Identification of watershed preference management areas under water quality and scarcity constraints: case of Jhajjar district watershed, India

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Abstract

Groundwater quality, scarcity and over-exploitation of available resources have produced several critical problems in Jhajjar district, Haryana, India. Health problems associated with drinking of polluted groundwater and its escalating demands make management of groundwater more complicated and require more innovative scientific analyses for good strategies of water management. In this study, a comprehensive water management plan has been developed for seven sub-watersheds of Jhajjar district using the remote sensing and geographical information system techniques. This research work addresses a central concern: how an integrated watershed management system can be applied, which can solve both water quality and scarcity problem in semi-arid climatic conditions. About 30 parameters including linear, areal and relief aspects of watersheds were determined for these watersheds. The focus was given on the characteristics of drainage basins such as permeability, soil quality, slope, run-off time and time of concentration for watershed during a rainfall event. Analysis results show that most of the basins are of an elongated shape with low drainage density and texture, which makes recharge plan difficult. Based on the outcome of the morphometric analysis of sub-watersheds, various suitable recharge sites have been proposed along with recharge structures for various stream orders. This study will address the immediate need to incorporate groundwater quality and will also help in replenishing the groundwater resources if implemented.

keywords Groundwater quality · Scarcity · Watershed · GIS · Morphometric analysis · Recharge structures

Introduction

Water security is a challenge to the developing world today. The present-day agricultural practices, industrialization, urbanization and rising water demands are putting increasing pressure on the quality of both surface and groundwater resources. Further, climatic conditions–rainfall and temperature and their altered patterns are impacting the water cycle and natural recharge processes (Mall et al. 2007; Kumar et al. 2014; Karkra et al. 2017). The cumulative impact of these factors has resulted in the depletion of the groundwater table in aquifers around the world. The most concern countries in this regard are north-west India, north-east Pakistan, central USA, north-east China, Iran with an estimated groundwater depletion of 283 ($\pm$40) km3a$-$1 in 2000, which was earlier 126 ($\pm$32) km3a$-$1 in 1960 (Wada et al. 2010). In addition to scarcity, the quality of groundwater is also failing on drinking standards due to geogenic and anthropogenic contamination, causing many types of health problems to human beings. Understanding the emerging issue, the United Nations has considered Access to Water (Goal 6) as one of the main goals of the 2030 Agenda for Sustainable Development. Goal 6 targets to achieve water security and access to improved water quality by reducing the pollution, minimizing the release of hazardous chemicals, increasing the recycling and reuse and implementing integrated water resource management plans. Many such initiatives are under implementation by organizations like

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Global Environment Facility (GEF), Food and Agriculture Organization, UNESCO's International Hydrological Programme (UNESCO-IHP), the International Association of Hydrologists (IAH), the World Bank, United States Agency for International Development (USAID), etc., in this direction. The organizations are working towards economic, policy, institutional, environmental and technical aspects of groundwater management, and are addressing the issue by providing education, capacity building, and enhanced water resources management and governance (Varady et al. 2012; USAID 2017; Kumar et al. 2017).

In India, the approach of watershed management is considered a principal strategy for comprehensive development of water resources primarily in the arid and semi-arid areas of the country. Existing policies of the government of India give more emphasis on strengthening such projects (Wani et al. 2008). In India, the first-generation programme of watershed development and management (1969–1974) was for the soil conservation and its management, while in the second-generation (1974–1979) watershed development and management programme emphasis was given on water conservation, further in the 3rd generation (mid-1990s) programme emphasis has been given on participatory approach for management and development of watershed activities (Joshi et al., 2004). There were several programmes in India at state and national levels, related to watershed like Desert Development Programme (DDP), Integrated Mission for Sustainable Development (IMSD) and Drought Prone Area Programme (DPAP); however, in 2008 several individual programmes were merged into a single programme, which is known as "Integrated Watershed Management Program (Alemayehu et al. 2009; Imam 2011).

Watershed management is an integrated approach, wherein land and water management practices are followed to reduce the surface run-off of water in the basin. This helps to increase the infiltration, reduce the soil erosion and replenish the groundwater aquifer. To prepare a watershed development plan, morphometric analysis of the drainage basin plays an integral part of development process, thereby studying the measurement and mathematical analysis of the Earth's surface, shape and dimension of its landforms (Rekha et al. 2011).

Today, GIS is an efficient tool for displaying and interpreting spatial data of the real world into desired information. The high-resolution digital elevation model (DEM) coupled with GIS is widely used by researchers to perform hydrological investigation, extraction of drainage patterns, delineation of watersheds, morphometric analysis of watersheds followed by evaluation in terms of soil conservation measures, water-holding capacity, identification of potential sites for recharge structure, etc. (Rekha et al. 2011; Romshoo et al. 2012; Kumar 2013; Rama 2014; Pande and Moharir 2017, Sekar and Sellamuthu 2018; Rais and Javed

2014; Chowdhury et al. 2018). The methodology is popular because it is a rapid, precise and cost-effective method. However, the interpretation of results depends upon the quality and resolution of satellite images that can affect the accuracy of size, length and slope of the topographic features and impact results. Further, it is pertinent to perform the ground surveillance in the application-based studies before investing into an implementation plan.

The present study was undertaken in Jhajjar district, Haryana, which is a part of the north-western region of India. As mentioned above, the groundwater table is at an alarming level in the Jhajjar district, similar to some other parts of the region. The district is divided into five blocks, of which Jhajjar and Salhawas fall under the over-exploited category, Bahadurgarh in critical, and Beri and Matanhail blocks under the semi-critical stage of groundwater development (CGWB 2013). A large population of the district depends upon groundwater for drinking needs. However, the quality of groundwater is not satisfactory with less than 30% drinking water availability and high concentration of quality parameters. The reported values for some parameters were fluoride—0.37–6.86 mg/L, chloride—20–2345 mg/L, nitrate—0.2–876 mg/L, sulphate—14–728 mg/L and hardness—159–2610 mg/L (CGWB 2016). In concern to the limited availability of drinking water, a detailed study is required for groundwater resources in the district. Although previous studies on groundwater resources of north-western states include the works of Kumar et al. (2016), CGWB (2015), Kushwaha et al. (2016), Brar (2014), etc., on groundwater vulnerability mapping using DRASTIC model, aquifer mapping for the National Capital Region, Haryana (Panipat–Sonipat–Rohtak Tract, Jhajjar–Rewari–Gurgaon Tract and Faridabad–Palwal Mewat Tract) using groundwater simulation model, morphometric studies in Takarala–Ballowal and Siswan Nadi watersheds of Punjab, respectively, studies are primarily not focused to Jhajjar district. The present study that focused on Jhajjar district has adopted a distinct approach where the geospatial and mathematical assessments of watersheds develop a comprehensive watershed management plan for the Jhajjar district. The study will be beneficial for developing groundwater management plans for the district.

Study area

The Jhajjar district lies between 28 °22′ and 28 °50′ North latitudes and between 76 °17′ and 76 °58′ East longitudes. There is no perennial river that flows through the district. Sahibi is the only ephemeral river flowing during the monsoon period. Due to the lack of natural drainage, the rainwater accumulated in the low areas is drained into Drain No. 8,

an artificial drain constructed to carry the excess water from Jhajjar and adjacent areas of Haryana region.

Methodology

The morphometric analysis is performed with the help of Digital Elevation Model (DEM) and survey of India toposheets nos. H43W6, H43W7, H43W9, H43W10, H43W11, H43W13, H43W14 and H43W15 on 1:50,000 scale. The DEM used is of Indian Remote Sensing Satellite Cartosat-1 (1 arc sec (~ 30 m) available on Bhuvan portal of NRSC/ISRO. The DEM image of Jhajjar district used in this study is depicted in Fig. 1.

The DEM of Jhajjar district was processed in Arc GIS 10.1 to compute flow direction and flow accumulation raster. Using the flow accumulation map, 7 sub-watersheds (SW) were delineated. SWs were further processed using Spatial Analyst Tool of ArcGIS to demarcate the drainage pattern. Based on the drainage pattern, the morphometric analysis of delineated basins was carried out. The parameters such as area, perimeter, length of the basin, stream order and stream length were computed by GIS software. The other morphological parameters were derived using the mathematical formulae suggested by Horton (1945), Strahler (1957, 1964), Schumm (1956), Miller (1953), and Melton

(1965). The list of morphometric parameters and formulae is given in Table 1. The prioritization of sub-watershed (SW) was done using the weighted rank method. Weightage to the selected parameters was provided based on their role in augmenting the groundwater table in the watershed. Finally, SWs were reclassified into high-, medium- and low-priority watersheds. Subsequently, suitable recharge structures on different stream orders were proposed for groundwater management in Jhajjar district. The methodology used in the study is shown in Fig. 2.

Results and discussion

The findings of the study are discussed in three sections, viz. morphometric analysis, prioritization of watershed and proposed locations for recharge structures. The flow accumulation map, delineated sub-watershed and drainage patterns in sub-watersheds are presented in Figs. 3, 4, 5, respectively.

Morphometric analysis of sub-watersheds

The morphometric study of watershed helps in evaluating the size of the basin, its characteristics, geometry and water-holding capacity that will be useful in watershed
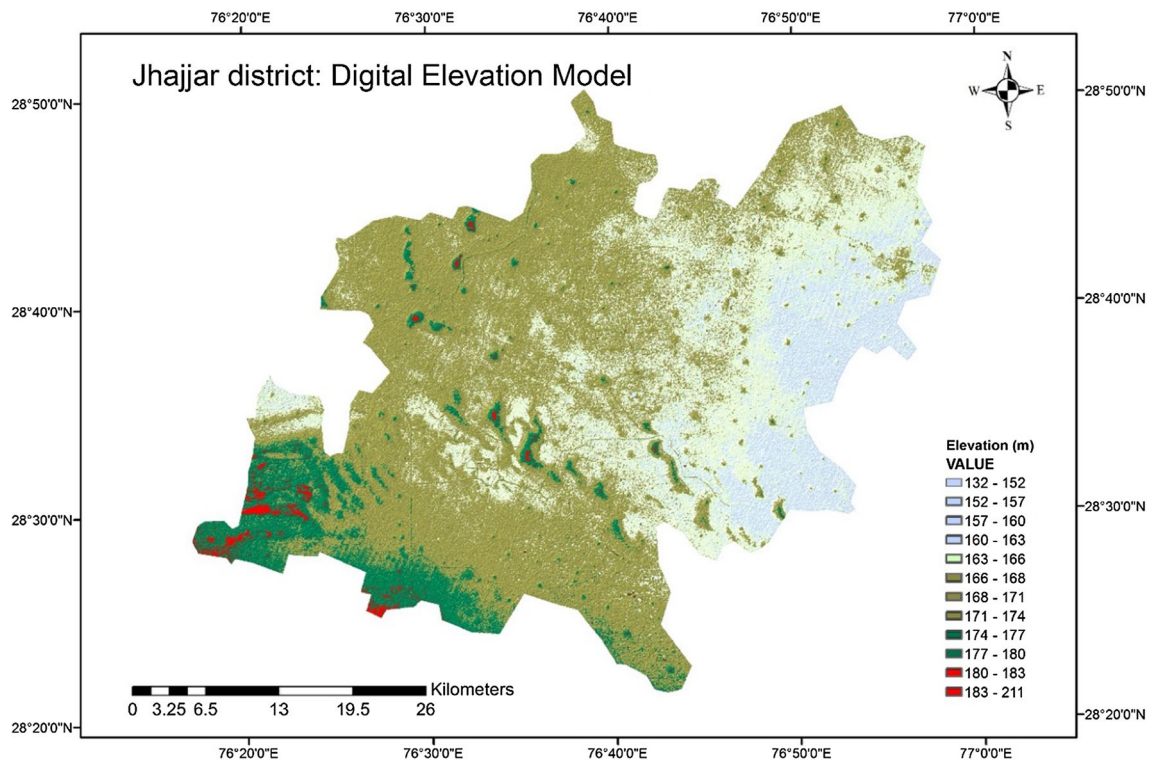

