The Indian Geographical Journal
Volume 100 (1) June - 2025, pp 82-100
ISSN 0019-4824

GROUNDWATER STRESS UNDER THE GREEN REVOLUTION: EVIDENCE FROM THE WESTERN HARYANA PLAINS, INDIA

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Abstract

Groundwater depletion in northwestern India has intensified under the bequest of the Green Revolution, particularly in semi-arid agrarian regions such as the Western Haryana Plains (WHP). The present study provides a comprehensive block-level assessment of groundwater recharge, extraction, and development stages across 31 administrative blocks over four decades (1974-2018) using the GWREC-97 methodology integrated with GIS analysis. Groundwater recharge was estimated from rainfall, canal seepage, and irrigation return flow, while domestic and irrigation withdrawals were quantified to determine net annual availability and development status. Results indicate that total annual recharge (1,84,564 ha-m) is insufficient to sustainably balance the high groundwater draft (1,52,395 ha-m), of which over 90% is attributed to irrigation. The rapid expansion of rice–wheat cropping systems and the proliferation of electric tubewells have significantly accelerated extraction rates. Spatial patterns reveal acute groundwater stress in northern and northeastern blocks, with eleven blocks categorised as over-exploited and several exceeding cent percent extraction of groundwater. The persistent recharge-draft imbalance highlights an unsustainable trajectory of groundwater use. The study underscores the urgent need for crop diversification, regulation of tubewell expansion, and improved irrigation efficiency to ensure long-term hydrological sustainability and regional water security in the WHP.

Keywords: Groundwater Stress, Green Revolution, Western Haryana Plains, Geospatial Techniques

1. Introduction

Globally, groundwater depletion is emerging as a critical sustainability challenge. According to NASA's Gravity Recovery and Climate Experiment (GRACE), 13 of the Earth's 37 largest aquifers examined between 2003 and 2013 experienced little to no recharge, leading to severe depletion. The aquifer system in northwestern India is among them (Chen et al., 2016). Between 2000 and 2015, global groundwater extraction contributed to 11% increase in irrigated cropland and 92.4% rise in agricultural value-added, from USD 1.64

trillion to USD 3.17 trillion (World Bank, 2024).In India, groundwater supports approximately 62% of irrigation, 85% of rural, and 50% of urban water supply (CGWB, 2022).Since the onset of the Green Revolution in the 1960s, groundwater gradually became the primary irrigation source, with the net groundwater-irrigated area increasing from 6 million hectares (Mha) in 1950 to 45 Mhaby 2010.Of India's 82 million farm households, 26 million own tubewells, and nearly one million new tubewells are added annually (Beero and Narayanamoorthy, 2014). The extensive overdraft of groundwater for food-grain cultivation is now triggering serious ecological consequences.The introduction of modern drilling and electric pumping technologies, combined with subsidised or free electricity and weak groundwater governance, has further accelerated groundwater exploitation (Foster et al., 2021). India now faces a groundwater crisis, particularly in semiarid regions where water tables are declining by 2–3 meters annually. Of the country's 7089 groundwater assessment units, 1226 are classified as critical or overexploited, indicating extraction beyond recharge limits (CGWB, 2022; Sahu and Pradhan, 2024). One key driver of groundwater decline is the cultivation of water-intensive crops such as rice and sugarcane in unsuitable regions (Mizan et al., 2022).The Haryana Plains, a semi-arid to arid region, are among India's most agriculturally developed regions but face severe groundwater stress due to extensive tubewell irrigation (Singh and Sharma, 2010). Since the Green Revolution, the adoption of high-yield, water-intensive crops like wheat and paddy has sharply increased water demand—from 34.96 BCM in 2021 to projected 45 BCM by 2045 (CGWB, 2022). The region lacks perennial rivers, and rainfall remains the primary source of recharge. Approximately two-thirds of the area is underlain by brackish groundwater, compounded by a rising water table and inadequate natural drainage. The Western Haryana Plains (WHP), consisting of sandy-alluvial tracts and Aravalli outliers, receive an average annual rainfall of about 360 mm (Sharma, 2020). Several studies have applied the GWREC-97 (Groundwater Resources Estimation Committee, CGWB) methodology to evaluate groundwater resources at regional scales. For example, Singh and Sharma (2010) used this approach to assess groundwater in the Rewari district of Haryana. The method estimates dynamic groundwater resources, annual extraction, and utilisation rates based on parameters such as rainfall infiltration, irrigation return flow, and canal seepage (Malik and Rajeshwari, 2015; Sharma, 2020). However, most previous research has focused on district-level analyses over short time frames, while block-level assessments spanning longer periods remain limited across the Western Haryana Plains. Therefore, the primary objective of this study is to evaluate the stages of groundwater extraction in the WHP between 1974 and 2018 and to map their spatial distribution across districts using GIS techniques.

2. Study area

The study area, Western Haryana Plains (WHP), spans over four districts, Sirsa, Fatehabad, Hisar, and Bhiwani, and covers an area of around 15,646 square kilometres and lies between latitudes 28° 22° to 29° 59° North and longitudes 74° 27° to 76° 28° East (Kumar& Rao, 2021) (Fig. 1). Administratively, WHP is divided into four districts with 31 blocks, 381 inhabitants per square kilometre, and a population of over 5.6 million (Table 1).

Based on occupational structure, it is evident that agriculture continues to be a main source of income in the region, employing more than 60% of the total workforce. The area has a semi-arid and tropical steppe type climate, experiencing hot summers and cold winters. The south-west monsoon contributes around 80% of the total annual rainfall and temperatures ranging from 5 ˚C to 43 ˚C with an average temperature of 26.5 ˚C. Aeolian sediments, loess, and sand dunes are found across the plains, which are formed possibly by wind erosion. Aeolian sediments, such as sands and sand dunes, have the potential to create excellent reservoirs; however, in most cases, they are located above the groundwater level in the region (CGWB 2021). The WHP is covered with coarse loam, sandy loam, loamy sand and sandy soils. The research area is mostly irrigated through canal networks fed by the Yamuna, Ghaggar, and Sutlej rivers. Except for the water that flows down the slopes of the Aravali mountains seasonally.

