EVOLUTION OF CHALIYAR RIVER DRAINAGE BASIN: INSIGHTS FROM TECTONIC GEOMORPHOLOGY

Thesis submitted to the
Cochin University of Science and Technology

by
Ambili V

In partial fulfilment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

Under the Faculty of Marine Sciences

Department of Marine Geology and Geophysics
Cochin University of Science and Technology
Cochin-682 016

October 2010

DECLARATION

I hereby declare that the thesis entitled **"Evolution of Chaliyar River Drainage Basin: Insights from Tectonic Geomorphology"** is an authentic record of research work carried out by me under the supervision and guidance of Prof. A.C. Narayana, formerly from Department of Marine Geology and Geophysics, School of Marine Sciences, Cochin University of Science and Technology, in the partial fulfillment of the requirement of the Ph.D degree in the Faculty of Marine Sciences and no part thereof has been presented for the award of any other degree in any University/Institute.

Cochin-682016

5 October 2010 **Ambili V**

CERTIFICATE

I certify that the thesis entitled, **"Evolution of Chaliyar River Drainage Basin: Insights from Tectonic Geomorphology"** is an authentic record of research work carried out by Ms. Ambili V under my supervision and guidance at the Department of Marine Geology and Geophysics, Cochin University of Science and Technology, in the Faculty of Marine Sciences in partial fulfilment of the requirements for the degree of Doctor of Philosophy and no part thereof has been presented for the award of any degree in any University/Institute.

1 October 2010

A. C. Narayana
(Research Supervisor)
Formerly Cochin University of Science and Technology

ACKNOWLEDGEMENT

This thesis would not have been possible without the guidance, support and help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of the research work. It is a pleasure to convey my gratitude to them all in my humble acknowledgement.

It is difficult to overstate my gratitude to Prof. A.C. Narayana, for his supervision, guidance and advice throughout the research work as well as providing me unflinching encouragement and support in various ways. His truly scientific intuition and passion to the subject exceptionally inspired me as a student, a researcher and a geologist. I am indebted to him and would have been lost without his support.

I would like to gratefully acknowledge the support of some very special individuals. I owe a huge debt of gratitude to Dr. B.P. Radhakrishna, who had the patience to hear my work and give suggestions for improving the quality of the work. I am also grateful to Prof. Vishwas Kale for his valuable suggestions on varied aspects of my studies, even during his busy schedule.

I sincerely thank Prof. C.G Nambiar, former Head, and Dr. M. Ravishankar, Head, Department of Marine Geology & Geophysics, for their timely suggestions and support in completing the work. I am thankful to the present and former Director, School of Marine Sciences, Cochin University of Science and Technology, for making facilities available during the period of my research. The support received from Prof. P. Seralathan and Prof. K. Sajan is acknowledged.

I owe deepest gratitude to my organization, Geological Survey of India for giving permission to do research and also giving all the laboratory support required during the study. I am particularly grateful to Shri M.P. Muraleedharan, Director (Rtd.) for all the support provided for the field studies. I am greatly obliged to Shri S. Singanenjam, Supt. Geologist, for extending all the support during the final stage of the research work. I wish to express my warm and sincere thanks to Shri C. Muraleedhran, Sr. Geologist, GSI for supplementing my research work with some field data. I also warmly thank Shri P.S. Anil Kumar, Sr. Geologist, for the encouragement, support and advice during my difficult times as an elder brother. I extend my sincere thanks to my colleagues Dr. Mathew Joseph, M.N. Praveen, and Dr. Soney Kurien for their support during the research work.

Many thanks go in particular to Kurien.V. Kunneth, Supt. Chemist for supporting me with all the laboratory facility for chemical analysis. I am grateful to Shri K.N.K Kartha, Sr. Chemist, Shri Rajashekharan and Shri N.S Nair (Chemists) for their constant support in analysing the samples.

I am extremely thankful to Prof. K.V. Subbarao and other staff members of UCESS, University of Hyderabad, for rendering all the facilities during the final stages of the thesis.

My sincere thanks are due to Dr. Rama Raju, Scientist (F), AMD, Hyderabad who gave lessons in raster analysis using GRASS.

This work would not have been accomplished without the tremendous help and assistance rendered by Dr. Shinu. N, Yunus P, C. Remya, C.P.Ambika, Siva Parvathi, Ganga Bhavani, Naga Lakshmi V, Dr. C.P. Priju, N. Sravanthi, Sarang P.B, Dr. Sheena V. Dev, Vinu Prakash, Dr. K.P. Jaikiran, Dr, Lasitha, Dr. Nisha, Biju Longhinos, K.B Santhosh and Vinod.

I thank all the non-teaching staffs of the Department of Marine Geology and Geophysics and School of Marine Sciences for their help.

I am grateful to my undergraduate teachers, Dr. P.K. Sabu, Shri Benno Joseph, Dr. K.N. Krishna Kumar and Shri S.S. Anil Kumar who created a passion for the subject. My post graduate teachers Dr. M.S. Pandian is greatly acknowledged for his untimely support.

I am out of words to express my respect and gratitude to my parents who supported me, taught me, guided me and loved me. Their blessings, moral and physical support made this thesis possible. I am grateful to my brother Arjun for his constant support and encouragement. I express my love and thanks to my in laws for their support during the research work. I am indebted to my husband Premesh for his understanding, endless patience and constant encouragement to improve my academic qualification and knowledge. I really feel proud of my six year old son, Amithrajith, who has adjusted and sacrificed my care on many occasions during this period.

I pray to thee, the Almighty without His grace nothing is possible.

Ambili V

CONTENTS

		Page No.
Chapter 1	**Introduction**	**1-19**
1.1	General	
1.2	International and National Status of Tectonic Geomorphology	
1.3	Objectives of the present work	
1.4	Study area	
1.5	Previous work in the study area	
1.6	Physiography	
1.7	Regional geology	
1.8	Geology of the study area	
1.9	Climate	
Chapter II	**Morphometry**	**20-48**
2.1	Introduction	
2.2	Materials and Methods	
	2.2.1 Linear aspects	
	2.2.2 Areal aspects	
	2.2.3 Relief aspects	
	2.2.4 Hypsometric analysis	
2.3	Results and Discussion	
	2.3.1 Morphometric characteristics	
	2.3.2 Hypsometry	
2.4	Summary	
Chapter III	**Drainage characteristics and Landforms**	**49-90**
3.1	Introduction	
3.2	Methodology	
	3.2.1 Materials and data used	
	3.2.2 Drainage analysis	
	3.2.3 Stream classification	
	3.2.4 Delineation of landforms	
3.3	Results and Discussion	
	3.3.1 Drainage network	
	3.3.2 Streams and their behaviour	
	3.3.3 Landforms	
3.4	Summary	

Chapter IV Field Geology and Geomorphology **91-126**

4.1 Introduction
4.2 Lithology
4.3 Structure
4.4 Landforms
4.4.1 Erosional landforms in the upper reaches of the Chaliyar River drainage basin
4.4.2 Fluvial landforms
4.5 Field evidences of active tectonism
4.5.1 Unpaired terraces
4.5.2 Deflected stream
4.5.3 Palaeo-alluvial fans
4.5.4 Landslides
4.5.5 Faults
4.6 Summary

Chapter V Tectonic Geomorphology **127-195**

5.1 Introduction
5.2 Methodology
5.2.1 Stream profile analysis
5.2.2 Quantification of geomorphic indices
5.2.3 Delineation of geomorphic markers
5.2.4 Morphostructural analysis
5.3 Results and Discussion
5.3.1 River profiles
5.3.2 Geomorphic indices of active tectonics
5.3.3 Geomorphic markers of active tectonics
5.4 Lineaments
5.5 Morphostructures
5.6 Class designation of relative tectonic activity
5.7 Process response model of active tectonics
5.8 Summary

Chapter VI Sedimentology **196-218**

6.1 Introduction
6.2 Materials and Methods
6.2.1 Sediment samples
6.2.2 Textural analysis

6.2.3 Geochemical analysis
6.3 Results and Discussion
6.3.1 Texture
6.3.2 Bivariate plots
6.4 Geochemistry
6.5 Depositional environment
6.6 Summary

Chapter VII Summary and Conclusion **219-230**

7.1 Summary and Conclusion
7.2 Recommendation

References **231-258**

LIST OF TABLES

Table. 1.1 General geology of Chaliyar River drainage basin (GSI, 1995)

Table 2.1 Linear morphometric parameters of sub-basins of Chaliyar River and its drainage basin.

Table 2.2 Bifurcation ratio and hierarchical morphometric parameters of the Chaliyar River drainage network

Table 2.3 Areal morphometric aspects of nine sub-basins of Chaliyar River and its total drainage basin of Chaliyar River (**C**: total drainage basin).

Table 2.4 Relief morphometric aspects of all nine sub-basins of Chaliyar River and total drainage basin of Chaliyar River (C: total drainage basin).

Table 2.5 Mean, minimum and maximum elevations and the computed hypsometric integral of nine sub-basins. C represents the total drainage basin.

Table 3.1 Average valley slope of the Chaliyar River along its profile. The river was divided into 17 segments along the profile.

Table 3.2 Sinuosity ranges computed for segments along river centre line and sinuosity categories *(after Brice 1982).*

Table 3.3 Sinuosity computed for the segments of the tributaries and trunk system of Chaliyar River.

Table 3.4 Width to height ratio computed for the trunk stream of Chaliyar River with stream type (Rosgen, 1986 and Harman et al., 1999).

Table 3.5 Width to depth ratio computed for the tributaries of Chaliyar River with stream type and characteristics (Rosgen, 1986 and Harman et al., 1999).

Table 3.6 Entrenchment ratios computed for the Chaliyar River along its longitudinal profile.

Table 3.7 Classification of 17 segments of the Chaliyar River based on Rosgen stream classification for natural rivers as a function of continuum of physical variables within the stream reaches (from Application of the Rosgen stream classification system to North Carolina, 1999).

Table 5.1 Power law relationships between drainage area and slopes for the 9 tributaries of Chaliyar River

Table 5.2 Relationship of knick points observed in the river profiles and underlying lithology.

Table.5.3 Stream-length – gradient index (SL), Slope index (S) and mountain front sinuosity (S_{mf}) computed for the sub-basins of Chaliyar River.

Table 5.4 Valley floor width to depth ratio (V_f), Asymmetry factor (AF) and Transverse Topographic Symmetry Factor (TTSF) for the 9 tributaries of Chaliyar River.

Table. 5.5 Inventory of the landslides reported in Chaliyar river drainage basin (database from Geological Survey of India (2009), Kerala Unit and archive of Malayala Manorama Daily)

Table 5.6 Azimuthal distributions of streams and lineaments in the nine sub-basins of Chaliyar River

Table 5.7 Relative tectonic activity class designation (after Keller and Pinter, 1996)

Table 5.8 Relative tectonic activity classification for the sub-basins of Chaliyar River drainage basin (after Keller and Pinter, 1996).

Table 5.9 Classification of the Iat (relative tectonic activity index) in the sub-basins of Chaliyar River drainage basin after El Hamdouni et al, 2007. (SL= stream length gradient index; Af= asymmetry factor; Hi= hypsometric integral; Vf= valley floor width to valley height ratio; Smf= index of mountain front sinuosity).

Table 6.1 Textural parameters of the stream sediment samples of Chaliyar River and for tributaries that flow in Nilambur valley area.

Table 6.2 Textural parameters of the younger terrace (T_1) samples of Chaliyar River and for tributaries that flow in Nilambur valley area.

Table 6.3 Textural parameters of the older terrace (T_2) samples of Chaliyar River and for tributaries that flow in Nilambur valley area.

Table 6.4 Major element concentration of the stream sediments (SS), younger terrace (T_1) and older terrace (T_2) samples of Chaliyar River from Nilambur valley (all the values are in wt%).

Table 6.5 Chemical index of actuation computed for the stream sediments (SS) and terraces samples (T_1 and T_2).

LIST OF FIGURES

Fig. 1.1 Digital Elevation Model (DEM) aspect map (source: SRTM) of Chaliyar River drainage basin with its main tributaries and important locations. The terrain map of Peninsular India (source: Google Erath) is shown on the right side top; whereas the bottom right shows the map of Kerala (the shaded area is Chaliyar River drainage basin).

Fig. 1.2 Geological map of Chaliyar River Drainage basin (after GSI, 1995). Trend of foliation is NW-SE, ENE-WSW, N-S, and NE-SW with steep dips of 70-80^o.

Fig. 2.1 SRTM derived DEM-aspect map of Chaliyar River basin and 9 sub- basins showing the drainage network. (a) Sub-basin - 1 drained by Cherupuzha; (b) sub-basin - 2 drained by Iruvahnipuzha; (c) sub-basin - 3 drained by Kurumanpuzha; (d) sub-basin - 4 drained by Kanjirapuzha; (e) sub-basin - 5 drained by Chaliyarpuzha (f) sub-basin - 6 drained by Karakodupuzha; (g) sub-basin - 7 drained by Punnapuzha; (h) sub-basin - 8 drained by Karimpuzha and (i) sub-basin - 9 representing the Kuthirapuzha tributary.

Fig. 2.2 Semi-logarithmic plot of the stream number against stream orders for the nine sub-basins and Chaliyar River basin. Weighted mean bifurcation ratio (R_b) for each sub-basin is given in the plots. Regression coefficient values for the exponential curves are indicated.

Fig. 2.3 Semi-logarithmic plots of the mean stream length against stream orders for nine sub-basins and Chaliyar River basin. Linear regression coefficient values are indicated.

Fig. 2.4 Semi-logarithmic plot showing the relationship between the basin area and total stream length of 9 sub-basins of the Chaliyar River.

Fig. 2.5 Schematic hypsometric curves, indicating the relative area above certain relative elevation for landscapes in the stage of youth, maturity and old age (after Strahler, 1957; Scheidegger, 1988).

Fig. 2.6 Hypsometric curves for nine sub-basins of the Chaliyar River (after Strahler, 1957; Scheidegger, 1988. (a) Sub-basin - 1 (Cherupuzha); (b) sub-basin - 2 (Iruvahnipuzha); (c) sub-basin - 3 (Kurumanpuzha); (d) sub-basin - 4 (Kanjirapuzha); (e) sub-basin - 5 (Chaliyarpuzha); (f) sub-basin - 6 (Karakodupuzha); (g) sub-basin - 7 (Punnapuzha); (h) sub-basin - 8 (Karimpuzha); (i) sub-basin - 9 (Kuthirapuzha). Hi is the hypsometric integral computed and broken line indicates the hypsometric curve.

Fig. 3.1 Key to the Rosgen classification of natural rivers as a function of continuum of physical variables within the stream reaches (Rosgen, 1999).

Fig. 3.2 SRTM derived aspect map of Chaliyar River drainage basin showing the major tributaries and the Nilambur valley. Five of its major tributaries – Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha, Karakodupuzha, Punnapuzha, Karimpuzha and Kuthirapuzha join within the Nilambur valley.

Fig. 3.3 Drainage map of Chaliyar River showing 1^{st} to 7^{th} order streams. The numbers (1-9) denote nine sub-basins of the river.

Fig. 3.4 Drainage patterns observed in Chaliyar River drainage basin. (a) Trellis pattern in Punnapuzha, (b) rectangular pattern in Chaliyarpuzha, (c) deranged or contorted patterns in Cherupuzha and Iruvahnipuzha, (d) radial pattern at Mysore mala,(e) rectangular pattern in the higher order streams at the confluence of Chaliyarpuzha and Punnapuzha, (f) parallel drainage pattern in the upper reaches of Iruvahnipuzha, (g) sharp bend in the stream course Chaliyar NW of Kurathimala, (h) sharp angular bends in Punnapuzha shifting stream course from NW to SW direction and then shifting the flow direction to west further downslope.

Fig. 3.5 Google earth imagery, enhanced by using Erdas Imagine, shows anabranching and channel migration in (a) Punnapuzha River with braids and sand filled channels at Karnadokundu, (b) Karimpuzha River with braids and abandoned channel at Chekuthankundu.

Fig. 3.6 Anabranching river system and changes observed between the year (a) 1969 and (b) 2005 in the middle reaches of Karimpuzha River between Chekuthankundu and Nedungayam. Channel migration, disappearance of Kallathodu and development of braids/islands in two different years are clearly seen.

Fig. 3.7 The tributaries and trunk system of Chaliyar River area divided into segments and are numbered. The sinuosity of the river course was computed for each segment.

Fig. 3.8 Stream types in Chaliyar River based on Rosgen classification of natural rivers as a function of continuum of physical variables within the stream reaches (after Rosgen, 1999). Left panel shows the planar view and right panel shows the sectional view of the stream.

Fig. 3.9 Stream classification based on the nature of source area (after Sinha and Friend, 1994). The streams in Chaliyar River drainage basin are classified as mountain-fed, foothill-fed, plain-fed and mixed-fed streams.

Fig. 3.10 Geomorphological map of Chaliyar River drainage basin derived from the toposheets, aerial photographs and IRS-P6 LISS III imagery.

Fig. 3.11 Radiometrically enhanced Google Earth imagery showing (a) point bars in Chaliyar River, (b) braided bars in Karimpuzha River, (c) channel bars in the Chaliyar River as it reaches the river mouth, and (d) channel fills along Chaliyar River delineated from the tassled cap enhanced IRS-P6 LISS III imagery with 4,3,2 band combination.

Fig. 3.12 Distribution of channel fills in Chaliyar River drainage basin. Channel fills are more in the low lying areas of the basin where the elevation ranges from 20 to 60 m.

Fig. 3.13 Palaeochannels delineated from the radiometrically enhanced Google Earth imagery. (a) Abandoned palaeochannels of Chaliyar River at Nilani-Kaippini area, (b) palaeochannels of Karimpuzha tributary between Nedungayam and Karadikundu, (c) palaeochannel in Athithodu stream of Punnapuzha tributary, and (d) palaeochannel in Kallanthodu stream of Punnapuzha tributary .

Fig. 3.14 Radiometrically enhanced IRS-P6 LISS III imagery showing (a) alluvial fans in Chaliyar River drainage basin, (b) well developed T_1 terrace along the Chaliyar River, (c) T_2 terraces of Chaliyarpuzha and Punnapuzha, (d) T_3 terrace developed on the left bank of Chaliyarpuzha, (e) marsh and swamps observed all along the Chaliyar River, and (f) DEM of Nilambur valley showing well-developed T_1, T_2 and T_3 terraces.

Fig. 3.15 Enhanced IRS-P6 LISS III images showing (a) & (b) residual hills located north of Wandur and north of Arikkod, (c) Valleys and interfluves in the eastern margin of Chaliyar Basin, (d) Pediments at the foothills of Nilgiri hill ranges, (e) NE-SW trending linear structural hills in Chaliyar Basin, (f) Structural hills in the western part of the Nilambur valley. Broad swerve of the ridge crest can be observed on the high hills ranges of Nilambur Kovilakom Forest.

Fig. 4.1 Wayanad Supracrustals of Chaliyar River drainage basin. (a) Talc-tremolite-actinolite schist (Location: north of Konnamannu); (b) highly fractured magnetite quartzite bands. Intense lateritization in the terrain has obliterated the physical characteristics of the rock (Location: Tumbimala); (c) amphibolite band in the hornblende-biotite gneiss (Location: Kariam - Muriam Reserve Forest); (d) enclaves of amphibolite in the hornblende - biotite gneiss (Location: Manali).

Fig. 4.2 Charnockite Group of rocks in Chaliyar River drainage basin. (a) Charnockite hill (Location: Adyanpara); (b) massive charnockite exposed in a quarry (Location: north of Nellikkaparamba); (c) charnockite gneiss (Location: Arikkod); (d) Pyroxene granulite lens in the charnockite gneiss. (Location: Ayirani).

Fig. 4.3 Migmatitic rocks in Chaliyar River drainage basin. (a) Hornblende-biotite gneiss (Location: Kurumbalkotta), and (b) Garnet-biotite gneiss (Location: Kodinji).

Fig. 4.4 Younger intrusive rocks in Chaliyar River drainage basin. (a) Dolerite dyke cutting across the Chaliyar River course trending NE-SW; (b) Pegmatite vein in hornblende-biotite gneiss (Location: Kunnathupoyi); (c) sulphide rich quartz vein in the amphibolite country rock. This quartz vein form the host rock for primary gold (Location: Devala); and (d) Quartz veins within the lateritized country rock. Fractures in the quartz vein are with limonitic stain (Location: Chungathara).

Fig. 4.5 Laterite profile of about 4 m thick. The top portion has a thin layer of regolith (~3 cm) and is underlain by the charnockitic bedrock (Location: West of Edakkara).

Fig. 4.6 Foldings in the migmatitic rocks in Chaliyar River drainage basin. a) Tight appressed intrafolial fold (F_1) in hornblende-biotite gneiss; b) Tight to open folds (F_2) in hornblende- biotite gneiss (Location: left bank of Chaliyar River at Canoli); c) F_2 fold in the hornblende- biotite gneiss at Nilambur; d) folding in the sheared hornblende gneiss at Edavanna. Broken lines show the folded bands.

Fig. 4.7 Faults observed in Chaliyar River drainage basin. (a) Mega-scale faults at Adyanapara falls. E - W trending younger fault (F_1) cut across the N - S trending F_2 fault; (b) Meso-scale fault in the charnockite gneiss at the left bank of Karimpuzha (Location: Nedungayam); (c) Meso-scale fault in the biotite gneiss (Location: Chattallur); (d) Micro-scale fault in the hornblende-biotite gneiss. Location: Manali

Fig. 4.8 Shearing observed in the rocks of Chaliyar River drainage basin. (a) Brittle shearing with N-S trend in charnockite (Location: Adyanpara waterfalls); (b) Mylonite developed in a ductile shear zone (Location: Arimbrakuttumala).

Fig. 4.9 Different erosional landforms in the study area. (a) Residual hill (Location: Kurathimala); b) structural hill (Location: Polakkod); (c) Denudational hills seen in the upper reaches of Punnapuzha River; (d) vertical cliffs where the Precambrian rocks are well exposed (Location: Adyanpara).

Fig. 4.10 Types of terraces in Chaliyar River drainage basin. (a) Unpaired terrace of Chaliyar River at Mambad. The left bank terrace (T_1) is 1 m thick and is rock cut, while the right bank terrace (T_1) is almost at the level of present day stream bed. T_2 terrace is about 5 m thick and covered by thick vegetation; (b) unpaired terrace of Chaliyar River at Arikkod. T_1 terrace on the right bank is depositional while the left bank is erosional terrace (T_2). Variation in the elevation of terraces is clearly observed; (c) Strath terrace observed along the left bank of Chaliyar River at Edavanna; (d) Strath terrace observed along the left bank Kuthirapuzha at Vadapuram; (e) Strath terrace observed along the right bank Chaliyar River at Mambad, and (f) paired terrace (T_1) of Iruvahnipuzha at Mukkam.

Fig. 4.11 River incision in Chaliyar River drainage basin. (a) Filled terrace (T_1) which have been re-incised as seen on the left bank of Chaliyarpuzha at Ambalappoyi area. Pebble bed at the bottom is overlain by a layer of silty sand and clay; (b) Chaliyar River getting incised along a fault plane in the bedrock. Lateritized older terrace (T_2) can be seen on the eastern side of the photograph (Location: near Manavedan School, Nilambur); (c) bed rock incision along the fault plane at Nedungayam in Karimpuzha River. Here strath terrace has a thickness of 12 m from the water surface at the time of photo capturing (15/05/2007); (d) Well developed T_2 terrace of about 10 m thickness on the right bank of Chaliyar River at Canoli Teak Garden. The thickness of T_2 and absence of T_1 terrace signifies the incision of the river through T_2 terrace; (e) T_2 terrace on the right bank being incised by the Chaliyar River at Tana; (f) Erosion of T_2 terrace on the right bank and development of T_1 terrace on the left bank of Chaliyar river at Tana

Fig. 4.12 Depositional terraces of Chaliyar River and its tributaries. (a) Thickly vegetated well - developed T_1 terrace along Chaliyar River at Edavanna; (b) T_1 terrace developed on the left bank of Chaliyar River at Panankayam; (c) T_1 terrace on the left bank of Chaliyar River near Nilambur; (d) stabilized T_2 terrace of Punnapuzha River near Nallathanni; (e) slumped T_2 terrace of Chaliyar River near Bhudan Colony. Here the thickness of terrace is about 6 m and is mainly composed of semi-consolidated fine grained sand; (f) loosely scattered quartz pebbles of T_2 terrace over the laterite near to the temple at Mannathi. This pebble bed extends over an area of about 2 km^2 from the present day Chaliyar River to the west.

Fig. 4.13 (a) Canopy of teak plantation over the T_2 terrace at Canoli Forest area. (b) Upper part of the vertical profile (top 1m) of the T_2 terrace shows thick column of fine sand stabilized but not oxidized.

Fig. 4.14 (a) T_2 terrace of Chaliyar River along the right bank consisting coarse-to fine- grained sand. At places the sand horizons are oxidized; (b) vertical section of T_2 terrace on the right bank of Chaliyar River. Below a thin layer of soil coarse-grained to fine grained sand is seen which shows graded bedding. Below the graded bedded sandy horizon, cross-bedding is seen which is further followed by graded bedded sandy horizon (Location: Tana).

Fig. 4.15 Oldest terraces of Chaliyar River. (a) T_3 terrace of Chaliyar River well exposed when excavated for agricultural activity (Location: Kaippini); (b) T_3 terrace exposed in a well section. The 7 m thick pebble bed is very compact and lateritized; (c) Quartz pebble in the lateritized T_3 terrace exposed at Patiripadam; (d) Lateritized quartz pebble bed well - exposed in a well- section at Patiripadam; (e) sub-rounded to rounded pebbles seen in the T_3 terrace exposed along a road cutting at Nilani; (f) Gravel bed exposed in a well section at Nilani. Gravels vary in size from few cm to 45 cm.

Fig. 4.16 Erosional terraces in Chaliyar River drainage basin. (a) Erosional terrace developed along Ezhuvathodu stream which flows through alluvial fan deposit; (b) polymictic pebble beds in the terrace within the alluvial fan (Location: Vellimattom).

Fig. 4.17 Palaeochannels at different locations in Chaliyar River drainage basin. (a) Palaeochannel of Karimpuzha stream at Karappuram and (b) at Kallanthodu, palaeochannel of Karimpuzha flowing southwest is active only during rainy season; (c) palaeochannel of Punnapuzha at Valluvasseri Reserve Forest; (d) palaeochannel of Punnapuzha at Chungathara. Presently silty clay is mined for tile and brick manufacturing; (e) palaeochannel of Chaliyar River at Kurathipadam; f) palaeochannel of Chaliyar River at Ichambatur - Ramachampadam area.

Fig. 4.18 Vertical cross - sections showing sediment deposit in a palaeochannel. (a) Sediment is made up of assorted pebbles, gravel, sand and silt; (b) sediment composed of quartz pebbles, sand and silt. Oxidized sand/silt and limonitic oozes are prominent in this vertical profile (Location: Valluvasseri Reserve Forest). Graded bedding is observed with sediment grading from pebbles to fine sand.

Fig. 4.19 Sediment deposits of alluvial fans. (a) Vegetation seen over the palaeo-alluvial fan at Nedungayam; (b) sub-rounded to rounded pebbles and boulders exposed in a trench at Nedungayam; (c) rounded to sub-rounded boulders and pebbles that have been excavated from the pit. Size of the boulders varies from few cm to 1 m (Location: Nedungayam); (d) rounded to sub-rounded pebbles exposed in pits dug for rubber plantation at Kaippini.

Fig. 4.20 a) Pebble beds beneath the thick vegetation exposed along a road cutting (Location: South of Kaippini); b) older pebble bed seen east of Yutirkulam. Quartz pebbles are embedded in compact and highly ferruginous matrix; (c) Younger pebble bed in a palaeochannel of Karimpuzha near Nedungayam; (d) Slightly oxidized pebble beds in a vertical section palaeochannel at Valluvasseri Reserve Forest.

Fig. 4.21 Stream bed characteristics from the upstream to downstream portion of rivers in the Chaliyar River drainage basin. (a) Rapids in a sub-tributary of Chaliyar River (Location: Thusharagiri); (b) waterfall in one of the tributaries of Chaliyar River (Location: Adyanpara); (c) boulder stream bed of Karimpuzha (Location: Chekuthankundu; (d) sub-angular to sub-rounded pebble bed in the upper reaches of Chaliyarpuzha (Location: Nilambur Kovilakam Forest); (e) sub-angular to sub-rounded gravel beds of Chaliyar River; (f) Sandy stream bed of Punnapuzha stream in its lower reach (Location: Edakkara).

Fig. 4.22 Sand bars with moderate vegetation cover (a) in Chaliyarpuzha stream at Ambalappoyi area; (b) in Punnapuzha stream in Nellukuthu Reserve Forest. Vegetation type and density indicates the stability of the bars.

Fig. 4.23 Braiding observed in the river channel at different places in the Chaliyar River drainage basin. (a) Karimpuzha stream west of Chekuthankudu (stabilized braided deposit by thick vegetation); (b) at Karulayi (partially stabilized braided deposit; (c) & (d) Punnapuzha River observed at Karandakundu (stabilized) and near Edakkara respectively. Both braided deposits are stabilized.

Fig. 4.24 Meandering and point bar deposit in Chaliyar River at a) Arikkod and (b) Edavanna. These point bar deposits are composed of medium- to coarse-grained sand. At places alternate bands of sand and silt are also observed.

Fig. 4.25 Channel fills observed in the Chaliyar River sub-basin at (a) Enanti and at (b) Muthedam. Channel fills consist of medium to coarse-grained and silty clay admixture. Most these channel fills in the study area are used for paddy cultivation.