Fig. 1 DEM of Jhajjar district

Table 1 Formulae used for calculation of morphometric parameters

S. no.	Parameter	Formulae	References
Linear aspects			
1.	Stream order (U)	Hierarchical rank	Strahler (1952)
2.	Stream number (Nu)	Total number of stream segments of order U	Horton(1945)
3.	Stream length (Lu)	Stream length of order u	Strahler (1964)
4.	Mean stream length ($\overline{Lu}$)	Lu/Nu	Strahler (1964)
5.	Stream length ratio (RLu)	Lu/Lu-1	Strahler (1964)
6.	Bifurcation ratio (Rb)	Nu/Nu + 1	Strahler (1964)
7.	Mean bifurcation ratio ($\overline{\overline{Rb}}$))	Average of bifurcation ratios of all order	Strahler (1964)
8.	RHO coefficient (ρ)	$\overline{Lu}$ /Rb	Horton (1945)
Areal aspects			
9.	Watershed area (A)	Software analysis	Schumm (1956)
10.	Perimeter (P)	Software analysis	Schumm (1956)
11.	Basin length (L_b)	Software analysis	Schumm (1956)
12.	Form factor (Rf)	$A/(Lb)^2$	Horton (1932)
13.	Elongation ratio (Re)	$((2/Lb) \times (A/3.41)^{0.5})$	Schumm (1956)
14.	Circulatory ratio (Rc)	$4\prod(A/P^2)$	Miller (1953)
15.	Drainage texture (Dt)	Total Nu/P	Horton (1945)
16.	Texture ratio (Rt)	N1/P	Schumm (1956)
17.	Compactness coefficient (Cc)	$0.2841 \times (P/(A^{0.5}))$	Gravelius (1914)
18.	Stream frequency (Fs)	Nu/A	Horton (1932)
19.	Drainage density (Dd)	Lu/A	Horton (1932)
20.	Constant of channel partner (C)	1/Dd	Schumm (1956)
21.	Drainage intensity (Di)	Fs/Dd	Faniran (1968)
22.	Infiltration number (In)	FsxDd	Faniran (1968)
23.	Drainage pattern (Dp)		Horton (1932)
24.	Length of overland flow (Lg)	A/(Lux2)	Horton (1945)
Relief aspects			
25.	Minimum height of basin (z)	Software analysis	
26.	Maximum height of basin (Z)	Software analysis	
27.	Total basin relief (H)	Z-z	Strahler (1952)
28.	Relief ratio (Rh)	H/Lb	Schumm (1963)
29.	Ruggedness number (Rn)	Ddx(H/1000)	Strahler (1964)
30.	Melton ruggedness number (MRn)	$H/(A^{0.5})$	Melton (1965)

management. The morphometric parameters are categorized as linear, areal and relief Aspects.

Linear aspects

The linear aspects of a drainage basin include the study of stream networks. The information on numbers of stream segments in a drainage basin, their hierarchical orders, length of stream segments, mean stream segments, bifurcation ratio, etc., are determined and explained below.

Stream order (U) Stream order is an important parameter as it provides information about the size of the watershed. The stream order of the watershed was calculated using the Strahler method as shown in Fig. 6 (Strahler 1957). It is calculated from the starting source of stream segments. The streams flow from the start point of a drainage basin, which is generally a high relief point, called streams of the first order (U), and the stream segments starting from the confluence of two streams of the first order are called streams of second order (U + 1), and so on. The tail point of each stream is defined as the point from where a stream of higher order starts. The streams of lower order are mostly seasonal, while the streams of third and above order have a substantial amount of water. The sub-watersheds in the study area are fourth- and fifth-order watersheds, SW1 and SW2 are fifth-order basins, and other 5 basins (SW3 to SW7) are fourth order.

Stream number (Nu) Stream number was calculated using GIS software. It is a total number of stream segments per stream order. Stream number depends upon the factors

Fig. 2 Methodology used in the study
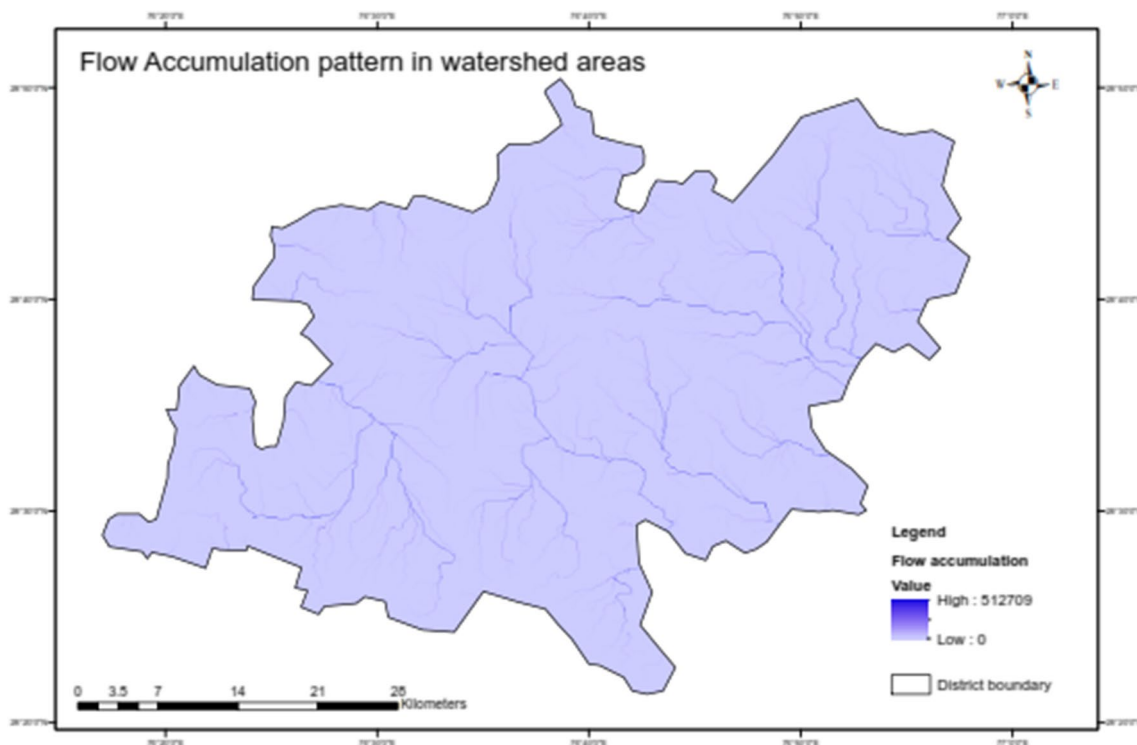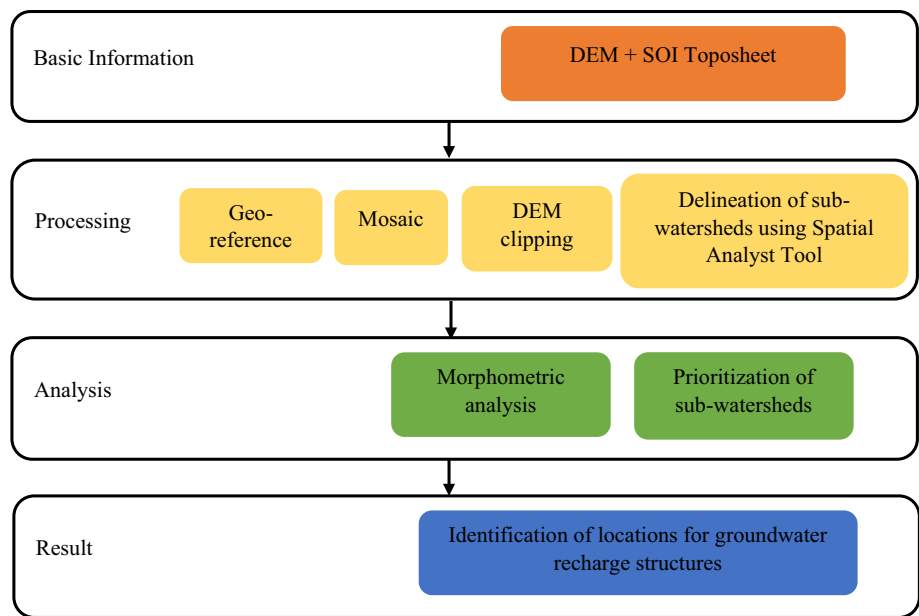
Fig. 3 Flow accumulation map

such as geology, soil type, slope, vegetation and rainfall in a watershed (Sujatha et al. 2015). The presence of more number of streams in a watershed indicates large run-off conditions. Besides, the number of first-order streams indicates the probability of flash flood after heavy rainfall in the downstream (Pande and Moharir 2017). The stream number for sub-watersheds is shown in Table 2.

