

Dynamic groundwater resources of National Capital Territory, Delhi: assessment, development and management options

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Abstract Groundwater is one of the important source of water supply to meet the requirements of National Capital Territory (NCT) of Delhi, India which is a fast developing urban conglomeration. An assessment of dynamic groundwater resources of NCT Delhi has been attempted based on the methodology known as Ground Water Resources Estimation Methodology—1997. The methodology includes assessment of annual replenishable groundwater resources using water level fluctuation approach and empirical norms, estimation of the annual quantity of groundwater withdrawal and categorization of the assessment units based on the status of groundwater utilization and water level trend. Annual replenishable groundwater resources of NCT Delhi is about 297 million cubic meter (mcm) while the annual groundwater draft is about 480 mcm. This is because of over-exploitation of replenishable resources in seven out of nine districts of the Capital Territory. Based on the assessment of dynamic groundwater resources, a broad groundwater management plan has been proposed in this paper. This include augmentation of groundwater resources through rain water harvesting schemes to be implemented on a large scale, regulation on groundwater withdrawal in vulnerable areas, development of Yamuna flood plain aquifer and declaration of Delhi ridge as groundwater sanctuary.

Keywords National Capital Territory Delhi · Annually replenishable groundwater resources · Ground water resource estimation methodology—1997 ·

Rain water harvesting · Groundwater recharge · Over-exploitation · Groundwater regulation · Yamuna flood plain

Introduction

National Capital Territory (NCT) of Delhi is the capital of India located in Northern part of the country between latitude $28^{\circ}24'15''$ and $28^{\circ}53'00''$ N and longitudes $76^{\circ}50'24''$ and $77^{\circ}20'30''$ E (Fig. 1). The geographical area of the city is 1,483 km².

Administratively, it is divided into nine districts. The city is undergoing rapid changes and expansion both in its land use pattern as well as in its demographic profile. Water resource is one of the basic ingredient for infrastructure buildup of the metropolis. The present annual water requirement for drinking, domestic, irrigation and industrial uses has been estimated as 1,435 million cubic metre (mcm) out of which only 1,044 mcm is being supplied by the civic authorities namely Delhi Jal Board (adopted from CGWB 2006b). This includes 166 mcm of groundwater (adopted from CGWB 2006b). The future annual water requirement based on the population projection for the year 2021 has been estimated to be around 2,269 mcm, while future annual availability of water from all sources (including groundwater) has been envisaged as 1,367 mcm only, leaving a wide gap between demand and supply (adopted from CGWB 2006b).

In order to find a solution to this apparent mismatch between demand and supply, a systematic study was required on the availability of water resources which can be exploited for utilization on sustainable basis. The definition of groundwater resource which can be exploited for utilization varies from place to place. In India, National Water

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Fig. 1 Administrative map of National Capital Territory of Delhi



Policy (Ministry of Water Resources 2002) stresses that ‘exploitation of groundwater resources should be so regulated as not to exceed the recharging possibilities, as also to ensure social equity’. The annual ground water recharge is also termed as dynamic groundwater resources or annually replenishable groundwater resources. This is estimated following the guidelines of Ground Water Estimation Committee—1997 (GEC 1997) evolved under the aegis of Govt. of India. The annual recharge is compared with the utilization of the resource and an assessment unit is categorized based on the status of utilization and water level trend. Future groundwater management programme in NCT Delhi has been envisaged based on the

hydrogeological set up and the present scenario of groundwater resources development in the area.

Groundwater scenario of NCT Delhi

The Delhi region is bounded by the Gangetic alluvial plain in the north and east, the Thar desert in the west and Aravalli hill ranges to the South (Kaul and Pandit 2004). It is covered with alluvium deposits occasionally traversed by linearly elongated quartzite ridges. Delhi quartzite of Proterozoic age acts as a basement rock in major part of the area. Wherever, it is exposed as ridge, it acts as a

prominent recharge zone. The fracture and joint planes in the quartzite formation facilitate weathering of the rocks leading to a favourable condition for groundwater occurrence and movement. Discharge of wells in these formations depends on the degree of weathering and number and nature of joints and fractures encountered by the wells. The alluvial deposits are major repository of groundwater in the area. Wells are extensively constructed in the Yamuna flood plains which are Younger alluvial deposits, fine grained Older alluvial deposits in the Chattarpur basin, South Delhi and also in the Older alluvial

deposits in Western and northern parts of NCT Delhi. Hydrogeological setup of the area is presented in Fig. 2.

Variations in groundwater regime in different aquifers in NCT Delhi have been brought out through the descriptions of three representative cross-sections (Figs. 3, 4, 5) in separate parts of NCT Delhi.

The sub-surface disposition of basement hard rock and Older alluvium is revealed in a WNW-ENE cross-section in the South West district of the city (Fig. 3).

Thickness of alluvium has been recorded up to 300 m depth. The alluvial deposits consist of alternate layers of