Fig. 4.26 (a) Chaliyar River close to its mouth. The river banks comprise thick layer of sediments (sand, silt, clay intercalation). A number of tile factories are located along the river banks; (b) Chaliyar River mouth with broad flood plain at Beypore.

Fig. 4.27 Unpaired terrace of Chaliyar River at Edavanna.

Fig. 4.28 (a) Chaliyar River showing deflection in the river profile north of Kurathimala. The stream takes right angle bend at the junction of the two normal fault axes. Left bank is the upthrown part of the faults. Fault F_1 is older to F_2 fault; (b) highly fractured rock along the fault plane along Punnapuzha. Deviation in the channel course along the fault zone and ponding are clearly seen.

Fig. 4.29 (a) Angular rock fragments (quartz, charnockite and hornblende gneiss) seen in an abandoned well-section at Anappara; (b) angular assorted rock fragments of quartz, charnockite and hornblende gneiss seen along a road cutting at Mamankara. Inset figure shows the close shot of the angular fragments.

Fig. 4.30 Large boulders of charnockite embedded in the fine to medium grained sand horizon. These boulders are rootless and are distributed in the downstream part of Karakkodupuzha suggesting a rolled down-mass during landslides.

Fig. 4.31 Features of landslides observed in Chaliyar River drainage basin (a) Scar of the landslide seen on the ridge, west of Nadugani; (b) close-up view of the landslide scar of Fig. 4.31a; (c) scars of the landslide seen on a ridge northwest of Nadugani. Broken line indicates the lineament trends and the circle portion shows two adjacent scars of landslides that took place at two different period; (d) Close up view of the scars of two landslides shown in Fig. 4.31c; (e) Scar of an palaeo-landslide observed on a ridge, NW of Nadugani. Broken lines indicate the trend of lineaments; (f) scar of palaeo-landslide, north of Nadugani.

Fig. 4.32 Evidences of faulting in Nilambur valley. (a) Vertical fault scarp face on the western side of Adyanpara waterfalls The fault zone has N-S general trend; (b) fault zone appears to be a horst and graben (microtopography) type multiple faults; (c) & (d) slicken slide faces along a fault zone in charnockite gneiss at Vellimattam and Nedungayam respectively. Arrow indicates the direction of movement.

Fig. 4.33 (a) Pseudotachylite vein within the brittle shear zone at Adyanpara waterfalls. Pseudotachylite otherwise known as *fault rock* is an evidence of frictional melting of the wall rocks during rapid fault movement associated with a seismic event; (b) pseudotachylite where parallel fractures/joints are observed. Broken line indicates the contact zone of the pseudotachylite with country rock.

Fig. 5.1 Longitudinal profiles of nine tributaries of Chaliyar River derived from Digital elevation Model of SRTM data (a) Cherupuzha, (b) Iruvahnipuzha, (c) Kurumanpuzha, (d) Kanjirapuzha, (e) Chaliyarpuzha, (f) Karakodupuzha, (g) Punnapuzha, (h) Karimpuzha and (i) Kuthirapuzha. Bold line indicates the stream profile and dotted line indicates the drainage area as a function of downstream distance.

Fig. 5.2 Regression analysis for nine tributaries of the Chaliyar River. (a) Cherupuzha (0.496) (b) Iruvahnipuzha (0.542), (c) Kurumanpuzha (0.554) (d) Kanjirapuzha (0.681), (e) Chaliyarpuzha (0.474), (f) Karakodupuzha (0.360), (g) Punnapuzha (0.226) , (h) Karimpuzha (0.549) and (i) Kuthirapuzha (0.521). R^2 value for each tributary is given in the parenthesis.

Fig. 5.3 Stream profile concavity as a function of Θ. Curves are normalized by their maximum height at $x=x_c=0.01$ (after Tucker and Whipple, 2002).

Fig. 5.4 Longitudinal profiles for the nine tributaries of Chaliyar River on a semi-logarithmic scale. Numbers in the figure denote deviation values (D) in metres. Karimpuzha has deviated maximum from the normal profile (2200 m) whereas Cherupuzha has minimum deviation from normal profile of about 90 m. Rivers flowing through uniform lithology (Kurumanpuzha (1850 m), Kanjirapuzha (1250 m), Karimpuzha (2200 m), Punnapuzha (860 m) and Kuthirapuzha (700 m)) exhibits more deviation than the rivers through varying lithology (Chaliyar (550 m), Karakodupuzha (200 m) except for Iruvahnipuzha (1350 m). Values given in the parenthesis indicate deviation in metres.

Fig. 5.5 Normalized stream profiles/dimensionless curves H/H_0 vs. L/L_0 (ratio of elevation vs. ratio of distance). Cherupuzha (13.43), Iruvahnipuzha (44.61), Kurumanpuzha (74.22), Kanjirapuzha (65.30) and Chaliyarpuzha (43.49). b) Karakodupuzha (13.43), Punnapuzha (76.87), Karimpuzha (103.52) and Kuthirapuzha (42.38). K in the figure indicates knickpoints and SL indicates stream-length gradient index. Values given in the parenthesis indicate SL i.e. stream-length gradient index.

Fig. 5.6 Longitudinal profiles of the nine tributaries of Chaliyar River along with the geological cross-section and plot of SL index as a function of stream length downstream.(a) Cherupuzha, (b) Iruvahnipuzha, (c) Kurumanpuzha, (d) Kanjirapuzha, (e) Chaliyarpuzha, (f) Karakodupuzha, (g) Punnapuzha, (h) Karimpuzha and (d) Red circle represents the knickpoints in the profile. SL=Average SL index values and K = knickpoint and values in parenthesis is the elevation above MSL at which knickpoint occurs.

Fig. 5.7 (a) Normal fault across the stream at Adyanpara waterfall. Down throw of the fault is 12 m as observed in the field; (b) strath and fill terrace of Chaliyar River at Arikkod observed on the left and right banks respectively; (c) fractures observed in the strath terrace of Chaliyar River at Puttalam. Two sets of terrace trending NNW-SSE and ENE-WSW are marked with dashed lines of yellow and light pink respectively. The sudden shift in the course of the river from west to NNW is due to the NNW-SSE trending river along normal fault and (d) T_1 terrace on the right bank of Chaliyar River at Tana. Thickness of T_1 is about 7 m.

Fig. 5.8 (a) Transverse profile of Karimpuzha at Nedungayam. T_1 terrace is strath terrace with two parallel normal faults; (b) transverse section of Chaliyarpuzha at Ambalappoyi as observed in the field. The profile shows wide valley with unpaired terraces. T_0 and T_1 are well developed on the right bank. T_1 on the right bank composed of sand silt intercalation is well developed while T_1 in the left bank composed of pebbles undergoes erosion (degradation). T_2 is having thickness of ~ 6 m on either bank (paired). T_3 composed of cobbles and pebbles and are lateritized at places; (c) block diagram of the unpaired terraces of Chaliyarpuzha at Nilani. T_0, T_1, T_2 and T_3 are well developed on the western bank. Currently T_1 terrace on the left (eastern) bank is being eroded and (d) schematic diagram of the development of alluvial fan followed by a single movement along a fault.

Fig. 5.9 Location of alluvial fan deposits in Chaliyar River drainage basin. (1) Nedungayam, (2) Karakkodu, (3) Bhudan Colony, (4) Vellimattam and (5) Pattakarimba.

Fig. 5.10 (a) Schematic diagram showing the development of offset streams; (b) beheaded stream and shutter ridge in Chaliyar basin at Tambattimala. The E-W ridge forms the shutter ridge. The stream flows through a normal fault trending ENE-WSW direction and joins Punnapuzha. This normal fault has resulted in the formation of shutter ridge (Tambattimala) which obstructed the southward flow of the streams

Fig. 5.11 Deflection of stream due to WNW-ESE trending strike-slip fault (F_2-F_2') as observed in the enhanced Google earth map. The fault (F_2-F_2') off-sets the N-S trending (F_1-F_1') fault and deflects the south flowing stream to ESE direction.

Fig. 5.12 Relationship of lineaments and landslides in the Chaliyar River drainage basin. a) Map showing NE-SW and ENE-WSW lineaments with buffer zone of 0.55 km. Majority (about 70%) of the landslides fall well within the buffer zone. b) Map showing NW-SE lineaments with buffer zone of 0.66 km. About 50% of the landslides fall within the buffer zone.

Fig. 5.13 (a) Compressed meandering in i) Cherupuzha, ii) Iruvahnipuzha, iii) Punnapuzha and iv) Kuthirapuzha and (b) Compressed meander loop of Chaliyar River at Edavanna. Compressed meandering has formed as a result of strike-slip faults that enhanced channel migration in the slip direction.

Fig. 5.14 Angular drainage pattern in the 3rd, 4th, 5th, 6th and 7th order streams observed Chaliyar River drainage basin. Flow direction of the streams is determined by the lineaments. Younger lineament when cross cuts the older one stream takes the direction of the younger lineament.

Fig. 5.15 (a) Active faults or lineaments that control the drainage pattern and the present day ponding in Punnapuzha and Karimpuzha Rivers. Vertical or horizontal movements along these faults have changed the gradient of these rivers resulting in the blockage in the flow at Karulayi, (b) River ponding in Punnapuzha at Edamala south of Chungathara and (c) River ponding in Karimpuzha at Karulayi.

Fig. 5.16 Spectrally enhanced Google earth imagery showing river ponding in Karimpuzha stream at (a) Karulayi and (b) Nedungayam.

Fig. 5.17 Lineament map of Chaliyar River drainage basin superimposed over SRTM derived aspect map. Five sets of lineaments could be delineated trending NW-SE, NNW-SSE, N-S, NE-SW and ENE-WSW directions. Sub-basins are represented by different colours and numbers.

Fig. 5.18 SRTM derived DEM map showing the (a) NW-SE trending lineaments, (b) NNW-SSE trending lineaments, (c) N-S trending lineaments, (d) NE-SW trending lineaments and (e) ENE-WSW trending lineaments.

Fig. 5.19 Acute bends in the course of Chaliyar River at its lower reaches as observed in Google Earth Imagery. Westerly flowing river suddenly takes a swerve in the NW direction. At Vazhakkad the stream again takes a right angle bend to flow in ESE direction. The river again takes a shift in NW direction. Deflection of the river in similar pattern is repeated at Ramanattukara and Feroke and finally dedouches into the sea flowing SW.

Fig. 5.20 (a) NE-SW trending lineaments that caused channel migration in Chaliyar River, (b) N-S trending normal fault (F_1-F_1') with vertical fault scarp and F_2-F_2' caused the development of shutter ridge which was later off-set by F_3-F_3' faults, (c) and (d) series of fault system (en-echelon faults) resulted in the formation of Nilambur valley within the Chaliyar River drainage basin.

Fig. 5.21 Drainage network of sub-basins of Chaliyar River with the correspondent rose diagrams of the stream directions of 1^{st}, 2^{nd}, 3^{rd} and 4^{th} order streams for (a) Sub-basin - 1 (Cherupuzha), (b) Sub-basin - 2 (Iruvahnipuzha), (c) Sub-basin- 3 (Kurumanpuzha), (d) Sub-basin - 4 (Kanjirapuzha), (e) Sub-basin - 5 (Chaliyarpuzha), (f) Sub-basin - 6 (Karakodupuzha), (g) Sub-basin - 7 (Punnapuzha), (h) Sub-basin - 8 (Karimpuzha) and (i) Sub-basin - 9 (Kuthirapuzha).

Fig. 5.22 Rose diagram showing the general trend of lineaments in (a) Chaliyar River drainage basin, (b) Sub-basin - 1 (Cherupuzha), (c) Sub-basin - 2 (Iruvahnipuzha), (d) Sub-basin - 3 (Kurumanpuzha), (e) Sub-basin - 4 (Kanjirapuzha), (f) Sub-basin - 5 (Chaliyarpuzha), (g) Sub-basin - 6 (Karakodupuzha), (h) Sub-basin - 7 (Punnapuzha), (i) Sub-basin - 8 (Karimpuzha) and (j) Sub-basin - 9 (Kuthirapuzha).

Fig. 5.23 Trend of lineaments superimposed on the stream direction for different orders for (a) Sub-basin – 1, (b) Sub-basin - 2, (c) Sub- basin - 3, (d) Sub-basin - 4, (e) Sub- basin - 5, (f) Sub-basin - 6, (g) Sub-basin - 7, (h) Sub-basin - 8 and (i) Sub-basin - 9. Black shade indicates stream orientation and red colour indicates lineament trend.

Fig. 5.24 Rose diagram showing (a) the preferred drainage flow direction of 5^{th} order streams in the Chaliyar River drainage basin, (b) lineament trends in the Chaliyar River drainage basin (c) the preferred drainage flow direction of 6^{th} order streams in the Chaliyar River drainage basin and (d) lineament trends in the Chaliyar River drainage basin.

Fig. 5.25 Distribution of the Iat index of relative active tectonics in the Chaliyar River drainage basin.

Fig. 5.26 (a) Schematic diagram showing simple shear associated with strike-slip faulting produces preferred orientation of fractures, faults and folds. (b) extensional and contractional landforms developed by simple shear modified after Sylvester and Smith (1976) and Keller et al. (1982); (c) pressure ridges and sags associated with restraining and releasing bends and/or steps along strike-slip faults (after Dibble, 1977; Keller, 2002).

Fig. 6.1 SRTM derived DEM - aspect map of the Chaliyar River drainage basin showing stream sediments and terrace samples location points.

Fig. 6.2 Relative percent of sand-silt-clay of (a) stream sediments (SS); (b) younger terrace samples (T_1); (c) older terrace samples (T_2) in Nilambur valley area of Chaliyar River drainage basin.

Fig. 6.3 Ternary diagram showing grain size distribution of stream sediments, younger terrace (T_1) and older terrace (T_2) of Nilambur valley of Chaliyar River drainage basin.

Fig. 6.4 Grain size parameters of the stream sediments (SS), younger terrace (T_1) and older terrace (T_2) of Nilambur valley. (a) Mean size; (b) Sorting; (c) Skewness; (d) Kurtosis.

Fig. 6.5 Bivariate plots (a) Mean grain size vs standard deviation (sorting); (b) Mean grain size vs skewness; (c) standard deviation (sorting) vs skewness. R is the linear regression coefficient.

Fig. 6.6 Plots of grain size parameters. (a) Depositional processes derived from CM diagram for stream sediments, and T_1 and T_2 terrace samples (after Passega, 1972); (b) Friedman's (1961) bivariate plot of standard deviation (sorting) vs. skewness applied for the sand fractions of the samples from the stream sediment (SS), and terraces of two levels (T_1 and T_2) of Chaliyar river; (c) Bivariate plot of mean size vs. sorting after Tanner, 1991) for stream sediments and terrace samples of Chaliyar River from Nilambur valley.

Fig. 6.7 Weathering trends of the sediments of Chaliyar River in Nilambur valley. A-CN-K and A-CNK-FM diagrams of (a) stream sediments; (b) younger terrace (T_1) (c) older terrace (T_2) samples. Ka=kaolinite; Chl=chlorite; Gi=gibbsite; Sm=smectite; Il=illite; Pl=plagioclase; Kf=K-feldspar; Bi=biotite; Mu=Muscovite; A= Al_2O_3; K= K_2O, CN= $CaO+Na_2O$.

CHAPTER I
INTRODUCTION

1.1 General

Tectonic geomorphology is a relatively new, interdisciplinary field that encompasses structural geology, tectonics and surface processes. The most common goal of tectonic geomorphology research is to use Quaternary landforms and stratigraphy to infer the nature, patterns, rates, and history of near-surface processes. Tectonic geomorphology has proven to be a useful tool for identifying and quantifying active and geologically recent tectonic deformation (Pinter, 1996). Further, this subject provides a whole kit of tools for deciphering the most recent activity on structures (Pinter, 1996, Burbank and Anderson, 2001; Keller and Pinter, 2002). Tectonic geomorphology is a prime method to give insights on the recent, last phases of orogenic deformation, which is the result of the uninterrupted interaction between tectonic processes that tend to build up topography and counteracting surface processes. Ongoing tectonic deformation sustains these geomorphological features, whereas decreasing deformation or its cessation leads to their rapid deterioration by weathering and erosion.

In tectonically active mountain regions, the drainage network reflects the interaction between surface processes and the growth and propagation of the thrust faults and folds that have led to the formation of an orogen (Jackson and Leeder, 1994; Delcaillau et al., 1998; Alvarez, 1999; Burbank and Anderson, 2001; Schlunegger and Hinderer, 2001; van der Beek et al., 2002; Delcaillau et al., 2006; Ribolini and Spagnolo, 2008). The planar geometry of a present-day fluvial network sometimes leads to the identification of past drainage characteristics that can greatly improve the reconstruction of different deformative events that have determined the topographic growth of a mountain region (Harvey and Wells, 1987; Burbank et al., 1999; Friend et al., 1999; Mather, 2000; Jones, 2004).

Alluvial river systems respond primarily to changes in sediment and water supply, which are controlled by a number of key factors. Major extrinsic controls on river behaviour in a given geological setting are tectonics, land-use and climate change. In lowland settings, sea-level may also influence river behaviour. Additionally, river systems can respond dynamically to change within the system itself (intrinsic controls), for example base level changes brought about by river capture and lithologic variations (e.g. Mather et al., 2002; Stokes et al., 2002). A change in fluvial behaviour follows when the internal thresholds of the system are crossed (Schumm, 1979; 2000).

Stream geomorphology is intrinsically linked to tectonics. Rivers are sensitive to changes in tectonic deformation, adjusting over different periods of time depending on the physical properties of the host rocks, climatic effects and tectonic activity. Thus, the drainage system of a region records the tectonic deformation and stages of its evolution (Gloaguen, 2008).

River basins display organised relation between the constituent parameters of landforms and drainage. River morphology is the shape or form of the river along its length and across its width. Transporting materials are used in eroding the river bed (degradation) and thus shaping its morphology. Rivers have altered their channels through erosion and deposition through its geological history. Tectonic movement can change the base level of erosion, affect alluvial processes and evolution, and result in deformation of alluvial landforms. The study of landforms and deposits developed or modified by tectonic processes can provide relevant information about the activity of the related tectonic structures (Silva et al, 2003). Hence, selected aspects of river and stream morphometry can throw light on the evolution of escarpments (e.g. Kale, 2007) and neotectonic activity (eg. Chamyal et al., 2003; Luirei and Bhakuni, 2008; John and Rajendran, 2008; Mrinalini Devi, 2008).

West flowing rivers that originate from Western Ghats are fast flowing short rivers, and show various stages of gradation due to intense rainfall and high relief. These streams are characterized by rapids and waterfalls in the upper reaches, but gains maturity when they reach the plains. These rivers have steep gradients (~1/250) in the upper reaches suggesting youthful stages of development. Unlike other major rivers of India, these rivers do not develop deltas which may be due to the high energy shoreline (Soman, 2002). Most of these river courses are structurally controlled and coincides with prominent lineament directions. Chaliyar River flowing west is known for its placer gold deposit in Nilambur valley area. Occurrence of placer gold restricted only to Nilambur valley inspired to study the physiography of Chaliyar River drainage basin. The morphology of Chaliyar River drainage basin with oval shaped Nilambur valley in the centre where most of its tributaries flowing SE, S, SW, W and NE get merged and then flowing SW is typical for Chaliyar River.

1.2 International/National Status of Tectonic Geomorphology

Throughout the history of work on fluvial deposits, geologists and sedimentologists have tended to favour either climatic or tectonic controls of changes. Improvement in understanding the complex interactions of these controls increasingly shows that this is a gross over-simplification. New awareness of the numerous and complex feedbacks in the systems is making it imperative that the size of features and their time and spatial relationships are compared and determined.

The studies pertaining to the river basins began mostly in the early part of 19th century explaining the difference in their hydrological regimes. Studies by Horton (1932, 1945), Strahler (1952), Chorley (1957) and Schumm (1956) deal with the conceptual evolution of drainage basin, in terms of geomorphic approach. The studies on fluvial geomorphology and hydrology of large tropical rivers have been more focused during the last two decades (Kale et al., 1994; Sinha and Friend, 1994; Sinha and Jain, 1998; Kale, 1999, 2002; Dettinger and Diaz, 2000; Gupta, 2002; Thorne, 2002).

Extensive studies have been carried out from different parts of the globe to establish the control of the endogenic tectonic processes on the surface geomorphic features (Scheidegger and Ai, 1986). Drainage pattern of an area acts as a sensitive tool in discovering the tectonic processes that express themselves as the structural design of the bed rock. Relationship between the drainage patterns to the fractures in the bedrock is a well documented concept (Vaidhyanadhan, 1971; Bannister and Arbor, 1980; Pohn, 1983; Deffontaines and Chorowicz, 1991; Polishook and Flexor, 1983; Radakrishna, 1992; Sinha Roy, 2001; Burbank and Anderson, 2001; Delcaillau et al., 2006). Streams respond to vertical displacement along faults by aggradation or degradation has been well documented by Holbrooke and Schumm (1999); Marple and Talwani (1993); Personious (1995).

Howard (1967) discussed in detail about the utility of drainage analysis for geological interpretation especially in low lying flat terrain. In regions of active plate motions, the drainage analysis forms a major tool in identifying the neotectonic movements and also in quantifying the displacements along the faults and fractures. (Ouchi, 1985; Schumm, 1986; Dumont et al., 1991; Deffontaines et al., 1994; Jackson et al., 1996; Audin et al., 2003; Pellegrini et al., 2003).

Morphometric analysis to draw conclusions on neotectonic activity in South Central Indiana by Miller (1998); in NE Lithuania by Cesnulevicius (2003); in Hungary by Petrovszki (2009); in Southern Western Ghats by Thomas et al. (2010) are some of the pioneer works that establish the relationship of morphometry and tectonism. Avena et al. (1967) introduced few parameters of the hierarchy of the drainage network like hierarchical anomaly number and hierarchical anomaly index. Ribolini and Spagnolo (2008) studied drainage network geometry versus tectonics in French-Italian Alps.

Fluvial responses to active tectonics was affirmed by various researchers like Burnett and Schumm (1983); Gregory and Schumm (1987); Marple and Talwani (2000); Valdiya and Rajagopalan (2000); Sinha and Roy, (2001). Tectonism constructs landscapes through uplift and subsidence; climate affects the degradation of the landscapes by chemical and physical erosion. These aspects were extensively studied by Ouchi (1985); Keller (1986); Keller and Pinter (2002); Holbrook and Schumm (1999) and Schumm et al. (2002) and provided detailed reviews of response of alluvial rivers to active tectonics and suggested that rivers respond differently during longitudinal and lateral tilting. The concept of landscape evolution space (LES) is introduced as a tool for assessing landscapes and geomorphic systems, intended to be a systematic means for assessing the various factors that contribute to the potential for change in geomorphic systems (Phillips, 2000). Tucker (2004), studied the drainage basin sensitivity to tectonics and climatic forcing, while Burningham (2008) and Catuneanu et al. (2001) studied the contrasting geomorphic response to structural control. Tectonics and landscape evolution with response to non-cyclic unique events on the time scale of global tectonics were studied by Benvenuti et al. (2008), Gelabert et al. (2005), Guarnieri et al. (2008), Giambni et al. (2005), Coltorti et al. (2000), Ollier (1995) and others. Field-based investigations, laboratory experiments and numerical models have shown that variation in the style of bedrock deformation, due to rock uplift, causes perturbations in the fluvial network (Ouchi, 1985; Burbank, 1992; Gupta1997; Mueller and Talling, 1997; Jackson et al., 1998; Hasbargen and Paola 2000; Hallet and Molnar, 2001; Vetel et al., 2004; Ghassemi, 2005).

Geomorphic evolution of longitudinal profiles have been studied by many researchers like Siedl et al. (1994), Radoane et al. (2002), vander Beek et al. (2003), Duvall et al. (2004), Anderson et al. (2005), Bishop et al (2007), Harma et al (2007), Phillips et al. (2008) and Singh et al. (2010). The shapes of longitudinal profiles reflect the stage of watershed evolution, channel sediment and bedrock types, tectonics, climate and sea-level change were explained by various researchers (Yatsu, 1955; Seidl and Dietrich, 1992; Sambrook Smith and Ferguson, 1995; Snyder et al., 2003; Goldrick and Bishop, 2007). Importance of bedrock river incision in landscape evolution has spurred research on the morphology and distribution of bedrock channels (Miller, 1991; Wohl, 1992b, 1998, 1999; Tucker and Slingerland, 1994; Montgomery et al., 1996; Montgomery and Buffington, 1997; Tinkler and Wohl, 1998; Whipple and Tucker, 1999; Massong and Montgomery, 2000; Snyder et al., 2000; Whipple et al., 2000; Montgomery and Gran, 2001). The study of the longitudinal profiles of the streams could be a useful way of assessing the Late Cenozoic tectonism on the development of the drainage network (Mackin, 1948; Rhea, 1993; Giamboni, 2005; Howard et al., 1994; Radoane et al., 2003; Gelabert et al., 2005). River longitudinal profiles can have knick points or knickzones which indicate either a stream in disequilibrium where the upstream retreat communicate changes in the base level to the upstream valley (Bishop et al., 2005) or dynamic equilibrium between fluvial processes and tectonic movements (Snow and Slingerland, 1990; Weissel and Seidl, 1998; Whipple, 2001; Bishop et al., 2005; Babault et al., 2006; Larue, 2008).

Morphometric parameters were used to explain the geomorphic evolution by various workers (Bagchi, 1960; Niyogi, 1968; Basu and Kar, 1968; Singh and Kumar, 1969). Sen (1971) studied the relationship between longitudinal profiles and bed rock over which they flow. Agarwal (1972); Pal (1973); Subrahmanyan (1974); Padmaja (1975); Sen (1977); Bedi (1978); Reddy and Reddy (1983); Rawat et al. (1983;) Singh et al. (1985) gave an account on the quantitative geomorphic parameters and made an attempt to draw a conclusion on the geomorphic evolution of different drainage basins. Vaidyanathan and Nageshwara Rao (1978) treated some aspects of the geomorphic evolution of Krishna delta. Malik and Mohanty (2007) suggested the tectonically active nature of the major and secondary hinterland faults and its influence on the evolution of drainage and landscape along northwestern Himalaya.

Radhakrishna (1993) explained the Neogene uplift and geomorphic rejuvenation of Indian Peninsula. Structure and tectonics of the south west continental margin of India was highlighted by Subrahmanyan et al. (1995). Neotectonically controlled catchment capture of Banas and Chambal basins were discussed by Kale (1999). Kale (2002) gave an overview on the fluvial geomorphology of Indian rivers. Jain and Sinha (2004) explain the fluvial dynamics of anabranching river system with reference to Bhagmati River in Himalayan foreland basin. Factors influencing the sinuosity of Pannagon stream, a tributary of Muvattupuzha River in Central Kerala was discussed in depth by Aswathy et al. (2008). Rao et al. (1996) gave evidences of late Quaternary neotectonic activity and sea level changes along the western continental margins of India. Gunnel and Fleiout (1998) described the shoulder uplift of the western Ghat passive margin. Prasad et al. (1998) studied the geomorphology, tectonism and sedimentation in Nal Region, Western India and conclude that tectonics play a vital role in the evolution of this region. Geomorphic signatures of active tectonics in Bist Doab interfluvial tract of Punjab were studied by Bhatt et al. (2009). Chamyal et al. (2003) explain the Late Quaternary geomorphic evolution of the Lower Narmada Valley, Western India and its implications for neotectonic activity along the Narmada–Son Fault. Maurya et al. (1997) explained the Holocene valley fill terrace on the lower Mahi valley, Gujarat. Valdiya (2001) suggests that Late Quaternary horizontal strike-slip and oblique-slip displacements are responsible for temporary blockages of river flow in Kerala and in western Karnataka region. The modifications of Holocene landforms, including formation of deep incisions across ridges in the undulating terrains, the descent of old winding rivers has cascades and water falls through gorges across fault-delimited ridges, the occurrence of planar scarps and triangular facets devoid of gullies are with but a few straight furrows, the repeated blockages of streams as they cross or follow the NNW-SSE trending faults, and the higher than normal seismicity in some areas of faulted Dharwar terrain, indicating geologically recent and continuing tectonic movement (Valdiya, 2001).

River Response to neotectonics in central and southern Kerala was studied by Valdiya and Narayana (2007). Their investigations are directed to find out whether the anomalous behavior of rivers and their tributaries and the landform peculiarities in central Kerala represents a terrain that responds to neo-tectonic activity. They suggest that activities along the lineament manifest in swerving of rivers and change of the originally meandering system to a one characterized by loops of a variety of shapes – U-shaped, box like, distorted triangular and rectangular. Valdiya and Narayana (2007) further conclude that ongoing vertical and horizontal movements on the faults have altered the gradient of rivers creating impediments or barriers and the resulting blockage. They suggest that present day ponding of the rivers suggest ongoing/neo-tectonic movements.

In Precambrian terrain with structures resulting from multiple facies of metamorphism and ductile deformation and superimposition of brittle joints and faults, the relationship between drainage and structure is poorly understand. Further, there is a general observation that the terrains are also quite inactive and drainage pattern would generally be dendritic due to the prolonged exposure to weathering and denudation. To unravel the role of active tectonism in the drainage basin evolution in such Precambrian terrane, the present study was taken up and is unique due to its multidisciplinary approach. An integrated approach, combining morphometric, morphostructural, longitudinal profile analysis and qualitative and quantitative geomorphologic and field evidences has been employed to bring a comprehensive picture of the tectonic history of Chaliyar River drainage basin.

1.3 Objectives of the Present work

The present study envisages the following objectives.

