Journal of Earth Science, *Vol. 25*, *No. 6*, *p. 1018–1032*, *December 2014* *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-014-0505-8

Basin Geomorphology and Drainage Morphometry Parameters Used as Indicators for Groundwater Prospect: Insight from Geographical Information System (GIS) Technique

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ABSTRACT: Influence of structural and lithological controls of various drainage patterns and their stream orientations (for 2nd, 3rd and 4th order steams) were identified to evaluate the direction and controlling factors of drainage network. To investigate the prospect of groundwater, hydrogeomorphological features of river basin viz. Mulki-Pavanje were identified and mapped. To evaluate the characteristics of the basin, different morphometric parameters (linear, areal and relief) were computed in sub-basin wise (SB-I to -VII). The linear parameters suggest drainage network is controlled by geomorphology. The form factor (F_f), elongation ratio (R_e) and circularity ratio (R_c) suggest that the basin is in an elongated shape. The drainage density (D_d) indicates resistant/permeable strata under medium-dense vegetation with moderate relief. The areal parameters of the sub-basins (except SB-I and III) indicates moderate ground-slopes associated with moderately permeable rocks, which promote moderate run-off and infiltration. Drainage texture (T) of the whole basin indicates coarse texture while the SB-I, and III showing an intermediate texture. The relief parameters namely ruggedness number (R_n) infers low basin relief and poor drainage density. To identify the most deficit/surplus zones of groundwater suitable weightages were assigned to the hydrogeomorphological units and morphometric parameters. The study reveal that the basin manifest that SB-III shall be most deficit zone of groundwater, whereas SB-VII, VI and V are found to show increase in groundwater potentiality. Groundwater prospect area in this basin is estimated to be 7% area under poor, 44% area under moderate and 49% area under good to excellent. This paper demonstrated the potential application of geographical information system (GIS) techniques to evaluate the groundwater prospect in absence of traditional groundwater monitoring data.
KEY WORDS*:* hydrogeomorphology, drainage morphometry, prioritization, groundwater prospect, Mulki-Pavanje River Basin, remote sensing.

0 INTRODUCTION

The drainage-parameters and drainage-patterns provide surface and sub-surface information to understand the influence of drainage morphometry on landforms and their characteristics (Obi Reddy et al., 2004). The geological and geomorphological backgrounds of an area control the occurrence, movement and storage of groundwater. Geomorphological factors directly or indirectly affect the hydrogeological setting of the area, whereas physiographic elements like relief and slope illustrate the amount of runoff and infiltration (Singh et al., 2011). Morphometric studies of river basin comprise a distinct morphologic region and have special relevance to drainage pattern and geomorphology, which include evaluation of river basin through measurement of various stream properties (Doornkamp and Cuchlaine, 1971; Strahler, 1957). Robust geometric relationships persist between characteristics of drainage basin, stream networks, and channel geometry, which can be utilised to derive stream-watershed relationships for a given area, and to predict expected channel shape parameters (Flint, 1974; Smart and Surkan, 1967; Strahler, 1964, 1957; Schumm, 1956; Leopold and Maddock, 1953; Horton, 1945, 1932).

Several studies pertaining to soil and water conservation measures have proved that river basin/watershed analyses play an important role in the strategy of comprehensive land and water management (Rao, 2009; Gosain and Rao, 2004; Khan et al., 2001; Ramesh et al., 2001; Biswas et al., 1999; Prasad et al., 1997). Surface drainage characteristics of many river basins and sub-basins at different parts of the globe have been studied using conventional and/or remote sensing methods (Srinivasa et al., 2008; Agarwal, 1998; Krishnamurthy et al., 1996; Morisawa, 1959; Leopold and Miller, 1956). Remote sensing (RS) and geographic information system (GIS) are the efficient techniques to evaluate the quantitative characterisation of stream network, basin geometry, watershed management/ development, and micro- or sub-basin levels of prioritisation

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Manuscript received May 7, 2014.
Manuscript accepted September 21, 2014.

Avinash, K., Deepika, B., Jayappa, K. S., 2014. Basin Geomorphology and Drainage Morphometry Parameters Used as Indicators for Groundwater Prospect: Insight from Geographical Information System (GIS) Technique. *Journal of Earth Science*, 25(6): 1018–1032. doi:10.1007/s12583-014-0505-8

studies (Deepika et al., 2013; Avinash et al., 2011; Tripathi, 1999; Sharda et al., 1993; Prasad et al., 1992). Recent advancement in these technologies updated the status of earlier studies on morphometric analysis and prioritisation of sub-watersheds/sub-basins.

In this paper, an integrated approach of remote sensing and GIS are used to study the Mulki-Pavanje (M-P) River Basin, India, and demarcated the favourable zones for groundwater through geomorphology and morphometric parameters. Basin geomorphology has been mapped and interpreted based on lithological characteristics, and the area of each geomorphic unit has been quantified. The basin characteristics have been quantitatively computed from the linear, areal and relief morphometric parameters, using the established mathematical equations (Table 1). Finally, sub-basin-wise prioritization was executed to determine the deficit and surplus zones of groundwater, based on the weightage of geomorphological and morphometric parameters.

1 STUDY AREA

The Mulki-Pavanje (M-P) River Basin extends from 12º57'N to 13º12'N latitudes and 74º45'E to 75º03'E longitudes in Dakshina Kannada and part of Udupi districts, Karnataka, India, with a total catchment area of 587 km^2 (Fig. 1). The M-P rivers originate in the midlands (below the western Ghats) at an altitude of about 240 and 200 m, respectively and have a common estuary near Mulki. The Pavanje River is a 5th order stream with a total length of about 35 km and the Mulki River is the 6th order stream with a total length of about 41 km. The different drainage patterns such as dendritic/sub-dendritic, trellis, rectangular, radial, annular, deranged, and braided are observed in this basin.

The M-P Basin is broadly comprised by Archaean age of Peninsular gneissic complex, such as South Canara granite (~158 km^2) in northern and eastern portions and migmatitic (banded/streaky) gneisses (~519 km^2) in southern/middle portions of the basin. Tertiary laterite (~132 km^2) and coastal sand (~19 km^2) formations are found in the southern part and coastal area, respectively (Abbas et al., 1991). Whereas, few dikes are found in northeast part of the basin (Fig. 2).

Physiographically the basin can be divided as midland and lowland regions. Tropical humid climate with very hot summer and high monsoon rainfall prevail in the basin. The average annual maximum temperature is 30.9 ºC and minimum is 23.7 ºC. On an average, annual rainfall is ~3 900 mm, of which about 80% is received during the south-west (SW) monsoon (June–September) and the remaining during the northeast (October–January) and inter-monsoon (February–May) months (Avinash et al., 2010). Humidity reaches maximum during the south-west monsoon due to heavy precipitation, low temperature and limited evaporation.

