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Paleochannels and their potential for artificial groundwater recharge in the western Ganga plains

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SUMMARY

Over the last few decades, a steep general decline in the groundwater table is being observed in the western Ganga Plains (India), the average rate being about 0.15 m/year. The area comprises of dominantly vast stretches of alluvial plains within which there occur three major paleochannels of the Ganga river, characterized by serpentine-meandering pattern and having an average width of almost 4–6 km and strike length of about 60–80 km. From the point of view of artificial recharge of groundwater, the paleochannels hold a distinct promise. The paleochannel-aquifer geometry has been delineated by integrating satellite sensor and well-litholog data. The first aquifer ($\approx$25–30 m thick) in the alluvial plains is unconfined and consists of fine to medium sand whereas the second aquifer is confined. The paleochannel-aquifer is unconfined and is mainly composed of coarse sandy material along with boulder and pebbles beds and extends to a depth of about 65 m. The aquifer is well inter-connected with the adjacent alluvial aquifers. Analyses of soil samples from boreholes systematically sited on the paleochannel and its either flanks indicate that the value of hydraulic conductivity ranges from 30 to 75.3 m/day for samples falling in the paleochannel, and that between 13.5 and 22.3 m/day for the alluvial plain aquifers. The natural groundwater recharge rate due to precipitation, estimated using tritium tagging technique, is found to be 18.9–28.7% in the paleochannel area, and 6.3–8.9% in the alluvial plains. Data from stable isotopes of groundwater samples from the first unconfined aquifer indicates that the alluvial plains aquifer gets recharged by both rainfall and/or canal water, whereas rainfall is the dominant source for groundwater recharge in the paleochannel-aquifer. Monitoring of groundwater levels for 2 years (2006 and 2007), both during pre- and post-monsoon periods has been systematically carried out and it has been observed that groundwater flows away from the paleochannel in both pre- and post-monsoon periods, indicating that recharging of aquifers in alluvial plains is also through paleochannels. Thus, it may be inferred that such paleochannels can play a very important role in artificial recharge of groundwater.

1. Introduction

Groundwater is a precious natural resource of limited extent and volume. With the increasing use of groundwater for agricultural, municipal and industrial needs, the annual extraction of groundwater happens to be generally far in excess of its net average natural recharge. Additionally, interventions in hydrological regime and climate change have impact on natural recharge. Consequences of overexploitation of groundwater include alarming fall of water table all over the world, which has resulted in lower agricultural productivity, sea water intrusion in coastal aquifer, land subsidence, droughts, etc. (Clarke, 1991; Falkenmark and Lundqvist, 1997; de Villiers, 2000; Tsakiris, 2004).

Scientists, technocrats and planners have unanimously agreed and understood that replenishing the groundwater artificially is possibly the most important practical measure to arrest such aggressively falling groundwater tables. Therefore, artificial recharge or managed recharge of aquifer is becoming an important aspect of studies all over the world (Barksdae and Debuchanne, 1946; Beeby-Thompson, 1950; Todd, 1959; Wright and du Toit, 1996; Romani, 1998; CGWB, 2000; Bouwer, 2002; Asano and Cotruvo, 2004; Ong'or and Long-Cang, 2009).

Replenishment of groundwater by artificial recharge of aquifers in the arid and semi-arid regions of India is essential, as the intensity of normal rainfall is grossly inadequate to produce any moisture surplus under normal infiltration conditions. Although artificial groundwater recharge methods have been extensively used in the developed nations for several decades, their use in developing nations, like India, has occurred only recently. Techniques such as canal barriers, construction of percolation tanks

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and trenches along slopes and around hills have been used for some time, but have typically lacked a scientific basis (e.g., knowledge of the geological, hydrological and morphological features of the areas) for selecting the sites on which the recharge structures are located (Bhattacharya, 2010).

The Indo-Gangetic Plains, where this study has been carried out, is a land of fertile soil, moderate climate and generally abundant water. These factors have combined to make this a region of plenty for human settlement for centuries. Groundwater is a major source of water available for consumption in this area. However, over the years due to swelling population, increasing industrialization and intensive agriculture, the demand of water has increased manifold. Simultaneously, the available per-capita water resource has been reduced due to generally declining groundwater table (Joshi and Tyagi, 1994; Rodell et al., 2009). Hence, there is a urgent need to plan management strategies and take up augmentation measures for groundwater in this region.

1.1. Study area and scope

The study area is a part of Indo-Gangetic Plains falling between longitudes 77°30′E to 78°10′E and latitudes 29°10′N to 29°50′N and lies in the districts of Saharanpur and Muzaffarnagar of Uttar Pradesh (Fig. 1). Geologically, the Pleistocene to Recent alluvial deposits cover the area. Morphologically, four major landforms – piedmont, plains associated with river, interfluves and paleochannels have been recognized in the area (Kumar et al., 1996).

The study area has a moderate to sub-tropical monsoon climate. The rainy season (monsoon) extends from 15th June to 15th September. The average annual rainfall of the area is 1000 mm, of which about 85% is received during the monsoon season. From October to end of June next, generally dry conditions prevail except for a few showers received during the winter.

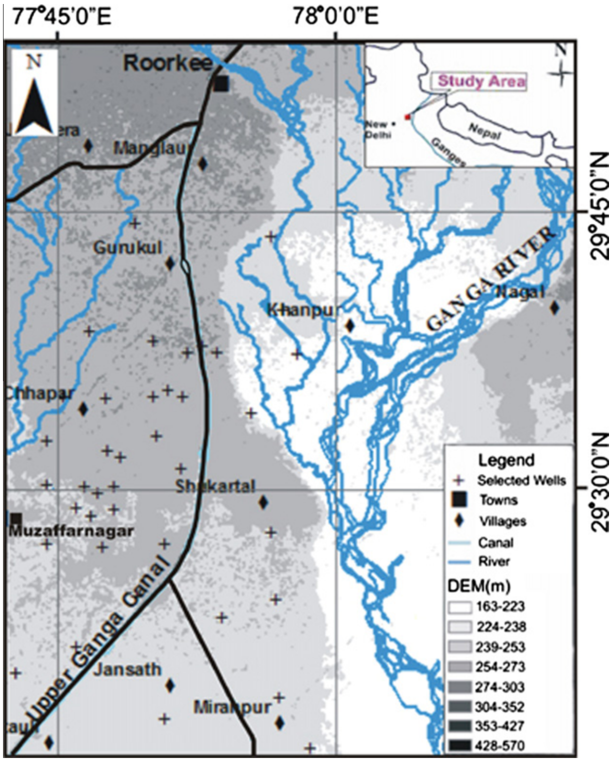

Fig. 1. Location map of the study area over the digital elevation model; note the terrain is nearly flat regionally sloping from north to south; selected well locations are also marked.

