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# A numerical scheme for groundwater development in a watershed basin of basement terrain: a case study from India

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**Abstract** The development of watershed basins to increase groundwater recharge potential is becoming a major issue in India due to an acute shortage of groundwater resources, resulting from the marked expansion of land-use activities and the explosive growth in population. It is necessary to study the regional characteristics in order to identify potential artificial groundwater recharge zones. A combination of morphometric analysis coupled with hydrogeological information is used to prepare a generalized scenario for watershed development plans. A numerical scheme is, thus, proposed for the relative evaluation of surface rock-permeability in relation to morphometry (stream order, stream length, drainage density, channel maintenance, overland flow, basin shape, etc.). An attempt is made, from the morphometrical studies of the Varaha watershed of the Precambrian Eastern Ghats basement terrain in Eastern India, to illustrate how the numerical scheme is helpful as a tool in watershed development planning programs. This method involves the designation of various recharge-related measures, based upon the relative ranking of surface-material permeability after comparison with the hydrogeological conditions of sub-basins of the river basin. The scheme can also help to pin-point areas of study on a local scale, and thus facilitate developmental programs to augment groundwater recharge.

**Keywords** Morphometric analysis · Hydrogeological conditions · Numerical scheme · Basement terrain · India

## Introduction

The growth of population, in countries like India, and the consequent development, leads to increasing stress on

water use, such as for drinking, irrigation and industrial needs. The increase in the usage of water has affected both surface and groundwater supplies, resulting in an acute water crisis. In addition, low intensity and erratic monsoons create further shortages of surface-water supply. As a result, the demand for groundwater resources has increased tremendously from year to year, causing a drastic decline of groundwater levels. Over-exploitation of groundwater has led to the drying up of the aquifer zones in several parts of the country. Efficient management planning for watershed development is, therefore, essential to increase the recharge of the basin. The siting of facilities to enhance the recharge is also of great importance in planning the development of watershed programs.

Infiltrating recharge water, to reach the groundwater body, depends on the surface rock-permeability, which is, generally, low, especially in the hard rock terrain (Precambrian basement) of Central and Southern India (Fig. 1). Topographical, geomorphological, hydrological, geological and hydrogeological conditions play a significant role in the planning and execution of measures to be undertaken in watershed development programs. For example, topographic features can be considered in the selection of favourable sites in most of the recharge areas. Evaluation of the drainage characteristics of a basin, using quantitative morphometric analysis in relation to geomorphological features, which can provide useful information on the hydrological nature of rocks exposed within the drainage basin, is a reliable index of rock-permeability and also gives an indication of yield of the watershed basin (Wisler and Brater 1959). The hydrogeological conditions of the host rocks, which depend on the degree of weathered and fractured zones, give an indication of occurrence, movement and storage of groundwater as well as the sources of recharge of the groundwater (Fetter 1990). The combination of these factors can give useful clues about the nature of the geological framework of a watershed, surface water flow and the recharge potential. Hence, this integrated approach can be useful in developing an effective plan for the identification of suitable sites for recharge and water harvesting, and thereby increasing the available resources.

The interrelationship between rock type, structures and drainage network in different parts of India has been studied by Vaidyanadhan (1962 and 1964), Mukhopadhyay (1973),

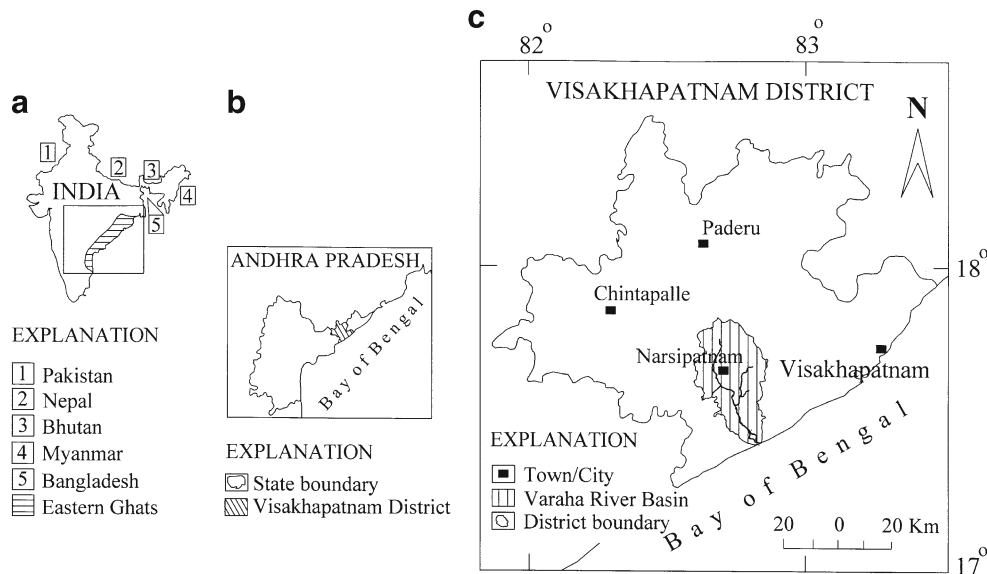
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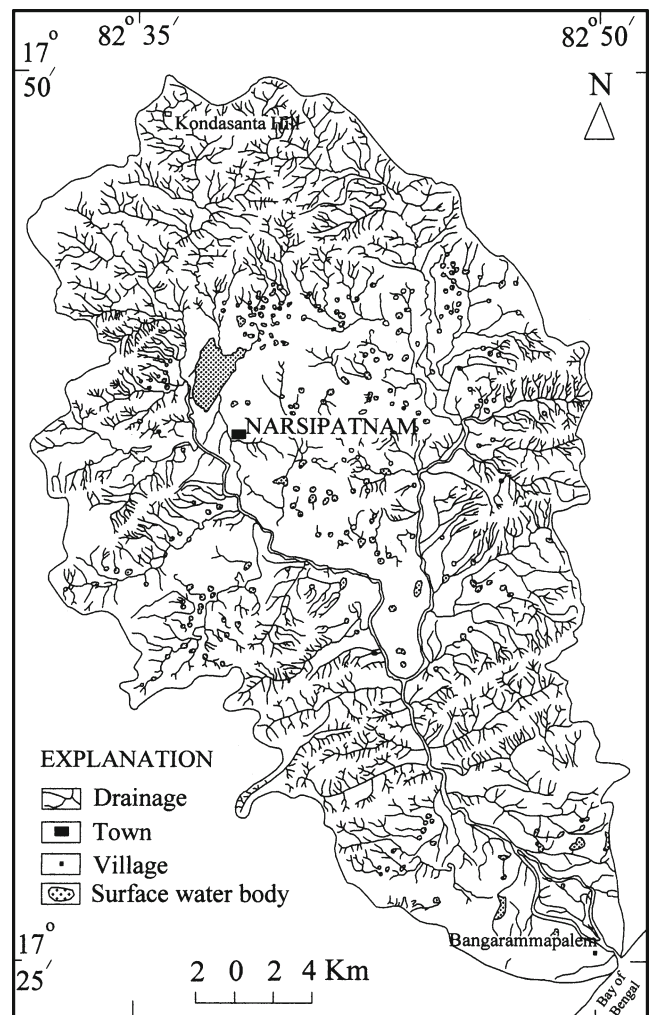
**Fig. 1** a Location of the Eastern Ghats in India (after Ramkrishnan and Vaidyanadhan 2008), b location of the Visakhapatnam District in the State of Andhra Pradesh and c location of the Varaha River Basin in the Visakhapatnam District

Kaila et al. (1979), Sankara Pitchaiah and Rao (1985), Sinha Roy (1985), Moeen and Babu (1988), Varadarajan and Ganju (1989), Raju et al. (1995), Rao and Babu (1995), Pakhmode et al. (2003), Gangalakunta et al. (2004), Sreedevi et al. (2005), John Devadas et al. (2006), and Manu and Anirudhan (2008). The aim of the present paper is to establish the numerical relationship between morphometric analysis and hydrogeological information for a comprehensive understanding and relative evaluation of the surface-material permeability, and also for selecting suitable sites for recharging the groundwater on a regional scale. However, the present study is focused mainly on the available data. More comprehensive evaluations could be made in the future by incorporating additional data on vegetation, the quantification of rock-permeability and probability of the rate of recharge of the groundwater in the different geological formations on the basis of the rate of rainfall, which are critical for determining the infiltration behavior of the ground surface. To illustrate the numerical relation between morphometric analysis and hydrogeological conditions, an attempt has been made, with the available data, for the Varaha River Basin located in Visakhapatnam District, Andhra Pradesh, India (Fig. 1), and which is underlain by the hard rocks of the Precambrian Eastern Ghats basement.

## Study area

### Location and climate

The Varaha River Basin in the eastern part of India is located between longitudes 82°30'–82°53' E and latitudes 17°23'–17°55' N (Fig. 2). The area occupied by the river basin covers 1,133 km<sup>2</sup> and distributed within it are about 290 villages, with a population of 0.4 million. The climate

