Chapter 11
Groundwater Resources in Punjab and Bist-Doab Area: An Appraisal and Overview

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INTRODUCTION

Punjab, a land of five rivers (in hindi Punch nada), namely, Beas, Sutlej, Ravi, Chenab and Jhelum are historically part of larger Punjab region comprising parts of Afghanistan and Pakistan on international front and states of Haryana and Himachal Pradesh (trifurcated into 3 states: punjabi speaking Punjab, and hindi speaking Haryana in 1966 and Himachal Pradesh in 1971), parts of Jammu & Kashmir and Delhi at national front.

Punjab is historically considered as the breadbasket and a role model for green revolution in India. However, it is presently under serious threat of groundwater level decline, salinity problem and also aquifer contamination.

To understand the issues, trends and challenges of groundwater resource, a comprehensive outlook on characteristic and property, which shape and are responsible for such abnormality to happen, is needed for deriving a technically sound sustainable solution. To appraise the issues and challenges, an overview covering hydrogeology, changing scenarios of groundwater resources, soils, trends in groundwater levels, quality of groundwater, etc. together with an indepth analysis of the Bist-Doab area, as a case study are described. The data and results compiled from different publications are duly acknowledged.

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HYDROLOGICAL AND HYDROGEOLOGICAL FEATURES

The following sections describe the characteristic aspects, which have direct bearing on the occurrence and prospects of groundwater resource in an area.

Physiography

Punjab has five divisions covering 22 districts (Jalandhar 7, Patiala 5, Firozepur 4, and 3 district each in Faridkot and Ropar), 82 tehsils, 87 subtehsils and 147 blocks (Kaler, 2016) with Chandigarh as the state capital. Geographically, Punjab lies in 29.30° N to 32.32° N latitude and 73.55° E to 76.50° E longitude with a total area of 50,362 km^2 and shares international boundary with Pakistan on the west and national boundary with states of Jammu & Kashmir, Himachal Pradesh, Haryana and Rajasthan on the north, northeast and south, respectively.

Physiographically, Punjab is characterized in 8 sub-units, namely, Hills (Shiwalik), Tableland, Intermontane valleys, Piedomont Plains (Upper piedmont & Lower Piedmont), Sirowal Zone, Alluvial Plains, flood plains and Sand Dunes (CGWB, 2014). The Siwalik hills cover 900 km^2 in the northeastern part. These hills traverse NW–SE direction and are made up of predominating bands of clays alternated with sands of varying grade and form the boundary with the neighbouring Himachal Pradesh. Sediments of the eroded upper Siwalik have formed the flat tableland in the lower Shiwalik zone. This fertile zone supports the local agricultural activities (in Hopshiarpur district). Inter-montane Sutlej valley is 40 km long, 5 km wide and about 50 m thick filled sediment stretch between Nangal and Ropar towns along the Sutlej river.

The transitional area of width varying 6 to 10 km between the alluvial plains and Shiwalik hills is occupied by the Piedmont plains, locally known as *Kandi* belt. These Piedmont plains have distinct features and are divided into different zones on the basis of these features. Zone with extremely dissected large number of sub-parallel streams, loose to semi-consolidated very coarse materials; poor vegetation and rain fed condition prevailing is the *upper piedmont zone* while the zone having large fan shaped body; lesser coarser sediments; fine textured soils; parallel drainage pattern; flat to undulating slope; irrigated; higher tree population dense forests and orchards is the *lower piedmont zone*. Area towards more southwest of *Kandi* with gentle is the *Sirowal Zone*.

Alluvial plains formed by the alluvium transported by the rivers mark the main physiographic unit are: (i) Recent (or active): Flood Plains-composed of unconsolidated material deposited along the banks of the rivers, which are subjected to periodic or occasional flooding. (ii) Abandoned flood plains (or older flood plains): Fairly wide with flat surfaces; are less prone to flooding but are fertile; therefore, are under intensive cultivation. (iii) Upland areas.

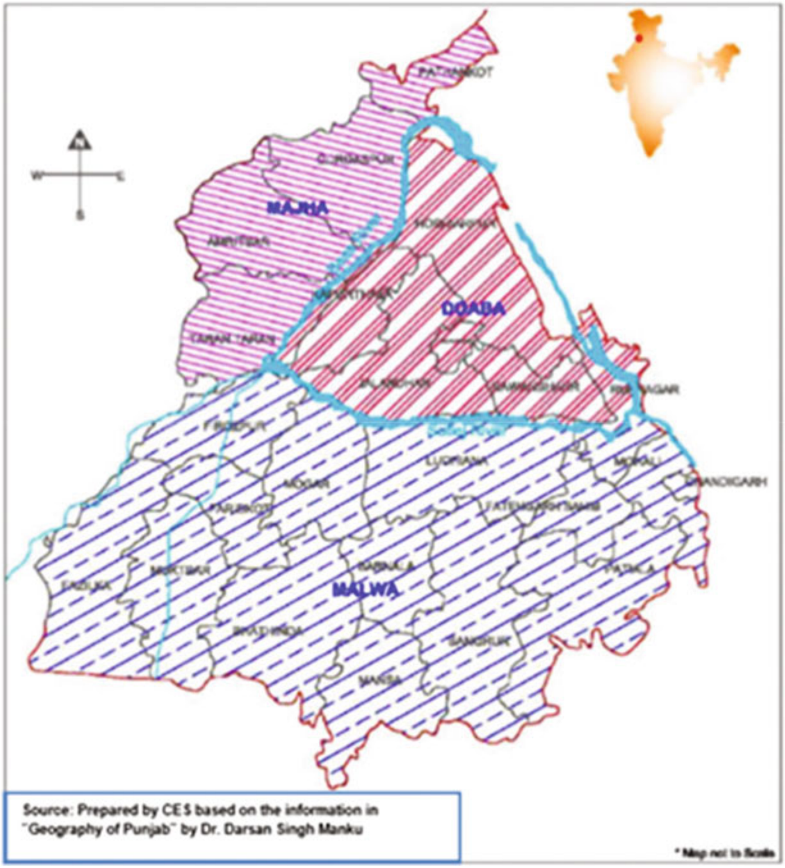

Figure 1. Physiography of Punjab showing three zone of Majha, Malwa and Doaba.

South-western part of the State comprising about 28% of the area, experiences semiarid type of climate and has isolated '*Sand Dunes*' of varying size and height.

Sutlej and Beas rivers divide the state into three zones, viz. Malwa, Doaba (land of two rivers *Do* means two, *Ab* means river) and Majha (Fig. 1).

Demography

As per Census (2011), Punjab had a population of 27.7 million that represented 2.29% of country's population with average population density of 550 persons/km^2, which is about 70% more than the national average of 327 persons/km^2. The trend of population growth showed a gradual fall in the last three decades from 20.26% (1981-1991) to 13.73% (2001-2011).

Climate and Rainfall

Punjab has a subtropical climate with summer, monsoon, transition and winter as four distinct seasons in a year. Summer temperature reaches upto 47°C and winter temperature drops upto 1°C. About 80% of normal annual rainfall of 648.8 mm occurs during the monsoon season, which varies from 260 mm (in extreme north-west parts) to 720 mm (northern region) and in few locations in Shiwaliks that increases as high as 1000 mm. The distribution of mean monthly rainfall of 30 years (1981-2010) in Fig. 2 (Sharma et al., 2017) shows that June to September are the monsoon months with July as the peak month followed by August.

Soils

Major soils are loamy (Ustochrepts of Ustic), Kandi soils, Podzolic and forest soils, sierozems, flood plain (bet soils or ustifluvent) soils, sodic and saline soils, sandy and desert soils (calciorthids).