Further, Horton's law of stream numbers (1945) was evaluated to express the negative correlation between the stream number (Nu) and the corresponding order (U). The law states that if the stream order increases, stream number decreases at each successive stream order. The relationship is expressed by the linear regression of **Log Nu vs. U**. The drainage network corresponds to Horton's law in all

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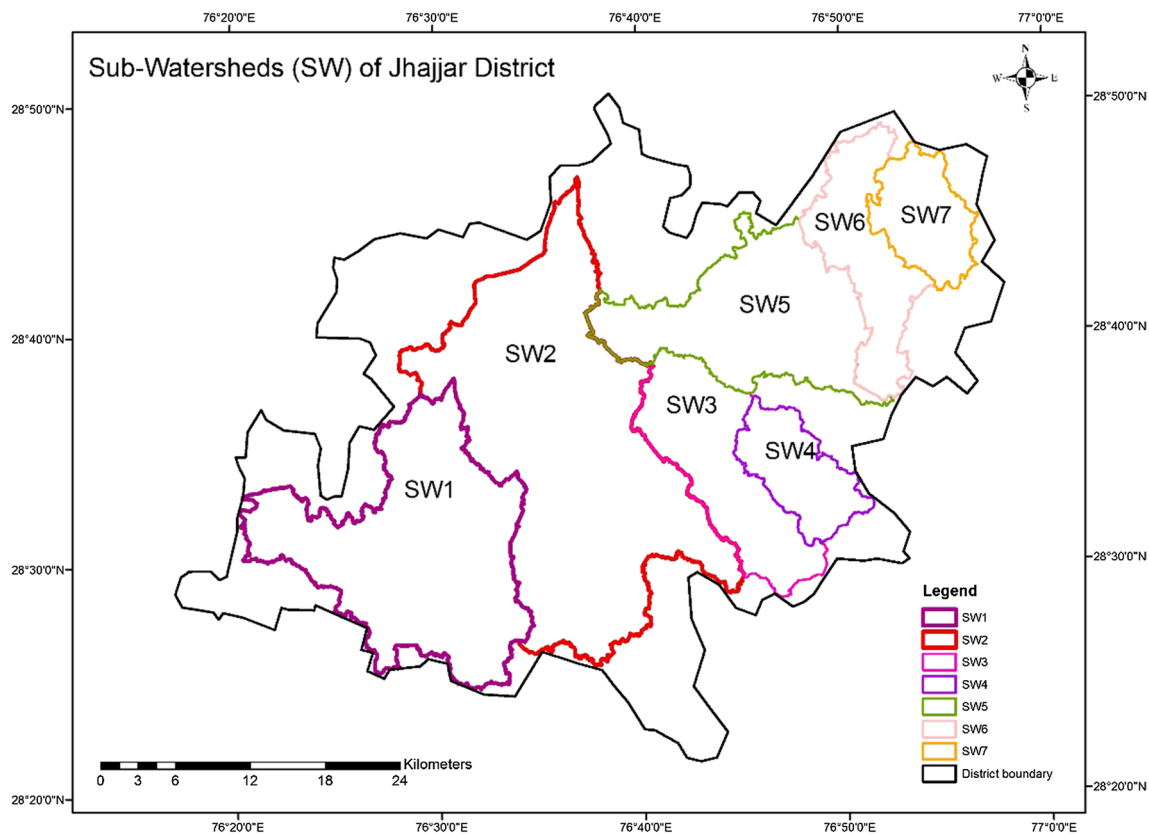
Fig. 4 Delineated sub-watersheds of Jhajjar district

sub-watersheds with slight variation in SW3 as shown in Fig. 7. The stream number of fourth-order stream is more than the third-order stream in SW3.

Stream length (Lu) The stream length of the segments was obtained through GIS software. It is an important factor to understand surface run-off characteristics in a watershed. The small length of the streams indicates an area with large slope and fine texture, and longer length represents flat gradient basins (Oruonye et al. 2016).

Mean stream length ($\overline{Lu}$) Mean stream length is calculated by dividing the total length of stream segments of an order by the total number of stream segments. The value of $\overline{Lu}$ differs for sub-watersheds, as it is directly proportional to the size and topography of the basin. Strahler (https://link.springer.com/article/10.1007/s13201-015-0298-7—CR231964) indicated that $\overline{Lu}$ is a characteristic property related to the size of the drainage network and its associated surfaces.

Stream length ratio ($\overline{RLu}$) Horton states the stream length ratio as the ratio of the mean of length segment of order $\overline{Lu}$ to the mean of length segment of order $\overline{Lu}$ - 1 that is likely to be constant throughout the successive orders in a

drainage basin. The sub-watersheds in the studied area have varied stream length ratios for different orders. Variation in stream length ratio indicates late youth stage of geomorphic development (Reddy et al. 2017). The calculated values of stream length, mean stream length, stream length ratio of sub-watersheds are given in Table 3.

Bifurcation ratio (Rb)/mean bifurcation ratio ($\overline{Rb}$) The bifurcation ratio is expressed as the ratio of the number of stream segments of a given order U to the number of stream segments of the next higher order (U + 1). The ratio is useful to predict various features of a drainage basin. Horton (1945) specified that the bifurcation ratio of less than two indicates flat or rolling drainage basin, whereas three to four is highly stable and dissected drainage basins. Strahler (1969) mentioned that bifurcation ratios are constant from one order to other in a uniform stage of development, and variation in the ratio at different orders indicates geological and lithological developments in the basin (Kumar and Chandrakantha, 2016). High Rb values indicate high overland flow, while low Rb values reflect high infiltration rate and less number of stream segments in the watershed.

The bifurcation ratio is different for different orders. The mean bifurcation ratio of sub-watersheds is 3.46, 2.10, 2.12,
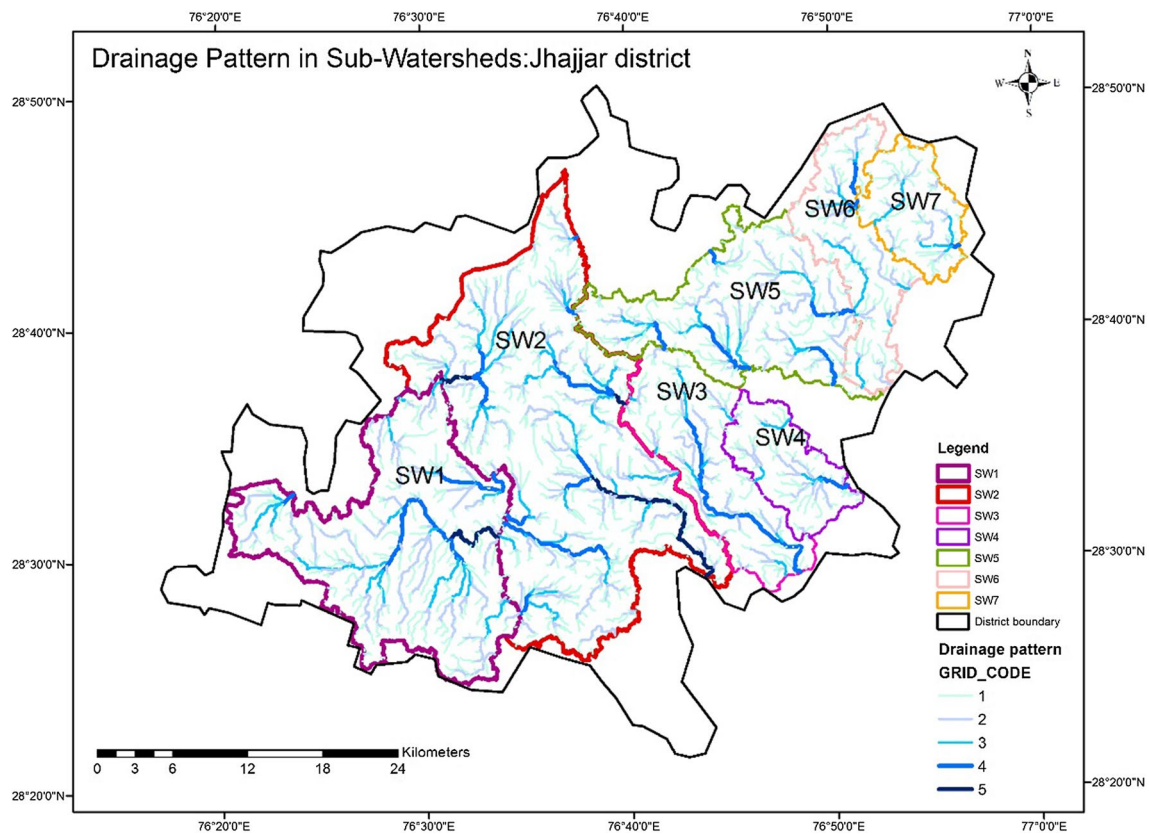
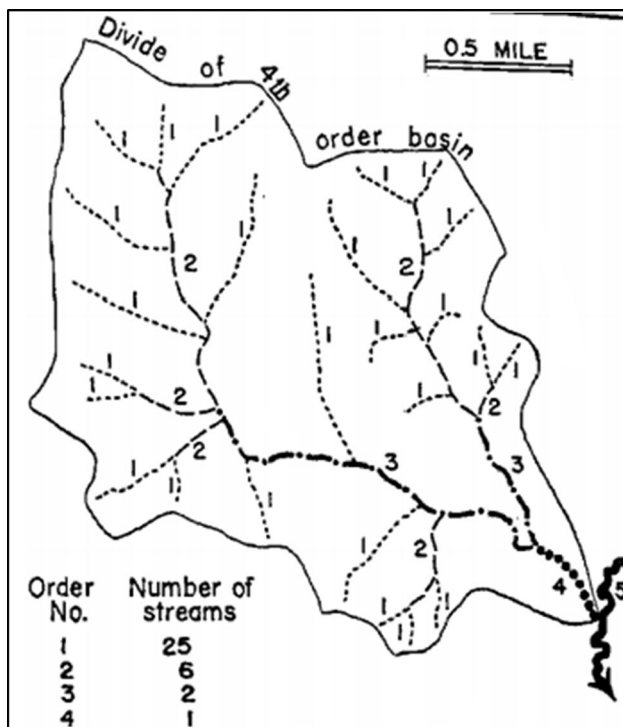**Fig. 5** Drainage pattern in sub-watersheds

**Fig. 6** Method of designating stream orders

2.94, 2.04, 2.57 and 5.32 for SW1 to SW7, respectively. Low values of mean bifurcation ratio indicate the influence of geomorphology on the development of drainage basin instead of structural control. The value for bifurcation ratio varies largely in SW4 and SW7 due to the topological changes and high slope of the watershed.

Weighted mean bifurcation ratio ($\overline{\text{Rbw}}$) The bifurcation ratio varies from one order to other in most watershed areas. Therefore, to determine a single value, Strahler (1953) proposed the concept of weighted mean bifurcation ratio. The ratio is calculated by multiplying the bifurcation ratio for each successive pair of orders by the total number of streams involved in the ratio and taking the mean of the sum of these values. The values of the weighted mean bifurcation ratio are close for seven sub-watersheds, 2.43, 2.16, 2.15, 2.81, 2.12, 2.35 and 2.85 for SW1 to SW7, respectively. The values of Rb, $\overline{\text{Rb}}$ and $\overline{\text{Rbw}}$ are given in Table 4.

RHO coefficient (ρ) It is defined as a ratio of stream length ratio to bifurcation ratio. It is a significant parameter to determine the relationship between the drainage density and the physiographic development of the basin used to assess the storage capacity of the drainage network (Horton 1945).

