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Morphometric analysis and vertical electrical sounding in groundwater prospecting: a case study from a Himalayan foothill river basin, NW India

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ABSTRACT

The present paper exercises applied methods of morphometry and vertical electrical soundings in groundwater studies in a Himalayan foothill river basin, NW India. The drainage density indicates coarse drainage texture and highly permeable geological materials. The form factor indicates a flatter peak of flow for longer duration and high infiltration. The stream frequency and relief ratio suggest less resistant rocks of the region causing higher infiltration. The result of VES applied as appraisal of the morphometric parameters reveals potentially productive aquifer horizons of fine sand, medium sand, gravelly sand and dry sand. The thickness of fine sand, medium sand and dry sand layers are 8.5 m, 70.75 m and 28.5 m respectively. The transverse resistant value for dry sand, fine sand and medium sand range from 3900 Ωm^2 to 3990 Ωm^2, 620 Ωm^2 to 780 Ωm^2 and 960 Ωm^2 to 9380 Ωm^2 respectively suggesting good transmissivity of these aquifer horizons.

Keywords: Morphometry analysis, vertical electrical sounding, Markanda basin, Himalayan foothills, NW India.

1. Introduction

The demand for groundwater has multiplied manifold with rapid growth in population, agricultural and industrial activities in many parts of the world which has severely affected the available groundwater resources now-a-days. Groundwater is one of the prime sources for sustenance of people, agricultural activities and other anthropogenic uses in Northwestern India. The region is becoming overly dependent on groundwater, consuming it faster than it is naturally replenished and causing water tables to decline unremittingly (Chatterjee and Purohit 2009). A study based on NASA Gravity Recovery and Climate Experiment satellites survey indicates that the level of groundwater in this region has depleted at a mean rate of 4.0 ± 1.0 cm yr^{-1} equivalent height of water (17.7 ± 1.0 km^3 yr^{-1}) and concludes that if measures are not taken soon, the consequences may lead to reduction of agricultural output and shortages of potable water, leading to extensive socioeconomic stresses (Rodell et al. 2009).

Therefore, watershed development ideas become important for better utilization and management of groundwater in this part of India. One of these ideas may be the deployment of morphometric analysis analysis (Grohmann 2004; Sreedevi et al. 2005) along with geoelectrical method. The morphometric attributes may be evaluated with reference to the groundwater prospect in the basin, and the geoelectrical investigation may be applied for the appraisal of the morphometric result. Therefore, the present paper is an attempt to integrate these two applied methods for a potential benefit to groundwater prospecting in the Markanda river basin located in the Himalayan foothills.

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2. Materials and methods

2.1 Study area

The Markanda river basin spreads between 30^{0} 00′ and 30^{0} 40′ North latitudes and 76^{0} 32′ and 77^{0} 24′ East longitudes in the Siwalik foothills, NW India (Figure 1). The river originates from Nahan in the Siwalik hills of Himachal Pradesh and flows towards southwest in the Gangatic alluvial plains of Haryana. The basin covers an area of 1547 km^{2}. The area falls under sub-tropical and semi arid region with the annual average rainfall of 1100 mm in the hilly region and 750 mm in the plain. The geological set up of the basin consists of sedimentary rocks of Tertiary to Quaternary alluvium deposits. Rocks belonging to Tertiary age occupy the northern part of the basin, while alluvium deposits of Quaternary age occupy the southern part.