Fig. 2 Hydrogeological map of National Capital Territory of Delhi

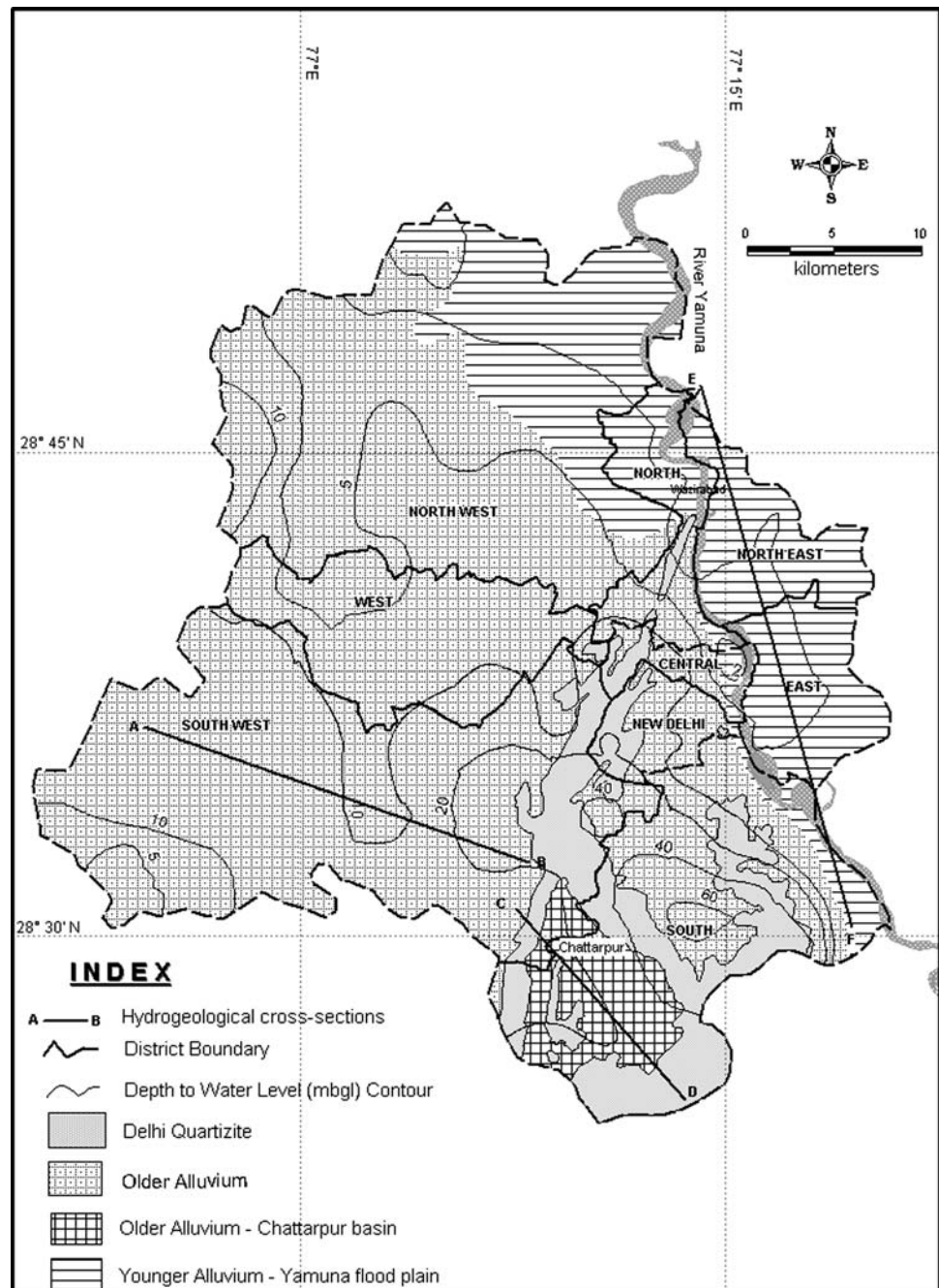


Fig. 3 Hydrogeological cross-section across South West district

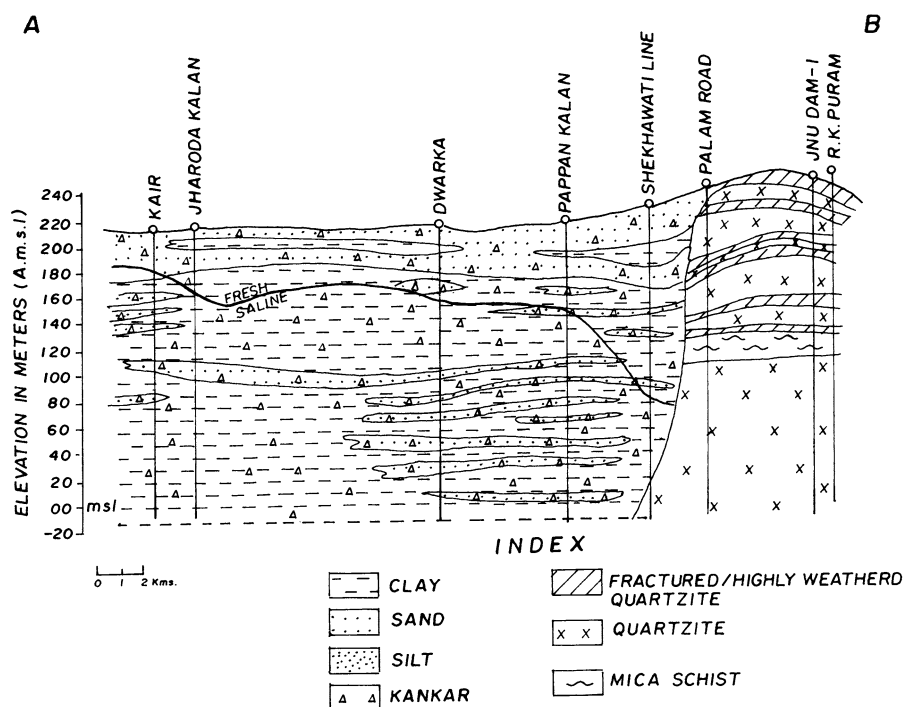
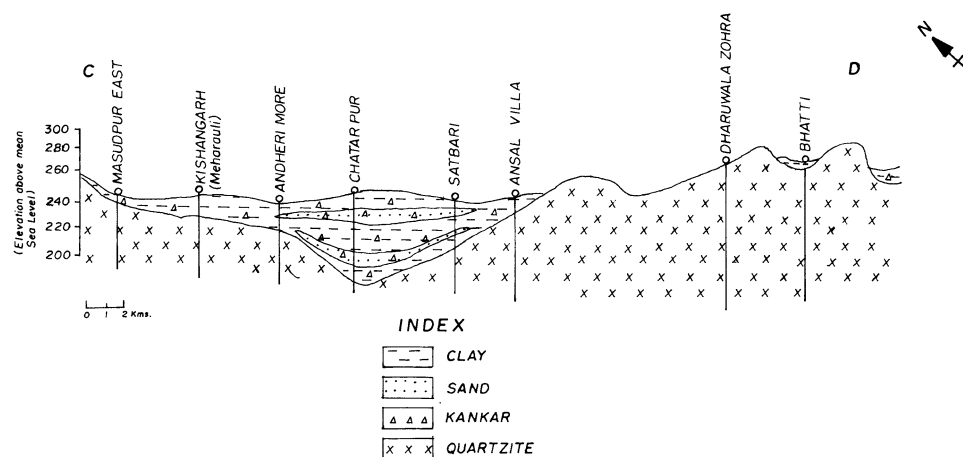


Fig. 4 Hydrogeological cross-section across Chattarpur basin, South Delhi



silt, clay, sand and Kankar (local name of small calcareous concretions mixed with small gravels). The major water bearing horizon is fine to coarse grained sand with Kankar. Prominent zones are between 30 and 35 mbgl (metre below ground level) at shallower horizon and between 115 and 120 mbgl at deeper horizon. Occurrence of sandy zones decrease with depth. Depth to water level in major part of the South West district is between 5 and 20 mbgl except near the ridge area where water level is deeper, mostly in the depth range of 22–50 mbgl. The transmissivity of the Older alluvium formation ranges from 63 to 158 m²/day, hydraulic conductivity ranges between 3 and 4 m/day (Bhatnagar and Gupta 1989). Groundwater is saline at greater depths. The fresh/saline water interface in the major part of the area is in the depth range of 25–28 mbgl

(CGWB 2006b). Shekhar et al. (2005) mentions of greater depth to fresh/ saline interface (80–90 mbgl) in the areas adjacent to hard rock.

In the Chattarpur basin, South district, a NNW-SSE cross-section (Fig. 4) across the basin reveals the disposition of basement topography along with the sequence of valley-fill sediments of Older alluvium. The undulating basement is made up of Delhi quartzites. Bore wells constructed in quartzitic body reveal that moderately fracture zones are prevalent in the depth of 30–90 m and the fractures gradually decrease in number as depth increases. The sediments overlying the quartzites are composed of unconsolidated clay, silt, sand and varying proportions of Kankars in alternate finer and coarser horizons. The coarser sediments form lenses and pinch out towards the basin

Fig. 5 Hydrogeological cross-section across Yamuna flood plain

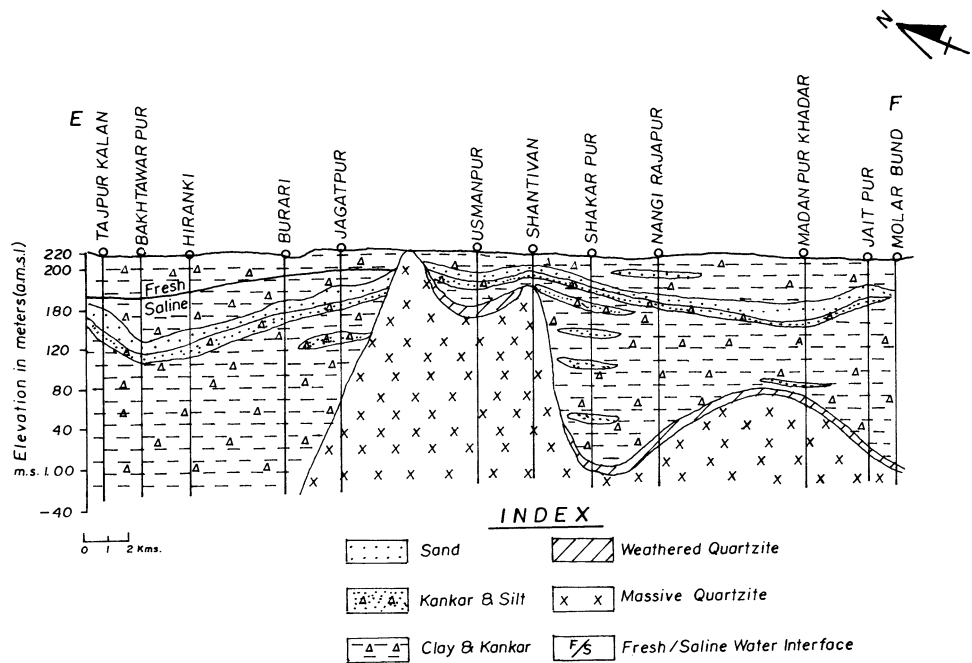


Table 1 Hydraulic properties of rock formations in NCT Delhi

Sl. no.	Nature of formation	Depth (m)	Discharge (m ³ /h)	Drawdown (m)	Transmissivity (m ² /day)
1	Younger alluvium	40–50	150–300	5–8	730–2,100
2	Older alluvium	30–115	18–135	2–24	130–403
3	Quartzite	50–150	2–18	1.5–30	5–135

Source: CGWB (2006b)

boundary. Generally two to three water-bearing zones have been encountered. Shallower zones are mostly at the depth range of 20–35 mbgl and the deeper zones are at 30–70 mbgl. A still deeper water-bearing zone is encountered at 80–115 mbgl at places where the sediment thickness is more. The groundwater level is deep because of the heavy withdrawal of groundwater. The shallowest water level recorded in the area is around 20 mbgl. Except for few such in lairs, in major part of the basin, the water level ranges from 40 to 60 mbgl. The thickness of fresh water zone varies from 30 to 85 m (CGWB 2006b). Transmissivity of the Older alluvial formation varies from 1 to 134 m²/day and hydraulic conductivity ranges from 0.07 to 4.48 m/day (Bhatnagar and Gupta 1989).