2 MATERIALS AND METHODS

2.1 Data Products and Image Processing

In the present study, groundwater prospect zones of the M-P River Basin have been evaluated based on lithology, geomorphic units and morphometric parameters. The basin is delineated using survey of India (SOI) topographic maps (No. 48 K/16, L/13 and O/4 of 1 : 50 000 scale) of 1967-70 edition and Indian remote sensing satellite (IRS)–P6, linear imaging

Table 1 Mathematical equations used for computation of various morphometric parameters

Morphometric parameters	Formula	Reference
Linear parameters		
Length (L)	L=1.312$A^{0.568}$ where, L=basin length (km), A=area of the basin (km^2)	Nookaratnam et al. (2005)
Stream order (u)	Hierarchical rank	Strahler (1964)
Stream length (L_u)	Length of the stream	Horton (1945)
Mean stream length (L_{sm})	$L_{sm}=L_u/N_u$ where, L_{sm}=mean stream length, L_u=total stream length of order 'u' N_u=total no. of stream segments of order 'u'	Strahler (1964)
Stream length ratio (R_L)	$R_L=L_u/L_{u-1}$ where, R_L=stream length ratio, L_u=total stream length of order 'u', L_{u-1}=the total stream length of its next lower order	Horton (1945)
Bifurcation ratio (R_b)	$R_b=N_u/N_{u+1}$ where, R_b=bifurcation ratio , N_u=total no. of stream segments of order 'u', N_{u+1}=number of segments of the next higher order	Schumm (1956)
Mean bifurcation ratio (R_{bm})	R_{bm}=average of bifurcation ratios of all orders	Strahler (1957)
Areal parameters		
Form factor (F_f)	$F_f=A/L^2$ where, F_f=form factor, A=area of the Basin (km^2), L=basin length (km)	Horton (1945, 1932)

Table 1 Continued

Morphometric parameters	Formula	Reference
Areal parameters		
Elongation ratio (R_e)	$R_e=1.128\sqrt{A}/L$ where, R_e=elongation ratio, A=area of the basin (km^2), L=basin length (km)	Schumm (1956)
Circularity ratio (R_c)	$R_c=4\pi A/P^2$ where, R_c=circularity ratio, π=3.14, A=area of the basin (km^2), P=perimeter (km)	Miller (1953); Strahler (1964)
Shape factor (B_s)	$B_s=L^2/A$ where, B_s=shape factor, L=basin length (km), A=area of the basin (km^2)	Horton (1932)
Compactness co-efficient (C_c)	$C_c=0.282\ 1P/A^{0.5}$ where, C_c=compactness coefficient, P=perimeter (km), A=area of the basin (km^2)	Gravelius (1914)
Drainage density (D_d)	$D_d=L_u/A$ where, D_d=drainage density, L_u=total stream length of all orders, A=area of the basin (km^2)	Horton (1945,1932)
Stream frequency (F_s)	$F_s=\sum N_u/A$ where, F_s=stream frequency, $\sum N_u$=total No. of streams of all orders, A=area of the Basin (km^2)	Horton (1945,1932)
Drainage texture (T)	$T=D_d\times F_s$ where, T=drainage texture, D_d=drainage density, F_s=stream frequency	Horton (1945)
Constant of channel maintenance (C)	$C=1/D_d$ where, C=constant of channel maintenance, D_d=drainage density	Schumm (1956)
Length of overland flow (L_o)	$L_o=1/2D_d$ where, L_o=length of overland flow, D_d=drainage density	Horton (1945)
Relief parameters		
Basin relief (R)	$R=H-h$ where, R=basin relief, H=maximum elevation in meter, h=minimum elevation in meter	Hadley and Schumm (1961)
Relief ratio (R_r)	$R_r=R/L$ where, R_r=relief ratio, R=basin relief, L=longest axis in kilometer	Schumm (1956)
Ruggedness number (R_n)	$R_n=R\times D_d$ where, R_n=ruggedness number, R=basin relief, D_d=drainage density	Schumm (1956)
Gradient ratio (G_r)	$G_r=(a-b)/L$ where, G_r=gradient ratio, a=elevation at source, b=elevation at mouth, L=longest axis in kilometer	Sreedevi et al. (2005)

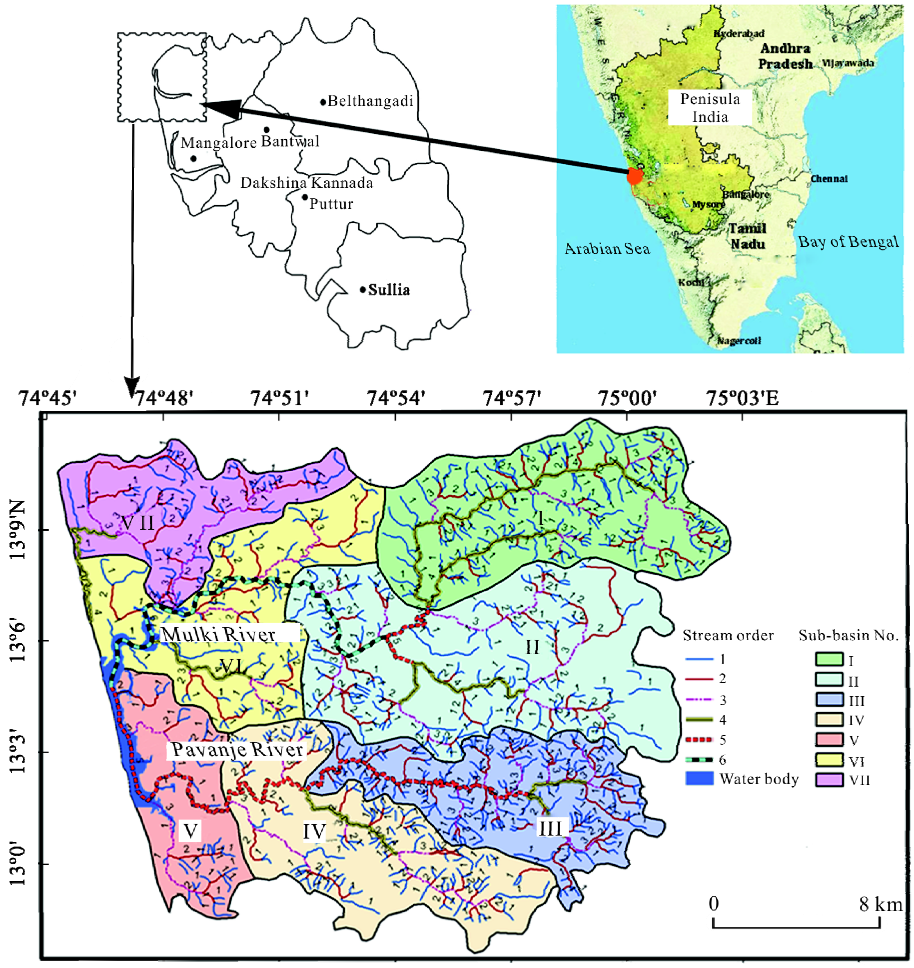

Figure 1. Map showing the various sub-basins (SB-I to VII) and stream orders of M-P River Basin delineated from SOI topographic maps and satellite images.

self scanner (LISS-III, 23.5 m resolution) images of 2008. The satellite images were geo-referenced using more than 50 ground control points (GCPs), distributed uniformly across the basin and carefully selected both on the IRS images and topographic maps using ERDAS Imagine v9.1 software to derive a polynomial transformation of the first (affine) order. The overall accuracy of the transformation, expressed as the root mean square error (RMSE) for geo-referenced images was not permitted to exceed more than 0.2 pixel (or 0.1 pixel for image-to-image registration, where GCPs can be more accurately located), corresponding to approximately 1 m (map-to-map) to less than 7 m (map-to-image or image-to-image) on the ground. After geo-referencing in geographic (lat/long) projection, a nearest neighbour interpolation method (as no change occurs in pixel values) was used to rectify and resample the images into a universal transverse of mercator (UTM) projection, WGS 84, Zone 43 North.

The geo-coded satellite images were enhanced to identify the drainage patterns and delineate the basin using digital enhancement techniques such as linear/contrast stretching, edge enhancement, filtering, band-ratioing and colour compositing. These digital data sets were used for systematic analyses of various morphometric, lithological and landform characteristics of the river basin. Based on tone, texture, shape, shadow and colour of enhanced images, drainage, lithology and hydrogeomorphic units were delineated and updated.