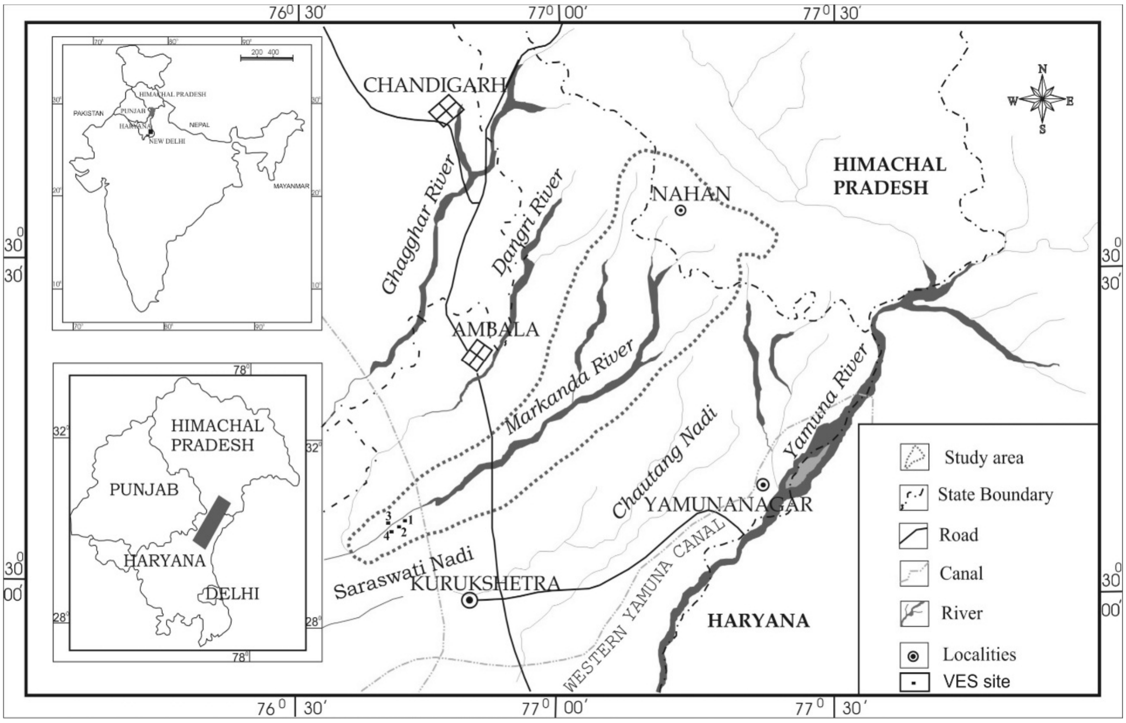


Figure 1: Map showing the Markanda and its neighboring river basins in northwest India

The rocks of Tertiary age belong to sandstones, conglomerates, limestones, claystones, mudstones, shales and siltstones of Siwalik Group (Paleocene to Pliocene Period) and represent the thick continental molasse deposits in the Himalayan Foreland Basin (Prakash et al. 1980; Kumar et al. 1999). They include fluvial sediments deposited by hinterland rivers flowing towards south, northeast and southwest from the Lesser and Greater Himalayas. The alluvium deposit ranges in age from Pleistocene to Recent and is composed of clay, silt, sand, and gravel. At places, especially in the older parts of the deposits, the calcareous material popularly known as kankar is present. The alluvium deposit was formed by deposition of sediments brought by Himalayan rivers into a trough between the Himalaya in the north and Deccan plateau in the south (Nakata 1972). The main structures present in the area are series of thrusts like Main Boundary Thrust (MBT), Krol Thrust, Nahan Thrust, Markanda Thrust and Himalayan Frontal Thrust (HFT) which have brought rocks into juxtaposition with one another. In Siwalik hills, between HFT and MBT, numerous active faults and neotectonic features have been documented (Philip et al. 2006; Kumar et al. 2001). Active deformation along the HFT is expressed by scarps, uplift and folding of late Quaternary and the Holocene (Nakata 1972).

2.2 Experimental studies

In the present work, seven toposheets (Index No. 53F/2, 53F/3, 53F/6, 53F/7, 53B/12, 53B/15 and 53B/16) of Survey of India (SOI) on 1: 50,000 scales have been used for extraction of drainage network. Initially the toposheets were scanned and georeferenced in remote sensing software Erdas Imagine 10. Polyconic projection system was adopted using Modified Everest (1956) Spheroid and Indian datum. Digitization and measurement of stream network was carried out by using ArcView 3.2a GIS software. The stream order was given to each stream by following Strahler stream ordering technique (Strahler 1964). Then, morphometric parameters such as stream order (N_u), bifurcation ratio (R_b), stream length (L_u), drainage density (D_d), stream frequency (F_s), elongation ratio (R_e), circularity ratio (R_c) and form factor ratio (R_f) were computed. Morphometric analysis is a technique of measurement and mathematical analysis of various landform parameters. These parameters involved linear aspects such as (N_u), (R_b), (L_u) and areal aspects such as (D_d), (F_s), (R_e), (R_c) and (R_f).