Table 2 Stream number with respect to stream order

Sub-watersheds	I	2	3	4	5	Total
SW1	812	404	145	89	12	1462
SW2	1096	516	251	84	69	2016
SW3	291	165	39	103		598
SW4	185	77	19	8		289
SW5	423	175	125	54		777
SW6	270	113	71	19		473
SW7	116	75	22	2		215
Total	3193	1525	672	359	81	5830
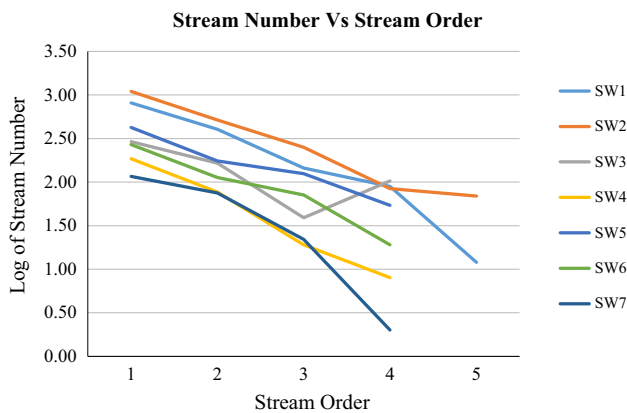
Fig. 7 Horton's law of stream number

The mean RHO coefficient of the sub-watersheds varied from 0.22 to 0.53. RHO values of the basins indicate moderate storage capacity during flood periods.

Areal aspects

The area (A), perimeter (P) and basin length (Lb) of the sub-watersheds were computed using Arc GIS-10.1 software. The areal parameters are provided in Table 5.

Form factor ratio (Rf) The form factor is the ratio of the area of a watershed to the square of its length. The value gives an idea of the shape of the watershed. Lower Rf value indicates an elongated basin. The water flows in such basins for a longer duration with a flat peak. The Rf values of sub-watersheds are given in Table 5. The Rf values of SW3 and SW6 are lower as compared to other sub-watersheds. It is easy to manage the flood flows in elongated basins than to circular basins (Reddy et al. 2002).

Elongation ratio (Re) Elongation ratio is the ratio of the diameter of a circle of the same area as the basin to the maximum basin length (Schumm 1956). It is a significant parameter to analyse the shape of the watershed. The low Re value indicates a steep slope and an elongated basin. An

index of elongation ratio, proposed by Schumm and further interpreted by Strahler, is used to evaluate the shape of the watersheds, i.e. circular (0.9–0.10), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7) and more elongated (< 0.5). The drainage basin in Jhajjar district is mostly elongated in shape. The elongation ratio of SW1 to SW7 calculated was 0.85 (oval), 0.69 (elongated), 0.40 (more elongated), 0.69 (elongated), 0.66 (elongated), 0.46 (more elongated) and 0.75 (less elongated), respectively.

Circulatory ratio (Rc) Circularity ratio is defined as the ratio of watershed area to the area of a circle having the same perimeter as the watershed (Miller 1953). The value of 1 indicates the circular shape of the watershed. The Rc values of sub-watersheds were less than 0.5 indicating the characteristics of an elongated basin with moderate relief.

Drainage texture (Dt) Drainage texture is defined as a ratio of the sum of stream segments to the perimeter of the watershed area. It depends upon the soil type, slope and water-holding capacity of the basin. More number of stream segments in a basin indicates impermeable surface. The Dt values of seven basins ranged from 4.51 to 12.74 and represent moderate-to-very-fine texture conditions. The higher values of Dt relate to poor permeability in the basins.

Texture ratio (Rt) Texture ratio is the ratio between first-order stream and perimeter of watershed. It depends upon the soil type, infiltration and basin relief. The high value of Rt indicates low infiltration and more run-off. It depicts the presence of large number of first-order streams in the basin that means there is a variation in topology. The lowest value of texture ratio was calculated for SW 1 (2.43) and highest for SW2 as 6.92.

Compactness coefficient (Cc) Cc of a watershed is the ratio of the perimeter of the watershed to the circumference of a circular area, which equals the area of the watershed (Pareta and Pareta 2011). Cc is inverse of circulatory ratio and expresses run-off in the drainage basin. It is dependent on the slope of the watershed. Lower the value of Cc, more

Table 3 Stream length, mean stream length, stream length ratio of sub-watersheds

U	Nu	Lu	$\overline{Lu}$	$(R\,\overline{Lu})$	U	Nu	Lu	$\overline{Lu}$	$(R\,\overline{Lu})$
Sub-watershed 1					Sub-watershed 2				
1	812	216.55	0.27		1	1096	346.81	0.32	
2	404	125.09	0.31	1.16	2	516	169.82	0.33	1.04
3	145	52.79	0.36	1.18	3	251	76.19	0.30	0.92
4	89	23.97	0.27	0.74	4	84	35.36	0.42	1.39
5	12	6.22	0.52	1.92	5	69	21.15	0.31	0.73
	1462	424.61				2016	649.33		
Sub-watershed 3					Sub-watershed 4				
1	291	92.34	0.32		1	185	49.43	0.27	
2	165	48.39	0.29	0.92	2	77	24.55	0.32	1.19
3	39	15.23	0.39	1.33	3	19	7.44	0.39	1.23
4	103	21.25	0.21	0.53	4	8	2.92	0.36	0.93
	598	177.21				289	84.34		
Sub-watershed 5					Sub-watershed 6				
1	423	147.37	0.35		1	270	71.99	0.27	
2	175	66.35	0.38	1.09	2	113	34.68	0.31	1.15
3	125	29.07	0.23	0.61	3	71	20.07	0.28	0.92
4	54	19.51	0.36	1.55	4	19	4.01	0.21	0.75
	777	262.29				473	130.75		
Sub-watershed 7									
1	116	48.13	0.41						
2	75	18.74	0.25	0.60					
3	22	11.92	0.54	2.17					
4	2	0.74	0.37	0.68					
	215	79.53							

Here, U = stream order, Nu = stream number, Lu = stream length, $\overline{Lu}$ = mean stream length, $\overline{RLu}$ = stream length ratio

the run-off and erodibility. The compactness coefficients of sub-watersheds were in the range of 1.69–3.00. The lowest Cc value was calculated for SW4 and SW7 and highest for SW6.

Stream frequency (Fs) Stream frequency of a drainage basin is the total number of stream segments per unit area. The Fs values of watersheds varied between 3.39 and 5.61. A high value of stream frequency relates to an impermeable subsurface material, low infiltration capacity and high relief conditions.

Drainage density (Dd) Drainage density is a parameter calculated as the total length of stream segments divided by an area of the basin. It is a measure of how well a basin is drained by its stream segments. It depends upon the permeability, slope, vegetation cover and surface run-off of the basin area.

High values of Dd indicate fine drainage texture, impermeable land, steep slope and limited vegetation cover that contribute to the larger run-off in a watershed. Such basins are susceptible to flood risk due to a rapid run-off

in channels. The Dd values of sub-watersheds indicate that all basins have moderate permeability and low infiltration properties.

Constant of channel partner (C) Constant of channel maintenance (C) is the reciprocal of drainage density. It is a measure to know minimum area required for the development of 1-km-long drainage channel (Schumn 1956). The values of C for sub-watersheds were in the range of 0.64–0.75 km²/km. Low value indicate structural disturbances in the basin having high run-off and low permeability.

Drainage intensity (Di) Drainage intensity is defined as the ratio of stream frequency to the drainage density (Faniran 1968). The drainage density calculated was 2.70–3.44 for sub-watersheds. The values obtained for drainage density, drainage intensity and stream frequency indicate that the sub-watersheds have medium permeability and low infiltration characteristics.

Infiltration number (In) It is defined as a product of drainage density and stream frequency. The number provides

Table 4 Stream order, stream number, bifurcation ratio, mean bifurcation ratio and weighted mean bifurcation ratio of sub-watersheds

U	Nu	Rb	$N_U + N_{U-1}$	$Rb*(N_U+(N_{U-1}))$	$\overline{Rb}$ w	U	Nu	Rb	$N_U + N_{U-1}$	$Rb*(N_U+(N_{U-1}))$	$\overline{Rb}$ w
Sub-watershed 1						Sub-watershed 2					
1	812					1	1096				
2	404	2.01	1216	2444.04		2	516	2.12	1612	3423.94	
3	145	2.79	549	1529.63		3	251	2.06	767	1576.78	
4	89	1.63	234	381.24		4	84	2.99	335	1001.01	
5	12	7.42	101	749.08		5	69	1.22	153	186.26	
		3.46*	2100	5103.99	**2.43**			2.10*	2867	6187.99	**2.16**
Sub-watershed 3						Sub-watershed 4					
1	291					1	185				
2	165	1.76	456	804.22		2	77	2.40	262	629.48	
3	39	4.23	204	863.08		3	19	4.05	96	389.05	
4	103	0.38	142	53.77		4	8	2.38	27	64.13	
		2.12	802	1721.06	**2.15**			2.94	385	1082.66	**2.81**
Sub-watershed 5						Sub-watershed 6					
1	423					1	270				
2	175	2.42	598	1445.45		2	113	2.39	383	915.13	
3	125	1.40	300	420.00		3	71	1.59	184	292.85	
4	54	2.31	179	414.35		4	19	3.74	90	336.32	
		2.04	1077	2279.80	**2.12**			2.57	657	1544.29	**2.35**
Sub-watershed 7											
1	116										
2	75	1.55	191	295.41							
3	22	3.41	97	330.68							
4	2	11.00	24	264.00							
		5.32	312	890.10	**2.85**						

Here, U = stream order, Nu = stream number, Rb = bifurcation ratio, $\overline{Rb}$w* = mean bifurcation ratio, $\overline{Rb}$w, weighted mean bifurcation ratio (w), $N_U + N_{U-1}$ = number of streams used in the ratio

Table 5 Areal aspects of sub-watersheds

S. no.	Parameters	SW1	SW2	SW3	SW4	SW5	SW6	SW7
1.	Area	280.99	428.81	122.31	63.42	178.87	84.32	63.36
2.	Perimeter	126.15	158.29	72.65	47.51	103.97	97.07	47.69
3.	Basin length	21.27	32.46	30.24	12.53	21.97	21.50	11.42
4.	Form factor	0.62	0.41	0.13	0.40	0.37	0.18	0.49
5.	Elongation ratio	0.85	0.69	0.40	0.69	0.66	0.46	0.75
6.	Circulatory ratio	0.222	0.215	0.291	0.353	0.208	0.112	0.350
7.	Drainage texture	11.59	12.74	8.23	6.08	7.47	4.87	4.51
8.	Texture ratio	6.44	6.92	4.01	3.89	4.07	2.78	2.43
9.	Compactness coefficient	2.14	2.17	1.87	1.69	2.21	3.00	1.70
10.	Stream frequency	5.20	4.70	4.89	4.56	4.34	5.61	3.39
11.	Drainage density	1.51	1.51	1.45	1.33	1.47	1.55	1.26
12.	Constant of channel partner	0.66	0.66	0.69	0.75	0.68	0.64	0.80
13.	Drainage intensity	3.44	3.10	3.37	3.43	3.43	3.62	2.70
14.	Infiltration number	7.86	7.12	7.08	6.06	6.37	8.70	4.26
15.	Drainage pattern	Dendritic						
16.	Length of overland flow	0.33	0.33	0.35	0.38	0.34	0.32	0.40

information about the infiltration characteristics of the watershed. The infiltration number is inversely related to infiltration capacity; hence, greater the number, lower the infiltration rate. The lowest infiltration number was calculated for SW7 as 4.26.