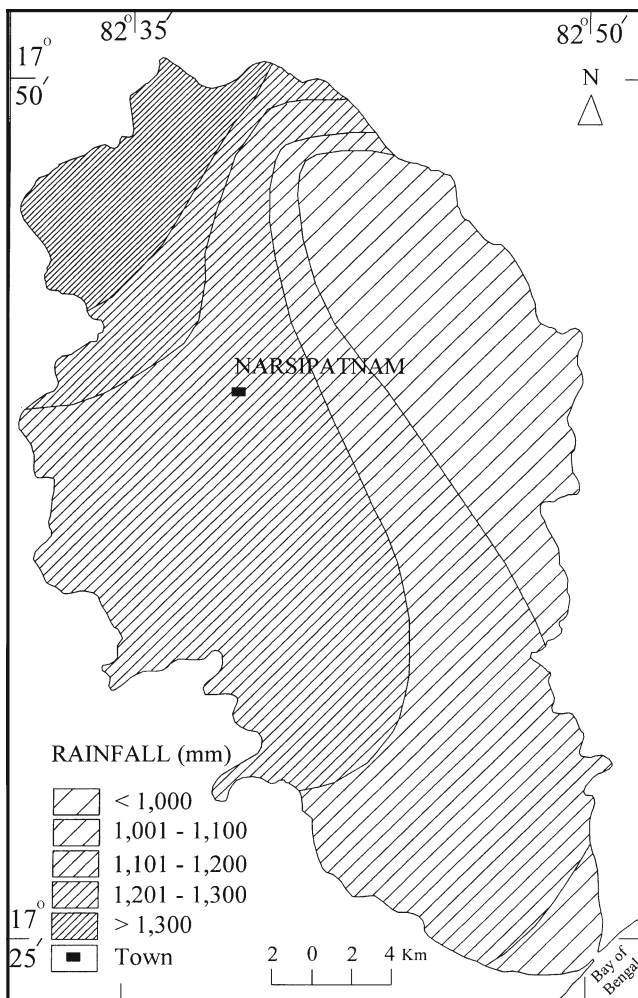


**Fig. 2** Drainage of the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

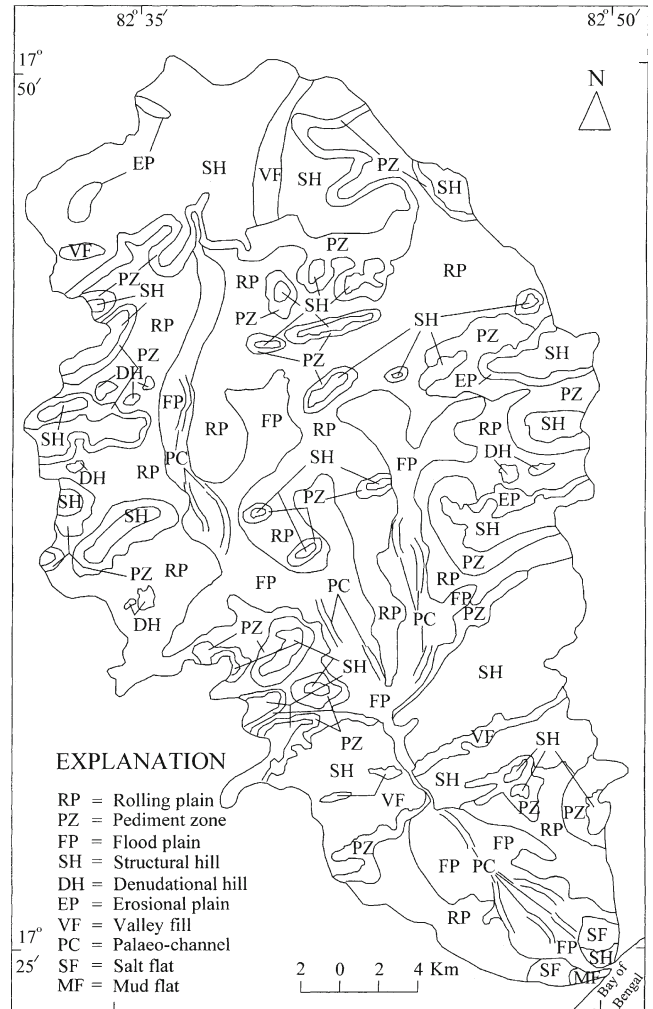
of the area is sub-tropical. The average annual temperature ranges from 20°C in winter (December–February) to 36°C in summer (March–May). The basin receives an average annual rainfall of about 1,210 mm, with significant seasonal variations (Subba Rao 2008). The maximum rainfall (58%) precipitates during the south-west monsoon (June–September). The north-east monsoon (October–November) contributes 28% of the total rainfall. The rest of the rainfall (14%) comes in the remaining period of the year. However, the area also receives heavy rain due to cyclones that come from the Bay of Bengal (Rao and Babu 1995). Very high rainfall (>1,300 mm) occurs in the northwestern part and very low rainfall (<1,000 mm) in the northeastern and southeastern parts (Fig. 3).

**Geomorphology**

Geomorphic features observed in the study area are denudational hill, erosional plain, structural hill, pediment zone, rolling plain, flood plain, palaeo-channel, valley fill, salt flat and mud flat (Fig. 4). The denudational hills occur



**Fig. 3** Spatial distribution of rainfall in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

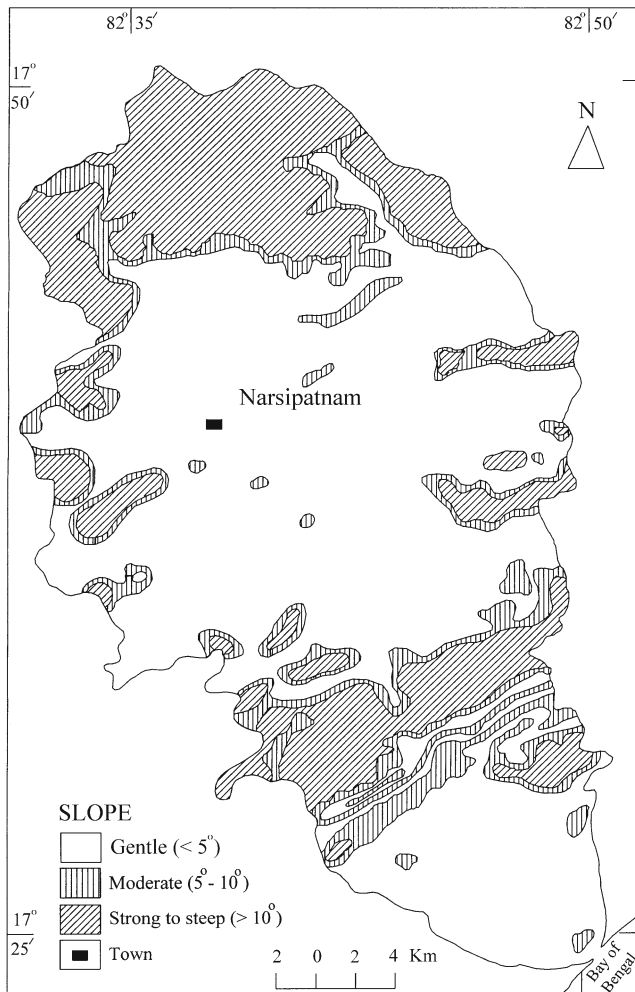


**Fig. 4** Geomorphological features in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India (after Subba Rao 2008)

as isolated zones in the eastern and western parts, with a high relief of 400 to 600 m above mean sea level (amsl). They are covered with various sizes of boulders and sparse vegetation. The isolated erosional plains are observed in the eastern and northwestern parts of the area. The structural hills, resulting from structural disturbances, are observed in the northern, eastern, western and southern parts, and are made up of resistant rocks, with sharp, conical, rocky, narrow to broad and rounded summits. They have a strong to steep slope (>10°: Fig. 5). The fault scarps formed by the surficial processes on the structural hills are visible as bare rock surfaces. Due to strong to steep slope of the structural hills, debris has been deposited by the fluvial action, with the thickness increasing from the foot-hills towards the plains. The pediment zones occur in the foot-hills of the structural hills, and are developed by a combination of erosion, weathering, sheet wash and plantation, with gentle (<5°) to moderate (5°–10°) slopes.

Most of the river basin is covered by rolling plain (Fig. 4), with an altitudinal variation of 2–15 m amsl,





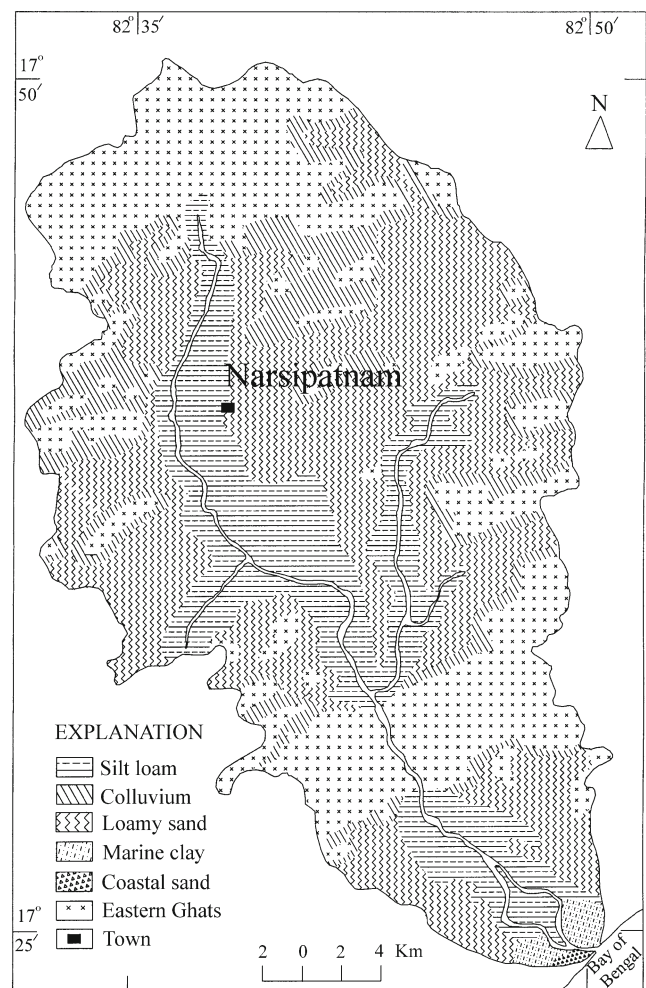
**Fig. 5** Slope in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

resulting from the differential erosion and deposition of materials. The flood plain, formed by the processes of erosion and deposition of gravel, pebbles, sand, silt and clay, has a gentle slope of  $5^\circ$  along the river course. In the upper reaches, the width of the flood plain is narrow, while in the lower reaches, it is much wider. The palaeochannels are observed in the upper, middle and lower parts of the flood plain. The valley fills are a result of the weathering and deposition by the action of streams of materials like boulders, cobbles, pebbles, gravels, sand, silt and clay. The area occupied by the valley fills shows a gentle slope. In the coastal plain, salt flats and mud flats occur, which are gently sloping. The study area is, therefore, characterized by the undulating topography, sloping towards the southeast.

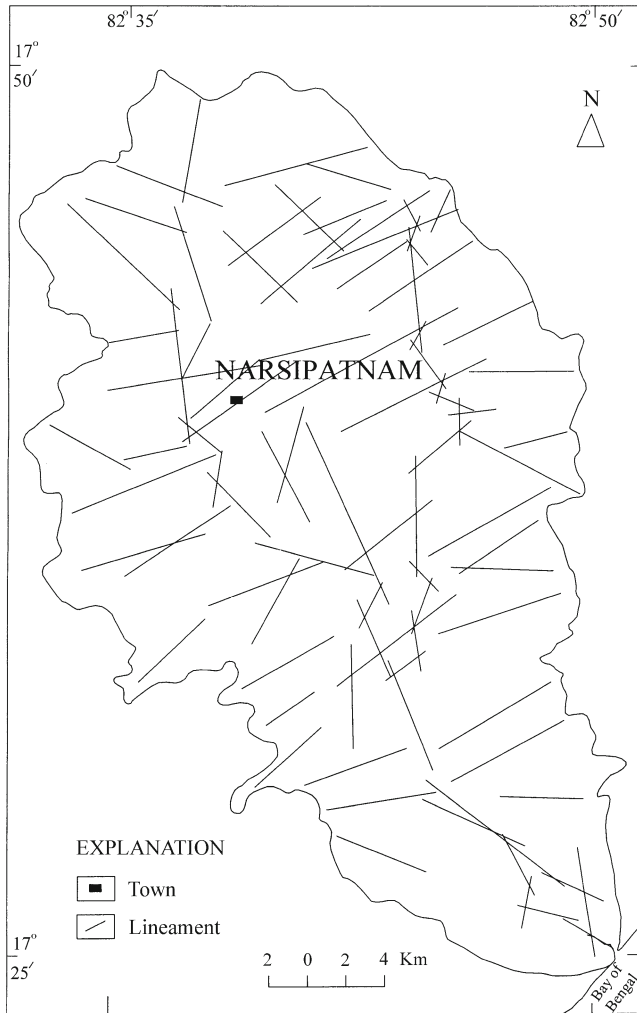
The River Varaha originates in a part of the Eastern Ghats mountain range (Kondasanta Hill) at an altitude of about 1,165 m amsl, and flows 62 km southeastwards to join the Bay of Bengal (Fig. 2). The drainage is mostly dendritic and is ephemeral in nature. A number of tanks (surface-water bodies) are seen on the surface.