The Indo-Gangetic Plains are almost devoid of any significant relief features and are composed of unconsolidated alluvial deposits. The area slopes down gently from north to south, at an average gradient of less than 0.38 m per km. The physiography of the area is marked by the landforms that are characteristics of a river flood plain; viz. river channel, ox-bow lakes, and point bars. The drainage is a part of well integrated drainage system of the Ganga river, with almost all the streams flowing south-eastwards, concomitant with the regional slope. The Ganga is one of the important Himalayan river which carries sufficient water all round the year, though with seasonal fluctuations. Besides, the Upper Ganga Canal, which is more than 150 years old, forms an important irrigation system in the area.

Hydrogeologically, the Indo-Gangetic Plains comprise of extensive, multiple alluvial aquifer systems. The total thickness of the alluvium is not definitely known but may extend up-to about 7 km. Within the Indo-Gangetic Plains, the strata are found to exhibit variations, both vertically and horizontally, and this heterogeneity leads to variation of groundwater availability in the area (Taylor, 1959; Singhal and Gupta, 1966; Mithal et al., 1973). However, on a regional scale, the aquifers are inter-connected and hydraulically continuous almost throughout the Plains, the depth of water table varying from 3 to 18 m below ground level in the top unconfined aquifer.

The western Gangetic Plains form a region of high agricultural productivity with the prevalent two- to three-crop per annum system, accompanied by intensive use of groundwater for irrigation. The region forms the granary of India – a population of 1/5th of the world.

Due to large scale development of groundwater for agricultural, industrial and municipal use, the overall decline in groundwater levels has been observed in many parts of western Gangetic Plains (Fig. 2). Some wells have even dried up during the last few years. Thus, to sustain the livelihood, and local agricultural activity, artificial recharge of groundwater is urgently needed in the area.

In the present work, a systematic study has been taken up for developing a strategy for artificial recharge of groundwater. The main objectives of the research work include: (a) mapping of spatial distribution of porous and permeable stretches (which happen to be parts of paleochannels of the Ganga river) using remote sensing data and (b) evaluation of hydrogeological characteristics of paleochannel-aquifers and also the adjacent alluvial plains, from the point of view of artificial recharge.

2. Data sources and methodology overview

The data used in this study can be broadly categorized into three main groups – (a) remote sensing data, (b) ancillary data, and (c) field data.

Remote sensing data from Indian Remote Sensing (IRS) satellite mission (www.nrsa.gov.in) has been used in the present study. The data from IRS satellites is available in various resolution bands, i.e., LISS-II (36 m); LISS-III (23 m) and LISS-IV (5.8 m) but in identical spectral bands, viz., green (0.52–0.59 μm), red (0.62–0.69 μm), and near-infra-red (0.0.76–0.89 μm) bands. As the objective of the present study is to delineate paleochannels, which constitute regional/major geomorphological features, LISS-II, medium spatial resolution data (edge-enhanced with Laplacian isotropic filter) has been used. Specifications of the sensor are given in Table 1. The IRS LISS-II data have been widely used in recent times for a variety of applications – in geosciences, landuse/landcover mapping, hydrogeological mapping, urban planning, biodiversity characterization, disaster management, etc. (e.g., Navalgund, 2001; Gupta, 2003). In this study, the remote sensing LISS-II sensor data have been used

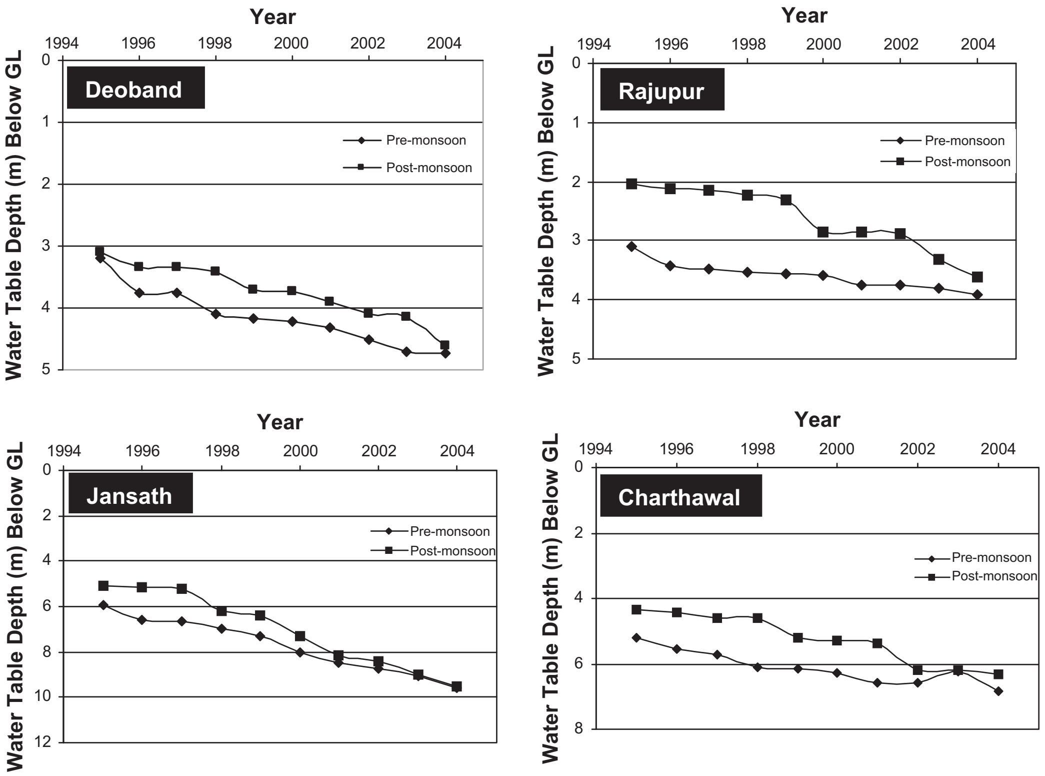

Fig. 2. Typical drop in groundwater levels in the wells during 1995–2004 (data courtesy of Groundwater Division, Muzzaffarnagar, Uttar Pradesh.

Table 1
Salient characteristics of the satellite sensor data used.

Satellite/sensor	IRS-1B, LISS-II
Date of acquisition	2 November, 1998
Spatial resolution	36.25 m
Swath width	74 km
Quantization	8-bit
No. of bands	4
Spectral resolution	Band1 (Blue): 0.46–0.52 μm Band2 (Green): 0.52–0.59 μm Band3 (Red): 0.62–0.68 μm Band4 (NIR): 0.77–0.86 μm

for extracting information on geomorphology, vegetation cover, and lineaments and for paleochannel mapping.