Loamy, Kandi and sierozem soils cover nearly 70% of area of the state with distribution of 25%, 23% and 22%, respectively. Loamy soils are fertile and productive soil group. Kandi soils formed by deposits of river torrents of Shiwalik hills are badly eroded, less productive and are suitable for dry farming. Podzolic and forest soils are developed mainly in steep slopes and rugged topography and these are stony, gravelly and sandy and are prone to water erosion. These soils are covered by shrub and deciduous forest. *Sierozems,* the grey soils when irrigated produce highest wheat, and rice cultivation is also done on these soils. The Bet soils

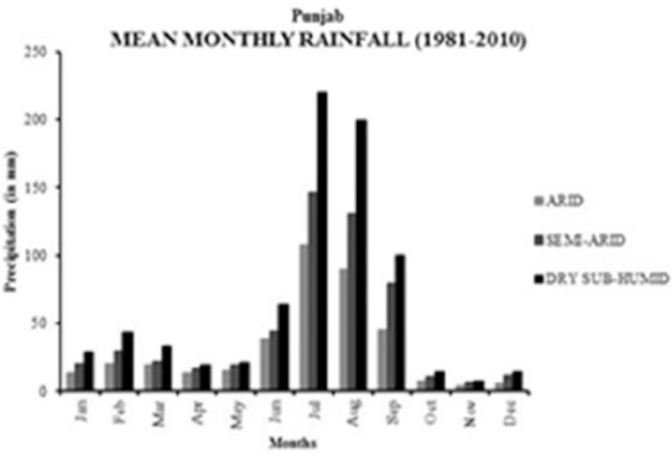

Figure 2. Distribution of mean monthly rainfall of Punjab (Source: Sharma et al. 2017 based on IMD, Pune and Directorate of Land Records, Jalandhar).

distributed on 7% area of the state are found on flood plain areas of rivers, streams or choes. Sodic and saline soils are developed mainly in waterlogging areas. Sandy and desert soils covering about 20% of the area occur mainly in south-western and south central Punjab and are favourable for cotton, citrus, oilseeds, wheat and fodder, cotton, moth, citrus, wheat, bajra and other kharif cultivation. The desert soils are prone to wind erosion especially in summer. Table 1 presents region and district-wise population, area, and soil types of the Punjab state.

Rivers of Punjab

Three rivers namely, Sutlej, Beas and Ravi, which are tributaries of Indus system, form the main drainage system of Punjab (Fig. 3). Two major rivers, Sutlej and Beas, traverse in the state while Ravi and Ghaggar—an intermittent and endorheic river—touch the northern and southern borders of the state, respectively. At Harike head-work, the two rivers Beas and Sutlej join and continue thereafter, as Sutlej. Besides these major rivers, the state is also drained by several small rivers like White Bein, Black Bein, Ghaggar river and seasonal revaluates. The area in Punjab in between the Beas and Sutlej is called Doaba.

Agriculture

Punjab is an agrarian state with 70% population engaged in agricultural activities. The state has intensified the agriculture activities using fertilizers, pesticides, machinery, irrigation intensification, etc. with the inception of green revolution in 1960’s. As a result, the country was relieved from importing food grains and the state’s economy increased rapidly. By the year 2000, area under cultivation reached to 83% of the geographical area (50.362 lakh hectares), cropping intensity increased to 189%, and 98% of cultivable area came under assured irrigation, use of fertilizer reached to 235 kg/ha (which is 1.84 times the national average of 128 kg/ha) and farming became mechanised. According to National Sample Survey Report (NSS Rep no 45, 54^{th} round) of 1992, Punjab had 1024 tractors and 584 power tillers per 100 km^2. This was nearly 10 times more than the national average of 109 tractors and 41 power tillers per 100 km^2.

Water and Irrigation

Irrigation water requirement is supported by canal and ground water. Surface water and groundwater (GW) development in the state started with the onset of green revolution. By 1986-87, the state had 218 minor irrigation schemes operational per

Table 1. Region and district-wise population, area and soil cover

Region	*District*	*Population (Census, 2011)*	*Area*		*Soil cover*
			Sq. km.	*% of state*	
Doaba	Hoshiarpur	15,86,625	3365	6.68	Kandi soils, Sierozems, podzolic and forest soil
	Jalandhar	21,93,590	2632	5.23	Loamy, sierozems, Sodic and saline soils
	Kapurthala	8,15,168	1632	3.24	Loamy, Sierozems, Sodic and saline soils
	Shaheed Bhagat Singh Nagar (NawanShahr)	6,12,310	1267	2.52	Loamy, Kandi soils, podzolic and forest soil
Majha	Amritsar	24,90,656	2647	5.26	Sierozems, Sodic and saline soils
	Gurdaspur	16,21,725	2635	5.23	Kandi soils, podzolic& forest soil and Sodic and saline soils
	Pathankot	6,76,598	929	1.84	Kandi and loamy soils
	Tarn Taran	11,19,627	2449	4.86	Sierozems
Malwa	Ajitgarh (Mohali)	9,94,628	1093	2.17	Loam with sandy patches
	Barnala	5,95,527	1410	2.80	Loam and Sandy loam
	Bathinda	13,88,525	3385	6.72	Loamy, Sandy and desert soils
	Faridkot	6,17,508	1469	2.92	Sandy, sierozems, Sodic and saline soils
	Fatehgarh Sahib	6,00,163	1180	2.34	Sierozems
	Fazilka	10,63,737	3113	6.18	Sodic and saline soils
	Firozpur	9,65,337	2190	4.35	Sodic and saline soils and sandy and desert soils
	Ludhiana	34,98,739	3767	7.48	Sierozems, Loamy, Sandy and desert soils
	Mansa	7,69,751	2171	4.31	Loamy, desert soils, Sodic and saline soils
	Moga	9,95,746	2216	4.40	Loamy
	Patiala	18,95,686	3218	6.39	Sierozems, loamy and sandy soils
	Rup Nagar (Ropar)	6,84,627	1369	2.72	Kandi soils, podzolic and forest soil
	Sangrur	16,55,169	3610	7.17	Sierozems, laomy, sandy, desert soils and Sodic and saline soils
	Muktsar	9,01,896	2615	5.19	Loamy, Sandy, desert soils and Sodic and saline soils
		2,77,43,338	50,362	100	

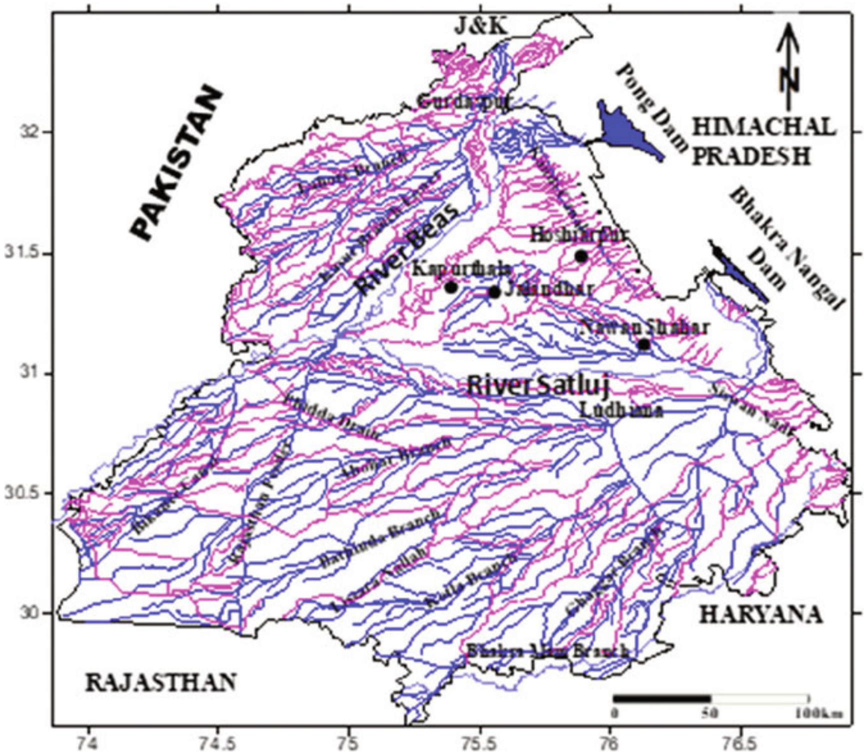

Figure 3. Drainage systems of rivers in Punjab.