Yamuna active flood plain aquifer is about 35 km along river Yamuna occupying an area of around 97 km². Delhi quartzite is the bed rock formation occurring at depth between 30 m and 203 mbgl. Older alluvium overlies the bedrock. They predominantly consists of clay and Kankar formation. Transmissivity of the formation increases with increased proportion of Kankar varying from 130 to 350 m²/day (CGWB 2006b). Rao et al. (2007) using Inverse Modelling approach determined the hydraulic conductivity

of Older alluvium in Palla area of Yamuna flood plain as 9.8 m/day. Younger alluvium which overlies the Older alluvium are predominantly fine to medium grained sand with intervening silt and clay layers. Multiple layers of sandy horizons occur (Fig. 5), most prominent being sand mixed with gravel occurring at the lower portion of Younger alluvium. This is a high yielding aquifer especially in Palla well field area. Total thickness of Younger alluvium varies between 45 and 55 m. Aquifer system of Younger alluvium is unconfined with depth to water level ranging from 2.5 to 7.00 mbgl. Transmissivity of the aquifer system of Younger alluvium varies between 730 and 2,100 m²/day with hydraulic conductivity varying between 13 and 60 m/day. The quality of groundwater is fresh down to 30–65 m, below which the water is brackish to saline. Aquifer system of Younger alluvium has a potentiality to sustain high yielding wells (CGWB 2006b). A number of well fields have been developed in these formations to augment city’s water supply programme most well known being Palla well field.

The recorded discharge of wells drilled under groundwater exploration programme in different geological formations in NCT Delhi and the various hydraulic properties of these formations are given in Table 1.

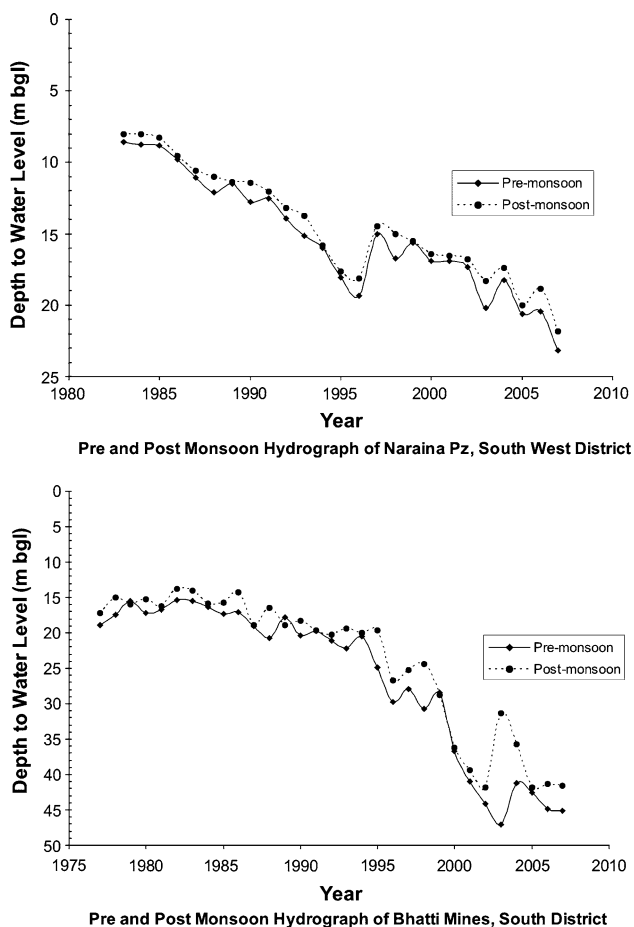


Fig. 6 Hydrographs of selected monitoring wells

Declining groundwater level in parts of Delhi—an environmental concern

In major portion of Delhi, groundwater has declined by an alarming extent. In absolute terms, the water level has declined by more than 41 m in 22 years in Lado Sarai,

South district (1985–2007), more than 27 m in 13 years in Gadaipur, Chattarpur basin, South district (1994–2007), 30 m in 11 years in R.K. Puram, South West district (1996–2007). These declines are mostly in the range of around 200 cm/year or even more. In some other places where long term records of water level are available such as Dhobighat (South district), Satbari and Ayanagar (Chattarpur basin, South district), Naraina (South West district), Kitcher Road, Safdarjung tomb, Ugrasen ki Baoli (New Delhi district), the water level trends show decline in the range of 36–120 cm/year. Some of the representative hydrographs are presented in Fig. 6.

Average water level trend in the South, South West, New Delhi, West and North West districts are declining at the rate of 23–136 cm/year in pre-monsoon (before onset of rainy season, May) and post-monsoon (after culmination of rainy season, November) seasons between 1994 and 2003. Other districts have also recorded decline of more than 20 cm/year which is considered as significant decline, in either pre-monsoon or post-monsoon seasons (Table 2). The only exception being North district, which at places faces the problem of water logging. The declining trend in water level is leading towards a detrimental ecological consequence by the way of gradual reduction in the thickness of available fresh water zone. A study in South West district has indicated that thickness of fresh water zone is depleting at the rate of 50–300 cm/year (Shekhar 2006). A noteworthy extent of area (about 114 km²) in South West and North West districts are completely devoid of fresh groundwater (CGWB 2006a). In these areas, the EC is more than 5,000 $\mu\text{s}/\text{cm}$ at 25°C and groundwater is neither suitable for domestic nor for irrigation purpose. Persistent decline in water level is thus a serious environmental concern for the city as this may lead to further increase in the extent of the saline area and resultant reduction in the availability of fresh water resource.

Table 2 Average long term trend of water level in NCT Delhi

District	Trend–pre-monsoon (May) (cm/year)	Significant decline ^a (yes/no)	Trend–post-monsoon (November) (cm/year)	Significant decline ^a (yes/no)
Central	–19.9	No	–9	No
East	–29	Yes	–9	No
North	–2	No	–15	No
New Delhi	–73	Yes	–60	Yes
North East	–14	No	–23	Yes
North West	–23	Yes	–38	Yes
South	–136	Yes	–136	Yes
South West	–127	Yes	–129	Yes
West	–30	Yes	–31	Yes

^a Significant decline is more than 20 cm/year

Groundwater resource estimation

In order to find out the reasons for continuous decline in groundwater levels as have been observed in several parts of NCT Delhi, an assessment of annual groundwater recharge vis-a-vis annual draft of groundwater has been carried out (CGWB 2006a). Assessment was for the climatic year 2003–2004, which is between July, 2003 (onset of rainy season) and June, 2004 (summer season of next calendar year).

Methodology

The methodology used for estimating the annual replenishable groundwater resources of NCT Delhi is known as Groundwater resources estimation methodology—1997, henceforth referred in the paper as GEC-1997. The methodology has been recommended by Govt. of India for groundwater resource estimation for all the states and Union Territories of the country. GEC-1997 involves estimation of annual groundwater recharge from rainfall and other sources including irrigation, water bodies and artificial recharge and determination of present status of groundwater utilization.

