be pointed to as the biggest threat to sustained rural drinking water access [2]. The vast majority (over 85%) of rural drinking water in India is borewell-based and groundwater in over a third of the country is already classified by India's Central Ground Water Board as "semi-critical" (with extraction at 70-90% of recharge), "critical"

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(with extraction of 90-100% of recharge), or "over-exploited" (with extraction exceeding annual recharge) [3].

Both in India and globally, rural water supply schemes account for a negligibly small fraction of freshwater appropriations, as compared to, for instance, roughly 70% for agriculture and 20% for industrial and commercial uses [4] Although rural drinking water service delivery may not yet significantly affect water, the reverse is not true. In fact, groundwater overexploitation is already affecting the rural drinking water security in India and is recognized by the Indian government as a significant threat for policy and planning purposes [5]. Nevertheless, there is a paucity of well-documented examples of the interaction between water resources and rural water supply and quantification of the threat in volumetric and economic terms is largely missing from the discourse.

Prior studies have discussed groundwater depletion in South India [6–8]. These studies typically either use GRACE (~300 sq km resolution) or fine resolution models (~1 sq km) calibrated against monitoring well data. These efforts typically rely on depletion estimates from water balance approaches, modeled or observed. In alluvial systems contouring monitoring well observations can give a fairly accurate estimate of water levels in individual borewells. In hard-rock systems, however, there is a high level of heterogeneity observed in the field which can be at the scale of 10s of meters [9,10]. The monitoring well density is comparatively sparse. As a result, models cannot easily predict the risk of failure of individual wells. To understand the risk of failure and cost incurred to drinking water authorities, broader scale estimates of depletion need to be linked to individual wells. This necessitates field based observational data.

This research gap is particularly noteworthy in the context of India's ambitious *Jal Jeevan Mission* (JJM), which seeks to deliver a piped connection of safe drinking water to every Indian household by 2024. Although the *Jal Jeevan Mission* does not include expenditures for operation and maintenance costs of rural water supply, it does address water source sustainability by funding the replacement of failed borewells [5]. In addition, the consolidation of responsibilities for drinking water service provision and water resources within a single government institution (via the establishment of the Ministry of Jal Shakti in 2019) and the emphasis on source sustainability in Jal Jeevan Mission guidelines signals seriousness in the government's intent to drive convergence.

In this study, our research objective was to understand how groundwater depletion impacts rural water supply, in quantitative terms. We collected and analyzed primary data from two *Gram Panchayats* in the Aralumallige subwatershed, in Bengaluru Rural District in Karnataka state in South India to answer three questions: first, *what is the extent of groundwater depletion and how does it impact drinking water borewells*? Second: *what is the primary driver of groundwater depletion?* Third, *how much additional investment is required each year to replace wells that cease to function and what is the additional pumping cost imposed by deeper borewells?*

2. Methods

Study area

The Aralumallige subwatershed (Fig 1) of the Upper Arkavathy watershed is a 20 km^2 catchment in the outskirts of Bengaluru. It falls within the Bengaluru Rural district within Karnataka state in peninsular India. Portions of three different *Gram Panchayats* of Bengaluru Rural district fall within the catchment: Aralumallige, Doddathumakuru, and Majarahosahalli (Fig 1).

The catchment is semi-arid, with an average annual rainfall of about 800 mm spread over a few months, as compared to an average annual potential evapotranspiration across the catchment of ~1700 millimeters [11]. The area is thus moisture-limited for much of the year, which