2.2 Geomorphic and Morphometric Analyses

Basin geomorphology has been mapped and interpreted based on lithological characteristics using soil, geology and SOI topographic maps as well as the satellite images in GIS environment. Visually interpreted geomorphic units were mapped and the percentage area of each geomorphic unit has been quantified at sub-basin-level and given in Table 2. The basin area has been classified into different geomorphic units such as denudational hills (DH), pediment (PD), residual hills (RH), inselbergs (I), lateritic uplands (LU), pediplain, flood plain (FP), piedmont plain (PP), and valley fills (VF).

Drainage and contour layers of the whole basin have been extracted by digitising the SOI topographic maps using ArcGIS v.9.1 software. Drainage layer was further updated with linearly stretched and edge enhanced false colour composite (FCC) of LISS-III images. Based on drainage characteristics and relief variability (landscape morphology assessed in terms of elevation, slope, and degree of dissection), the basin has been subdivided into seven sub-basins viz. SB-I to SB-VII (Fig. 1). The triangular irregular network (TIN) was generated by interpolating the contour layer (at 20 m interval) which in turn was used to generate the height and slope maps using 3D Analyst tool of ArcGIS v9.3 software. Drainage network were analysed as per the laws of Horton (1945), and the stream ordering was carried out using Strahler stream order method (Strahler, 1964). Based on established mathematical equations (Table 1), the sub-basin wise morphometric parameters (linear, areal and relief) were calculated and given in Tables 3–7. The methodology followed in the study is shown in Fig. 3.

2.3 Sub-Basin-Wise Prioritisation Techniques

Geomorphic units and morphometric parameters have been computed to evaluate the groundwater prospects of the M-P River Basin. The method used by Avinash et al. (2011) and Biswas et al. (1999) has been followed for prioritisation of sub-basins. The groundwater prospect for each unit has been categorised into two major categories—(i) poor to moderate, and (ii) good to excellent—for prioritising the sub-basins. Priority was

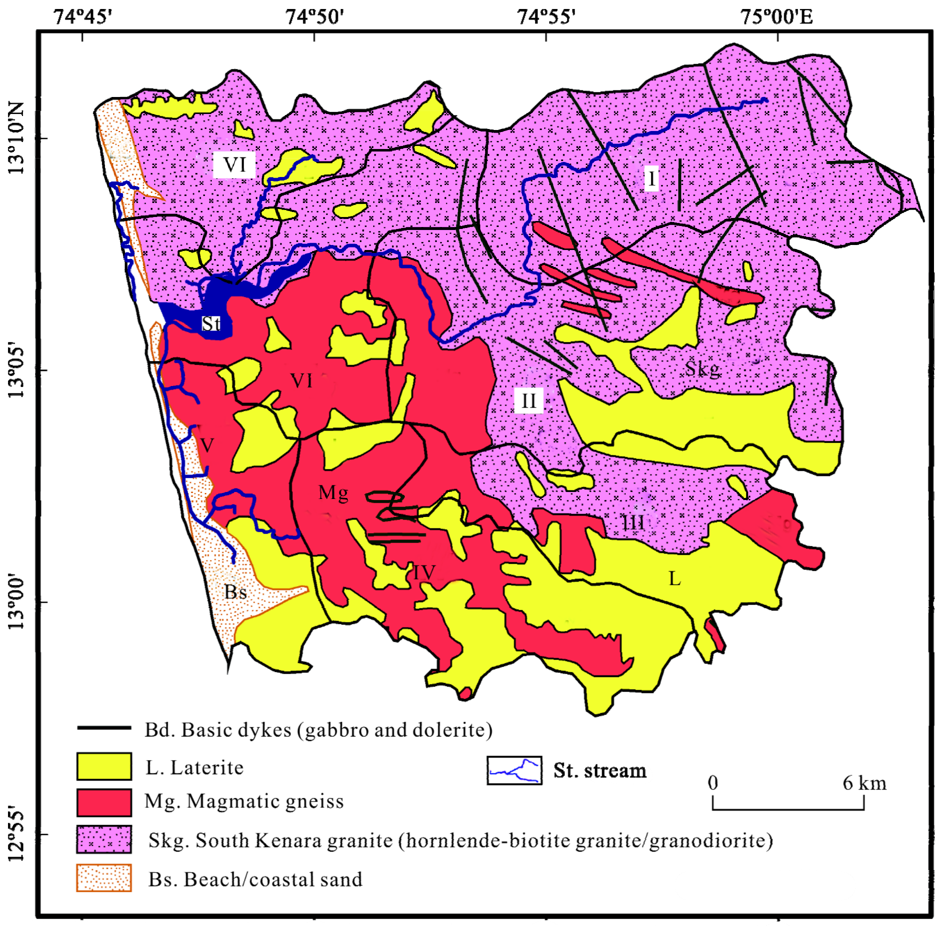

Figure 2. Geology map illustrating the distribution of lithology and rock types of the M-P River Basin (after resource map of Udupi and Dakshina Kannada districts, Karnataka, compiled by Geological Survey of India, 1991).

Table 2 Sub-basin-wise areal coverage (in terms of %) of various geomorphic units of the M-P Basin

Features	Water potential	SB-I (%)	SB-II (%)	SB-III (%)	SB-IV (%)	SB-V (%)	SB-VI (%)	SB-VII (%)
DH	Poor	2.4	7.8	6.4	0.0	0.0	0.0	0.0
PD	Good	0.8	4.3	1.5	0.0	0.0	0.0	0.0
RH	Poor	4.1	0.0	1.70	0.0	0.0	3.2	1.72
I	Poor	1.7	3.5	7.0	0.0	0.4	0.69	1.8
LU	Moderate	2.3	0.0	0.0	0.0	0.0	0.0	0.0
PPS	Moderate	41.4	44.2	34.4	52.5	50.1	46.0	39.9
PPM	Good	46.5	39.6	23.4	39.5	37.6	41.2	53.4
PP	Good	0.0	0.0	3.1	0.0	0.0	0.0	0.0
VF	Very good	0.0	0.1	22.4	8.0	0.001	2.9	2.5
FP	Excellent	0.74	0.4	0.01	0.0	11.9	6.0	0.72

DH. Denudational hills; PD. pediments; RH. residual hills; I. inselbergs; LU. lateritic uplands; PPS. shallow weathered pediplain; PPM. moderately weathered pediplain; PP. piedmont plain; VF. valley fills; FP. flood plain.

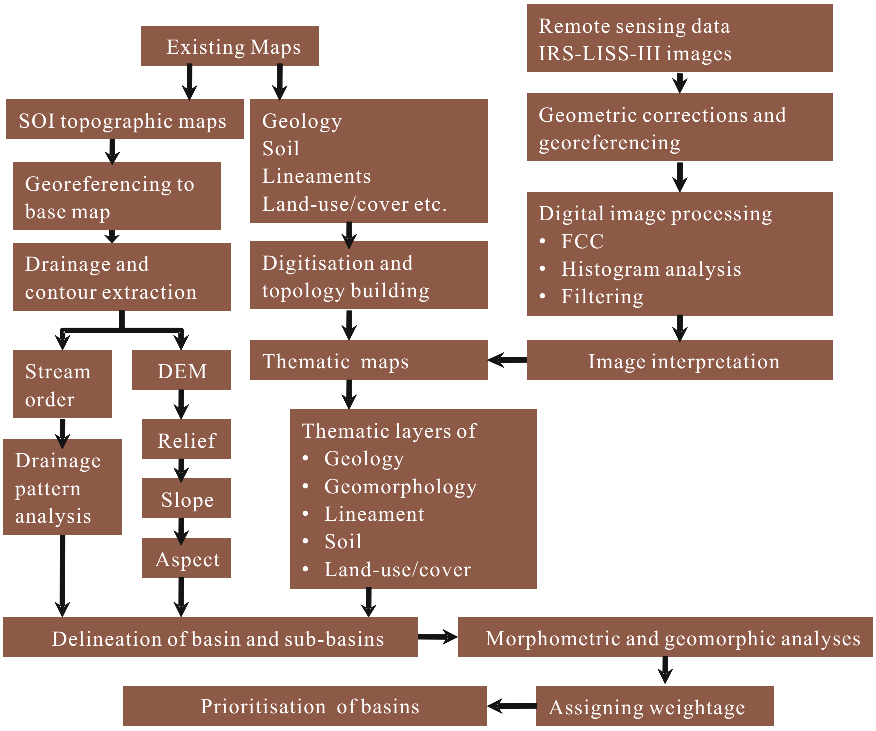

Figure 3. Flow chart showing the details of methodology adopted in this study.