Groundwater recharge estimation in GEC-1997 is computed season-wise (monsoon season when predominant rainfall occurs and non-monsoon season). In monsoon season, water level fluctuation method (WLF) and empirical norms are used for recharge estimation and in non-monsoon season only empirical norms are used. WLF method which is more commonly referred in International journals as Water table fluctuation method (WTF) (Scanlon et al. 2002; Healy and Cook 2002) is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as:

$$R = S_y dh/dt = S_y \Delta h / \Delta t \quad (1)$$

(Scanlon et al. 2002; Healy and Cook 2002)

Where S_y is specific yield, h is water table height and t is time. WTF approach has been widely applied for estimating groundwater recharge (Healy and Cook 2002). Rasmussen and Andreasen (1959) studied the water budget of the Beaverdam Creek basin on the Delmarva Peninsula of Maryland, USA. WTF approach was used for computation of monthly recharge. Rehm et al. (1982) conducted a recharge study for an upland area in central North Dakota, USA. They used three different methods for estimating groundwater recharge: WTF, Hantush method, flow-net analysis. van der Somen and Geirmaert (1988) studied the regional recharge-discharge of aquifer systems

on the crystalline basement of Burkina Faso on the West African Shield. WLF method was employed to estimate the natural recharge. In Teesta Barrage, Bangladesh, while carrying out spatial assessment of groundwater use potential for irrigation, groundwater recharge was estimated using WTF method (Wahid et al. 2007). Besides the application of WLF method which is actual field manifestation of recharge to groundwater, GEC-1997 has several other advantages. The method is a lumped approach and therefore relatively simple. It is suitable with regard to the data normally available from groundwater level monitoring programme of State and Central Government agencies and there is provision for an alternate approach based on Rainfall Infiltration Factor (RIF) which serves as a check to WLF estimate. RIF are norms for rainfall infiltration contributing to groundwater recharge which are evolved based on studies undertaken in various water balance projects in India. However, considering the heterogeneity of the hydrogeological setup normally encountered in the field and complexities in the groundwater flow hydrodynamics, the estimations arrived at using GEC-1997 should be followed by micro-level studies before a large scale groundwater management plan is contemplated.

Recharge estimation using GEC-1997

Estimation of recharge involves following steps:

1. Work out recharge during monsoon season (July to October) using WLF method

$$R = h \times S_y \times A + D_G \quad (2)$$

Where,

- R possible recharge, which is gross recharge minus the natural discharges in the area in the monsoon season (hectare metre)
- h WLF between pre-monsoon (May) and post-monsoon (November)
- A area of computation of recharge (hectare)
- S_y specific yield
- D_G groundwater draft during monsoon season (hectare metre)

In Eq. (2), recharge (R) is expressed as volume change in the ground water reservoir over a period of time, i.e. monsoon season. Since recharge have been aggregated over a period of time, hence the unit L/T in Eq. (1) is converted to L^3 in Eq. (2).

2. Segregate the resultant recharge [arrived at Eq. (2)] into recharge from rainfall and recharge from other sources.

$$R_{Mrfi}(WLF) = h \times S_y \times A + D_G - R_{Mc} - R_{Msw} - R_{Mt} - R_{Mgw} - R_{Mwc} \quad (3)$$

Where,

R_{Mrfi} recharge from rainfall during monsoon for the i th particular year

R_{Mc} recharge due to seepage from canals during monsoon for the i th particular year

R_{Msw} recharge from surface irrigation during monsoon for the i th particular year

R_{Mt} recharge from storage tanks and ponds during monsoon for the i th particular year

R_{Mgw} recharge from groundwater irrigation during monsoon for the i th particular year

R_{Mwc} recharge from water conservation structure during monsoon for the i th particular year

3. Normalize rainfall recharge for estimating recharge corresponding to the normal monsoon rainfall.

$$R_{Mrf}(\text{normal}) = R_{Mrfi} \times [r(\text{normal})/r_i] \quad (4)$$

Where

$R_{Mrf}(\text{normal})$ normal monsoon rainfall recharge

R_{Mrfi} monsoon rainfall recharge for the i th particular year

$r(\text{normal})$ normal monsoon rainfall

r_i monsoon rainfall of the i th particular year

This was done in order to neutralize the effect of excessive or less than average rainfall on groundwater recharge estimation of a particular year.

4. Compute rainfall recharge using RIF

$$R_{Mrf}(\text{RIF}) = f \times A \times r_M(\text{normal}) \quad (5)$$

Where, f is RIF,

A the area of computation of recharge (hectare) and

r_M normal rainfall in monsoon season (metre)

5. Compare the rainfall recharge figure arrived at Eq. (4) [$R_{Mrf}(\text{WLF})$] with rainfall recharge figures using RIF [$R_{Mrf}(\text{RIF})$] for normal monsoon rainfall arrived at Eq. (5).

$$PD = \left[\frac{(R_{Mrf}(\text{normal, WLF method}) - R_{Mrf}(\text{normal, RIF method}))}{R_{Mrf}(\text{normal, RIF method})} \right] \times 100 \quad (6)$$

where,

PD Difference in WLF & RIF estimate expressed as a percentage of RIF estimate

If,

a) if PD is within $\pm 20\%$, $R_{Mrf} = R_{Mrf}(\text{WLF})$

b) if PD is $< -20\%$, $R_{Mrf} = 0.8 \times R_{Mrf}(\text{RIF})$

c) if PD is $> 20\%$, $R_{Mrf} = 1.2 \times R_{Mrf}(\text{RIF})$

6. Work out the total normal recharge during monsoon period.

$$R_{(\text{monsoon})} = R_{Mrf} + R_{Mc} + R_{Msw} + R_{Mt} + R_{Mgw} + R_{Mwc} \quad (7)$$

7. Work out the normal rainfall recharge during non-monsoon period (November to June of Next year) using RIF.

$$R_{NMrf}(\text{RIF}) = f \times A \times r_{NM}(\text{normal}) \quad (8)$$

8. Compute recharge from other sources during non-monsoon season.

$$R_{NMc} + R_{NMsw} + R_{NMt} + R_{NMgw} + R_{NMwc} \quad (9)$$

9. Work out total recharge during non-monsoon season.

$$R_{(\text{non-monsoon})} = R_{NMrf} + R_{NMc} + R_{NMsw} + R_{NMt} + R_{NMgw} + R_{NMwc} \quad (10)$$

10. Annual replenishable groundwater resource is the sum total of monsoon and non-monsoon recharge.

$$\text{Annual replenishable groundwater resources} = R_{(\text{monsoon})} + R_{(\text{non-monsoon})} \quad (11)$$

11. Deduct the allocation for natural discharge from replenishable resource to obtain net groundwater availability for utilization.

$$\begin{aligned} \text{Net annual groundwater availability} &= \text{annual replenishable groundwater resource} \\ &- \text{allocation from natural discharge during non} \\ &- \text{monsoon season} \end{aligned} \quad (12)$$

Groundwater budgeting

In order to assess the status of utilization of groundwater resources in an assessment unit, the annual groundwater draft for irrigation, domestic and industrial uses are estimated. The percentage of annual groundwater draft for all

Table 3 Criteria for categorization of assessment units

Sl. no.	Stage of ground water development	Significant long term decline		Categorization
		Pre-monsoon	Post-monsoon	
1	≤70%	No	No	Safe
2	>70% and ≤90%	No	No	Safe
		Yes/no	No/yes	Semi-critical
3	>90% and ≤100%	Yes/no	No/yes	Semi-critical
		Yes	Yes	Critical
4	>100%	Yes/no	No/yes	Over-exploited
		Yes	Yes	Over-exploited

uses to the Net annual groundwater availability gives the stage of groundwater development.

Stage of groundwater development (%)
 = (annual groundwater draft / net annual groundwater availability) × 100 (13)

The assessment units are then categorized with regards to the status of groundwater utilization based on the twin criteria—a. Stage of groundwater development and b. Long term trend of pre- and post-monsoon water levels. Detailed criteria are given in Table 3.

Safe areas have groundwater potential for development. In semi critical areas cautious groundwater development is recommended. In critical and over exploited areas, there should be intensive monitoring and evaluation and future groundwater development be linked with water conservation measures (GEC 1997).