100 km^2 area against the National average of 75. In 1993-94, the number of GW withdrawal structures (electric and diesel pumps) in the states rose to 18.8 pumps per 100 km^2 against the national average of 1.4 pumps (electric + diesel) per 1000 km^2 for the same period (MI Census 1993-94). In 2009-2010, 13.15 lakh tube wells were operational in the state. The surface water is distributed through network of 10 main canals and distributaries over a length of 14,500 km. However, post 90's, although the economy continued to increase but the share of the agriculture in the total GDP started decreasing with the progressive increase in the share from the secondary and tertiary sectors contribution in the total GDP (Fig. 4).

The state has intensive agricultural inputs (Table 2) showing 97-98% irrigated area of the total cropped area (in hectare) during 2007-2011. Area irrigated (in hectare) by using water from different sources is given in Table 3. Irrigation by the use of GW is nearly 2.6 times more than the other surface water sources including canal water.

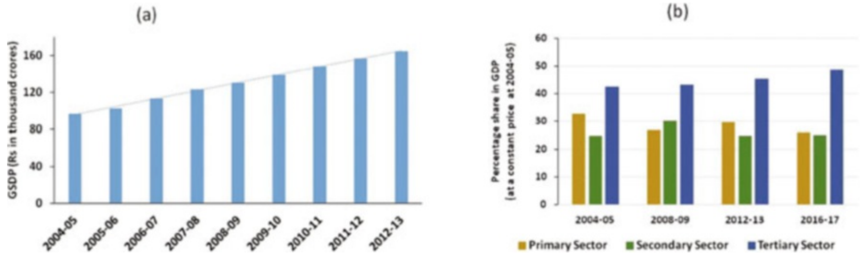

Figure 4. Economic growth of Punjab during 2004-11: (a) annual trend of gross state domestic product (GSDP), and (b) share of sectors in the total state GDP for the period between 2004-05 and 2010-11. (Source: Annual Plan 2011-12, Department of Planning, Govt. of Punjab).

Table 2. Status of cropped and irrigated area in Punjab ('000 ha.) during 2007-11

Year	*Total cropped area*	*Irrigated area*	*% of irrigated area to cropped area*
2007-08	7870	7689.3	97.7
2008-09	7912	7723.6	97.6
2009-10	7876	7714.2	97.9
2010-11	7882	7723.8	98.0

Source: Statistical Abstract, Punjab

Table 3. Area irrigated by using water from different sources in Punjab ('000 hectare)

Year	*Govt. canal*	*Private canal*	*Tube-well and well*	*Other sources*	*Total*	*% of net irrigated area to net area sown*
2007-08	1142	-	2922	4	4068	97.2
2008-09	1110	3	2950	1	4064	97.4
2009-10	1111	3	2955	2	4071	97.9
2010-11	1113	3	2954	-	4070	97.9

Source: Statistical Abstract, Punjab

Groundwater Aquifer

The seismic surveys by ONGC have indicated that the basement rocks dip gently towards the Himalayan foothills and correspondingly the sediment thickness increases towards the foothill. The aquifer basin is deep and wide in the north-western segment and gets narrower to the southwest, and the basement topography rises gradually in that direction. A high basement occurs in the subsurface corresponding to the present water divide between the rivers in the Punjab and Yamuna of the Ganga system. The crest of the buried ridge is ~ 450 m below ground level (bgl). Sediment thickness is about 450 m at Dasuya, Hoshiarpur which decreases to 154 m in south-western parts of Punjab. The alluvial deposits formed

Table 4. Aquifer extent, geometry and yield of different districts

District	*Total area (km^2)*	*Aquifer thickness*	*Average yield (m^3/hr)*
Faridkot, Moga, Bathinda, Mansa, southern parts of Sangrur and Ferozepur district	12,000	Upto 50 m with local discontinuity	50
South of Fazilka to north of Moga, north eastern parts of the district of Gurdaspur, Hoshiarpur, Nawanshahar, Patiala, Ropar and Anandpur Sahib valley	7,000	Upto 300 m	50-150
Amritsar, Kapurthala, Fatehgarh Sahib, Ludhiana, Patiala districts and parts of Sangrur, Gurdaspur, Ferozepur, Patiala, Nawan- shahar, Jalandhar and Ropar district	29,000	Upto 450 m	150
Hilly terrain in parts of Ropar, Gurdaspur, Hoshiarpur and Nawanshahar district	2,000	Semi-consolidated formations below	< 50
Plateau area (beet area) in Garhshankar block of Hoshiarpur district	750	100-370	100-200
In parts of Gurdaspur district and Anandpur Sahib block		40-150	Artesian flowing aquifers 1-70

Table 5. Block-wise groundwater development as assessed by the GWD of Punjab (total blocks = 138)

Category (GW draft in % of annual net recharge)	*Year: 2000* No. of block (% of area)	*Year: 2005* No. of block (% of area)	*Year: 2010* No. of block (% of area)
Over-exploited (Dark) (> 100%)	73 (52.90)	103 (75.18)	110 (79.71)
Critical (85-100 %)	11 (7.97)	5 (3.65)	3 (2.17)
Semi critical (65-85 %)	16 (11.59)	4 (2.92)	2 (1.45)
Safe (<65%)	38 (27.54)	25 (18.25)	23 (16.67)

Source: Jain, A.K., Department of Soil & Water Engineering, PAU, Ludhiana

by the mighty rivers of Punjab have developed extensive thick multiple freshwater aquifers throughout the state. More than 5 thick freshwater aquifers are encountered in Majha region at a depth within 500 m bgl. In the south-western part, freshwater aquifers are underlain by brackish/saline water. Table 4 presents district- and area-wise aquifer thickness and average yield of the respective aquifer. Major parts of the state have aquifer yield that ranges between 50 and 200 m^3/hr except parts of Gurdaspur district and Anandpur sahib block.

Groundwater Department (GWD) of the state together with the Central Groundwater Board (CGWB) assesses the status of GW exploitation every five years. The focus of such assessment is to examine the level of exploitation and categorising under different status with respect to the annual recharge. Table 5 presents the GW

Table 6. Groundwater Potential of Punjab (2006)

Annual replenishable groundwater resource (in BCM)	18.22
Provision for domestic, industrial and other uses (in BCM)	1.822
Available groundwater resources for irrigation (in BCM)	16.398
Utilizable groundwater resources for irrigation (in BCM)	14.755
Gross draft (in BCM)	20.307
Net draft (in BCM)	14.215
Balance groundwater resource for future use (in BCM)	2.179
Level of groundwater development (%)	86.71

Source: DWSS, Punjab, 2006*

exploitation status of block assessed in different years. Out of 138 assessment blocks, the number of over-exploited (annual GW extraction > annual recharge) blocks has continuously increased during 2000 to 2010, while the critical (annual GW extraction is between 85 and 100% of the annual recharge), semi-critical (annual GW extraction is between 65 and 85% of the annual recharge), and safe aquifer (extraction < 65%) have reduced during these period. The GW potential in Punjab (Table 6) shows that the average stage of GW development is ~86.7% against the annual replenishable GW resources of 1.821577 mham, i.e., 18.21577 BCM (billion cubic meter). Table 6 also gives distribution of GW for different sectoral usages.

Increased GW over-exploitation has been observed in the north and central part of Sutlej basin while water logging and increased salinity reported in the south-western part and in lower Sutlej basin, problems of high levels of fluoride, selenium and arsenic in the GW have also been reported. Over exploitation of GW, implying a negative balance of GW storages, withdrawal being more than the GW recharges has been experienced in most parts of the basin (NAPCC, 2011).