Drainage pattern (Dp) The drainage pattern in basins is dendritic in nature. The dendritic pattern develops in a terrain, where the bedrock is uniform in nature.

Length of overland flow (Lg) Overland flow comprises the water that flows over the ground surface to stream channels. The overland flow occurs due to the inability of water to infiltrate the surface either because of high intensity of rainfall or because of poor infiltration capacity. Horton (1945) defined the length of overland flow as half of the reciprocal of drainage density. The length of overland flow ranged between 320 and 400 metres in the studied basins.

Relief aspects

The relief aspect in the morphometric study is important to understand the hydrological response of the watershed. The parameters evaluated include basin relief, relief ratio and ruggedness number. The values of relief aspects are given in Table 6.

Basin relief (R) Schumm (1956) defined basin relief (R) as the difference between the maximum and minimum elevations of a drainage basin. It determines the slope for stream segments and the volume of sediments transported with the stream.

Relief ratio (Rr) It is the ratio of basin relief to the basin length. The Rr value relates the steepness and erosion in the basin due to the slope of the watershed. Schumm suggested that sediment loss per unit area is closely correlated with the relief ratio in a watershed area. The relief ratio of SW4 and SW7 is higher in comparison with other sub-watersheds, indicating higher run-off in the sub-watersheds.

Ruggedness number (Rn) The ruggedness number is calculated as the product of basin relief and drainage density. A high value of Rn indicates the steep slope and high drainage density. Such basins are susceptible to flood risk.

Melton ruggedness number (MRn) Melton (1965) defined the Ruggedness number as the ratio of basin relief to the square root of the basin area. Wilford et al. (2004) defined the classification of the watershed into a debris flow, debris flood and flood hazard watersheds. As per the classification, the sub-watersheds are debris flood basins. In this type of basin, stream segments deposit a significant amount of sediments beyond the channel on the fan.

Prioritization of sub-watersheds

For prioritization of sub-watersheds, the morphometric parameters, such as elongation ratio, drainage density, stream frequency, drainage texture, texture ratio and RHO coefficient of delineated sub-watersheds, were calculated using the weighted rank method. Parameters were selected and assigned weight based on the positive correlation with improving the ground water table as shown in Table 7.

Various researchers have used the parameters for the identification of groundwater recharge potential zones in a watershed (Sreedevi et al. 2005; Patil and Mali 2013; Patil and Mohite 2014 Tolessa and Rao 2013; Kandpal et al. 2018; Chandniha and Kansal 2017). The elongation ratio and drainage density are assigned to 0.20 weight each. The elongation ratio is a shape parameter and its low value of elongation ratio is susceptible to high erosion and sedimentation load (Reddy et al. 2002) and drainage density is important as related to peak discharge time in a watershed area (Wilford et al. 2004). Stream frequency is the measure of peak discharge, and a high value indicates flash floods in a watershed. Drainage texture is influenced by infiltration capacity. The coarse drainage texture shows a longer duration to peak flow. Similarly, texture ratio depends on the underlying lithology, infiltration capacity and relief aspect of the terrain and one of the useful parameters in drainage basin morphometry (Altaf et al. 2013). RHO coefficient is a parameter to determine the amount of water

Table 6 Relief aspects of sub-watersheds

S. no.	Parameters	SW1	SW2	SW3	SW4	SW5	SW6	SW7
1.	Minimum height of the basin	152.00	139.00	139.00	136.00	137.00	136.00	136.00
2.	Maximum height of the basin	193.00	194.00	195.00	198.00	199.00	197.00	179.00
3.	Total basin relief (H)	41.00	55.00	56.00	62.00	62.00	61.00	43.00
4.	Relief ratio (Rhl)	1.93	1.69	1.85	4.95	2.82	2.84	3.76
5.	Relative relief ratio	32.50	34.75	77.08	130.51	59.63	62.84	90.17
6.	Ruggedness number (Rn)	0.06	0.08	0.08	0.08	0.01	0.09	0.05
7.	Melton ruggedness number (MRn)	2.45	2.66	5.06	7.79	4.64	6.64	5.40

Table 7 Assigned weights and ranks to morphological parameters

Parameter	Weight-age factor	Assigned ranks			References
Elongation ratio	0.2	Circular	0.9–1.0	5	Pareta and Pareta 2011
		Oval	0.8–0.9	4	
		Less elongated	0.7–0.8	3	
		Elongated	0.5–0.7	2	
		More elongated	<0.5	1	
Drainage density	0.2	Very coarse	< 2	5	Tavassol 2016
		Coarse	2 to 4	4	Smith 1950
		Moderately coarse	4 to 6	3	
		Fine	6 to 8	2	
		Very fine	> 8	1	
Stream frequency	0.15	Low	0–5	5	Venkatesan 2014
		Moderate	5 to 10	4	
		Moderately high	10 to 15	3	
		High	15 to 20	2	
		Very high	20 to 25	1	
Drainage texture	0.15	Very coarse	< 2	5	Pareta and Pareta 2011
		Coarse	2 to 4	4	
		Moderately coarse	4 to 6	3	
		Fine	6 to 8	2	
		Very fine	> 8	1	
Texture ratio	0.15	Low	< 3	5	Gradation based on the fact that Lower the value of texture ratio, more the capacity for the storage of water in a watershed
		Moderate	3 to 4	4	
		Moderately high	4 to 5	3	
		High	5 to 6	2	
		Very high	> 6	1	
RHO coefficient	0.15	Low	< 0.2	1	Gradation based on the fact that higher the value of RHO coefficient, more the capacity for the storage of water in a watershed
		Medium	0.2 to 0.3	2	
		Medium–high	0.3 to 0.4	3	
		High	0.4 to 0.5	4	
		Very high	> 0.5	5	

that could be stored during the flood period. It relates the drainage density to physiographic development of a watershed (Arshad 2009; Pande and Moharir 2017).

Once the weights were assigned, ranks were provided to each sub-watershed based on the morphometric analysis. The final calculation of prioritization of sub-watersheds is done using the following equation:

Prioritized Sub-Watershed

$$= (\text{Drainage density} \times 0.2) + (\text{Elongation ratio} \times 0.20)$$
$$+ (\text{Stream frequency} \times 0.15) + (\text{Drainage texture} \times 0.15)$$
$$+ (\text{Texture ratio} \times 0.15) + (\text{RHO Coefficient} \times 0.15)$$

The final calculation for all sub-watersheds was done by multiplying the weight for each parameter by its rank and adding the resulting values. Based on the total, the sub-watersheds were divided into three major classes (high, medium and low zones). The calculations are provided in Table 8, and the final prioritization map of the study area is shown in Fig. 8.

Groundwater recharge structures for the study area

The results of morphometric analysis divulge the need for suitable recharge structures for watershed development. In this study, four types of recharge structure based on stream orders, geomorphology and soil conditions of basins are proposed.

First-order stream: The first-order streams are seasonal streams having a limited amount of water. They are numerous in number and generally formed in the upper parts of the watersheds. The overland flows of drainage basins pass the

Table 8 Final prioritization chart

Parameters	Weightage	SW1	SW2	SW3	SW4	SW5	SW6	SW7
Elongation ratio	0.2	4	2	1	2	2	1	3
Drainage density	0.2	5	5	5	5	5	5	5
Stream frequency	0.15	5	5	5	5	5	5	5
Drainage texture	0.15	1	1	1	2	2	3	3
Texture ratio	0.15	1	1	4	4	3	5	5
RHO coefficient	0.15	3	4	4	3	5	3	2
Compounded results		3.30	3.05	3.30	3.50	3.65	3.60	3.85
Priority		Medium	Low	Medium	Medium	High	High	High
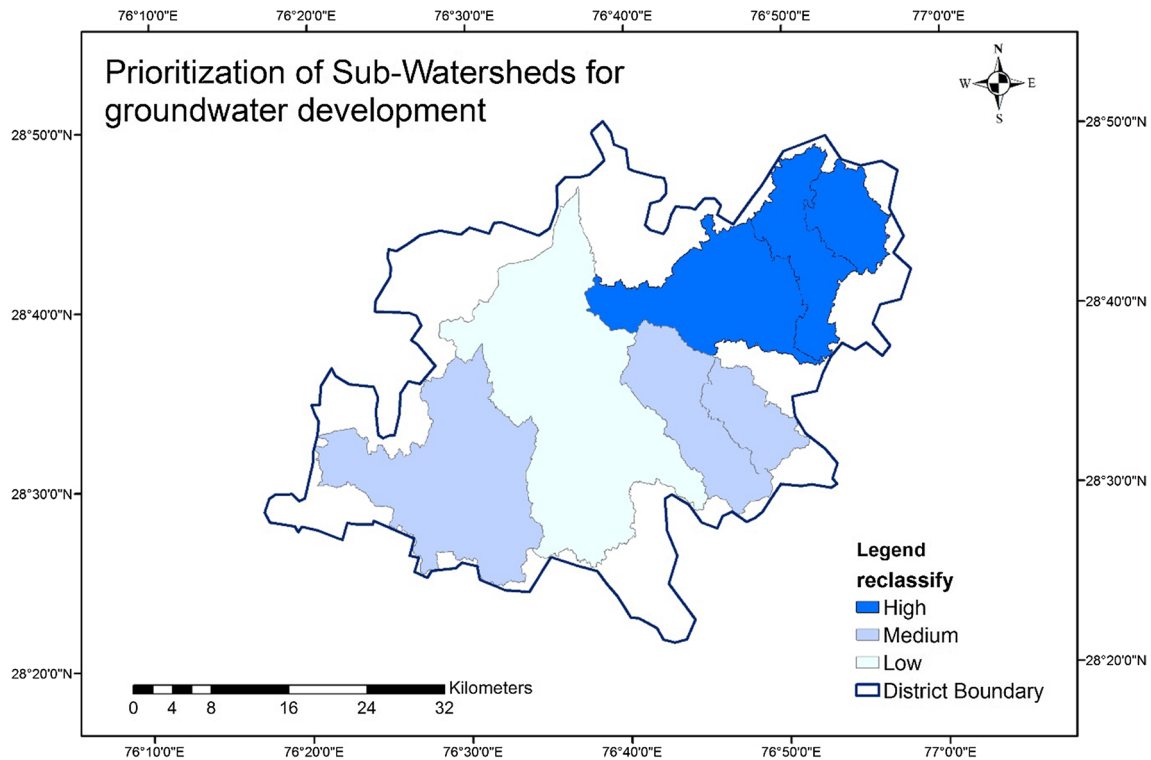
Fig. 8 Map showing prioritized sub-watersheds

water to first-order streams. The proposed recharge structure for first-order streams is vertical shaft without injection well. The vertical shaft will be supported with check dams of 20 cm height to lower down the water flow in a watershed. It helps to store the water that further percolates into the ground through a vertical shaft and infiltration process. The vertical shaft can be designed depending upon the length of the stream segments, and diameter can be selected depending on the amount of flow in the watersheds.