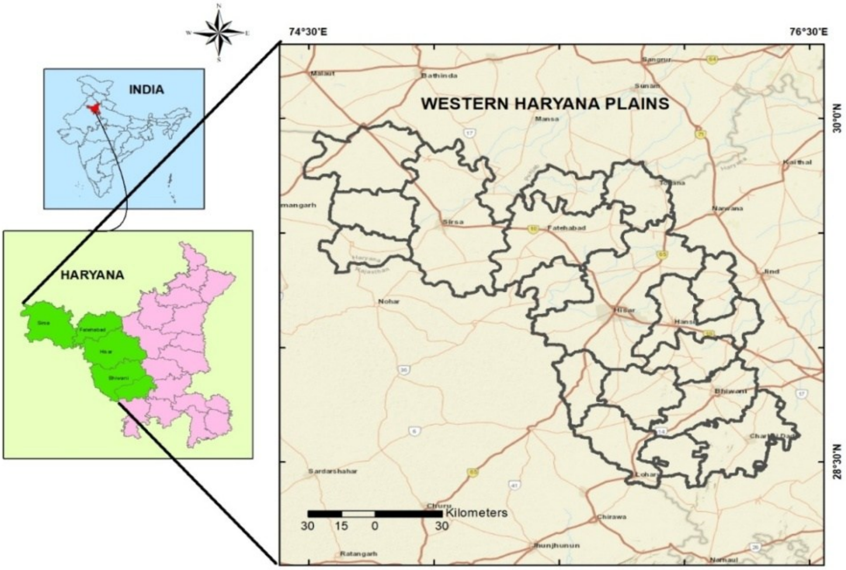

Figure 1: Location map of the study area – the Western Haryana Plains.

3. Materials and Methods

In the present study, the Groundwater Resource Estimation Committee (GWREC-97) methodology was adopted to estimate the groundwater development and its stages of utilisation. The necessary parameters taken into consideration were rainfall, canal seepage and return flow from irrigation as groundwater availability parameters; population and tubewell irrigation as groundwater draft parameters; and depth of groundwater table in the calculation of groundwater development stages (Singh and Sharma, 2010).

Monthly rainfall data were obtained from the India Meteorological Department (IMD), tubewell data from District Statistical Offices, water levels from Groundwater Cells, canal data from Irrigation Departments, crop data from the Directorate of Agriculture, topographical maps from the Survey of India, satellite images from the Earth Explorer website, and demographic data from the District Statistical Handbooks (Census of India), Haryana. An administrative block was taken as an assessment unit for both kharif and rabi seasons in the study. The dataset used for the present analysis is given in Table 2.

Table 1. Names of blocks in different districts of Western Haryana Plains.

Name of district	Name of block	No. of blocks	No. of villages	Total Population	Population density (Person/ sq. km)
Bhiwani	Badhra, Bawani Khera, Bhiwani, Dadri-I, Dadri-II, Loharu, Kairu, Siwani, Tosham	09	436	1634445	342
Hisar	Adampur, Agroha, Barwala, Hansi-I, Hansi-II, Hisar-I, Hisar-II, Narnaund, Uklana	09	257	1743931	438
Fatehabad	Bhattu Kalan, Bhuna, Fatehabad, Jakhal, Ratia, Tohana	06	226	942011	373
Sirsa	Baragudha, Dabwali, Ellenabad, Nathusari Chopta, Odhan, Rania, Sirsa	07	322	1295189	371

(Source: Director of Land Records, Panchkula, Haryana, 2018 & Census of India)

Table 2. Details of data sets and thematic layers used in the present study.

Dataset	Source of data	Time period	Utilization
Monthly rainfall	India Meteorological Department, New Delhi, and Groundwater Cell, Panchkula, Haryana	1974-2018	Estimation of groundwater recharge
Groundwater level	Groundwater Cell, Panchkula, Haryana	1974-2018	Estimation of groundwater draft
Number of tubewells	District Statistical Office (Bhiwani, Hisar, Fatehabad, Sirsa of Haryana).	1974-2018	Estimation of groundwater draft for irrigation use
Diesel and electricity-operated tubewells	Groundwater Cell and Directorate of Agriculture, Panchkula		
Water discharge and running days of canals	Department of Irrigation (Districts: Bhiwani, Hisar, Fatehabad, Sirsa of Haryana)	1974-2018	Estimation of recharge from canal seepage
Irrigated area under different crops (Block-wise)	Directorate of Agriculture, Panchkula, Haryana.	1974-2018	Estimation of recharge as return flow from irrigated fields
Topographical sheets	Survey of India, Regional Office, Chandigarh, Haryana	1974	For preparing the base map and calculating the total length of canals
Satellite images	Landsat 7 ETM+&IRS P6 LISS IV	2017-2018	
Demographic information	Districts Statistical Handbooks (Census of India), Statistical Abstracts of Haryana	1971-2011	Estimation of groundwater for domestic use

3.1 Estimation of Recharge from Rainfall (R_{rf})

To estimate the recharge from rainfall, we used the average monthly rainfall data for each block. Water level fluctuation (WLF) and rainfall infiltration factor (RIF) methods were used to estimate the groundwater recharge from rainfall. WLF determines the change in storage (S) by multiplying water level fluctuations between pre- and post-monsoon seasons with the area of the aquifer and specific yield using the following equation:

$$S = h \times S_y \times A \quad (1)$$

Where h is the rise in water level in meters, S_y is the specific yield (0.16 for unconsolidated formation), and A is the area of the aquifer in hectares (ha).

The groundwater recharge from rainfall (R_{rf}) by WLF is calculated as:

$$R_{rf}(WLF) = S + (DG – R_c – R_{sw} – R_{gw}) \quad (2)$$

Where, S = Change in storage (ha-m), DG = Gross groundwater draft for all uses (ha-m), R_c = Recharge from canal seepage (ha-m),R_{sw} = Recharge from surface water irrigation (ha-m), andR_{gw} = Recharge from groundwater irrigation (ha-m).

