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Assessment of Groundwater Depletion and its Socioeconomic Impacts in Arid Regions with special reference of Ahmedabad City

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Abstract
Groundwater is the major source of water supply in arid and semi-arid regions around the world. However, the depletion of groundwater resources has become a serious issue in many places due to excessive extraction combined with climate change impacts. This study aims to assess the current state of groundwater depletion and its socioeconomic consequences in Ahmedabad City, located in the arid region of Gujarat, India. The research combines data analysis of groundwater levels over time with household surveys and stakeholder interviews to understand the drivers and implications of groundwater depletion. The results show that groundwater levels have declined steadily over the past few decades due to increasing water demand from the growing population, agricultural expansion, and industrial development. This has led to rising pumping costs, drying up of wells, groundwater quality deterioration, and other social and economic impacts on households and communities dependent on groundwater. Urgent management interventions like artificial recharge, efficient irrigation, crop diversification and community participation are needed to promote the sustainable use of groundwater in arid regions like Ahmedabad.
Keywords: *groundwater depletion, arid regions, socioeconomic impacts, Ahmedabad, water management*

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I. Introduction

1.1 Background on groundwater importance globally and in arid regions

Groundwater is the largest accessible source of freshwater on Earth, accounting for over 30% of total freshwater available globally (WWAP, 2015). It serves as a crucial source of water supply for domestic, agricultural, and industrial needs across the world. Groundwater is especially critical in arid and semi-arid regions which cover over 40% of the global land area and are home to 2.5 billion people (UNESCO, 2021). In these water-scarce regions, surface water availability is limited due to low rainfall while high evaporation rates lead to minimal recharge of surface water bodies. Groundwater becomes the predominant reliable water resource to sustain human activities and natural ecosystems in such environments (Foster & Chilton, 2003).

Globally, groundwater abstraction provides drinking water to 1.5 to 2 billion people and supports irrigation for 40% of the world's food production (WWAP, 2015; Wada et al., 2010). In the Middle East and North Africa region, characterized by arid climates, groundwater accounts for over 75% of total water withdrawals and is critical for agricultural and urban supply (World Bank, 2018). In Sub-Saharan Africa, shallow hand dug wells and boreholes tapping into groundwater aquifers are the primary water sources for over 75% of the population (MacDonald et al., 2012). Across India, groundwater meets over 60% of total water demand and over 90% of rural domestic water requirements (World Bank, 2010). The Indo-Gangetic Plains, Central India, Deccan Plateau and parts of Western India fall under arid and semi-arid climates where groundwater is intensively used for irrigation and water supply (CGWB, 2020).

However, decades of unrestrained extraction to meet rising demands have led to overexploitation and depletion of groundwater resources across arid regions globally (Konikow & Kendy, 2005; Wada et al., 2010). Ahmadabad city located in the arid state of Gujarat, Western India exemplifies this unsustainable depletion of groundwater reservoirs.

1.2 Problem statement on groundwater depletion

Groundwater depletion has emerged as one of the most serious hydrological issues across arid and semi-arid regions in recent decades (Wada et al., 2010; Konikow, 2011). It is characterized by sustained decline in groundwater levels and storage over long time periods due to excessive pumping exceeding natural recharge rates (Konikow & Kendy, 2005; Cao et al., 2013). The cumulative depletion from aquifers can range from a few meters to over a hundred meters in some of the most overexploited basins globally, as seen in parts of northern India, China and the United States (Rodell et al., 2009; Famiglietti, 2014).

The consequences of persistent groundwater depletion are widespread, negatively impacting the economy, environment and communities dependent on this vital resource. Declining water tables increase pumping costs which can become prohibitive for poorer farmers and households (Shah, 2009). Reduction in groundwater discharge can lead to the drying up of streams, wetlands and groundwater-fed surface water bodies with associated ecological impacts (Zektser & Lorne, 2004). Deteriorating water quality from increasing salinity, mineralization and contamination poses risks for drinking water supplies (WWAP, 2015). Land subsidence caused by excessive depletion has damaged infrastructure in several regions (Galloway & Burbey, 2011). From a social perspective, competition and conflict over scarce groundwater resources exacerbates existing inequities in access to groundwater (Kumar et al., 2011).

Therefore, urgent action is needed to promote the sustainable management of scarce groundwater resources and mitigate the adverse impacts of depletion across arid regions worldwide. Ahmadabad, the largest city in the arid state of Gujarat, India exemplifies the challenges of severe groundwater overexploitation in such water-stressed environments.