assigned to every geomorphic unit based on the areal coverage and groundwater prospect. For example, the unit has 'poor to moderate' groundwater prospect with largest areal coverage of that particular sub-basin is ranked as 1, next largest areal coverage is ranked as 2 and so on. On the contrary, the unit has 'good to excellent' groundwater prospect with smaller areal converge in a particular sub-basin is ranked as 1, next smaller areal coverage is ranked as 2 and so on. After ranking all the geomorphic units, the ranked values for each sub-basin were averaged to arrive at a compound value (*C*g) (Table 8). The morphometric parameters such as linear/areal (bifurcation ratio, drainage density, drainage texture, and stream frequency) and shape (form factor, elongation ratio, circularity ratio, shape factor) have been used for prioritising sub-basins to demarcate sub-basin-wise the most deficit zone of groundwater. In linear/areal parameter, the highest value among the seven sub-basins was ranked as 1, next higher value was ranked as 2 and so on. On the contrary, the shape parameters, the lowest value was ranked as 1, next lower value was ranked as 2 and so on. After ranking the every morphometric parameter, the ranked values for each sub-basin were averaged to arrive at a compound value (*C*m) (Table 8).

The total compound value was calculated by the sum of geomorphic units (*C*g) and morphometric parameters (*C*m) as given in Table 8. Based on the total compound value, first priority (1) is assigned for least compound value which indicates most deficit sub-basin for groundwater prospects. Likewise next higher value is assigned for next priority (2) and so on. The last priority number (7) indicates that sub-basin is most surplus zone for groundwater potential.

3 RESULTS AND DISCUSSION

Drainage network analysis provides information pertaining to lithology, hydrological nature, drainage characteristics and exogenic/endogenic processes within the basin. To evaluate the directions and controlling factors of drainage network, stream orientation analyses were computed. The different drainage patterns identified in the basin will be useful to understand the influence of structural and lithological control. Various geomorphic units and the morphometric parameters of the basin are used to identify the deficit/surplus zone of groundwater in the basin.

3.1 Orientation of Drainage System

Stream direction can be used as one of the proxies for geologically recent tectonic activity (Eyles et al., 1997). The statistical analysis of the azimuthal distribution of stream channels in the drainage network of the basin shows preferential orientations, which is likely to be controlled by tectonics. Stream orientation analysis was computed basin-wise (for 2nd, 3rd and 4th order streams) to evaluate the directions and controlling factors of drainage network (Fig. 4). In the M-P Basin, 2nd order streams are oriented generally towards N to E directions (0º–90º), predominantly towards N, NE and E directions. Third order streams are predominantly oriented towards NNW, NE, E and S directions. Streams of 4th order are generally found to be oriented towards NNW, NEE, ESE, SE, SSE, S, WNW and NW directions (Fig. 4). These directions indicate that the basins are controlled either by lithology or by structure. Hence, to validate drainage control and orientation, ground based surveys are necessary.

3.2 Hydrogeomorphology of the Basin

The basin is characterised by different erosional and depositional geomorphic features, such as denudational hills, pediment, residual hills, inselbergs, lateritic uplands, pediplain, piedmont plain, valley fills, and flood plain, which are used to demarcate the surplus/deficit zones of groundwater (Fig. 5). Sub-basin-wise each geomorphic unit was quantitatively estimated and percentage of groundwater potential in each unit is computed and given in Table 2.

Denudational hills (DHs) consist of jointed and fractured granites or gneisses, formed due to differential erosion and weathering. These are good runoff zones with poor groundwater potential whereas some infiltration possibilities are expected through fractures/joint planes and topographic cuts. The drainage density is found to be medium and runoff coefficient is high in this unit. The total areal extent of this unit is ~18 km^2 in the whole basin and found at the middle and eastern part of the basin only in SB-I (2.4%), SB-II (7.8%) and SB-III (6.4%) (Table 2; Fig. 5).

Pediments (PD) are gently sloping rock flooring areas with erosional bedrock of low relief between hills and plains developed by the process of weathering, which cover a total area of 7.7 km^2. Sub-basin II covers the major portion (4.3%) of this unit (Table 2) with a few patches in SB-I, -II and -III. This unit has low permeability and infiltration rate while the groundwater prospects are normally poor due to massive, compact nature of rocky surface. However, granitic terrains with numerous fractures or joints permit infiltration and storage of groundwater (Deepika et al., 2013; Avinash et al., 2011).

Residual hills (RHs) formed by the differential erosion and weathering of pre-existing plateaus, plains and complex tectonic mountains, where groundwater prospects are commonly found to be poor due to high surface runoff and less infiltration (Avinash et al., 2011; Javed et al., 2009). In this basin, RHs are exposed in patches with a total areal coverage of 9.2 km^2. Maximum (4.1%) areal extent of this unit is found in SB-I followed by 3.2% in SB-VI and 1.7% each in SB-III and VII (Table 2).

Inselbergs (I) are the remnants of weathering and denudation, found mostly within granitic terrain and acts as runoff zone where groundwater potential is very poor. In the basin studied, this unit is found in all the sub-basins (except SB-IV)

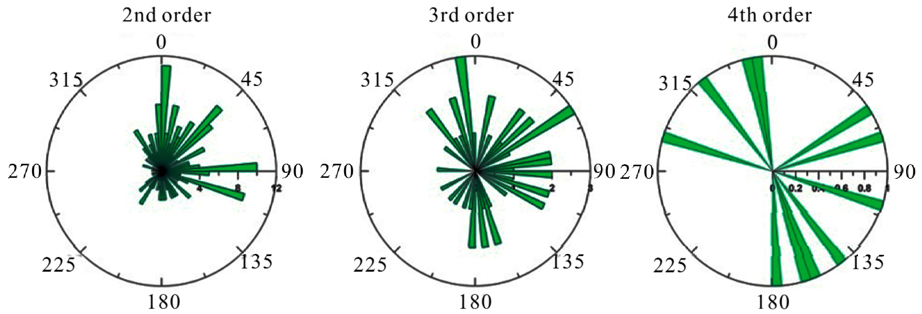

Figure 4. Orientation of 2nd, 3rd and 4th order streams of the M-P Basin.