The groundwater recharge from rainfall (R_{rf}) by RIF is calculated as:

$$R_{rf}\ (RIF) = f \times A \times R_k \quad (3)$$

Where, f = Rainfall infiltration factor (0.22 for unconsolidated formations), A = Area of the aquifer (ha), R_k= Average annual rainfall (mm) during kharif season

The percentage difference (PD) is calculated as (CGWB 1997, Chatterjee et al. 2009):

$$PD = \frac{\text{Rrf (Normal WLF)} - \text{Rrf (Normal RIF)}}{\text{Rrf (Normal RIF)}} \times 100 \quad (4)$$

The calculated values of groundwater recharge from rainfall are taken if

PD is within ± 20%, and then Rrf (Normal) is taken as the value estimated from the WLF method.

PD is < -20%, then Rrf (Normal) is taken as 0.8 times the value estimated from the RIF method.

PD is > +20%, then Rrf (Normal) is taken as 1.2 times the value estimated from the RIF method.

3.2 Estimation of Recharge from Irrigation Return Flow (R_{irf})

The recharge from irrigation return flow from fields (R_{irf}) was calculated individually for both the paddy and non-paddy crops. The return flow from irrigated fields was estimated by multiplying the volume of water used for irrigation in paddy and non-paddy crops in a block by the return flow factor of that block. The sum of the return flow from paddy and non-paddy crops is measured as the groundwater recharge as return flow from irrigated fields. Mean return flow factor values at the block level have been taken into consideration as per GWREC-97. The volume of groundwater utilised for irrigation in a block is the sum of the canal and groundwater applied in a particular season. For surface water irrigation, season-wise water released in each canal has been collected from the district subdivisions of the Irrigation Department. The block-wise estimation of canal water availability was done by calculating the length of canals passing through the respective blocks and proportionally distributing the water released in that canal in a particular season. 60% of the total water released in a canal is considered water applied for irrigation (GWREC 97). The requirement of water for rice crops in each block was calculated by multiplying the total depth of irrigation required for paddy as 63.5 cm by the total area of that block under paddy cultivation (Hassan et al. 2015).

3.3 Estimation of Recharge from Canal Seepage(R_{cs})

The study area is served by many canal networks namely Sub Sunder Branch (SSB), Bhiwani Sub Branch (BSB), Siwani, Deosar Feeder and Loharu Feeder (Bhiwani), Fatehabad Branch of Bhakra canal, Barwala Branch, Balsamandh and Pabra Sub-Branch of Barwala Link and Sirsa branch from Bhakra Main Line, Hisar Major Distributary and Deosar Feeder of Western Yamuna Canal System through Hansi Branch (Hisar), Bhakra Main Canal, Fatehabad Distributary (Fatehabad) and Bhakra Main Branch, Sukhchain Distributary, Northern Ghaggar Canal and Fatehabad Distributary (Sirsa). Groundwater recharge through canal seepage (Rcs) depends on factors such as the canal's size, cross-section, flow depth, soil characteristics of the canal bed, site location, and the level of adjoining drains. Canals may be either lined (cemented) or unlined (natural) (Chattrejeeet al. 2009).

Recharge through canal seepage (R_{cs}) was calculated using the following equation:

$$R_{cs} = W_a \times S_f \times NCR_d \quad (5)$$

Where, W_a = Wetted area in million square meters of each canal, S_f = Seepage factor (4 ha-m/day/million square meters) of wetted area, NCR_d = Number of canal running days.

The statistics on wetted area were collected from the Irrigation and Water Resource Department, Panchkula, Haryana. The predominant soil types in the study area are sandy, loamy, and sandy loam. Therefore, for lined canals, the seepage factor is 4 ha-m/day/mi. sq. m of the wetted surface and the number of days the water is released in a canal during the kharif and rabi seasons was considered in the analysis (Kumar and Kumar 2021, CGWB 2011).

3.4 Net Annual Groundwater Availability (NAgwa)

The net annual groundwater availability (NA_{gwa}) is the sum of the recharge from all sources after deducting the allocated natural discharges from the gross annual replenishable groundwater resource.

To calculate NA_{gwa}, the following equation is used:

$$NA_{gwa} = AR_{gwr} - N_d \quad (6)$$

Where, AR_{gwr}= Annual replenishable groundwater resource (ha-m),which is the sum of R_{rf}, R_{irf} and R_{cs} during both kharif and rabi seasons, and N_d = Natural discharge (ha-m) is kept 5% of the gross annual groundwater recharge if the WLF method is used, while it is taken as 10% if the RIF method is employed to compute rainfall recharge.

3.5 Estimation of Groundwater Draft for Domestic Use(GDdu)

Block-wise domestic water demand (GD_{du}) was assessed by considering the growth rate of the population of their respective district based on the available Census data from 1971 to 2011. To get the average annual population data for estimating the domestic draft during the study period from 1974 to 2018, the average values of the particular census year were taken into consideration. Water demand for domestic uses is considered to be 100 litres per capita per day (CGWB 2004). Total domestic draft was estimated by multiplying the total population of each block in a particular year by the per capita demand. The average of the volume of groundwater drafted from the years 1974 to 2018 was considered as the average domestic draft. Out of the annual domestic draft, 40% was considered as kharif draft and 60% as rabi draft (Kumar and Srinivas, 2012;Ray et al., 2017).

3.6 Estimation of Groundwater Draft for Irrigation Use (GDiu)

The groundwater draft for irrigation (GD_{iu}) was estimated by multiplying the unit tubewell draft by the number of tubewells in each block (CGWB 1997, Singh and Sharma 2010). The mean of the groundwater draft by tubewells for irrigation for a period of 44 years was considered as the mean annual irrigation draft of groundwater for each block in the study area. Out of this annual draft, 25% was taken as kharif draft and 75% as rabi draft (Sitender and Rajeswari, 2012).

3.7 Stages of Groundwater Development (SGd)

The stage of groundwater development (SG_d) was calculated as the percentage of gross groundwater draft to the net groundwater available in each block:

$$SG_d\ (\%) = \frac{GD}{NA_{gwa}} \times 100 \quad (7)$$

Where, SG_d = Stage of groundwater development (%); GD= Groundwater draft for all uses (ha-m); NA_{gwa} =Net annual groundwater availability (ha-m).