## Geology

Geological units in the Varaha watershed basin belong to the Precambrian Eastern Ghats and Recent Formations (Fig. 6). The Precambrian rocks include khondalites and charnockites, with quartzite, migmatite, pegmatite, and granite intrusives. The khondalites are the most dominant rocks, while the charnockites occur as isolated pockets. The mineral assemblages of the former rocks are quartz, plagioclase, orthoclase, garnet, sillimanite, apatite, biotite and opaques, with medium to coarse-grained and gneissic texture. The latter rocks consist of minerals of quartz, orthoclase, plagioclase, ortho- and clino-pyroxenes, garnet, biotite, apatite, zircon and opaques, with fine to medium-grained and granulitic texture. The direction of foliation of the rocks is NE–SW, with a deviation towards the NNW–SSE, N–S and NNE–SSW, with a dip of  $70^\circ$  southeast due to structural disturbances of the Eastern Ghats. Most lineaments show the NE–SW trend (Fig. 7), following the general strike (NE–SW) of the Eastern Ghats (Fig. 8).



**Fig. 6** Geology of the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India (after Subba Rao 2008)

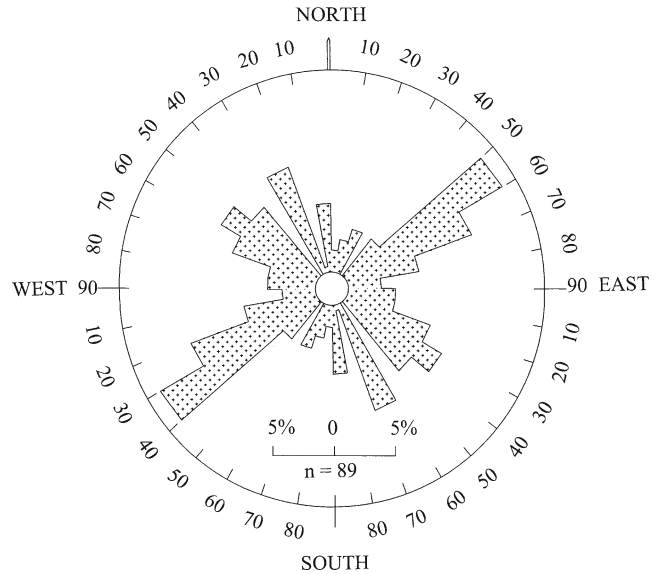


**Fig. 7** Lineaments in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India (after Subba Rao 2008)

The Recent Formations, occurring over the basement rocks, include silt loam, loamy sand, colluvium, coastal sand and marine clay (Fig. 6), with fine to coarse-grained textures. A  $\text{CaCO}_3$  concretion, locally known as *kankar*, occurs as intercalations in the soil zone.

### Hydrogeology

The hard rocks (Precambrian Eastern Ghats) of the Varaha River Basin lack primary porosity. Secondary porosity, due to weathering and tectonic activities, causing the development of weathered rock and fracture zones within the hard rock, is very important. The weathered product is mostly clayey in nature because of the higher content of feldspar in the country rocks (Subba Rao 1992) and hence, it has lower permeability. This type of weathered product is capable of storing only a limited amount of groundwater. The fractured zone acts as a good aquifer formation by virtue of its higher permeability, thus facilitating the storage and movement of groundwater. However, this



**Fig. 8** Orientation of lineaments in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

zone reduces in thickness, with depth (Davis and Turk 1964; Vincent 1979; Subba Rao 1992).

The sub-surface geology of the study area (Fig. 9) shows that the depth of the topsoil is from 2 to 3 m from the ground surface. The topsoil is followed by a clayey sand zone (2–5 m depths below ground level), a sandy clay zone (5–10 m), a clayey sand zone (10–15 m), a sandy clay zone (14–20 m), a weathered zone (17–47 m) and a fractured zone (indefinite) near the river, while the topsoil is followed by a clayey sand zone (2–5 m), a sandy clay zone (2–7 m), a weathered zone (6–25 m) and a fractured zone (20–55 m) away from the river. Hard rock is observed below the weathered and fractured rocks.

The development of groundwater is through shallow hand dugwells and deep drilled boreholes. The diameter of the shallow wells ranges from 3 to 12 m. The groundwater is used for both drinking and irrigation. Groundwater exists under unconfined conditions in both the weathered and fractured zones. The alluvial deposits, occurring in the river basin, are essentially composed of various proportions of silt, clay, sand, gravel and pebbles. The coastal sands are composed of mostly sand, with a little clay, while the marine clay consists of silt and clay, with a little sand. Alternating layers of clayey sand and sandy clay, observed at different depth levels near the River Varaha on the lithologs (Fig. 9), support a multi-aquifer system under confined conditions.

### Morphometric analysis

Morphometry is a measurement and mathematical analysis of the configuration of the earth's surface, and of the shape and dimensions of its landforms. The quantitative analysis of the morphometric characteristics of a watershed basin

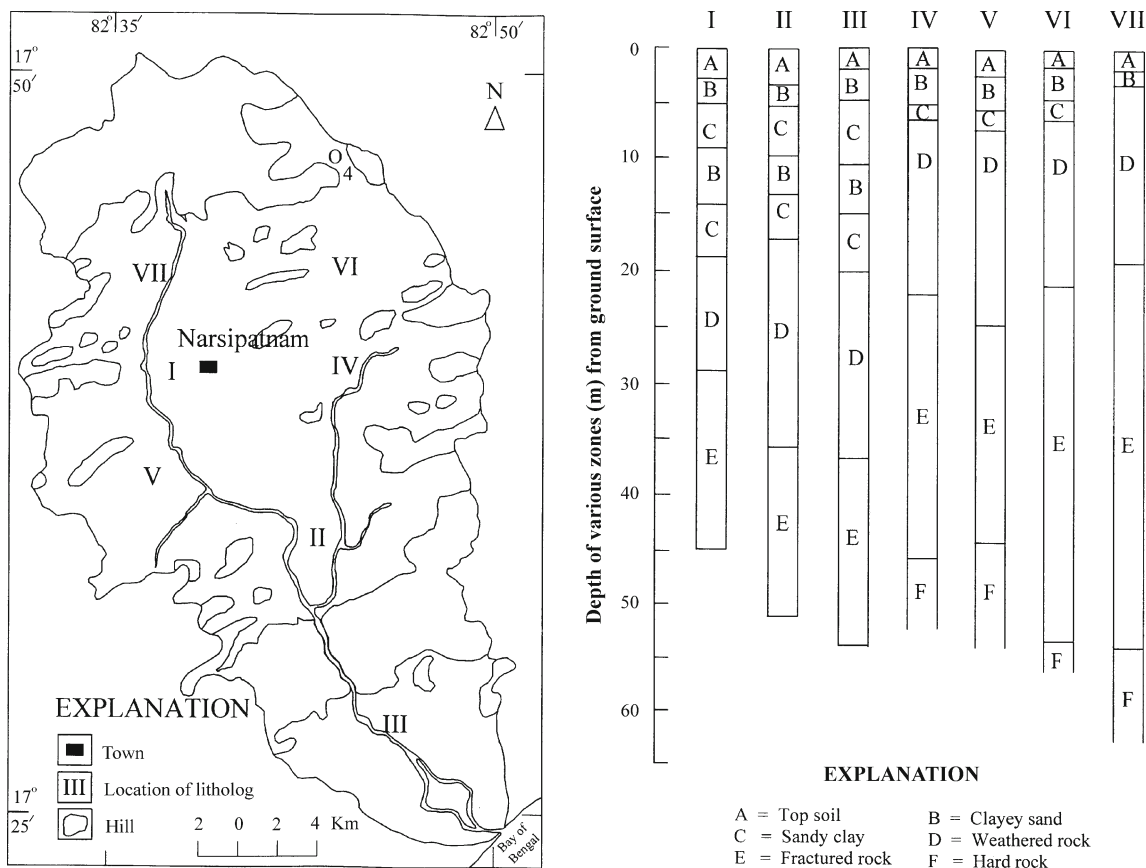


Fig. 9 Lithologies in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

covers two aspects: (1) linear aspects and (2) areal aspects. The former includes stream orders, bifurcation ratio, stream lengths and stream length ratio, while the latter includes drainage density, constant of channel maintenance, length of overland flow, stream frequency, drainage texture, circularity ratio and elongation ratio. These are the important drainage characteristics required for an assessment of a watershed development plan, in association with hydrogeological information.

The linear and areal aspects, denoting the structural characteristics of the underlying hard rocks, are studied in the Varaha River Basin, using the Survey of India Topographical Maps 65 K/9, 65 K/10, 65 K/11, 65 K/13, 65 K/14 and 65 K/15 on a scale of 1:50,000, and following the methods of Horton (1932, 1945), Strahler (1952 and 1964), Schumm (1956), Chorley (1957) and Melton (1958). Calculation of the linear and areal aspects is made as given by Dornkamp and King (1971).

Hydrogeological setting is a composite description of all the geological and hydrological factors, controlling the groundwater flow into, through, and out of an area. Morphometric analysis in relation to hydrogeological conditions, especially in hard rock terrain, is a complex task, because of the variation of rock-permeability from place to place, which controls the rate of run-off and infiltration. Hence, a numerical scheme for the relative ranking of drainage characteristics is proposed for an easy

understanding and relative evaluation of the permeable rocks in relation to a watershed development plan of the area. In this scheme, the average values of the linear and areal aspects, and also their standard limits suggested by earlier researchers (Smith 1950; Strahler 1957 and 1964; Chow 1964; Dornkamp and King 1971) are taken into account to classify the relative evaluation (ranking) of the surface-material permeability. For understanding an overall scenario of the watershed development plan, and also for convenience and to avoid ambiguity in too many classes on a regional scale, the evaluation system in the numerical scheme is broadly categorized into three classes. This overall picture could be very helpful for further pin-pointing study of the watershed development programme on a local scale.