Second-order stream: When the two streams of the first-order confluence at a point, they form the second-order stream. These streams have double the amount of water to that of first-order streams. The proposed recharge structure on second-order streams is also vertical shaft without injection well; however, the size of the check dam is

increased to 30 cm height as the amount of water flows in second-order streams is larger than the first-order streams.

Third-order stream: The third-order stream is formed on merging of two streams of second order in a watershed. Third-order streams have a large amount of water and are perennial in nature. The proposed recharge structure is a horizontal shaft with an injection well and check dam of 40 cm height. As ample amount of water is available, construction of the horizontal shaft at such locations will help to store and augment the groundwater table. The injection well will help in percolating the water to deep levels more than 15 metres below groundwater level (bgl).

Fourth-order stream and principal drainage line: The proposed recharge structure for fourth-order streams and at principal drainage line is horizontal shaft (with injection

well) within L-shaped bunds of 30 cm height. These streams are formed on the confluence of two streams of third order. In many watershed areas, fourth-order streams are itself principal drainage line or meet with higher-order streams to form principal drainage line. These streams have a very large amount of water that should be recharged into the groundwater through a properly designed structure. The L-shaped bunds within a stream would be useful to move water along a longer path, thereby improving natural recharge. The horizontal shaft with an injection well within L-shaped bunds

is useful for passing the water directly to deep aquifers. The check dams on fourth order and principal drainage line shall be made of high-strength concrete to control the large amount of water. It is useful in reducing the water flow in the watershed, thus reducing run-off and maximizing infiltration to augment water table (Misra et al. 2015).
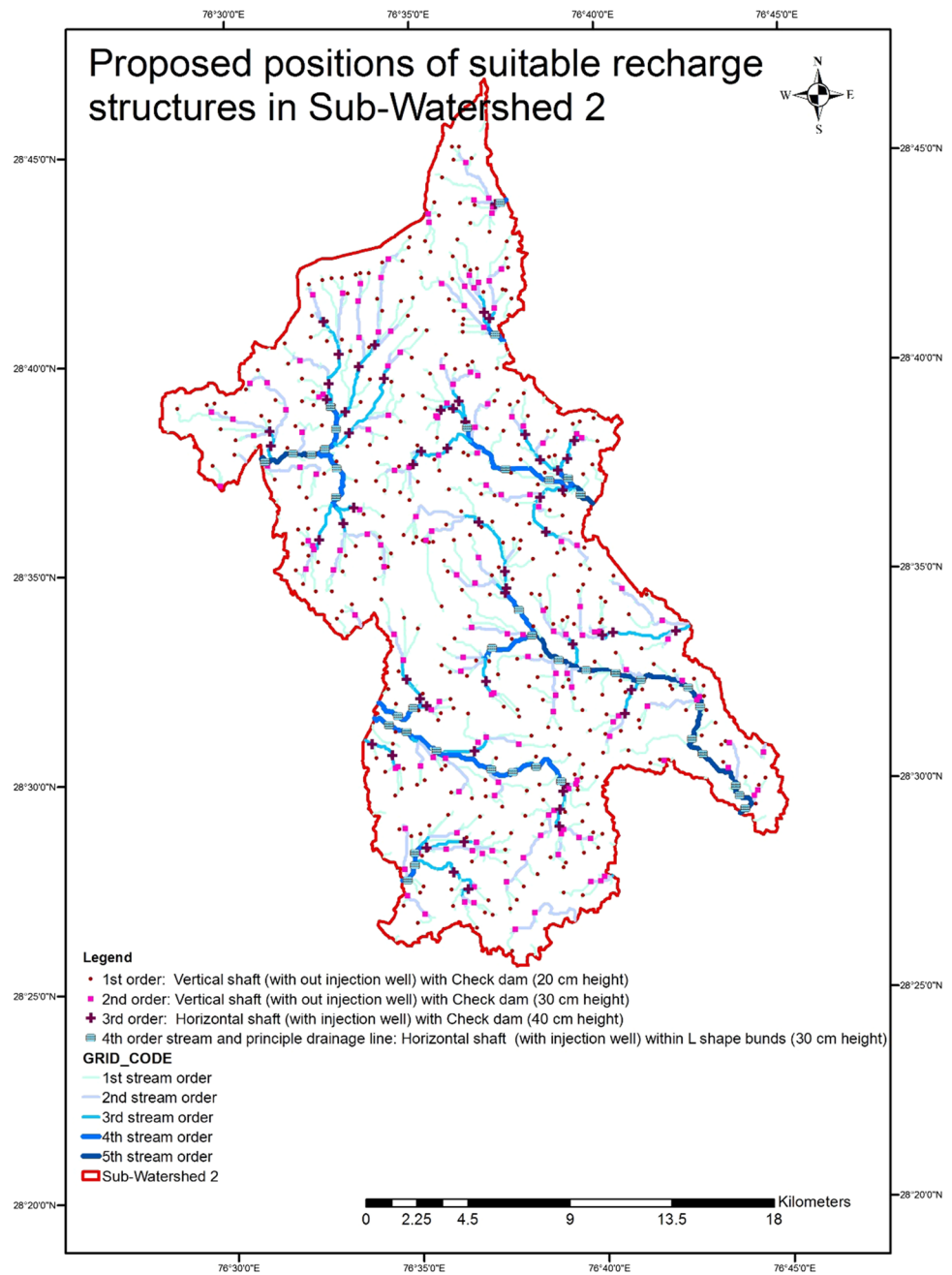
The proposed locations of recharge structures for sub-watersheds 1 to 7 of Jhajjar district are shown in Figs. 9, 10, 11, 12, 13, 14, 15, respectively.

Fig. 9 Proposed positions of suitable recharge structures in sub-watershed 1
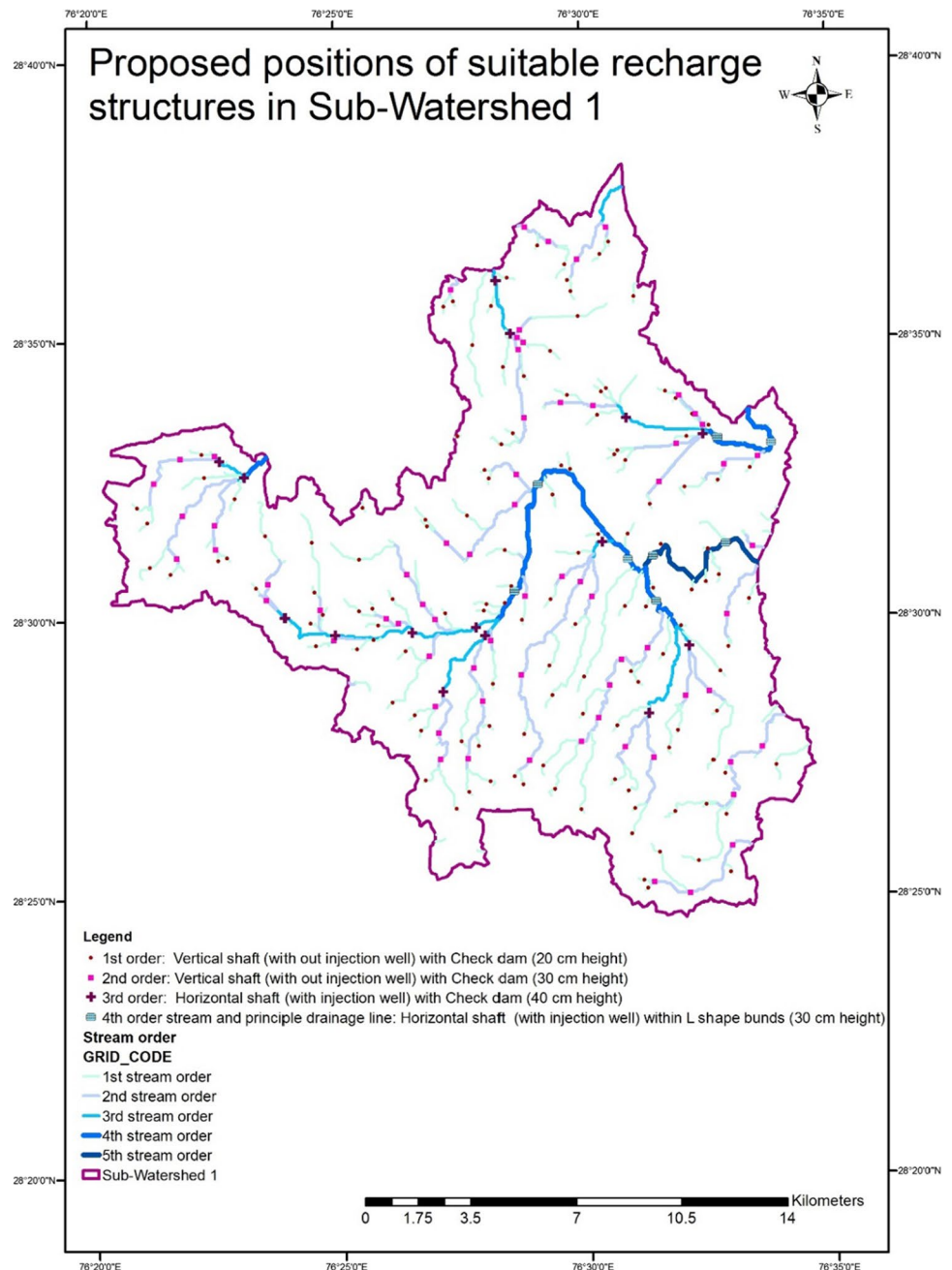
Fig. 10 Proposed positions of suitable recharge structures in sub-watershed 2