3.8 Categorisation of Assessment Units

Finally, the assessment units were categorised on the basis of stage of groundwater development and long-term trend of pre- and post-monsoon water levels (GWREC 1997). The long-term groundwater level fluctuations were computed for the period from 1974 to 2018. The depth of water level for pre-monsoon is recorded in the month of June, and for post-monsoon in the month of October. The significant rate of water level decline was taken as more than 20 cm per year (CGWB 2007, Malik and Rajeswari 2015). Assessment units are categorised into four categories, namely safe, semi-critical, critical and over-exploited.

4. Results and Discussion

4.1. Groundwater Recharge from Rainfall(R_{rf})

Rainfall is the major source of groundwater recharge in the study area. The average annual rainfall trend in the Western Haryana Plains shows that an erratic behaviour with intermittent rise and fall. The highest and the lowest average annual rainfall in the study area recorded were 509 mm (1976) and 167 mm (2002), respectively (Fig. 2).

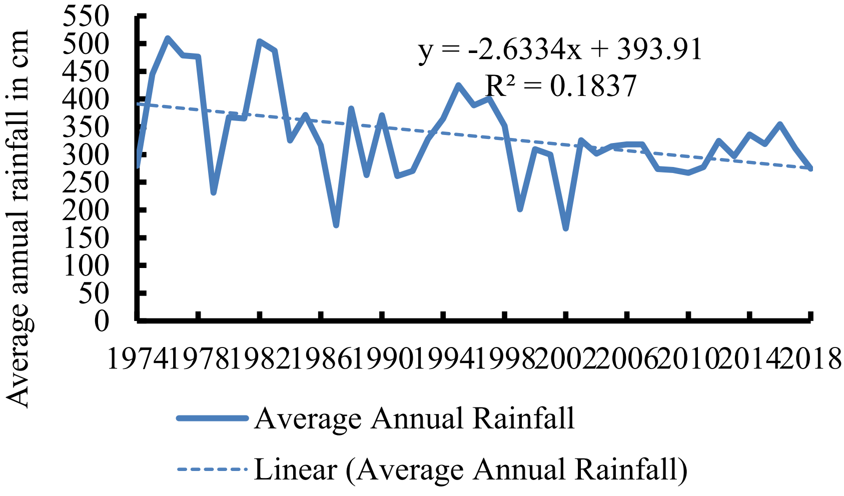

Figure 2: Trend in average annual rainfall over Western Haryana Plains (1974-2018).

During 1974-2018, it was only in seven instances, i.e. 1975, 1976, 1978, 1982, 1983, 1995 and 1997, when the average rainfall crossed the 400 mm mark. WHP recorded a declining trend with an average of 227 mm.Among the 31 blocks in the study area, 14 received above-average rainfall, with the Badhra block recording the highest (426 mm), and the lowest rainfall was observed in the Baragudhablock (113 mm). The data shows block-wise groundwater recharge during the rabi and kharif seasons across the districts of Bhiwani, Hissar, Fatehabad, and Sirsa (Table 3).Rabi recharge ranges from a minimum of 115 ha-m to a maximum of 888 ha-m, while kharif recharge varies widely between 642 ha-m and 6,275 ha-m. Consequently, total annual recharge spans from 805 ha-m to 7,163 ha-m. Most locations record totals between 1,500 and 4,500 ha-m, indicating moderate recharge conditions (Fig. 3). Higher totals are associated with strong monsoon infiltration, whereas lower values reflect limited recharge potential and possible groundwater stress.Blocks with higher recharge generally correspond to regions with greater precipitation and more-permeable, unconsolidated alluvial formations, thereby enhancing infiltration capacity (CGWB, 2005).

4.2 Groundwater Recharge from Irrigation Return Flow(R_{irf})

In the study area, the irrigation is practised by both surface and groundwater sources. The canal water is generally released for irrigation in almost all the blocks of the study region. The irrigation return flow is the portion of excess irrigation water that drains beyond crop evapotranspiration and eventually recharges the aquifer. It varies widely, from nearly 0% in drip irrigation systems to about 50% in standing-water paddy cultivation (Rushton et al., 2020). The classification of irrigated land into rice and non-rice crops is necessary in order to accurately compute the return flow from both types of crops. The category of non-rice encompasses the irrigated area of all crops except for rice, while the rice category solely comprises the irrigated area of the rice crop in the kharif. The region shows substantial cultivation of water-intensive crops, particularly rice in the kharif season and wheat during rabi. The non-rice crops hold a predominant position in the kharif season across various blocks, namely Badhra, Kairu, Loharu, Tosham, and Siwani. The R_{irf} values vary widely from a minimum of 805 ha-m to a maximum of 5,021 ha-m, indicating strong spatial differences in irrigation practices and soil permeability. Most locations record recharge between 1,000 and 2,500 ha-m, suggesting moderate return flow contribution (Fig. 3). Lower values likely correspond to efficient irrigation methods, while higher values indicate intensive irrigation and greater percolation losses. The pattern might be explained by the fact that rice is grown on larger areas and has higher percolation rates than other crops. Because wheat needs more water input during the rabi season, there is also a direct correlation between the area under wheat and irrigation return flow. While blocks dominated by other crops have relatively lower return flow, blocks with large irrigated wheat lands show higher return flow.

4.3. Groundwater Recharge from Canal Seepage

The seepage process originating from canals is a crucial factor in the restoration of groundwater storage within an aquifer. It was found in the study area that the length of the canal irrigation system is highest in Hissar district,with the longest in Sirsa (279 km). The length of canals is shortest in Fatehabad and Bhiwani districts. Canal seepage occurs when water conveyed through unlined or partially lined canals infiltrates surrounding soils and percolates downward to recharge groundwater. The recorded values ranged between 346 ha-m and 1364 ha-m, indicating considerable spatial variability in seepage losses and recharge potential (Table 4). Higher values over 550 ha-m indicate significant percolation, which is typically linked to unlined canals and prolonged flow duration, whereas lower values throughout the research area probably represent lined canals, decreased discharge, and impermeable soils. The analysis of spatial distribution reveals that Fatehabad block exhibits the highest wetted area while Kairu block exhibits the lowest wetted area. During the kharif 14301 ha-m seepage was estimated, while 11520 ha-m was observed during the rabi season by canal seepage in the Western Haryana Plains from 1974 to 2018. During the kharif season, an abundance of water is made available in the river as a result of rainfall from the southwest monsoon. This water is subsequently released into canals.