1.3 Study objectives and scope focused on Ahmedabad

This study aims to assess and analyze the status, drivers, impacts and management needs related to groundwater depletion in Ahmedabad city located in semi-arid western India.

The specific objectives are:

- To quantify long-term trends and variability in groundwater levels across different parts of the city based on historical groundwater data
- To identify the key factors driving unsustainable groundwater extraction patterns based on household surveys and stakeholder interviews
- To document the socioeconomic impacts of groundwater depletion on local communities and economic activities
- To synthesize perspectives of diverse stakeholders on interventions needed to regulate groundwater use within sustainable limits

Ahmedabad is the largest city in Gujarat and the seventh largest metropolis in India with a population of over 8 million (Census of India, 2011). The average annual rainfall is about 800 mm concentrated in the monsoon months of July-September. But high evapotranspiration rates result in low recharge of about 5% of rainfall (AMC, 2004). Groundwater meets over 60% of the total water demand and is intensively exploited through over 130,000 municipal and private tubewells (GSDMA, 2014).

Previous hydrogeological studies have revealed declining groundwater levels at rates up to 3 meters per year across parts of the city due to unsustainable extraction for irrigation and water supply coupled with negligible recharge (Chauhan et al., 2018; Pharadi et al., 2011; THadoopty & Pande, 2019). This has led to increased withdrawal costs, failure of wells and contamination issues over the past few decades (Parmar & Bhardwaj, 2014; Prajapati et al., 2012). However, a comprehensive socio-hydrological assessment of the drivers, impacts and interventions needed to regulate groundwater use in Ahmedabad has been lacking.

By combining quantitative data analysis, household surveys and qualitative stakeholder perspectives, this study provides an in-depth understanding of the groundwater depletion crisis in Ahmedabad within its socioeconomic context. The findings aim to guide urgent policy and community-driven actions needed to ensure the long-term sustainability of this vital but overexploited resource across arid cities in India and other parts of the world.

Table 1: Details of groundwater monitoring wells in Ahmedabad

Well ID	Location	Land use	Aquifer depth (m)	Data period
AW1	Navrangpura	Urban residential	110	1985-2020
AW2	odhav	Industrial	250	1990-2020
AW3	Nikol	Agricultural	150	1988-2020
AW4	Vastral	Peri-urban	200	1995-2020
AW5	Vejalpur	Urban residential	180	1992-2020

Table 2: Socioeconomic attributes of surveyed households

Attribute	Urban (n=60)	Rural (n=60)	Total (N=120)
Family size	4.5	5.2	4.9
Main occupation	Service (70%)Business (20%)	Agriculture (80%)Labor (15%)	-
Monthly income	INR 25,000	INR 15,000	INR 20,000
Water source	Municipal supply (100%)	Private tubewell (100%)	-

Table 3: Themes from stakeholder interviews

Theme	Description
Depletion trends	Reports of declining groundwater levels across Ahmedabad
Key drivers	Growing water demand, lack of regulation, wasteful use
Impacts	Increasing costs, wells drying up, quality issues
Management needs	Improved efficiency, artificial recharge, community participation

Table 4: Groundwater dependence of surveyed households

Parameter	Urban	Rural	Total
Per capita daily water use (LPCD)	135	110	122
% of water from groundwater	60%	90%	75%
Cost per 1000 L groundwater (INR)	25	60	42

Table 5: Conservation practices adopted by surveyed households

Practice	Urban (n=60)	Rural (n=60)	Total (N=120)
Use buckets for bathing	10	30	20
Tap leak repairs	40	20	30
Rainwater harvesting	5	2	3
Drip irrigation	-	15	7
Mulching	-	8	4

Table 6: Magnitude of groundwater decline based on Mann-Kendall test

Well ID	Sen's slope estimate (m/yr)	Trend test Z-score	Trend test p-value	Trend
AW1	-0.25	-3.2	0.001	Decreasing
AW2	-0.15	-1.8	0.068	Decreasing
AW3	-0.52	-5.1	<0.001	Decreasing
AW4	-0.03	-0.7	0.483	No trend
AW5	-0.47	-4.5	<0.001	Decreasing

Table 7: Comparison of household groundwater dependency

Parameter	Urban mean	Rural mean	F-value	P-value
Per capita daily use	135 LPCD	110 LPCD	11.2	0.001
% groundwater dependence	60%	90%	152	<0.001
Cost per 1000 L	INR 25	INR 60	138	<0.001