Toposheets of Survey of India have been used for generation of base map showing contours, point elevations, drainage network and roads, etc. Soil map obtained from the National Bureau of Soil Survey and Land Use Planning (1999) has been used for extracting information on soil characteristics of the study area. Hydrogeological data such as specific yield and storage coefficient of aquifer have also been collected from various existing reports and literature (Table 2). Besides, extensive dedicated field work was carried out during July 2005–July 2007 for collecting various field data. Mention must be made of dedicated drilling operations carried out at selected 17 locations (2 up-to 60 m and 15 up-to 20 m deep) to collect sub-surface lithologic data. As palaeochannels of the Ganga river have been considered as the most important sites for artificial recharge for the present research, these paleochannels have been mapped from remote sensing data and sites for drilling have been selected systematically within the paleochannels and on either side on the adjacent alluvial plains. Besides, existing well-log data from 70 vertical boreholes in the study area have been collected, tabulated, and analyzed.

The broad methodology adopted in the present study has been outlined in Fig. 3. The entire study has been carried out in the GIS environment. A base map has been prepared by scanning, georeferencing, mosaicking and digitizing the Survey of India (SOI) topographic maps at 1:50,000 scale. The various data layers including remote sensing image data have been co-registered with the base map. Point data obtained from field and laboratory experiment are properly overlaid on the base map using GIS tools. As the optical remote sensing data invariably contains the atmospheric haze components due to atmospheric interaction, the 'dark-object subtraction' technique (Chavez, 1988; Gupta, 2003) has been adopted for its correction. The remote sensing data has been processed using ERDAS Imagine-8.7 software for geometric and radiometric corrections and supervised classification. The GIS analysis has been carried out using ILWIS-3.3 and ARCVIEW-3.2 software. Litholog data analysis and correlation has been carried out by using ROCKWORKS-2006 software.

The various data sets including aquifer soil characteristics data, groundwater level data, stable isotope analysis data and tritium injection analysis data, etc., have been integratively used for aquifer characterization and hydrogeologic studies.

3. Mapping of major paleochannels

Owing to its synoptic view and map like format the satellite remote sensing imagery is a viable source of gathering quality regional data on landforms and landuse/landcover (LULC) (Gupta, 2003; Jensen, 1996; Lillesand and Kiefer, 1999). In this area, five LULC classes have been identified (Fig. 4) viz. agricultural plains, paleochannel, water body, built-up area, and marshy land. The landcover types are closely related to the landform units. The salient characteristics of the LULC classes are given below:

(a) Agricultural plains: The agricultural land having good vegetation cover appears in shades of red color on the color infra-red

Table 2
Overview of the field data used.

Data type	Purpose	Source
Litholog data	To construct aquifer geometry, and to estimate vertical hydraulic conductivity	Dedicated field drilling operation at selected locations Existing data collected from State Tube Well Division, Uttar Pradesh
GPS data (differential GPS)	To determine latitudes, longitudes and ground height (from mean sea level) of water level recording stations	Dedicated field work using Differential GPS survey
Groundwater level data	To estimate unsaturated aquifer thickness and ground water flow direction	Water level field observation and monitoring conducted during dedicated field work. Existing data collected from State Groundwater Division Uttar Pradesh
Rainfall data	To estimate surface runoff and recharge rate	State Groundwater Division Uttar Pradesh
Tracer data (Tritium injection)	To find out recharge rate and specific yield	Dedicated field work/experimentation
Ground water sample	To obtain information on recharge source through stable isotope analysis	Dedicated field work/experimentation
Soil samples	To obtain soil textural information	Dedicated field work/experimentation

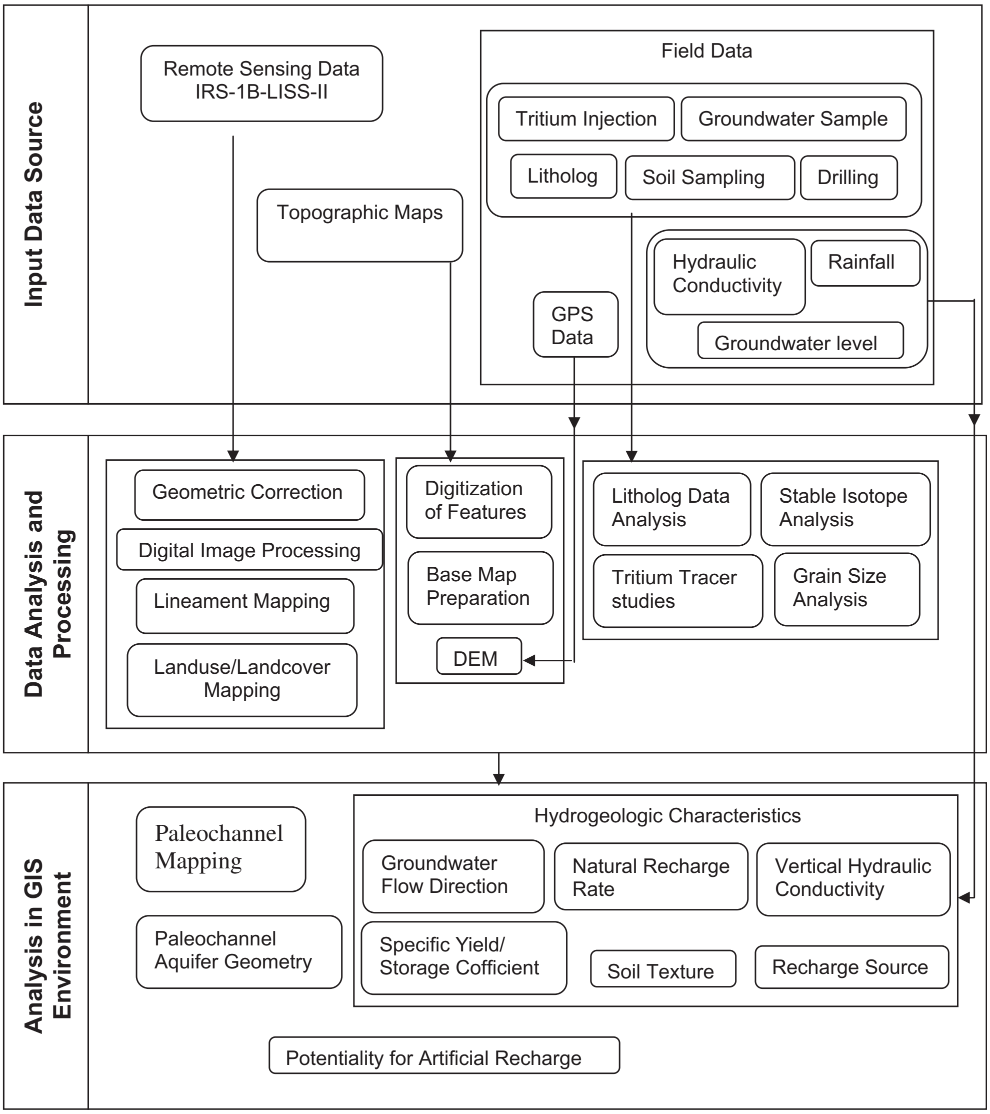

Fig. 3. Methodology overview.