- To understand the drainage system of Chaliyar River drainage basin.
- To delineate/infer lithological and structural controls on the evolution of Chaliyar River drainage system.
- To understand the role of tectonics in the evolution of Chaliyar River drainage basin and to assess the degree of tectonic activity.

- To decipher various geomorphic features and landforms, their characteristics and evolution.
- To propose a morphotectonic model for the evolution of Chaliyar River drainage system and Nilambur valley.

1.4 Study Area

Chaliyar River drainage basin is cored by Precambrian Peninsular Shield covering an area of 2923 km^2 and lies between Murat and Kabini basins in the north and Kadalundi basin in the south. It is bound by latitudes 11°06’07”N and 11°33’35”N and longitudes 75°48’45”E and 76°33’00”E falling in Survey of India (SOI) degree sheets 58A and 49M (Fig. 1.1). The basin comprises parts of four districts viz. Kozhikode district cover an area of 626 km^2 in the northwest, Wayanad district over an area of 112 km^2 in the north, Malappuram district spreads over an area of 1784 km^2 in the east and south and Nilgiri district of Tamil Nadu over an area of 378 km^2 in the northeast.

Chaliyar River forms the third largest river in Kerala rising in the Elambaleri hills in the Wayanad plateau. Six major streams Chaliyarpuzha, Punnapuzha, Kanjirapuzha, Karimpuzha, Iruvahnipuzha and Cherupuzha constitute the Chaliyar River drainage system. Other important tributaries are Kurumanpuzha, Pandipuzha, Maradipuzha, Kuthirapuzha and Karakkodupuzha. Most of these rivers have their origin in the Nilgiri hills in the east and Wayanad hills in the north, where they form a number of rapids and waterfalls. The river joins the Lakshadweep Sea south of Kozhikode near Beypore after flowing over a distance of about 169 kms in the name ‘Beypore’ River.

1.5 Previous work in the Study area

The area forms part of the Western Ghat and extensive study of southern part of the Western Ghat was carried by Radhakrishana (1967); Gunnel and Fleitout (2000); Ollier(1985); Subramanya (1987); Widdowson (1997); Gilchrist and Summerfield (1994); Chand and Subrahmanyam (2003).

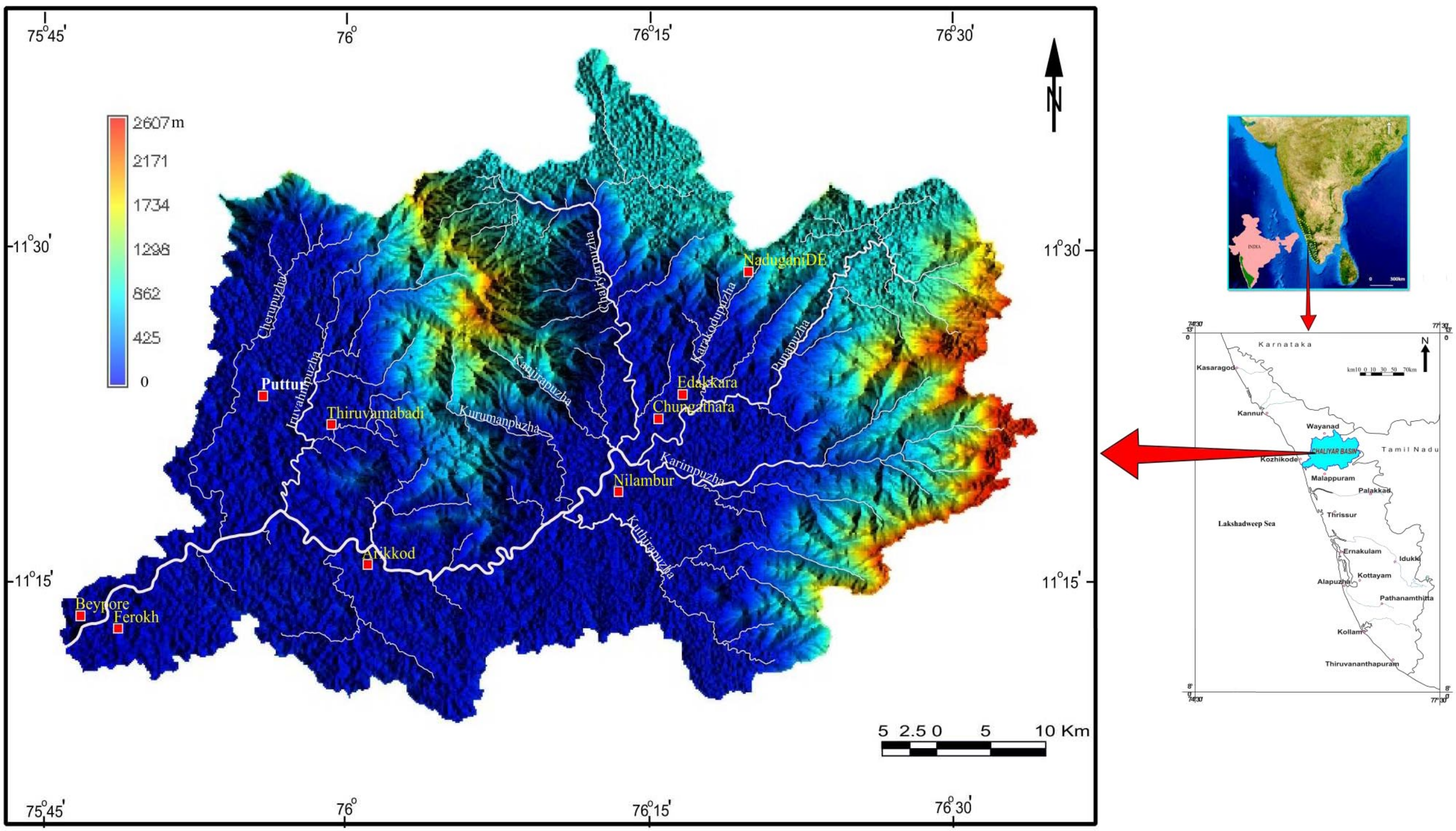


Fig. 1.1 Digital Elevation Model (DEM) aspect map (source: SRTM) of Chaliyar River drainage basin with its main tributaries and important locations. The terrain map of Peninsular India (source: Google Erath) is shown on the right side top; whereas the bottom right shows the map of Kerala (the shaded area is Chaliyar River drainage basin).

Cvetkovic (1980) carried out drainage network analysis and concluded that the major patterns observed in the basin are dendritic and rectangular with medium texture. The geomorphological studies of laterites by Sambandam and Krishnan Nair (1982) in parts of Nilambur valley has led to the identification of five sets of landforms formed during polycycles of erosion. PIXE analysis of trace pollutants in Chaliyar river water were carried out by Kennedy et al. (1998). Geochemistry and Mineralogy of Chaliyar River Sediments with Special Reference to the Occurrence of Placer Gold were studied by Hariharan (2001). Xavier et al. (2005) gave a detail study on the fluxes of nitrogen in Chaliyar River.

Geological mapping on different scales was carried out in this area by Geological Survey of India officers Sawarkar (1965), Nambiar and Rao (1980), Rengamannar, et al. (1984), Anil Kumar (1985) and Anil Kumar (1995). Exploration of primary and placer gold was taken up different organizations like KMEDP, Geological survey of India and Directorate of Mining and Geology, Kerala State. Some of the important investigations and exploration works carried out are: Young (1829); Lake (1890); Crookshank (1940); Thiagarajan (1958); Narayanaswami (1958), Rao (1965); Mahadevan (1965); Cvetkovic, 1980; Cvetovic and Krishnakumar, (1981.); Pillay and John (2002). Nilambur valley is known for gold panning along Chaliyar River and its tributaries like Punnapuzha, Karimpuzha, Kanjirapuzha and Chaliyarpuzha since previous century (Ainslie, 1826; Nicolson 1874; Smyth 1880). Gold occurrences have been reported in older gravels forming terraces and recent placers found in present day river channels draining the area (Sawarkar, 1965, 1980; Nair et al., 1987). First report on the primary gold mineralization from Wayanad - Nilambur belt and auriferous gravel of Nilambur valley were from Geological Survey of India (eg., Crookshank, 1940; Narayanaswami, 1963; Mahadevan, 1965; Sawarkar, 1980) and the exploration for primary/lateritic/placer gold was carried out by KMED project (eg., Cvetkovic, 1980; Anthrapar et al., 1985), CESS (Narayanaswamy, 1994; Narayanaswamy and Krishna Kumar, 1996) and Geological Survey of India (eg., Nair and Suresh Chandran, 1996).

1.6 Physiography

The Chaliyar river basin can be physiographically divided into four well-defined units viz., highland, midland, low land and coastal plains. Based on the relief pattern and topographic alignment, the basin can be divided into five physiographic sub-units.

(i) High ranges with an elevation ranging from 600m to 2600m. This form part of the Wayanad plateau and the high hill ranges with steep slopes of the Western Ghats, (ii) Foot hills of Western Ghat with elevation ranging from 300 to 600 m above MSL comprise rocky mounds and slope areas of the high hills, (iii) Upland regions consisting of the ridges and valleys, isolated hills with altitudes ranging from 100-300 m. At places these units are lateritic, (iv) Mid-land zone with elevation ranging from 10 to 100 m characterized by rolling topography with lateritic ridges, isolated hills and alluvial valleys, and (v) Low-land characterized by coastal stretches and alluvial plains with an elevation of < 10 m.

Highlands are depicted by the hill ranges of Nilgiri and Wayanad plateau of the Western Ghats with elevations > 600 m above MSL and forms an important physiographic province. The average elevation of the Wayanad plateau is 966 m above MSL and the highest peak is the Elambaleri hills rising to a height of 2260 m from where the Chaliyar River originates. The basin has its highest elevation of about 2554 m at Makurti peak in the east. The topography is very rugged and the crest of the mounds and hills are generally very sharp and narrow with very steep slopes. Deep gorges and mountain-fed streams are characteristics of the hill ranges.

The undulating western fringe of the highlands and the lateritized spurs forms the midland region. Midland region of the Chaliyar River drainage basin with elevation ranging from 300-600 m occupy a very narrow strip of elongated spurs separated by ravines merge with relatively gentler slopes of the lowlands.

Lowlands consists of dissected peneplain with an altitudinal range of 10-300m includes the Nilambur valley, which runs in NE-SW direction and is broadest in the central part with an elevation ranging between 10 to 40 m above MSL. The plains have a rolling topography with isolated mounds with a maximum elevation of 212 m. Floodplains, river terraces, channel and valley fills, colluviums and isolated mounds and hills are parts of the lowlands. The coastal plain in the west where the river debouches into the sea has an elevation reaching a maximum of 10 m above MSL. Coastal alluvial plains, floodplains, marshes, river terraces and palaeo-beach ridges constitute the coastal plain.

1.7 Regional geology

The high grade metamorphic terrane occurring in the southern tip of India known by the name Southern Granulite Terrane (SGT) consists of major units of the Archaean continental crust, such as granulites, gneisses, greenstones and a variety of younger intrusions. The SGT is considered as an ensemble of fragmented and imbricated crustal blocks separated by east-west trending crustal-scale shear systems, which include Cauvery shear zone (CSZ) and Achenkovil shear zone (ASZ) (Chetty, 2006). South of Achenkovil shear zone (ASZ), exposes an assemblage of migmatised meta-sedimentary and met-igneous rocks. From north of Achenkovil shear zone to the southern flank of Palghat Gap, the rocks are mainly charnockite (massive charnockite and charnockite gneiss) and migmatites. Northern flank of the Palghat gap is consists of metasedimentary sequence of khondalite and cal-granulite with crystalline limestone bands. Northern part of Kerala comprises granulites, schists and gneisses intruded by younger acid and alkaline plutons (Soman, 2002).

Ancient Supracrustals are represented by ultramafite and metasedimentary schistose rocks found to occur as en-echelon linear bands and enclaves within the charnockite and gneisses. The high-grade Wayanad Supracrustals rocks are correlated with the Sargur Schist Complex of the Karnataka (Nair, et al., 1975; Adiga, 1980). The schistose rocks are characterized by intense deformation, medium-to high-grade metamorphism, migmatization and lack of sedimentary structures. The schist complex consists of metaultramafite, schist, metapelite, metapyroxenite, serpentinite, talc-tremolite rock and amphibolite. The metasedimentaries of Wayanad Supracrustals occur as thin linear bodies within the migmatites. These consist of pelite, psammopelite and quartzite. The predominant rock types are corundum- mica schist, kyanite schist, quartz-mica schist and iron stone (Anil Kumar et al., 1993).

The rocks of Peninsular Gneissic Complex (PGC) are exposed in the northern parts of Kerala adjoining Karnataka. This consists of a heterogeneous mixture of granitoid materials. The equivalent rocks of PGC in Kerala include sheared hornblende-biotite gneiss, biotite-hornblende gneiss, foliated granite and pink granite gneiss.

The Khondalite Group of rocks includes calc-granulites, quartzite and garnetiferous-sillimanite gneiss and paragneisses of pelitic parentage and are well-developed in the southern part of the State, particularly, in Thiruvananthapuram and Kollam districts. Calc-granulite and quartzite occur as bands within the paragneisses and amidst the Charnockite Group or rocks and migmatitic gneisses.

Charnockite Group of rocks shows great diversity in lithology comprising pyroxene granulite, hornblende pyroxenite, magnetite quartzite, charnockite, hypersthene-diopside gneisses and cordierite gneiss. Charnockite and charnockite gneiss have preponderance over all other crystalline rocks covering 40-50% of the total area of the State. The charnockite are well-exposed in the central and northern parts of Kerala including the high–hills of the Western Ghats. The oldest rock, so far dated in Kerala is the massive charnockite, which yielded U-Pb zircon age of 2930$\pm$50 Ma (Soman, 2002).

Migmatite includes variety of gneissic rocks which are next in importance to charnockite as a dominant litho-assemblage (Rajan and Anilkumar, 2005). Quartzo-feldspathic gneiss, garnet-biotite gneiss, hornblende gneiss, hornblende-biotite gneiss, quartz-mica gneiss are the major rock units and show migmatitic structures such as agmatites, nebulites, schlierens, ptygmatic folds, quartzo-felspathic neosomes and ferromagnesian paleosomes (Muraleedharan and Raman, 1989).

Basic dyke emplacements within the Archaean crystalline rocks of Kerala are spread throughout the entire length and breadth of the State. Of these, dolerite dyke occurring north of the Palakkad gap had given Proterozoic age whereas in the south this dyke is of Phanerozoic age. The older basic dykes are metamorphosed along with the country rocks and are now recognized as epidiorite and amphibolite. Another set of dykes, apparently post-dating the regional metamorphic event are subjected to thermal metamorphism (Rajan and Anilkumar, 2005). Dykes in north Kerala show, NW-SE, NE-SW and NNW-SSE trends. Host rocks are charnockite, gneisses and Supracrustals

(Radhakrishna et al., 1991). Dykes are mainly dolerite but occasional metagabbro or metanorite are also traced. Younger basic intrusive in Kerala, mainly represented by dyke swarms in NNW-SSE to NW-SE trend, cut across all the metamorphic rocks and the earlier structural trends. Their unmetamorphosed nature and stratigraphic relation with the country rocks prompted their correlation to the Deccan Trap volcanism. The basic dykes have been emplaced into the migmatites and charnockite in NNW-SSE to NW-SE and ENE-WSW directions along distensional and shear fractures respectively. Dolerite dykes of Kerala are mostly quartz tholeiites rarely clinotholeiite (Rajan and Anilkumar, 2005).

Granites occur as later emplacements along crustal fractures and faults. The Achenkovil – Tamraparni tectonic zone, the Attapadi shear zone, Bavali shear zone and the Moyar shear zone are all marked by granitic emplacements. Some of them are located at Amblavayal, Kalpatta, Pariyaram, Munnar, Chengannur and Angadimogar. Pegmatite veins occur throughout the terrain and are mineralogically classified as simple and complex based on mineralization (Soman, 2002).

The Tertiary sedimentary formations lie unconformably over the Precambrian rocks. Mio-Pliocene sedimentary rocks are fairly widespread in the southern coastal belt, their remnants being noticeable in the central and northern coastal areas. These sedimentary rocks consist of a series of variegated clay and sandstones with lenticular seams of lignite, known as Warkalli Formation, underlain by Quilon Formation which is more compact marly sand with shell fragments and thin horizons of limestone (King, 1882).

The Archaean crystalline rocks and the Tertiary sedimentary rocks are extensively lateritised. The laterite has wide areal distribution in the State and occurs at all levels upto 2000 m, height though mostly restricted to an altitude of 50-150 m above MSL in the coastal and midland region. A few bauxite patches also occur within the laterites.

Recent to sub-Recent sediments of coastal sands, sticky black clay with carbonized wood, silty alluvium and lagoonal deposits are observed mostly in the low-lying areas. Alluvium is observed along the major river valleys. At places, along coastal tracts, there are raised sandy beaches composed of fine grained reddish sandy loam known as “Terri” sands. Palaeo-beach ridges alternate with marshy lagoonal clay in the coastal area in the entire stretch of Kerala coast. The Quaternaries of the coastal plain have been classified into (i) the Guruvayur Formation representing the earlier strandline deposits with an elevation of 5-10 m; (ii)the Viyyam Formation of tidal plain deposits; (iii) Periyar formation being mainly of fluvial deposits and (iv) the Kadappuram Formation representing the beach deposits (Nair, 2007).

1.8 Geology of the study area

The area forms part of the Precambrian metamorphic shield with rocks of Wayanad Group, Peninsular Gneissic Complex, Charnockite Group and Migmatite Complex, which are traversed by younger basic and acid intrusive (Fig. 1.2). Small isolated capping of Tertiary deposit (Warkali Formation) is seen to the west. The Quaternary sediments unconformably overlie the basements rocks of the coastal tracts and valleys.

Wayanad Group

The oldest rock type exposed in the area belongs to the Wayanad Group. They include small linear bands and enclaves of talc-tremolite-actinolite schist, irregular and linear bands of amphibolite/metagabbro, carbonate rock, fuchsite quartzite, thin impersistant bands of hornblende granulite and banded iron formation. The supracrustals of Wayanad Group occur as small patches, lenses, bands and enclaves within the rocks of the Charnockite Group and Migmatite Complex.

Peninsular Gneissic Complex (PGC-I)

Peninsular Gneissic Complex consists of heterogeneous mixture of granitoid materials. Sheared hornblende-biotite gneiss of Peninsular Gneissic Complex is restricted to the northern part and is mainly composed of biotite, hornblende, quartz and feldspar and is well-foliated and at places shows augen and agmatitic structures. The percentage of hornblende and biotite varies from place to place.

Charnockite Group

Charnockite/charnockite gneiss is the most widespread rock type in the study area and has preponderance over all the crystalline rocks covering about 50% of the total area in the basin. Charnockite Group of rocks makes up the high hills and steep slopes flanking the undulating terrain in the eastern and western part of the basin.

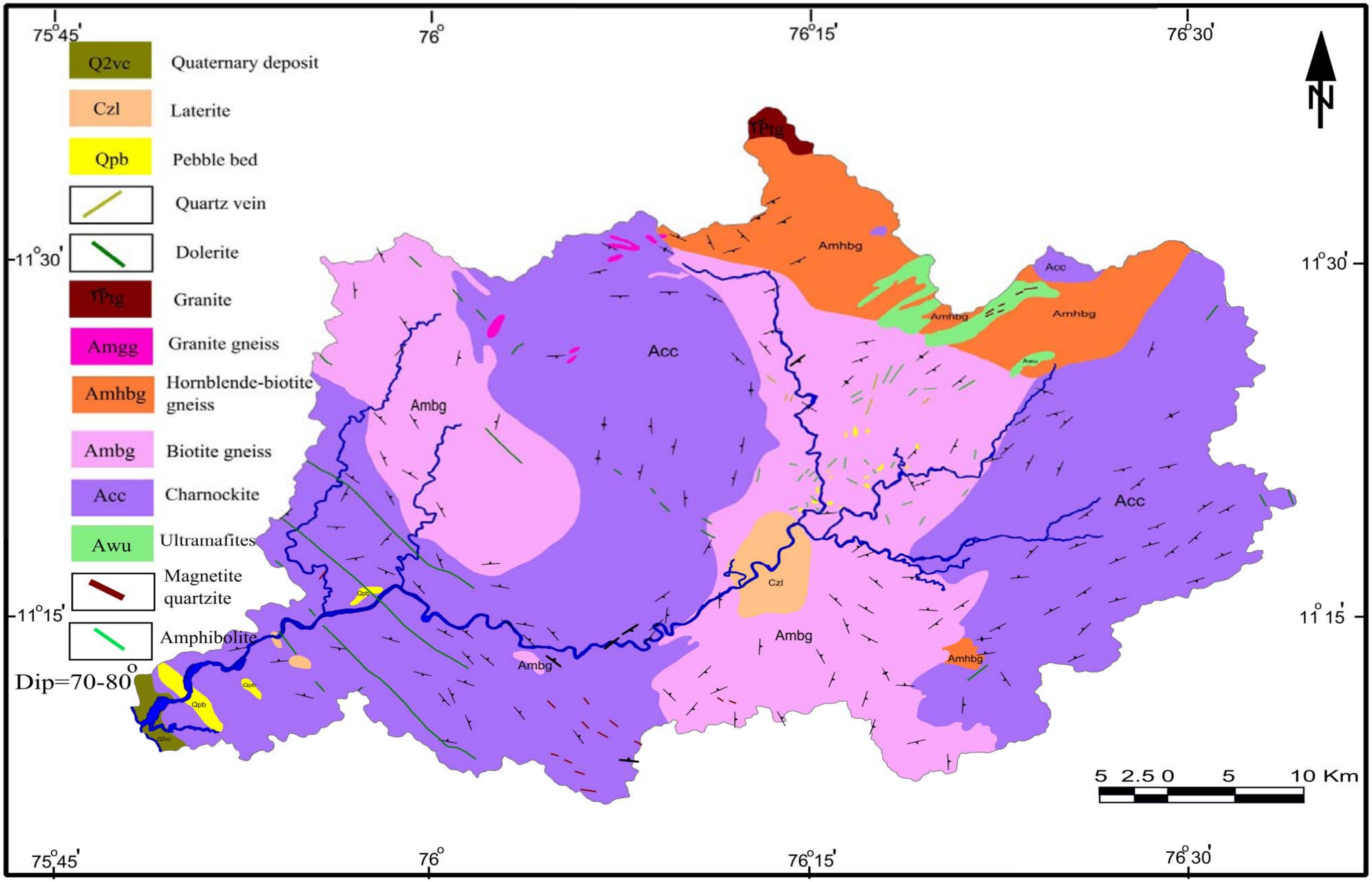


Fig. 1.2 Geological map of Chaliyar River drainage basin (after GSI, 1995).General trend of foliation is NE-SW, NW-SE, NNE-SSW and ENE-WSW dipping steeply (70-80º).

Table 1.1 General geology of Chaliyar River drainage basin (GSI, 1995)

Era	**Period**	**Group**	**Lithology**
Quaternary	Holocene	Marine	Sand
		Fluvio-marine	Clay and silt
		Fluvial	Sand, silt, clay
	Pleistocene	Palaeo-marine	Sand
			Pebble bed
Tertiary	Mio-Pliocene		Laterite
	Mesozoic	Acid Intrusive	Quartz vein
	(61-144 Ma)	Basic intrusive	Pegmatite
			Dolerite
	Proterozoic	Migmatite Complex	Hornblende gneiss
			Hornblende-biotite gneiss
P			Granite gneiss
R			
E		Charnockite Group	Charnockite/charnockite gneiss
C			Pyroxene granulite
A			
M	Archaean	Peninsular Gneissic Complex	Hornblende-biotite gneiss
B			
R			Magnetite quartzite
I			Quartz-mica schist
A		Wayanad Group	Fuchsite quartzite
N			Amphibolite
			Metapyroxenite
			Talc-tremolite-actinolite schist
	Base not recognized		

Charnockite is mainly intermediate type consisting essentially of hypersthene, diopside, secondary hornblende, biotite, sodic plagioclase and waxy quartz. In some areas it occurs as thin bands and well-foliated and is often veined by pegmatite along the foliation planes. Pyroxene granulite of Charnockite Group occurs as small lenses and enclaves within the gneisses and charnockite. It is a melanocratic, fine-grained rock with granulitic texture.

Migmatite Complex

Migmatite Complex comprises hornblende gneiss, hornblende-biotite gneiss and granite gneiss. These are medium grained, coarse-grained, mesocratic showing gneissic to granular texture and composed of hornblende, biotite, plagioclase, quartz and garnet as major minerals. Hornblende-biotite gneiss is seen as linear bodies trending NW-SE and show lit par lit relation with the granite gneiss. Granite gneiss occurs as oval shaped body and is feebly foliated, pink and equigranular. The origin of granite gneiss is attributed to stress-induced injection of acid materials into the host rock (Rajan and Anil Kumar, 2005). The rocks of Migmatite Complex show migmatitic structures such as agmatite, nebulites, schlierens, ptygmatic folds, quatrzo-feldspathic neosomes and ferromagnesian palaeosomes.

Younger Intrusive

Basic and acid intrusives of Mesozoic Period are very common in this terrain. NNW-SSE to NW-SE trending basic dykes occur in the study area at places. They cut across all the older metamorphic rocks and structural trends. Their unmetamorphosed nature and stratigraphic relation with the country rocks prompted their correlation to the Deccan Trap volcanism (Rajan and Anil Kumar, 2005). The gabbro dykes are sheared. Quartz veins and pegmatite veins criss-cross almost all the rock types in the area. Most of these quartz veins are major source for primary gold.

Laterite

Lateritization is very prominent in the midlands within the charnockite and migmatites. Laterite in this area is about 2 to 8 m thick and is very hard, cavernous and ferruginous. Laterite is restricted to the mid-land regions and restricted to an altitude of 100-200m above MSL. Laterite after the crystalline rocks is compact and the top crust is moderately indurated (Rajan and Anil Kumar, 2005). Quartz veins, joints and fractures can be traced in a laterite profile.

Quaternary sediments

Quaternary sediments are confined to the coastal tracts and valleys and along the river stretch. Based on the environment of deposition, these deposits are further subdivided into different morphostratigraphic units-marine, palaeomarine, fluvial and fluviomarine. The oldest unit is the palaeo-beach deposit of marine origin consisting of medium- to coarse-grained sand, composed mainly of quartz. The tidal and mud-flat deposits of fluvio-marine origin comprising mainly silt and black clay, beach and barrier beach deposits of marine origin consisting of medium- to fine-grained quartz sand with minor amount of heavy minerals and the point bar, channel bars and flood plain deposits of fluvial origin which is an admixture of sand, silt and clay are grouped into the recent deposits. Pebble beds are observed on either side of the Chaliyar River mouth at Beypore. These pebble beds are predominantly composed of quartz but occasionally charnockite gneiss pebbles are also observed. They are well-rounded to spherical in shape with clayey matrix. The thickness of the pebble bed is about 1 to 6 m and is seen at 20 m above MSL.

Structure

The trend of foliation of the rocks is generally NW-SE with steep dips to either side. The foliation trend swings to ENW-WSW in Nilambur valley. Tight appressed folds of asymmetrical nature, which have given rise to axial plane foliation with characteristic platy mineral alignment is the earliest formed folds (F_1). F_2 folds (post-folial) are open symmetrical folds and control the disposition of major lithologies. F_3 folds are open warps which deform the F_1 and F_2 folds and have a broad swerve in ENE-WSW direction is also decipherable in the study area.

1.9 Climate

The basin enjoys a tropical humid climate with sweltering summer and high monsoon rainfall. Generally March and April are the hottest and December and January are the coolest. The maximum temperature ranges from 22ºC to 32.9ºC and the minimum temperature ranges from 22ºC to 25.8ºC. The average annual maximum temperature is 30.9ºC and minimum is 23.7ºC. The temperature starts rising from January reaching the peak in April. It decreases during the monsoon months. On an average about 3000 mm of rainfall occurs annually in the basin.

The principal rainy seasons are the southwest (June-September) and northeast (October-November) monsoons in India. The pre-monsoon months (March-May) are characterized by major thunderstorm activity and the winter months (December-February) by minimal cloudiness and rainfall (Ananthakrishnan et al. 1979). *Sahyadri* (Western Ghats) has a significant influence on the intensity and distribution of rainfall over Peninsular India. As a mountain barrier, the *Sahyadri* polarizes precipitation along its crest. As moist airflow during the southwest monsoon ascends, the windward slope receives copious rainfall (Anu and Mohankumar, 2004). Thus, the *Sahyadri* forms the watershed for a large number of rivers. These rivers have high run-off and sediment load during the monsoon months.

Southwestern India experiences a tropical climate with seasonally reversing wind patterns and large variations in precipitation. Along the west coast of India, the southwest (SW) monsoonal winds of oceanic origin are established by mid-May. During the SW monsoon, winds blow from southwest during May-September, but change to a northeasterly direction during the northeast (NE) monsoon. These winds continue to grow strong until June, when there is a sudden 'burst' or strengthening of the southwest winds. The winds are the strongest during July and August, but become weak in September, ahead of the NE monsoon, which lasts through October and November. The wind speed is generally 15-20 km/hr during the SW monsoon, but lower (10-12 km/hr) during the NE monsoon. Summer (southwest) monsoon (June-September) accounts for a major part of the average annual rainfall (> 300 cm), whereas the winter monsoon (October-January) accounts for about 50-60 cm rainfall. Temperature in the region ranges between 23° and 37°C (Narayana, 2006).