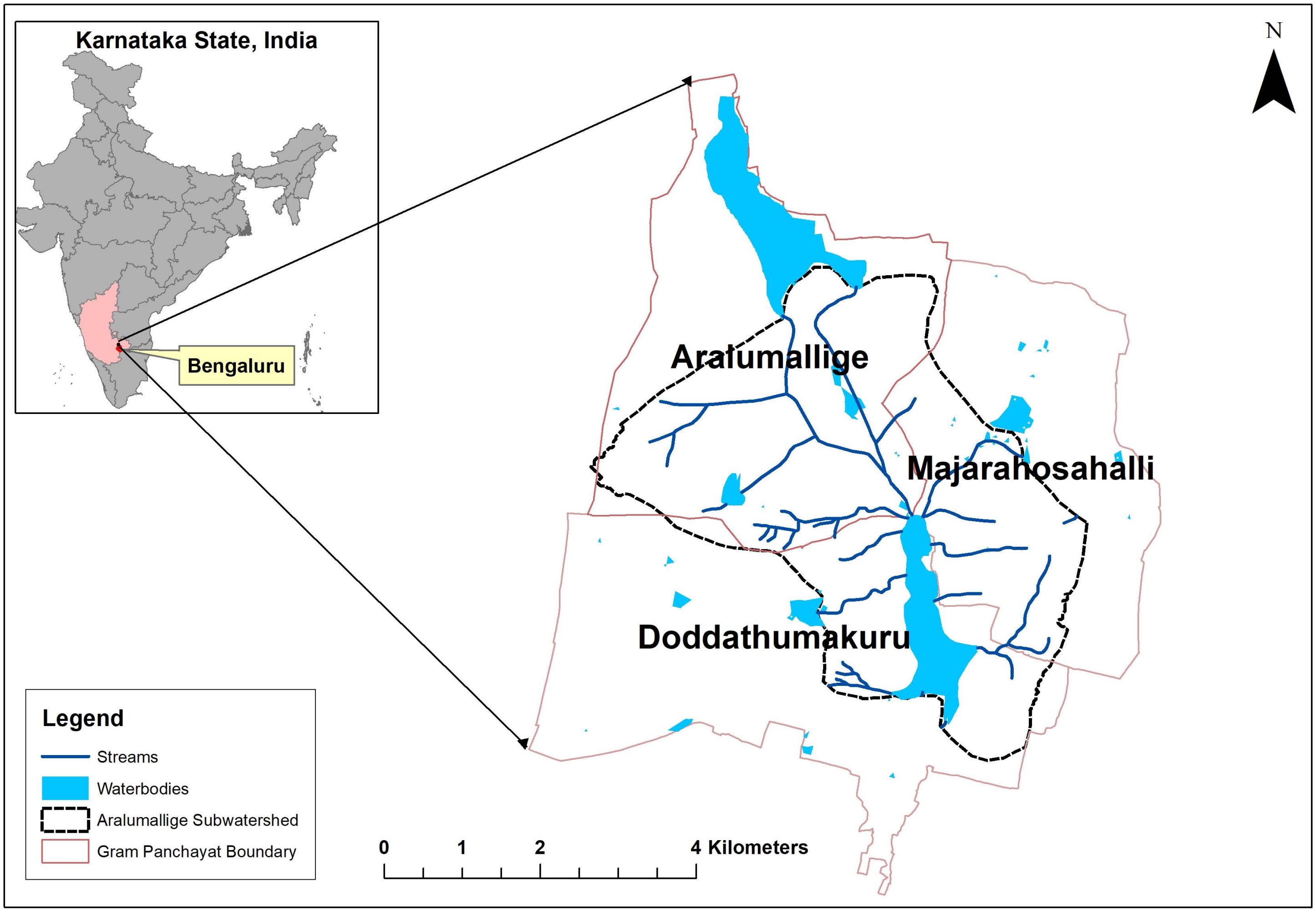

Fig 1. Map of the Aralumallige subwatershed in southern Karnataka. Source for map of India with state and village boundaries: https://onlinemaps.surveyofindia.gov.in.

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means that without irrigation, farmers can only grow a single rainfed crop per year. Because groundwater is the sole source of irrigation, it can only be practiced by farmers with borewells. As groundwater levels fell, there was competitive deepening of borewells; [11].

The Aralumallige subwatershed is underlain by hard rock aquifers composed of granites, granitic gneisses and migmatites. Hard rock aquifers are formed over billions of years as the unweathered bedrock develops joints and fractures due to tension release. Over time, chemical weathering occurs along the joints forming a thin zone of partly weathered rock material that form aquifer systems when saturated. Hydrogeological studies in peninsular India [12,13] show hard rock aquifers characterized by a dense horizontal fracturing in the first few meters (the "weathered rock zone"), with the density of fractures decreasing with depth. The groundwater formations of the Aralumallige subwatershed are heavily exploited. There was complete dewatering of the weathered rock zone by the 1990s, and borewells have deepened every few years [11]. Because the quantum of water yielded by dewatering fractures is very small, borewell yields at deeper groundwater levels are very low.

Multiple agencies have responsibilities for drinking water supply in this study area. While technical support is provided by the state Rural Development and Panchayati Raj (RDPR) department, responsibilities for scheme construction and operations are devolved to institutions set up under India's three-tier Panchayat Raj Institutions (PRI) system for local governance. Only the highest tier (*Zilla Panchayat*) and lowest tier (*Gram Panchayat)* are involved in rural drinking water supply. The *Zilla Panchayat* (comprising around 150 to 200 *Gram Panchayats* in Karnataka) operating at the district level allocates funds for capital expenditure and awards tenders for the installation of borewells and conveyance infrastructure. The *Zilla Panchayat* then hands the system over to the *Gram Panchayat*, which usually comprises three to ten revenue villages. The *Gram Panchayat* manages and maintains the water supply system. Each *Gram Panchayat* receives some funding from the central government's 15th Finance Commission Fund as well as from the state government through the "*Shasana Badda Anudhana*" scheme for public services (*Gram Panchayat Panchayat Development Officer* Personal Communication, 2022). Additionally, each *Gram Panchayat* sets and collects property tax and applicable tariffs as utility revenue from households.

Rural drinking water schemes in the Bengaluru Rural district have evolved considerably since their inception in the 1970s. Early schemes were primarily handpumps, at a time when groundwater levels were shallow and functional open hand dug wells were common. Populations without access to local open wells had to walk a few kilometers each way to the nearest hand pump. While drinking water schemes were hand pump-based, private installation of borewells with pumps for irrigation had already begun in the 1970s and expanded quickly with the free electricity policy for irrigation that began in the early 1980s [11]. By the early 1990s, the Aralumallige subwatershed's shallow aquifer had been completely exhausted [11] and the *Gram Panchayats* began to drill borewells to provide municipal supply via public standpipes. Initially, one or two public standpipes were installed in every street (*Gram Panchayat* Assistant Engineer, Personal Communication, 2022) with the goal of supplying at least 40 liters per capita per day (LPCD).

After 2005, the *Gram Panchayats* began to invest in reticulated piped networks and household connections. The networks are currently being expanded to all households under the Jal Jeevan Mission (JJM) with increased service delivery benchmarks of 55 LPCD.