(CIR) composite. This landform unit occupies most of the study area.

(b) Paleochannels: The paleochannels are marked by sinuous/serpentine shape and appear as pale-white stretches on CIR composite. On the near-infra-red (NIR) band image, they appear in very light tones, implying extremely low surface soil moisture, i.e., very high permeability. In the field, the paleochannel areas are marked by rather sparse vegetation.

(c) Water body: The water bodies (the Ganga river and its various branches and the Upper Ganga Canal) appear in shades of

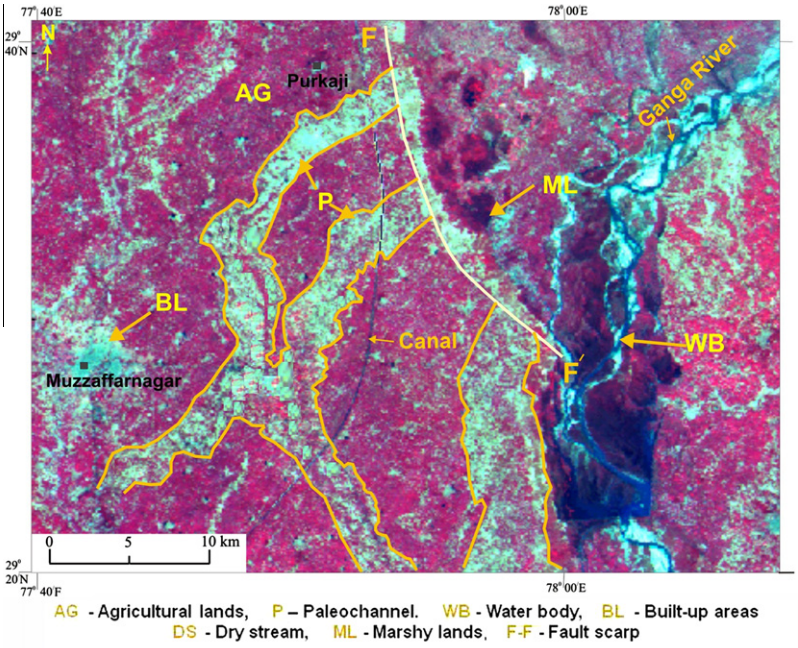

Fig. 4. Color infra-red (CIR) composite of IRS-LISS-II image data; NIR band coded in red color; Red band coded in green color and Green band coded in blue color. The various landuse/landcover classes are: AG-Agricultural plain; P-Paleochannel; BL- Built-up area; ML-Marshy land; WB-Water body. Fault scarp (F–F′) is also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

blue–cyan–deep blue[1] on CIR composite and very dark on the NIR band image.

(d) Marshy land: The numerous water ponds lying in the lowland mark the marshy land, and appear on banks of the Ganga river.

(e) Built-up area: The cities and villages can be identified by blocky texture and bluish-gray color on the CIR composite.

Integrating the information from CIR composites, LULC map, and extensive field observations, paleochannels have been traced and a paleochannel map has been generated. The existence of paleochannels has also been cross-checked from litholog data. It is observed that in the northern part, the paleochannels are cut by a fault-scarp, with the south-western block relatively upthrown by about 15–20 m.

In the study area, three major paleochannels exhibiting broadly successive shifting and meandering pattern have been deciphered (Fig. 4). All the paleochannels are quite wide (4–6 km) suggesting their formation by a large river. The paleochannels are approximately N–S trending and when extended upstream tend to meet the point where the present Ganga river debouches from the Himalayan ranges into the alluvial plains, suggesting that these paleochannels belong to the Ganga river. Further, the paleochannels are located to the west of the present day course of the river Ganga, suggesting that the Ganga river has shifted successively eastwards (Kumar et al., 1996). Litholog data indicates that the river paleochannel deposits are significantly different from the vast alluvial deposits in soil characteristics (particle size distribution, see later). The paleochannels are composed of coarse sand with pebbles, boulder, cobbles, etc. and appear genetically related to the well developed regionally extensive earlier river system. Low surface moisture and rather sparse vegetation on the paleochannels are indicative of highly permeable, porous, coarse grained materials with high infiltration rate.

4. Paleochannel-aquifer geometry

The study of aquifer geometry is important as it provides valuable information on aquifer areal extent, thickness, volume, aquifer boundaries and interconnectivity between adjacent aquifers. This information has implications in lateral groundwater movement and artificial groundwater recharge (Tait et al., 2004; Srivastava, 2005; Samadder et al., 2007).

Well-log data provide information on lithologic variation with depth, and have been long used for generating sub-surface cross-sections. However, such interpretations have a limitation that the spatial (lateral) control as seen on the surface is often not adequate. In this study, remote sensing together with litholog data have been used for interpreting aquifer geometry, as remote sensing data provides valuable information on spatial (lateral) disposition of geological features such as soil, rock types, faults, landforms, drainage, and water bodies (Hendrix and Price, 1986; Gupta, 2003; Jaiswal et al., 2003). Litholog data from about 85 wells has been used to construct the aquifer geometry in the area. Construction of sub-surface lithological cross-section, aquifer geometry, and final interpretation has been made by aggregating and synthesizing all the information – such as the base map, the CIR composite image, the paleochannel map, well location map, and the elevation data. One representative interpreted geological cross-section across the paleochannel is given in Fig. 5. It is observed that the first aquifer in the alluvial plains is an unconfined in nature and consists of fine to medium sand with a number of lenses of clay and kankar. Generally, the thickness of this aquifer varies from about 25–33 m. The upper most aquiclude (clay) starts from the base of the unconfined aquifer and extends up-to a depth of about 40 m and has a thickness of about 5–8 m. The second aquifer with a thickness of about 15–20 m is confined in nature and mainly consists of fine to medium grained sand along with

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[1] For interpretation of color in Figs. 1, 4–8, and 10, the reader is referred to the web version of this article.