GROUNDWATER RESOURCES

An estimate of GW potential by NAPCC in 2011 (Table 7) shows that the net annual GW resource in the state was 21.44 BCM, of which the net annual draft was 31.16 BCM reflecting an annual deficit of 9.72 BCM. The GW assessment conducted by CGWB in 2004 showed that out of 138 blocks in the state, 103 were "over-exploited". The stage of GW development was estimated to 145%. This eventually put the state into an "over-exploited" category. Table 7 also gives status of groundwater in past years. The average water table depth was 7.32 m in 1998 and that had depleted to 12.79 m bgl in 2012, indicating an annual fall of 41.6 cm/yr. In central Punjab, the decline was between 0.11 m/year and 1.34 m/year (NAPCC, 2011). The north-eastern part of the state showed GW depth between 5 m and 10 m, in the north-central it was between 10 m and 15 m, and in areas around major cities, namely, Jalandhar, Ludhiana, Amritsar, Patiala, Fatehgarh Sahib, Nawashahar and Sangrur,

Table 7. Status of groundwater in Punjab in 2011 (Source: NAPCC, 2011)

Annual groundwater availability	21.44 BCM
Groundwater extraction	31.16 BCM
Average level of groundwater development	145%
Level of groundwater extraction in districts of Fatehgarh Sahib, Amritsar, Jalandhar, Kapurthala, Ludhiana, Mansa, Moga, Nawanshahar, Patiala and Sangrur .	144% to 254%
Over-exploited groundwater blocks	103 out of 137
Critical blocks	5
Over-exploited blocks in 1984	64
Over-exploited blocks in 2006-07	103
Decline in groundwater level reported by CGWB	4.5 to 13.5 m
Area identified for groundwater recharge estimated by CGWB	16450 km^2
Waterlogged area	200,000 ha
Salinity affected area	1,000,000 ha

Proportion of area and the water table depth in different agro-climatic zones of Punjab

Year	Northeast zone			Central zone			Southwest zone		
	<3	3-10	>10	<3	3-10	>10	<3	3-10	>10
1998	0	81	19	0	65	35	12	84	04
2004	0	70	30	0	18	82	03	65	32
2010	0	61	39	0	12	88	12	48	40
2011	0	50	50	0	13	87	19	41	40
2012	0	58	42	0	21	79	08	44	48

Figure 5. Agro-climatic zones of Punjab and % of state geographical area falling under these zones. (Source: Baweja et al., 2017)

the groundwater table (GWT) was more than 20 m bgl. Depth to GW was at 33 m bgl at Ludhiana and 50 m bgl in Garshankar block of Hoshiarpur district. Out of 50,362 sq. km area of the state, about 39,000 sq. km (78%) showed a decline in GWT. However, the decline in GWT was not spatiotemporally uniform in the whole state. Figure 5 presents depiction of area under different zones and Table 8 describes ranges of GWTs in different years in those zones. Figure 6 portrays the yearly trend (decline) of GWTs (bgl) of two hydrograph stations; one in Gujarwala of Ludhiana district and the other in Nakodar block of Jalandhar district from 1973 to 2005. A continuous decline with no sign of GWT reversion was common in more than 75% area of the state. The fluctuation of GW levels (RL of ground surface—depth to GWT beneath the respective ground surface) of two hydrograph stations, namely,

Table 8. Trend of groundwater level in districts of Punjab (Source: NAPCC, 2011)

Zones	*District*	*Trend (decline) (in m/yr)*
Zone I: North-eastern area	Hoshiarpur	0.68-0.07
	Nawashahar	-
	Ropar	-
	Fatehgarh Sahib	0.025-0.58
	Patiala	0.5
Zone II: North-central area	Jalandhar	-
	Ludhiana	0.11-1.34
	Kapurthala	0.20-1.00
	Moga	0.20-1.00
	Mansa	-
	Sangrur	0.65
Zone III: South-western area	Faridkot	-
	Ferozepur	-
	Muktsar	-
	Bathinda	-

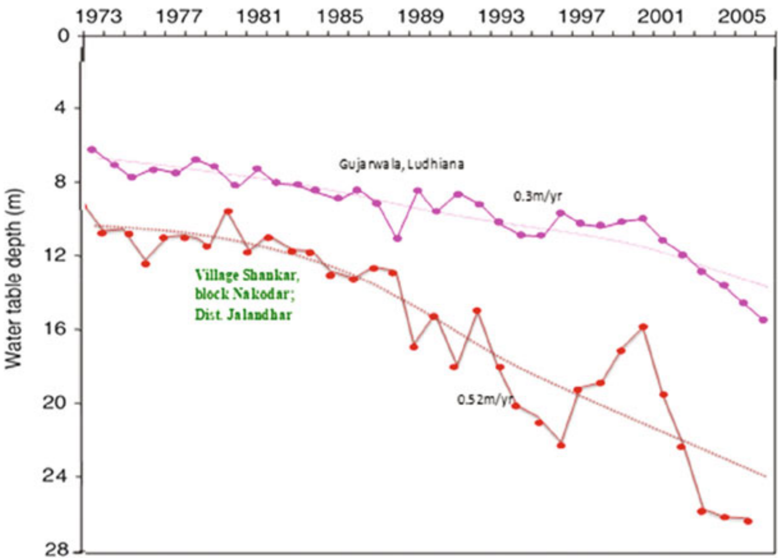

Figure 6. Depth to water level in Punjab during 1973-2005.

Bajwara and Noormahal (Fig. 7) for the period 1998-2011 in the month of July showed a continuous decline in GWL @ 0.64 m/year for the Bajwara and 0.79 m/year for Noormahal site. Some improvement in GWL in few locations like Noormahal (Fig. 7), was reported. However, the overall GWL followed a declining trend. This sign of improvement in local scale was either due to augmentation of groundwater by artificial recharge or due to reduced groundwater extraction or both.

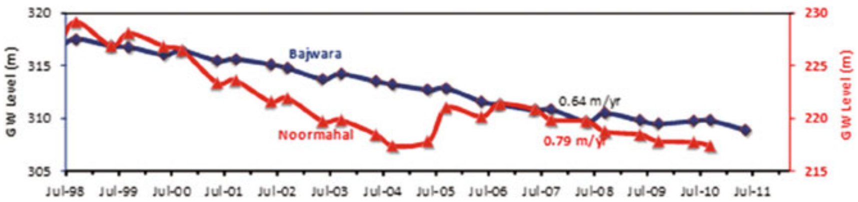

Figure 7. Groundwater fluctuation at Bajwara and Noormahal, Bist Doab during 1998-2010.

Table 9. Fluoride and nitrate contamination in GW of Punjab (Source: NAPCC 2011)

District	*Fluoride concentration (ppm)*	*Nitrate concentration (ppm)*
Bhatinda	-	61-401
Faridkot	-	60-287
Firozpur	1.63-3.4	69-241
Fatehgarh Sahib	1.54	-
Ludhiana		70-206
Mansa	1.58-8.3	70-206
Moga	1.96-5.36	-
Muktsar	-	83-940
Patiala	2.05-2.80	47-52
Sangrur	1.71-11.30	107-1180

Water Quality

About 75-80% of water for domestic requirement is fulfilled by groundwater (GW). Groundwater quality (GWQ) analysed by the state departments under various projects have shown that GWQ is good in northern and central zones, and is mostly saline in southern and south-western parts of the state. Isolated saline patches are also present in Mansa Moga, Sangrur and SAS Nagar districts. In general, there is an increasing trend of salinity in the direction from north-east to south-west (Chopra and Krishan, 2014; Krishan et al., 2013, 2014, 2017). CGWB (2013) reported (Table 9) presence of high levels of fluoride, iron, TDS (Krishan et al., 2015), chloride and nitrate in the unconfined aquifers in some blocks of Punjab. Out of 22 districts in Punjab, high level of fluoride content in GW were reported from 7 districts, viz. Firozepur, Fatehgarh Sahib, Mansa, Moga, Muktsar, Patiala and Sangrur. The maximum amount of fluoride (> 11 mg/l) was reported from the Sangrur district. The GW nitrate contamination was mostly reported from Bathinda, Faridkot, Firozpur, Ludhiana, Mansa, Muktsar, Patiala and Sangrur district. High contamination of nitrate and fluoride was mainly reported from Malwa region. In addition to fluoride and nitrate contamination, occurrence of heavy metals namely, chromium, uranium, cadmium, etc. was also reported from Malwa region. Recent studies had reported presence of heavy metal contaminants in the deeper aquifers. It is speculated that it might be due to induced flow carrying contaminants from shallow to deeper aquifer.

In brief, the state has a complex hydrogeology and the socio-economy of the state immensely depends on the groundwater conditions. Major factors that affect the groundwater conditions include increasing area under agriculture sector, growing cropping intensity, large scale groundwater extraction from multiple aquifers system, more water use under irrigation practices, excessive use of fertilisers and pesticides, contamination from industrial and sewage effluents, impact of structures like reservoirs, network of canal and its distributaries, etc. on GW.