Data collection

To establish the impacts of groundwater depletion on drinking water supplies, we carried out a census of borewells that included data on functionality. We decided to collect data on wells because we did not feel confident in available secondary data, for several reasons. First, the Aralumallige subwatershed is underlain by hard-rock aquifers; although monitoring well records are available for the area going back to the 1990s, the monitoring well densities are sparse and do not offer accurate estimates of groundwater properties at a regional scale, due to the high spatial heterogeneity typical of fractured hard rock aquifers. Second, trend analyses from existing borewell records are skewed by survivor bias: dry wells are dropped from the Central Ground Water Board (CGWB) well dataset as water levels decline [10]. The surviving wells present an inaccurate biased picture of stability. Third, because investment in agricultural borewells is private, no reliable public record exists of all abstraction wells.

To address the extent of groundwater depletion and to determine how it impacted rural drinking water supply, we mapped functional and abandoned wells over time. We were only able to obtain complete data for Doddathumakuru and Aralumallige *Gram Panchayats*. Our dataset contained geotagged data on year of construction, well depth, and year of failure (if applicable) for both the Gram Panchayat and private borewells. These data allowed us to recreate the snapshots of functional and abandoned wells in the years 1981, 1991, 2001, 2011 and 2017, which coincided with census years for which other data were available. For example, if a well was constructed in 1984 and abandoned in 1998, it would not appear in the 1981 map, it would appear as a functional well in 1991, and as an abandoned well in 2001, 2011 and 2017. Additionally, we conducted a census of private borewells in 2017 to supplement our dataset.

We conducted two distinct well census efforts: The first census was of private irrigation borewells that took place between September to November 2016 [9], and the second was of *Gram Panchayat* drinking water borewells between March and July 2022. By definition, a census of wells, means every single well in the watershed was included. I.e.; a sample of 100%.

Irrigation well census. An irrigation well census involves walking through the landscape, plot by plot, and mapping all wells, both functioning and abandoned. This was done not through a household survey but by surveyors traversing the area over several months. The surveyors identified and geotagged both abandoned and functioning wells.

At each farmer's plot in the village, our field team introduced itself and interviewed the well owner to record the year of construction, use (agricultural, domestic, commercial), status (functional vs. non-functional), depths of yielding fractures and year of failure (if applicable). We also collected data on plot size and crop selection during each of the three seasons, from which we could develop a complete water use account of the village. Our relatively rapid time-frame was accelerated by our familiarity with many farmers in the study area from previous research. Nonetheless, this process was cumbersome and expensive as many wells were visited repeatedly till the information was obtained and the farmer was located for an interview.

During the 2016 data collection period, we inventoried and geo-tagged 645 unique borewells. irrigation wells in Aralumallige subwatershed. Of these, 62% were found to be abandoned. Using the dates of construction and year of failure, we were able to estimate the number of wells functioning in any given year as well as the borewell failure rate.

Drinking water well census. Between March and July 2022, we identified functioning drinking water borewells using a list from the *Gram Panchayat* office. For older, abandoned borewells, we first conducted focus group discussions with village "watermen" (watermen are assigned with the responsibility of monitoring and maintaining local water supply schemes installed by the government.) and then accompanied each waterman through the village to locate both current and old abandoned wells. We later shared the digital geographic information system (GIS) map layers with the *Gram Panchayat*. A total of 254 unique drinking water wells were geotagged.

Irrigation water abstraction estimation. To understand the primary drivers of groundwater depletion in the subwatershed, we estimated irrigation water abstraction using the method laid out by Brouwer and Heibloem [14], necessitating as inputs the irrigated area, cropping patterns, and irrigation technologies employed over time. This in turn required the generation of our own land use/land cover estimates, for which we used classification tools in Google Earth Engine. Landsat images were used for the years 1992-93, 2000-01, 2010-11, 2020-21 covering the changes in land use/land cover over four decades, with sufficient temporal resolution to determine intra-annual frequency of irrigation (as indicated by multiple vegetation peaks over the course of the year). This was necessary because global land use/ land cover products available for this region could not differentiate irrigated agriculture given the small plot sizes and high heterogeneity, especially the intra-annual variations in the cropping patterns [15]. We choose Landsat images since they offer the longest record of data [16,17]. We used 'USGS Landsat 5 TM Surface Reflectance Tier 1' for 1993 & 2011, 'USGS Landsat ETM+ 7 Surface Reflectance Tier 1' for 2001 and 'USGS Landsat 8 OLI Surface Reflectance Tier 1' for 2021. For the year 2011 we relied on data from Landsat 5 TM rather than Landsat 7 ETM+ because of line stripping error in the latter sensor. We verified the estimates with field visits and interviews with farmers and provided details on the method employed for computing land use and cover change in Supplemental information (S1 Text).

Based on discussions with farmers in the subwatershed between 2017 and 2022, we reconstructed a history of the irrigation methods employed. We identified flood irrigation as the only method of irrigation until 1991, and drip irrigation slowly growing up to 30% by 2001, 50% in 2011, and 90% by 2021. We assumed the efficiencies of flood and drip irrigation to be 60% and 90%, respectively (*i.e.,* 60% of flood irrigation water and 90% of the drip irrigation water is evapo-transpired) [18]. We assume that post 1990's the main source of irrigation in this region is groundwater [11], Personal Communication with farmers in Aralumallige subwatershed, 2022]

Following Brouwer and Heibloem [14]:

$$\text{IN} = \text{ET Crop} - P_e \tag{1}$$

Where IN = Irrigation water need

ET Crop = crop water need (i.e., evapotranspiration of a specific crop type)

P_e = effective rainfall (i.e., the portion of rainfall that can be effectively used by plants, equivalent to rainfall minus runoff minus evaporation minus deep percolation)

We calculated ET Crop by multiplying the phenological crop coefficient (K_c) value by the average seasonal potential evapotranspiration (PET) for the region [19].