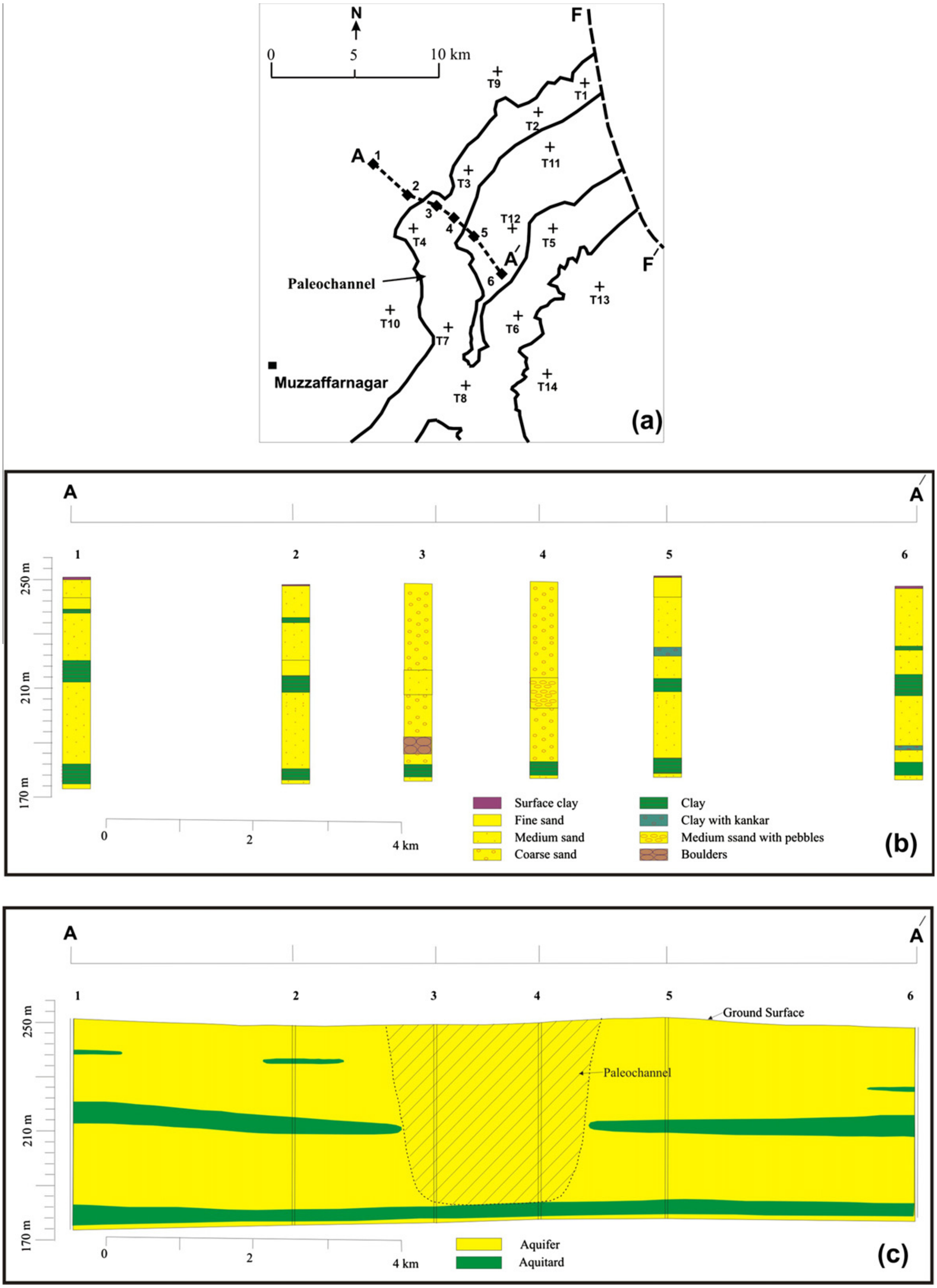

Fig. 5. (a) Location map of well-log sites (1–6) for lithologic cross-section "A–A′" shown in figure (b) and (c); locations of tritium injection sites (T1–T14) are also indicated. (b) Representative lithologic description of wells 1–6 (c) Interpreted geological cross-section along A–A′ through the above wells.

some lenses of kankar. The paleochannel-aquifer is unconfined and is mainly composed of coarse sandy material along with pebbles and boulders. During the construction of lithological cross-section and interpretation of aquifer geometry, it was observed that the aquifers also exhibit vertical displacements along normal fault at places (Samadder et al., 2007).

5. Hydrogeological characteristics

From the foregoing it is obvious that from the point of view of artificial recharge of groundwater, the paleochannels hold a distinct promise. Therefore, it is important to study the hydrogeologic characteristics of both the paleochannels and the adjacent alluvial plains – their recharge rate and hydrogeologic mutual interconnectivity, groundwater flow pattern, etc., in order to assess the suitability of these units for possible artificial groundwater recharge.

5.1. Soil texture

Twenty surface soil samples were collected from sites located on both the paleochannels and alluvial plains (Fig. 6). The soil samples have been subjected to grain size analysis to determine soil texture (Table 3). From the particle size distribution, the percentage for each of the soil fractions (sand, silt and clay) have been determined and textural class assigned as per USDA textural triangle (Brown, 1990; Bouwer, 2002).

Table 3 indicates that the areas occupied by paleochannels have higher sand fraction (58.3–78.6%) as compared to the alluvial plains (15.1–28.8%). On the other hand, the surface soil of the alluvial plains has silt as the dominant fraction (51.9–69.3%). Clay varies from 7.3% to 16.3% in paleochannels and 11.8–24.2% in alluvial plains respectively. This shows that the paleochannels comprise dominantly sandy loam type of soil, on the other hand, the alluvial plains are characterized by relatively finer silty loam type of soil (Fig. 7).

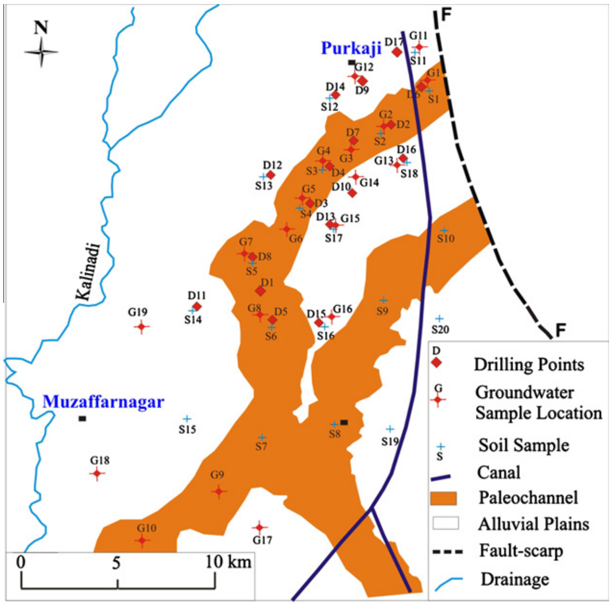

Fig. 6. Distribution of drilling sites, groundwater sample locations, and soil sample locations in relation to paleochannels and the adjacent alluvial plains.

Table 3
Percentage of sand, silt and clay content in soil samples.