Further, to appraise the morphometric result and substantiate the groundwater potential in the basin, electrical resistivity method was adopted. The resistivity measurements are normally made by injecting current into the ground through two current electrodes, and measuring the resulting voltage difference at two potential electrodes. From the current and voltage values, an apparent resistivity value is calculated. To determine the true subsurface resistivity, an inversion of the measured apparent resistivity values is carried out using curve matching technique. In symmetrical, four electrode configurations, Schlumberger and Wenner methods are conventionally used for groundwater exploration. In the present study, Schlumberger configuration has been adopted for VES. Schlumberger configuration allows a clearer definition of subsurface conditions for a given outer electrode spacing and uses less man power because the central electrodes do not need to moved every time the outer electrodes are moved (Davis and DeWiest 1966). VES using Schlumberger configuration have been carried out at Balapur, NW of Tangoli, Danipur and Tangoli (figure-01). Resistivity survey gives thorough understanding of the subsurface situation in terms of aquifer disposition, geometry of deeper aquifers, aquifer yield and buried palaeochannels (Srivastava 2005; Kshetrimayum and Bajpai 2011). VES had proven to be a very suitable method in groundwater exploration (Kelly 1976; Edet and Okereke 2002). The electrode configuration has been followed by keeping maximum current electrode spacing of 1km. The hydrogeological interpretation was carried out on the basis of standard resistivity values of geologic formations given by earlier workers (Sri Niwas and Singhal 1981; Sri Niwas and Lima 2003; Singhal et al. 1998). The interpretation of resistivity curves has been made by following two layer master curves prepared by Mooney and Wetzel (1956) and Orellana and Mooney (1966). The result was correlated with the tubewell lithologs collected from the Central Ground Water Board and Public Health Division, Haryana. Further, the transverse resistance, also known as Dar Zarrouk parameter, has been calculated for indirect estimation of transmissivity. Transverse resistance is calculated by multiplying the aquifer thickness by its resistivity value for a column of unit cross sectional area of the layer (Ponzini et al. 1983). Therefore,

$$TR_i = h_i \times \rho_i$$

Where TR_i is transverse unit resistance of the i^{th} layer, h_i is thickness of the i^{th} layer in the column and ρ_i is true resistivity of the same layer.

3. Results and discussion

The result of morphometric analysis of the Markanda basin has been summarized in Table 1 and Table 2.

3.1 Stream order (N_u)

Based on the Strahler (1964) stream ordering technique, the Markanda basin belongs to 7th stream order basin (Figure 2). Out of total number of streams (2192), 1628 are 1st order stream, 425 are 2nd order stream, 101 are 3rd order stream, 25 are 4th order stream, 9 are 5th order stream, 3 are 6th order stream and one in 7th order stream. It has been observed that streams belonging to 1st, 2nd, 3rd, and 4th order flow past the hilly terrain of Siwalik sandstones and shales which are characterized by steep slopes, while 5th, 6th and 7th order streams occupy the alluvial plain.