Basic data and norms used for recharge estimation

The assessment of groundwater resource of NCT Delhi was done on district-wise (administrative unit) basis for the

year 2003–2004. The estimations are based on database compiled for—water level, rainfall, irrigated area, number of groundwater structures, net irrigation requirement of prevailing cropping pattern, technical specifications of canals and drains, water bodies and water conservation structures. The sources of database include Central Ground Water Board, Census of India 2001 (Office of the Registrar General, India 2003), Delhi Statistical Handbook (2000), III Census of Minor Irrigation Schemes (2005), Office of Divisional Commissioner, Irrigation and Flood Control Department, Government of Delhi (2000), Water—unreliable supply in Delhi (Zerah 2000), personal communications from Irrigation Departments of Delhi and Haryana, Indian Meteorological Department, Delhi Jal Board, Directorate of Economics and Statistics, Government of National Capital Territory of Delhi and Non-government organizations namely Centre for Science and Environment and TAPAS.

The water level data used for WLF computations are for the 5 years from 1999–2000 to 2003–2004. WLF is highest in North-east district where average WLF is 0.93 m and lowest in South district about 0.30 m. The general range of WLF in NCT Delhi is 0.30–0.50 m. The specific yield values are obtained from the norms recommended in GEC–1997 which in turn are based on average figures derived from long duration pumping tests done on similar hydrogeological formations, i.e. silty alluvium and quartzites. The specific yield values taken for the recharge estimations in NCT Delhi are 0.10 for alluvium and 0.015 for quartzite. Similarly, RIFs are taken from the norms suggested in GEC-1997 which were evolved based on case studies on rainfall–recharge relationship. RIFs taken for current studies are 0.22 for alluvium and 0.06 for quartzite. RIF have been adjusted for areas having watershed development programmes and those covered with paved areas. Norms used for computation of recharge from sources other than rainfall is given in the Table 4.

Table 4 Norms used for groundwater recharge estimation (recharge sources other than rainfall)

Recharge source	Formation/cropping pattern	Seepage/return flow factor
Canal seepage	Normal soil with some clay content alongwith sand	Unlined canals—15 ham/day/million sq.m. wetted area; lined canals—3 ha m/day/million sq.m. wetted area
Irrigation	Paddy	20–50% of irrigation water applied depending on water level and source of irrigation—canal/well
	Wheat, jowar, fruits/vegetables	5–30% of irrigation water applied depending on water level and source of irrigation—canal/well
Water bodies (tanks and ponds)		0.00144 m/day/ha of water spread area
Water conservation structures		Based on capacity of the structure

Table 5 Various sources of groundwater recharge in NCT Delhi

District	Rainfall (in mm)	Canals and drains	Irrigation (in ha)	Water bodies numbers (average covered area in hectares)	Water conservation structures (number of schemes implemented)
Central	647.4	Nil	0	6 (1.17)	30
East	451.8	Eastern Yamuna Canal, minor drains	637	32 (0.98)	7
North	808.3	Najafgarh drain	0	0 (0)	21
New Delhi	724.1	Nil	0	3 (1.23)	116
North East	887.6	Eastern Yamuna Canal, minor drains	304	3 (0.53)	1
North West	508.9	Western Yamuna Canal, Munda Minor, Budanpur Minor, Najafgarh drain, Mungeshpur drain, minor drains	22290	203 (0.69)	37
South	645.7	Minor drains	2001	97 (1.23)	348
South West	570.2	Najafgarh drain, minor drains	17766	208 (0.66)	253
West	388.6	Najafgarh drain, minor drains	2273	6 (2.75)	112

Sources of groundwater recharge

Rainfall

Rainfall is the main source of groundwater recharge in NCT Delhi. The monsoon season extends from July to October of which the period of predominant rainy season is early July to September. The normal annual rainfall of NCT Delhi is 611.8 mm. About 81% of annual rainfall occurs during South-West monsoon period. The rest of the annual rainfall is received as winter rains and as thunderstorm rains in the pre- and post-monsoon months. The rainfall data used for recharge estimations are collected from 15 rain gauge stations around Delhi. The minimum normal annual rainfall has been recorded in West District (390 mm) whereas maximum normal annual rainfall has been recorded in North-East district (890 mm) (Table 5; Fig. 7).

Canal seepage

National Capital Territory Delhi is characterized with extensive network of canal systems and drains (Table 5) (Fig. 7). Seepages from these canals and drains are also an important contributor to the groundwater regime of the region. Western Yamuna canal and its distributaries and series of small and big drains joining Najafgarh drain are some of the prominent structures in North West district. Major portion of the Najafgarh drain passes through South West district, followed by West and North districts in the upstream direction. North East and East districts are characterized by Eastern Yamuna canal. Apart from the major ones enumerated above, several smaller drains are flowing through the districts of North West, West, East, North East, South and South West.

Irrigation

In the outskirts of NCT Delhi there are rural belts where agriculture is the major occupation. Agriculture is supported by irrigation which is more prevalent in the rural areas of North West and South West districts where both water intensive crops like paddy as well as less water requiring crops like wheat, jowar, fruits, vegetables etc. are grown. The irrigation potential created through groundwater in NCT Delhi as per the 3rd Minor Irrigation Census (2001–2002) is about 450 km² (MOWR 2005).

Tanks and ponds

Delhi has a rich heritage of tanks and ponds, which were constructed by the rulers of the capital kingdom from ancient times. Though many such structures have gone into disuse because of poor maintenance, water accumulated in these bodies during rainy season, contribute to the groundwater through seepages. Records of around 500 structures could be compiled (Table 5), most of them are from North West and South West districts (personal communication from TAPAS).

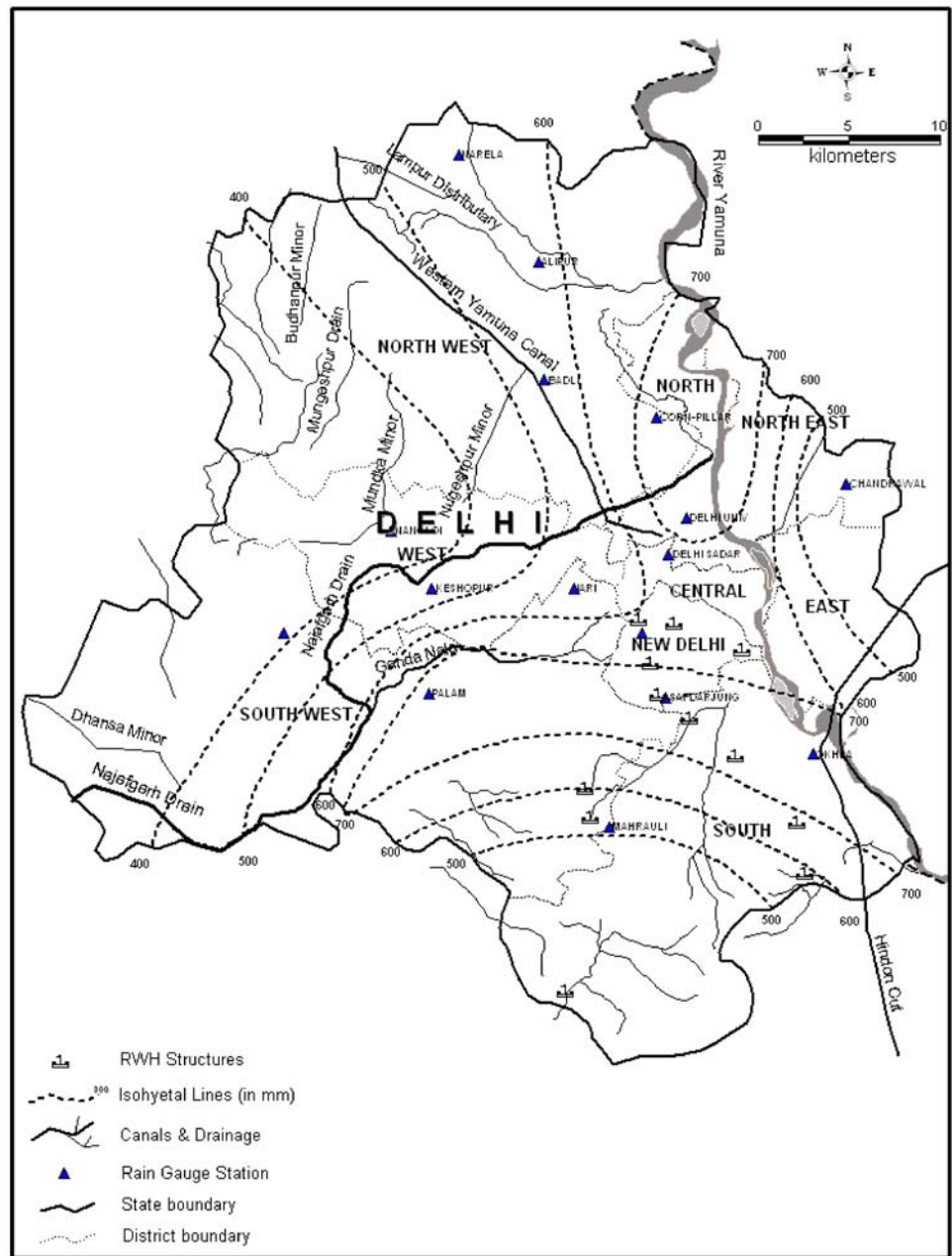
Water conservation structures

Data of about 950 artificial recharge and rain water harvesting structures were considered in the present estimation of groundwater resource. These are mostly located in South, South West and North West districts.