The classes, which are categorized broadly for the relative evaluation of the surface rock-permeability, are expressed numerically. The determination of the weight of each class is the most crucial part in an integrated analysis, as the consideration of relative importance leads to a better representation of the actual ground situation. Hence, a weight is assigned to each class in accordance with its relative importance. The weight ranges from 1 (least significant) to 3 (most significant), as shown in Table 1. For example, the rock formations, which are associated with gentle ground slopes, form highly permeable surfaces, with low run-off, providing more opportunity for the

**Table 1** Criteria for relative evaluation of surface rock-permeability in relation to ground slope, rock surface, nature of streams, run-off, infiltration and weight in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Relative surface rock-permeability	Ground slope	Rock-surface	Nature of streams	Run-off	Infiltration rate	Weight
Low	Steep	Fine-grained	Larger number of shorter stream lengths	High	Low	1
Medium	Moderate	Medium-grained	Medium number of medium stream lengths	Medium	Medium	2
High	Gentle	Coarse-grained	Smaller number of longer stream lengths	Low	High	3

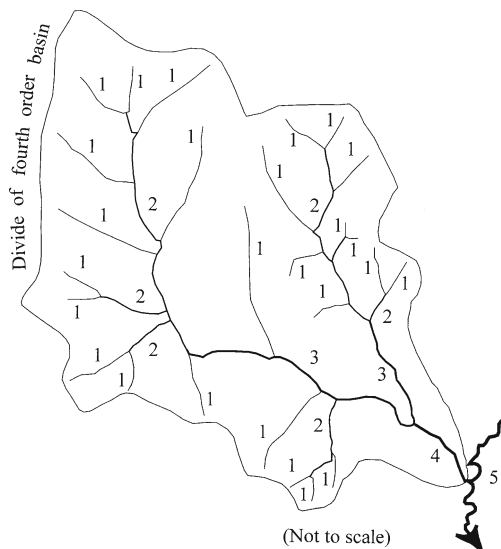
recharge water to infiltrate into the aquifer zone, and thus these formations receive the highest weight of 3. The rock surfaces, which are coarse-grained, enable more recharge water to infiltrate into the aquifer system by virtue of the higher permeability and fracture porosity of the hard rocks, while the areas of a smaller number of relatively longer stream lengths also characterize the higher rock-permeability. The highest weight of 3 is, therefore, assigned to the areas associated with coarse-grained rock formations as well as with smaller number of longer stream lengths.

**Stream order**

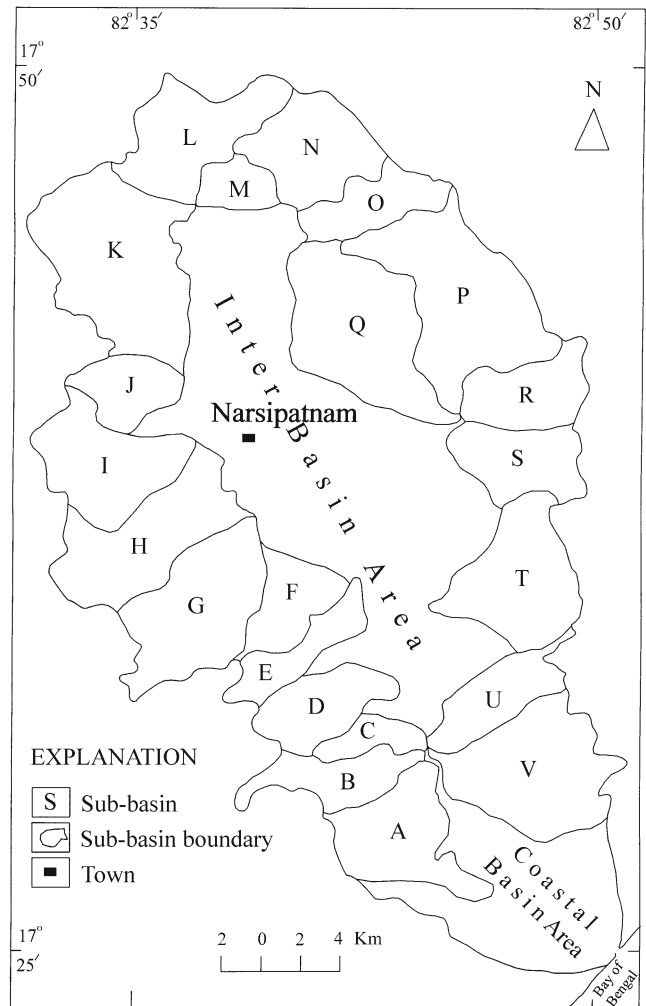
The first step in the morphometric analysis of a basin is designation of stream orders. The stream order (u) is a dimensionless number, which can be used for comparison of geometry for drainage networks on different linear scales. The drainage network of the Varaha River Basin is classified into stream orders, as followed by Strahler (1952). In this analysis, the smallest fingertip tributaries are designated as first-order streams; where the two first-order streams join, a second-order stream is formed; where the two second-order streams join, a third-order stream is developed and so on (Fig. 10). The main stream through

which all the discharge of water passes is, therefore, considered as the stream of the highest order.

The Varaha watershed basin is divided into 22 sub-basins (Fig. 11), which are designated as ‘A’ to ‘V’ for the analysis and for comparative evaluation of the drainage basins in relation to hydrogeological conditions. All the sub-basins in the river basin have fourth-order streams (Table 2). However, relatively few smaller streams of lower orders are observed in the inter-basin area, joining the main river course (Fig. 2). As their number is small,



**Fig. 10** Designation of the stream orders (after Strahler 1957) in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India



**Fig. 11** Sub-basins in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India



**Table 2** Basin area, basin length, basin perimeter, number of streams and bifurcation ratio of the sub-basins in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Sub-basin	Basin area (a; km <sup>2</sup> )	Basin length (l; km)	Basin perimeter (p; km)	Number of streams (Nu) of different stream order (u)					Bifurcation ratio Rb (Nu/Nu+1)			
				1	2	3	4	∑Nu	1/2	2/3	3/4	Av <sup>a</sup>
A	37.40	10.10	28.90	43	9	2	1	55	4.78	4.50	2.00	3.76
B	16.35	10.30	24.40	69	16	2	1	88	4.31	8.00	2.00	4.77
C	10.52	6.10	14.15	66	14	2	1	83	4.71	7.00	2.00	4.57
D	28.10	8.20	19.60	85	20	3	1	109	4.25	6.67	3.00	4.64
E	19.15	6.30	23.70	44	9	2	1	56	4.89	4.50	2.00	3.80
F	19.70	6.50	19.80	41	12	3	1	57	3.42	4.00	3.00	3.47
G	52.30	12.25	28.75	55	15	3	1	74	3.67	5.00	3.00	3.89
H	53.50	11.30	31.50	85	20	4	1	110	4.25	5.00	4.00	4.42
I	47.00	8.00	25.95	70	18	4	1	93	3.89	4.50	4.00	4.13
J	20.00	5.90	16.00	72	15	2	1	90	4.80	7.50	2.00	4.77
K	59.00	12.00	31.80	174	36	6	1	217	4.83	6.00	6.00	5.61
L	41.45	10.45	27.55	137	31	6	1	175	4.42	5.17	6.00	5.20
M	11.70	4.60	14.00	33	8	2	1	44	4.13	4.00	2.00	3.38
N	31.90	5.80	23.75	83	18	6	1	108	4.61	3.00	6.00	4.54
O	20.00	7.90	18.00	43	15	4	1	63	2.87	3.75	4.00	3.54
P	81.10	13.50	37.70	65	20	5	1	91	3.25	4.00	5.00	4.08
Q	63.60	12.25	31.10	48	15	3	1	67	3.20	5.00	3.00	3.73
R	27.80	8.00	21.50	80	20	5	1	106	4.00	4.00	5.00	4.33
S	32.65	8.25	23.00	79	12	3	1	95	6.58	4.00	3.00	4.53
T	42.20	10.20	26.20	74	16	6	1	97	4.63	2.67	6.00	4.43
U	22.85	8.10	24.00	68	15	2	1	86	4.53	7.50	2.00	4.68
V	56.60	10.20	28.50	32	8	2	1	43	4.00	4.00	2.00	3.33
Av <sup>b</sup>	36.13	8.92	24.54	70.27	16.45	3.50	1	91.23	4.27	4.99	3.50	4.25

<sup>a</sup> average<sup>b</sup> average (basin as a whole)

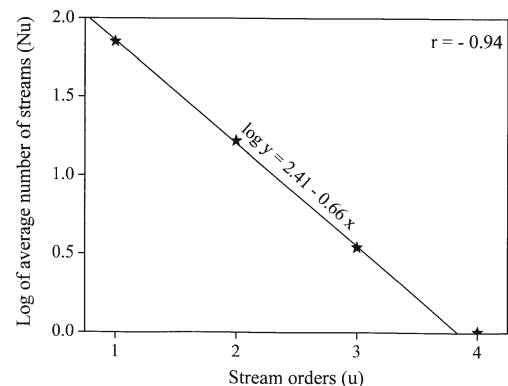
they are less reliably representative (Strahler 1954) and hence, they are not counted here.

The total number of streams ( $\sum Nu$ ) in the sub-basins of the river basin varies from 43 (sub-basin V) to 217 (sub-basin K), being an average of 91.23 (Table 2). In the sub-basins, the number of first-order streams is 32–174 (total 1,546; average 70.27), the second-order streams 8–36 (total 362; average 16.45), the third-order streams 2–6 (total 77; average 3.50) and the fourth-order streams 1 (total 22; average 1). The first-order streams originate from different places at topographic-highs and the consequent streams join finally as a main stream at topographic-lows so that the higher number of streams is observed in the first-order streams and the lower number of streams in the fourth-order streams. The lower number of streams (1–6) in the third- and fourth-orders of the sub-basins indicates the occurrence of mature topography adjacent to the stream concerned, while the higher number of streams (8–174) in the first- and second-orders of the sub-basins indicates that the topography is still under erosion, as it is observed in the field.

The fourth-order river basin covers an average area of 36.13 km<sup>2</sup> (Table 2). The sub-basin C covers the lowest area of 10.52 km<sup>2</sup>, while the sub-basin P covers the highest area of 81.10 km<sup>2</sup>. The remaining sub-basins A, B, D–O and Q–V have their coverage areas between the areas covered by the sub-basins C and P. The variation in the stream orders and their coverage areas is caused by the differences in the physiographic and structural conditions (Sreedevi et al. 2005). The average length (l) of a sub-basin within the

whole Varaha River Basin is 8.92 km. The shortest sub-basin length (4.60 km) is found in the sub-basin M, while the greatest length (13.50 km) is found in the sub-basin P. The perimeter (p) of the sub-basins varies from 14.00 km (sub-basin M) to 37.70 km (sub-basin P), with an average of 24.54 km.