The winds are the strongest during July and August, but become weak in September, ahead of the NE monsoon, which lasts through October and November. The wind speed is generally 15-20 km/hr during the SW monsoon, but lower (10-12 km/hr) during the NE monsoon. Summer (southwest) monsoon (June-September) accounts for a major part of the average annual rainfall (> 300 cm), whereas the winter monsoon (October-January) accounts for about 50-60 cm rainfall. Temperature in the region ranges between 23° and 37°C.

Rivers in mountainous terrains commonly carry higher sediment loads and yields than do upland rivers, whose loads and yields in turn, are higher than those of lowland rivers. A better relationship was documented between the annual variability of rainfall and sediment transport. The positive relationship among rainfall, run-off and sediment discharge suggests that precipitation and run-off exert a first order control on the sediment discharge of Kerala Rivers (Narayana, 2007). Tectonic uplift/subsidence alters the fluvial regime with resultant changes in rates of sediment erosion and deposition.

Chapter II
MORPHOMETRY

2.1 Introduction

A drainage basin, with all its elements and attributes, can be described as an open system with a continuous exchange of matter and energy with the surroundings. The evolution of any drainage basin is the result of interactions between matter and energy and the resistance of the topographical surface. The matter and energy act upon the variables defining the characteristics of a river basin. Some of these characteristics of a river basin can be quantified by morphometric studies (Zăvoianu, 1985). Drainage basins are basic hydrologic units that have been used for morphometric and geomorphic characterization since the earliest published records (Strahler, 1952). They evolve under a close control of interplay between tectonics and climate (Rockwell et al., 1984; Bull and Knuepfer, 1987; Keller and Pinter, 1996, Delcaillau et al., 1998; Burbank and Anderson, 2001).

Surface drainage characteristics of many river basins and sub-basins in different parts of the globe have been studied using conventional methods (Horton, 1945; Strahler, 1952, 1957, 1964; Morisawa, 1959; Leopold and Miller, 1956). River basins comprise a distinct morphologic region and have special relevance to drainage pattern and geomorphology (Doornkamp and Cuchlaine, 1971; Strahler, 1957). Active tectonics in any region may be best recognized in river morphology that is highly sensitive to change in gradient. The river systems adjust to gradient changes vis.-a-vis. active tectonics, and thus can mimic the regional tectonic framework in terms of their drainage network.

Morphometric analysis is a major advance in the quantitative description of the geometry of the drainage basin. Morphometry is the measurement and mathematical analysis of configuration of the earth surface and the shape and dimensions of its landforms (Clarke, 1973). Morphometric studies involve evaluation of streams through the measurement of various stream properties viz., linear, areal and relief aspects. The linear, relief and areal aspects of a drainage basin provide the quantitative information on the geometry of a fluvial system, and can be correlated with the hydrologic information (Rao, 1984). It is an important tool in studies related to neotectonics and geomorphology, where the natural landscapes to planet's interior dynamics is often masked by fast action of weathering and where the presence of drainage network anomalies and relief pattern discontinuities may be related with recent terrain movements (Zuchiewicz, 1991). Systematic analysis of morphometric parameters through integrated remote sensing and GIS could be effectively used in understanding the morphologic and hydrologic characteristics of Chaliyar River drainage basin. The foregoing analysis clearly indicates the relation among the various attributes of the morphometry of the basin that helps to understand their role in sculpturing the terrain. In this chapter linear, areal and relief aspects of Chaliyar River drainage basin are discussed.

2.2 Materials and Methods

Survey of India toposheets 58A/2, A/3, A/4, A/6, A/7, A/8, and A/11, 49M/15 and M/16 on 1:50,000 scale are used for delineation and digitization of the drainage basin boundary. Drainages from 1st order to the highest order are digitally traced from these toposheets on 1:50,000 scale for morphometric analysis.

Remote sensing and GIS techniques are effectively used as tools in morphometric analysis. High Spatial Resolution Indian Remote Sensing Satellite, IRS-P6 LISS (Linear Image Self Scanning)-III sensor data acquired on 8th February, 2005, 05.33 hrs in conjunction with Survey of India (SOI) toposheets (1:50,000 scale) are used for systematic analysis of various morphometric, lithological and landform characteristics of the river basin. The topological information of the Chaliyar River drainage basin is geo-referenced and digitized using ArcGIS tools with respect to the SOI toposheets. Drainage basin boundary is delineated from SOI toposheets and later updated using linear stretched and edge enhanced LISS III satellite imagery. Drainages are digitally traced and the basin is subdivided into nine sub-basins (1 - 9) drained by Cherupuzha, Iruvahnipuzha, Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha, Karakodupuzha, Punnapuzha, Karimpuzha and Kuthirapuzha tributaries respectively. Stream orders and stream numbers are assigned to each streamlet. Stream lengths as per stream orders were measured using ArcGIS 9 version. Basin area, length and width of the sub-basins and the main Chaliyar basin are measured. Morphometric analysis is carried out and morphometric parameters are obtained at sub-basin level. All these parameters are graphically represented using Grapher, Zigmaplot and Origin 50.

Quantitative estimation of morphometric parameters is carried out for 9 sub-basins of Chaliyar River drainage basin. Morphometry of the drainage basin comprising three aspects - linear, areal and relief. These are computed from drainage maps following the procedures proposed by Horton (1945); Langbein (1947); Strahler (1952, 1968); Schumm (1956); Smart and Surkan (1967); Avena et al. (1967); Waugh (1995); Gupta (1999); El Hamdouni (2007); Guarnieri et al. (2008); Thomas et al., (2009); Dehbozorgi et al. (2010).

Linear aspects include stream order (U), stream number (N_u), stream length (L_u), bifurcation ratio (R_b), mean length of streams of corresponding orders, stream length ratio, and mean stream length ratio. Areal aspects comprise basin area (A_u), stream frequency (F_u), circularity ratio (R_c), elongation ratio (R_l), form factor (R_f), compactness factor (R_{cf}), constant of channel maintenance and drainage density (D_d). Relief aspects include basin relief (R_l), relief ratio (R_r), ruggedness number (R_n), channel gradient (R_s), sinuosity ratio (S_r) and hypsometric integral (H_i). All these parameters are computed and analysed for the Chaliyar River drainage basin and its 9 sub-basins and presented in Table 2.1 - 2.5 and Fig. 2.1 - 2.6).

2.2.1 Linear aspects

The first step in drainage-basin analysis is designation of stream orders (Horton, 1945, Suresh 2000), which is not only the index of the size and scale, but also to afford and approximate index of the amount of stream flow, that can be produced by a particular network. The following linear aspects of the drainage system of Chaliyar River are determined and the data are presented in Table 2.1.

Stream order

Stream order is directly proportional to the size of the contributing watershed, to channel dimensions and to stream discharge at that place in the system. The stream order from 1 to 7 are determined in the study area from the integrated drainage map prepared from SOI toposheet, aerial photographs and IRS P-6, LISS III satellite imagery.

Stream number (N_u)

The count of stream channel in its order is known as stream number. Total number of streams in each order for the sub-basins is counted separately. Stream number is also directly proportional to size of the watershed and channel dimension. It is obvious that the number of streams of any given order will be fewer than for the next lower order but more numerous than for the next higher order.

Bifurcation ratio

Horton (1945) and Strahler (1952) had defined bifurcation ratio as number of streams of one order to the number of the next higher order which can be expressed as

$$R_b = (N_u)/(N_{u+1}) \quad \text{(i)}$$

where N_u is the number of streams in a given order and N_{u+1} is the number of streams in the next higher order. Average value of R_b for a given channel network can be estimated by determining the slope of the best fitted regression of logarithm of numbers (ordinate) on order (abscissa). The regression coefficient (R^2) is identical with the logarithm of R_b**.**

Direct bifurcation ratio (R_{bd})

Direct bifurcation ratio (R_{bd}) explains the nature of the drainage networks without considering the hierarchical anomalies (Guarnieri et al., 2008). Direct bifurcation ratio (R_{bd}) for all the streams of different orders is computed using the equation,

$$R_{bd} = N_{du}/N_{u+1} \quad \text{(ii)}$$

where N_{du} is the number of the fluvial segments of a given order that flow in segments of the next higher order N_{u+1} (Avena et al, 1967).

Bifurcation index (R)

Bifurcation index is the difference between the bifurcation ratio (R_b) and direct bifurcation ratio (R_{bd}) and it gives the useful information on the typology of the active erosive processes and on the evolution of basin, and depends on the presence of hierarchical anomalies (Guarnieri et al., 2008). Bifurcation index of the streams is determined by the equation

$$R = R_b - R_{bd} \quad \text{(iii)}$$

Hierarchical anomaly number (H_a)

Hierarchical anomaly number (H_a) corresponds to the minimum number of the first order segments necessary to make the network perfectly hierarchical (Avena et al, 1967; Guarnieri et al., 2008).

Hierarchical anomaly index (Δ_a)

Hierarchical anomaly index (Δ_a) is defined as the ratio of the number of hierarchical anomaly (H_a) to the number of the first order network (N_1) (Avena et al, 1967; Guarnieri et al., 2008).

$$\Delta_a = H_a / N_1 \quad \text{(iv)}$$

Hierarchical anomaly number and hierarchical anomaly index are determined for the drainage system of the study area and data are given in Table 2.2.

Horton (1945) has worked out a relationship between the total number of stream segments and the constant bifurcation ratio as

$$N_t = (R_b^K - 1)/(R_b - 1) \quad \text{(v)}$$

where, K is the highest order of the basin, R_b is taken as the average value of the bifurcation ratio for the basin and N_t is the total number of stream segments.

Stream length

Stream length was measured with the help of ArcGIS software. To obtain the mean length of channel L_u of order u, the total length is divided by the number of segments N_u of that order (Horton, 1945), thus

$$L_u = \frac{\sum_{1=1}^{N} L_u}{N_u} \quad \text{(vi)}$$

where L_u is the mean length of the channel of a given order, and N_u is the total number of streams in that particular order.

Length of overland flow (Lf)

Length of overland flow is the length of water over the ground before it gets concentrated into definite stream channels which affect both hydrologic and physiographic development of drainage basins (Horton 1945). The distance covered from the water divide to the nearest channel represents the length of overland flow, and is an important variable on which run off and flood processes depend (Zăvoianu, 1985).

Sinuosity ratio (S_i)

Sinuosity ratio gives an idea how the channel deviates from a straight path-wandering and meandering (Smart and Surkan, 1967). It is the ratio of channel length (L_u) of the main stream in a basin to the basin length (L_b) and is determined by the equation

$$S_i = L_u / L_b \quad \text{(vii)}$$

It is of great use in understanding the geomorphic characteristic of a basin and is used in the morphometric studies to distinguish between the various types of terrain and to ascertain the degree of establishment made by a drainage line in the area of influence. The degree of stream sinuosity fluctuates with time and stage of development of the basin in relation to the topographical and geological background. Channels with sinuosity index < 1.1 is described as straight, those between 1.1 and 1.5 are sinuous and those with sinuosity ratio > 1.5 are called meandering channels (Charlton, 2007).

2.2.2 Areal aspects

In addition to the mathematical relationship found in stream ordering, various aspects of drainage network forms are also found to be quantifiable based on the spatial distribution and area of the drainage basin. Areal aspects rely on the spatial scale variation of the drainage basin and is attributed to the inherent capability of the stream system to adjust itself by size adjusts in the stream segments. The following areal aspects of Chaliyar river drainage basin are computed and presented in the Table 2.3.

Basin area (A_u)

Basin area of a given order is defined as the total area projected on a horizontal plane contribution overland flow to the channel segments of the given order, which includes all tributaries of the lower order. Basin size helps to determine the amount of water reaching the river. Larger the catchment area, greater will be the potential of flooding. Basin area of each sub-basin is measured using ArcGIS software.

Drainage density (D_d)

This is an important indicator of the linear scale of land-form elements in stream eroded topography. Drainage density is the total length of all the streams in the basin to the area of whole basin (Horton, 1945). Factors affecting drainage density are the erodibility of the rock and climate. Drainage density (D_d) is computed using the following equation as suggested by Horton (1945)

$$D_d = \sum L_u / A_u \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(viii)}$$

where L_u is the total length of the streams in a basin and A_u is the area of the basin.

Stream frequency (F_u)

It refers to the number of streams per unit area. Horton (1945) introduced stream frequency and discusses the importance to ground water recharge characteristics in a river basin. It expresses the competence with which the channel system fills the basin outline (Chorley et al, 1985). Stream frequency is calculated by dividing the total number of streams (N_u) in a basin by the total basin area (A_u).

$$F_u = \sum N_u / A_u \text{ ....(ix)}$$

Circularity ratio (R_c)

Circularity ratio is the ratio of the area of a circle having the same circumference as the perimeter of the basin (Miller, 1953). This ratio is obtained from the equation

$$R_c = \frac{4\Pi A_u}{P^2} \text{ ....(x)}$$

where P is the perimeter of the drainage basin.

Elongation ratio (R_e)

Elongation ratio is the ratio between diameter of a circle having same area as that of the drainage basin and the maximum length of the basin (Schumm, 1956) and is determined by employing the formula

$$R_e = D_a / L_{max} \text{ ....(xi)}$$

Elongation ratio indicates how the shape of the basin deviates from a circle and is considered as the index to mark the shape of the basin.

Form factor (F_f)

Horton (1932) proposed the form factor in order to express the shape of the basin quantitatively. Form factor governs the water course that enters the main stream (Gregory and Walling, 1985). If the basin is wider, the form factor will be comparatively higher and vice versa. Form factor is one of the parameters that explain the basin configuration. It is the ratio of the basin area to the square of the basin length (Strahler, 1968), and is expressed as

$$F_f = A_u / L_u^2 \text{ ....(xii)}$$

Compactness factor (R_{cf})

Compactness factor is used to express the basin shape, as a factor of deviation of the basin area from a circle having the same area of the drainage basin (Gupta, 1999). This is computed from the equation

$$R_{cf} = A_c / A_u \text{ ....(xiii)}$$

where Ac is the area of circle having the same perimeter.

2.2.3 Relief aspect

Relief aspects of a drainage basin have great influence on the hydrologic response, and depend on the channel type and relative gradient of the basin. The following relief aspects of Chaliyar River drainage basin are determined and presented in Table 2.4.

Basin relief (R_h)

Importance of basin relief as a hydrological parameter has been recognized long before (Sherman, 1932, Horton, 1945; Strahler, 1964). Basin relief is an important factor in understanding denudational characteristics of the basin. Basin relief (R_h) is the difference between the maximum and minimum elevation of a drainage basin (Schumm, 1956). It is a parameter that determines the stream gradient and influences flood pattern and volume of sediment that can be transported (Hadley and Schumm 1961). Basin relief is computed by employing a simple function

$$R_h = H - h \qquad \text{(xiv)}$$

where H is maximum elevation and h is minimum elevation within the basin.

Relief ratio (R_r)

Relief ratio (R_r) is a dimensionless ratio of basin relief to the basin length (Schumm, 1956), and is expressed by the equation

$$R_r = R/L_b \qquad \text{(xv)}$$

Ruggedness number

In order to combine the qualities of slope steepness and length, a dimensionless number is developed which is the product of relief and drainage density (Strahler, 1958) and is determined by the equation

$$R_n = R_h \times D_d \qquad \text{(xvi)}$$

Stream gradient

Stream gradient is the ratio of drop in a stream per unit distance, usually expressed as meters per kilometer. It is commonly used to measure the river slope and define relative difference in uplift (Merrits and Vincent, 1989). Hack (1957) explained that channel gradient is affected by lithology for basins of similar sizes. Steep gradient generally occurs in areas of resistant bed rock. A high gradient indicates a steep slope and rapid flow of water (i.e. more ability to erode); whereas a low gradient indicates a more nearly level stream bed and sluggishly moving water, that may be able to carry only small amounts of very fine sediment. High gradient streams tend to have steep, narrow V-shaped valleys, and are referred to as young streams. Low gradient streams have wider and less rugged valleys, with a tendency for the stream to meander.

Stream gradient is computed by the formula

$$S = \frac{E_1 - E_2}{L_s} \qquad \text{(xvii)}$$

Where E_1-E_2 is the difference in the elevation between two points on the stream and L_s is the distance along the stream.

2.2.4 Hypsometric analysis

Hypsometric analysis was for the first time introduced by Langbein (1947) to express the overall slope and forms of the drainage basin. Hypsometric analysis is the study of the distribution of ground surface area, or horizontal cross-sectional area, of a landmass with respect to elevation (Strahler, 1952). Hypsometric analysis (a dimensionless parameter) permits comparison of drainage basins irrespective of scale issues (Dowling et al., 1998). Hypsometric curves and hypsometric integrals are important indicators of watershed conditions (Ritter et al., 2002). The shape of the hypsometric curve explains the temporal changes in the slope of the original basin (Giamboni et al., 2005). It helps in understanding the cycle of erosion (Strahler, 1952; Giamboni et al., 2005; Singh et al., 2008) and in inferring characteristics of the complex morphologic processes in a basin (Strahler, 1952; Harlin, 1984; Moglen and Bras, 1995). Schumm (1956) demonstrated the relationship between hypsometric curve and the stage of geomorphic evolution of a basin and established significant relationship between the hypsometric integral and both the relief ratio and stream gradient for young basins those with less than 25% of the mass removed. Recently it has been found useful to infer runoff partitioning and changes in hydrological response (Vivoni et al., 2006).

Hypsometric curve is obtained by plotting the relative area along the abscissa and relative elevation along the ordinate. The relative area is obtained as a ratio of the area above a particular contour to the total area of the watershed encompassing the outlet. Relative elevation is calculated as the ratio of the height of the given contour (h) from the base plane to the maximum basin elevation (H) (Sarangi et al., 2001; Ritter et al,, 2002; Singh et al., 2008). Hypsometric integral (H_i) is obtained from the hypsometric curve and is equivalent to the ratio of the area under the curve to the area of the square formed by covering it. In the present study, the elevation-relief ratio method proposed by Pike and Wilson (1971) is used. The relationship is expressed as

$$H_i = \frac{Elev_{mean} - Elev_{min}}{Elev_{max} - Elev_{min}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(xviii)}$$

where $Elev_{mean}$ is the weighted mean elevation of the drainage basin estimated from the identifiable contours of the delineated drainage basin; $Elev_{max}$ and $Elev_{min}$ are the maximum and minimum elevations within the drainage basin.

Hypsometric integral expresses the unconsumed volume of drainage basin as a percentage of that delimited by the summit plane, base plane and perimeter. The value of hypsometric integral as a relative measure of erosion is limited to its higher values or to situations where the elevation of the original summit plane can be estimated. In the present study, the drainage basins are classified by the shape of the hypsometric curve, absolute distribution of the elevation and by the hypsometric integral. The hypsometric curve and integrals for the Chaliyar basin and its nine sub-basins are presented in Table 2.5 and Fig. 2.6.

2.3 Results and Discussion

Morphometry is to derive information in quantitative form about the geometry of the fluvial system that can be correlated with hydrologic information. Morphometric descriptors represent relatively simple approaches to describe basin processes and to compare basin characteristics. Morphometry helps in the quantitative description of the geometry of the drainage basins and in characterization of the drainage network, comparing the characteristics of several drainage networks and examining the effect of variables such as lithology, rock structure, rainfall etc.. Spatial analysis of the morphometric parameters provide us with some valuable information regarding their distribution and relation to the structure and tectonics of the area.

2.3.1 Morphometric characteristics

Digitally traced drainage map of Chaliyar River drainage basin (Fig. 2.1) is the base for the morphometric computation. Linear aspects like stream order, number and length are counted and measured respectively from the drainage map.

Morphometry based on linear aspects

In the linear aspects, stream order (U), stream length (L_u), bifurcation ratio (R_b), mean length of streams of orders, stream length ratio, and mean stream length ratio were analyzed (Table 2.1). In each case, Horton's law of geomorphology is tested for Chaliyar River drainage basin.

Stream order (U)

Stream order is not only the index of size and scale of the drainage basin, but also can approximate the amount of stream flow. In the sub-basins of Chaliyar River the highest orders are 4 to 7 indicating the moderate size of the sub-basins. Sub-basins 2, 4, 7, 8 and 9 are comparatively larger in size than sub-basins 1, 3 and 5 (Table 2.1). The stream order of Chaliyar basin is 7, which indicates a moderate to high stream discharge, channel dimension and size of the basin.

Stream Number (N_u)

In general, the number of the stream segments decreases as the order increases. The higher stream number indicates lesser permeability and infiltration. Total number of streams in sub-basin - 1 is 497 and in sub-basin - 2 is 1274. Total number of streams in sub-basins 3, 4 and 5 is 566, 369 and 1928 respectively. Sub-basins 6, 7, 8 and 9 have 227, 1411, 1263 and 565 number of streams respectively. Total number of streams in Chaliyar River drainage basin is 9417 (Table 2.1). Plots of log of stream number against stream order for each sub-basin are represented in Fig. 2.2. High R-squared (R^2) values suggest that the best fitted model to explain the relation of stream order and stream number is the exponential trendline.

Bifurcation ratio (R_b)

Bifurcation ratio, a measure of the degree of ramification of drainage network and has a significant control over the runoff (Chorley 1969; Mesa 2006). The bifurcation ratio will not be precisely the same from one order to the next, because of possibility of variations in watershed geometry and lithology, but tends to be a constant throughout the series. As the bifurcation ratio increases, the basin shape will be elongated and as the ratio decreases the basin gets broader and circular. Bifurcation ratios characteristically range between 3.0 and 4.0 for watersheds in which geologic structures do not distort the drainage pattern. The theoretical minimum value of 2.0 is rarely approached under natural conditions.

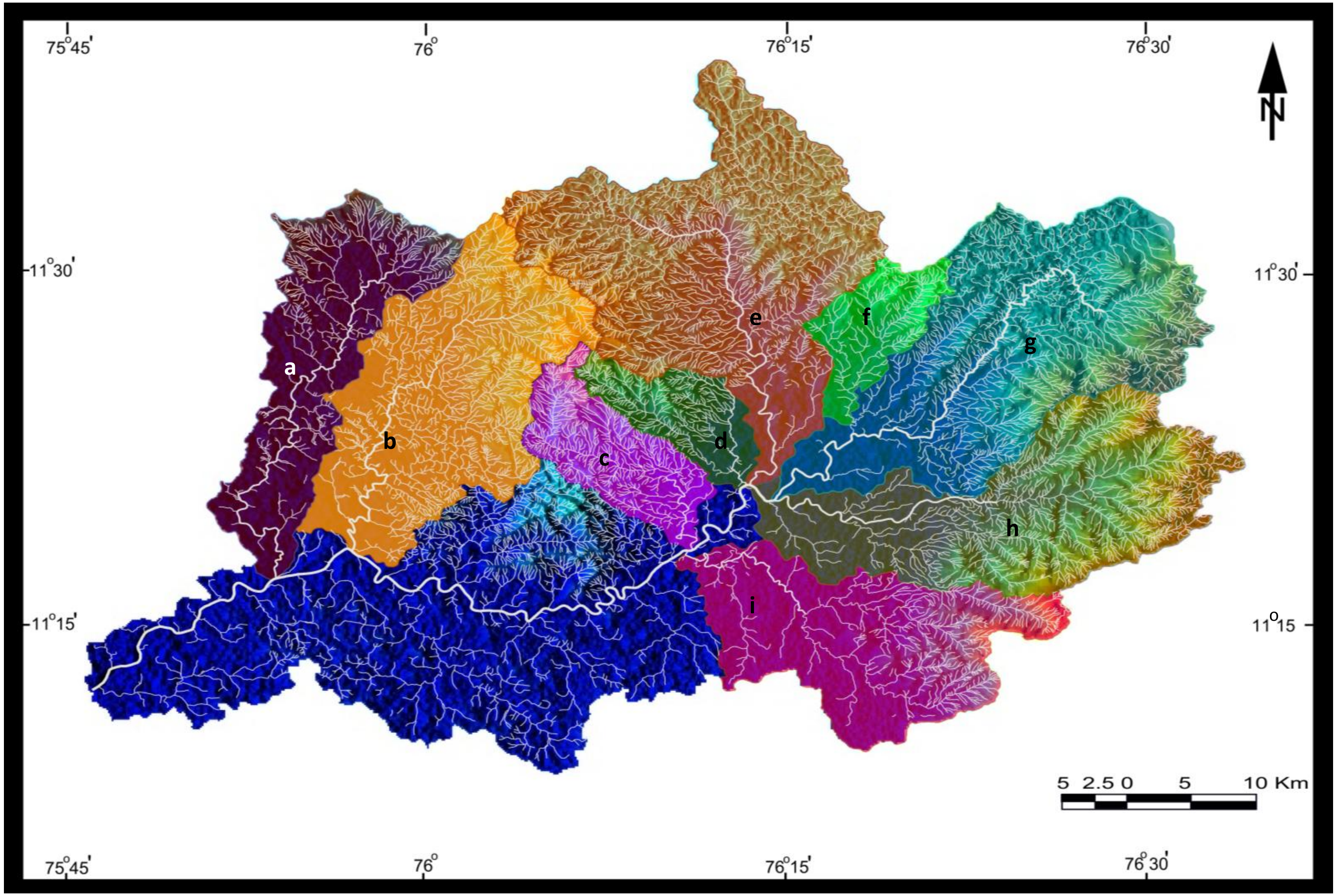


Fig. 2.1 SRTM derived DEM-aspect map of Chaliyar River basin and 9 sub-basins drainage showing the drainage network. (a) Sub-basin - 1 drained by Cherupuzha; (b) sub-basin - 2 drained by Iruvahnipuzha; (c) sub-basin - 3 drained by Kurumanpuzha; (d) sub-basin - 4 drained by Kanjirapuzha; (e) sub-basin - 5 drained by Chaliyarpuzha (f) sub-basin - 6 drained by Karakodupuzha; (g) sub-basin - 7 drained by Punnapuzha; (h) sub-basin - 8 drained by Karimpuzha and (i) sub-basin - 9 representing the Kuthirapuzha tributary.

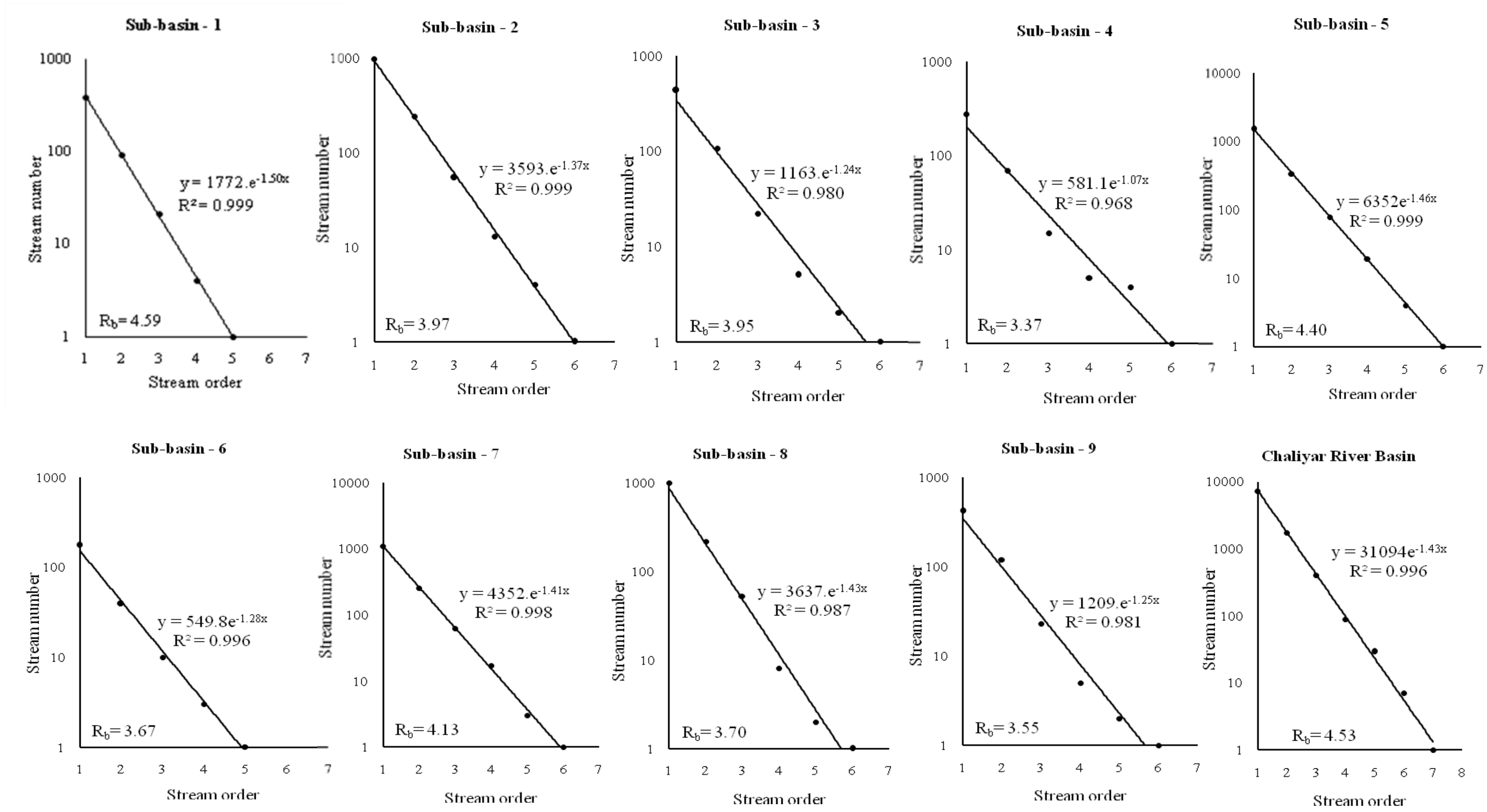


Fig. 2.2 Semi-logarithmic plot of the stream number against stream orders for the nine sub-basins and Chaliyar River basin. Weighted mean bifurcation ratio (R_b) for each sub-basin is given in the plots. Regression coefficient values for the exponential curves are indicated.