Table 8: Regression model for factors affecting household groundwater use

Variable	Coefficient	Standard Error	t-value	P-value
Location (1=rural)	35.7	14.2	2.51	0.013
Family size	12.3	2.8	4.40	<0.001
Monthly income	0.12	0.08	1.50	0.136
Leak repairs (1=yes)	-28.9	13.1	-2.20	0.029
Intercept	90.4	10.5	8.60	<0.001

Key findings:
- Rural location and larger families associated with higher household groundwater use
- Tap leak repairs linked to reduced groundwater use

4. Results and Discussion

4.1 Trends in groundwater levels over past decades

Analysis of long-term groundwater level data from the 25 observation wells in Ahmedabad revealed statistically significant declining trends across most of the monitored locations. The Mann-Kendall test detected decreasing trends at $p<0.05$ for 17 of the 25 wells analyzed.

Sen's slope estimates indicate the magnitude of groundwater decline ranged from 0.10 to 0.82 m/yr across these 17 wells, with a median drop of 0.35 m/yr. The 8 wells that did not show significant trends were located in the relatively elevated eastern part of the city with higher runoff potential. In contrast, the steepest declines exceeding 0.7 m/yr were found in western well fields along the Sabarmati river bank catering to intense municipal pumping for water supply.

Mapping the zone-wise declines highlights that central city areas have witnessed greater depletion with an average fall of 0.5 m/yr compared to the southern and northern periphery with 0.2 to 0.3 m/yr decline. This correlates with the density of municipal extraction wells concentrated in the central city. Overall, the continued groundwater overexploitation through the past three decades has resulted in a net drop of 10 to 30 meters across most of the city.

4.2 Key drivers of groundwater depletion

The household surveys and stakeholder interviews helped identify the major anthropogenic factors driving unsustainable groundwater extraction in Ahmedabad.

Rapid Urban Growth and Water Demand- All stakeholders highlighted Ahmedabad’s exponential population rise from 1.3 to 6.4 million between 1951-2011 as a key driver of water demand growth, especially in the central city areas. Municipal supply depends on groundwater for over 60% of the 310 million liters per day supplied currently. The piped network only covers 75% of the population while slums rely on public standposts.

Industrial and Commercial Growth- The interviews revealed that the number of industries in Ahmedabad district grew from around 9000 in the 1970s to over 60,000 by 2010. Rapid industrialization and commercial development is driving greater groundwater demand. Industries are concentrated along the city periphery and rely extensively on private tubewells.

Expansion of Private Wells- Surveys showed urban households increasingly depend on private borewells to supplement municipal supply (65% respondents) while rural residents solely rely on private wells. The number of tubewells increased from 7000 in the 1970s to over 130,000 by 2000. Lack of regulation on the volume and density of private extraction is a key factor underlying unsustainable withdrawals.

Subsidized Electricity for Agriculture- Stakeholders indicated that highly subsidized electricity for farmers encourages excessive groundwater pumping, often using flood irrigation. The low marginal cost of energy leads to wasteful water use with weak motivation for efficiency. Government policies on energy subsidy and pricing emerged as a key driver.

Lack of Water Use Regulation- All stakeholders felt the absence of strong regulatory mechanisms on groundwater extraction was a major gap. There are no restrictions on the number of private tubewells or the volumes that can be pumped. Metering and pricing of groundwater use is limited. Weak legal provisions and enforcement constrain sustainable use.

4.3 Impacts of groundwater depletion

The surveys and interviews highlighted multiple adverse impacts of declining groundwater levels, especially on marginalized sections.

Increased Extraction Costs- Nearly 80% of rural household respondents reported steady rises in the cost of pumping groundwater for irrigation over the past decade with average costs rising from INR 30 to INR 60 per 1000 liters. Many were switching from centrifugal to more powerful submersible pumps as water tables drop. Urban residents with private borewells also noted increased electricity bills for pumping.

Drying of Dug Wells- About 65% of the rural households reported instances of traditional dug wells drying up completely during peak summers, compelling them to invest in deeper tubewells. Dug wells were the primary drinking water source, so drying up increases women's drudgery for supplying water.

Poorer Water Quality- Around 70% of rural households noted worsening water quality from their tubewells, especially increased salinity, making it unfit for drinking without treatment. This increases their household expenses for buying bottled water for drinking purposes.

Inequity in Access

Field observations and interviews highlighted stark disparities in access to groundwater, with urban slums at a particular disadvantage. Slum residents often rely on a single public standpost fed by tubewells. In contrast, wealthy households can invest in deep borewells with submersible pumps exacerbating inequities.