The last one decade witnessed a new range of techniques (high resolution remote sensing and GIS analysis, isotopic techniques, automated field based systems etc.) in addition to the conventional technique for assessment of anthropogenic influence on groundwater system especially in the Bist-Doab region of Punjab. The following section provides an illustration of outcome acquired from these new techniques.

BIST-DOAB REGION: A CASE STUDY

The Bist-Doab region is between rivers Beas and Sutlej. This region is known as one of the most fertile area in the world in terms of agricultural productivity, and was the centre of the green revolution in India. Even today, it is recognized as one of the largest per capita producers of wheat in the world. A geomorphologic map of Bist-Doab region is shown in Fig. 8.

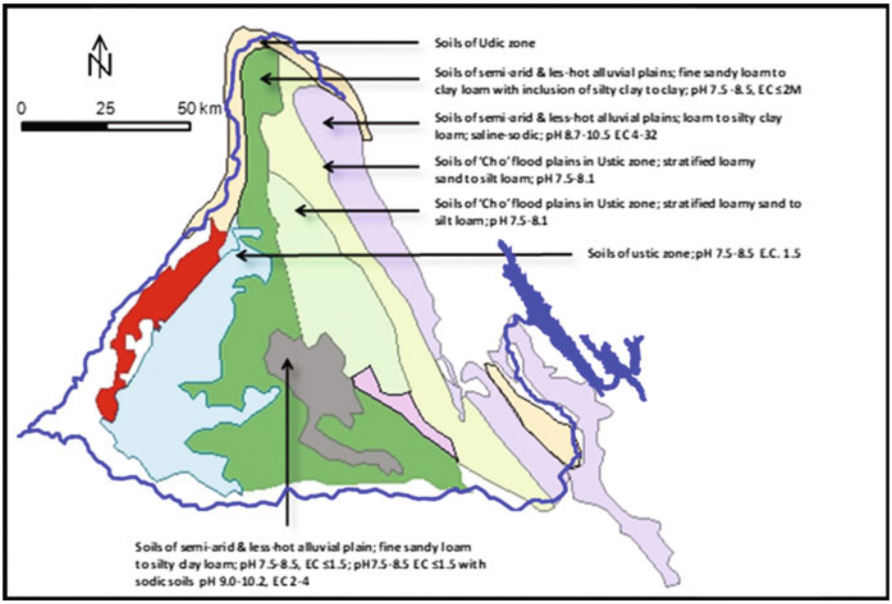

Figure 8. Geomorphological map of Bist-Doab tract, Punjab

Table 10. Aquifer groups in Bist-Doab region

Zones	*Texture*	*Thickness*
Aquifer Group I	Coarse sand beds separated locally by thin clay beds.	72-94 m
Clay Layer	A regionally extended confining clay layer that separates aquifer I from aquifer II.	It is 16 (at Kapurthala) to 32 m (at Hoshiarpur) thick.
Aquifer Group II	Alternating sequences of thin layers of sand, clay and gravel beds and, occasionally with kankar. The clay beds are thin and pinch out.	80-105 m thickness (81 m at Hoshiarpur district 85 m at Kapurthala district 87 m at Jalandhar district 105 m at SBS Nagar district.)
	Aquifer Group II is followed by a regionally confining layer upto the depth of 250 m bgl.	

The region is bounded by Shivalik hills in the north-east, the river Beas in the north-east and west, and by river Sutlej in the south (Fig. 8). Doab has the highest road density than all other areas in Punjab. The area is drained by perennial rivers, Sutlej and Beas and their tributaries. The two rivers join at village Harike and thereafter, continue as Sutlej river. The Bist-Doab region comprises districts Hoshiarpur, Kapurthala, Jalandhar and SBS Nagar of Punjab. Hydrogeologically, the region is characterised by two aquifer groups I and II extended upto a depth of 250 m bgl (Table 10). The two aquifer groups I and II are separated by regionally extended thick clay layer. Each aquifer group is composed of thick sand-gravel beds separated by small, thin clay beds that pinch out locally (Table 10). A fence diagram prepared by CGWB for the Bist-Doab area showing possible connectivity of the geological strata is shown in Fig. 9. This fence diagram will help understand the extent of different aquifers and their geometry and also recognises that Bist-Doab region has muti-aquifer systems with intermittent clay layers. No pumping test data were available for determining the aquifer parameters exclusively for these groups. However, on the basis of pumping tests data of wells tapping multiple aquifer groups the storage coefficient S values were estimated that ranges from 2.5×10^{-3} to 7.1×10^{-3} with an average of 3.85×10^{-3}.

Land-Use Changes (LUCs)

High resolution satellite data of 1975-2015 used for investigating the impact of social development on land-use changes (Table 11). showed that built-up area grew from 1.36% (1975) to 16.32% (2015), mainly due to conversion of 10.8% agricultural land into built-up land. The river area has increased from 2.33% (in 1975) to 2.52 % (in 2015) due to inclusion of additional 0.33% barren area and 0.23% agricultural area into the flood zone. The agricultural area increased from 58.87% (1975) to 64.73% (2015). This increase resulted from the change of 3% of shrub and 1.5% of sandy area into agricultural land. Reservoir area which was 0% in 1975

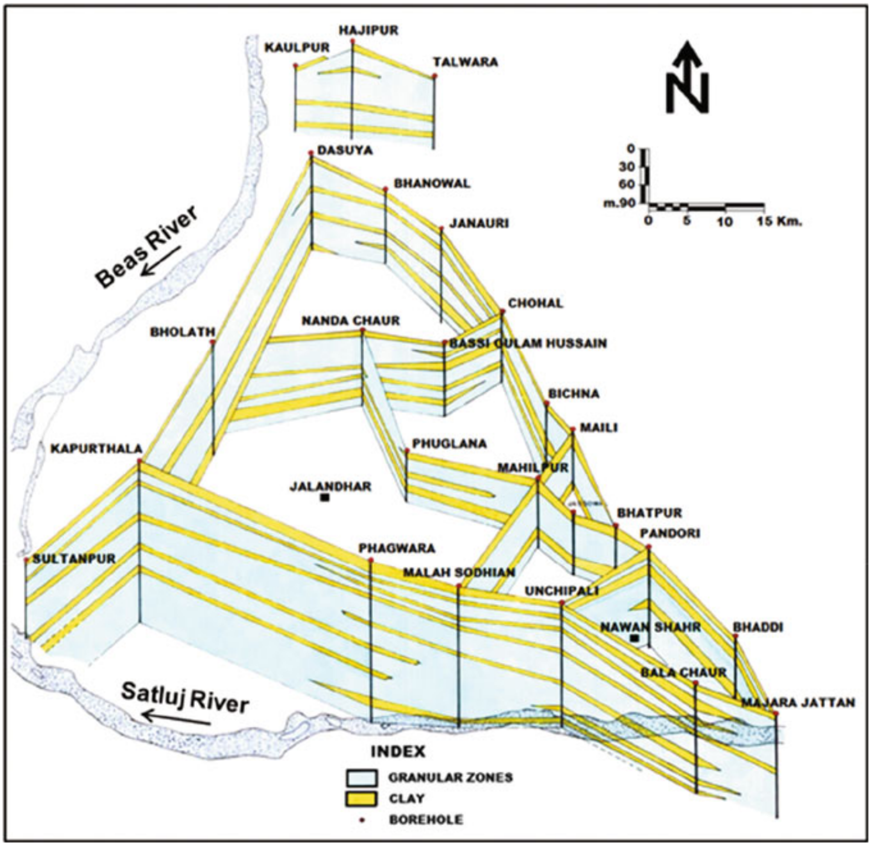

Figure 9. Bist-Doab fence diagram

increased to 0.22% because of 8 minor dams (Chohal, Dhamsal, Dholbaha, Janauri, Mailli, Patiari, Saleran and Thana), which came up during this period.