Conclusion

Abstraction of groundwater for irrigation, commercial and domestic purposes has resulted in depleting the quality and quantity of groundwater resources in Jhajjar district. In addition, the weathering and dissolution of salts in the unconsolidated formation continuously escalate the salts in the aquifers. As a consequence, groundwater of Jhajjar district is not suitable for drinking purpose. Groundwater salinity and high concentration of fluoride are the major problems
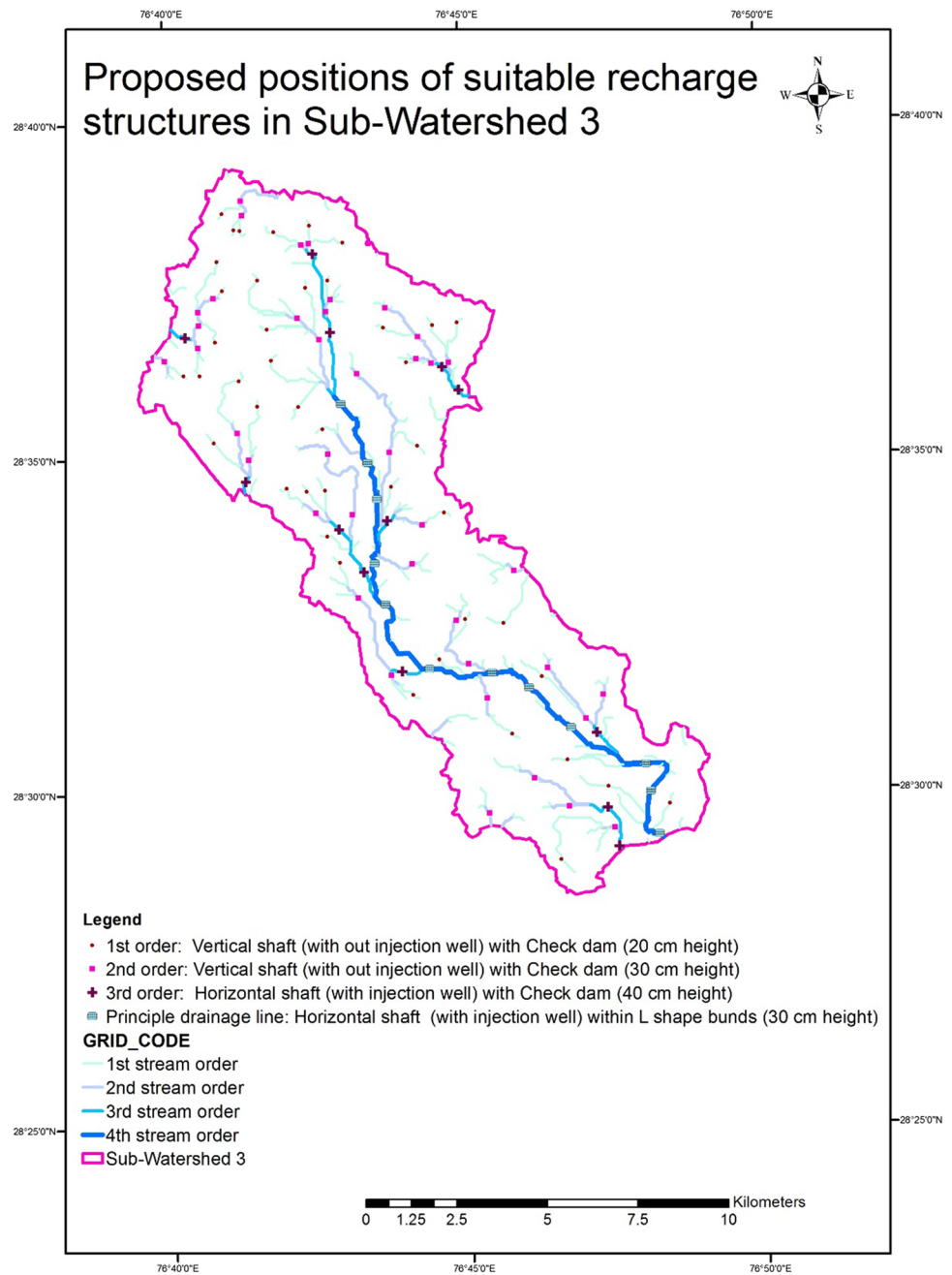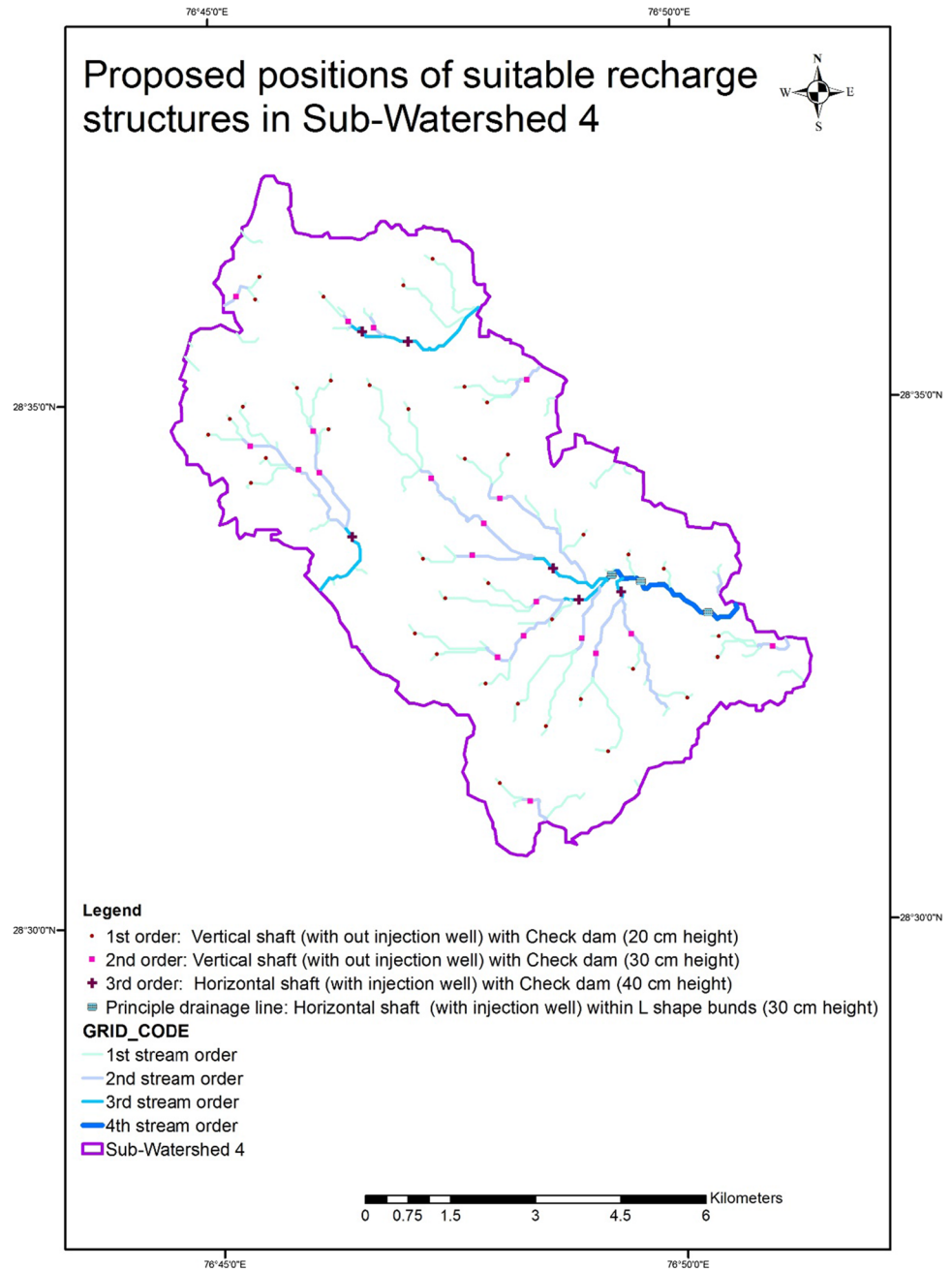
of groundwater. Researchers have found many water quality parameters above the permissible limits of drinking water standards as prescribed by BIS (Yadav and Lata 2003; Yadav et al. 2009; Gulab, 2014; Gupta and Misra 2018) in samples of groundwater. The fluoride concentration is more in shallow aquifers of the district, due to that dental fluorosis is

**Fig. 12** Proposed positions of suitable recharge structures in sub-watershed 4

Proposed positions of suitable recharge structures in Sub-Watershed 4

Legend
- 1st order: Vertical shaft (with out injection well) with Check dam (20 cm height)
- 2nd order: Vertical shaft (with out injection well) with Check dam (30 cm height)
- 3rd order: Horizontal shaft (with injection well) with Check dam (40 cm height)
- Principle drainage line: Horizontal shaft (with injection well) within L shape bunds (30 cm height)

GRID_CODE
- 1st stream order
- 2nd stream order
- 3rd stream order
- 4th stream order
- Sub-Watershed 4

prevalent in the area. Salinity is another culprit that covers 45% area of the district, causing the groundwater as well as soil salinity. Concerning the situation, water resource management is vital for Jhajjar district.

The watersheds are considered as best units for the management of water resources; therefore, this study presented a view on watershed development and its potential on replenishment of groundwater resources in the district. The study has applied GIS technique for the delineation of sub-watersheds, and subsequently, the morphometric analysis is performed to understand the basin characteristics for the potential to develop recharge structures.

Fig. 13 Proposed positions of suitable recharge structures in sub-watershed 5
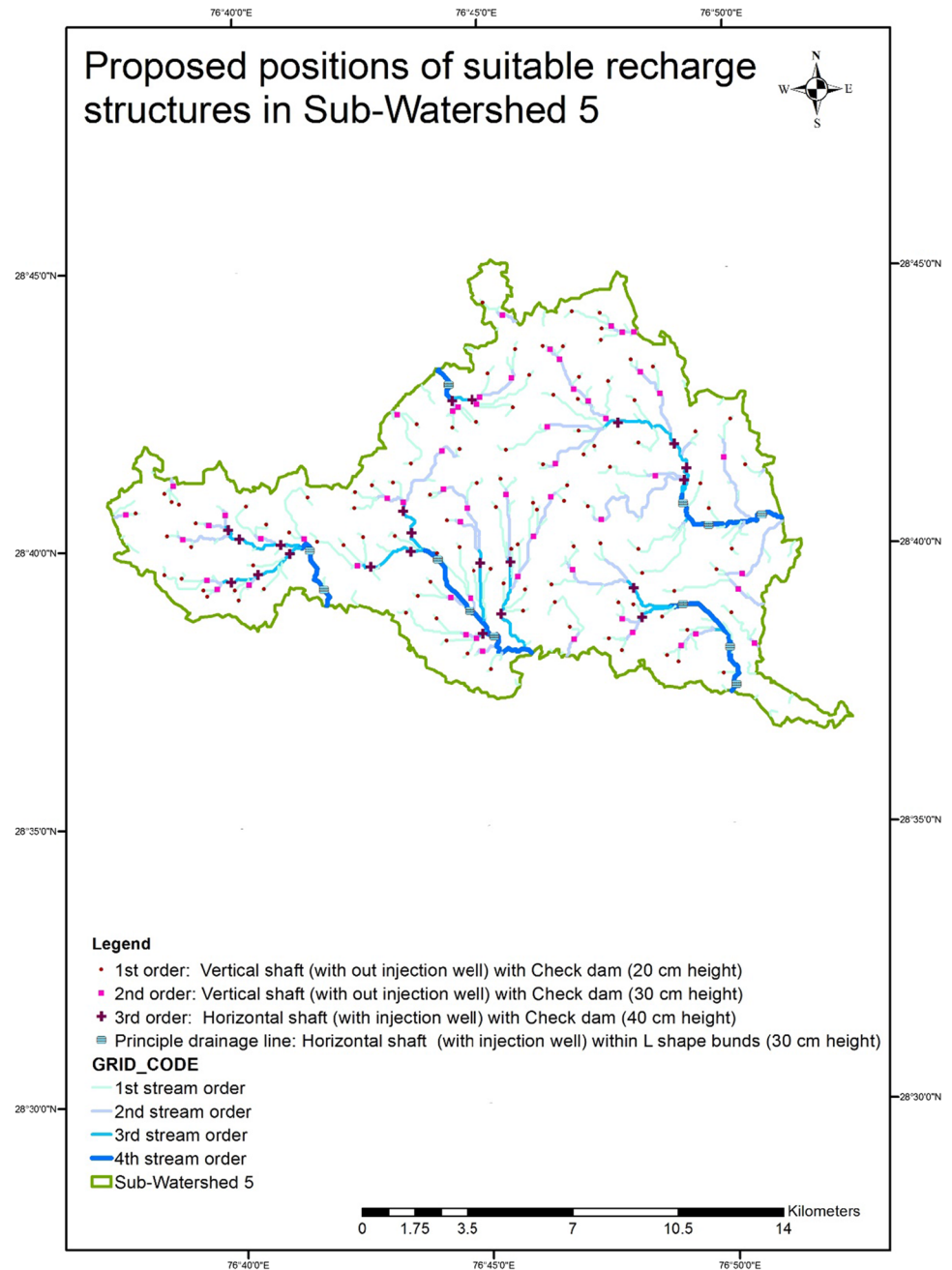
The sub-watersheds are of fourth and fifth orders having substantial amount of water flows. These are elongated in shape with moderate relief and have no significant structural control; however, a high value of bifurcation ratio was observed for third- and fourth-order streams of SW1 and SW7 that may be due to the structural changes in that area. There are few stream segments in per unit area, which is a control factor to run off, although such basins are poorly drained basins with slow hydrological responses. Drainage texture is moderate to fine indicating low infiltration capacity of the subsoil. The summarized results reveal that sub-watersheds of Jhajjar district have medium permeability and low infiltration characteristics. Based on the prioritization of