We calculated Pe using the formula

- $P_e = 0.8$ P-25 if $P > 75$ mm/month
- $P_e = 0.6$ P-10 if $P < 75$ mm/month.

Drinking water abstraction estimation. We estimated groundwater withdrawals by the *Gram Panchayat* for domestic purposes using the per capita (liters per capita per day or LPCD) norm specified in the National Rural Drinking Water Programme (NRDWP) Guidelines for 2013 and *Jal Jeevan Mission* Operational Guidelines for 2019 (40 LPCD for the decades during 1991 and 2001, and 55 LPCD after 2019) [5,20]. In the absence of actual water supply data, we assume that the *Gram Panchayats* delivered the minimum volume for domestic purposes, multiplying the LPCD norms by population size enumerated in the Census of India for the years 1991, 2001, and 2011.

We also note that a significant portion of the domestic water in the study area is used for livestock. We assume two domestic cows per household for the decades beginning in 1991, 2001, and 2011 and one per household for the decade beginning in 2021, with an upper limit of the daily water requirement per cow of 80 liters [21]. Using these data, decadal domestic water consumption was estimated for the years 1991, 2001, 2011 and 2021 (population data for 2021 was extrapolated using the previous decade's census data and growth rate) Table 1.

Groundwater recharge estimation. We assumed that 5% of precipitation infiltrates the subsurface and recharges the underlying aquifer. Recharge rates typically consist of recharge from rainfall and recharge from other sources (such as surface water reservoirs and irrigation return flows). Recharge only begins to occur after rain events of a certain magnitude, but research suggests that recharge rates are not significantly higher for more intense events, so using annual average rainfall is appropriate.

Table 1. Estimation of 2021 population.

Sample Village Name	Population in 2001	Population in 2011	Decadal Growth Rate	Decadal Growth Rate in %	Estimated Population for 2021
	By Census 2001	By Census 2011	(Population in 2011-Population in 2001)/Population in 2001	Decadal Growth Rate * 100	(Population in 2011) + (Population in 2011 * Decadal Growth Rate)
Alahalli	939	1172	0.25	24.81	1463

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Empirical measurements of rainfall done using the chloride mass balance (CMB) and water table fluctuation (WTF) methods suggest rainfall infiltration factors of 1-7% in hard rock regions, with 5% being the typical assumption used in models [22]. The Central Ground Water Board's (CGWB's) Groundwater Estimation Committee estimates recharge in Doddaballapur Taluk to be 8% with rainfall alone accounting for 5% [23].

Given that there are no other major sources of recharge in the Aralumallige catchment, a rainfall infiltration factor of 5% was applied to the average annual rainfall [24–26] Table 2.

Costs of withdrawals. To quantify the cost of pumping over time and to understand how much of this is because of over-exploitation of groundwater, we obtained current drilling and electricity costs from the *Gram Panchayat* offices. We interviewed farmers and *Gram Panchayat* staff to reconstruct historical trends, asking them to recall the cost of wells they drilled in each decade since 1981. Because these were based on interviews and multi-decadal recall, the data are the best estimates. They were also expressed in nominal terms and had to be both adjusted for inflation (considering 2022 as base year) as well as for changes in depth of borewells over time.

Costs of replacement of failed borewells. To quantify the cost of reinvestment to replace failed borewells, we estimated the total number of functioning wells, the number of failed borewells, the number of additional wells that would be required to serve the growing population and changing per-capita water supply norms. To estimate these costs, we needed to consider several factors: inflation, the increasing depth of borewells, and improvements in technology, which resulted in a decline in the inflation adjusted per-foot cost of drilling.

Table 2. Sources of data used to estimate water demands.

Variable	Data	Source of Data
Irrigation water demand [14]		
Land use/ Land Cover	Satellite Imagery	'USGS Landsat Level 2, Collection 2, Tier 1 datasets from Google Earth Engine (https://earthengine.google.com/)
	Verification	Field surveys using NOTECAM (https://notecam.derekr.com/index-EN.html)
Irrigation Water Demand	Cropping patterns of farmers using farm census of all irrigated farmers and some rainfed farmers in 2017.	Field surveys
	FAO Irrigation Water Use Methodology	FAO Crop Coefficient Table (Allen et al.1998, Chapter 6)
	Potential Evapotranspiration	FAO Average Seasonal Potential Evaporation Rates Rao et al. 2012
	Rainfall	IMD Gridded Daily Rainfall Data https://imdpune.gov.in/cmpg/Griddata/Rainfall_25_Bin.html
	Drip Irrigation	Farm census and field surveys
GW Recharge	Recharge Coefficient	Scanlon et al. 2005
Drinking water demand		
Population	Population Census	Government of India 1991, 2001, 2011 census https://censusindia.gov.in/census.website/ extrapolated to 2021 using decadal growth rate.
Liters per capita per day (LPCD)	Quantum supplied was first assumed to be 40 LPCD, revised to 55 LPCD after 2011. A pipeline leakage loss of 20% as assumed.	Ministry of Drinking Water and Sanitation 2013; Ministry of Jal Shakti 2019

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Multiple studies have estimated the cost of drilling deeper wells using data obtained from farmer surveys. The data show a substantial variability in hard rock regions depending on local physical as well as economic scarcity of groundwater resources. Therefore primary data for this specific watershed was needed. For the farmer owned wells we were able to follow a similar methodology based on the costs obtained from farmer interviews. For the drinking water wells however, no official record was available [27–30].