Groundwater Fluctuation

State and Central groundwater boards' historical data on groundwater levels involved measurement from bore-wells using rope and weight method on quarterly intervals in a year. Such data cannot be used to investigate diurnal changes, impact of high groundwater withdrawal on neighbouring pumps, impact of flood wave in the region, etc. In recent years, these manual methods of data monitoring are getting replaced by automatic water level recorders which can record water level by piezometers at desired intervals and for several months without being physically

Table 11. Percent Land-use Land cover change (source Kaundal et al., 2018)

1975	*2015*										
		River	*Reservoir/ Pond*	*Dense scrub*	*Open Scrub*	*Barren area*	*Built-up area*	*Agricultural Area*	*Current fallow*	*Sandy area*	*Total*
	River	1.61	0.01	0.33	0.05	0.04	0.01	0.09	0.15	0.04	2.33
	Reservoir/ Pond	0	0	0	0	0	0	0	0	0	0
	Dense scrub	0.05	0.16	5.27	1.40	0.16	0.32	0.15	0.14	0.05	7.70
	Open Scrub	0.01	0.01	0.21	0.35	0.08	0.33	3.40	0.45	0.06	4.90
	Barren area	0.33	0.01	0.30	1.37	0.09	0.46	0.17	0.20	0.17	3.10
	Built-up area	0.00	0.00	0.00	0.01	0.00	1.33	0.01	0.01	0.00	1.36
	Agricultural Area	0.23	0.00	0.16	0.29	0.44	10.81	45.58	0.27	1.09	58.87
	Current fallow	0.06	0.00	0.06	0.47	0.05	0.19	0.10	0.11	0.55	1.59
	Sandy area	0.23	0.03	0.01	0.66	0.12	2.87	1.52	0.24	0.76	20.15
	Total	2.52	0.22	6.34	4.60	0.98	16.32	64.73	1.57	2.72	100

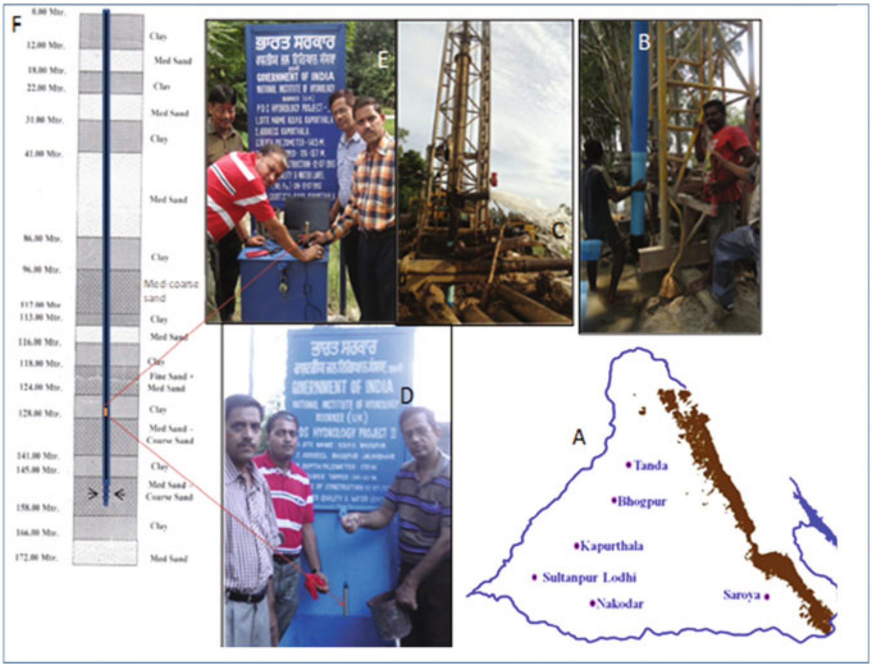

Figure 10. Piezometer (Pz) development in Bist-Doab: (A) Location points of Pz, (B) lowering of Pz pipes, (C) cleaning of Pz, (D) lowering data logger, (E) Measurement of recorded water level after 3 months and (F) Pz strata chart (of Tanda).

attended (Krishan and Rao, 2017). The data from these systems can also be transmitted using telemetry system at the data recording station.

In order to monitor the deep groundwater response to withdrawal and recharge continuously; under Purpose Driven Study in Hydrology Project Phase II, six deep piezometers (~150 m depth) were constructed (Fig. 10) and change in water level at those sites were recorded at hourly intervals. Figure 11 shows the daily drawdown and subsequent recoup as diurnal fall and rise in water levels. The water levels fall generally during day and recover by wee hours. In case of seasonal variations, water levels fall rapidly in pre-monsoon season and recharge through monsoon mostly during post-monsoon season when extraction is also less. Seasonal difference in water levels is shown in Fig. 11 (a) to (c).

Groundwater level fluctuation depending on the extraction and recovery rates in deep piezometers varies from 3 to 8.6 m and major 2-3 withdrawal events take place. Groundwater level started rising after 2 months of rainfall and continued for 3 more months (Table 12). This is also the time taken for transmitting hydraulic pressure from surface to aquifer.

Relationship between rainfall and groundwater depletion is not prominent in the Bist-Doab region as 42% is recharge from rainfall and 58% comes from other

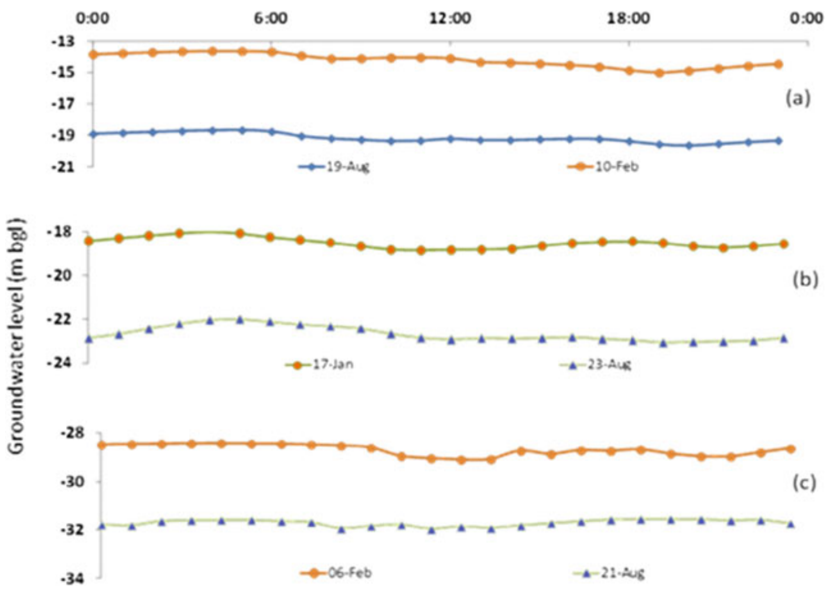

Figure 11. Trends of diurnal and seasonal groundwater levels in Bist Doab at sites: (a) Bhogpur, (b) Kapurthala and (c) Nakodar.

sources like leakage from reservoirs, tanks, ponds, water conservation structure, seepage from canal, irrigation return flow, etc. (Govt of Punjab, 2013).

Satellite based (GRACE data) GWL analysis

Groundwater depletion has been estimated by Rodell (2009) using satellite based GRACE data available from 2003. The GRACE derived results is also found to be well correlated with field based data (Fig. 12). The GRACE data based analyses showed the depletion in groundwater rate in northwest India (covering states of Punjab, Haryana, Delhi and Rajasthan) is about 20.4 Gt/yr averaged over the period 2003-2012 and 29.4 Gt/yr for 2003-2007 (Rodell, et al., 2009). Groundwater issues of Indo-gangetic basins were reported by researchers in detail (Bonsor et al., 2017; MacDonald et al., 2015, 2016)

ISOTOPE ANALYSIS

Isotopes have been used widely as tracers in hydrogeology for recharge estimation and source identification (Guay et al., 2006, Blasch and Bryson, 2007) and can also be used for studies of age depth profiles (Lapworth et al., 2014, 2015, 2016).