Landforms	Sample no.	Sand (%)	Silt (%)	Clay (%)
Paleochannels	S1	72.5	11.2	16.3
	S2	67.0	18.3	14.7
	S3	68.2	24.4	7.4
	S4	58.3	29.1	12.6
	S5	75.1	9.8	15.1
	S6	78.5	7.0	14.5
	S7	73.6	19.1	7.3
	S8	71.1	16.3	12.6
	S9	76.0	13.8	10.2
	S10	78.6	7.8	13.6
Alluvial plains	S11	20.5	55.3	24.2
	S12	26.0	52.5	21.5
	S13	22.3	61.4	16.3
	S14	15.1	69.3	15.6
	S15	28.8	54.7	16.5
	S16	18.3	63.2	18.5
	S17	21.7	66.5	11.8
	S18	20.7	58.5	20.8
	S19	28.6	51.9	19.5
	S20	24.2	62.2	13.6

5.2. Hydraulic conductivity

Hydraulic conductivity was estimated to ascertain the relative hydraulic properties of the paleochannels and the adjacent alluvial plains. As mentioned earlier, a series of 17 observation wells were drilled within and on both flanks of the paleochannels. Total 82 soil samples were collected from different depths of these wells and the soil texture was determined to assess the relative hydraulic properties of the aquifers.

Bulk hydraulic conductivity was estimated form the grading curves using Hazen approximation (Hazen, 1911). For this purpose, D_{10} has been calculated for each sample. In paleochannel-aquifer, the D_{10} values range from 0.21 to 0.33 mm, whereas, in alluvial plains, it ranges between 0.14 and 0.18 mm. The estimated bulk hydraulic conductivity for samples at different depths is found to range from 30 to 75.3 m/day for samples falling in the paleochannel and 13.5–22.3 m/day for the soils in the alluvial plains. The conductivity values, as determined by the pump testes also range from 10 to 48 m/day in and around the area (Pandy et al., 1963). Thus, the hydraulic conductivity determined using Hazen's Equation and from pumping tests is found to be in good agreement.

5.3. Recharge source identification

Stable isotopes of hydrogen (deuterium ^{2}H or D) and oxygen (^{18}O) are widely used to identify the sources of natural recharge to groundwater (e.g., Libby, 1946; Urey, 1947; Sinha et al., 2000; Longinelli et al., 2008). In the present case, recharge to the aquifers can take place only through two sources, i.e., (i) precipitation, and (ii) seepage from canal. Thus, to ascertain the source of natural recharge in different areas, water samples collected from different sources namely, (i) precipitation (Roorkee town), (ii) canal water (Roorkee town), (iii) groundwater from paleochannels (five sites), and (iv) groundwater from the adjacent alluvial plains (six sites) (Fig. 6), were subjected to isotopic analysis. Relative abundance of stable isotopes (δD and δ^{18}O) in water samples was analyzed using Dual Inlet Mass Spectrometer at National Institute of Hydrology, Roorkee, India. Plot of δ^{18}O and δD of different type of waters is shown in Fig. 8.

The δ^{18}O values of precipitation and canal water vary from -2.3 to -6.7 ‰ (wt. Av. -5.5‰), and -8.1 to -11.2‰ (Av. -9.7‰) respectively. Groundwater in paleochannels has δ^{18}O values in the range of -5.3 and -6.9‰, and that in the alluvial plains in the range -7.6 to -9.9‰. As δ^{18}O values in the paleochannel groundwater are close to that of precipitation, it can be inferred that the recharge in the paleochannels is mostly from direct precipitation. On the other hand, as δ^{18}O values in the groundwater of alluvial plains are intermediate between precipitation and canal, it indicates that the recharge in the alluvial plains is from both canal water as also precipitation. Further, as indicated earlier, the paleochannel-aquifers are hydraulically well connected with the adjacent alluvial plains; therefore there should be flow of groundwater between alluvial plains and paleochannels. The δ^{18}O data suggests that there is no flow of water from the alluvial plains to the paleochannels, as the δ^{18}O values indicate that the paleochannels are being recharged only from precipitation. Had there been any flow of water from the alluvial plains to the paleochannels, the δ^{18}O in paleochannels would have been intermediate between rainwater and canal water. Thus, the only possibility is the

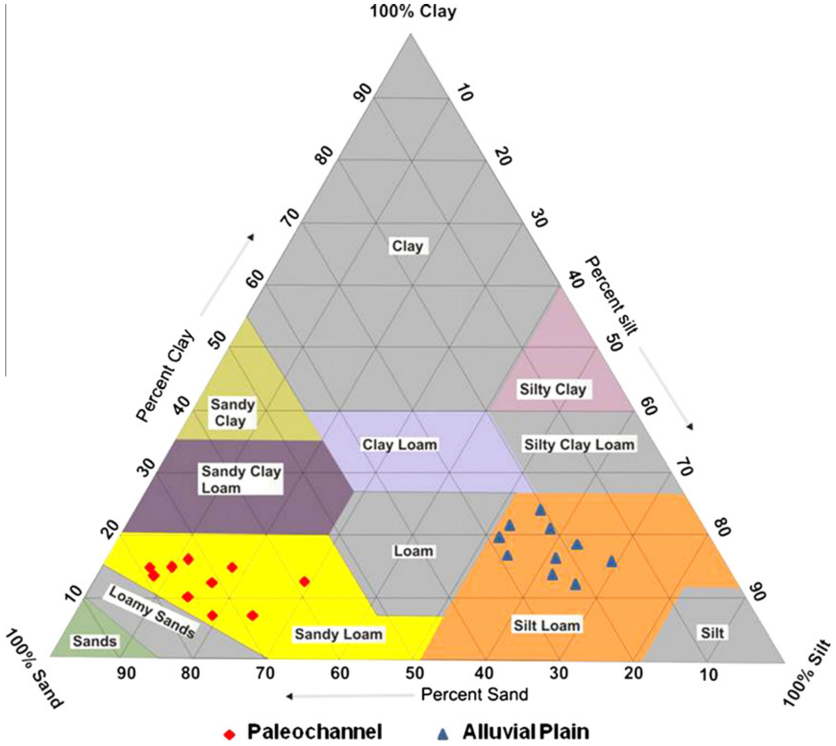

Fig. 7. Classification of soil texture as per USDA soil texture triangular diagram.