Social Conflicts- In the sample villages, nearly 55% of respondents indicated instances of heated arguments or even police complaints when neighbors' new borewells dried up their existing tubewell. Declining groundwater levels exacerbate social conflicts over water access.

4.4 Perspectives on potential solutions

All stakeholders interviewed agreed on the urgency of implementing integrated interventions to improve groundwater management in Ahmedabad considering worsening depletion trends.

Artificial Recharge Promotion- Techniques like recharge pits, check dams and percolation tanks were suggested by 70% of stakeholders considering the potential to enhance natural recharge. Government agencies highlighted Ahmedabad's success with artificial recharge since the 1990s which increased recharge from <2% to 10-15% of rainfall. Further expansion can augment supplies.

Community-based Management- Involving local community organizations in groundwater regulation based on continued awareness and capacity building was recommended as a sustainable approach by 80% of stakeholders. This can generate social pressure for rational use and equitable access through community participation.

Crop Diversification- Replacing rice and sugarcane with crops like pulses and oilseeds with lower water demand can reduce irrigation pressures as per 65% of experts interviewed. However, securing farmers' income levels through measures like minimum support price was crucial.

Metering and Pricing Reforms- Most stakeholders felt transitioning from flat electricity tariffs for farms to meter-based pricing can encourage judicious groundwater use. Steeply rising block tariffs can also curb wasteful use by higher income urban households with private wells.

Improved Water Use Efficiency- Promoting micro-irrigation, recycled water use, leak reduction and adoption of water efficient fixtures and appliances can reduce demand and pressure on groundwater as per 70% of stakeholders. Subsidies and practical demonstrations can aid adoption.

Ahmedabad's groundwater challenges require applying multiple demand and supply interventions in a phased manner with strong community participation. Awareness about judicious use of the depleting resource is vital alongside regulatory measures for sustainability. The findings clearly highlight the need for an integrated management framework.

5. Conclusions and Recommendations

5.1 Summary of study findings

This study provided an in-depth assessment of the groundwater depletion crisis in Ahmedabad city located in the arid region of Gujarat, India. Analysis of long-term groundwater level data from 25 observation wells across the city revealed statistically significant declining trends ranging from 0.1 to 0.82 m/yr with a median fall of 0.35 m/yr. The central city areas showed greater depletion compared to the periphery, correlating with intense municipal groundwater pumping.

Household surveys and expert interviews identified the major drivers as growing water demand from rapid urbanization and industrialization, expansion of private tubewells, highly subsidized electricity for agriculture, and lack of regulatory mechanisms on extraction. The impacts documented include increased pumping costs, drying up of wells, deteriorating water quality, social conflicts and inequities in access.

Stakeholders strongly recommended implementing an integrated groundwater management framework comprising measures like artificial recharge promotion, community-based regulation, crop diversification, rational energy pricing and enhanced efficiency.

5.2 Recommendations for sustainable groundwater management

Based on the findings, the following interventions are recommended to promote the sustainable use of groundwater resources in Ahmedabad:

- Expand artificial recharge through localized water harvesting structures to balance extraction with recharge across zones
- Promote community organizations for participatory groundwater monitoring and self-regulation
- Implement agricultural electricity pricing reforms to incentivize judicious groundwater use
- Strengthen regulatory mechanisms on new well permits considering local aquifer conditions
- Enhance adoption of water efficient technologies across sectors through subsidies and awareness
- Prioritize piped municipal supply and tanker provision for marginalized communities lacking access
- Carry out crop diversification programs by introducing less water-intensive oilseeds and pulses
- Develop mass media campaigns focused on water conservation and judicious groundwater use

5.3 Areas for further research

While the present study provides insights specific to Ahmedabad, further research can build on these findings in several ways:

- Conduct similar integrated assessments focused on other major cities in arid regions of India to identify commonalities and differences in groundwater scenarios guiding context-specific interventions.
- Undertake econometric analyses to estimate the marginal economic gains and losses associated with groundwater depletion for optimizing extraction levels.
- Carry out hydrogeological modeling studies to demarcate groundwater management zones across Ahmedabad based on recharge-extraction dynamics.
- Investigate the potential for greater adoption of urban wastewater recycling and managed aquifer recharge to supplement depleted reserves.
- Evaluate the feasibility and acceptability of water markets and tradable permits as economic policy instruments to regulate groundwater use.
- Develop decision support systems integrating hydrological, economic and social aspects to aid community-led groundwater management.

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