To estimate the cost of borewells in any given year, we interviewed three well drillers to obtain the average cost of wells drilled by them in each decade. We asked them to include the cost of motors, pipes and other accessories. This allowed us to obtain the nominal cost of a borewell and the nominal cost per foot. We then inflation adjust the borewell costs in each decade to 2022 USD (S2 Text).

We were able to estimate two types of costs: First, we estimated the cost of the investment stranded in each decade, by estimating the original cost of each borewell drilled. Second, we estimated the additional cost of replacing failed borewells by adding up the costs of each borewell drilled to replace a failed borewell. These analyses allowed us to estimate the cumulative costs borne by the drinking water sector due to groundwater depletion.

3. Results

Map of functional and abandoned borewells over time

We mapped functional and abandoned borewells over time to understand the impact of groundwater depletion on rural drinking water supply in the Aralumallige subwatershed. Dataset included geotagged information on borewell construction year, depth, and failure year (if applicable) for both Gram Panchayat and private borewells. Using this data, we were able to recreate snapshots of functional and abandoned wells in the years 1981, 2001, 2021. These maps helped us to assess the extent of groundwater depletion and its impact on drinking water supply in the region. The spatial snapshots of borewells over time show a deepening of wells throughout the landscape due to dropping water tables (Fig 2). There are almost five times as many private irrigation borewells (129 functioning in 2017) than *Gram Panchayat* drinking water borewells (26 functioning in 2017).

Histogram of well depths by decade of construction

The distribution of well depths changed substantially over time with respect to both private and *Gram Panchayat* borewells (Fig 2). Moreover, in the early years covered in the analysis, we found that private wells were deeper (Fig 3A). After 2000, however, *Gram Panchayats* also began drilling deeper borewells, to keep up with the declining water tables, although private borewells on average remain slightly deeper (Fig 3B),

One can generally rule out abandonment of wells due to water quality. Interviews with the *Gram Panchayat* officials revealed that of the 79 abandoned borewells, only two were abandoned due to elevated fluoride concentrations. Although nitrate levels are often higher than the prescribed norm of 50 milligrams/liter [31], apparently this has not led to well abandonment per the officials.

The analysis shows that almost 55% of all wells drilled in the Aralumallige subwatershed have failed, with 70% of drinking water wells failing within a decade of construction due to falling water table depths.

Table 3 shows expansion of irrigation from 2010-2020 despite high rates of well failure. Irrigated plots cover 40% of land in the subwatershed in 2021.