Table 3. Rainfall recharge during the rabi and kharif seasons in WHP.

District	Block	Average rainfall in the Rabi (m)	Average rainfall in the kharif (m)	Aquifer area (ha)	Total recharge (rabi)	Total recharge (kharif)	Total recharge (ha-m)
Bhiwani	Badhra	0.058	0.426	52275	668	3919	4587
	Bawani Khera	0.030	0.321	38529	255	2176	2431
	Bhiwani	0.053	0.269	76026	888	6275	7163
	Dadri -1	0.061	0.262	42066	560	2458	3018
	Dadri -2	0.055	0.371	41347	498	2702	3200
	Kairu	0.021	0.193	33346	154	1131	1285
	Loharu	0.047	0.306	67882	697	3651	4348
	Siwani	0.038	0.229	52594	433	2119	2552
	Tosham	0.028	0.179	59014	362	2784	3146
Hissar	Adampur	0.020	0.178	32189	140	1009	1149
	Agroha	0.024	0.239	32978	172	1387	1559
	Barwala	0.038	0.279	50251	418	3701	4119
	Hansi1	0.038	0.218	61021	515	2330	2845
	Hansi 2	0.037	0.234	29938	243	1233	1476
	Hisar 1	0.059	0.216	55144	717	2582	3299
	Hisar 2	0.050	0.257	72703	803	3276	4079
	Narnaund	0.040	0.188	40970	359	1500	1859
	Uklana	0.023	0.174	22971	115	703	818
Fatehabad	Ratia	0.048	0.186	53244	567	1745	2312
	Jakhal	0.048	0.236	15477	163	642	805
	Bhattukalan	0.053	0.268	36353	423	1714	2137
	Fatehabad	0.052	0.130	68710	786	1567	2353
	Tohana	0.059	0.203	34569	445	1782	2227
	Bhuna	0.052	0.213	39493	449	1478	1927
Sirsa	Baraguda	0.024	0.113	53803	281	1067	1348
	Dabwali	0.031	0.173	82653	571	4450	5021
	Ellenabad	0.045	0.124	54696	541	1197	1738
	Nathusari Chopta	0.034	0.217	73431	551	2805	3356
	Odhan	0.022	0.178	48752	233	1778	2011
	Rania	0.021	0.135	57447	263	1359	1622
	Sirsa	0.044	0.313	56185	544	3093	3637

By lining the unlined canals and maintaining and repairing the ones that are already lined, direct recharge through canal seepage can be minimized (Maanjhu and Anandha 2012). The elevated number of canal operating days during the kharif season, in comparison to the rabi season, leads to a greater amount of recharge during this period.

4.4. Total Groundwater Recharge and Net Annual Groundwater Availability

The annual groundwater recharge in the study area was estimated at 1,84,564 ha-m, comprising 79,081 ha-m from rainfall, 25,821 ha-m from canal seepage, and 79,664 ha-m from irrigation return flow. Recharge varied spatially, with the lowest value recorded in Bhiwani (2416 ha-m) and the highest in Sirsa (8,941 ha-m). Low recharge zones indicate limited aquifer replenishment, likely resulting from reduced rainfall infiltration, limited irrigation coverage, decreased canal seepage, and lower irrigation return flow. In contrast, moderate to high recharge areas reflect a balanced contribution from rainfall and irrigation sources.