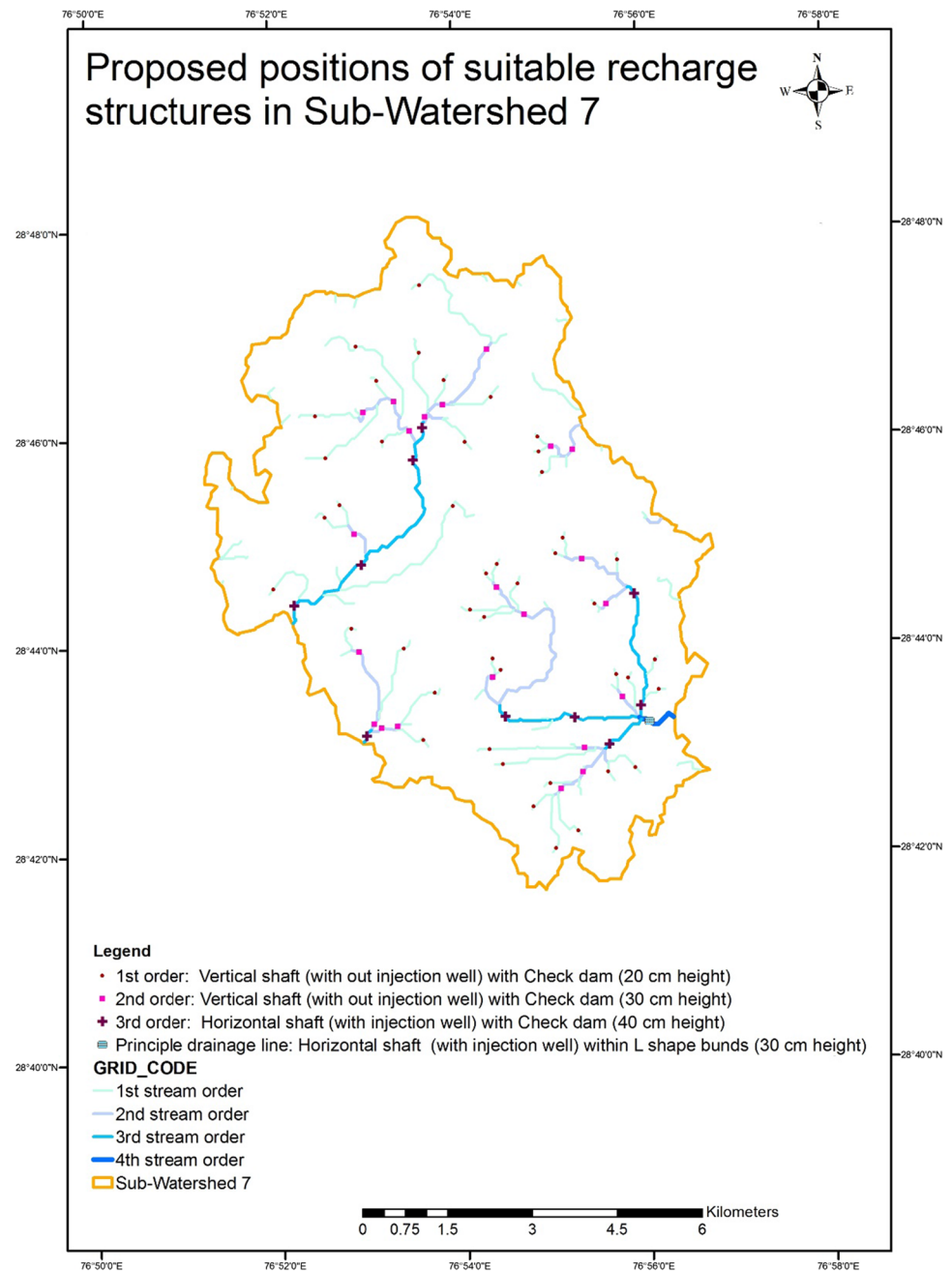**Fig. 14** Proposed positions of suitable recharge structures in sub-watershed 6
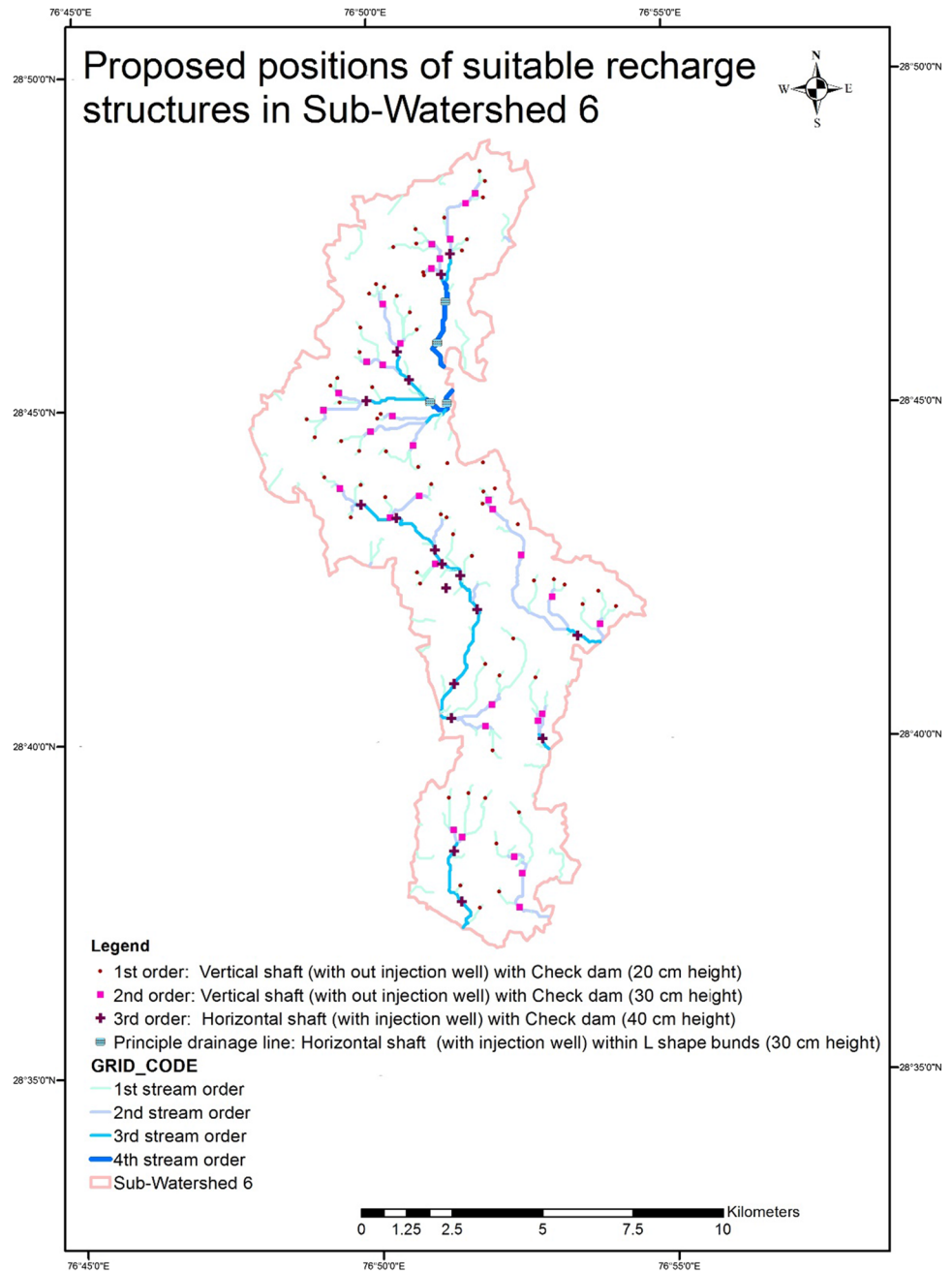
sub-watersheds, SW4, SW5 and SW7 are considered high, SW1, SW3 and SW6 medium, and SW2 low.

The proposed recharge structures are based on stream-order analysis, geomorphology and soil conditions of Jhajjar district. The soil covers in the district having sediments of clay, sand and kankar mixed in different proportions (CGWB, 2010). The recharge structures such as vertical and horizontal shafts (with and without injection wells) with check dams will be useful in augmenting the water to the shallow and deep aquifers in alluvial zones. The study infers that the deployment of watershed management practices in sub-watersheds will result in improvement in both the groundwater level and quality to large extent.

Proposed positions of suitable recharge structures in Sub-Watershed 7

Legend
- 1st order: Vertical shaft (with out injection well) with Check dam (20 cm height)
- 2nd order: Vertical shaft (with out injection well) with Check dam (30 cm height)
- 3rd order: Horizontal shaft (with injection well) with Check dam (40 cm height)
- Principle drainage line: Horizontal shaft (with injection well) within L shape bunds (30 cm height)

GRID_CODE
- 1st stream order
- 2nd stream order
- 3rd stream order
- 4th stream order
- Sub-Watershed 7

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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