Table 2.1 Linear morphometric parameters of sub-basins of Chaliyar River and its drainage basin.

Stream order (U)	No. of streams (N_u)	Stream length (L_u) (km)	Average length ($\overline{L_u}$) (km)	Bifurcation ratio (R_b)	Stream length ratio	Length of overland flow (L_f)
Sub-basin - 1						
1st order	381	238.68	0.63	4.19	0.34	0.30
2nd order	91	81.65	0.90	4.33	0.56	
3rd order	21	45.79	2.18	5.25	0.32	
4th order	4	14.4	3.6			
Total	**497**	**380.53**				
Sub-basin - 2						
1st order	962	558.87	0.58	4	0.30	0.18
2nd order	240	169.46	0.71	4.44	0.50	
3rd order	54	84.99	1.57	4.15	0.68	
4th order	13	58.06	4.47	3.25	0.44	
5th order	4	25.74	6.44	4	0.86	
6th order	1	22	22			
Total	**1274**	**919.12**				
Sub-basin - 3						
1st order	431	251.82	0.58	4.07	0.33	0.13
2nd order	106	84.11	0.79	4.82	0.37	
3rd order	22	31.09	1.41	4.4	0.45	
4th order	5	14.13	2.83	2.5	1.42	
5th order	2	20.06	10.03			
Total	**566**	**401.22**				
Sub-basin - 4						
1st order	275	143.18	0.52	3.99	0.25	0.16
2nd order	69	35.71	0.52	4.6	0.62	
3rd order	15	22.14	1.48	3	0.83	
4th order	5	18.32	3.66	1.25	0.68	
5th order	4	12.38	3.1	4	0.15	
6th order	1	1.8	1.8			
Total	**369**	**233.53**				
Sub-basin - 5						
1st order	1494	795.51	0.53	4.49	0.3	0.18
2nd order	333	234.87	0.71	4.27	0.59	
3rd order	78	137.53	1.76	4.11	0.64	
4th order	19	88.57	4.66	4.75	0.14	
5th order	4	12.33	3.08			
Total	**1928**	**1268.81**				
Sub-basin - 6						
1st order	174	109.09	0.63	4.46	0.25	0.2
2nd order	39	27.44	0.70	3.9	0.65	
3rd order	10	17.75	1.78	3.33	0.87	
4th order	3	15.4	5.13	3	0.78	
5th order	1	12	12			
Total	**227**	**181.68**				
Sub-basin - 7						
1st order	1075	653.65	0.61	4.25	0.33	0.19
2nd order	253	214.2	0.85	4.08	0.43	
3rd order	62	91.22	1.47	3.65	0.78	
4th order	17	71.45	4.20	5.67	0.17	
5th order	3	12.1	4.03	3	4.05	
6th order	1	49	49			
Total	**1411**	**1091.62**				

Table 2.1 continued

Stream order (U)	No. of streams (N_u)	Stream length (L_u) (km)	Average length ($\bar{L}_u$) (km)	Bifurcation ratio (R_b)	Stream length ratio	Length of overland flow (L_f)
Sub-basin - 8						
1st order	985	610.77	0.62	4.60	0.28	0.17
2nd order	214	167.80	0.78	4.12	0.48	
3rd order	52	82.21	1.58	6.5	0.7	
4th order	8	57.42	7.18	4	0.17	
5th order	2	9.80	4.9	2	2.14	
6th order	1	21	21	1	3.67	
7th order	1	77	77			
Total	**1263**	**1026**				
Sub-basin - 9						
1st order	416	273.95	0.66	3.53	0.30	0.28
2nd order	118	83.03	0.70	5.13	0.40	
3rd order	23	33.28	1.45	4.6	1.12	
4th order	5	37.23	7.45	2.5	0.62	
5th order	2	23	11.50	2	0.74	
6th order	1	17	17			
Total	**565**	**467.49**				
Chaliyar Basin						
1st order	7157	4222.78	0.59	4.13	1.29	
2nd order	1731	1318.46	0.76	4.30	2.20	
3rd order	403	675.87	1.68	4.53	2.83	-
4th order	89	421.64	4.74	3.07	1.51	
5th order	29	207.75	7.16	4.14	3.02	
6th order	7	151.40	21.63	7	3.56	
7th order	1	77	77			
Total	**9417**	**7074.89**				

Table 2.2 Bifurcation ratio and hierarchical morphometric parameters of the Chaliyar River drainage network

Sub-basin	Bifurcation ratio (R_b)	Direct bifurcation ratio (R_{bd})	Bifurcation index (R)	Hierarchical anomaly number (H_a)	Hierarchical anomaly index (Δ_a)
1	4.59	0.7	3.86	67	0.18
2	3.97	0.8	3.32	124	0.13
3	3.95	0.7	3.44	97	0.23
4	3.37	0.8	2.60	55	0.20
5	4.40	0.7	3.71	257	0.17
6	3.67	0.9	2.80	32	0.18
7	4.13	0.8	3.37	244	0.23
8	3.70	1.0	2.87	238	0.24
9	3.55	0.7	2.84	102	0.25

The bifurcation ratio of nine sub-basins of Chaliyar River drainage basin is found to be ranging from 1 to 6.5 (Table 2.1). The highest and lowest bifurcation ratio is for the streams within sub-basin - 8. The lower orders of all the sub-basins have bifurcation ratio > 4. This suggests that the basin is a highly dissected one and the upland zone of the basin is tectonically active as observed by San et al, 1998. High bifurcation ratio may also be due to the elongated shape of the basin (Strahler 1964 & Zavoianu, 1985). When compared with other rivers originating from Western Ghats, Chaliyar River has high R_b values. R_b of Achenkovil River ranges from 3.46 to 5.50 (Manu and Anirudhan, 2008) and that of the Muthirapuzha (a tributary of Periyar River) is 2.58 to 4.95 (Thomas et al, 2009). High values of bifurcation ratio can be found in drainage basins with young tectonic movements (Zuchiewicz, 1989).

Contrary to Horton's (1945) postulations of stream order, it has been found that bifurcation ratio varies widely from order to order in all the sub-basins of the study area. Guisti and Schneider (1965) suggested that bifurcation ratio within a basin decreases with increasing order, and that bifurcation ratio increases within the basin area initially and tend to become a constant. But in Chaliyar and its sub-basins, these concepts do not hold good. It is found that the correlation between the estimated number of stream segments as proposed by Horton's law for the sub-basins of Chaliyar River are 1590, 11625, 2834, 3469, 5604, 1775, 15530, 25630, 5102 respectively while the counted numbers are 497, 1274, 566, 369, 1928, 227, 1411, 1263, and 565 respectively. Estimated stream number for the whole of Chaliyar basin is 138182 while the counted number is 9417. Hence it can be concluded that Horton's law is not holding good for the sub-basins as well as for the Chaliyar River basin.

Hierarchical parameters of a drainage network can define the influence of tectonics on the drainage network. Hierarchical parameters computed for the sub-basins of Chaliyar River are hierarchical anomaly number and hierarchical anomaly index (Table 2.2). Higher values of these parameters indicate a poorly developed hierarchy and generally reflect active tectonics (Guarnieri et al., 2008).

Hierarchical index (Δ_a) is highly sensitive to the effects of active tectonics (Guarnieri et al., 2008). Hierarchical index (Δ_a) for sub-basin - 1 is 0.18; sub-basin – 2, Δ_a is 0.13; sub-basin - 3, Δ_a is 0.23; sub-basin - 4, Δ_a is 0.20; sub-basin - 5, Δ_a is 0.17; sub-basin - 6, Δ_a is 0.18; sub-basin - 7, Δ_a is 0.23; sub-basin - 8, Δ_a is 0.24 and sub-basin

- 9, Δ_a is 0.25 (Table 2.2). These high values indicate the influence of active tectonics on the drainage network organization.

Mean length (L_u)

Mean length of a stream-channel segment of order U is a dimensional property revealing the characteristic size of components of a drainage network and its contributing basin surface. Horton (1945) postulated that the length ratio R_L (ratio of mean length L_u of segments of order U to mean length of segments of the next lower order L_u-1) tends to be constant throughout the successive orders of a watershed. Stream lengths are decreasing with increasing order of stream in most cases but vary in the case of a few sub-basins (sub-basins - 3, 5, 7 and 8) (Table 2.1). The regression of logarithm of stream length versus the stream order is indicative of linear relationship; but with slight deviation (Fig. 2.3). Deviation in linearity in length of 5^{th} order stream is linked to the rejuvenation of drainage and tectonic upliftment. Mean stream length of a given order is generally greater than that of the lower order and any deviation in it may be due to variation in the slope and topography which again reflects on the tectonic activity. For sub-basins - 4, 5, 7 and 8, mean length of fourth order streams is greater than that of 5^{th} order streams which clearly indicate change in stream gradient due to tectonic upliftment.

Length of Overland Flow (L_f)

Surface runoff follows a system of down slope flow from the drainage divide (basin perimeter) to the nearest channel. Length of overland flow is one of the most important independent variables affecting both hydrologic and physiographic development of drainage basins and gives the sheet flow of water before it reaches a channel. It affects the quantity of water required to exceed a threshold of erosion. The length of overland flow of sub-basins of Chaliyar basin ranges from 0.13 to 0.3 (Table 2.1), indicating that the sheet flow is less and the lower order channels are well developed. Thus on an average, 100 sq. km of drainage area is sufficient to produce and maintain 265 km of channel (Fig. 2.4).

Sinuosity index (S_i)

Experimental studies as well as field observations (Schumm, 1981 and 1993) have demonstrated that much of the sinuosity variability of alluvial rivers reflects the variability of the valley slope. Thus, changes of valley-floor slope provide an

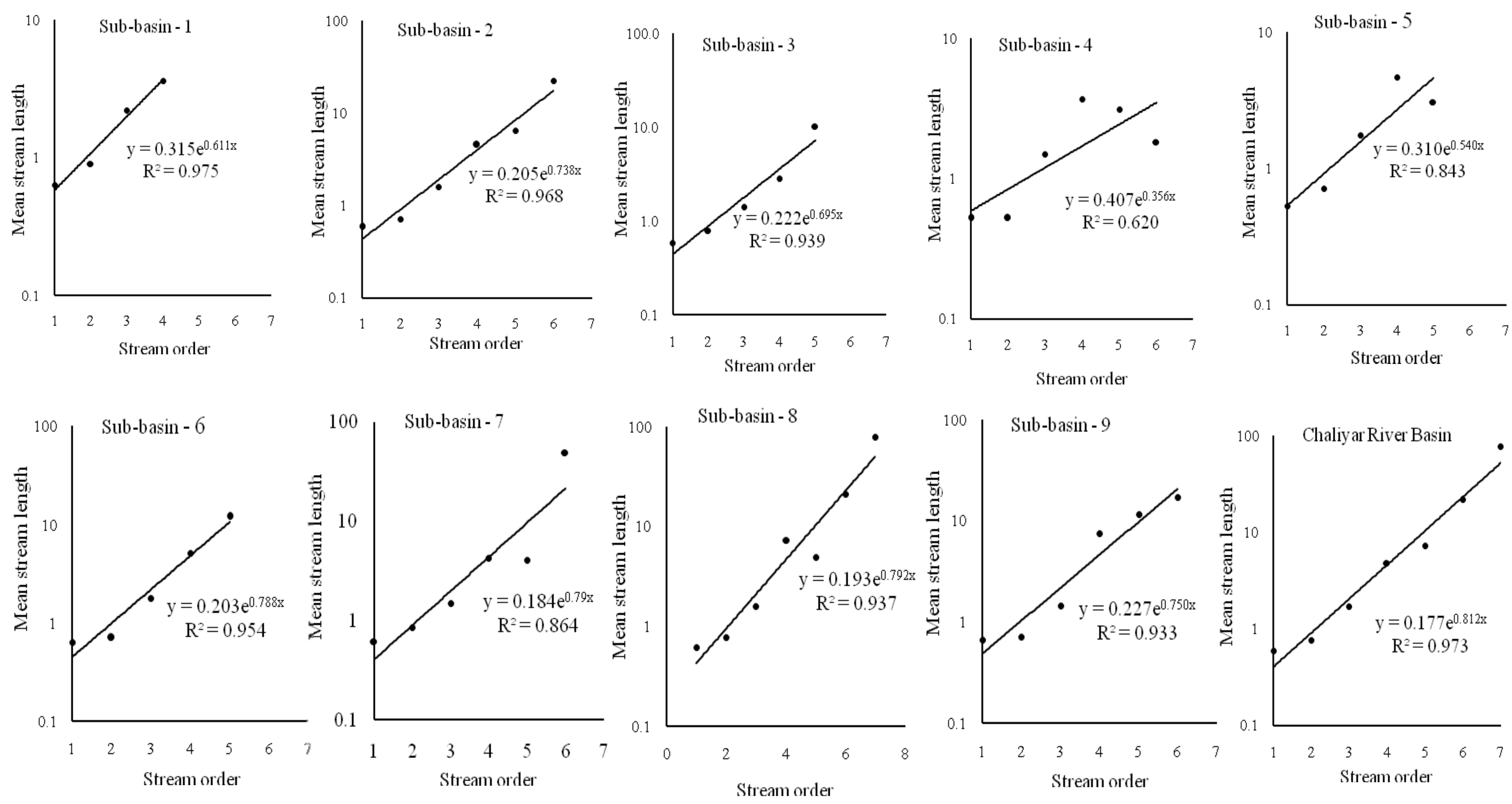


Fig. 2.3 Semi-logarithmic plots of the mean stream length against stream orders for nine sub-basins and Chaliyar River basin. Linear regression coefficient values are indicated.

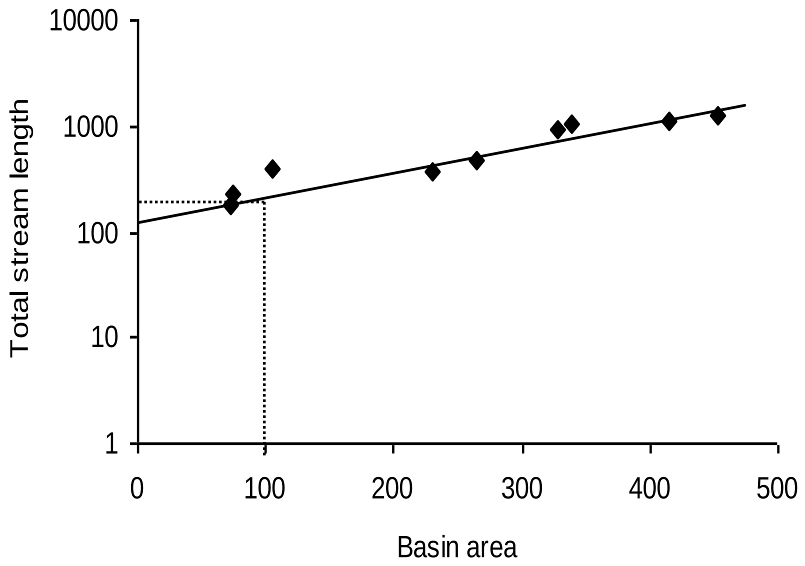


Fig. 2.4 Semi logarithmic plot showing the relationship between the basin area and total stream length of 9 sub-basins of the Chaliyar River.

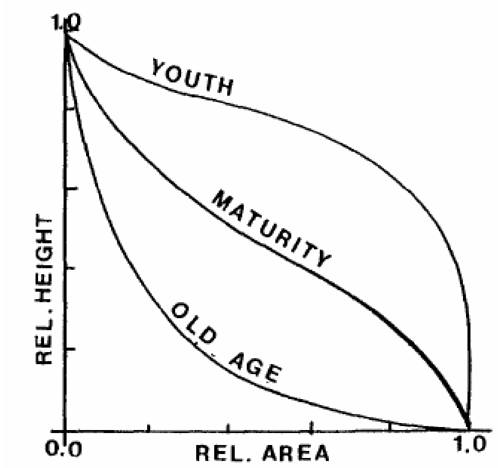


Fig. 2.5 Schematic hypsometric curves, indicating the relative area above certain relative elevation for landscapes in the stage of youth, maturity and old age (after Strahler, 1957; Scheidegger, 1988).

explanation of downstream changes of sinuosity. Tectonic activity can be one of the forces controlling the changes of valley floor slope, together with local changes of sediment and water supply due to river junctions or changes in lithology (e.g. Schumm, 1986).

The sub-basins of Chaliyar River have sinuosity ratio varying from 1.19 to 1.68 (Table 2.1). All the sub-basins except sub-basin - 3, are sinuous. Sub-basin - 3 is meandering (S_i=1.68). The total Chaliyar River basin, when considered as a single system shows sinuous nature (S_i=1.26).

Morphometry based on areal aspects

Areal aspects comprise basin area (A_u), stream frequency (F_u), circularity ratio (R_c), elongation ratio (R_l), form factor (R_f), compactness factor (R_{cf}), constant of channel maintenance and drainage density (D_d), and are given in Table 2.3.

Basin Area (A_u)

The drainage basin area is one of the important parameters like that of the length of drainage basin. The shape of the basin will contribute to the speed with which the runoff reaches a river. A long and thin catchment will take longer time to drain than a circular catchment. The area of the sub-basins is 229.62, 327.85, 105.52, 74.33, 453.65, 72.56, 415.12, 338.43 and 203.67 km^2 respectively (Table 2.3). The total area of the Chaliyar River drainage basin is 2964.88 km^2. The largest sub-basin of Chaliyar River is sub-basin - 5 drained by Chaliyarpuzha and the smallest is sub-basin - 6 drained by Karakodupuzha. The sub-basins of Chaliyar can be considered as elongated basins with average basin size.

Drainage Density (D_d)

Factors affecting drainage density are the erodibility of the rock and climate. The drainage density is low in semi-arid and arid climate but comparatively high in humid terrain (Gardiner, 1980). In general, low drainage density is favoured in regions

Table 2.3 Areal morphometric aspects of nine sub-basins of Chaliyar River and its total drainage basin of Chaliyar River (**C**: total drainage basin).

Sub-basin	Basin Area (A_u) (sq. km)	Length of the basin (L) (km)	Basin perimeter (P) (km)	Circularity ratio (R_c)	Elongation ratio (R_e)	Form factor (F_f)	Compactness factor (R_{cf})	Drainage density (D_d)	Constant of channel maintenance	Stream frequency (F_u)
1	229.62	33.54	100.86	0.28	0.51	0.20	1.88	1.67	0.60	2.17
2	327.85	30.32	100.84	0.41	0.67	0.36	1.57	2.80	0.37	3.89
3	105.52	18.98	56.28	0.42	0.61	0.29	1.55	3.80	0.26	5.36
4	74.33	16.16	45.28	0.46	0.60	0.29	1.48	3.14	0.32	4.96
5	453.65	35.45	127.01	0.35	0.68	0.36	1.68	2.80	0.36	4.25
6	72.56	16.61	47.98	0.40	0.58	0.26	1.59	2.50	0.40	3.13
7	415.12	37.11	116.72	0.38	0.62	0.30	1.62	2.63	0.38	3.39
8	338.43	37.09	115.44	0.32	0.56	0.25	1.77	3.03	0.33	3.73
9	263.67	29.30	97.47	0.35	0.63	0.31	1.69	2.80	0.36	2.14
C	**2964.88**	**87.09**	**353.04**	0.32	0.56	0.39	1.83	2.39	0.42	3.18

Table 2.4 Relief morphometric aspects of all nine sub-basins of Chaliyar River and total drainage basin of Chaliyar River (C: total drainage basin).

Sub-basin	Basin relief (R_h) (m)	Relief ratio (R_r)	Ruggedness number (R_n)	Stream gradient (S) (m/km)	Sinuosity index (S_i)
1	1480	0.04	2.45	44	1.46
2	2280	0.08	6.39	75	1.49
3	2280	0.13	8.67	120	1.68
4	2080	0.13	6.54	129	1.19
5	2080	0.06	5.82	59	1.37
6	1080	0.07	2.70	65	1.20
7	2480	0.07	6.52	67	1.53
8	2580	0.07	7.82	70	1.22
9	2380	0.09	6.67	81	1.42
C	2693	0.04	6.44		

Table 2.5 Mean, minimum and maximum elevations and the computed hypsometric integral of nine sub-basins. C represents the total drainage basin.

Sub-basin	Mean elevation (m)	Minimum Elevation (m)	Maximum Elevation (m)	Hypsometric integral
1	752.50	20	1620	0.46
2	1099.13	20	2160	0.50
3	1100.00	40	2160	0.50
4	1048.18	40	2020	0.51
5	1099.13	40	2140	0.50
6	601.54	40	1200	0.48
7	1250.77	40	2500	0.49
8	1298.52	40	2520	0.51
9	1203.20	40	2440	0.48
C	1300.74	20	2609	0.50

of highly resistant or highly permeable subsoil materials, under dense vegetation cover, and where relief is low.

Greater the drainage density and stream frequency in a basin, the runoff is faster and flooding is likely to be more (Kale and Gupta, 2001). Drainage density varies from 1.66 to 3.8 (Table 2.3), indicating high precipitation, low surface runoff and low incidence of flooding. The drainage density has its highest value for the sub-basins – 3 (3.80), 4 (3.14) and 8 (3.03) which may be attributed by tectonism and high rate of precipitation. Drainage density less than 3.5 indicates a coarse texture (Strahler, 1957). Sub-basin - 3 drained by Kurumanpuzha is fine textured (D_d=3.80) while all other 8 sub-basins are coarse textured.

Stream Frequency (F_u)

Greater the stream frequency, runoff is faster and flooding is more likely to occur. For the sub-basins of Chaliyar River, frequency varies from 2.1 to 5.4 (Table 2.3) revealing the slow to medium runoff and absence of flooding. Highest value of stream frequency is observed for sub-basin -3 and lowest for sub-basin - 9. Stream frequency for Chaliyar River drainage basin as a whole is 3.18 (Table 2.3).

Circulatory Ratio (R_c)

A stable, circular and homogenous basin will have the circularity ratio 1 or very close to 1. As the value deviates from 1, irregularity of the basin increases. If the circularity ratio is between 0.40 and 0.50, the drainage basin can be considered as strongly elongated. According to Waugh (1995), circular basin is more likely to have a shorter lag time and a higher peak flow than an elongated basin. The flow of water in an elongated basin is distributed over a longer period than in a circular one (Mustafa and Yusuf, 1999). Circularity ratio of the sub-basins of Chaliyar River drainage basin ranges from 0.28 to 0.46 (Table 2.3), which points out that the basins are highly irregular and elongated with longer lag time and low peak flow. Highest circularity ratio is shown by the sub-basin - 4 and lowest value by sub-basin - 1. Chaliyar River drainage basin as a whole has its circularity ratio value, 0.32 showing the highly irregular and elongated nature and has a longer lag time and a very low peak flow as explained by Waugh (1995), and Mustafa and Yusuf (1999).

Elongation Ratio (R_e)

For regions of very low relief, the value of elongation ratio is found to be very close to 1 (Suresh, 2000). When the value gets deviated from 1, the area will have a strong relief and steep ground slope. Elongation ratio < 0.5 is observed in areas of low tectonic activity and when it is between 0.5 and 0.75, the area is moderately tectonic active. When elongation ratio value is > 0.75, the area is of strong tectonic activity (Kryzsowski et al., 1995; Ramirez-Herrera, 1998). The sub-basins of Chaliyar show elongation ratio ranging between 0.5 and 0.68 (Table 2.3), which indicate that all the sub-basins are having a very strong relief and steep slopes and are moderately tectonic active. The highest elongation ratio is exhibited by sub-basin - 5 (0.68) and lowest by sub-basin - 1 (0.5). Chaliyar River drainage basin as a whole has its elongation ratio, 0.56 (Table 2.3). This indicates the high relief and steep slopes in the basin attributed by moderate active tectonism.

Form Factor (R_f)

Low form factor is indicated by basins which are elongated and narrow and high form factor indicates that the basin is broad and wide (Gregory and Walling, 1985). Low form factor also indicates less rainfall simultaneously over its entire area than an area of equal dimension but with a larger form factor (Gupta, 1999). Form factor values for the sub-basins of Chaliyar ranges from 0.2 to 0.36 revealing that the basins are very narrow and elongated (Table 2.3). The highest value of form factor is shown by the sub-basin - 2 and 5 and lowest value by sub-basin - 1. Chaliyar River drainage basin as a whole has a form factor value of 0.39. This low value indicates the elongated and narrow nature of the basin.

Compactness factor (R_{cf})

It is used to express the basin shape, as a factor of deviation of the basin area from a circle having the same area of the drainage basin. Compactness factor for the sub-basins of Chaliyar varies from 1.48 to 1.88, which indicates the elongated shape of the sub-basins (Table. 2.3). Compactness factor is highest for sub-basin - 1 and lowest for sub-basin - 4. Compactness factor for Chaliyar River drainage basin is 1.83. Higher compactness factor indicates that the basin is elongated.

Relatively young basins in active tectonic areas tend to be elongated in shape normal to the topographic slope of mountain (Khavari et al., 2009) with continued evolution or less active tectonic processes, the elongated shape tends to evolve to a more circular shape (Bull and McFadden, 1977). Rapidly uplifting mountain fronts generally produce elongated steep basins; and when tectonic activity is diminished or ceased, widening of the basins occurs from the mountain front up (Ramirez-Herrera, 1998). Elongated shape of the basins also indicate a young stage of evolution, caused by intense tectonic activity (Lykoudi and Angelaki, 2004)

Areal aspects computed for the sub-basins show that sub-basin – 1 drained by Cherupuzha is the most elongated and narrow sub-basin while sub-basins – 4 and 5 drained by Kanjirapuzha and Chaliyarpuzha respectively are elongated but not as elongated as other sub-basins of Chaliyar River. Chaliyar River drainage basin a whole can be considered as an elongated basin with steep slopes and sharp gradients.

Morphometry based on relief parameters

Relief aspects computed in the present study are basin relief (R_h), relief ratio (R_r), ruggedness number (R_n), channel gradient (S), sinuosity index(S_i) and hypsometric integral (H_i) (Table 2.4).

Basin relief (R_h)

Basin relief ranges from 1080 to 2580 m for the sub-basins. Highest basin relief (2580 m) is for sub-basin – 8 drained by Karimpuzha and lowest (1080 m) for sub-basin – 6, drained by Karakodupuzha. Basin relief of Chaliyar River drainage basin is 2693 m (Table. 2.4). The high R_h values are attributed by the palaeo- and neotectonic regimen of the Western Ghats. With increasing basin relief, steeper hill slopes and higher stream gradients, time of concentration of runoff decreases thereby increasing flood peaks.

Relief Ratio (R_r)

It measures overall steepness of a drainage basin and is an indicator of the intensity of an erosion process. The possibility of a close correlation between relief ratio and hydrologic characteristics of a basin could find that sediment load per unit area is closely correlated with relief ratio (Schumm, 1956). Relief ratio of sub-basins of Chaliyar River ranges from 0.04 to 0.13 (Table 2.4). All the sub-basins other than 3 and 4 have a relief ratio < 0.10 indicating the exposure of basement rocks as small ridges and mounds with lower slope values, while sub-basins - 3 and 4 have values > 0.10. This suggests that the area is marked by steeper slope and high relief, underlain by resistant rocks (Vittala et al., 2004)

Ruggedness number (R_n)

Ruggedness number summarizes the interaction of relief and dissection such that highly dissected basins with low relief areas as rugged and moderately dissected basins with high relief as rolled basin. Extensively high ruggedness number occurs for a high relief region with high stream density (Melton, 1965). Ruggedness number of sub-basins of Chaliyar River varies from 2.45 to 8.67 and for Chaliyar River drainage basin R_n is 6.44 (Table 2.4). Highest ruggedness number is exhibited by sub-basin – 3 and lowest value by sub-basin - 1. Chaliyar River drainage basin has ruggedness number 6.44. This high value reflects the moderate to high relief of the basin and highly dissected nature and structural complexity. Sub-basins 2, 3, 4, 5, 7, 8 and 9 have a high ruggedness number indicating that these basins are highly dissected basins with moderate to high relief and intrinsic structural complexity.

Stream gradient

A stream that flows upon a uniformly erodible substrate will tend to have a steep gradient near its source, and a low gradient nearing zero as it reaches its base level. Of course, a uniform substrate would be rare in nature; hard layers of rock along the way may establish a temporary base level, followed by a high gradient, or even a waterfall, as softer materials are encountered below the hard layer.

Stream gradient of sub-basins of Chaliyar River varies from 44 to 129 m/km (Table 2.4). Sub-basins 2, 3, 4, 6, 8 and 9 have higher stream gradient and shows the mountainous nature of the sub-basins. High stream gradient also indicates steep slope and rapid flow of water and tends to have steep narrow V-shaped valleys. Highest value of stream gradient is exhibited by the sub-basin - 4 drained by Kanjirapuzha and lowest value of stream gradient is shown by the sub-basin - 1 drained by Cherupuzha. Low stream gradient of sub-basins 1, 5 and 7 reflects on the flow the stream through plateau area. It also indicates more nearly level stream bed with wider and less rugged valleys and the streams will have a tendency to meander.