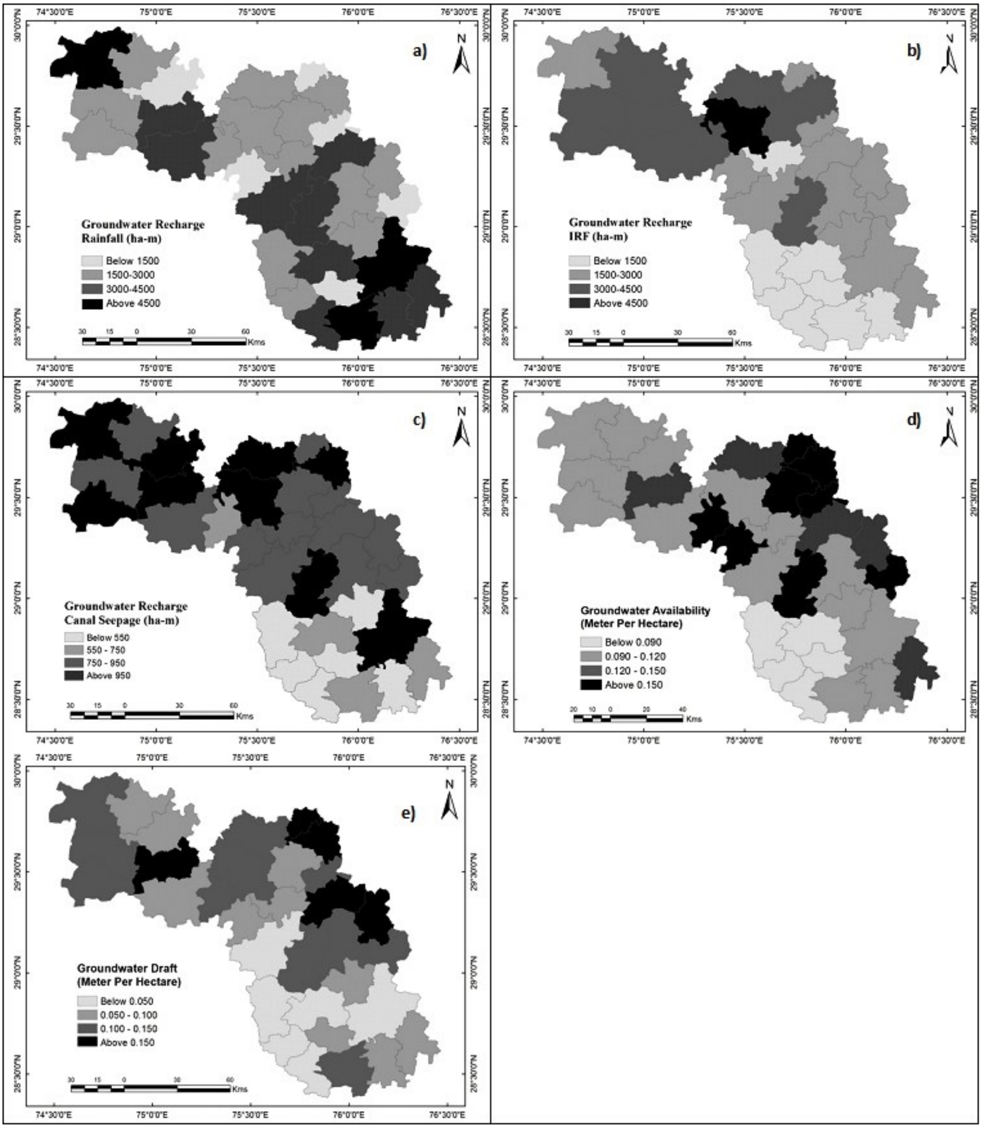

Figure 3. Spatial distribution of groundwater recharge a) from rainfall b) from irrigation return flow, c) from canal seepage and d) groundwater availability and e) groundwater draft in Western Haryana Plains (1974-2018).

Table 4. Groundwater recharge from all sources during the kharif and rabi seasons.

District	Block	Rainfall (ha-m)	Canal seepage (ha-m)	Irrigation returns flow (ha-m)	Total recharge (ha-m)
Bhiwani	Badhra	4587	573	637	5797
	Bawani Khera	2432	493	1733	4658
	Bhiwani	4487	1035	3318	8840
	Dadri -1	2500	585	2666	5751
	Dadri -2	3201	373	971	4545
	Kairu	1286	346	785	2416
	Loharu	4348	543	518	5409
	Siwani	2552	363	741	3656
	Tosham	3146	646	911	4703
Hissar	Adampur	1148	842	1790	3781
	Agroha	1560	816	1340	3716
	Barwala	4123	942	2118	7183
	Hansi1	2854	937	2314	6105
	Hansi 2	1476	845	1979	4299
	Hisar 1	2814	1147	3689	7650
	Hisar 2	4086	920	2379	7385
	Narnaund	1717	790	2597	5104
	Uklana	818	808	2684	4310
Fatehabad	Ratia	2312	1183	3596	7090
	Jakhal	805	928	2034	3766
	Bhattukalan	2136	708	3172	6016
	Fatehabad	2353	1364	4715	8431
	Tohana	1680	1091	3784	6556
	Bhuna	1927	804	3958	6689
Sirsa	Baraguda	1348	970	3906	6224
	Dabwali	5021	1109	2811	8941
	Ellenabad	1738	1151	3861	6749
	Nathusari Chopta	3356	798	3737	7892
	Odhan	2011	751	3283	6045
	Rania	1622	949	4226	6797
	Sirsa	3637	1011	3411	8060

Enhanced recharge in certain blocks can be attributed to higher precipitation and improved canal infrastructure, particularly from the Western Yamuna, Ghaggar, and Bhakra canal systems.Additionally, the cultivation of water-intensive crops such as rice (kharif) and wheat (rabi) contributes significantly to recharge through irrigation return flow, which accounts for over fifty per cent of total recharge during the rabi season.The spatial distribution map depicts that the per-hectare groundwater availability is found to be higher in the northern and northeastern blocks of the study area (Fig. 3).The net annual groundwater availability recorded was 1,83,120 ha-m in the study area. The areas with a well-established canal network and larger irrigated area, particularly with water-intensive crops such as rice during the kharif and wheat during the rabi, exhibit higher net groundwater availability during both seasons. The primary means of replenishing groundwater in these blocks is through rainfall, and as a result of reduced rainfall in the rabi season, groundwater availability is also found to be low.

4.5. Groundwater Draft for Domestic and Irrigation Use

Groundwater use for domestic purposes includes drinking water supply, household consumption through private hand-pumps and bore-wells, as well as public and municipal water supply systems. The total groundwater draft in a given block is primarily a function of per capita water demand and population size (CGWB, 2004). Population growth, urbanisation, and rising living standards have significantly increased domestic water demand in semi-arid regions like the Western Haryana Plains (WHP), where groundwater remains the dominant source of supply due to the limited availability of surface water resources (Sahu and Pradhan, 2024).Within the study area, the blocks of Bhiwani and Dadri I in Bhiwani district, Sirsa and Ellenabad in Sirsa district, Hansi I and Hisar I in Hisar district, and Fatehabad and Bhattu Kalan in Fatehabad district exhibit the highest population densities and consequently the greatest domestic groundwater extraction. The Hisar district recorded the highest groundwater withdrawal for domestic use. More than 60% of the total mean groundwater extraction for domestic purposes across the Western Haryana Plains was found to be in the Hisar and Bhiwani regions due to high populations and better canal-based water supply coverage (Table 5). A clear positive correlation was observed between population density and groundwater draft, aligning with the strong linkage between demographic growth and domestic groundwater stress in northern India (Kumar and Singh, 2018; Kaur and Ravindranath, 2020). The elevated domestic groundwater withdrawal in Bhiwani and Hisar can be attributed to factors such as increasing population pressure, construction activities, and higher per capita water consumption (Tiwari et al., 2019). While other parts have relatively limited extraction may be due to smaller populations, lower urbanisation, and the limited extent of irrigated areas. Additionally, deeper groundwater tables and higher costs associated with tubewell installation and maintenance likely contribute to reduced domestic groundwater abstraction in these areas (Kaur and Ravindranath, 2020).In total, the study area contains 70,686 electric-powered and 55,122 diesel-powered tubewells. The mean unit draft for diesel-operated tubewells is 0.6 ha-m yr^{-1}, compared to 1.1 ha-m yr^{-1} for electric-operated ones. A notable shift from diesel to electric pumps has occurred, largely due to subsidised electricity, higher discharge efficiency, and operational cost advantages (Sahu & Pradhan, 2024).Agriculture accounts for nearly 90% of the total groundwater draft during the *kharif* season and 92% during the rabi season, with domestic use contributing 8–10%. Spatially, Sirsa and Fatehabad exhibit thehighest annual irrigation draft. The intensity of groundwater extraction depends not only on the number and capacity of tubewells but also on cropping patterns and groundwater depth. The dominance of rice–wheat cultivation in Sirsa and Fatehabad drives high irrigation demand (Chatterjee et al., 2021), whereas deeper water tables and lower yields in Siwani, Kairu, and Tosham limit groundwater use (Sharma, 2020). These findings reflect broader regional trends of unsustainable groundwater dependence in northwestern India, intensified by energy subsidies, limited recharge, and intensive double-cropping systems (CGWB, 2022).