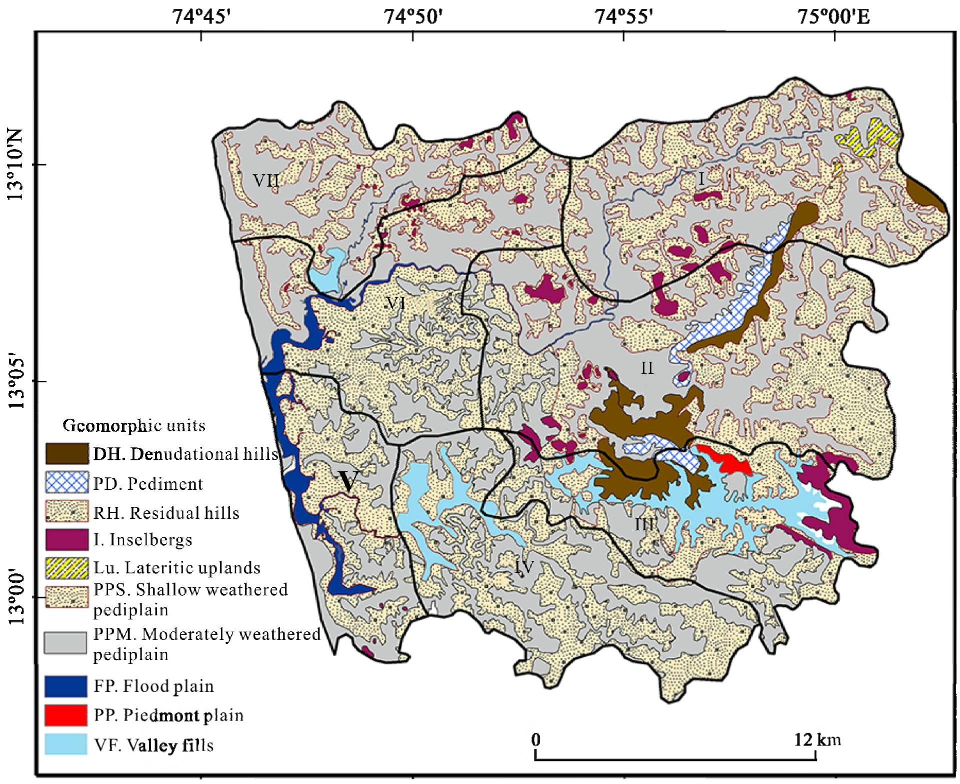

Figure 5. Distribution of different hydrogeomorphic units of the M-P Basin.

with a maximum of 7% in SB-III (Table 2). Total areal extent of this unit is estimated to be 13.5 km^2.

Lateritic uplands (LUs) are developed over Tertiary sediments and are characterised by moderate infiltration from rainfall and significant water-table fluctuation with moderately good groundwater prospect. The total areal extent of the LUs is estimated to be 2.3 km^2 which is observed only in SB-I (Table 2).

Pediplain is a gently inclined sloping surface of boulders, gravels and sand, extending from the abrupt base of steep mountain faces to the flat foreground (Singh et al., 2011). Groundwater prospects in this unit is good due to moderately thick (15–20 m) weathered material (Prakash and Mishra, 1993). On the basis of thickness of weathered zone, the pediplains have been sub-divided into: (i) Shallow weathered pediplain (PPS) and (ii) Moderately weathered pediplain (PPM). PPS represents the areas of nearly level terrain with low gradient, developed by continuous process of pedimentation and characterized by shallow weathered material ranging from 0 to 5 m with red soil cover and sparse vegetation. The groundwater prospect in this unit is found to be moderate. PPS is estimated to be occupied ~260 km^2 area of the basin, while 52.5% area is covered by SB-IV and 40% to 50% area is occupied by other basins (Table 2). PPM is found at nearly flat terrain with gentle slope and occur normally along all the major drainage courses which consists of relatively thick weathered material (5–15 m) covered with red soil and fairly thick vegetation and generally associated with lineaments (Avinash et al., 2011). Groundwater prospects in this unit are considered as moderate to good, depending upon thickness of the weathered zone. PPM is the second largest unit which covers 237 km^2 area of the basin. Maximum areal coverage of 53.4% of this unit is found in SB-VII and minimum areal coverage (23.4%) is found in SB-III (Table 2).

Piedmont plain (PP) is comprised of unconsolidated sediments of sand, silt and clay with boulders and pebbles and acts as a transmission zone having deep aquifers. Groundwater potential varies from moderate to good in the upper and lower piedmont zones. This unit is found only in SB-III and covers an areal extent of 2.3 km^2 (Table 2).

Valley fills (VFs) are the deposition of unconsolidated materials (boulders, pebbles, sand, silt, and clay) in the narrow valleys and are found along the upstream of the river courses. This unit is found to have high moisture content and covered by thick vegetations, hence, forms a good potential zone for groundwater potential (Pal et al., 1997; Pratap et al., 1997; Singh et al., 1993; Avinash and Srivastva, 1991). Its areal extent is estimated to be ~27 km^2 in this basin. The maximum area of this unit is estimated to be 22.4 % in SB-III and 8% in SB-IV with small patches in the remaining sub-basins except SB-I (Table 2).

Flood plain (FP) is the youngest geomorphic unit formed by erosion and deposition processes of gravel, pebbles, sand, silt and clay. This unit has high moisture content and gentle slope of about 5º, deposited all along the river course and its main tributary (Avinash et al., 2011; Rao, 2009). Groundwater prospects in this unit are usually very good to excellent. The areal extent of this unit estimated in this basin is 13 km^2. Major portion of this unit is found in SB-V (11.9%) and the remaining is distributed in other sub-basins except SB-IV (Table 2).

3.3 Morphometric Analysis

Morphometric parameters are useful for drainage network analysis, which provide information about lithology, hydrological nature, drainage characteristics and neotectonic activities within the basin (Deepika et al., 2013; Avinash et al., 2011). The basin morphometric characteristics comprise three major aspects: (i) Linear (basin length (L), stream order (u), bifurcation ratio (R_b), stream length (L_u) and stream length ratio (R_L)), (ii) areal (form factor (F_f), elongation ratio (R_e), circularity ratio (R_c), shape factor (B_s), drainage density (D_d), stream frequency (F_s), and drainage texture (T)), and (iii) relief (basin relief (R), relief ratio (R_r), ruggedness number (R_n), and gradient ratio (G_r).

3.3.1 Linear aspects

Sub-basins cover an average area of ~84 km^2 and average length (L) of ~16 km. The SB-V covers the lowest area of ~49 km^2, while the SB-II covers the highest area of ~138 km^2. Basin length of the SB-V is found to be shortest (12 km), whereas the SB-II is the longest (21.5 km) one.

Stream order (u) analysis is used for comparison of geometry of drainage networks on different linear scales. Stream ordering of the basin has been carried out according to Strahler's (1964) ordering system. The total number of streams in all the sub-basins varies from 57 (SB-V) to 216 (SB-III) (Table 3). Lower number of streams is the indication of matured topography of sub-basins, whereas the higher number of streams (first- and second-orders) indicates that the area is prone to erosion (Avinash et al., 2011). The geometric relation between the logarithm of average number of streams (N_u) vs. stream orders (u) shows an inverse linear relationship (R= -0.997). It indicates the 'N_u' decreases as the 'u' increases which supports the Horton's (1932) Law (Fig. 6).