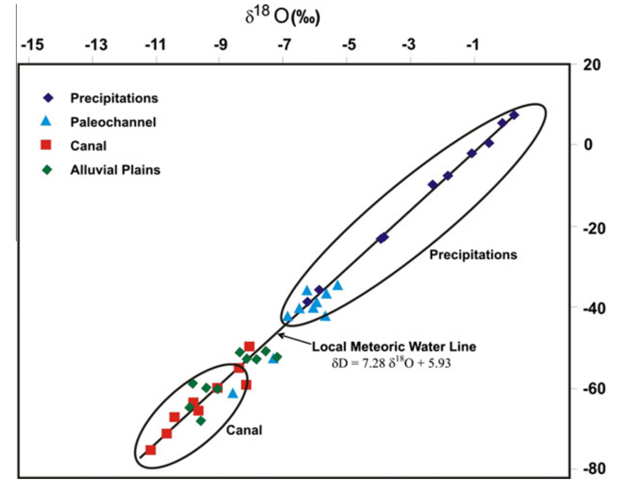

Fig. 8. δ^{18}O–δD plot of the recharging sources (precipitation and canal) and groundwater.

recharge of groundwater of alluvial plains with the water from paleochannels. This is further corroborated by groundwater level contour maps as discussed later (see Section 5.5).

5.4. Estimation of rate of natural groundwater recharge

Estimation of natural rate of groundwater recharge is very important for artificial groundwater recharge study because the surface infiltration systems designed to provide artificial recharge to groundwater require permeable soils (sandy loam, sands, gravel) that must have relatively high recharge rate so that the water can be transmitted adequately. A proper understanding of soil moisture movement in the unsaturated zone is of importance in understanding and estimating the groundwater recharge.

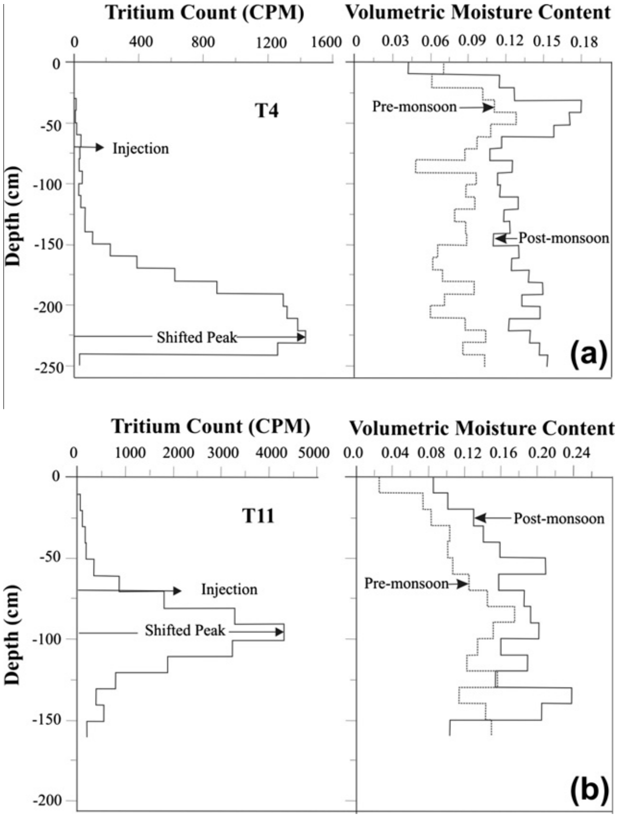

Fig. 9. Typical movement of tritium peak and soil moisture for (a) paleochannel areas, and (b) alluvial plains. Tritium injection sites are shown in Fig. 6a.

In general, the major source of recharge to groundwater in the study area is precipitation, more than 85% of which occurs during monsoon period (June–September) only. Conventional methods for estimating groundwater recharge require large volume of hydrometeorological and hydrogeological data accumulated over a considerable time span, which is normally inadequately available, lacking or even unreliable in many cases (de Vries and Simmers, 2002; Scanlon et al., 2002; Mondal and Singh, 2004; Chand et al., 2005). In view of the above needs and constraints, there has been an increasing emphasis on the use of isotopic/tracer techniques for soil moisture movement analysis and estimating groundwater recharge in the unsaturated zone. The technique of estimation of recharge rate by using artificial tritium method was first applied by Zimmerman et al. (1967a,b) in West Germany. The basic principle of this technique assumes that the soil water in the unsaturated zone moves downward "layer by layer" similar to a piston flow. Since the lateral molecular diffusion mixes the percolating water rather fast, this assumption is probably valid in most natural situations in the alluvial formations (NIH, 2000).

Table 4
Percentage recharge to groundwater at various experimental sites due to monsoonal rain.[a]

Location	Tritium peak shift (d) in cm	Average effective volumetric moisture content (Q_v) in peak shift region	Recharge to groundwater (%)
(a) Paleochannel			
T1	165.0	0.077	18.9
T 2	175.0	0.079	20.4
T3	155.0	0. 099	23.0
T4	153.0	0.122	28.7
T5	95.3	0.189	26.8
T6	75.4	0.143	16.0
T7	75.2	0.151	17.0
T8	57.0	0.201	17.0
(b) Alluvial plains			
T9	32.0	0.176	8.4
T10	30.8	0.184	8.4
T11	24.0	0.176	6.3
T12	30.8	0.196	8.9
T13	31.9	0.198	9.4
T14	39.9	0.187	11.0

[a] Annual recorded precipitation in the area (year 2006) = 790 mm. Recorded precipitation between injection time to sampling time = 673 mm.

The advantage of using tritium (^{3}H) is that the tritiated water molecule, HTO, does not behave differently from the other water molecules in the ground water cycle. The health hazard in handling tritium is also negligible because of its emission of soft beta particles having maximum energies of only 18 keV. Several workers (Zimmerman et al., 1967a,b; Munnich, 1968a,b; Datta et al., 1973; Sharma and Gupta, 1987; Sukhija et al., 1996; Athavale and Rangarajan, 2000; Israil et al., 2004) have applied the tritium tagging methods for soil moisture movement analysis in unsaturated zones of different geological and climatological conditions. In the present study, recharge rate has been estimated for both the landforms (viz. paleochannels and adjacent alluvial plains) by using tritium tagging technique. Athavale and Rangarajan (2000) has summarized the mean natural recharge values for 35 study areas in India, well distributed over 17 major river basins. The recharge rates ranged up-to 19.7% of the local average seasonal rainfall.

Field experiments have been performed at fourteen sites — eight within paleochannel and six on the adjacent alluvial plains, for natural recharge estimation (Fig. 5a). Tritium was injected at 70 cm depth (so that it is below the normal root zone) immediately before the monsoon period (June 2006). The soil samples were collected just before injection (in June, 2006) and after the monsoon (in October, 2006) at each 10 cm depth interval from soil column up-to a vertical depth of 250 cm (i.e., 25 samples per bore hole). The soil samples were analyzed for soil moisture content and tritium counts in the soil water. Tritium activity in the water extracted from soil samples was measured using liquid scintillation counter (LSC) (Model 'System 1409', Wallac Oy, Finland).