The geometric relation between the logarithm of average number of streams (Nu) and stream orders (u) is illustrated in Fig. 12. This shows an inverse linear relationship ( $r = -0.94$ ) because the number of streams (Nu) decreases as the stream order (u) increases. Further, there is a small deviation of plotting points from the straight line in Fig. 12, which supports the Horton's Law



**Fig. 12** Relation between stream orders and number of streams in the whole Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India



of Stream Numbers (Horton 1945). The Law states that the number of streams of each order forms an inverse geometric sequence, with order number. Most drainage networks show a linear relationship, with a small deviation from a straight line, when the logarithm of the number of streams is plotted against stream orders (Strahler 1952; Schumm 1956; Smith 1958; Melton 1958; Raju et al. 1995; Rao and Babu 1995; Sreedevi et al. 2005; John Devadas et al. 2006; Manu and Anirudhan 2008), as is also observed in the present study area (Fig. 12).

### Bifurcation ratio

In the Varaha River Basin, it is observed that the number of streams of a given order is higher than the number of streams of the next highest order (Table 2), as also stated by Strahler (1964). The ratio between the number of streams of an order (Nu) to that of the next highest order (Nu+1) is known as a bifurcation ratio (Rb). The Rb reflects the complexity and degree of dissection of a drainage basin. Strahler (1964) has stated that where the Rb is between 3 and 5, geological structures do not seem to exercise a dominant control over the drainage pattern for the watershed. Rb of greater than 5 indicates structurally controlled development of a drainage network (Strahler 1957).

The computed average values of Rb of the second-, third- and fourth-order streams of the Varaha River Basin are 4.27 (2.87–6.58), 4.99 (2.67–8.00) and 3.50 (2.00–6.00), respectively (Table 2). The average value of the Rb for the whole river basin varies from 3.33 to 5.61, with an average of 4.25. This is the universal value for maturely dissected drainage basins (Rao and Babu 1995). As stated, Rb values less than 5 indicate geomorphological control, while Rb values greater than 5 indicate structural control on the development of the drainage pattern. The observed average value of Rb (4.25) of all the sub-basins of the whole watershed basin is less than 5, which indicate that the structural control over the development of drainage network is not as pronounced as the geomorphic control (Table 3). However, the sub-basin S in the second-order streams, the sub-basins B–D J–L and U in the third-order streams, and the sub-basins K, L, N and T in the fourth-order streams have an Rb greater than 5. This indicates the influence of structural control on the development of the drainage network in these sub-basins. Structural disturbances of the Eastern Ghats are well-known (Prudhvi Raju and Vaidyanadhan 1981), supporting the above. It is also noted that the sub-basin O in the second-order streams, the

sub-basins N and T in the third-order streams, and the sub-basins A–G, J, M, Q, S, U and V in the fourth-order streams have Rb less than 3, which indicate absence of any significant structural control on the development of the drainage, as also reported in Kurzadi watershed in the Deccan Volcanic Province in Central India (Pakhmode et al. 2003).

### Stream length

The stream length (Lu) is a dimensional property used to understand the characteristic size of the components of a drainage network. It reflects the hydrological characteristics of the underlying rock surfaces over the areas of consecutive stream orders. A smaller number of relatively longer stream lengths are formed, where the rock-formations are permeable, while a larger number of smaller stream lengths are developed, where the rock-formations are less permeable (Pakhmode et al. 2003).

From Table 4, it is observed that the total stream length ( $\sum Lu$ ) is minimum (38.70 km) in the sub-basin M and maximum (194.80 km) in the sub-basin K, with an average of 74.13 km in the Varaha River Basin. Further, it is also noted that the Lu is a maximum (average: 42.86 km) in the case of first-order streams in all the sub-basins of the watershed, as geometrical similarity is preserved, generally, in the basins of increasing order (Strahler 1964). In all the basins, the Lu (average: 9.20 km) decreases in the second-order streams compared to the Lu (average: 42.86 km) observed in the first-order streams. However, a sudden increase in the Lu (average: 17.37 km) is found in the third-order streams, where the Lu is greater than the Lu observed in the second-order streams, while a sudden decrease in the Lu (average: 4.70 km) is noticed in the fourth-order streams compared to the Lu found in the third-order streams. The differences in the Lu of the first-, second-, third- and fourth-order streams are caused by the variations in the relief over which the streams occur (Raju et al. 1995).

On the other hand, a smaller number of relatively longer stream lengths are observed in the third- and fourth-order streams than in the first- and second-order streams in the Varaha River Basin (Tables 2 and 5). Therefore, the rock-formations drained by the third- and fourth-order streams are more permeable, with higher infiltration than the rock-formations drained under the first- and second-order streams, which are associated with low permeability and medium infiltration (Table 5). The average values of Lu computed, dividing the Lu by the Nu, in the first- and second-order streams are 0.62 (0.35–

**Table 3** Bifurcation ratio, Rb, in relation to controlling factor of the drainage pattern in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Range of Rb	Controlling factor of drainage pattern	Sub-basins		
		Second-order	Third-order	Fourth-order
<3	Natural control	O	N and T	A–G, J, M, Q, S, U and V
3–5	Geomorphic control	A–N, P–R and T–V	A, E–I, M, O–S and V	H, I, O, P and R
>5	Structural control	S	B–D, J–L and U	K, L, N and T

**Table 4** Stream lengths of the sub-basins in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Sub-basin	Total stream lengths Lu (km) in different u					Average Lu (km) in different u (Lu/Nu)				Stream length ratio RI (Lu/Lu-1)		
	1	2	3	4	$\sum Lu$	1	2	3	4	2/1	3/2	4/3
A	21.60	4.80	11.30	2.20	39.90	0.50	0.53	5.65	2.20	1.06	10.66	0.39
B	31.50	3.30	15.20	5.60	55.60	0.47	0.21	7.60	5.60	0.45	36.19	0.73
C	37.30	6.30	11.95	2.00	57.55	0.57	0.45	5.98	2.00	0.79	13.29	0.33
D	50.00	15.20	26.50	4.00	95.70	0.59	0.76	8.83	4.00	1.29	11.62	0.45
E	24.50	5.60	5.90	3.50	39.50	0.56	0.62	2.95	3.50	1.11	4.76	1.19
F	23.90	5.60	6.70	2.95	39.15	0.58	0.47	2.23	2.95	0.81	4.74	1.32
G	28.50	6.23	10.50	8.50	53.73	0.52	0.42	3.50	8.50	0.81	8.33	2.43
H	50.50	8.50	14.70	4.50	78.20	0.59	0.43	3.68	4.50	0.73	8.56	1.22
I	41.50	8.60	14.00	6.20	70.30	0.59	0.48	3.50	6.20	0.81	7.29	1.77
J	25.40	5.60	7.00	1.00	39.00	0.35	0.37	3.50	1.00	1.06	9.46	0.29
K	99.20	35.10	55.50	5.00	194.80	0.57	0.98	9.25	5.00	1.72	9.44	0.54
L	86.20	17.00	29.45	4.50	137.15	0.63	0.55	4.91	4.50	0.87	8.93	0.92
M	18.70	7.50	11.00	1.50	38.70	0.57	0.94	5.50	1.50	1.65	5.85	0.27
N	56.20	10.00	34.50	5.40	106.10	0.68	0.56	5.75	5.40	0.82	10.27	0.94
O	38.40	8.60	14.00	5.30	66.30	0.89	0.57	3.50	5.30	0.64	6.14	1.51
P	48.50	9.40	18.10	8.60	84.60	0.75	0.47	3.62	8.60	0.63	7.70	2.38
Q	33.80	7.00	19.90	6.50	67.20	0.70	0.47	6.63	6.50	0.67	14.11	0.98
R	42.20	4.50	15.50	6.50	68.70	0.53	0.23	3.10	6.50	0.43	13.48	2.10
S	51.00	6.50	12.00	4.50	74.00	0.65	0.54	4.00	4.50	0.83	7.41	1.13
T	55.70	9.50	14.50	9.30	89.00	0.75	0.59	2.42	9.30	0.79	4.10	3.84
U	47.50	11.20	17.00	2.00	77.70	0.70	0.75	8.50	2.00	1.07	11.33	0.24
V	30.80	6.40	16.90	3.90	58.00	0.96	0.80	8.45	3.90	0.83	10.56	0.46
Av	42.86	9.20	17.37	4.70	74.13	0.62	0.55	5.14	4.70	0.90	10.19	1.16

Av average (basin as a whole)

0.96) and 0.55 (0.21–0.98) km, and in the third- and fourth-order streams are 5.14 (2.23–9.25) and 4.70 (1.00–9.30) km, respectively (Table 4). These differences clearly support the distribution of number of streams along with their lengths in the order of streams, according to the occurrence of surface rock-permeability, in relation to topography.

The logarithm plot of average total stream lengths against stream orders is shown in Fig. 13. This demonstrates the negative linear relationship ( $r=-0.84$ ), which satisfies the Horton's (1945) Law of Stream Lengths. The Law states that the average lengths of streams of different orders in a drainage basin tend clearly to approximate a direct geometric sequence, as also confirmed in many watersheds (Leopold and Miller 1956; Schumm 1956; Broscio 1959; Morisawa 1959; Raju et al. 1995; Rao and Babu 1995; Sreedevi et al. 2005; John Devadas et al. 2006; Manu and Anirudhan 2008). However, the plotting points of average stream lengths against stream orders deviate from a straight line. This is caused by the differences in the development of the number of streams as well as in the formation of stream lengths, with respect to stream orders, as explained above.

Figure 14 illustrates the relation between the logarithm of average number of streams and the logarithm of average total stream lengths. This relation is drawn, taking

the values of number of streams and total stream lengths, with respect to their stream orders. Hence, this relation shows an inverse trend ( $r=-0.82$ ). Figure 14 clearly explains, further, that the stream lengths increase as the number of streams increases. This is because of the development of the drainage network, following the topographic features as well as the nature of the surface rock-permeability.

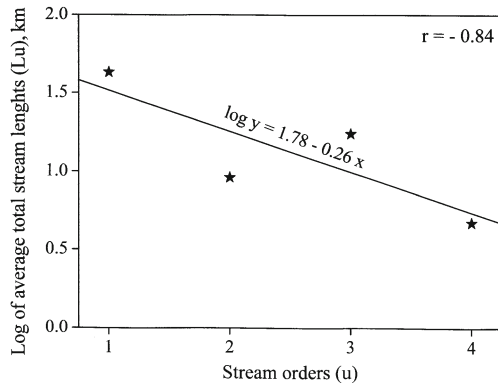
### Stream length ratio

The stream length ratio (RI) shows an important relationship with discharge of the surface flow and erosional stage of the basin. Horton (1945) has proposed using RI for the evaluation of relative permeability of rock formations in a basin. More specifically, it indicates if there is a major change in the hydrological characteristics of the underlying rock-surface over the areas of consecutive stream orders (Pakhmode et al. 2003). The RI is the ratio of the mean length (Lu) of a stream of any given order (u) to the mean length of a stream of the next lowest order (Lu-1; Horton 1945), which tends to be constant throughout the successive orders of the basin.