The bifurcation ratio (R_b) value for the whole basin or sub-basin-wise is <5 (maximum 3.13 for SB-II) which indicates control of drainage network is mainly pronounced by geomorphology and not by geological structures (Table 3). Lower R_b

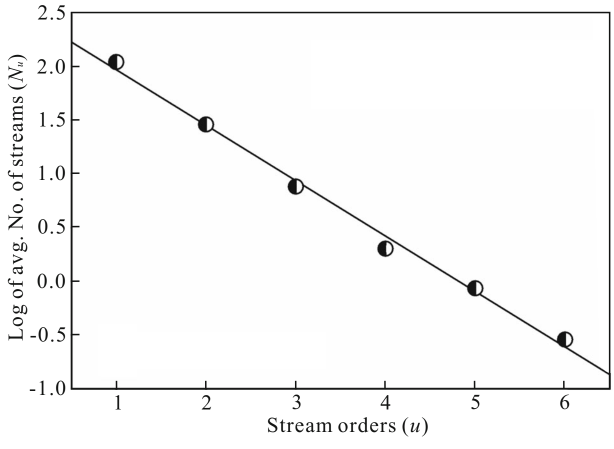

Figure 6. The relation between stream orders (u) and number of streams (N_u) in the studied basin.

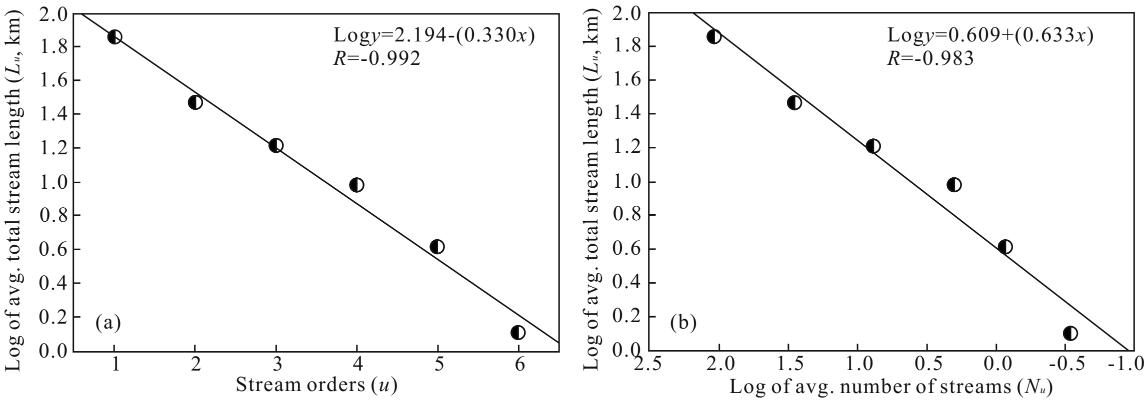

Figure 7. The geometric relationship between stream orders (*u*) and stream length (L_u) (a), and between number of streams (N_u) and stream length (L_u) of the whole M-P Basin (b).

values are also due to the presence of a large number of first-, second- and third-order streams in the sub-basins (Manu and Anirudhan, 2008) indicating that the drainage basin is underlined by uniform materials, and the streams are usually branched systematically (Pakhmode et al., 2003).

Stream length (L_u) is the significant hydrological feature used to understand the surface runoff characteristics and drainage network components of the underlying rock surfaces over the areas of consecutive stream orders. A small number of relatively longer streams are formed if the rock formations are permeable, whereas a large number of smaller streams are developed if the rock formations are less permeable (Pakhmode et al., 2003). Streams of relatively smaller lengths are characteristics of areas with larger slopes and finer textures, while longer lengths of streams are generally indicative of flatter gradients. In this basin, the total stream length (ΣL_u) is minimum (~53 km) in the SB-V and maximum (189 km) in the SB-I (Table 4), with an average of 132 km. Further, it is also noted that L_u is maximum (average of 71.84 km) in the case of 1st order streams in all the sub-basins whereas, the L_u decreases consequently with higher orders that indicate constant variation in relief over which streams occur. However, the average values of L_u computed for different stream orders are given in Table 4 and the logarithm of average 'L_u' vs. 'u' is shown in Fig. 7a. This plot indicates the negative linear relationship (R= -0.992) and supports the Horton's (1945) Law of stream length. It also indicates similarities in the development of the number of streams as well as in the formation of L_u, with respect to stream orders. Figure 7b illustrates the relation between the logarithm of average N_u and the logarithm of average L_u. This relation shows positive linear relationship (R=0.983) which clearly explains that the number of streams increases as the stream lengths increase.

Stream length ratio (R_L) has an important relationship with the surface flow discharge and the erosional stage of the basin (Sreedevi et al., 2005). An increasing trend in R_L from lower order to higher order indicates the mature geomorphic stage, whereas, R_L between successive stream orders varies due to differences in slope and topographic conditions (Magesh et al., 2011). The R_L for the 4th order streams of the basin shows a highest average value of 2.2 (0.47–5.47) compared to the average R_L for other orders of streams within the basin. The average R_L values of the 2nd order streams is 1.66 (1.15–2.07), 3rd order streams is 2.10 (1.21–3.11), 5th order streams is 1.62 (0.0–7.08) and of 6th order streams is 0.40 (0.0–2.80) (Table 4). The mean R_L of all the seven sub-basins varies from 1.02–2.37. The higher value (4th order) indicates that the rock formations in the area are comparatively gentler in slope and/or more permeable than the rock-surfaces drained by the remaining order of streams.

3.3.2 Areal aspects

The important shape parameters affect the stream flow hydrographs and peak flows of the basins. Shape parameters computed for the M-P Basin and its sub-basins are given in Table 5. Form factor (F_f) values of the basin vary from 0.30 (SB-II) to 0.34 (SB-V) with an average of 0.32 which indicates that the basin is narrow and elongated in form (Table 5; Fig. 1). Elongation ratio (R_e) varies from 0.61 (SB-II) to 0.66 (SB-V) with an average of 0.64 which reveals the fact that the basin is in an elongated shape (Table 5). Higher value of R_e indicates active denudational processes with high infiltration capacity and low run-off in the basin, whereas, lower R_e values indicate higher elevation of the basin susceptible to high headward erosion along tectonic lineaments (Deepika et al., 2013; Avinash et al., 2011; Manu and Anirudhan, 2008; Obi Reddy et al., 2004). R_e values suggest that the sub-basins are usually associated with high relief and steep ground slope. Circularity ratio (R_c) values of the basin range from 0.32–0.62 in the SB-III and -I, respectively with an average of 0.44 (Table 5) indicating that the basin is not in a circular shape and quantity of discharge is less. Low, medium and high values of R_c respectively give an indication of young, mature and old stages of tributaries in the sub-basins (Avinash et al., 2011).

Drainage density (D_d) is a quantitative measure of length of streams within a square grid of area which provides a numerical measurement of landscape dissection and run-off potential (Obi Reddy et al., 2004). According to Horton (1945), low D_d is an indication of prevalence of highly resistant/permeable strata under dense vegetation and low relief, whereas high D_d prevails in weak/impermeable rocks under sparse vegetation and mountainous relief regions. The areas of high D_d are not suitable for groundwater development because of high surface runoff. Therefore, lesser the D_d, higher is the probability of recharge or

Table 3 Sub-basin-wise computed linear parameters of the basin

Sub-basins/ basin	Basin area (a; km^2)	Basin length (L; km)	Basin perimeter (p; km)	Number of streams (N_u) of different stream order (u)							Bifurcation ratio R_b (N_u/N_{u+1})					
				1	2	3	4	5	6	$\sum N_u$	1/2	2/3	3/4	4/5	5/6	Mean R_b
I	100.06	17.95	45.16	165	39	7	2	1	-	214	4.23	5.57	3.50	2.00	-	3.06
II	138.16	21.56	61.65	141	41	11	2	2	1	198	3.44	3.73	5.50	1.00	2.00	3.13
III	73.85	15.11	53.69	159	42	11	3	1	-	216	3.79	3.82	3.67	3.00	-	2.85
IV	84.75	16.33	52.78	118	33	7	3	1	-	162	3.58	4.71	2.33	3.00	-	2.72
V	49.37	12.02	35.04	43	8	4	1	1	-	57	5.38	2.00	4.00	1.00	-	2.48
VI	85.33	16.40	53.40	76	21	7	2	-	1	107	3.62	3.00	3.50	-	-	2.02
VII	55.54	12.85	41.42	59	16	6	1	-	-	82	3.69	2.67	6.00	-	-	2.47
Average[a]	83.86	16.03	49.02	108.71	28.57	7.57	2.80	0.86	0.29	148	3.96	3.64	4.07	1.43	0.29	2.68
M-P Basin	587.05	112.22	343.14	761	200	53	14	6	2	1036	3.81	3.77	3.79	2.33	3.00	3.34

[a]. Basin as a whole.