Groundwater recharge pattern

The annual groundwater recharge of NCT Delhi has been estimated as 297.10 mcm (CGWB 2006a, b). Most important source of recharge is rainfall which contributes

Fig. 7 Map showing sources of recharge to groundwater in NCT Delhi



150.42 mcm, about 51% of the total annual recharge. In case of—East, North East, North West, South, South West and West districts, WLF estimates have been adopted for rainfall recharge during monsoon season. In rest of the three districts, RIF estimates has been adopted as ‘PD’ was more than $\pm 20\%$ (refer Eq. 6). Recharge from canal seepage is 68.42 mcm (23%). Recharge from irrigation through surface and groundwater sources and from horticulture in farm houses together contributes to 22% of the recharge which amounts to 63.87 mcm. Contribution from water bodies and water conservation structures are rather less significant. The groundwater recharge pattern of NCT Delhi is given in Table 6.

Volumetric estimates are function of area of the assessment unit. Thus relative comparison of recharge/draft for different assessment units is not possible. Hence volumetric resources are divided with area of the assessment unit to arrive at estimates per unit area. The annual groundwater recharge per hectare from all sources is 22 cm. It is maximum in South West and West districts, to the tune of around 30 cm. This is followed by North West district. Recharge is least in Central and New Delhi districts where it is 8–9 cm. The contribution of rainfall recharge are more in Central, East, North and North East districts, while in case of West and South West districts contribution from other sources have been more significant.

Table 6 Groundwater Recharge in NCT Delhi (in mcm)

District	Recharge during monsoon					Recharge during non-monsoon					Annual recharge (sum total of 1–10)
	Rainfall	Return flow from irrigation	Canal seepage	Seepage from water bodies	Water Conservation structures	Rainfall	Return flow from irrigation	Canal seepage	Seepage from water bodies	Water Conservation structures	
	1	2	3	4	5	6	7	8	9	10	
Central	1.59	0.00	0.00	0.01	0.08	0.39	0.00	0.00	0.00	0.02	2.08
East	3.97	0.20	0.36	0.02	0.02	0.63	0.41	0.73	0.01	0.00	6.36
North	4.89	0.00	0.64	0.00	0.09	1.23	0.00	1.30	0.00	0.02	8.17
New Delhi	1.86	0.00	0.00	0.00	0.82	0.44	0.00	0.00	0.00	0.20	3.31
North East	6.62	0.15	0.33	0.00	0.01	1.34	0.29	0.66	0.00	0.00	9.40
North West	44.19	11.18	3.23	0.11	0.39	6.21	22.36	6.62	0.06	0.08	94.43
South	21.88	1.57	0.01	0.05	5.89	2.58	3.33	0.01	0.03	0.79	36.14
South West	37.87	6.86	10.73	0.11	4.47	5.37	13.73	21.88	0.06	0.92	101.98
West	8.37	1.26	7.22	0.01	0.10	1.01	2.52	14.70	0.01	0.02	35.21
Total	131.23	21.23	22.51	0.32	11.85	19.19	42.64	45.91	0.17	2.06	297.10

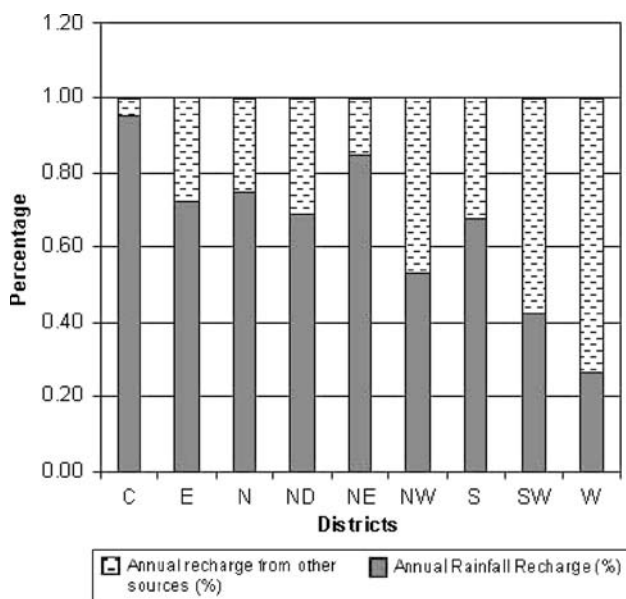


Fig. 8 Bar chart showing contribution to groundwater recharge through various sources

In West district, canal seepage has been quite prominent, while in South West district, canal seepage and return flow from groundwater irrigation contributes significantly to groundwater recharge (Fig. 8).

Effect of urbanization on groundwater recharge

Groundwater recharge in NCT Delhi is greatly influenced by the urbanization pattern of the city. Considering that the

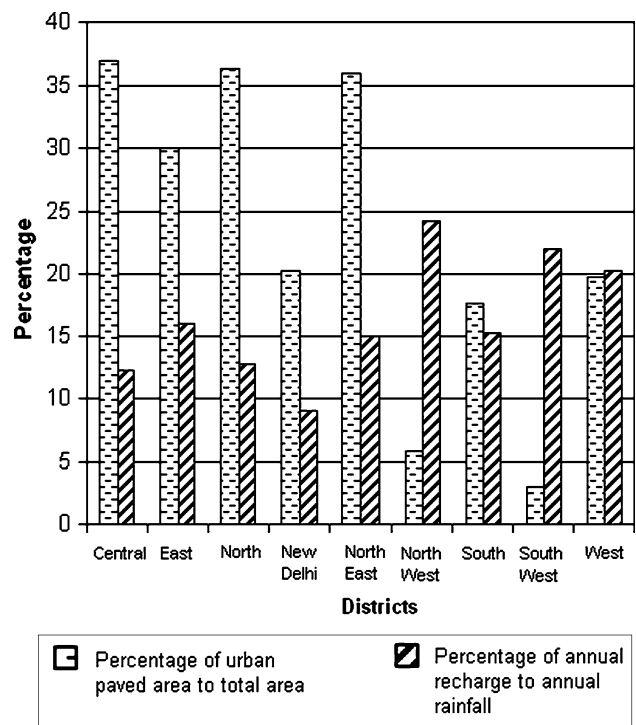


Fig. 9 Bar chart showing relationship between urbanization vis-a-vis groundwater recharge

average runoff coefficient of bare ground and green area is between 0.05 and 0.20 and that of paved area is between 0.50 and 0.85, it is obvious that concretization of bare ground and green areas are reducing the infiltration capacity in an area by more than three to four times. A comparison between the paved area in the urban clusters

and groundwater recharge indicates that the percentage of annual recharge to the annual rainfall is higher in the areas where percentage of urban paved area to the total area is less. This is particularly true in case of North West and South West districts as shown in Fig. 9.

Groundwater withdrawal pattern

Groundwater is predominantly being extracted for drinking and domestic purposes by the civic authorities namely Delhi Jal Board for city water supply and also by private individuals. Tubewells and handpumps are favourite modes of groundwater abstraction. Major consumers of groundwater are the institutions like hotels, hospitals, educational institutions, Government offices, Embassies and places of worships. Industrial units spread over 31 approved Industrial estates/areas as well as industries in the non-confirmed areas are also relying on groundwater to meet their water requirements. The present study has taken into consideration about 24,000 industries spread over these areas. Though the urbanization process is gradually encroaching over farm lands, still irrigation is prevalent at the outskirts of the city area and a major share of water supply for irrigation purpose comes from groundwater particularly in the North West and South West districts.