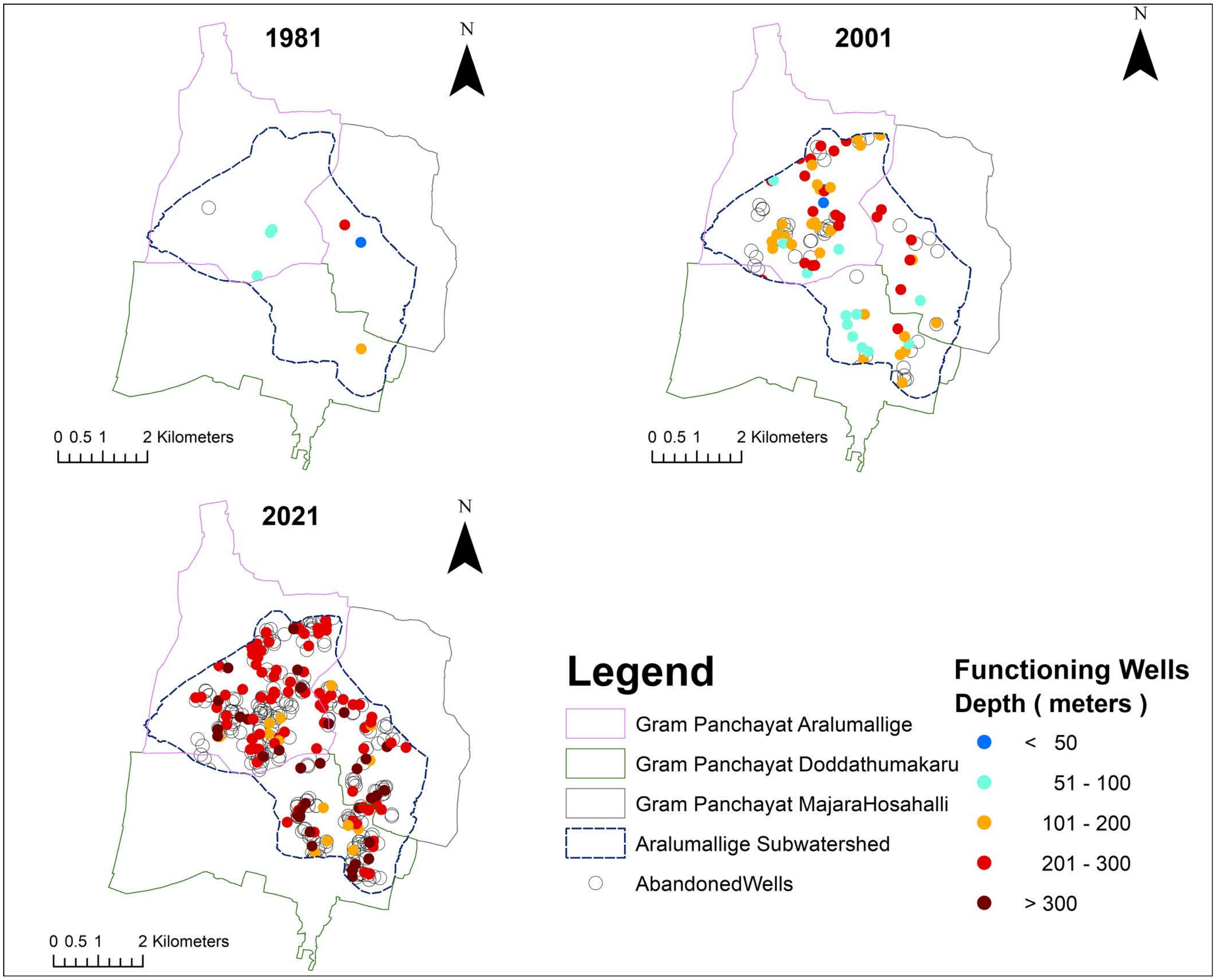

Fig 2. Snapshots of functional and abandoned wells at different points in time. Source for village boundary shapefiles: https://onlinemaps.surveyofindia.gov.in.

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Comparison of irrigation and domestic abstractions vs. recharge from rainfall

We applied the Food and Agriculture Organization (FAO) methodology [14] to estimate irrigation withdrawals and compared them to both withdrawals for drinking water by the *Gram Panchayat* and to recharge via rainfall. A detailed explanation is applied in Supplement S3 Text.

Fig 4 shows that irrigation withdrawals are 10-20 times higher than domestic withdrawals at different time periods, and that total withdrawals far exceed estimated groundwater recharge from rainfall. Even though only 25% of cropland is irrigated, groundwater in the region is already overexploited. Though the land under irrigation is expanding, the water extracted for irrigation is going down over the years due to the use of efficient micro-irrigation systems.

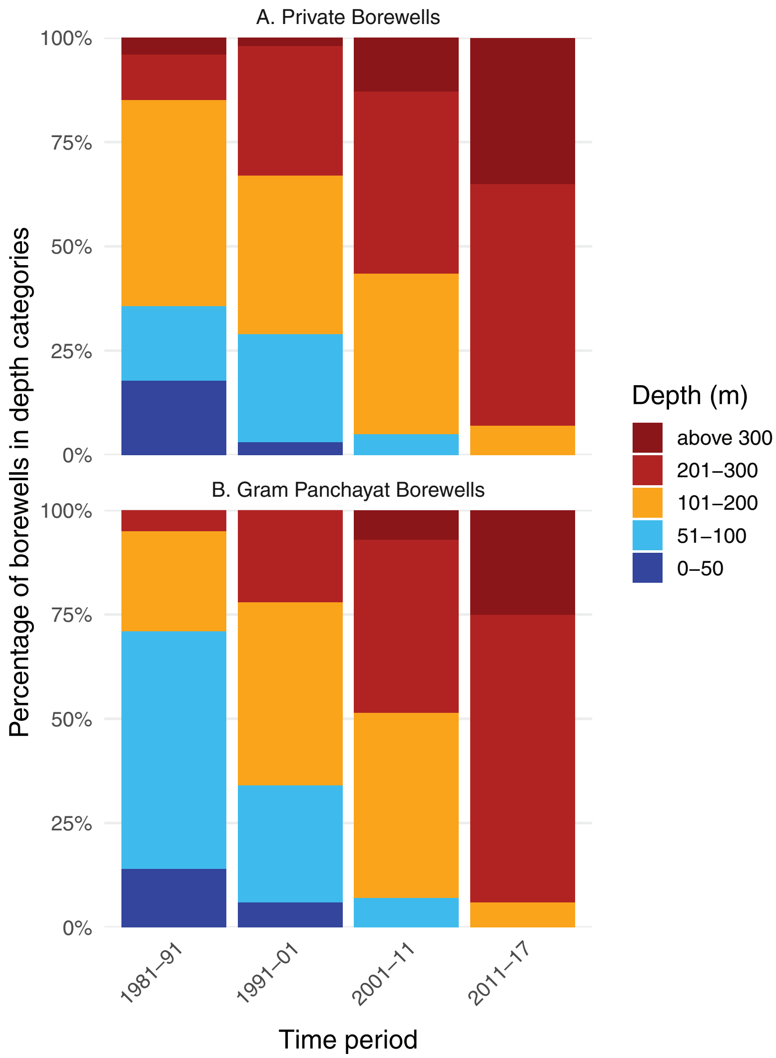

Fig 3. Frequency distribution of drilling depth of private (645) and Gram Panchayat borewells (254). The figure shows the fractions of wells by depth (in meter) drilled in each decade.

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Table 3. Land use land cover change over time (in hectares).