The average RI for the third-order streams shows a very high value of 10.19 (4.10–36.19) compared to the average RI for the second- and fourth-order streams within

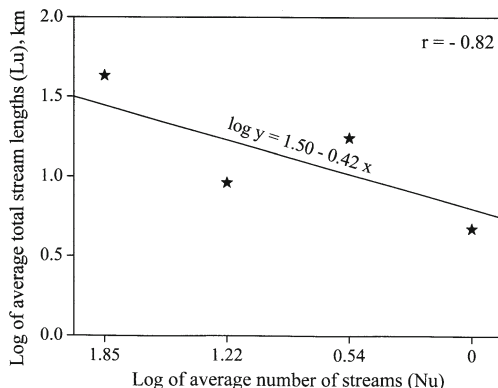
**Table 5** Nature of streams, surface rock-permeability, run-off and infiltration rate with respect to weight in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Nature of streams	Surface rock-permeability	Run-off	Infiltration rate	Sub-basin	Weight
Larger number of shorter stream lengths	Low	High	Low	First-order	1
Medium number of medium stream lengths	Medium	Medium	Medium	Second-order	2
Smaller number of longer stream lengths	High	Low	High	Third- and fourth-orders	3



**Fig. 13** Relation between stream orders and stream lengths in the whole Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

the Varaha watershed basin. This indicates that the rock-formations in the areas drained by the third-order streams are gentler in slope and/or are more permeable than the rock-surfaces drained under the lower order streams. Hence, a major length of the third-order stream flows over an area, which is likely to have permeable surfaces. The average RI for the second- and fourth-order streams of the river basin is 0.90 (0.43–1.72) and 1.16 (0.24–3.84), respectively. This shows that these streams flow over relatively less permeable rocks compared to the third-order streams. Another important factor is that there is a relative variation in the value of RI of the second- and fourth-order streams. Hence, the second-order streams are likely to run through the rocks of greater homogeneity than the fourth-order streams. The second-order streams flow where there is poor development of permeability in the rock-surfaces, and are mainly controlled by geomorphological conditions (Table 3); the third-order streams flow where there is greater development of permeability in the rocks, and are governed by both geomorphological and structural factors; and the fourth-order streams flow where there is medium development of permeability of the rock-materials, and are also developed by both geomorphological and structural features, but not to the same extent as the third-order streams. Hence, the geomorphological and



**Fig. 14** Relation between number of streams and stream lengths in the whole Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

structural factors clearly support the causes for the differences in the development of surface rock-permeability in the areas drained by the second-, third- and fourth-order streams.

### Drainage density

The drainage density (Dd) is an important indicator of the linear scale of landform elements in a stream-eroded topography (Horton 1945). It directly expresses the closeness of spacing of the streams and indirectly reflects the structural framework of the underlying rocks of the watershed basin. According to Langbein (1947), the Dd is a significant factor in determining the time of travel of water. He has also reported that the Dd varies from 0.55 to 2.09 km/km<sup>2</sup>, with an average of 1.03 km/km<sup>2</sup> in humid regions. Strahler (1964) is of the opinion that a low Dd is favoured in regions of highly resistant or highly permeable strata under dense vegetation and low relief, while a high Dd is supported in regions of weak or impermeable rocks under sparse vegetation and mountainous relief.

The Dd is the ratio of the total stream lengths of all orders within a basin to the area of the basin (Horton 1945). Accordingly, the computed values of Dd for the Varaha River Basin are presented in Table 6. The Dd for the watershed basin has a range of 1.02 (sub-basin V) to 5.47 (sub-basin C) km/km<sup>2</sup>, with an average of 2.42 km/km<sup>2</sup>. This suggests that the nature of the surface strata of the river basin is permeable, which is a characteristic feature of a coarse-drainage density, the value of Dd being less than 5 (Smith 1950; Strahler 1957).

For a relative comparison of the permeable strata of the sub-basins, the sub-basins are classified into three categories based on the drainage density (Table 7). They are (1) low Dd (<1.5 km/km<sup>2</sup>), (2) medium Dd (1.5 to 2.5 km/km<sup>2</sup>) and (3) high Dd (>2.5 km/km<sup>2</sup>). Some sub-basins (E, F, J and R–T) have lower values of Dd (1.99–2.47 km/km<sup>2</sup>), which come within the range of 1.5 to 2.5 km/km<sup>2</sup>. The rock surfaces drained by these basins are of moderately permeable strata, with medium run-off and infiltration. Highly permeable strata have caused the development of sub-basins A, G–I, P, Q, and V, as these basins have values of Dd less than 1.5 km/km<sup>2</sup> (1.02–1.50 km/km<sup>2</sup>), which support lower run-off and greater infiltration. The sub-basins B–D, K–O and U show a Dd ranging from 3.31 to 5.47 km/km<sup>2</sup>, i.e., Dd values of more than 2.5 km/km<sup>2</sup>. These basins are associated with low permeability strata, with more run-off and less infiltration.

### Constant of channel maintenance

The constant of channel maintenance (C) is the inverse of the Dd (Schumm 1956). The constant C tells the number of km<sup>2</sup> of watershed surface that is required to maintain one linear kilometer of stream channel. Generally, the higher the constant C of a basin, the greater the permeability of the rocks of that basin.

Table 6 shows the computed values of constant C for the fourth-order of the Varaha watershed. The values of

**Table 6** Drainage density, constant of channel maintenance, length of overland flow, stream frequency, drainage texture, circulatory ratio and elongation ratio of the sub-basins in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Sub-basin	Drainage density $Dd = \sum Lu/a$ (km/km <sup>2</sup> )	Constant of channel maintenance $C = 1/Dd$ (km <sup>2</sup> /km)	Length of overland flow $Lg = 1/2Dd$ (km <sup>2</sup> /km)	Stream frequency $F = \sum Nu/a$ (per km <sup>2</sup> )	Drainage texture $T = (Dd \times F)$	Circularity ratio $Re = 4\pi a/p^2$	Elongation ratio $Re = (2/l).(a/\pi)^{0.5}$
A	1.07	0.93	0.47	1.47	1.57	0.56	0.66
B	3.40	0.29	0.15	5.38	18.29	0.34	0.44
C	5.47	0.18	0.09	7.89	43.16	0.66	0.73
D	3.41	0.29	0.15	3.88	13.23	0.92	0.61
E	2.06	0.49	0.25	2.92	6.02	0.44	0.80
F	1.99	0.50	0.25	2.89	5.75	0.63	0.77
G	1.03	0.97	0.49	1.41	1.45	0.79	0.67
H	1.46	0.68	0.34	2.00	2.92	0.68	0.73
I	1.50	0.67	0.34	1.98	2.97	0.88	0.97
J	2.00	0.50	0.25	4.50	9.00	0.96	0.86
K	3.32	0.30	0.15	3.68	12.22	0.73	0.72
L	3.31	0.30	0.15	4.22	13.97	0.69	0.69
M	3.31	0.30	0.15	3.76	12.45	0.75	0.84
N	3.33	0.30	0.15	3.39	11.29	0.71	0.99
O	3.32	0.30	0.15	3.15	10.46	0.78	0.64
P	1.04	0.96	0.48	1.12	1.16	0.50	0.75
Q	1.06	0.94	0.47	1.05	1.11	0.83	0.73
R	2.47	0.40	0.20	3.81	9.41	0.76	0.74
S	2.27	0.44	0.22	2.91	6.61	0.78	0.78
T	2.11	0.47	0.24	2.30	4.85	0.77	0.72
U	3.40	0.30	0.15	3.76	12.78	0.50	0.67
V	1.02	0.98	0.47	0.76	0.78	0.88	0.83
Av	2.42	0.52	0.26	3.10	9.16	0.71	0.74

Av average (basin as a whole)

constant C in the sub-basins range from 0.18 (sub-basin C) to 0.98 (sub-basin V) km<sup>2</sup>/km, with an average of 0.52 km<sup>2</sup>/km. This indicates that an area of about 0.50 km<sup>2</sup> is needed to support 1 km of stream channel. Considering the required watershed surface area for 1 km of stream channel in the study area, the sub-basins A, G–I, P, Q and V show higher constant C values (0.67–0.98 km<sup>2</sup>/km) than the value of 0.50 km<sup>2</sup>/km of constant C (Table 8). This means a large area is required for maintaining 1 km of stream channel in these basins, reflecting the occurrence of higher surface rock-permeability, which promotes a greater rate of infiltration. The sub-basins E, F, J and R–T show constant C values (0.40–0.50 km<sup>2</sup>/km) less than the value of 0.50 km<sup>2</sup>/km of constant C and which fall within the range of 0.30 to 0.50 of constant C values. This shows that a small area is required to maintain 1 km of stream channel in the sub-basins E, F, J and R–T, implying the occurrence of medium permeability rocks in those basins. A very low value (<0.30 km<sup>2</sup>/km) of constant C is observed in the sub-basins

B–D, K–O and U (0.18–0.30 km<sup>2</sup>/km) compared to the value of 0.50 km<sup>2</sup>/km of constant C. This indicates that a very small area is needed to support 1 km of stream channel, and thereby reflects the occurrence of lower permeability rocks in these sub-basins, where the rate of infiltration is low.

### Length of overland flow

Surface run-off follows a system of down slope flow-paths from the drainage divide to the nearest channel. This flow net, comprising a family of orthogonal curves with respect to the topographic contours, which locally converge or diverge from parallelism, depends upon a position in the river basin (Strahler 1964). The length of overland flow (Lg) is one of the most important independent variables, affecting both the hydrological and physiographical development of the drainage basins (Horton 1945). During the evolution of the drainage system, Lg is adjusted to a magnitude appropriate to the scale of the first-order

**Table 7** Drainage density, Dd, in relation to surface rock-permeability, run-off, infiltration rate with weight in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Dd (km/km <sup>2</sup> )	Surface rock-permeability	Run-off	Infiltration rate	Sub-basin	Weight	
Range	Average					
<1.5	1.17	High	Low	High	A, G–I, P, Q and V	3
1.5–2.5	2.15	Medium	Medium	Medium	E, F, J and R–T	2
>2.5	3.59	Low	High	Low	B–D, K–O and U	1



**Table 8** Constant of channel maintenance, C, in relation to surface rock-permeability, ground slope, infiltration rate with weight in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Constant C (km <sup>2</sup> /km)		Surface rock-permeability	Ground slope	Infiltration rate	Sub-basin	Weight
Range	Average					
<0.30	0.28	Low	Steep	Low	B–D, K–O and U	1
0.30–0.50	0.47	Medium	Moderate	Medium	E, F, J and R–T	2
>0.50	0.88	High	Gentle	High	A, G–I, P, Q and V	3

drainage basins. According to Horton (1945), the Lg is the length of stream flow-paths, projected to the horizontal from the point of drainage divide to a point on the adjacent stream channel, where the average Lg is equal to half the reciprocal of the average Dd.