Annual groundwater draft in NCT Delhi for 2004 has been estimated as 479.45 mcm, out of which 200.02 mcm (42%) is for irrigation purposes and 236.44 mcm (49%) is for domestic purpose. Groundwater withdrawal for industrial purposes are comparatively less, about 43.00 mcm (9% of total groundwater draft) (CGWB 2006a). Table 7 indicates the groundwater draft scenario of NCT Delhi.

Annual groundwater draft per hectare for all uses in NCT Delhi is around 35 cm. In South West district, the draft is around 60 cm. This is followed by South, West and

Table 7 Annual groundwater draft in NCT Delhi (in mcm)

District	Annual domestic draft	Annual industrial draft	Annual irrigation draft	Annual groundwater draft (1 + 2 + 3)
	1	2	3	4
Central	1.65	0.00	0.00	1.65
East	4.66	1.79	1.42	7.88
North	2.55	0.00	0.00	2.55
New Delhi	5.09	0.00	0.00	5.09
North East	8.11	1.93	1.50	11.53
North West	8.22	16.07	97.99	122.28
South	74.28	8.06	1.09	83.43
South West	117.67	4.39	85.67	207.73
West	14.21	10.75	12.35	37.32
Total	236.44	43.00	200.02	479.45

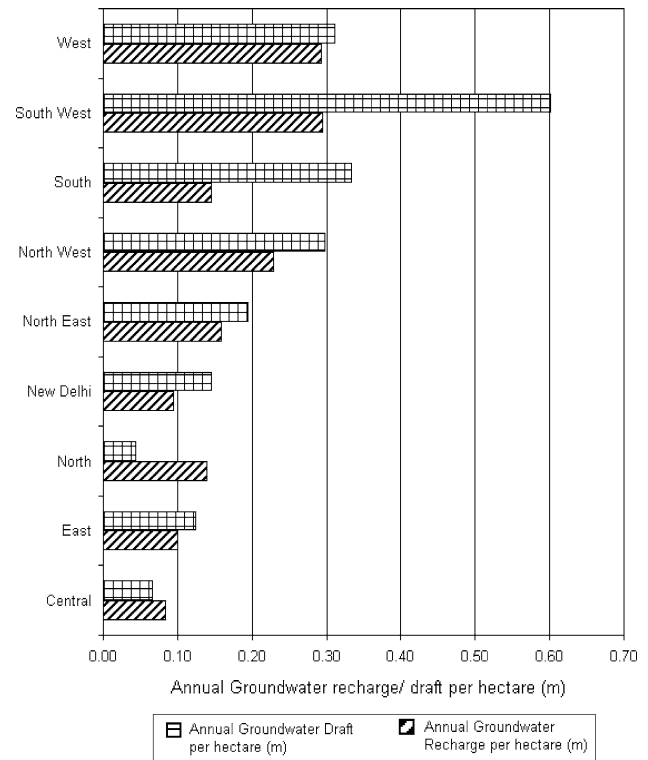


Fig. 10 Bar chart showing district-wise annual groundwater recharge per hectare vs. annual groundwater draft per hectare in NCT Delhi

North West districts in the range of 30–33 cm. Area-wise distribution of annual groundwater recharge and draft is presented in Fig. 10.

The groundwater draft is mostly for domestic use in urban sector and irrigation use in rural sector. While in the central part of the city in the districts of Central, North and New Delhi, 100% groundwater draft is for domestic use, groundwater withdrawal for industrial purpose is noticeably higher in East and West districts. The bordering areas of National Capital Territory in North West district is the major user of groundwater for irrigation purpose followed at considerably lower level by South West and West districts (Table 7).

Groundwater budgeting

The net annual groundwater availability has been calculated from annual replenishable groundwater resources (297 mcm) after keeping an allocation for natural discharge during non-monsoon season which is 16 mcm. The net annual groundwater availability is therefore 282 mcm. Since annual groundwater draft is around 480 mcm, the stage of groundwater development becomes 170%. Out of nine districts, seven districts are ‘over-exploited’ and two districts, i.e. North and Central are ‘safe’. The tabular presentation of groundwater resources is given in Table 8. The ground water resource assessments of the districts

Table 8 Annual Replenishable Groundwater Resource and Stage of development in NCT Delhi

Sl. no.	District	Annual replenishable groundwater resource (mcm)	Natural discharge (mcm)	Net groundwater availability (mcm)	Annual groundwater draft (mcm)	Stage of groundwater development (%)	Categorization
1	Central	2.08	0.21	1.88	1.65	88	Safe
2	East	6.36	0.32	6.05	7.88	130	Over-exploited
3	North	8.17	0.82	7.36	2.55	35	Safe
4	New Delhi	3.31	0.33	2.98	5.09	171	Over-exploited
5	North East	9.40	0.47	8.93	11.53	129	Over-exploited
6	North West	94.43	4.72	89.71	122.28	136	Over-exploited
7	South	36.14	1.81	34.33	83.43	243	Over-exploited
8	South West	101.98	5.10	96.88	207.73	214	Over-exploited
9	West	35.21	1.76	33.45	37.32	112	Over-exploited
	Total	297.10	15.53	281.56	479.45	170	

present the average status of groundwater utilization scenario of the area with respect to annual replenishable groundwater resource of the assessment unit as a whole. There could be variations in the status of the groundwater regime within the assessment unit and it will require micro-level studies before any long-term groundwater management plan is embarked upon in the vulnerable areas.

Groundwater management and environmental issues

Hydrogeological setup of NCT Delhi has constraints with regards to groundwater management and environmental issues. The major portion of Delhi is underlain mostly by the older alluvium which are mostly fine grained with moderate water yielding capacity. Moreover in the alluvial formations, fresh water is underlain by saline water which occur at varying depth. Hence restricting the availability of fresh water. On the other hand, in the hard rock formations (exposed in and around ridge area) level of fresh water is declining at a fast pace. These natural constraints in groundwater potential is further complicated with human interference, which has raised several environmental issues which needs to be addressed with suitable long term management plan. Firstly, during the urbanization process, bare grounds and green areas are getting concretized thereby reducing the scope of natural recharge to groundwater. Secondly, excessive withdrawal of groundwater at many places within this urban conglomerate has resulted in persistent decline in water level which is a serious ecological concern since this will reduce the available fresh water thickness and ultimately may lead to upconing of saline water. Rao et al. (2006) have visualized pumping needs in flood plains of river Yamuna to be accomplished through regulated pumping from production wells that control quality and quantity, namely skimming wells. In

order to control upconing of undulating saline water, they suggested this pumping must be staggered in space and time in perspective of environmentally sustainable groundwater withdrawal. Finally, the demand of water has not stabilized, rather it is still increasing as the metropolis is expanding. Therefore future groundwater management plans in NCT Delhi should address two vital though bipolar issues viz. maintenance of environmental balance by arresting the decline trend of groundwater and augmentation to drinking water supply for the increasing population through controlled groundwater resources development. The following paragraphs deal with the groundwater management options in NCT Delhi which include water harvesting measures for augmentation of groundwater resource and prevention of decline of water level, regulation on groundwater development, identifying new prospective areas for groundwater development in controlled manner and finally conservation of groundwater sanctuaries so that the natural recharge to the groundwater remains unhampered.