Table 4 Stream lengths and stream length ratio of different sub-basins of the basin

Sub-basin/ basin	Total stream lengths L_u (km) in different u							Average L_u (km) in different u (L_u/N_u)						Stream length ratio R_L (L_u/L_{u-1})					
	1	2	3	4	5	6	$\sum L_u$	1	2	3	4	5	6	2/1	3/2	4/3	5/4	6/5	Mean R_L
I	113.55	30.96	17.29	26.99	0.15	-	188.94	0.69	0.79	2.47	13.50	0.15	-	1.15	3.11	5.47	0.01	0.00	1.95
II	95.51	41.31	25.15	9.42	5.37	7.53	184.29	0.68	1.01	2.29	4.71	2.69	7.53	1.49	2.27	2.06	0.57	2.80	1.84
III	90.35	40.54	12.90	6.53	15.41	-	165.73	0.57	0.97	1.17	2.18	15.41	-	1.70	1.22	1.86	7.08	0.00	2.37
IV	72.00	27.71	17.33	6.84	6.97	-	130.84	0.61	0.84	2.48	2.28	6.97	-	1.38	2.95	0.92	3.05	0.00	1.66
V	28.65	11.03	10.86	1.27	0.76	-	52.56	0.67	1.38	2.71	1.27	0.76	-	2.07	1.97	0.47	0.60	0.00	1.02
VI	59.17	30.39	12.29	11.01	-	1.36	114.21	0.78	1.45	1.76	5.50	-	1.36	1.86	1.21	3.13	0.00	0.00	1.24
VII	43.69	23.52	17.52	4.27	-	-	89.00	0.74	1.47	2.92	4.27	-	-	1.99	1.99	1.46	0.00	0.00	1.09
Average[a]	71.84	29.35	16.19	9.48	4.09	1.27	132.22	0.68	1.13	2.26	4.82	5.19	4.45	1.66	2.10	2.20	1.62	0.40	1.59
M-P Basin	502.91	205.46	113.32	66.33	28.66	8.89	925.57	0.66	1.03	2.14	4.74	4.78	4.45	1.55	2.08	2.22	1.01	0.93	1.56

[a]. Basin as a whole.

Table 5 Computed values of various shape and areal parameters of different sub-basins

Sub-basins/basin	I	II	III	IV	V	VI	VII	Average[a]
Form factor (F_f)	0.31	0.30	0.32	0.32	0.34	0.32	0.34	0.32
Elongation ratio (R_e)	0.63	0.61	0.64	0.64	0.66	0.64	0.65	0.64
Circularity ratio (R_c)	0.62	0.46	0.32	0.38	0.51	0.38	0.41	0.44
Shape factor (B_s)	3.22	3.36	3.09	3.15	2.93	3.15	2.97	3.12
Drainage density (km^{-1}) (D_d)	1.89	1.33	2.24	1.54	1.06	1.34	1.60	1.57
Stream frequency (km^{-2}) (F_s)	2.14	1.43	2.92	1.91	1.15	1.25	1.48	1.76
Drainage texture (km^{-1}) (T)	4.04	1.91	6.56	2.95	1.23	1.68	2.37	2.96

[a]. Basin as a whole.

potential groundwater zones (Mohanty and Behera, 2010; Srinivas et al., 2008). D_d values of the M-P Basin range from 1.06 (SB-V) to 2.24 (SB-III) km/km^2, with an average of 1.57 km/km^2 (Table 5). Hence, values of D_d suggest that most of the sub-basins have resistant/permeable strata under medium to dense vegetation with moderate relief.

Stream frequency (F_s) mainly depends on lithology of the basin which reflects the texture of the drainage network and is related to permeability, infiltration capacity and relief of the sub-watershed. High value of F_s indicates greater surface run-off, steep slope, impermeable sub-surface material, sparse vegetation, high relief conditions and low infiltration capacity (Shaban et al., 2005; Obi Reddy et al., 2004; Horton, 1945, 1932). F_s values of this basin range from 1.15 (SB-V) to 2.92 (SB-III) with an average value of 1.76 per km^2 (Table 5). It means that about two streams are developed in an area of one km^2 in the basin. The low F_s values (<2 per km^2) found in all the sub-basins except SB-I and -III are an indication of occurrence of moderate ground slopes associated with moderately permeable rocks, moderate run-off and infiltration.

Drainage texture (T) is a measure of closeness of the channel spacing, depends on climate, rainfall, vegetation, soil and rock type, infiltration rate, relief and the stage of development (Schumm, 1956; Smith, 1950; Horton, 1945). Soft or weak rocks unprotected by vegetation characterize a fine T, while, massive and resistant rocks represent a coarse T. The T of the basin ranges between 1.23 (SB-V) and 6.56 (SB-III), with an average of 2.96 (Table 5). Based on the classification of Smith (1950), T indicates coarse texture for the whole basin, while, the SB-I, and -III showing an intermediate texture.

3.2.3 Relief aspects

Relief aspects of a basin play an important role in drainage development, surface and sub-surface water flow, permeability, landform development and associated features of the terrain (Vijith and Satheesh, 2006).

Basin relief (R) is an important factor to understand denudational characteristics of the basin, which controls the stream gradient and therefore influences the flood pattern and the amount of sediment transported (Hadley and Schumm, 1961). The height of the basin ranges from 20 to 240 m, which indicates low relief (220 m) of the basin (Table 6). Relief ratio (R_r) measures the overall steepness of a drainage basin and is an indicator of intensity of erosion operating on the slope of a basin. Relief ratio of the studied basin is 0.009 1, whereas that of the sub-basins vary from 0.002 9 (SB-V) to 0.031 7 (SB-II) (Table 6). The R_r values indicate that the SB-II is situated comparatively in higher elevated/hilly region than the other sub-basins.

Slope is the major controlling factor in the development and formation of different landforms and it is important to understand the groundwater movement of a basin. Slope of the basin varies from 0^o to 73^o (Fig. 8). Ruggedness number (R_n) indicates structural complexity of the terrain, relief, drainage density and the area susceptible to soil erosion (Sameena et al., 2009). The R_n of the basin is showing low value (0.35) indicating low basin relief (~220 m). R_n of the sub-basins, ranges from 0.06 (SB-V) to 0.42 (SB-I) suggest low relief and poor drainage density (Table 6). Gradient ratio (G_r) is an indication of the channel slope from which the run-off volume could be evaluated. Gradient ratio of the basin is 0.007 5 where sub-basin-wise values range from 0.002 9 (SB-V) to 0.026 0 (SB-II) (Table 7).