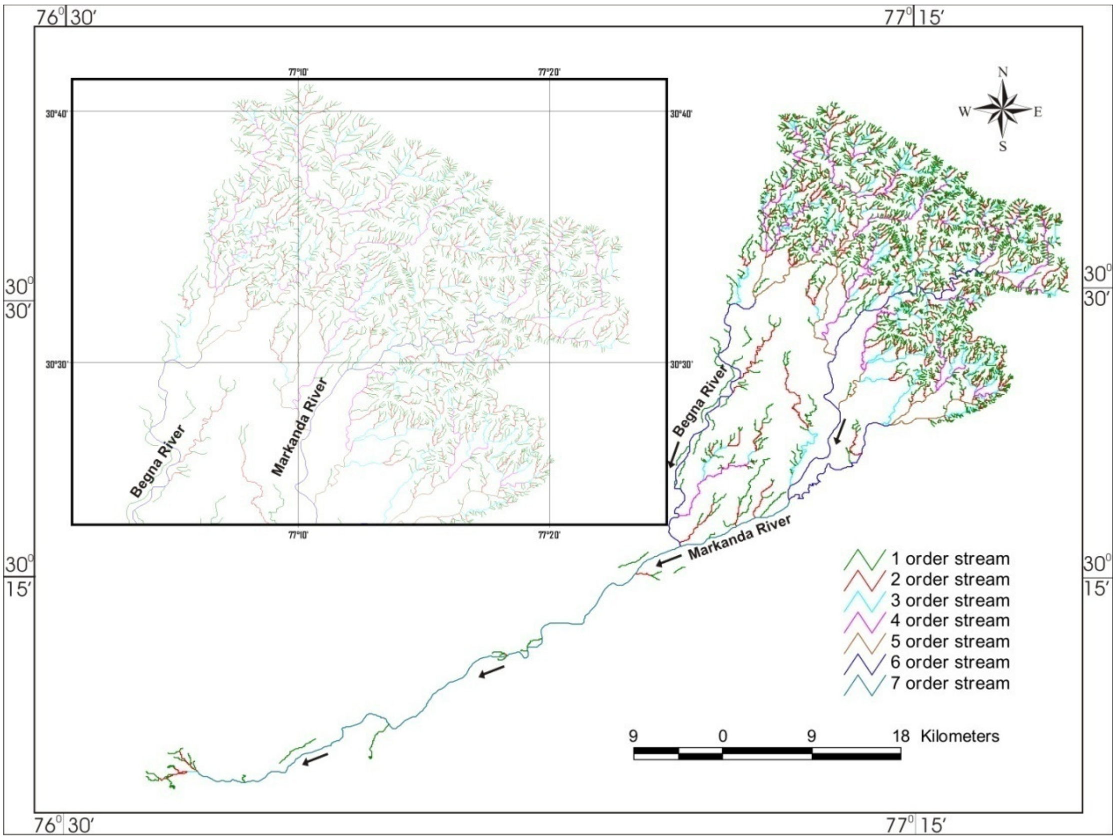


Figure 2: Map showing drainage network of the Markanda river and its tributaries with stream orders, inset shows magnified view of the upper headwater region.

3.2 Stream length (L_u)

The stream lengths of all segments of Markanda basin were calculated in GIS environment. It is observed that the total length of stream segments is longest in first order streams and decreases as the stream order increases. Horton's (1945) laws of stream numbers states that the number of stream segments of each order form an inverse geometric sequence with plotted against stream order. The plotting of logarithm of number of streams against stream order of the Markanda basin shows a straight line indicating the number of streams is negatively correlated with the stream order. This means that the number of streams usually decreases in geometric progression as the stream order increases.

Table 1: Results of the morphometric parameters of drainage network and their mathematical expressions in the Markanda basin, NW India

Basin area (km^2)	1547
Drainage density,($D_d = \Sigma L/A$),(km/km^2)	1.25
Stream frequency,($F_s = \Sigma N/A$),(km/km^2)	1.41
Form factor,($R_f = A/Lb^2$)	0.12
Circularity ratio,(km^2/km)	0.31
Elongation ratio,($R_e = d/Lb$),(km/km)	0.38
Relief ratio,($R_h = H\text{-}h/L$)	0.017

Table 2: Result of the morphometric parameters in the Markanda basin, NW India

Stream order	Stream length (km)	No. streams (segment)	Bifurcation ratio (R_b)	
1	1063	1628	1st order/2nd order	3.8
2	329	425	2nd order/3rd order	4.2
3	175	101	3rd order/4th order	4.0
4	134	25	4th order/5th order	2.7
5	81	9	5th order/6th order	3.0
6	92	3	6th order/7th order	3.0
7	69	1	Average (R_b)	3.4

3.3 Bifurcation ratio (R_b)

Bifurcation ratio is the ratio of the number of streams of any given order to the number of streams of the next higher order (Schumm 1956). It is given as

$$R_b = N_u/N_{u+1}$$

Where, 'N_u' is total number of streams of 'u' order, N_{u+1} is the total number of streams of the next higher order 'u+1'. Bifurcation ratio characteristically ranges between 3.0 and 5.0 for basins in which the geologic structures do not distort the drainage pattern (Strahler 1964) and with more than 10 where structural controls play dominant role with elongate narrow basins (Chow 1964). R_b of the Markanda basin is calculated to be 3.4 indicating that geologic structures do not have a prominent influenced within the drainage basin.

3.4 Drainage density (D_d)

Horton (1945) introduced the concept of drainage density which is defined as total stream length per unit area of a river basin and it is calculated as

$$D_d = \Sigma L/A$$

Where, 'ΣL' is the summation of all stream lengths in the watershed and 'A' is the total area drained by the streams. The drainage density has been one of the most commonly used parameters in studies relating hydrologic and geomorphologic characteristics(Schumm 1956). The 'D_d' has been interpreted to reflect the climate (Gregory and Gardiner 1975), vegetation vegetation (Melton 1958), bedrock geology (Wilson 1971), time (Kashiwaya 1983) and hypsometric integral (Strahler 1952). Low drainage density leads to coarse drainage texture, while high drainage density leads to fine drainage texture texture (Strahler 1964). According to Strahler (1964), values of drainage density below 12 are low density; those with values of between 12 and 16 are medium density basins while basins with values above 16 are high density basins. The average drainage density of the Markanda basin is calculated to be 1.25 km/km^2 indicating low drainage density and coarse drainage texture. It is suggested that low drainage density indicates highly permeable subsoil and thickly vegetative cover basin (Nag 1998). This is corroborated by the presence of highly permeable rocks of sandstone and alluvium in the region.