Table 5. Stages of groundwater development in Western Haryana Plains during 1974-2018.

District	Block	Net Groundwater Availability (ha-m)	Draft (ha-m)	Gap (ha-m)	Stage (%)	Category
Bhiwani	Badhra	5440	7061	-1621	130	Over exploited
	Bawani Khera	4460	3522	938	79	Semi critical
	Bhiwani	7926	3305	4621	42	Safe
	Dadri -1	6017	3850	2167	64	Semi critical
	Dadri -2	4256	2577	1679	61	Safe
	Kairu	2301	2807	-506	122	Over exploited
	Loharu	5261	3255	2006	62	Semi Critical
	Siwani	3432	1075	2357	31	Safe
	Tosham	4414	1607	2807	36	Safe
Hissar	Adampur	5262	2935	2327	56	Safe
	Agroha	3943	2304	1639	58	Safe
	Barwala	7290	2910	4380	40	Safe
	Hansi1	6700	6907	-207	103	Over-exploited
	Hansi 2	4791	3433	1358	72	Semi-critical
	Hisar 1	8890	6350	2540	71	Semi critical
	Hisar 2	7181	3437	3744	48	Safe
	Narnaund	5817	7198	-1381	124	Over-exploited
	Uklana	5086	2934	2152	58	Safe
Fatehabad	Ratia	6608	7894	-1286	119	Over exploited
	Jakhal	3510	3889	-379	111	Over exploited
	Bhattukalan	5598	3722	1876	66	Semi critical
	Fatehabad	7862	9797	-1935	125	Over exploited
	Tohana	6661	6289	372	94	Critical
	Bhuna	6245	3569	2676	57	Safe
Sirsa	Baraguda	5791	3684	2107	64	Semi Critical
	Dabwali	8597	9009	-412	105	Over-exploited
	Ellenabad	6421	7980	-1559	124	Over exploited
	Nathusari Chopta	7345	4973	2372	68	Safe
	Odhan	5672	4344	1328	77	Semi-critical
	Rania	6484	8455	-1971	130	Over exploited
	Sirsa	7859	11323	-3464	144	Over exploited

4.6. Stages of Groundwater Development in WHP

Analysing the balance between recharge and extraction provides insight into the sustainability of groundwater use. When extraction exceeds recharge, a decline in water levels is expected, whereas a surplus indicates potential for further groundwater development (Foster et al., 2021). Blocks exhibiting negative recharge–draft gaps indicate a deficit in groundwater availability, while positive values signify a surplus or stable condition (Table 5). The results reveal that 11 out of 31 blocks show negative values, indicating overextraction and unsustainable groundwater conditions. Notably, the Bhiwani block (Hisar district) recorded the highest groundwater recharge (7,926 ha-m) during

1974–2018, followed by Barwala (7,290 ha-m) and Hisar-II (7,181 ha-m). In contrast, Sirsa and Rania (Sirsa district) exhibited significant annual deficits of −3,529 ha-m and −1,971 ha-m, respectively, with Sirsa showing the most severe depletion (>3,000 ha-m deficit).Other critically affected blocks include Rania, Fatehabad, Badhra, Ellenabad, Narnaund, and Ratia, each exhibiting annual deficits exceeding 1,000 ha-m. Meanwhile, Kairu, Dabwali, Jakhal, and Hansi-I show moderate deficits (<1,000 ha-m). Conversely, Hisar-I, Bhiwani, and Baraguda recorded surplus availability (>3,000 ha-m), suggesting relatively stable hydrogeological conditions, while Tohana, Bawani Khera, and Odhan displayed marginal surpluses. The observed groundwater deficit patterns align closely with agricultural intensification trends in the region. High withdrawals in Sirsa, Fatehabad, and Rania correspond with intensive rice–wheat cropping systems, driven by Green Revolution technologies, subsidised power, and minimal regulation (Rodell et al., 2018). In contrast, blocks with coarser soils, deeper aquifers, or lower irrigation coverage show relatively stable conditions (Chatterjee et al., 2021). These findings reinforce that unsustainable irrigation practices remain the dominant factor shaping groundwater stress across the WHP, consistent with national-scale depletion patterns in northwestern India (CGWB, 2021; Sahu & Pradhan, 2024).

4.7. Spatio-Temporal Trends in Stages of Groundwater Development (1974-2018)

Based on the results of groundwater availability and groundwater draft across the study area, the stages of groundwater development were categorised(Fig. 4).In 1974, only two blocks in Bhiwani district were classified as semi-critical and over-exploited. However, by 1988, 12 blocks were categorized as semi-critical and three as critical, indicating an accelerating decline in groundwater levels linked to rapid tubewell proliferation and expansion of water-intensive crops such as rice and wheat (Foster et al., 2021).By 1998, the adverse effects of over-extraction were spatially evident across the WHP, particularly in Sirsa, Fatehabad, and Bhiwani districts, where five blocks were identified as over-exploited and three as critical.