Table 12. Seasonal variation in groundwater level in response to monsoon and withdrawal for irrigation at the observed AWLR sites in Bist-Doab region during 2011–12. (Source: Rao, et al., 2017)

Site name	*Start of water level rise after monsoon onset (days)*	*Date of maximum water level in Feb.*	*Maximum water level and end of monsoon time difference (days)*	*Groundwater level fluctuation (m)*	*Major withdrawal events*	*Average rate of recovery (m/hr)*
Bhogpur	60	5th	142	8.01	3	4.16
Tanda	62	20^{th}	162	2.74	2	0.57
Saroya	57	3^{rd}	145	8.6	3	9.84
Kapurthala	59	3^{rd}	141	4.89	2	2.35
SultanpurLodhi	57	20^{th}	150	3.29	2	2.35
Nakodar	48	1^{st}	143	3.9	1	0.85

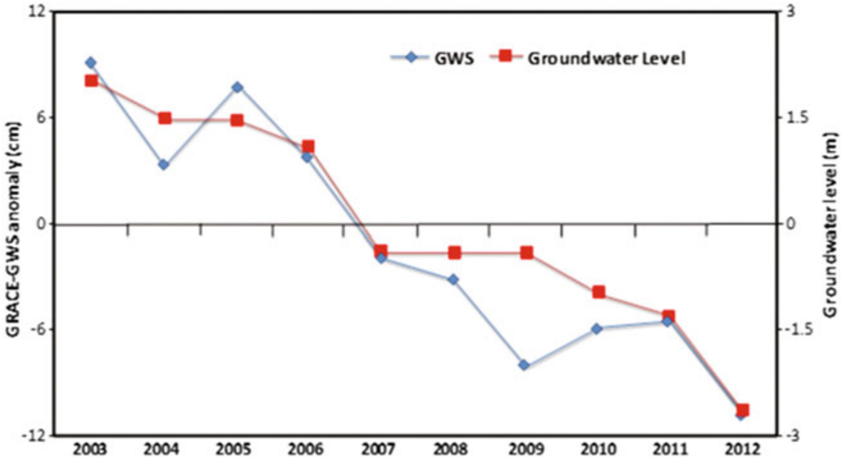

Figure 12. Comparison of anomalies in the GRACE-derived groundwater storage (GWS) and in situ groundwater level averaged from about 250 observation wells in Punjab based on data of 2003–2012.

Table 13. Equations of the characteristic isotopic lines and data range of source water

Water source	*Characteristic isotopic equation*	*Observed data range*	
		(dD, d^{18}O)min	*(d^{18}, dD)max*
Rainfall	$\delta D_R = 8.16\delta^{18}O+7.35$	(−12.9, −97.0)	(−0.02, +5.1)
Shallow groundwater	$\delta D_S = 7.26\delta^{18}O+1.06$	(−9.56, −73.07)	(−4.87, −32.06)
Deep groundwater	$\delta D_D = 6.92\delta^{18}O-0.84$	(−9.56, −73.1)	(−5.75, −36.0)
River Beas	$\delta D_{RB} = 6.31\ \delta^{18}O-0.81$	(−9.97, −65.27)	(−4.61, −34.07)
River Sutlej	$\delta D_{Rs} = 5.4\ \delta^{18}O-14.51$	(−11.9, −80.73)	(−8.1, −54.5)

The study conducted in the Bist-Doab region (Rao et al., 2017) demonstrated stable isotopic composition of deep and shallow groundwater, river water and rainwater and also dated the samples using environmental tritium analysis. Table 13 highlights the equation of the characteristic isotopic lines. Figures 13 and 14, respectively, present spatial distribution map of $\delta^{18}O$ and environmental tritium of groundwater. Figure 15 presents spatial distribution map of $MgHCO_3$, $CaHCO_3$ and $NaHCO_3$ in groundwater of Bist-Doab area.

The interpretation and description of isotopic composition are summarised as follows:

(i) Shallow groundwater showed $\delta^{18}O$ values between −6.8‰ and −10.5‰, whereas in deep aquifer values ranged between −6.8‰ and −8.4‰, that indicated recharge of shallow groundwater from that water source that contained depleted water (−8.4‰ to −10.5‰), such as the water that originates from canal and rivers (Sutlej, Beas etc.), and this type of water is less observable in the deeper aquifer.

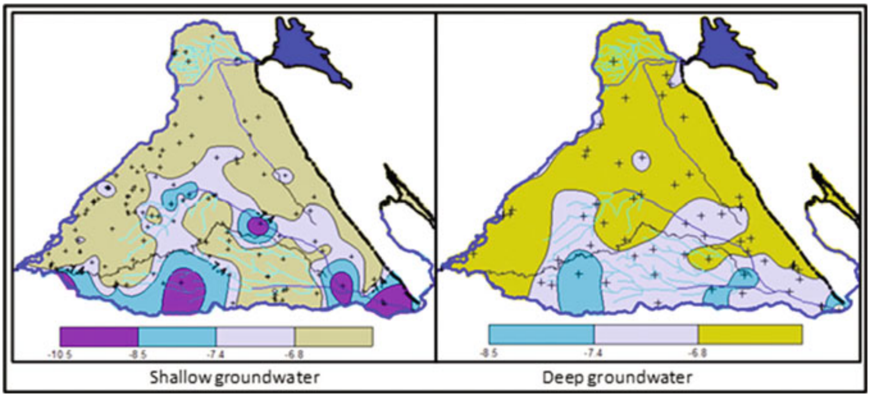

Figure 13. Spatial distribution of d^{18}O (in per mill) in shallow and deep groundwater.

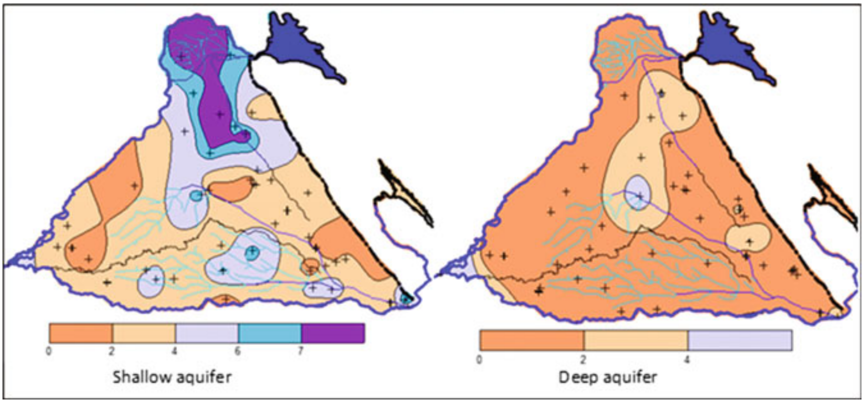

Figure 14. Spatial distribution of environmental tritium in shallow and deep groundwater.

(ii) Depleted groundwater ($\delta^{18}O < -6.8‰$) indicating recharge through canal to the shallow aquifer is very localised and this water is not moving down horizontal beyond a kilometre and therefore, not entering into the deeper aquifer.
(iii) Oxygen isotopic composition of groundwater (in shallow and deep aquifer) matches with the rainfall isotope value indicating rainfall is the main source of groundwater recharge, and recharge from other sources such as canals (originating from Sutlej and Beas rivers), river Beas and river Sutlej, is very small.
(iv) The isotopic mass balance has indicated that the shallow groundwater of the region is recharged through rain by 91%, through Sutlej canal by 8.6% and through the river Beas canal by 0.36% whereas, deep aquifer is recharged from canals' seepage by 5.1% (4.08% through Sutlej canal and 0.6% through Beas canal) and the remaining 94.9% is through rain.

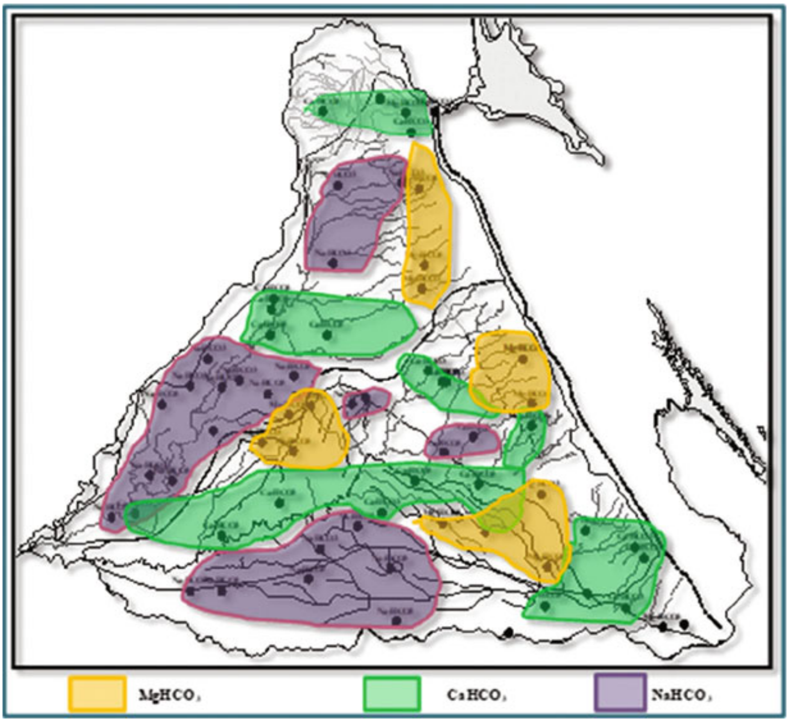

Figure 15. Spatial distribution of $MgHCO_3$, $CaHCO_3$ and $NaHCO_3$in groundwater.