3.5 Stream frequency (F_s)

F_s is the ratio of number of total stream segments of all orders within a basin and the basin area (Horton 1945) and is calculated as

$$F_s = \Sigma N/A$$

Where, 'ΣN' is the summation of number of stream segments and 'A' denotes the area of the basin. The average F_s of the Markanda basin is calculated to be 1.41 km/km^2.

3.6 Form factor (R_f)

R_f is the dimensionless ratio of basin area to the square of basin length(Horton 1932) and is calculated by

$$R_f = A/L_b^2$$

Where 'A' is the drainage area and 'L_b' is the length of the river basin. The length of the river basin is the longest dimension from the mouth to the farthest point on the perimeter of the basin.

The value of form factor varies from zero (highly elongated shape) to unity (perfect circular shape) (Horton 1932).The form factor value of the basin is calculated as 0.12 which indicates lower value of form factor and thus represents elongated in shape. The elongated basin with low form factor indicates that the basin will have a flatter peak of flow for longer duration and hence flood flows can be managed efficiently (Narendra and Rao 2006).

3.7 Circularity ratio (R_c)

R_c is the ratio of the area of river basin to the area of circle having the same perimeter as the basin (Miller 1953). It is a dimensionless ratio and use to express the outline of drainage basin (Strahler 1964). The circularity ratio of Markanda basin is calculated to be 0.31 indicating elongated basin with low discharge of runoff and highly permeability of the subsoil condition (Miller 1953).

3.8 Elongation ratio (R_e)

R_e is the ratio of diameter of a circle having the same area as of the basin and maximum basin length (Schumm 1956) and is given by

$$R_e = d/L_b,$$

Where 'd' is diameter of a circle having the same area as of the basin and 'L_b' is the maximum basin length. The R_e value of the basin is found out to be 0.38 suggesting that the region belongs to low relief and elongated in shape (Strahler 1964).

3.9 Relief ratio (R_h)

Relief ratio of a river basin indicates the overall steepness of drainage basin and is an indication of intensity of degradation processes operating on slopes of the basin (Schumm 1963). R_h is given by

$$R_h = H\text{-}h/L$$

Where, 'H' is the highest elevation in the basin (2200 m), 'h' is the lowest elevation in the basin (252 m) and 'L' is the longest axis of the basin (113 km). The relief ratio of the Markanda basin is calculated to be 0.017 indicating less resistant rocks of the area.

3.10 Geo-electrical study

After the morphometric attributes were evaluated with reference to groundwater prospect in the basin, geoelectrical investigation was applied for the appraisal of the morphometric result. The result of VES surveys in selected parts of the basin has been summarized in Table 3 and Table 4.

3.10.1 Site1: Balapur

The resistivity curve obtained from the Schlumberger configuration at Balapur reveals three subsurface layers (Figure 3a and Figure 4a). The topmost layer shows resistivity value of 72 Ωm and thickness of 2.2 m. This layer has been interpreted as surface clay. The second layer has resistivity value of 134 Ωm and thickness of 70 m indicating medium sand. The third layer has low resistivity of 11 Ωm and it has been interpreted as clay and kankar. The curve break (B) in the field curve indicates fine sand layer at the depth beyond 150 m (Figure 3a).

3.10.2 Site 2: NW of Tangoli

The field curve obtained from the Schlumberger configuration of this area points out four layers with resistivity values ranging from 30 Ωm to 114 Ωm. The layers are distributed within the depth of 47 m. The topmost layer has resistivity value of 110 Ωm and thickness of 2.3 m. This layer has been interpreted as dry surface sand. The second layer has true resistivity value of 55 Ωm and true thickness of 18 m indicating medium sand. This layer was found at the depth between 2.3 m and 20 m. The third layer has medium resistivity value of 30 Ωm encountered at the depth between 20 m and 47 m. This layer has total thickness of 26 m and has been interpreted as fine sand. The fourth layer has high resistivity value of 114 Ωm. This layer has been interpreted as medium sand. Curve break (CB) in the field curve indicates fine sand layer at the depth beyond 130 m (Figure 4b and Figure 5b).