The condition further deteriorated by 2008, when 15 blocks were classified as over-exploited and three as critical, reflecting persistent overdependence on groundwater for irrigation and limited surface water availability (Rodell et al., 2018; CGWB, 2022). By 2018, all blocks in Sirsa district, along with four in Fatehabad, two in Hisar, and three in Bhiwani, were declared over-exploited. The number of over-exploited blocks has increased consistently every decade, revealing an unsustainable trajectory of groundwater use.The north-eastern WHP exhibits the highest groundwater stress, while central and southern blocks, such as Badhra, Kairu, Narnaund, and Hansi, still show moderate availability. Groundwater assessment indicates a net availability of 1,83,120 ha-m, with 1,52,395 ha-m extracted annually, primarily for irrigation, resulting in a deficit of 30,725 ha-m between recharge and draft (Table 5). Eleven blocks-Badhra (130%), Kairu (122%), Hansi-I (104%), Narnaund (124%), Ratia (117%), Jakhal (111%), Fatehabad (122%), Dabwali (103%), Ellenabad (125%), Rania (130%), and Sirsa (145%)-have surpassed 100% development, classifying them as over-exploited (CGWB, 2022; Sahu and

Pradhan, 2024). Overall, only 12 of 31 blocks remain within the safe zone, confirming that the WHP is in a critical stage of groundwater development (Fig. 4). The lack of perennial rivers, limited canal infrastructure, and dominance of groundwater-based irrigation exacerbate depletion, posing serious implications for both agricultural sustainability and domestic water security (Singh and Singh 2020; Chatterjee et al., 2021).

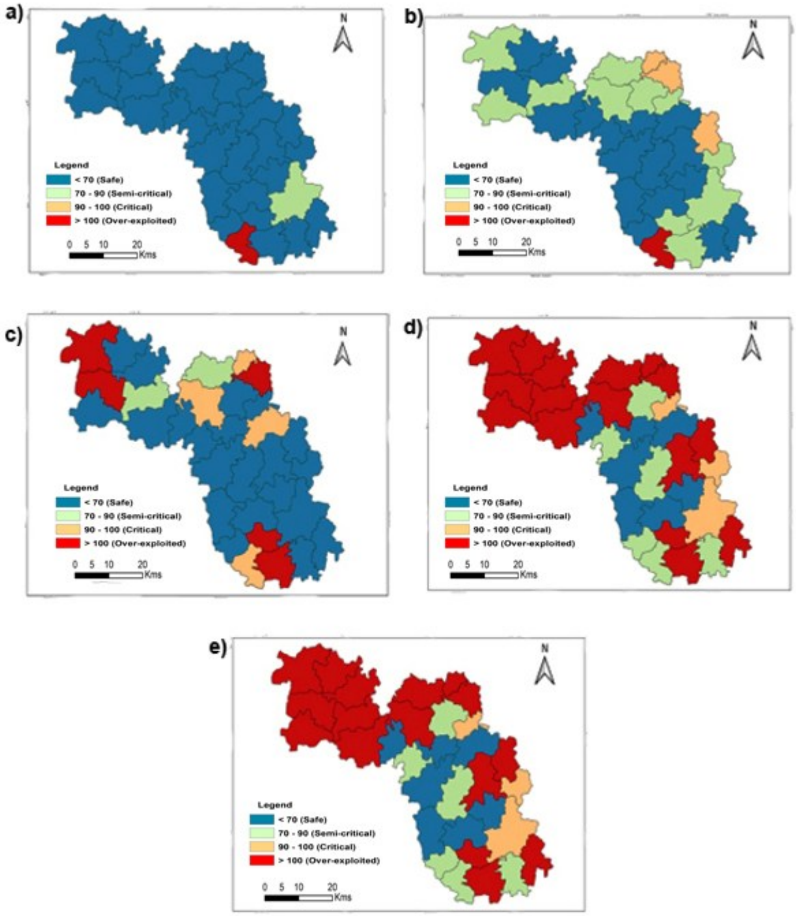

Figure 4: Stages of groundwater development in Western Haryana Plains, a) 1974, b) 1988,c) 1998, d) 2008 and e) 2018.

5. Conclusions

Irrigation planning in agriculture-dominated plains requires the comprehensive evaluation of multiple hydrological components, including groundwater availability, recharge, and extraction. A long-term evaluation (1974–2018) was conducted to assess the groundwater status across various blocks of the Western Haryana Plains (WHP) in northern India. A major shift toward rice–wheat cropping systems was observed, with the area under rice cultivation increasing dramatically from less than 1% of total cropped land in 1974 to

21% in 2018. This transition has significantly increased groundwater dependency, as rainfall in this semi-arid region averages only 227 mm annually, serving as the principal source of recharge. The estimated groundwater recharge was 1,84,564 ha-m, of which rainfall contributes 79,081 ha-m**,** canal seepage 25,821 and irrigation return flow accounts for 79,664 ha-m. Groundwater draft, including domestic and irrigation purposes, was recorded 1,52,395 ha-m from the net availability of groundwater, i.e. 1,83,120 ha-m. Irrigation withdrawals were considerably higher, mainly extracted through tubewells. Continuous over-extraction has led to a steady decline in groundwater levels, as annual withdrawals consistently exceed natural replenishment. Among the 31 blocks analysed, 20 were classified as critical to over-exploited**,** with the highest annual groundwater withdrawals recorded in the northern and eastern WHP, particularly in the Sirsa block (11,323 ha-m), followed by Fatehabad, Rania, Ellenabad, Ratia, and Narnaund**.** Increased reliance on tubewell irrigation has also driven land-use changes, converting sandy and wastelands into intensively cultivated farmland. Significant expansion of irrigated areas and conversion of sandy or wastelands into productive farmland were observed, primarily driven by the increased reliance on tubewell irrigation. This highlights the urgent need for regulatory measures to control the installation and electrification of tubewells, particularly in over-exploited blocks. Further, promoting horticulture and drip irrigation technologies could reduce water demand and enhance efficiency. At this stage, government interventions are needed to classify critical and over-exploited blocks as dark zones and impose restrictions on water-intensive crops such as rice and wheat, ensuring sustainable groundwater management in the Western Haryana Plains.

Acknowledgement

The authors extend their gratitude to the Directorates of Land Records, Groundwater Cell, Irrigation and Agriculture, Panchkula, Haryana, for providing the data.

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