The Lg computed for the fourth-order Varaha watershed basin is between 0.09 (sub-basin C) and 0.49 (sub-basin G) km<sup>2</sup>/km, and its average is 0.26 km<sup>2</sup>/km (Table 6). For a comparison of sub-basins with one another in respect of nature of flow-path, the Lg is classified as (1) low Lg (<0.20 km<sup>2</sup>/km), (2) medium Lg (0.20 to 0.25 km<sup>2</sup>/km) and (3) high Lg (>0.25 km<sup>2</sup>/km) in the study area (Table 9). The high Lg values (0.34–0.49 km<sup>2</sup>/km) in the sub-basins A, G–I, P, Q and V compared to the high LG (0.25 km<sup>2</sup>/km) indicate the occurrence of long flow-paths, and thus, gentle ground slopes, which reflects areas of less run-off and more infiltration. The low Lg values (0.09–0.20 km<sup>2</sup>/km) of less than 0.20 km<sup>2</sup>/km in the sub-basins B–D, K–O, R and U point to short flow-paths, with steep ground slopes, reflecting the areas associated with more run-off and less infiltration. The sub-basins E, F, J, S and T show Lg values between 0.22 and 0.25 km<sup>2</sup>/km, which fall in the range of 0.20 to 0.25 km<sup>2</sup>/km of Lg, indicating the occurrence of moderate ground slopes, where the flow-paths, run-off and infiltration are moderate.

### Stream frequency

The stream frequency (F) is also referred to as channel frequency. According to Horton (1932), F is the ratio of the total number of streams (Nu) in a basin to the basin area (a). A higher F reflects greater surface run-off and a steeper ground surface.

The computed values of F in the sub-basins of the fourth-order Varaha watershed range from 0.76 (sub-basin V) to 7.89 (sub-basin C) per km<sup>2</sup>. The average value of F in the watershed is 3.10 per km<sup>2</sup> (Table 6). This indicates the development of about three streams in an area of

1 km<sup>2</sup> in the basin. Taking into account the development of three streams in 1 km<sup>2</sup> in the whole river basin, high F values (>3 per km<sup>2</sup>) are observed in the sub-basins B–D, J–O, R and U (3.15–7.89 per km<sup>2</sup>; Table 10), indicating the occurrence of steep ground slopes, with lower permeability rocks, which facilitates greater run-off and less infiltration. The low F values (<2 per km<sup>2</sup>) in the sub-basins A, G–I, P, Q and V (0.76–2.00 per km<sup>2</sup>) reflect the gentle ground slopes, and greater rock-permeability in those basins, where the run-off is low and the infiltration is higher. The values of F in the range of 2–3 per km<sup>2</sup>, occurring in the sub-basins E, F, S and T (2.30–2.92 per km<sup>2</sup>), are caused by the occurrence of moderate ground slopes associated with moderately permeable rocks, which promotes moderate run-off and infiltration.

### Drainage texture

The drainage texture (T) is a measure of closeness of the channel spacing, depending on climate, rainfall, vegetation, soil and rock type, infiltration rate, relief and stage of development (Smith 1950). Soft or weak rocks unprotected by vegetation characterize a fine drainage texture, while massive and resistive rocks represent a coarse drainage texture. Sparse vegetation, with an arid climate, causes a finer drainage texture than that developed on similar rocks in a humid climate. According to Dornkamp and King (1971), the T of the rocks depends upon the type of vegetation and the climate. On the other hand, the T is a product of Dd and F. The T is classified as coarse drainage texture if it is less than 4; intermediate drainage texture, if it is between 4 and 10; fine drainage texture, if it ranges from 10 to 15; and ultra-fine drainage texture, if it is more than 15 (Smith 1950).

The T for the fourth-order Varaha River Basin is between 0.78 (sub-basin V) and 43.16 (sub-basin C), being an average of 9.16 (Table 6). This indicates an intermediate drainage texture for the whole watershed. However, the sub-basins A, G–I, P, Q, and V show T in

**Table 9** Length of overland flow, Lg, in relation to ground slope and flow-path, run-off, infiltration rate with weight in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Lg (km <sup>2</sup> /km)		Ground slope and flow-path	Run-off	Infiltration rate	Sub-basin	Weight
Range	Average					
<0.20	0.15	Steep slope and small flow-path	High	Low	B–D, K–O, R and U	1
0.20–0.25	0.24	Moderate slope and moderate flow-path	Medium	Medium	E, F, J, S and T	2
>0.25	0.44	Gentle slope and long flow-path	Low	High	A, G–I, P, Q and V	3

**Table 10** Stream frequency, F, in relation to ground slope and surface rock-permeability, run-off, infiltration rate with weight in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

F (per km <sup>2</sup> )		Ground slope and surface rock-permeability	Run-off	Infiltration rate	Sub-basin	Weight
Range	Average					
<2	1.40	Gentle slope and high permeable	Low	High	A, G–I, P, Q, and V	3
2–3	2.76	Moderate slope and medium permeable	Medium	Medium	E, F, S and T	2
>3	4.31	Steep slope and low permeable	High	Low	B–D, J–O, R and U	1

the range of 0.78–2.97, which come under a coarse drainage texture (Table 11). An intermediate drainage texture (T between 4.85 and 9.41) is observed in the sub-basins E, F, J and R–T. The sub-basins B–D, K–O and U, with T ranging from 10.46 to 43.16, show a fine drainage texture. Out of the fine drainage texture sub-basins, sub-basin C has a T value of 43.16, i.e., more than 15, which comes under the type of ultra-fine drainage texture. Because of the higher values of F and Dd, the drainage network in most of the sub-basins comes under the intermediate and fine drainage texture categories. In fact, a fine drainage texture reflects lower permeability strata, supporting lower infiltration, while a coarse drainage texture indicates higher permeability strata, promoting greater infiltration.

### Circularity ratio

The circularity ratio (Rc) is a quantitative expression of the shape of basin, which is expressed as the ratio of basin area (a) to the area of circle, having the same perimeter (p) as the basin (Miller 1953). This is a significant ratio, indicating the stage of dissection in any region, which also gives an index of the structural fabric of the underlying rocks. The stream length, stream frequency and stream gradient of the various orders play a significant role on the Rc rather than the slope conditions and drainage pattern of a basin. If the value of Rc is exactly 1.0, the basin is set to be a perfectly circular shape, in which the discharge greater in quantity (Miller 1953).

The value of Rc, ranging from 0.34 (sub-basin B) to 0.96 (sub-basin J) in the sub-basins (Table 6), is attributable to the differences in the geomorphological features in the Varaha River Basin. The average value of Rc computed for the fourth-order watershed is 0.71, which is less than one. This clearly indicates that the basin is not circular in shape, as shown in Fig. 2. The discharge is, therefore, not more in quantity, as in the case of circular shaped river basin.

### Elongation ratio

The elongation ratio (Re) is the ratio between the diameter of a circle of the same area as the basin and the maximum basin length (Schumm 1956). Table 6 shows the computed values of Re for the fourth-order Varaha watershed. The computed values of Re vary from 0.44 (sub-basin B) to 0.99 (sub-basin N). The average Re of the whole river basin is 0.74. This refers to the fact that the basin is an elongated shape, as is shown in Fig. 2. The Rc also supports that the river basin is elongated. The variations in the elongated shapes of the sub-basins within the watershed basin are caused by the effects of structural disturbances (Sreedevi et al. 2005).

### Watershed development plan

Rock-permeability induced by secondary porosity, resulting from weathering processes and tectonic effects, is the most significant hydrological property, which plays a vital role in the movement of groundwater from place to place. The greater the permeability, the higher the rate of groundwater recharge and the higher the rate of groundwater movement. The analysis of morphometric data, which is a reflection of the structural fabric and the type of underlying hard rocks, can provide useful information on the relative variation in permeability of the rocks exposed in any area. Hence, it is essential to compute the relative rock-permeability of the sub-basins of a given area, counting the morphometric characteristics, with respect to their weights. This approach can help to select suitable sites either for infiltrating recharge water to become groundwater or for storing recharge water on the surface. On the other hand, if the drainage characteristics are combined with the hydrogeological conditions of a given drainage basin, the strategy for assessing favourable recharge and water-harvesting measures could be rendered more effective.

Considering the relative surface rock-permeability assessed from the morphometric characteristics for the

**Table 11** Drainage texture, T, in relation to texture type, surface rock-permeability, infiltration rate with weight in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

T		Texture type	Surface rock-permeability	Infiltration rate	Sub-basin	Weight
Range	Average					
<4	1.71	Coarse	High	High	A, G–I, P, Q and V	3
4–10	6.94	Intermediate	Medium	Medium	E, F, J and R–T	2
>10	16.43	Fine	Low	Low	B–D, K–O and U	1

various sub-basins of the River Varaha in the fore-going section, a watershed development plan is proposed in the sub-basins for various recharge-related measures. Table 12 shows a summary of the morphometric characteristics assigned to each sub-basin, with their weights. A numerical scheme is proposed here combining the morphometric characteristics of each sub-basin in terms of total weight score of the various types of rock-permeability. On the basis of the total weight score, a generalized classification of the numerical scheme can be evaluated for a quick and easy watershed development plan. The numerical scheme is classified as a low surface rock-permeability zone, when the total weight score is less than 6; a medium surface rock-permeability zone, when the total weight score is between 7 and 12; and a high surface rock-permeability zone, when the total weight score is more than 13 (Table 13). As the classification of the numerical scheme represents a relative variation of the surface rock-permeability, the greater the total weight score, the higher the rock-permeability. According to the classification of the numerical scheme, the sub-basins B–D, K–O and U are considered as low surface rock-permeability zones, the sub-basins E, F, J and R–T are categorized as medium surface rock-permeability zones and the sub-basins A, G–I, P, Q and V come under high surface rock-permeability zones (Table 14).