2.3.2 Hypsometry

Hypsometry has been historically used as an indicator of geomorphic forms of catchments and landforms. Hypsometry reflects landscape runoff and erosional process but also is strongly dependent on channel network and catchment geometry. Width to length ratio of a drainage basin has a significant influence on the shape of the hypsometric curve, though little on the hypsometric integral. Hypsometric curve, a graphical representation of the area - elevation distribution in a basin, quantitatively describes geomorphic characteristics that have been shown to affect runoff. These characteristics include area, mean elevation above the basin outlet, slope, stream density, length of the longest water course, distance to centre of basin and relief ratio. It also provides a way to determine unique attributes of basin morphometry. Hypsometric skewness can indicate the shift in the location and the offsetting tail can reveal the amount of headward stream erosion on a basin. Positive skewness indicates the accelerated form of erosion in the basin's upper reaches (Harlin, 1984). Hypsometric integral is a numerical method to describe the overall shape of the longitudinal profile of a stream (Rhea, 1993) and reflects the relative amount of deformation and/or degradation that have occurred on each river.

Strahler's (1952) theoretical evolution of landscape distinguishes between three main stages: a youthful non-equilibrium stage where H_i = 0.6 to 1.0, a mature equilibrium stage where H_i = 0.35 to 0.6 and an old age with H_i = 0.0 to 0.35. This was later counter argued by Ohmori (1993) and showed that in areas with concurrent tectonics and denudation, the results of hypsometric integral are reverse of Strahler's theory. When a particularly resistant geological outcrop maintains a portion of the summit plane during considerable erosion of the rest of the basin, hypsometric integral may reach low values. In uniformly erodible material and continued erosion of the basin high point may stabilize hypsometric integral in a middle range of values between 0.35 and 0.6. In a tectonically very active zone, hypsometric integral will be > 0.6 and when it is >0.5, the area is tectonically active (Huertrez et al., 1999; Chen et al., 2003). If part of the hypsometric curve is convex in the lower portion, it may relate to uplift along a fault or perhaps uplift associated with recent folding (El Hamdouni et al., 2007). High values of hypsometric integral are possibly related to young active tectonics and low values related to older landscapes that have been eroded and less impacted by recent active tectonics (El Hamdouni et al., 2007).

Hypsometric integral for the sub-basins of Chaliyar River ranges from 0.46 to 0.51 showing that the streams are in matured equilibrium stage as by the concept of Strahler (1952). It also shows that the sub-basins of Chaliyar River are tectonically active as suggested by Huertrez et al. (1999), and Chen et al. (2003). Highest value of hypsometric integral is shown by the sub-basins 4 and 8 while sub-basin – 1 has the lowest value. Chaliyar River drainage basin has hypsometric integral value of 0.50 reflecting the tectonically active nature of the drainage basin as suggested by El Hamdouni et al, 2007 in the SW border of the Sierra Nevada.

Comparisons of the shape of hypsometric curve for different basins under similar climatic conditions and approximately equal area of the basins also provide relative insight into the past movement in the basins. Scheidegger (2004) suggested three stages - youth, mature and old stages of landscape evolution (Fig. 2.5). The shape of the hypsometric curve explains whether alteration in slope has taken place in comparison to the original basin (Singh et al., 2008). Fig. 2.6 shows the hypsometric curve for the nine sub-basins of Chaliyar River and suggests that the rivers are at the old age (concave shape) and also indicates greater importance of erosion as explained by Huertrez et al. (1999). Variation in the computed hypsometric integral and the curve can be attributed to the concurrent tectonism, and thus follows Ohmori's (1993) concept of hypsometry. The convexity in the lower portion of the hypsometric curve in the sub-basins may be due to uplift along fault zones as suggested by El Hamdouni et al., 2007.

2.4 Summary

Morphometric analysis of Chaliyar River drainage basin represents an interim phase during the quantification of morphology and tectonics and gives the topographic expression of the basin. Spatial analysis of the morphometric parameters has provided valuable information regarding the structure and tectonics of Chaliyar River drainage basin. Many of the morphometric characteristics seem to be relatively independent from the lithology.

The sub-basins of Chaliyar River drainage basin have moderate to high stream discharge and channel dimension as inferred from linear and areal aspects. Highly dissected nature, high relief and steep slopes of the sub-basins reflect the tectonically active nature of the upland zone. The higher bifurcation ratios and low form factors suggest the geological control of later tectonic activities on drainage organization. Drainage density and stream frequency also indicate high precipitation, low run off and low incidence of flooding. The poor correlation of bifurcation ratio with drainage density, stream frequency and basin length clearly indicates the axiom that stream organization depends on various factors like lithology, structure, climate

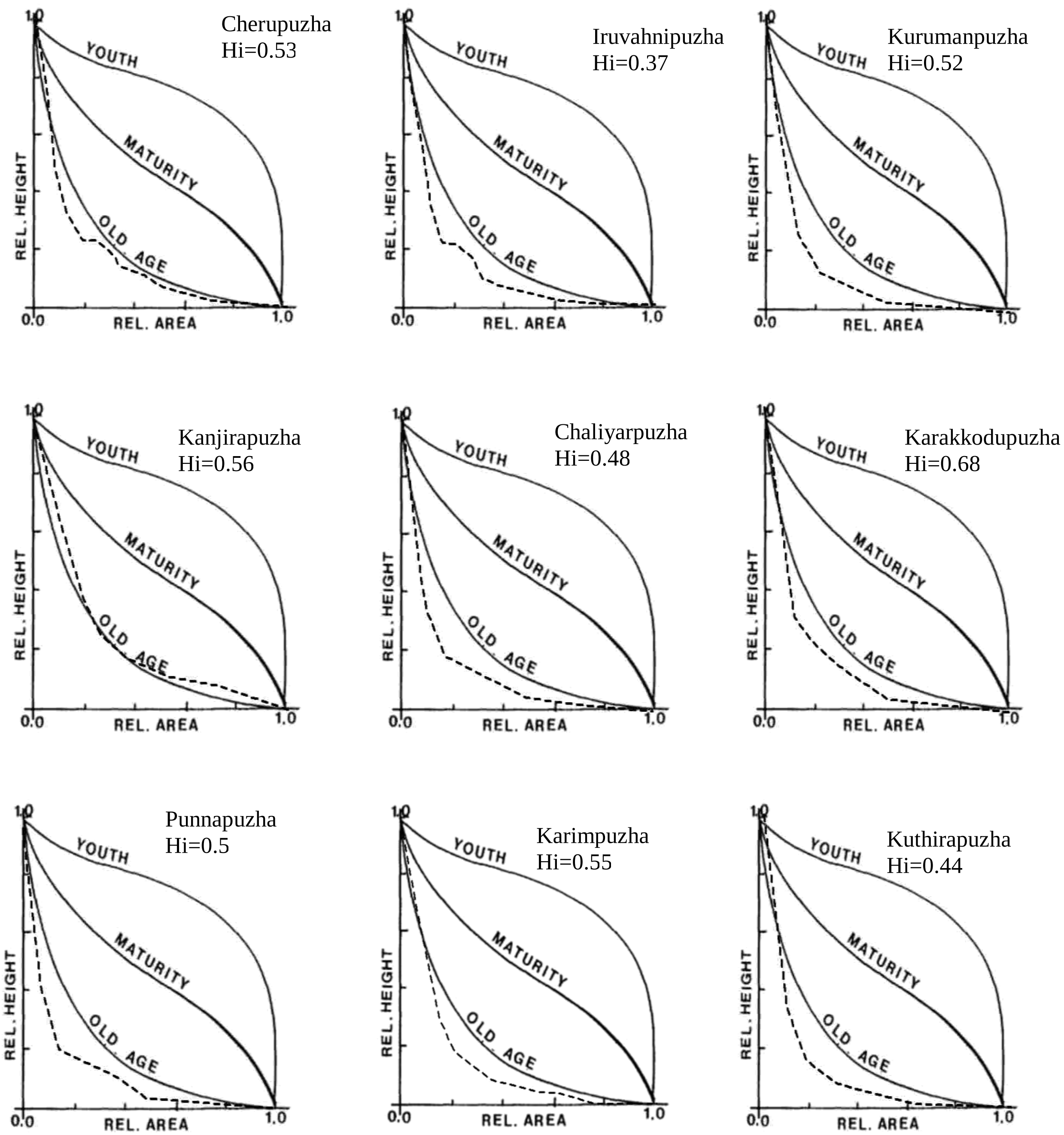


Fig. 2.6 Hypsometric curves for nine sub-basins of the Chaliyar River (after Strahler, 1957; Scheidegger, 1988. (a) Sub-basin - 1 (Cherupuzha); (b) sub-basin - 2 (Iruvahnipuzha); (c) sub-basin - 3 (Kurumanpuzha); (d) sub-basin - 4 (Kanjirapuzha); (e) sub-basin - 5 (Chaliyarpuzha); (f) sub-basin - 6 (Karakodupuzha); (g) sub-basin - 7 (Punnapuzha); (h) sub-basin - 8 (Karimpuzha); (i) sub-basin - 9 (Kuthirapuzha). Hi is the hypsometric integral computed and broken line indicates the hypsometric curve.

and vegetation as explained by Thomas et al., 2009. Elongated nature of the sub-basins are well established from the computed values of compactness factor, form factor, elongation ratio and circularity index. The average size, irregular and elongated sub-basins usually have longer lag time and low peak flow thus impedes flooding. The elongated nature of the sub-basins is mainly due to the gliding effect of thrusting and faulting; and erosional processes have been influenced by sub-surface lithology. Well-developed lower order streams may have reduced the sheet flow and about 100 km^2 drainage areas is sufficient to maintain 265 km of channel. Mean length of lower order streams is higher than that of its next higher order for sub-basins 4, 5, 7 and 8 indicating change in slope due to tectonic upliftment. Hierarchical classification of the sub-basins also point towards the influence of active tectonism in the drainage network organization.

All the tributaries of Chaliyar River other than Kurumanpuzha can be categorized as sinuous streams. Kurumanpuzha has been classified as meandering stream. Sinuosity of the stream increases when the stream tries to maintain constant gradient as the streams get steepened by lateral tilting of the basin.

The relief parameters indicate that upper reaches of Chaliyar River drainage basin is structurally complex with mountain landscape which have influenced the development of stream segments. Areas of high uplift show high values of basin relief, relief ratio and basin ruggedness (Pazzaglia, 1998). This once again affirms to the inference that the drainage pattern is controlled by relief, lithology and tectonics.

Chapter III

DRAINAGE CHARACTERISTICS AND LANDFORMS

3.1 Introduction

Drainage basin forms natural geomorphic unit and frequently display organized relation between constituent parameters of landform and drainage. Drainage characteristics and landforms constitute the backbone of fluvial geomorphology.

Fluvial geomorphology has gained importance during the last two decades (Vaidyanadhan, 1967, 1977; Kale et al., 1994; Sinha and Friend, 1994; Sinha and Jain, 1998; Kale, 1999, 2002; Dettinger and Diaz, 2000; Gupta, 2002; Thorne, 2002, Valdiya and Narayana, 2007), as it helps to understand the relationship of processes and evolution of landforms, which in turn helps for interpreting ancient fluvial sequences. The role of geomorphology is significant in the classification and evolution of various landforms developed in a river basin. The understanding of geomorphology of a terrain is important to study the process response models under different environmental stress and the strength of geomorphology is to provide framework for understanding current and historical behavior (Radhakrishnan, 2008). A basic principle of geomorphology is that, the geomorphic units can be expected to reflect the underlying lithology and the geological processes that have been at work (Reis et al., 2007). Establishing the link between landform and process remains a primary goal of geomorphology (Sugden et al., 1997). Geomorphology plays an important role in multidisciplinary research of river systems and to understand the process-form relationship and to account for the fluvial dynamics (Sinha et al., 2005).

Fluvial geomorphology examines the processes that operate in river systems and the landforms which they ultimately create, or have created (Miller and Gupta, 1999). Various geomorphic parameters like slope, river discharge and sediment load are responsible for the typical fluviatile characteristic of a river. Alluvial river systems respond primarily to changes in sediment and water supply, which are controlled by a number of key factors. Major extrinsic controls on river behaviour in a given geological setting are tectonism, landuse and climate change (Cheetham et al., 2008). Fluvial systems readily respond to rainfall and base-level changes, which can be triggered by both climatic and tectonic processes. Rivers play an important role in the evolution of a landscape and can give us valuable information with respect to erosion rates and tectonic movements. Since rivers respond rapidly to tectonic changes they are a prospective instrument to modern geomorphology (Wobus et al., 2006; Gloaguen, 2008).

River system that originates from the Western Ghat is an excellent domain for studying the processes of landscape evolution and its relationship with geology, geomorphology and climate.

This chapter reviews geomorphological channel classifications and their use for systematizing channel morphology and physical processes for the purpose of assessing channel condition and response potential based on the key to the Rosgen's classification of natural rivers as a function of continuum of physical variables. There are several tectonic landforms; such as off-set streams, shutter ridges, vine glass valleys and triangular facets, which are important for investigations of tectonic geomorphology (Kaewmuangmoon et al., 2008).

3.2 Methodology

Aerial photographs, Survey of India toposheets and satellite imageries are some of the important tools that have been used in the present study. Remote sensing is an important tool for understanding the dynamics of earth surface processes and in regional geomorphological mapping (Hayden, 1986). It offers an efficient, faster and low cost technique to supplement the preliminary geological and geomorphological investigations (Reis et al., 2007). The landforms of both primary and secondary nature are delineated using remote sensing techniques.

3.2.1 Materials and Data used

Toposheets

Survey of India toposheets (SOI) of 1:50,000 scale are used for terrain analysis and delineation of the drainage basin boundary. The SOI toposheets used are 58A/2, A/3, A/4, A/6, A/7, A/8, and A/11, 49M /15 and M/16.

Aerial photographs

Aerial photographs of 1:63,360 scale are used to study the geomorphic features and lineaments of the study area. Aerial photographs with flight number 570-A acquired in 1969 with different run numbers are used. Mosaic of the photographs was prepared and with the help of stereoscope the photographs were viewed to get the three-dimensional picture of the area. Different geomorphic features were delineated from this mosaic and were transferred to tracing sheet and digitized using ArcGIS 9.

Satellite imagery

Satellite images of IRS 1C LISS III FCC (bands 2, 3 and 4) acquired on 8th February 2005 are procured from National Remote Sensing Centre (NRSC), Hyderabad and was geo-coded using Survey of India toposheets on 1:50,000 scale (58A/2, A/3, A/4, A/6, A/7, A/8, and A/11, 49M /15 and M/16). Inherent elements within an image that can provide clues towards the details, identification and measurement of various features include tone, texture, shape, location and associated features. Enhancement of the satellite data using radiometric and spectral enhancement was accomplished with Erdas Imagine software. Delineated geomorphic features were then digitized and transferred to ArcGIS platform.

SRTM data

Shuttle Radar Topography Mission (SRTM) digital elevation data of 90 m resolution was downloaded from the CGIAR Consortium for Spatial Information site (http;//srtm.csi.cgiar.org) and digital elevation models and aspect map are prepared using GRASS (free and open source software).

3.2.2 Drainage analysis

Morphological analysis of landscape elements in the process of basin evolution by means of remote sensing observations are carried out in the present study. Satellite imagery, aerial photograph, topographic maps are used as first and generally non-exclusive tools for geomorphic interpretation, and corroborated with field observations. Drainage network is digitally traced on 1:50,000 scale using ArcGIS 9. Different drainage patterns observed in the basin are studied and classified (Fig. 3.4).

3.2.3 Stream classification

The objective of classifying streams on the basis of channel morphology is to set categories of discrete stream types so that consistent, reproducible descriptions and assessments of condition and potential can be inferred (Rosgen, 1996). The stream classification method devised by David Rosgen is a comprehensive guide to river and stream classification (Rosgen, 1994, 1996). Channel classifications use similarities of form and function to impose order on a continuum of natural stream types or morphologies. No single classification can satisfy all possible purposes or is likely to encompass all possible channel types. Several stream classifications based on geometrical features and phenomena are proposed (Davis, 1899; Rust, 1978; Kellerhals et al., 1976; Chalov, 1986, 1996; Church, 1992; Rosgen, 1999. Davis (1899) classified streams in terms of age (youthful, mature and old age) and this is the first recognized classification. Rust (1978) classified streams based on sinuosity and braiding. Kellarhals et al. (1976) classified streams based on planform, islands, channel bars and lateral channel activity. Chalov (1986, 1996) proposed a classification where incised rivers are treated separately. Church (1992) derived a conceptual river planform classification based on channel stability, stream gradient and sediment supply. Here in this study stream classification system proposed by Rosgen (1994) is mainly followed. In addition, source area classification proposed by Sinha and Friend (1994) is also attempted.

Rosgen classification

The Rosgen stream classification system categorizes streams based on channel morphology. The basic tenet of this classification approach is that the natural stream stability is achieved by allowing the river to develop a stable dimension, pattern, and profile such that, over time, channel features are maintained and the stream system neither aggrades nor degrades. The purpose of this classification is to predict river behavior from morphological description. The parameters considered in the classification are valley slope, sinuosity, width to depth ratio, median size of the bed material and entrenchment ratio.

Rosgen stream classification consists of four hierarchical levels. Level I, a geomorphic characterization, categorizes streams as “A, B, C, D, DA, E, F and G”. Level II gives the morphological description and requires field measurement. Based on the stream bed material, streams are assigned a number from 1 to 6 in level III, and level IV verifies predictions made by level III and consists of sediment transport, stream flow and stability measurements.

Each reach was classified according to the Rosgen classification system and used this classification to explain the local and regional drainage relationships. Based on this classification the four hierarchical levels (Ward, 2008) derived are:

(i) Level I: Geomorphic characterization that integrates topography, landform, and valley morphology. At a broad scale the dimension, pattern, and profile are used to delineate stream types.

(ii) Level II: Morphological descriptions based on field-determined reference reach information.

(iii) Level III: Stream “state” or condition as it relates to its stability, response potential, and function.

(iv) Level IV: Validation of the measurements.

Based on these levels the streams are classified (Rosgen 1994) as:

a) Type A streams are typically steep, entrenched, and confined channels. They can be thought of as “mountain streams”. Type A streams have a step-pool or cascading bed form with boulder, bedrock, cobble and, to some extent, gravel-bed channels.

b) Type B streams are typically moderately entrenched and less steep than Type A streams. The channel bed consists of a series of rapids and cascades with irregular scour pools.

c) Type C streams are slightly entrenched, meandering systems characterized by well-developed floodplains. They have a riffle-pool bed form and are typically wider than they are deep.

d) Type D streams are multiple-channel, or braided, systems that typically do not have a boulder or bedrock channel bed. Braided channels can occur across a wide range of morphological and topographic conditions.

e) Type E streams have a low width-to-depth ratio and exhibit a wide range of sinuosity and are found in a variety of landforms.

f) Type F streams are meandering, entrenched, and highly incised systems in low gradient landforms. In these systems, top-of-bank elevation is much higher than bankfull elevation.

g) Type G streams are deeply entrenched systems similar to Type A streams, except that they occur at bed slopes of 2 to 4 percent. Boulder and bedrock systems are usually stable. Cobble, gravel, and sand-bed G channels are unstable, often deeply incised, have high bank erosion rates, and are often a failed or failing Type B or E channel.

The criteria and measurements used to classify the stream based on Rosgen (1994) classification of natural rivers as a function of continuum of physical variables are single or braided channel determination, entrenchment ratio, width to depth ratio, sinuosity, water surface slope, median size of the bed material (Fig. 3.1).

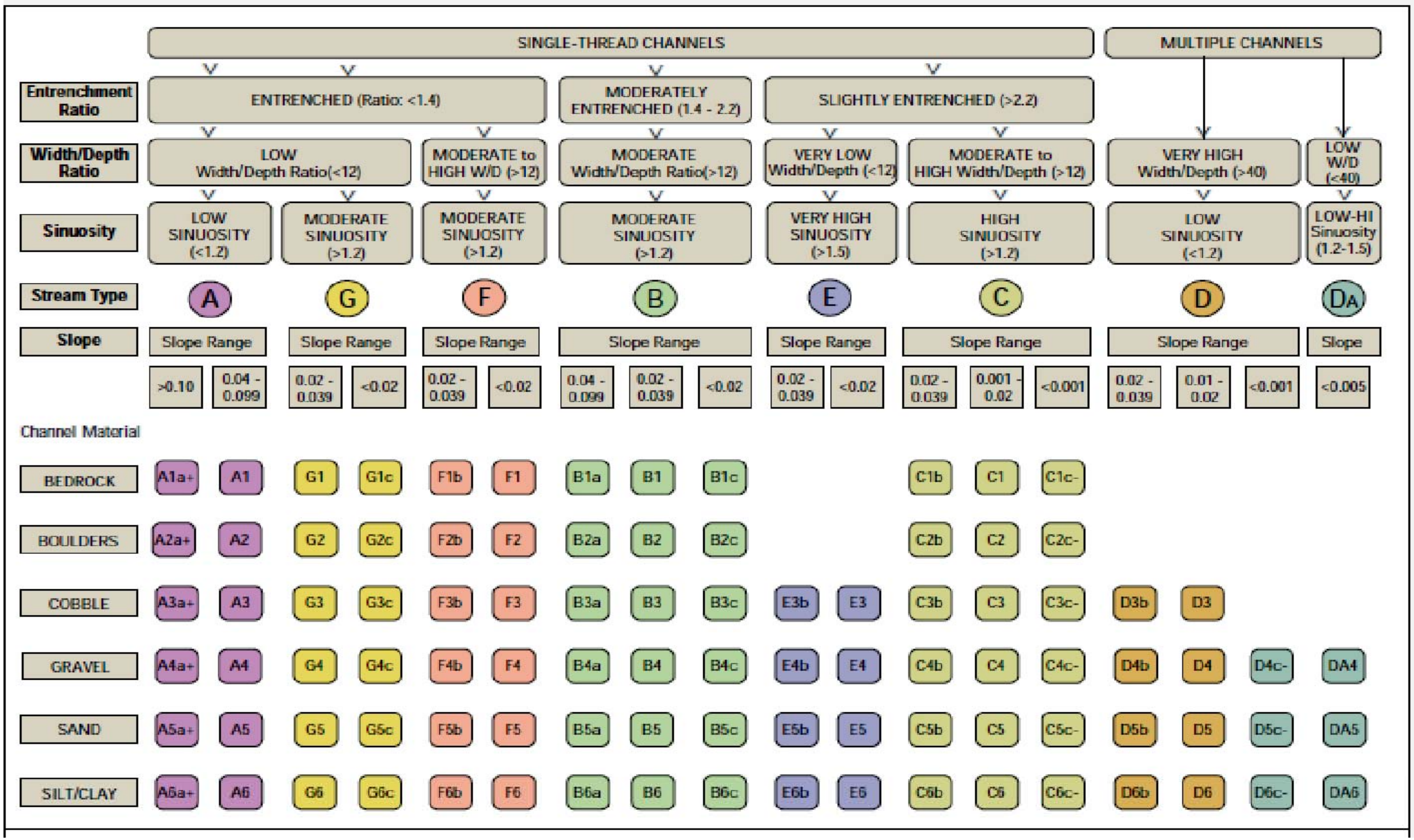


Fig. 3.1 Key to the Rosgen classification of natural rivers as a function of continuum of physical variables within the stream reaches (Rosgen, 1999).

Valley Slope

To measure valley slope, the river centre-line was divided into 10 km segments in downstream order. Using Shuttle Radar Topography Mission (SRTM) elevation data, the average elevation for each segment was calculated for all cells in a 10 m radius. The measured valley slopes are used as variables in geomorphic process reach classification.

Sinuosity

Sinuosity is computed from the stream length and valley length measured using ArcGIS 9. For this, the river centre-line was divided into five kilometer segments. Sinuosity values for each five kilometer segment in the downstream direction are calculated as given in the equation.

$$\text{Sinuosity} = \frac{\text{Stream Length}}{\text{Valley Length}} = \frac{\text{Valley Slope}}{\text{Channel Surface Slope}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

Sinuosity is classified based on the sinuosity categories for segments of river centre line (Modified after Brice, 1982) and the results are presented in Table. 3.1.

Entrenchment ratio

Some channels cut deeply into their floodplains, leaving steep banks on either side. Other channels pass gradually to their adjacent floodplains. This is measured as entrenchment ratio (Rosgen, 1994). This is determined by field measurements and expressed by the equation

$$\text{Entrenchment Ratio} = \frac{\text{Flood prone Area Width}}{\text{Bankfull Width}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(ii)}$$

Flood prone 'Area Width' is the width at twice the maximum bankfull depth.

Median size of stream bed material

This assesses the sort of material over which the water flows and is determined by field observation. The sorts of material include bedrock, boulders, cobbles, gravel, sand, and mud (i.e., silt & clay).

Width/depth ratio

Some channels are wide and shallow while others are deep and narrow. Width to depth ratio assesses the width and depth and is expressed by the equation

$$\text{Width/Depth Ratio} = \frac{\text{Bankfull Surface Width}}{\text{Bankfull Mean Depth}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iii)}$$

Bankfull Mean Depth determined from 20 equally spaced depth readings are taken from the bankfull stage to the stream bottom.

Source area classification

Source area classification of streams (Sinha and Friend, 1994) is carried out using Openjump software, by superimposing the drainage map over the aspect and Digital Elevation Model (DEM) map of the basin and differentiating the rivers that are originating from different sources such as mountain-fed, foothill-fed, plain-fed and mixed-fed.

3.2.4 Delineation of landforms

Landforms observed in the basin are delineated from the aerial photographs, satellite imagery and toposheets. Different enhancement techniques like spectral (principal component, decorrelation stretch and tassled cap) and radiometric enhancements (brightness inversion and decorrelation stretch) were applied to the geocoded LISS III imagery for extracting different landforms. These data are combined to a single platform using ArcGis software supplemented by extensive field work. Landforms of the study area thus delineated are presented in Fig. 3.10.

3.3 Results and Discussion

3.3.1 Drainage network

Rivers are responsible for sculpting uplifted terrain into arborescent valley networks and creating the relief. Rivers erode their valleys and in the process provide a system of drainage that is delicately balanced with the climate, topography, lithology and soil characteristics. Drainage basins are durable geomorphic features and provide insight to the long-term evolution of the landscape (Gelabert, 2005). Basin geometry develops in response to the nature and distribution of uplift and subsidence, the spatial arrangement of faults and joints, the relative resistance of different rock types and to climatically influenced hydrologic parameters (Burbank and Anderson, 2001). Structural controls on drainage development have been widely documented (Ollier, 1981 and Summerfield, 1991. Rivers are sensitive to changes in tectonic deformation, adjusting over different periods of time depending on the climate, physical properties of the host rocks and tectonic activity (Gloaguen, 2008). The interaction between tectonics and longitudinal profile development has been discussed by many (Snow and

Slingerland, 1987; Ohmori, 1991; Scheidegger, 1991; Howard et al., 1994 and Hovius, 2000. The shape and structure of the drainage constitute a response to the uplift process, more or less modulated by lithological parameters (Jackson and Leeder, 1994).

Chaliyar River basin is one of the important drainage systems originating from Western Ghats with a broad valley in the central part (Fig. 3.2). The regional drainage network consists of W, SW, SE and S flowing streams. It has numerous tributaries and the most important among them are Punnapuzha, Karimpuzha, Kurumanpuzha, Kuthirapuzha, Kanjirpuzha, Karakodupuzha Pandipuzha, Iruvanhipuzha and Cherupuzha etc. (Fig. 3.2). The Chaliyar River drainage basin is marked by geomorphological diversity manifested in terms of the morphological, hydrological and sediment transport characteristics. Most tributaries like Punnapuzha and Karimpuzha display braided as well as meandering morphologies as observed in Punnapuzha, Karimpuzha and Chaliyar River. Some of them show a systematic downstream change from braided to meandering as seen in Punnapuzha and Karimpuzha possibly due to downstream decrease in discharge and sediment supply.

Chaliyarpuzha, the main tributary of Chaliyar River flows southerly up to Nilambur and changes its course to southwest and finally in the western direction. Tributaries like Punnapuzha, Pandipuzha, Maradipuzha and Karakodupuzha flow in the south west direction and join the main stream at Nilambur (Fig. 3.2). Cherupuzha and Iruvahnipuzha flow SSW and join the trunk stream southerly with strong meandering at the confluences. Chaliyarpuzha follows an abrupt, rock-controlled straight line course, whereas Punnapuzha and Karimpuzha braids and meanders in the upper reaches. Most of the tributaries of Chaliyar River flow through a broad valley (Nilambur valley) with a comparatively narrow stream channel. Karakodupuzha, Punnapuzha and Karimpuzha flow through palaeo-alluvial fan deposit, hence can be called as inter-fan rivers with oscillatory shifting resulting in the formation of palaeochannels. The lower reaches of the Chaliyar River shows a sudden change in its course beyond 110 km from the source in the downstream direction. The channel takes a sharp bend at 110 km and from this location, the river exhibits meanders at consistent intervals. Two major tributaries join the right bank of the trunk stream beyond 110 km. Sudden change in the flow direction of the river courses in Chaliyar River drainage basin is structurally controlled and is attributed by active tectonism.