Due to the downward percolation of infiltrated water, the soil moisture in the subsequent layers is pushed down, shifting the tritium peak downwards. Therefore to measure the shift in the peak of tritium from the point of injection, the net tritium count rates for various sites were plotted as a histogram against the individual depth intervals. Fig. 9 shows the position of the original and shifted peaks of the injected tritium. The shift of the peak from original depth of injection (70 cm) was calculated. It has been observed that the shift in the peak is more in the paleochannel than in the adjacent alluvial plains indicating higher recharge in the

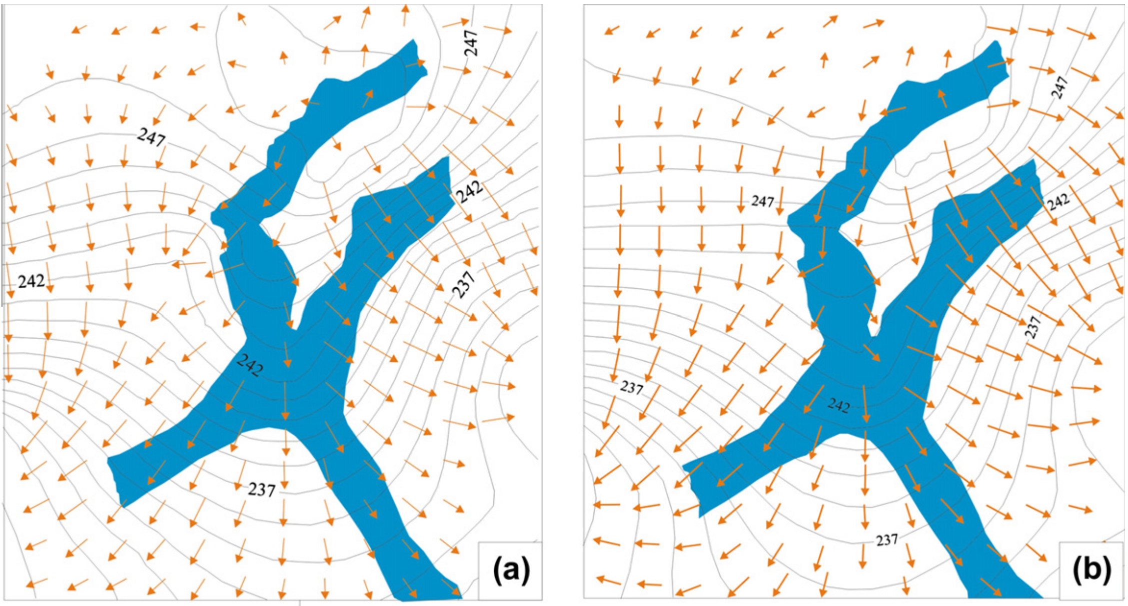

Fig. 10. Reduced groundwater level contours and flow direction maps for (a) pre-monsoon period, and (b) post-monsoon period (for the year 2006). Note the typical convex downwards contour pattern in the paleochannel-aquifer for both pre- and post-monsoon data sets.

paleochannels. Percent recharge to the groundwater during the monsoon (pre-monsoon to post-monsoon 2006) has been calculated using the following standard equation (Zimmerman et al., 1967a,b):

$$R = Q_v d(100/P)$$

where R is the percentage of recharge to ground water; Q_v is the effective average volumetric moisture content in tritium peak shift region, d is the shift of tritium peak in cm; and P is the precipitation and irrigation inputs in cm at the injection site. These two components are taken for the interval between injection and sampling. However, all the stations considered in this study are on non-irrigated patches.

The computed recharge rates at various experimental sites, as determined from field cum laboratory data of tritium peak shift, average volumetric moisture content in peak shift region and precipitation (in the time interval of injection and sampling) are given in Table 4. The results indicate a higher rate of recharge in the paleochannels (17.0–28.7%) as compared to alluvial plains (6.3–11.0%).

The groundwater recharge from the paleochannels to alluvial plains has not been attempted in the present study, as sufficient data is not available.

5.5. Groundwater flow

Groundwater table map has been generated to establish the groundwater flow direction with in the area. For this purpose, the depth to groundwater levels have been monitored in 37 observation wells (12 in the paleochannel-aquifers and 25 in the adjacent alluvium plains) over a period of 2 years (2006 and 2007) for both pre- and post-monsoon period. From this data, groundwater elevation with respect to mean sea level was computed by subtracting the depth to water level from reduced level of the measuring point. The computed groundwater elevation data was used to generate groundwater table contour maps and flow vector maps (Fig. 10). The figure indicates that groundwater flows away from the paleochannel for both pre- and post-monsoon period. The typical contour pattern (convex downwards) in the paleochannel-aquifer is interpreted to be due to high porosity and permeability and its higher vertical hydraulic conductivity. This further suggests that recharging of groundwater through paleochannels could lead to gradually recharging of the adjacent alluvial plains.

6. Concluding remarks

Based on the work carried out, the following broad summarization can be made:

1. In the western Ganga Plains, wide (4–6 km) and extensive (60–80 km long) stretches of paleochannels exist, which are sinuous/serpentine shaped and are characterized by low surface moisture and extremely sparse to poor vegetation.
2. Integrating borehole data and remote sensing images, subsurface aquifer geometry of the paleochannels and alluvial plains has been deciphered. The aquifers are interpreted to possess spatial variation in geometry and exhibit occasional vertical displacements along normal faults.
3. The paleochannels comprise of dominantly coarse sand with occasional pebbles, and extend up-to a depth of 50–60 m below the surface, which is responsible for very high hydraulic conductivity (30–75.3 m/day).
4. The tritium tagging data indicates that the recharge rate is much higher (up-to 28.7%) in the areas of paleochannels than in the areas of general alluvial plains (up-to 11.0%).
5. The groundwater contour map exhibits typical convex downwards pattern in the paleochannel-aquifer areas for both pre- and post-monsoon data sets; this indicates higher hydraulic conductivity and porosity in the paleochannel region. This further shows that if groundwater is recharged through paleochannels, it will slowly recharge the alluvial plains too.

Delineation of major paleochannels (4–6 km wide and 60–80 km long) generally N–S trending and extending up-to depth of >60 m below ground level, having very different hydrogeological characteristics, acting as almost conduits of very high hydraulic conductivity – can be considered as important findings of this study.

Thus, an integrated approach developed using remote sensing data, borehole data, field data, isotopic data and water level data, can be used to identify major paleochannels, their hydraulic connectivity with adjacent alluvial plains, rate and source of natural recharge and groundwater flow direction. Apart from the Ganga and Indus Plains in India, this methodology can be applied for identification of similar suitable recharge areas in the alluvial tracts of the world, such as, Hwang Ho Plains in Northern China, Po–Lombardy Plains of Italy, and Nile Plains of Egypt.

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