3.10.3 Site 3: Danipur

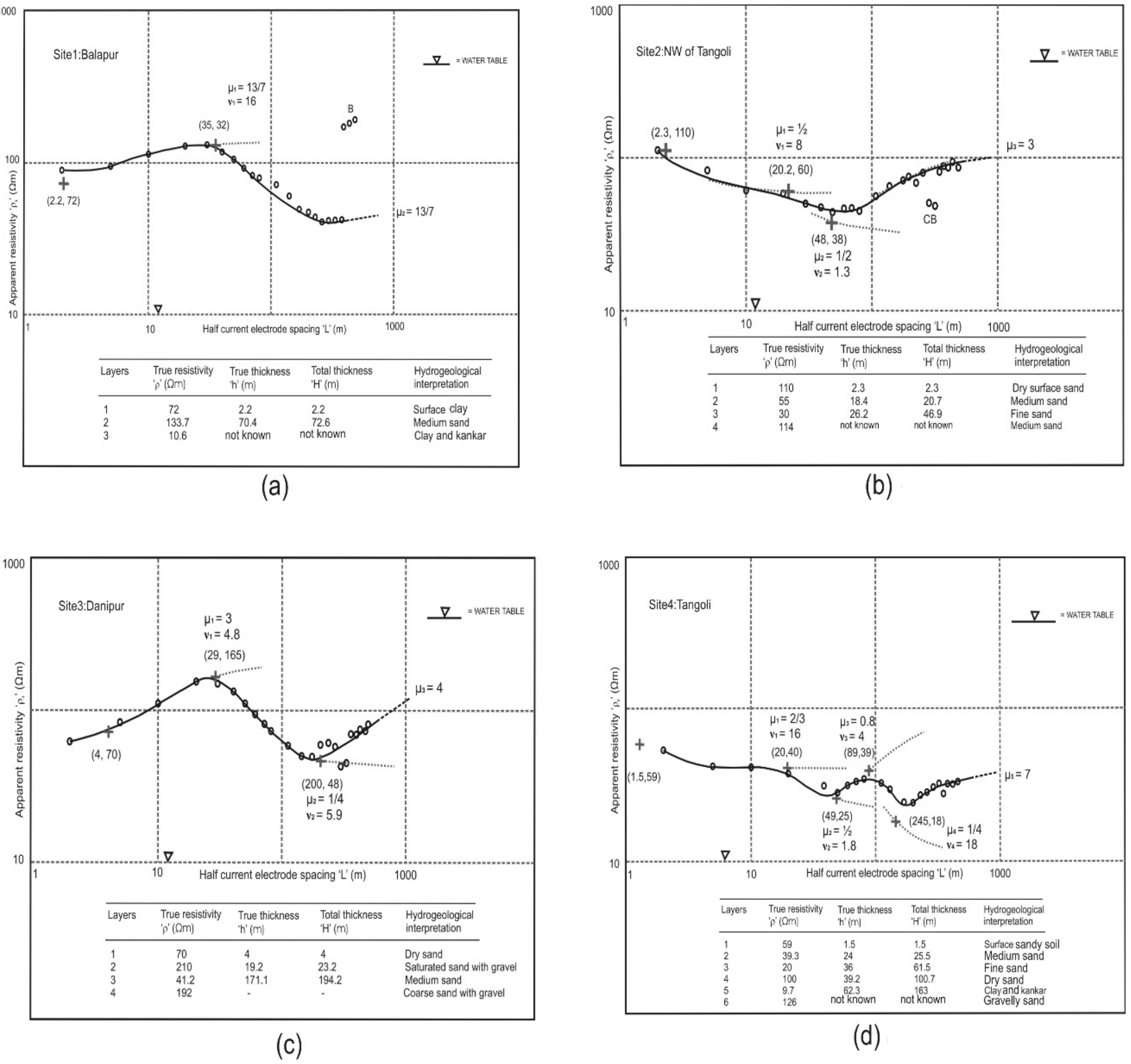
The field curve from Schlumberger configuration at Danipur revealed four subsurface layers ranging resistivity value from 70 Ωm to 192 Ωm. The topmost layer has resistivity value of 70 Ωm and thickness of 4 m. This layer has been related to dry surface sand. The second layer has high resistivity value of 210 Ωm and thickness of 19 m. This layer has been interpreted as dry sand. The third layer shows resistivity value of 41 Ωm and thickness of 171 m. This layer has been interpreted as medium sand. The fourth layer, shows high resistivity of 192 Ωm indicating gravelly sand (Figure 3c and Figure 4c).