Table 6 Relief aspects of different sub-basins

Sub-basin/basin	Elevation (m a.s.l.)		Basin relief (B_h) (H-h) (m)	Longest axis (L) (km)	Relief ratio (R_r)	Ruggedness number (R_n) $B_h \times D_d$ (km)
	Max (H)	Min (h)				
I	240	20	220	8.65	0.025 4	0.42
II	240	20	220	6.93	0.031 7	0.29
III	200	20	180	8.62	0.020 9	0.19
IV	160	20	140	13.71	0.010 2	0.19
V	60	20	40	13.65	0.002 9	0.06
VI	90	20	70	9.65	0.007 3	0.11
VII	100	20	80	10.88	0.007 4	0.18
M-P	240	20	220	24.08	0.009 1	0.35

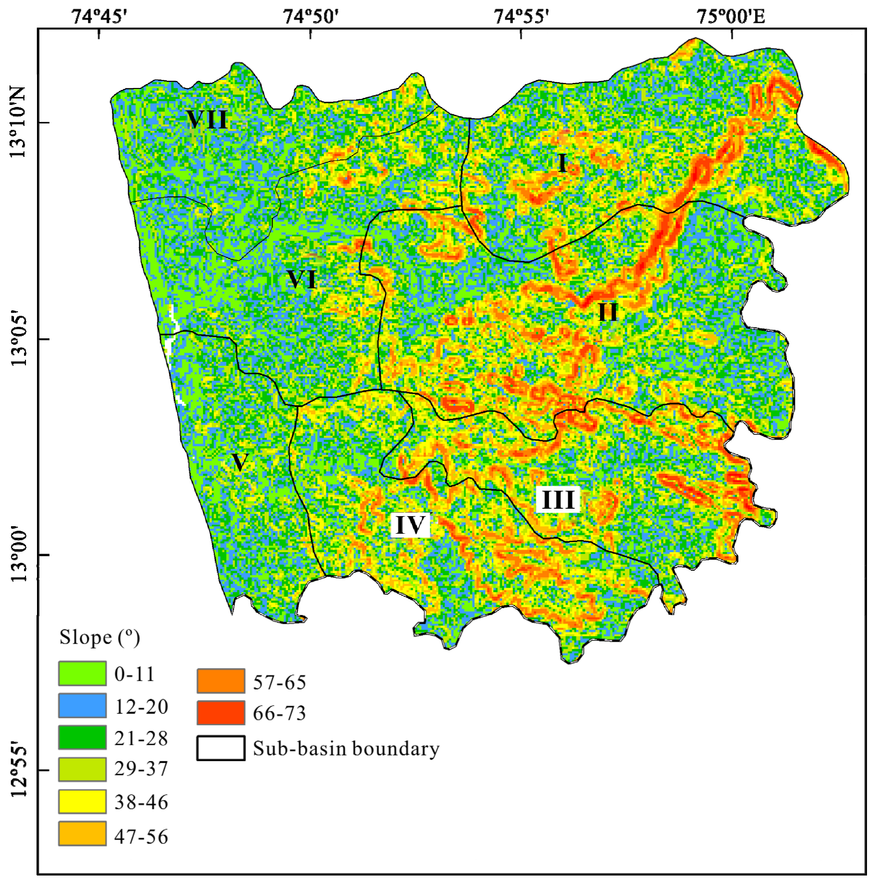

Figure 8. Sub-basin-wise slope variations (°) of the M-P Basin.

3.4 Prioritisation of Sub-Basins for Groundwater Prospects

The prioritisation studies of the M-P Basin demonstrate that the SB-III would be most deficit zone of groundwater while the SB-I, IV and II, are the next consequent deficit zones for groundwater. The SB-VII, VI and V are found to show increase in groundwater potentiality (Table 8). Area of groundwater prospects of this basin is estimated to be 7% under poor, 44% under moderate and 49% under good to excellent.

4 CONCLUSIONS

The studies on geomorphology and morphometric parameters are found to be the good proxies to evaluate the deficit and surplus zones of groundwater for river basins/watersheds. Stream orientation analysis of the M-P Basin reveals that the steams are oriented mainly towards (0º–90°) (2nd order), NNW, NE, E and S (3rd order), 50º–180º and 290º–350° (4th order) directions. Sub-basin-wise quantification of various geomorphic units of the basin resulted that area of groundwater prospects is estimated to be 7% under poor, 44% under moderate and 49% under good to excellent.

The R_b values of the whole basin and the sub-basins are less than 5 indicating the control of drainage network is mainly pronounced by geomorphology and not by geological structures. The empirical test for understanding the characteristic and components of a drainage network in all the sub-basins indicate that number of streams increases as the stream lengths increase. The values of F_f, R_e and R_c suggest that the shape of the basin is elongated and associated with high relief, steep ground slopes and quantity of discharge is less. The D_d values

Table 7 Gradient aspects of different sub-basins

Sub-basin/basin	Elevation (m a.s.l.)		Fall in height	Length of main	Gradient ratio
	Source (a)	Mouth (b)	(a-b) (m)	stream (L) (km)	(a-b/L)
I	180	20	160	8.65	0.018 5
II	200	20	180	6.93	0.026 0
III	160	20	140	8.62	0.016 2
IV	120	20	100	13.71	0.007 3
V	60	20	40	13.65	0.002 9
VI	60	20	40	9.65	0.004 1
VII	80	20	60	10.88	0.005 5
M-P	200	20	180	24.08	0.007 5

Table 8 Sub-basin-wise prioritisation of the basin based on geomorphology and morphometric parameters. The first priority (1) indicates the most deficit zone of groundwater prospect, while the last priority (7) indicates the potential of groundwater

Geomorphic units	SB-I	SB-II	SB-III	SB-IV	SB-V	SB-VI	SB-VII
DH	3	1	2	4	4	4	4
PD	2	4	3	1	1	1	1
RH	1	4	4	4	4	2	3
I	4	2	1	7	6	5	3
LU	1	2	2	2	2	2	2
PPS	5	4	7	1	2	3	6
PPM	6	4	1	3	2	5	7
PP	1	1	2	1	1	1	1
VF	1	3	7	6	2	5	4
FP	5	3	2	1	7	6	4
Compound value (*C*g)	2.90	2.80	3.10	3.00	3.10	3.40	3.50
Morphometric parameters							
F_f	2	1	5	4	7	3	6
R_e	2	1	5	4	7	3	6
R_c	7	5	1	3	6	2	4
B_s	6	7	3	4	1	5	2
R_b	2	1	3	4	5	7	6
D_d	2	6	1	4	7	5	3
T	2	5	1	3	7	6	4
F_s	2	5	1	3	7	6	4
Compound value (*C*m)	3.13	3.88	2.50	3.63	5.88	4.63	4.38
Total compound value (*C*g+*C*m)	6.03	6.68	5.60	6.63	8.98	8.03	7.88
Final priority	2	4	1	3	7	6	5

indicate that most of the sub-basins have resistant/permeable strata under medium to dense vegetation with moderate relief. Low F_s values of all the sub-basins except SB-I and III indicate the occurrence of moderate ground slopes and permeable rocks, which promote moderate run-off and infiltration. The drainage texture of the basin indicates coarse texture while the SB-I and -III indicating an intermediate texture. The SB-II is situated comparatively in higher elevated/hilly region than the other sub-basins and its R_r is higher. The R_n of the basin indicates low basin relief and poor drainage density.

Prioritisation results of the basin indicate that the SB-III is the most deficit zone of groundwater, whereas, SB-I, IV, II, VII, and VI show decrease in deficiency of groundwater, while SB-V is found to be surplus zone of groundwater potential. The prioritisation based on the results of geomorphology and morphometric analyses clearly indicate the hydrogeological relationships among various parameters of the basin, facilitate to understand the river processes and groundwater prospects.

ACKNOWLEDGMENTS

The first author (AK) thanks Director, National Centre for Antarctic and Ocean Research (NCAOR), and Dr. A J Luis for continuous support and encouragement.

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