(v) Groundwater is recharged mainly from rainfall in the foot-hills and higher altitude regions of Shiwalik hills. The recharged groundwater moves down to the plains and in the process the shallow aquifers and deeper aquifers are recharged by leakage. After a small amount of intermittent recharge from Sutlej canal, the composite groundwater is finally discharged into the rivers Sutlej and Beas as base-flow.

(vi) The seasonal variation in isotopic composition of shallow aquifer indicated that during rabi season (November-March), groundwater levels are deep and the canal discharge is high. Thus, the seepage from canal contributes the local shallow aquifer. During the monsoon period, canal discharge is low and land is filled-up with rain. During this season, recharge to groundwater occurring from rainfall makes the isotopic composition of groundwater similar to that of the rainfall.

(vii) Intense groundwater withdrawal over the past five decades has resulted into deepening of groundwater levels by several tens of meters. Therefore, the induced canal water isotopic signature is penetrating progressively to greater depths in the aquifer. With the progress of groundwater withdrawal from deeper depths and its replenishment through fresh (young age) water (including canal irrigated water), the average age of groundwater in the region is decreasing, that is, groundwater withdrawal from deeper depths is bringing the semi-static deeper aquifer groundwater into dynamic condition and induced the recharge from shallow aquifer.

(viii) The regional distribution and assessment of environmental tritium activity in groundwater indicated that age of groundwater in the shallow aquifer is ~16 years in ~40 % of area, 10 years in 20% of area and less than 6 years in the remaining 20% of the area. For deep aquifer, 84% of the area contains groundwater having age >25 years. The extraction of deeper groundwater and the induced flow from the overlying aquifer, age of the deeper groundwater is expected to reduce. The over-exploitation is changing the natural recharge rate of groundwater and its residential time.

(ix) In recharging zone, groundwater of $MgHCO_3$ and $CaHCO_3$ types found while in discharging zone it is $NaHCO_3$ type. Progress of groundwater depletion causes the removal of old mineralised groundwater which gets replaced by fresh/young groundwater of $MgHCO_3$ and $CaHCO_3$ composition (Rao et al., 2017; Purushothaman et al., 2013).

CONCLUSIONS

The Punjab state, historically considered as bread-basket and a role model for green revolution in the country, is now suffering from declining ground water problem, groundwater salinity and aquifer contamination. The Punjab basin is rich in water resources due to rich aquifers (thickness about 4.5 km in the northeast to about 400 m in the southern parts) and the five major rivers. Since the time of green revolution, the state has put all its efforts in maximising the food grain productivity. Towards this, vast areas of the state has intensified the rice and wheat cropping system, started using farming machines, chemical fertilisers, pesticides, herbicides, intensified irrigation practices through constructing huge number of groundwater extraction units, canal networking, reservoir constructions, promoting farming by providing cheap credit, free electricity, conversion of barren lands into agricultural, etc. As a result, irrigated area and the agricultural productivity doubled since 1965. However, indiscriminate extraction of groundwater for cultivating water intensive crops even in areas where groundwater recharge (e.g. Doab region) is low, led to falling of groundwater at a rate exceeding 1 m/yr. In areas where canal network is dense (like southwest Punjab), the canal irrigation is getting overused. Less extraction of groundwater, excessive use of surface water and poor groundwater transmission characteristic led to waterlogging and salinity problem in these areas (like south and southwest Punjab). Use of chemical fertilisers, pesticides, burning of crop residues for quick clearance of farms, uncontrolled disposal of urban waste on open surface, into open water bodies and rivers, poorly managed landfills and open dumps started contaminating soil, decreased soil fertility and polluted groundwater. Monitoring and compilation of water level and water quality over the past few decades has shown concentrations of cadmium, lead, cyanide and chromium, exceeding the permissible limits in the shallow aquifers of ground water in south west Punjab. Number of dark blocks started increasing in the Bist-Doab and adjoining region (e.g. groundwater at Ludhiana is 33.5 m bgl), the blocks with waterlogging, salinity and water contamination zones started increasing in the south and southwest parts of Punjab (e.g. groundwater at Muktasar is 1.12 m). In south-western zone flooding was obvious due to flood irrigation practice and presence of sandy-clay and sandy-silt type of soils which are not allowing water to penetrate into deep under the earth surface. Technological advancements indirectly promoted the consequences by replacing ordinary pumps with high power centrifugal pumps, high speed of well construction, developing hybrid and salt tolerant crops.

In the water declining zone, the only comfortable areas, where the water level did not lower much, happened to be in the vicinity of rivers or canals. However, in the waterlogging zone water table are rising due to the negligible draft of groundwater. Presently, total area under water logging conditions is 200,000 hectare on one hand and total area under salinity is 1,000,000 hectare on the other.

In recent days, new range of technologies have come up and these provide immense information on the changing groundwater resources and the factors influencing it. Some such technique includes remote sensing and GIS, satellite based system (e.g. GRACE) to estimate change in groundwater reserve at regional scale, isotope techniques, noble gas analysis, geophysical imaging and airborne survey systems, automated groundwater level (with other parameters like temperature, conductivity etc.) recorders with real time data acquisition system (RTDAS) etc. These systems find vide scope in groundwater monitoring and management. Remote sensing images in the Bist-Doab clearly indicated human influence on water and environment through change in landuse and land cover. GRACE data has reconfirmed the drying groundwater resource in Punjab during 2003-12. Isotopic data has provided vital information on groundwater dynamics, induced flow of groundwater from shallow to deeper aquifers and surface water groundwater interaction zones in the Bist-Doab region. Automated water level recorders installed at 6 sites in Bist-Doab clearly indicated groundwater level fluctuation from hourly scale to seasonal scale occurring from combined effect of monsoon recharge, irrigation withdrawal and daily water withdrawals. Thus, these techniques can be effectively utilised in understanding the hydrological processes from micro to regional scale and management methods for augmentation of groundwater reserve.

To protect and conserve groundwater resources, the state government has also initiated several programmes in recent years. To prevent waterlogging and groundwater salinity issues the state has developed programmes on canal linings, improving the surface drainage system, construction of tertiary canals and water courses. To protect the falling groundwater resource, the state has signed MoU with Israeli institutions to prepare master plan for projections of the water resources, alternate water supply schemes and economic analysis of water use. The government has also taken up comprehensive action plan to check pollution levels in the Beas and Sutlej rivers as well as to restore the water quality of state rivers. *To control the soil and water contamination issues the state has implemented* State Solid Waste Management Policy *from 2018.* The state has also notified action plan for reuse of treated waste water for various urban activities (Notification No.5/29/2017-1lg4/2717) and already implemented Punjab Preservation of Subsoil Water Act, 2009, that encourages paddy planting in consonance with onset of monsoon to avoid extraction of ground water if planted earlier.

The state has installed automated water level recorders in the state installed piezometers for continuous monitoring of water level in shallow and deep aquifers. Under the ongoing National Hydrology Project, the state is going to install 5 automated weather stations with real time data acquisition system. Punjab has five major perennial rivers of which Sutlej and Beas passes from area adjoining to the severely depleted groundwater zone. The state needs to develop *interlinking of these rivers and canal system in the depleted groundwater zone to reduce pressure on the groundwater resource.*

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