Class\Year	1993	2001	2011	2021	Period
Irrigated Plantations	208	36	53	230	Annual
Double Cropped Paddy	12	0	0	0	June-Jan
Irrigated Mixed Crops	291	549	661	1000	June-Jan
Irrigated Total	511	585	714	1230	
Settlement	6	6	13	34	Annual
Unirrigated Plantations	67	54	135	529	Annual
Rainfed Paddy	23	0	0	0	June-Sept
Rainfed Other	1080	995	799	53	June-Oct
Perennial Waterbody	29	44	0	0	Annual
Seasonal Waterbody	57	32	22	22	June-Jan
Fallow/Open Land	284	327	305	119	Annual
Prosopis sp.	0	15	69	69	Annual

https://doi.org/10.1371/journal.pwat.0000138.t003

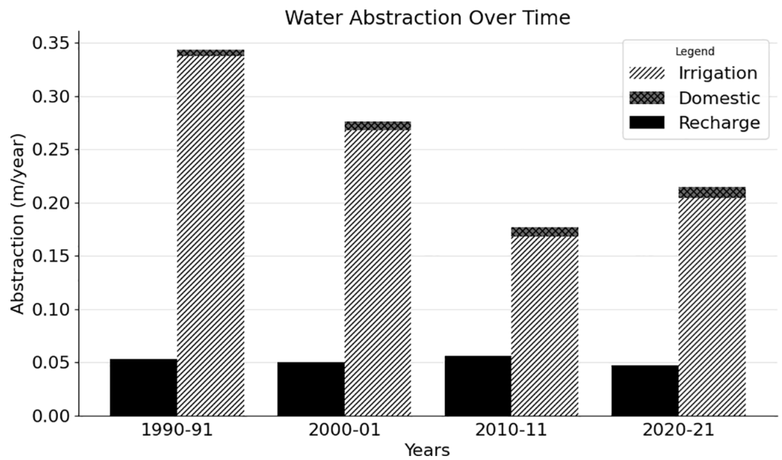

Fig 4. Comparisons of estimated groundwater abstraction amounts for domestic and irrigation versus estimated groundwater recharge.

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Comparison of increased demand vs. investment

To determine the additional investment incurred to develop new water production for domestic water supply to replace wells that have been taken out of operation, we compared the investment that would have been needed to meet increased water demand to the actual investment since 2011.

Increased demand is estimated by the increase in population times increase in LPCD. As 2011 was the first full year of implementation of the National Rural Drinking Water Programme guidelines, and the whole population should have been receiving 40 LPCD, 2011 was used as a baseline. After 2019, this was increased to 55 LPCD based on the Jal Jeevan Mission guidelines. Based on this we could estimate the percentage increase in the number of borewells (assuming no significant change in yield).

To estimate the cost of drilling deeper borewells for drinking water in response to groundwater depletion, we assumed a counterfactual scenario wherein no borewells failed so that any additional wells added after the 2000 only be needed to meet increased domestic demand due to population growth and revision of the LPCD norms. There were 23 functioning drinking water wells in 2011 (Table 4). Between 2011 and 2021, population increase and the increase in the per capita volumetric norm from 40 to 55 LPCD should have resulted in an increase in the number of functioning wells to 34. In other words, only 11 new borewells for drinking water would have been drilled between 2011 and 2021 in the Aralumallige and Doddathumakuru *Gram Panchayats* in the absence of groundwater depletion.

In reality, however, borewell failure did occur. Functioning wells failed and new wells we drilled to compensate for them. We could estimate the increased cost in two ways:

1) the stranded investment – i.e., the cost of the original borewells

2) the duplicate investment – i.e., the cost of new borewell to replace the failed ones.

Note that the inflation adjusted cost of the replacement borewells will not be the same as the cost of original borewells because they are likely to be deeper. On the other hand, drilling costs per foot have consistently declined, so the difference is likely to be small.

The data suggest in the 1990s when drinking water borewell drilling lagged demand. But from 2001 to 2021, new wells drilled kept pace with increased demand and replacement of failed borewells. In fact, 41 new borewells were drilled and 30 wells failed, leaving 34 functioning borewells at the end of 2021 (Table 5).

The total cost of drilling the 41 new borewells for both *Gram Panchayats* between 2011 and 2021 was $US 269,657. This includes both wells drilled to meet new demand and replace failed borewells. Of this amount, the cost of replacing failed borewells, works out to $US 197,206. The original cost of 30 borewells that failed in this decade for both *Gram Panchayats* was $US 183,399 (based on Indian Rupee to US Dollar conversion factor of 76.9 in 2022).

But not only did the capital costs increase, but groundwater pumping costs also increased with falling water tables. According to staff at the two *Gram Panchayats*, electricity costs tripled during the last decade (Personal Communication with Yogesh, Assistant Executive Engineer, Department of Rural Development and Panchayat Raj, Doddaballapur, 2022). Average Gram Panchayat drinking water borewell depths increased from 183 meters during the period 2001 - 2011 to 321 meters during 2011 – 2021 period. The increase in electricity bills are partly due to the increase in depth of the wells and partly due to interest accumulated on arrears.

Indeed, just a single line item, the cost of electricity for pumping drinking water wells in Aralumallige and Doddathumakuru Gram Panchayats exceed all sources of revenue they received - taxes, state and central government allocations. The nominal flat rate tariff from drinking water customers (50 to 100 Indian Rupees per month per household) constitutes less than 20% of the total Gram Panchayat revenue collected. But these allocations are meant to cover all costs including cleaning and maintaining gutters, paying staff salaries etc., not just water and sanitation. (Table 6). As a result, both *Gram Panchayats* are in major arrears to the state electricity board, which is accumulating interest. These debts go back almost a decade.

The total cost of electricity for pumping, as measured by the annual electricity bills (including interest on arrears), which includes new electricity charges plus interest on arrears, is four times higher than the capital cost of drilling to replace failed borewells each year (~8200 USD for drilling and electricity connection of 300 meters deep borewell as per 2020). In recent years, the two *Gram Panchayats* have been running collection drives to raise tax revenues to clear these debts, because access to other government development programs are tied to their

Table 4. Number of functioning borewells for every decade from 1981 to 2021.