Groundwater resources augmentation through rain water harvesting in urban areas

The rapid urbanization has detrimental ecological impact on the groundwater regime as reduction in availability of open area reduces the scope for natural recharge to groundwater. An estimated 194 mcm of surface runoff is generated annually in NCT Delhi which flows to the polluted drains leading to the wastage of this vital natural resource. The remedial solution to this unavoidable adverse consequence of urban development is artificial recharge to groundwater. Several experimental studies have been conducted on artificial recharge studies in NCT Delhi (Fig. 11) which have proven the efficacy of techniques/structures like roof top rainwater harvesting and storm

Fig. 11 Map showing areas presently notified by CGWA and locations where studies were undertaken on groundwater management options in NCT Delhi



water recharge structures. Roof top rainwater harvesting is an ideal technique for buildings with large roof area in the urban settlements. In Indian Institute of Technology, South district, roof top rainwater harvesting scheme have been implemented through the construction of injection wells for the building having roof area of 1,660 m². (CGWB, Year unspecified). The sustainability of existing water supply wells have increased in the immediate vicinity of the structure. An increment of 2–3 m in the rise in water table column have been observed in the WTF before and after the rainy season. In case of natural streams where urban storm water is diverted, check dams are suitable artificial structures. In Jawahar Lal Nehru University campus, South

West district, which is in the vicinity of the ridge area, four check dams having the catchment areas between 0.45 and 1.26 km² have been constructed (CGWB, Year unspecified). The implementation of the scheme has improved the discharge of the water supply wells in the neighbourhood. An increment of upto 2.55 m in the rise in water table column have been observed in the WTF before and after the rainy season. Diversion of storm water through lateral shafts and recharge pits have been experimented in Lodhi Garden, New Delhi district which is spread over an area of 0.36 km² and characterized by undulating topography. Implementation of the scheme has resulted in—reduced flooding in the neighbourhood area, additional rise in water

level by 0.33 m after rains as compared to pre-project period (CGWB, Year unspecified). Similar schemes need to be implemented in the areas where continuous decline in water level is reported. It must be mentioned here that contaminated rainwater to be avoided for rainwater harvesting. Further regular maintenance of artificial recharge structures is equally important for effectiveness of the schemes.

Regulations on groundwater development activities in over-exploited and critical areas

In view of depletion in groundwater resources, Central Ground Water Authority of India has notified South and South West districts for regulated development of groundwater resource (CGWA 2000; Fig. 11). In these notified areas, installation of new structure for extraction of groundwater structures are not permitted without prior approval of the Authority. Effective implementation of notification could be achieved through a pro-active approach by sensitizing persons and users at different levels with regard to the need for judicious use and scientific management of groundwater. Mass awareness campaign is an effective tool in this regard. Another important activity in the notified areas would be regular and intensified monitoring of groundwater regime so that effectiveness of various corrective measures adopted for improvement of the situation like regulation, artificial recharge etc. could be analyzed and future course of action could accordingly be decided.

Groundwater development prospects in Yamuna flood plain

As mentioned earlier, the water resource assessments of the districts have been done using lumped approach considering the district as a whole, though at micro-level there could be variation in groundwater utilization scenario. Hence, though at district level, seven out of nine districts in NCT Delhi are categorized as over exploited, micro-level studies have indicated that there are limited scope for ground water development in the Yamuna flood plain areas in NCT Delhi to meet the partial demand of domestic water. The underlying concept for groundwater utilization in Yamuna flood plain is that the flood waters which are available for short period of time during monsoon can be utilized for replenishment of desaturated aquifers on account pre-monsoon groundwater withdrawal. Thus substantial groundwater yields can be obtained from Yamuna flood plains prior to flooding by considerably lowering the water table and making scope for additional recharge. The withdrawal of groundwater during dry season when needs are

maximum would permit use of groundwater to its optimum capacity.

In the northern part of Yamuna flood plain in Palla well field in North Delhi (Fig. 11) 90 tubewells were constructed by Central Ground Water Board to augment the drinking water supply of NCT Delhi. Based on numerical modelling and system simulation approach using SEAWAT 2000 simulator and ANN tool, Rao et al. (2007) have suggested that nearly 25–30 MGD of water can be withdrawn safely during both monsoon and non-monsoon seasons to meet drinking water standards (i.e. salinity <1,000 mg/l) in Palla wellfield to augment drinking water supply of NCT Delhi. Similar studies need to be carried out in other areas within Yamuna flood plain for exploring the scope for establishing additional well fields for augmenting the city's water supply programme.

Groundwater sanctuary in Delhi quartzite ridge

Environmentally least effected landform in NCT Delhi is Delhi quartzite ridge (Fig. 11). Endowed with fair collection of flora and fauna, the ridge is the most prominent natural green belt in the city. These are also the potential recharge zones for the aquifers underlying the ridge area and also the surrounding alluvial areas (Mohiddin et al. 2006). Any kind of developmental activities like urbanization, mining activities etc. would significantly affect the groundwater regime of the area. Such activities would also jeopardize the ecological balance of the environment. A typical case of human activity in Delhi ridge and resultant effect on groundwater regime was noticed in Bhatti mine areas at Delhi—Haryana border in South Delhi (Fig. 11). It was observed that dewatering of mines in Aravalli hills has affected groundwater regime of the mine area as well as buffer zone resulting in deepening of groundwater level in the surrounding areas. As a result Hon'ble Supreme Court of India issued directives effecting ban on the mining activities and pumping of groundwater in and from an area upto 5 kms. from the Delhi—Haryana border in the Haryana side of the ridge and also in the Aravalli Hill around Bhatti quartzite mining area and its buffer zone (Commonwealth Legal Information Institute 2004). After stoppage of pumping, the rise in water levels and increase in discharges in neighbourhood wells have been recorded. In few observation wells located in the vicinity of mining area—namely Bhatti and Balbir Nagar, rise in groundwater levels have been observed after stoppage of abstraction of groundwater from deep mines. The groundwater levels in open wells and tube wells in these areas have shown a rise of 2–4 m between May 2002 to May 2006, after the closure of dewatering of mines. Considering the importance of Delhi quartzite ridge in maintaining the overall environmental balance, it is recommended that Delhi quartzite

ridge be declared as Groundwater sanctuary which would be conserved for the purpose of recharge to groundwater and diversification of flora and fauna. Recharge capabilities of Aravalli ridge could be further enhanced through construction of check dams, nala bunds (series of small bunds across small stream channels) and stream diversion channels in the seasonal streams which can harness a portion of the runoff in a normal rainfall.

Conclusions

Urban hydrogeology throws a formidable challenge to scientists and resource planners since hydraulics of groundwater are further complicated by intense human interference in these areas. Management of the resource by maintaining the ecological balance is the main thrust in urban areas. National Capital Territory of Delhi being a fast growing urban centre of an economically growing nation like India presents a typical case study on urban hydrogeology.

The assessment of dynamic groundwater resources of NCT Delhi was done based on lumped estimate following GEC-1997 methodology. Since these estimates are based on long-term average (normal) rainfall figures (and not biased by individual rainfall events), they have practical utility in overall groundwater planning and management on a regional scale.

The annual replenishable groundwater resource of the entire NCT Delhi is about 297 mcm. In the districts of South, South West, New Delhi, West, North West, North East and East, the annual rate of groundwater extraction is more than the recharge. The groundwater levels are also showing steady decline in these areas. These districts are therefore categorized as ‘over-exploited’. Groundwater development in Central and North districts are within the recharge limit and are categorized as ‘safe’. In general groundwater quality is fresh at shallower depth (varying from 10 to 80 m below groundwater level depending on the location) below which it is saline. However, the thickness of the fresh water zone is gradually reducing due to excessive extraction.

In view of rapidly changing demographic profile and land utilization pattern of NCT Delhi which greatly affects the groundwater regime, there is a need for periodical assessments of groundwater resources. Future study should be undertaken for detailed assessment of development potentials of the entire aquifer systems existing in NCT Delhi. Impact of urbanization process on groundwater quality also needs to be studied.

Groundwater management strategies for NCT Delhi can be broadly framed based on the present assessments using GEC-1997. Depleting groundwater resources in the over-

exploited districts can be augmented through rainwater harvesting in the hydrogeologically suitable areas. Groundwater regulatory measures to be imposed in severely over-exploited areas through pro-active approach. It is recommended to undertake limited groundwater development programmes in Yamuna flood plain in case of need. However, such groundwater development programmes should be undertaken only after carrying out detailed water balance studies aided with discrete groundwater flow modelling. Delhi ridge which is acting as a recharge zone in the region should be protected as groundwater sanctuary. For effective outcome of these management strategies, stakeholders should be actively involved in the implementation process. Mass awareness and mass mobilization of the people on the various facets of groundwater management in NCT Delhi is therefore an utmost necessity. There should a holistic management approach for the entire water resources of NCT Delhi in the broader perspective of technical, ecological, social and economical considerations.

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