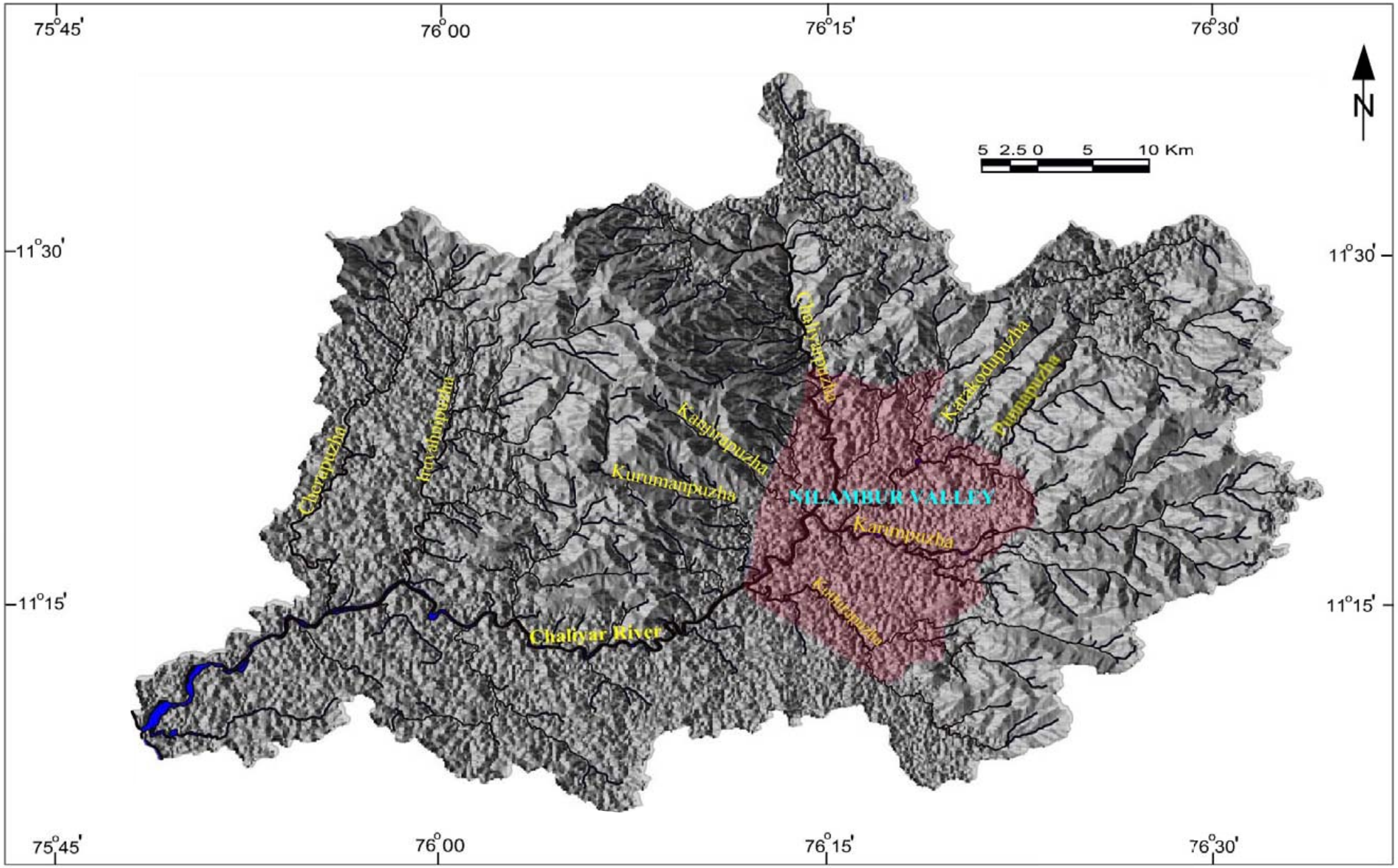


Fig. 3.2 SRTM derived aspect map of Chaliyar River drainage basin showing the major tributaries and the Nilambur valley. Five of its major tributaries – Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha, Karakodupuzha, Punnapuzha, Karimpuzha and Kuthirapuzha join within the Nilambur valley.

Detailed map of Chaliyar River drainage basin shows that the river attains 7th order when it flows over 45 km from its source (Fig. 3.3) with all its major tributaries joining the trunk stream at Nilambur. The basin has been divided into 9 sub-basins (numbered 1 to 9 respectively) through which the main tributaries like Cherupuzha, Iruvahnipuzha, Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha, Karakodupuzha, Punnapuzha, Karimpuzha and Kuthirapuzha drain.

Drainage pattern

Channel pattern of a river depends on its planform geometry and the processes operating within its reach (Rachna et al., 2004). The difference between the hardness of rock formation and surface slope are the main characteristics that control the design of the drainage pattern (Zernith, 1932). Drainage pattern also indicates the surface geomorphic episodes which have been modified due to the factors like isostatic or tectonic changes. A well-developed drainage pattern implies relative low infiltration and impervious materials while absence of surface drainage is the indication of high infiltration and general pervious nature of the surface material. Howard (1964) related drainage pattern to geologic information. Stream patterns are very sensitive to active tectonic movements, being dependent on the type and relative direction of deformed structures (Schumm et al., 2000). Drainage pattern has the potential to record evidence of the kinematics of folds and faults (Jackson et al., 1998).

In general, the Chaliyar River shows dendritic, sub-dendritic and rectangular drainage patterns (Fig. 3.4). Lower order streams display dendritic to sub-dendritic drainage pattern. First order streams mainly show dendritic pattern and flows through homogenous lithology (charnockite/charnockite gneiss) and without any control by the underlying geologic structure as observed in the eastern and central parts of the basin. Sub-dendritic drainage pattern in the basin is characterized by sharp, nearly right-angle bends and are lithologically and structurally controlled. Second order streams are mainly sub-dendritic and flow in NW or NE direction following the main lineament trend. These streams flow through the high hill ranges of Western Ghats and through narrow V-shaped valleys. Trellis drainage pattern is observed in the Punnapuzha tributary (Fig. 3.4a). Secondary tributaries are parallel to the main stream and conspicuously elongated and join the main stream approximately at right angles. Rectangular drainage pattern is very common in 3rd and 4th order streams and follow general structural trend of the area. Northeast flowing streams at many places suddenly take sharp right-angle bend and flow in the SE direction (Fig. 3.4b). Rectangular drainage pattern overprinted over dendritic pattern which is very common in the north of Nilambur may be the result of the later right angle fault system. Deranged or contorted drainage patterns have been developed in Cherupuzha and Iruvahnipuzha (Fig. 3.4c). Deranged drainage pattern has no coherent pattern to the rivers and develops where there has been much geologic disruption or where the areas are of low relief, low slope and high sediment load. Radial pattern is observed at Mysore kunnu (∆448) (Fig.3.4d). Parallel drainage pattern is observed on the upper reaches of Iruvahnipuzha (Fig. 3.4e). At the confluence of Punnapuzha stream with Chaliyar River, sharp right angle bend is observed (Fig. 3.4f). Pronounced change in the course of the Chaliyarpuzha tributary north of Kurathimala (Fig. 3.4g), and the sharp swing in Punnapuzha tributary from NNE flow direction to W direction and then sudden swirl to the south suggest structural control over the drainage pattern (Fig. 3.4h).

Anabranching drainage pattern is observed in the middle reaches of Punnapuzha and Karimpuzha (Fig. 3.5a,b). These are multiple channel systems separated by vegetated, semi-permanent alluvial islands usually excised from existing flood plain but also some times developed by within-channel accretion (Nanson and Knighton, 1996). Anabranching river systems are now regarded as a separate class in river classifications owing to their distinctive morphological/hydrological characteristics and fluvial processes (Jain and Sinha, 2004). The development of anabranches is related to rapid and frequent avulsions of the river channels. The understanding of anabranching streams are relatively new in comparison with other channel patterns and were identified on the basis of sinuosity and sediment load parameters (Rust, 1978; Brice, 1984; Schumm, 1985; Jain and Sinha, 2003). The suspended load in such streams is insignificant and the bed load content is very high (Schumm, 1985; Jain and Sinha, 2003). Valley width to depth ratio is greater than 100. The anabranching in the midstream reaches of Karimpuzha is a response to its inability to transport high sediment load caused by block faulting that has attributed to the development of alluvial fan and also due to dominance of aggradation process. Changes in the stream course in the last few decades could be explained by comparing the aerial photographs of 1969 and satellite imagery, LISS III acquired in 2005 (Fig. 3.6).

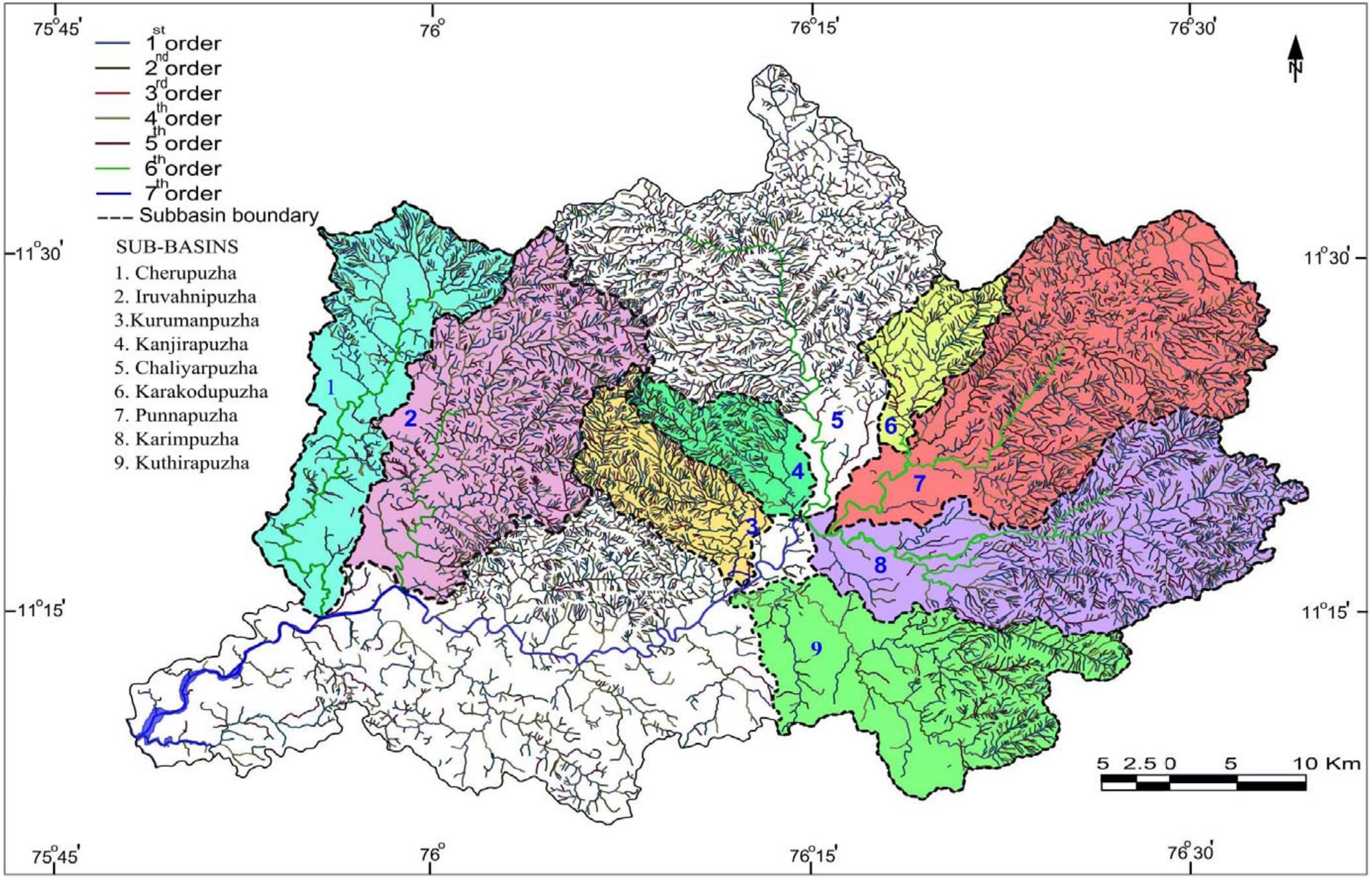


Fig. 3.3 Drainage map of Chaliyar River showing 1st to 7th order streams. The numbers (1-9) denote nine sub-basins of the river.

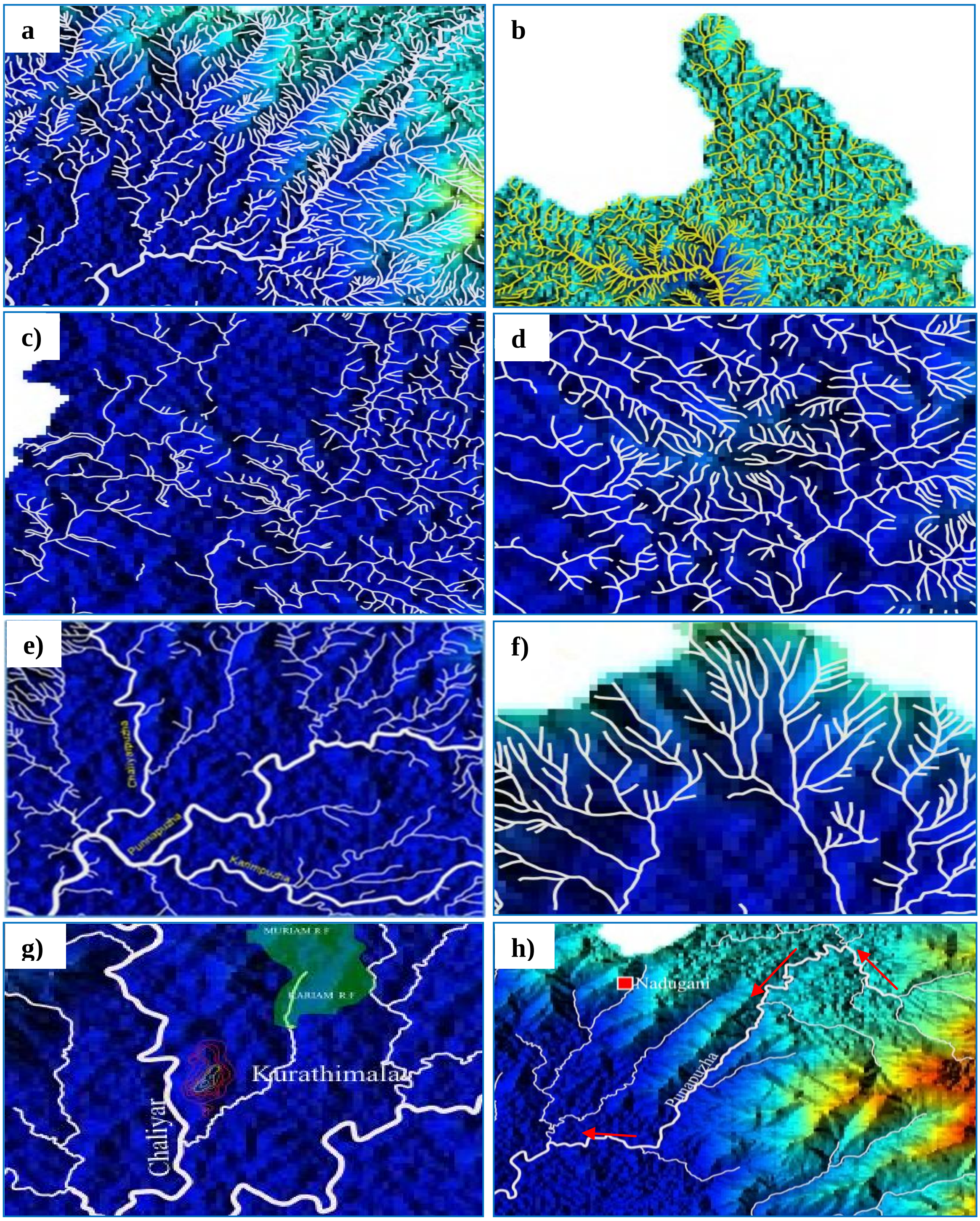


Fig. 3.4 Drainage patterns observed in Chaliyar River drainage basin. (a) Trellis pattern in Punnapuzha, (b) rectangular pattern in Chaliyarpuzha, (c) deranged or contorted patterns in Cherupuzha and Iruvahnipuzha, (d) radial pattern at Mysore mala,(e) rectangular pattern in the higher order streams at the confluence of Chaliyarpuzha and Punnapuzha, (f) parallel drainage pattern in the upper reaches of Iruvahnipuzha, (g) sharp bend in the stream course Chaliyar NW of Kurathimala, (h) sharp angular bends in Punnapuzha shifting stream course from NW to SW direction and then shifting the flow direction to west further downslope.

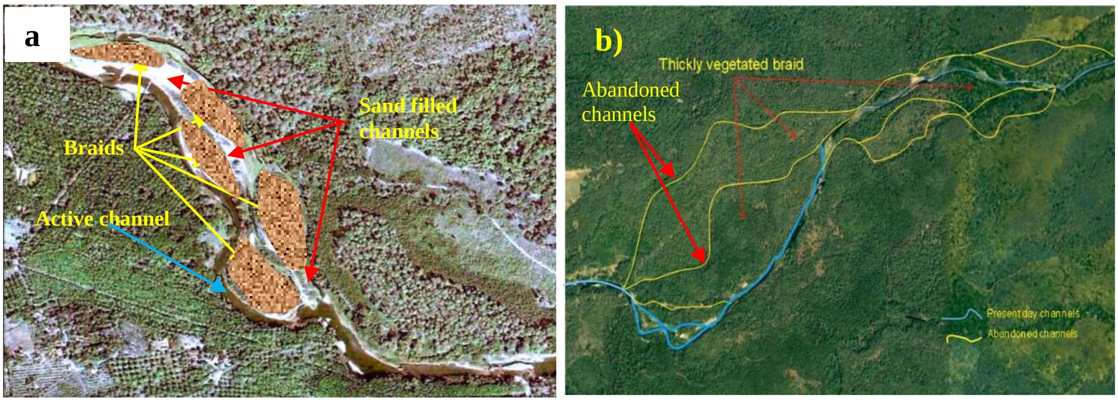


Fig. 3.5 Google earth imagery, enhanced by using Erdas Imagine, shows anabranching and channel migration in (a) Punnapuzha River with braids and sand filled channels at Karnadokundu, (b) Karimpuzha River with braids and abandoned channel at Chekuthankundu.

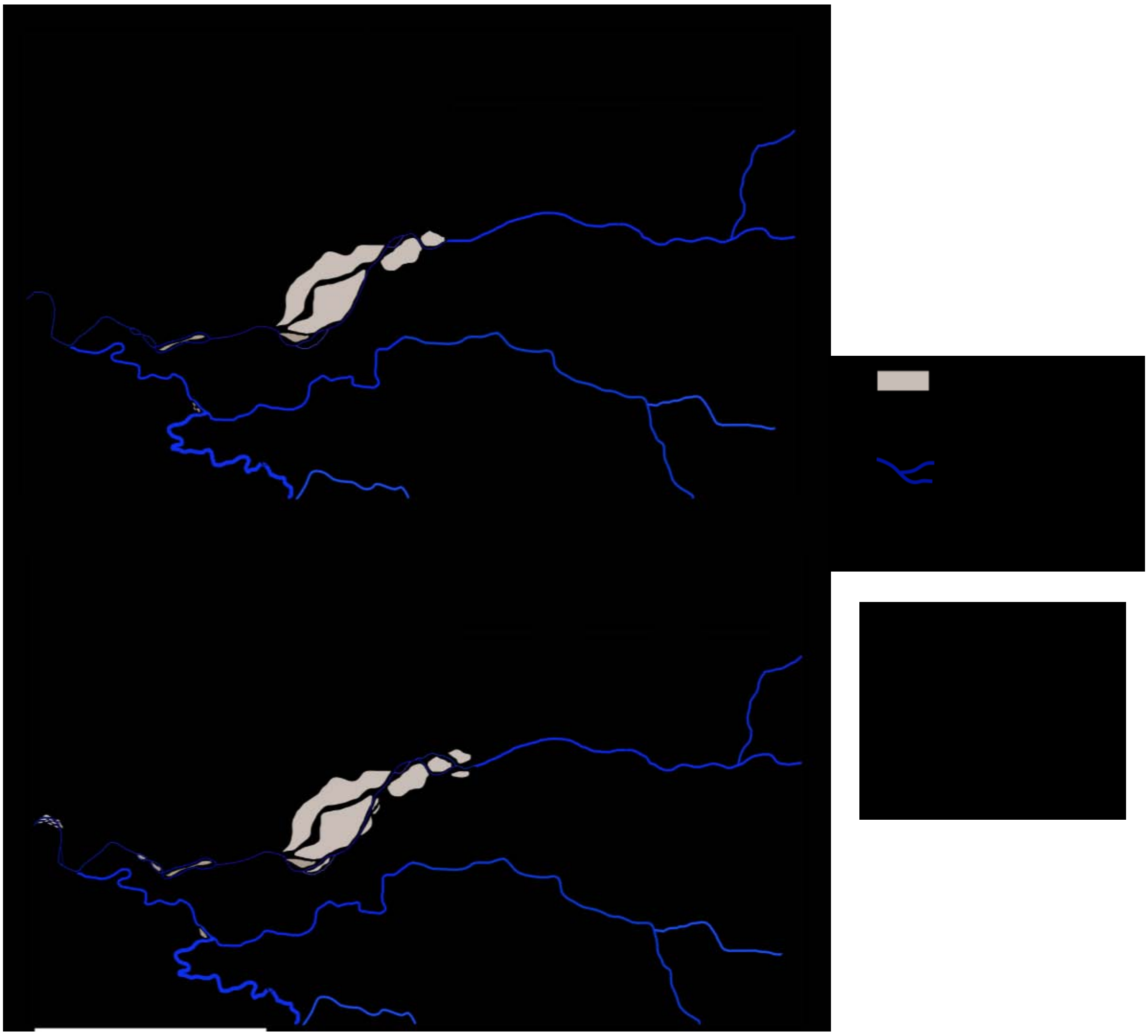


Fig. 3.6 Anabranching river system and changes observed between the year (a) 1969 and (b) 2005 in the middle reaches of Karimpuzha River between Chekuthankundu and Nedungayam. Channel migration, disappearance of Kallathodu and development of braids/islands in two different years are clearly seen.

In the interpreted map of Karimpuzha from the aerial photographs of 1969 show that the braided channels are wider and the braided bars are narrow. The number of braided bars are 5, while that in the imagery interpreted map (database: 2005), the number of braided bars have been increased to 7 and new braided bars are developed on the upstream part of the stream. The braided bars observed from aerial photographs are sparsely vegetated but those observed in satellite imagery exhibits a thick vegetation cover. Migration of channels towards southern direction is also observed. Kallanthodu, which was a well developed stream at that time has been dried off and has only marginal flow during monsoon.

3.3.2 Streams and their behaviour

Stream channels are important both as avenues of sediment transport that deliver eroded material from continents to the oceans and as environments for freshwater ecosystems that have economic and social significance. Over geologic time, channels respond to tectonic uplift, erosion of the landscape and climate change. Over historical time, channels respond to changes in discharge and sediment supply from both land use and such extreme events as floods and droughts. The wide variety of channel types, adjustment of individual channels to local factors, and potential time lags between perturbation and response complicate the interpretation and prediction of changes in channel form and processes. This complexity fostered the development of classification schemes to guide identification of functionally similar portions of channel networks.

For a stream to be stable, it must be able to consistently transport its sediment load, both in size and type, associated with local deposition and scour. Channel instability occurs when the scouring process leads to degradation, or excessive sediment deposition results in aggradation (Ward, 2008).

Valley Slope

Valley slope can be interpreted as an independent channel-shaping control and representation of watershed physiography over temporal scales of 10^1–10^2 years (Schumm and Lichty, 1965; Knighton, 1998). Total steam length of 169 km is divided into 16 segments at 10 km interval, except one segment that has been divided at 9 km interval to measure the valley slope. Valley slope calculated for Chaliyar River drainage basin at these 17 locations indicate that the average slope angle from the stream head to the mouth varies from 0.55 to 0.02 radians (Table 3.1).

Table 3.1 Average valley slope of the Chaliyar River along its profile. The river was divided into 17 segments along the profile.

Segments	**Latitude (decimals)**	**Longitude (decimals)**	**Slope measured at different points (degrees)**					**Average valley slope**	
			Slope1	**Slope2**	**Slope3**	**Slope4**	**Slope5**	**Degrees**	**Radians**
1	11.54	76.12	32	30	29	34	32	31.4	**0.55**
2	11.52	76.15	24	21	24	23	23	23	**0.40**
3	11.49	76.23	21	20	23	22	22	21.6	**0.38**
4	11.45	76.24	18	16	15	17	16	16.4	**0.29**
5	11.42	76.25	17	17	16	18	17	17	**0.30**
6	11.35	76.26	15	16	14	14	15	14.8	**0.26**
7	11.28	76.22	15	14	14	16	17	15.2	**0.27**
8	11.26	76.19	14	13	13	13	14	13.4	**0.23**
9	11.23	76.16	12	11	12	12	11	11.6	**0.20**
10	11.22	76.14	12	11	10	10	12	11	**0.19**
11	11.22	76.1	12	11	11	12	10	11.2	**0.20**
12	11.22	76.06	10	8	9	10	9	9.2	**0.16**
13	11.22	76.04	8	9	8	8	9	8.4	**0.15**
14	11.24	76	8	8	8	7	9	8	**0.14**
15	11.24	76.97	7	7	6	7	5	6.4	**0.11**
16	11.16	75.81	5	4	3	5	4	4.2	**0.07**
17	11.2	75.85	0	1	3	0	2	1.2	**0.02**

Table 3.2 Sinuosity ranges computed for segments along river centre line and sinuosity categories *(after Brice 1982).*

Category	**Sinuosity**
Straight	1.00 - 1.05
Sinuous	1.06 - 1.25
Meander	1.26 - 2.00
Torturous	2.01+

Sinuosity

Stream sinuosity is an index of channel pattern and is defined as the ratio of stream length to straight line length between two points (Knighton 1998). It is the degree to which a river departs from a straight line (Schumm and Khan, 1972). In single thread channels, sinuosity aids in interpretation of suspended sediment carrying capacity, lateral channel stability, and valley confinement (Brice 1974; 1982; Schumm 1977). Table 3.2 shows sinuosity ranges computed for segments along river centre line and sinuosity categories (after Brice 1982).

Sinuosity is calculated separately for five major tributaries (Cherupuzha, Iruvahnipuzha, Chaliyarpuzha, Punnapuzha and Karimpuzha) of Chaliyar River and also for the trunk system and the results are presented (Fig. 3.7; Table 3.3). In Cherupuzha, out of 9 segments, 4 are classified as sinuous, 3 as meandering, 1 as torturous and 1 as straight course. Iruvahnipuzha is divided into 16 segments out of which 11 are grouped as sinuous, 3 as meandering courses, 1 torturous and 1 as straight course. 17 segments made for Chaliyarpuzha show 9 straight courses, 6 sinuous and 2 meandering courses. In the case of Punnapuzha, out of 13 segments, 8 segments are sinuous, 3 meandering and 2 straight courses. Karimpuzha is divided into 12 segments out of which 5 segments are grouped into sinuous; 5 segments are straight and 2 segments as meandering categories. Chaliyar River trunk system is divided into 16 segments out of which 12 segments are categorized as sinuous, 2 as meandering and 2 as straight courses. On the whole 54% of the total segments of main trunk system and tributaries can be grouped into sinuous category, while 25% of the segments as straight and the remaining 20% as meandering courses.

Width to depth ratio

The role of bedrock-channel incision on the evolution of mountainous topography has become a central concept in geomorphology (Seidl and Dietrich, 1992; Burbank et al., 1996). The width to depth ratio is computed using field measurements of the bankfull width to the mean bankfull depth. The break between single channel classifications is 12, meaning that the bankfull width is 12 times greater than the mean bankfull depth. Stream types with width/depth ratios > 12 are classified as “B,” “C,” and “F.” Stream types with < 12 width/depth ratio are classified as “A,” “E,” and “G.” The “D” type streams have a width/depth ratio > 40 and the “DA” stream types are < 40

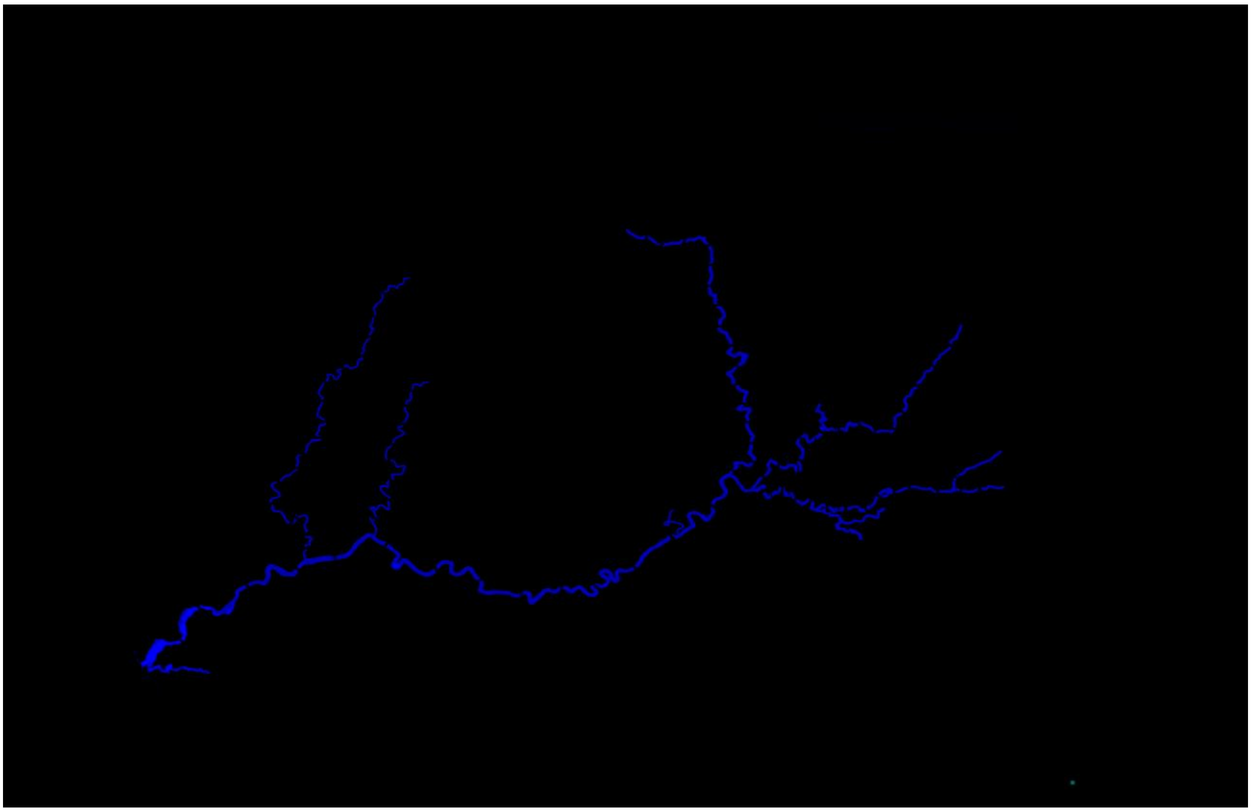


Fig. 3.7 The tributaries and trunk system of Chaliyar River area divided into segments and are numbered. The sinuosity of the river course was computed for each segments.