Year	Population	LPCD	Minimum Supply Needed (ML/Year)	Number of actual functioning borewells	Borewells/ 1000 people
1981	6037	40	88	6	1.0
1991	7521	40	110	21	2.8
2001	9043	40	132	14	1.5
2011	9575	40	140	23	2.4
2021	10382	55	208	34	3.3

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Table 5. Number of wells required, and actual wells drilled at each decade starting 1981 till 2021.

Decade	Total wells needed at end of decade*	Wells at start of decade	New wells needed to meet rise in demand	Wells failed during the decade.	Total new wells needed	New wells actually drilled	Wells at end of decade
1981-1990	20	6	14	6	20	21	21
1991-2000	24	21	3	25	28	18	14
2001-2010	25	14	11	18	29	27	23
2011-2021	37	23	14	30	44	41	34

*The total number of wells needed is based on a population demand. It assumes an average yield of 5.5 MLD/borewell, based on historical average yields. This assumes average yields have remained constant.

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Table 6. O&M Expenditure vs. Sources of funding for water supply Operation & Maintenance costs in 2022[1].

Gram Panchayat	Pumping Cost USD/yr[2]	15th Finance Commission (Central Govt.) diverted to electricity board USD/year	Shaasana Baddha Anudhaana (Statutory Grants) Fund (State Govt.) for electricity USD/year	Tax Revenues USD/Year	Current arrears to electricity board (USD) accumulated over the last two decades
Aralumallige	$92,328	$32,510	$11,704	~$32,000	$249,675
Doddathumakuru	$49,415	$39,012	$13,004	~$25,000	$184,655

[1]All costs are based on electricity bills in 2022. 1 USD ~ 76.9 INR in 2022.

[2]Data sources are interviews with Assistant Engineers and electricity bills.

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payment of these debts to state agencies. But given that the entirety of the *Gram Panchayat* revenues do not cover even a fraction of the annual electricity bills, this seems a Sisyphean endeavor. At the moment, the borewell capital costs are covered by *Jal Jeevan* Mission funds, but in the future, it is possible that capital costs of borewells could become an additional burden if current trends persist.

4. Discussion and conclusion

The case study of Aralumallige and Doddathumakuru *Gram Panchayats* near Bengaluru in peninsular India, illustrates the danger of attempting to address rural water supply independently of sound water resources planning.

First, groundwater depletion is a severe problem that is largely driven by the free supply of electricity to farmers for irrigation borewells, which promotes the over-abstraction of groundwater [32]. Irrigation water use has declined despite increases in irrigated area because of the increase in drip irrigated area, However, abstraction still far exceeds groundwater recharge from rainfall. It is also noteworthy that in the fractured hard rock aquifer regions of India, there is no obvious spatial correlation among functioning wells, meaning that simple rules of thumb on well spacing may not suffice [11].

Second, groundwater depletion imposes a major financial burden on local communities. Both new borewell drilling for drinking water supplies and increasing pumping costs are significant, with the latter constituting a bigger burden. *Gram Panchayats* must continue to raise local taxes to keep up with rising electricity bills associated with water service provision, and even those are proving to be insufficient.

Third, the levers for limiting or reversing groundwater depletion are few and far between. Charging farmers for electricity has hitherto not been politically viable, and the current focus at all levels of government is on recharging of groundwater, rather than reducing groundwater abstraction. This is evident from government programs like *Sujala* (Karnataka Watershed Development Project), a World Bank-funded project implemented in 11 districts in Karnataka to improve the productive potential of selected watersheds and to strengthen community and institutional arrangements [33], and *Jal Shakti Abhiyan* (Catch the Rain), a campaign by the Government of India in water-stressed districts to promote water conservation and water resource management [34].

Finally, to our knowledge, there has been no comprehensive sector-wise analysis of the causes and implications of recurrent water service delivery "slip-backs" in India. This study suggests problematic water resource management has substantial impacts on rural drinking water supply. Using extensive primary and secondary data in the Aralumallige subwatershed, we found that groundwater depletion is attributable to over-exploitation by irrigation, imposing a substantial financial burden on local authorities, and in turn, households themselves. These costs compete directly with other development priorities like schools and primary health care facilities. Drinking water schemes in these areas are not sustainable and continued access to piped drinking water is at serious risk.

Even if groundwater levels do rise in wet years, there are so many abandoned wells that the latent abstraction capacity is quite significant. Based on field interviews, farmers immediately install pumps and resume pumping. The Aralumallige catchment is in a state of dynamic equilibrium: the high density of abandoned borewells in the catchment means that recovering water table depths will not result from physical measures alone. Incentives to farmers would have to be fundamentally altered, and this is a politically fraught proposition.

There are serious risks to drinking water security in these regions going forward, and there is reason to believe that these risks are neither particular or unique, but are shared by a large number of rural areas across Karnataka and the rest of peninsular India. Drinking water service providers need to recognize these threats to rural drinking water security and advocate for a fundamentally different approach to planning. Given the burden on the *Gram Panchayat* budgets, perhaps a case may be made for payments to farmers to transition to diversified income portfolios that can both increase farmer incomes and reduce abstraction.

Supporting information

S1 Text. LULC products and the need for a custom irrigation-centric approach.
(DOCX)

S2 Text. Inflation-adjusted borewell drilling costs.
(DOCX)

S3 Text. Application of FAO methodology to the calculation of irrigation water abstraction.
(DOCX)

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