Similar to the occurrence and movement of groundwater in an area, the potential zones for artificial recharge to groundwater are also controlled by various factors, such as rainfall, slope, soils, geomorphological features, lineaments and lithology. As these factors are responsible for the development of hydrogeological conditions in an area,

**Table 12** Summary of morphometric characteristics with respect to their weights in the sub-basins of the Varaha River, Visakhapatnam District, Andhra Pradesh, India

Sub-basins	Morphometric characteristics with respect to their weights					Total weight score
	Dd	C	Lg	F	T	
A	3	3	3	3	3	15
B	1	1	1	1	1	5
C	1	1	1	1	1	5
D	1	1	1	1	1	5
E	2	2	2	2	2	10
F	2	2	2	2	2	10
G	3	3	3	3	3	15
H	3	3	3	3	3	15
I	3	3	3	3	3	15
J	2	2	2	1	2	9
K	1	1	1	1	1	5
L	1	1	1	1	1	5
M	1	1	1	1	1	5
N	1	1	1	1	1	5
O	1	1	1	1	1	5
P	3	3	3	3	3	15
Q	3	3	3	3	3	15
R	2	2	1	1	2	8
S	2	2	2	2	2	10
T	2	2	2	2	2	10
U	1	1	1	1	1	5
V	3	3	3	3	3	15

1 low permeable zone, 2 medium permeable zone, 3 high permeable zone

**Table 13** Classification of numerical scheme in respect of surface rock-permeability in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Range of total weight score	Classification of numerical scheme in respect of surface rock-permeability
<6	Low surface rock-permeability zone
7–12	Medium surface rock-permeability zone
>13	High surface rock-permeability zone

they play an important role in the relative evaluation of groundwater potential zones (Subba Rao 2006). The factors, helping to identify potential groundwater recharge zones observed in each sub-basin are shown in Table 15. This provides a broad strategy on a regional scale for searching for suitable sites within the study area for watershed development measures to be undertaken. This hydrogeological information is compared with the classification of the numerical scheme to obtain better results for water resource development through artificial recharge practices.

The rock-surfaces in the sub-basins A, G–I, P, Q and V, as shown in Table 12, are more permeable than those in the remaining sub-basins (B–F, J–O and R–U). This is because of the lower values of Dd (<1.5 km/km<sup>2</sup>), F (<2 per km<sup>2</sup>) and T (<4), and the higher values of constant C (>0.50 km<sup>2</sup>/km) and Lg (>0.25 km<sup>2</sup>/km; Tables 7–11), as compared to the respective values in the rest of the sub-basins. The streams of sub-basins A, G–I, P, Q and V flow mainly over the areas occupied by the valley fills, rolling plain and flood plain (Table 15), which are composed of various proportions of boulders, cobbles, gravel, pebbles and sand, with small amounts of silt and clay. These areas are considered as good potential zones for groundwater recharge due to their rapid infiltration capacity of water. The soils, i.e., loamy sand, silt loam and colluvium, occurring in the sub-basins are coarse-grained materials and hence, they have high permeability; thus, the water can infiltrate easily into the ground, through the coarse-grained material, as recharge. The relative magnitude of slope of the sub-basins A, G–I, P, Q and V is gentle (<5°), which serves to build-up the hydraulic gradient, to favour lower surface run-off and more infiltration. This leads to a greater chance of groundwater accumulation. The presence of lineaments in the sub-basins A, G–I, P, Q and V, which are the surface manifestations of structurally controlled linear features, with inherent characteristics of porosity and permeability, could also result in better zones for accumulation and movement of groundwater through

**Table 14** Distribution of sub-basins, according to the classification of numerical scheme in the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Numerical scheme	Distribution of sub-basins
<6	B–D, K–O and U
7–12	E, F, J and R–T
>13	A, G–I, P, Q and V

**Table 15** Dominant hydrogeological factors in the sub-basins of the Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India

Sub-basins	Rainfall					Slope			Soil type			Geomorphological features							Lineament density			Lithology			
	VL	LW	MM	HG	VH	GE	ME	SS	SL	CM	LS	RP	PZ	FP	SH	DH	EP	VF	PC	LO	MD	HI	WR	FR	MR
A		√				√	√		√	√	√	√	√	√				√		√				√	
B			√												√					√					√
C			√												√					√					√
D			√				√		√	√		√								√			√		
E			√			√			√	√		√								√			√		
F			√			√			√	√		√								√			√		
G			√			√			√	√		√								√			√		
H			√			√	√		√	√		√								√			√		
I			√			√	√		√	√		√								√			√		
J			√	√		√	√		√	√		√								√			√		
K				√	√		√		√	√		√								√			√		
L				√	√		√		√	√		√								√			√		
M			√	√	√		√		√	√		√								√			√		
N			√	√	√		√		√	√		√								√			√		
O				√	√		√		√	√		√								√			√		
P	√					√	√			√		√								√			√		
Q	√					√	√			√		√								√			√		
R	√	√				√	√	√		√		√								√			√		
S	√					√	√			√		√								√			√		
T	√	√				√	√			√		√								√			√		
U		√				√	√			√		√								√			√		
V		√				√	√		√	√		√		√				√		√			√		

VL very low (<1,000 mm), LW low (1,001–1,100 mm), MM medium (>1,101–1,200 mm), HG high (1,201–1,300 mm), VH very high (>1,300 mm), GE gentle, ME moderate, SS strong to steep, SL silt loam, CM colluvium, LS loamy sand, RP rolling plain, PZ pediment zone, FP flood plain, SH structural hill, DH denudational hill, EP erosional plain, VF valley fills, PC palaeo-channel, LO low, MD medium, HI high, WR weathered rock, FR fractured rock, MR massive rock

infiltration. Rainfall is the main recharge source of groundwater in the study area (CGWB 2001). Although rainfall is very low (<1,000 mm) in the sub-basins P and Q, compared to the sub-basins A, G–I and V, the density of lineaments in the sub-basins P and Q is high, with their intersections leading to more effective recharge of the groundwater by the infiltrating water. The occurrence of weathered and fractured rocks in the sub-basins provides the necessary permeability and storage space, which act as good potential groundwater recharge zones, as explained above. The hydrogeological information given for the sub-basins indicates higher storage and transmission capacities, which also support the nature of higher rock-permeability conditions inferred from the morphometric analysis. Therefore, the sub-basins A, G–I, P, Q and V are the most suitable for recharge-related work to improve the groundwater conditions more effectively.

Among the rest of the sub-basins (B–F, J–O and R–U), the sub-basins B–D, K–O and U have the higher values of Dd (>2.5 km/km<sup>2</sup>), F (>3 per km<sup>2</sup>) and T (>10), and the lower values of constant C (<0.30 km<sup>2</sup>/km) and Lg (<0.20 km<sup>2</sup>/km; Tables 7–11). This is indicated by the lower surface rock-permeability, as these sub-basins run mainly over the pediment zone and structural hills (Table 15). These geomorphological features observed in the sub-basins B–D, K–O and U lack surface rock-permeability and hence, they have insignificant capacities of water storage and transmission. Further, the sub-basins have a strong to steep slope (>10°). Steeply sloping ground can encourage active run-off and little or no infiltration so that

these areas are unfavourable as potential recharge zones. The areas of the sub-basins B–D, K–O and U are occupied by loamy sand and colluvium. The areas are mainly underlain by massive rocks, which are not favourable for potential recharge zones, as they are impermeable and can not provide storage space. They have a low density of lineaments and receive very low (<1,000 mm) to very high (>1,300 mm) rainfall. Although these areas favour the infiltration of water from the surface due to occurrence of coarse texture soils, the strong to steep slope with limited occurrence of lineaments supports more surface run-off and less water infiltration. Furthermore, the areas occupied by the sub-basins B, C, L, M and U are mainly confined to the hilly terrain, while the remaining sub-basins D, K, N and O are in areas, with moderate to steep slopes. Hence, the areas of the sub-basins D, K, N and O as a whole also come under low surface rock-permeability zones. The morphometric characteristics observed in the sub-basins B–D, K–O and U are in good agreement, with the hydrogeological conditions found in the field. Therefore, the sub-basins, B–D, K–O and U, can be used to harvest run-off and to store it on the surface, leading to surface-water development.

On the other hand, the surface rock-formations drained by the sub-basins E, F, J and R–T are moderately permeable, as these basins show moderate values of Dd (1.5–2.5 km/km<sup>2</sup>), F (2–3 per km<sup>2</sup>), T (4–10), constant C (0.30–0.50 km<sup>2</sup>/km) and Lg (0.20–0.25 km<sup>2</sup>/km; Tables 7–11). The areas are associated with medium to high rainfall, gentle to moderate slope, silt loam, colluvium and loamy sand soils, rolling



plain, pediment zone, flood plain, low density of lineaments and weathered rocks (Table 15). The moderate slope, pediment zone, low density of lineaments and weathered rocks in the sub-basins can reduce the active role of other factors, such as high rainfall, coarse-grained soils and flood plain, in creating potential groundwater recharge zones. Therefore, the hydrogeological features observed in the sub-basins E, F, J and R–T are matched well, with the medium rock-permeability conditions assessed from the morphometric analysis. The medium surface rock-permeability can help to maintain the required rate of groundwater recharge.

As all the important hydrogeological conditions correlated well with the classification of the numerical scheme to suggest ideal locations for potential groundwater recharge zones, the sub-basins have the capability for water resource development through artificial recharge measures. The watershed development plan, as suggested in the present study area, is broad and based on regional studies. However, the plan not only constitutes an integrated and systematic approach, but also provides basic information to conduct detailed surveys in local studies to select specific sites and measures for water resources development and management. Therefore, this type of study can be useful as a tool based on hydrogeological conditions for the proper identification of sites for recharge measures at the planning stage of the sustainable development of a watershed basin. This plan can also be applicable to other similar terrains, provided the numerical scheme is computed dependant upon the local variations of hydrogeological features as well as the individual morphometric characteristics, with respect to their weight factors.

## Conclusions

It is concluded that the numerical scheme proposed for the relative ranking of sub-basins of the River Varaha, based on morphometric analysis in relation to hydrogeological conditions at a regional scale, can be a useful technique for the relative evaluation of surface rock-permeability in the basement terrain, and thereby for identifying suitable sites for rainfall infiltration that constitute favourable zones for recharge to the groundwater system in the watershed development plan. Accordingly, the numerical scheme classifies the areas occupied by the sub-basins of the watershed into three types: low surface rock-permeability zones, medium surface rock-permeability zones and high surface rock-permeability zones, for taking various recharge-related measures.

Sub-basins A, G–I, P, Q and V are considered as suitable areas for groundwater recharge measures, as they come under high surface rock-permeability zones. The numerical scheme classifies the sub-basins E, F, J and R–T as medium surface rock-permeability zones and hence these sub-basins are favoured to maintain the required rate of groundwater recharge. For surface water development, the sub-basins B–D, K–O and U can be suitable, as these

sub-basins are categorized as low surface rock-permeability zones. The scheme can be very helpful to planners and decision-makers to further pin-point study areas by selecting, more easily and effectively, recharge and water-harvesting measures on a local scale, and it can also be used in other similar terrain conditions, with appropriate modifications.

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