3.10.4 Site 4: Tangoli

The field curve obtained from Schlumberger configuration at Tangoli recognizes six subsurface layers of different resistivity values. The topmost layer has relatively high resistivity of 59 Ωm and thickness of 1.5 m. This layer has been well related to surface sandy soil. The second layer shows relatively low resistivity value of 40 Ωm and thickness of 24 m. This layer has been interpreted as medium sand. The third layer has low resistivity of 20 Ωm and thickness of 31 m. This layer was encountered at the depth between 25 m and 61 m, and has been interpreted as fine sand. The fourth layer has high resistivity value of 100 Ωm and thickness of 39 m. This layer has been interpreted as dry sand.

Table 3: Interpreted results of Vertical Electrical Resistivity Sounding (VES) from Schlumberger configurations at Kurukshetra district, Haryana, India

Site No.	Name of location	Geographic Lat/Long	No. of layers	Resistivity value (Ωm)	Thickness (meter)	Total depth (meter)	Geological interpretation
1	Balapur	30^0 06′18″N 76^0 33′34″E	I	72	2.2	2.2	Surface clay
			Ii	134	70	72.2	Medium sand
			Iii	11	Not known	Not known	Clay and kankar
2	NW of Tangoli	30^0 06′19″N 76^0 31′30″E	I	110	2.3	2.3	Dry surface sand
			Ii	55	18	20.3	Medium sand
			Iii	30	26	46.3	Fine sand
			Iv	114	Not known	Not known	Medium sand
3	Danipur	30^0 06′02″N 76^0 32′40″E	I	70	4	4	Dry surface sand
			Ii	210	19	23	Dry sand
			Iii	41	171	194	Medium sand
			Iv	192	Not known	Not known	Gravelly sand
4	Tangoli	30^0 05′11″N 76^0 31′56″E	I	59	1.5	1.5	Surface sandy soil
			Ii	40	24	25.5	Medium sand
			Iii	20	31	56.5	Fine sand
			Iv	100	39	95.5	Dry sand
			V	10	62.3	157.8	Clay and kankar
			Vi	126	Not known	Not known	Gravelly sand



(a)

Layers	True resistivity 'ρ' (Ωm)	True thickness 'h' (m)	Total thickness 'H' (m)	Hydrogeological interpretation
1	72	2.2	2.2	Surface clay
2	133.7	70.4	72.6	Medium sand
3	10.6	not known	not known	Clay and kankar

(b)

Layers	True resistivity 'ρ' (Ωm)	True thickness 'h' (m)	Total thickness 'H' (m)	Hydrogeological interpretation
1	110	2.3	2.3	Dry surface sand
2	55	18.4	20.7	Medium sand
3	30	26.2	46.9	Fine sand
4	114	not known	not known	Medium sand

(c)

Layers	True resistivity 'ρ' (Ωm)	True thickness 'h' (m)	Total thickness 'H' (m)	Hydrogeological interpretation
1	70	4	4	Dry sand
2	210	19.2	23.2	Saturated sand with gravel
3	41.2	171.1	194.2	Medium sand
4	192	-	-	Coarse sand with gravel

(d)

Layers	True resistivity 'ρ' (Ωm)	True thickness 'h' (m)	Total thickness 'H' (m)	Hydrogeological interpretation
1	59	1.5	1.5	Surface sandy soil
2	39.3	24	25.5	Medium sand
3	20	36	61.5	Fine sand
4	100	39.2	100.7	Dry sand
5	9.7	62.3	163	Clay and kankar
6	126	not known	not known	Gravelly sand

Figure 3: Interpretation of Schlumberger resistivity field curves with hydrogeological interpretation at Balapur (a), NW of Tangoli (b), Danipur (c) and Tangoli (d), Haryana, India.

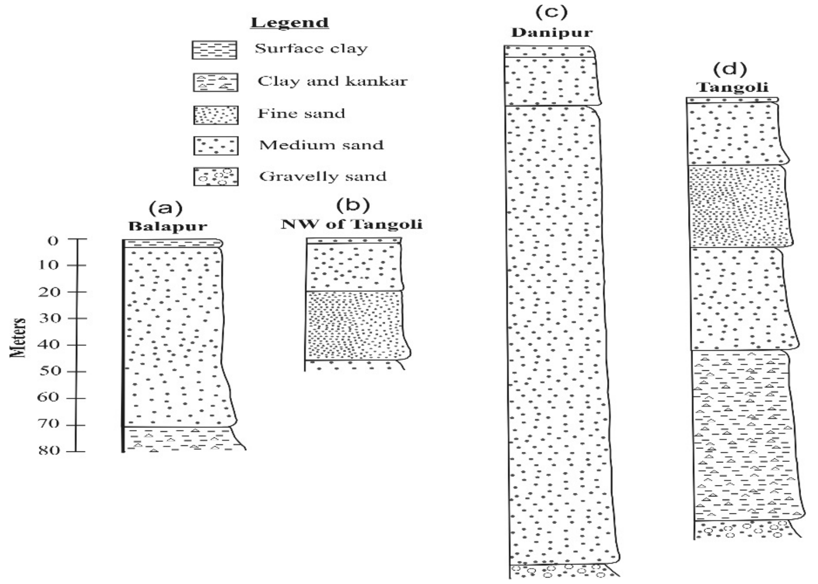


Figure 4: Resistivity log sections at Balapur (a), NW of Tangoli (b), Danipur (c) and Tangoli (d), Haryana, India

The fifth layer has low resistivity value of 10 Ωm and thickness of 62.3 m. This layer has been interpreted as clay and kankar. The sixth layer has high resistivity value of 126 Ωm indicating gravelly sand (Figure 3b and Figure 4b).

Table 4: Transverse resistance values for subsurface aquifer horizons at Kurukshetra district, Haryana, India

Name of VES Site	Total Resistivity value ‘ρ’ (Ωm)	Aquifer zone (meter)	Depth range of aquifer horizon (meter)	Transverse resistance(Ωm^2)
Balapur	134	Medium sand	2 to 70	9380
NW of Tangoli	85	Medium sand	2 to 44	990
		Fine sand		780
Danipur	251	Dry sand	4 to 190	3990
		Medium sand		7011
Tangoli	160	Medium sand	2 to 94	960
		Fine sand		620
		Dry sand		3900

4. Conclusion

Over the years, the demand for groundwater has increased manifold due to swelling population, increasing industrialization and intensive agriculture in the NW part of India. Also, the available per-capita water resource has been reduced due to generally declining groundwater table. Therefore, there is urgent need to plan for groundwater development using applied methods. One of such method is morphometric analysis along with geoelectrical method. The morphometric attributes may be evaluated with reference to the groundwater prospect, and the geoelectrical investigation may be applied for the appraisal of the morphometric result. The morphometric analysis indicates that the drainage network of the Markanda basin is marked by dendritic pattern in nature. This may be due to more or less homogeneous lithology and less structural controls. The average drainage density of the Markanda basin is 1.25 km/km^2 indicating coarse drainage texture and the nature of the geological materials (sandstone and alluvium) are highly permeable. High drainage density is observed over the hilly terrain of Siwalik sandstones and shales, while low drainage density is observed over the highly permeable alluvium of Gangetic Plain. Low drainage density areas are more favourable for identification of groundwater potential zones. The form factor value of the basin (0.12) indicates elongated basin. The elongated basin with low form factor indicates that the basin will have a flatter peak of flow for longer duration and hence flood flows can be managed efficiently. The circularity ratio value of the basin (0.31 km^2/km) indicates elongated basin with low discharge of runoff and highly permeability of the subsoil condition. The relief ratio of the basin (0.017) indicates less resistant rocks resulting in infiltration. The interpretation result of four VES surveys carried out within the basin revealed that there are many potentially extensive and productive subsurface aquifer horizons. These aquifer layers are recognized as fine sand (20 Ωm to 30 Ωm), medium sand (40 Ωm to 134 Ωm), gravelly sand (126 Ωm to 192 Ωm), and dry sand (70 Ωm to 210 Ωm). The average thickness of fine sand layer is 28.5 m, for medium sand layer, it is 70.75 m and for dry sand layer, it is 28.5 m. The transverse resistance (TR) values for aquifers at the survey sites are calculated to be 620 Ωm^2 to 9380 Ωm^2. The TR value for dry sand ranges from 3900 Ωm^2 to 3990 Ωm^2, while the same for that of fine sand and medium sand ranges from 620 Ωm^2 to 780 Ωm^2 and 960 Ωm^2 to 9380 Ωm^2 respectively. The highest TR value is found in medium sand and lowest in fine sand. The TR values of aquifer layers at Balapur, NW of Tangoli, Danipur and Tangoli are calculated to be 9380 Ωm^2, 1770 Ωm^2, 11001 Ωm^2 and 5480 Ωm^2 respectively (Table 3). The best TR value is observed at Danipur site and poorest TR value is observed at NW of Tangoli. The TR values of these aquifer horizons suggest promising groundwater prospect as it is evident by successfully installed tubewells in these locations. Thus, the present study shows implementation of morphometry and geoelectrical methods together to assess the groundwater potential in a river basin located in Himalayan foothill. Such studies are very useful for rainwater harvesting and watershed management plans.

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