Table.3.3 Sinuosity computed for the segments of the tributaries and trunk system of Chaliyar River.

Karimpuzha		Punnapuzha		Cherupuzha		Iruvahnipuzha		Chaliyarpuzha		Chaliyar River	
Sinuosity	Geomorphic character	Sinuosity	Geomorphic character	Sinuosity	Geomorphic character	Sinuosity	Geomorphic character	Sinuosity	Geomorphic character	Sinuosity	Geomorphic character s
1.09	Straight	1.17	Sinuous	0.83	Straight	1.26	Sinuous	1.07	Straight	1.24	Sinuous
1.06	Straight	1.06	Straight	1.16	Sinuous	1.26	Sinuous	1.04	Straight	1.45	Sinuous
1.07	Straight	1.13	Sinuous	1.13	Sinuous	1.18	Sinuous	1.05	Straight	1.01	Straight
1.05	Straight	1.14	Sinuous	1.35	Sinuous	1.12	Sinuous	1.17	Sinuous	1.78	Meander
1.01	Straight	1.13	Sinuous	1.20	Sinuous	1.49	Sinuous	1.08	Straight	1.59	Meander
1.15	Sinuous	1.14	Sinuous	2.14	Torturous	1.75	Meander	1.03	Straight	1.33	Sinuous
1.14	Sinuous	1.10	Straight	1.55	Meander	1.12	Sinuous	1.10	Straight	1.23	Sinuous
1.13	Sinuous	1.30	Sinuous	1.92	Meander	1.26	Sinuous	1.15	Sinuous	1.24	Sinuous
1.52	Meander	1.25	Sinuous	1.69	Meander	1.43	Sinuous	1.09	Straight	1.42	Sinuous
1.15	Sinuous	1.50	Meander			1.15	Sinuous	1.92	Meander	1.49	Sinuous
1.15	Sinuous	1.15	Sinuous			1.21	Sinuous	1.41	Sinuous	1.22	Sinuous
1.56	Meander	1.80	Meander			1.03	Straight	1.23	Sinuous	1.06	Straight
		1.52	Meander			1.52	Meander	1.77	Meander	1.33	Sinuous
						1.14	Sinuous	1.08	Straight	1.23	Sinuous
						2.42	Torturous	1.07	Straight	1.18	Sinuous
						1.71	Meander	1.12	Sinuous	1.14	Sinuous
								1.34	Sinuous		

(Harman et al., 1999). Width to depth ratio for 20 sections in the trunk system of the Chaliyar River suggests that the stream can be classified as B, C, F types (Table 3.4), and 78 sections in the tributaries group the streams into A, B, C, E, F and G types (Table 3.5).

Entrenchment Ratio

The entrenchment ratio is a measurement of channel incision and is computed from the measurements made in the field. Specifically, it is the flood-prone width divided by the bankfull width. The flood-prone width is measured at the elevation of twice the maximum depth at bankfull. Lower entrenchment ratios indicate channel incision. Large entrenchment ratios mean that there is a well-developed floodplain. Entrenchment ratio measured at 26 sections in the Chaliyar River profile ranges from 1.01 to 19.96 (Table 3.6).

Median size of the bed material

The Chaliyar River and its tributaries are divided into 10 km long segments. In each segment, the stream material consists of bedrock, boulders, pebbles, sand and clay (Table 3.7). The upper reaches of the streams are mainly composed of boulders and pebbles and lower reaches composed of gravel and sand (Fig. 4.21 c to f, *Chapter IV*). Grain size decreases gradationally from the upper reaches to river mouth. The grain size attains sand size at the 6^{th} order level when the stream length is about 45 km from the source.

Chaliyar River has been divided into 17 segments of 10 km length and based on entrenchment ratio, width to depth ratio, sinuosity and valley slope, it is classified and various classes are shown in Table 3.8. The segments mainly belong to type A, B, C, E and F classes as per Rosgen classification (1996). The upstream portion of Chaliyar River represented by 1^{st} segment belongs to type A, which is characterized by step pools (Fig. 3.8a). Just at the break of physiographic slope, the stream changes to type D, which is characterized by shifting braids (Fig. 3.8b). As the river enters the Nilambur valley, it can be classified as E type or evolutionary single thread channel, which is characterized by narrow riffle pool with little deposition (Fig. 3.8c). When Chaliyar River starts to flow through the Nilambur valley represented by segments 6 and 7, it attains the characteristic features of type B and C (Fig. 3.8d, e). B is the basic single

Table 3.4 Width to height ratio computed for the trunk stream of Chaliyar River with stream type (Rosgen, 1996 and Harman et al., 1999).

Location	Latitude (degrees)	Longitude (degrees)	Width/depth ratio	Stream type	
				After Rosgen, 1996	After Harman et al., 1999
1	11.16	75.80	374.34	B, C, F	D
2	11.17	75.81	200.00	B, C, F	D
3	11.18	75.81	321.68	B, C, F	D
4	11.18	75.83	70.74	B, C, F	D
5	11.21	75.85	14.30	B, C, F	DA
6	11.21	75.87	54.54	B, C, F	D
7	11.23	75.89	31.04	B, C, F	DA
8	11.24	75.92	33.22	B, C, F	DA
9	11.25	75.94	31.69	B, C, F	DA
10	11.27	75.98	144.63	B, C, F	D
11	11.25	76.00	18.90	B, C, F	DA
12	11.25	76.03	32.00	B, C, F	DA
13	11.24	76.04	27.43	B, C, F	DA
14	11.22	76.07	82.61	B, C, F	D
15	11.22	76.09	24.36	B, C, F	DA
16	11.22	76.10	37.74	B, C, F	DA
17	11.22	76.14	39.51	B, C, F	DA
18	11.24	76.15	30.88	B, C, F	DA
19	11.24	76.16	25.70	B, C, F	DA
20	11.29	76.23	30.83	B, C, F	DA

Table 3.5 Width to depth ratio computed for the tributaries of Chaliyar River with stream type and characteristics (Rosgen, 1996 and Harman et al., 1999).

No.	**Width/depth ratio**	**Characteristic features**	**Stream type**	
			After Rosgen, 1996	**After Harman et al., 1999**
Cherupuzha				
1	70.99	V-shaped valleys, actively incising, high uplift	B, C, F	D
2	238.00	Broad valleys, low uplift rates	B, C, F	D
3	68.20	V-shaped valleys, actively incising, high uplift	B, C, F	D
4	64.28	V-shaped valleys, actively incising, high uplift	B, C, F	D
5	12.04	V-shaped valleys, actively incising, high uplift	B, C, F	DA
Iruvahnipuzha				
6	3.90	V-shaped valleys, actively incising, high uplift	A, E, G	DA
7	22.64	V-shaped valleys, actively incising, high uplift	B, C, F	DA
8	2.18	V-shaped valleys, actively incising, high uplift	A, E, G	DA
9	27.00	V-shaped valleys, actively incising, high uplift	B, C, F	DA
10	44.57	V-shaped valleys, actively incising, high uplift	B, C, F	D
11	55.28	V-shaped valleys, actively incising, high uplift	B, C, F	D
12	456.21	Broad valleys, low uplift rates	B, C, F	D
13	16.98	V-shaped valleys, actively incising, high uplift	B, C, F	DA
14	170.46	Broad valleys, low uplift rates	B, C, F	D
15	138.97	Broad valleys, low uplift rates	B, C, F	D
Kurumanpuzha				
16	46.33	V-shaped valleys, actively incising, high uplift	B, C, F	D
17	44.29	V-shaped valleys, actively incising, high uplift	B, C, F	D
18	13.57	V-shaped valleys, actively incising, high uplift	B, C, F	DA
19	11.79	V-shaped valleys, actively incising, high uplift	A, E, G	DA
20	10.77	V-shaped valleys, actively incising, high uplift	A, E, G	DA
Kanjirapuzha				
21	7.41	V-shaped valleys, actively incising, high uplift	A, E, G	DA
22	9.25	V-shaped valleys, actively incising, high uplift	A, E, G	DA
23	6.23	V-shaped valleys, actively incising, high uplift	A, E, G	DA
24	4.97	V-shaped valleys, actively incising, high uplift	A, E, G	DA
Chaliyarpuzha				
25	6.29	V-shaped valleys, actively incising, high uplift	A, E, G	DA
26	2.56	V-shaped valleys, actively incising, high uplift	A, E, G	DA
27	1.33	V-shaped valleys, actively incising, high uplift	A, E, G	DA
28	102.44	V-shaped valleys, actively incising, high uplift	B, C, F	D
29	5.90	V-shaped valleys, actively incising, high uplift	A, E, G	DA
30	8.29	V-shaped valleys, actively incising, high uplift	A, E, G	DA

Table 3.5 continued

No.	Width/depth ratio	Characteristic features	Stream type	
			After Rosgen, 1996	After Harman et al., 1999
31	5.90	V-shaped valleys, actively incising, high uplift	A, E, G	DA
32	8.42	V-shaped valleys, actively incising, high uplift	A, E, G	DA
33	8.52	V-shaped valleys, actively incising, high uplift	A, E, G	DA
34	7.47	V-shaped valleys, actively incising, high uplift	A, E, G	DA
35	4.17	V-shaped valleys, actively incising, high uplift	A, E, G	DA
36	6.82	V-shaped valleys, actively incising, high uplift	A, E, G	DA
37	112.55	Broad valleys, low uplift rates	B, C, F	D
Karakodupuzha				
38	5.07	V-shaped valleys, actively incising, high uplift	A, E, G	DA
39	5.14	V-shaped valleys, actively incising, high uplift	A, E, G	DA
40	24.90	V-shaped valleys, actively incising, high uplift	B, C, F	DA
41	30.75	V-shaped valleys, actively incising, high uplift	B, C, F	DA
42	11.90	V-shaped valleys, actively incising, high uplift	A, E, G	DA
43	18.38	V-shaped valleys, actively incising, high uplift	B, C, F	DA
44	10.69	V-shaped valleys, actively incising, high uplift	A, E, G	DA
45	8.47	V-shaped valleys, actively incising, high uplift	A, E, G	DA
46	13.37	V-shaped valleys, actively incising, high uplift	B, C, F	DA
47	7.46	V-shaped valleys, actively incising, high uplift	A, E, G	DA
48	142.87	Broad valleys, low uplift rates	B, C, F	D
Punnapuzha				
49	23.98	V-shaped valleys, actively incising, high uplift	B, C, F	DA
50	14.65	V-shaped valleys, actively incising, high uplift	B, C, F	DA
51	17.15	V-shaped valleys, actively incising, high uplift	B, C, F	DA
52	15.78	V-shaped valleys, actively incising, high uplift	B, C, F	DA
53	12.15	V-shaped valleys, actively incising, high uplift	B, C, F	DA
54	7.90	V-shaped valleys, actively incising, high uplift	A, E, G	DA
55	6.24	V-shaped valleys, actively incising, high uplift	A, E, G	DA
56	42.12	V-shaped valleys, actively incising, high uplift	B, C, F	D
57	78.63	V-shaped valleys, actively incising, high uplift	B, C, F	D
58	202.58	Broad valleys, low uplift rates	B, C, F	D
Karimpuzha				
59	13.14	V-shaped valleys, actively incising, high uplift	B, C, F	DA
60	7.60	V-shaped valleys, actively incising, high uplift	A, E, G	DA
61	61.05	V-shaped valleys, actively incising, high uplift	B, C, F	D
62	3.30	V-shaped valleys, actively incising, high uplift	A, E, G	DA
63	6.56	V-shaped valleys, actively incising, high uplift	A, E, G	DA
64	283.61	V-shaped valleys, actively incising, high uplift	B, C, F	D

Table 3.5 continued

No.	Width/depth ratio	Characteristic features	Stream type	
			After Rosgen, 1996	After Harman et al., 1999
65	40.24	V-shaped valleys, actively incising, high uplift	B, C, F	D
66	32.93	V-shaped valleys, actively incising, high uplift	B, C, F	DA
67	11.99	V-shaped valleys, actively incising, high uplift	A, E, G	DA
68	10.17	V-shaped valleys, actively incising, high uplift	A, E, G	DA
69	6.73	V-shaped valleys, actively incising, high uplift	A, E, G	DA
70	7.02	V-shaped valleys, actively incising, high uplift	A, E, G	DA
Kuthirapuzha				
71	126.43	Broad valleys, low uplift rates	B, C, F	D
72	24.54	V-shaped valleys, actively incising, high uplift	B, C, F	DA
73	21.09	V-shaped valleys, actively incising, high uplift	B, C, F	DA
74	17.65	V-shaped valleys, actively incising, high uplift	B, C, F	DA
75	8.24	V-shaped valleys, actively incising, high uplift	A, E, G	DA
76	22.70	V-shaped valleys, actively incising, high uplift	B, C, F	DA
77	19.69	V-shaped valleys, actively incising, high uplift	B, C, F	DA
78	13.25	V-shaped valleys, actively incising, high uplift	B, C, F	DA

Table 3.6 Entrenchment ratios computed for the Chaliyar River along its longitudinal profile.

Sl No.	Latitude (decimal)	Longitude (decimal)	FPW (m)*	BFW (m)*	ER*
1	11.16	75.80	471.85	418.28	1.13
2	11.18	75.82	1138.49	1041.84	1.09
3	11.24	75.90	323.41	302.58	1.07
4	11.32	76.24	145.56	28.27	5.15
5	11.27	75.97	166.47	142.90	1.16
6	11.25	76.00	105.25	59.67	1.76
7	11.24	75.99	195.43	167.66	1.17
8	11.25	75.90	193.32	147.32	1.31
9	11.25	76.04	90.33	54.33	1.66
10	11.24	76.04	102.50	94.00	1.09
11	11.24	76.05	183.17	143.41	1.28
12	11.22	76.06	195.89	194.26	1.01
13	11.22	76.10	200.00	155.82	1.28
14	11.23	76.12	151.00	98.82	1.53
15	11.22	76.13	232.40	162.83	1.43
16	11.23	76.13	145.72	49.54	2.94
17	11.22	76.14	152.07	76.61	1.98
18	11.23	76.14	180.72	74.00	2.44
19	11.23	76.15	142.30	60.64	2.35
20	11.24	76.15	122.08	70.34	1.74
21	11.23	76.16	146.96	65.88	2.23
22	11.23	76.16	181.65	92.97	1.95
23	11.24	76.16	148.37	135.22	1.10
24	11.28	76.22	205.77	53.17	3.87
25	11.29	76.21	122.00	74.16	1.65
26	11.41	76.25	386.26	19.35	19.96

**FPW-Flood prone width, BFW-Bankfull width, ER-entrenchment ratio*

Table 3.7 Classification of 17 segments of the Chaliyar River based on Rosgen stream classification for natural rivers as a function of continuum of physical variables within the stream reaches (from Application of the Rosgen stream classification system to North Carolina, 1999)

Sl. No	Latitude (in decimal)	Longitude (in decimal)	Entrenchment Ratio	Width to depth ratio	Sinuosity	Class	Stream bed material (based on grain size)	Rosgen Class
1	11.54	76.12	Moderately entrenched	Low	Low	A	Bed rock, boulders, cobbles and pebbles	A1b
2	11.52	76.15	Moderately entrenched	Low	Low	D	Boulders, cobbles and pebbles	D2b, D3b
3	11.49	76.23	Slightly entrenched	Very Low	high	E	Boulders, cobbles and pebbles	E3b
4	11.45	76.24	Slightly entrenched	Very Low	high	E	Pebbles, gravel and sand	E3b, E4b, E5b
5	11.42	76.25	Slightly entrenched	Very Low	Very high	E	Pebbles, gravel and sand	E3b, E4b, E5b
6	11.35	76.26	Moderately entrenched	Low	moderate	B	Gravel and sand	B4a, B5a
7	11.28	76.22	Slightly entrenched	Moderate	High	C	Gravel and sand	C4b, C5b
8	11.26	76.19	Entrenched	Moderate to high	Low	F	Sand	F5b
9	11.23	76.16	Slightly entrenched	Moderate to high	Very high	E	Sand	E5b
10	11.22	76.14	Moderately entrenched	Moderate	Moderate	B	Sand	B5a
11	11.22	76.10	Entrenched	Moderate	Moderate	F	Sand	F5b
12	11.22	76.06	Entrenched	Moderate	Moderate	F	Sand	F5b
13	11.22	76.04	Entrenched	Moderate	Moderate	F	Sand	F5b
14	11.24	76.00	Entrenched	Moderate	Moderate	F	Sand	F5b
15	11.24	75.97	Entrenched	Moderate	Moderate	F	Sand	F5b
16	11.16	75.81	Entrenched	Moderate	Moderate	F	Sand	F5b
17	11.2	76.85	Entrenched	Moderate	Moderate	F	Sand	F5b

thread channel dominated by riffles and C is the classic riffle-pool type with point bars and well-drained meanders. At the confluence of Chaliyarpuzha, Punnapuzha and Karimpuzha the stream type varies from F to E and then to B migrating from entrenched meander to evolutionary narrow riffle-pool and again to the basic riffle dominated type. When it reaches the 7th order it attains all the characteristic features of type F where stream becomes an entrenched meander (Fig. 3.8f).

Based on the stream form and function, Chaliyar River and its tributaries can be classified into three broad categories (after Schumm, 1977) viz. (i) headwater zone (zone of erosion); (ii) transfer zone (zone of transportation) and (iii) depositional zone (zone of deposition). Headwater streams are typically higher gradient, incised channels that carry sediment from slope and in-channel upland sources and are limited with sediment supply. The upper reaches of all the rivers comprising 1st to 4th order streams in the Chaliyar basin can be grouped as 'A' type channel of Rosgen's classification. Transfer zone streams are characterized by wide flood plains and meandering channels and form the Rosgen's B and C channel types. These streams have moderate gradient, U-shaped valleys and carries large amount of sediments (bed and bank) during peak flows. Most of the 5th and 6th order streams in the study area can be classified as transfer zone streams and are B and C channel types of Rosgen classification.

Depositional stream features are wide valley bottom, well developed broad flood plains and terraces and are grouped as Rosgen's C, D and E - channel types. Though this zone is depositional, significant transport through the valley bottom is a dominant process depending upon the channel stability and channel type. The trunk stream or the 7th order stream at it lower reaches can be called as a depositional stream with a characteristic wide flood plain. Punnapuzha and Karimpuzha even though of 6th order show all the properties of depositional stream even in the middle reaches.

Source area classification

Based on the source area classification (after Sinha and Friend, 1994), Chaliyar River and its tributaries are classified into i) Mountain-fed streams; ii) Foothill-fed streams; iii) Plain-fed streams; iv) Mixed-fed streams (Fig. 3.9).

Mountain-fed streams are mainly of lower orders and originate from the Western Ghats ranging in elevation from 350 to 2600 m. Rapids and falls are observed in these streams (Fig. 4.21a,b, *Chapter IV*). Foothill-fed streams are those streams which are formed in the foot hills of mountain ranges and are mainly of lower to mid orders. These streams show braiding and meandering in its upper reaches. Plain-fed streams are those which develop from denudational and isolated hills in the plains. These streams are also seen very close to the river mouth and also in the Nilambur valley area. Mixed-fed streams are common in terrains adjacent to both hills and peneplain. Cherupuzha is a plain-fed stream with mixed-fed upper reaches. Iruvahnipuzha is a foothill fed stream with mountain-fed upper reaches. Kurumanpuzha and Kanjirapuzha are mountain-fed. Chaliyarpuzha is a mountain fed stream in the upper reaches and becomes plain-fed when it reaches Nilambur valley. Punnapuzha, Karimpuzha and Kuthirapuzha are mountain-fed streams in the upper reaches and are plain-fed in the lower reaches. Karakodupuzha is mountain-fed in the upper reaches, and then becomes foothill fed and finally at the confluence with Punnapuzha it becomes plain-fed (Fig. 3.9).

3.3.3 Landforms

Dominant geomorphic processes that are active in Chaliyar River basin are denudational, fluvial and marine. Fluvial processes are dominant in the area and resulted in the formation of number of erosional and depositional units. Diffusive process or slope wash is an important geomorphic process in flanks of the Western Ghats (Chattopadhyay et al., 2007).

It is observed that the processes in Chaliyar River drainage basin are depositional, denudational/erosional and structural geomorphic units (Fig. 3.10).

Depositional landforms

Depositional landforms in the study area are channel belt, point and braided bars, channel fills and palaeochannels.

Active channel belt

Active channel belt, constitutes present day active channel and channel bed, can be considered as the youngest geomorphic surface. Topographically, this geomorphic unit occurs at an elevation ranging from 0 to 10 m. Stream bed of Chaliyar River can be divided into younger zone with rapids, waterfalls, middle zone with braided channels and meanders and the older zone with broad flood plains, meanders, point bars and side bars.

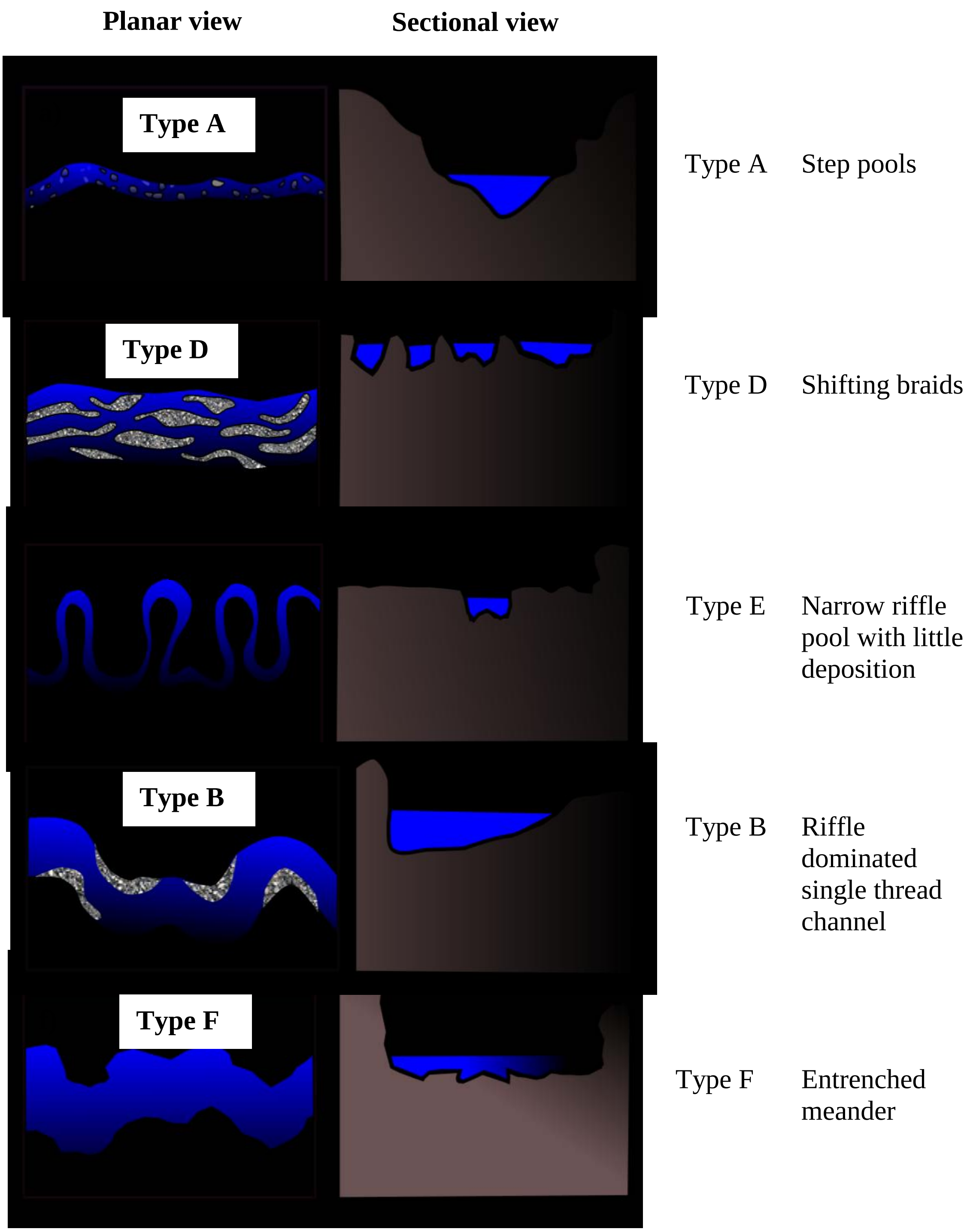


Fig. 3.8 Stream types in Chaliyar River based on Rosgen classification of natural rivers as a function of continuum of physical variables within the stream reaches (after Rosgen, 1999). Left panel shows the planar view and right panel shows the sectional view of the stream.

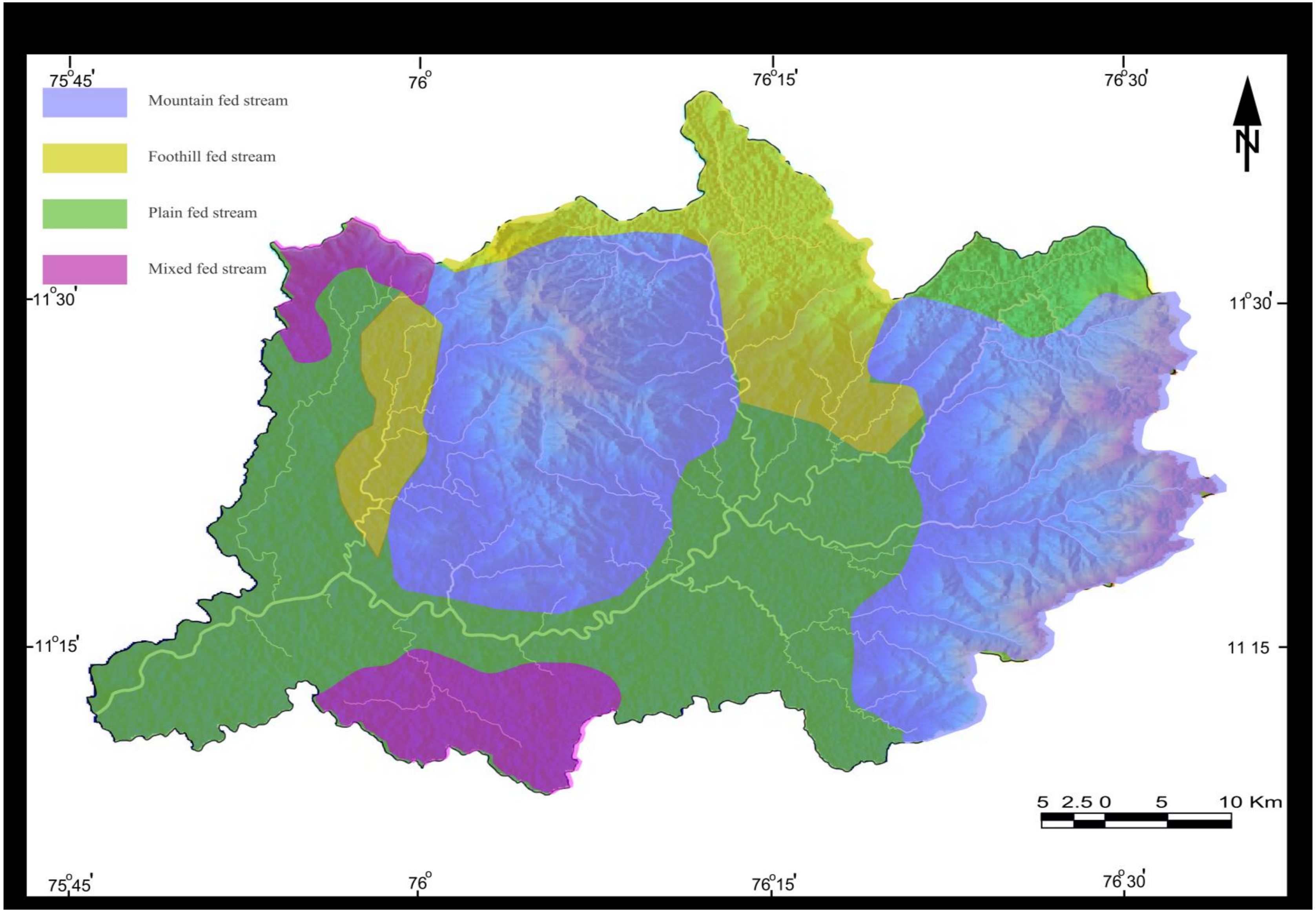


Fig. 3.9 Stream classification based on the nature of source area (after Sinha and Friend, 1994). The streams in Chaliyar River drainage basin are classified as mountain-fed, foothill-fed, plain-fed and mixed-fed streams.

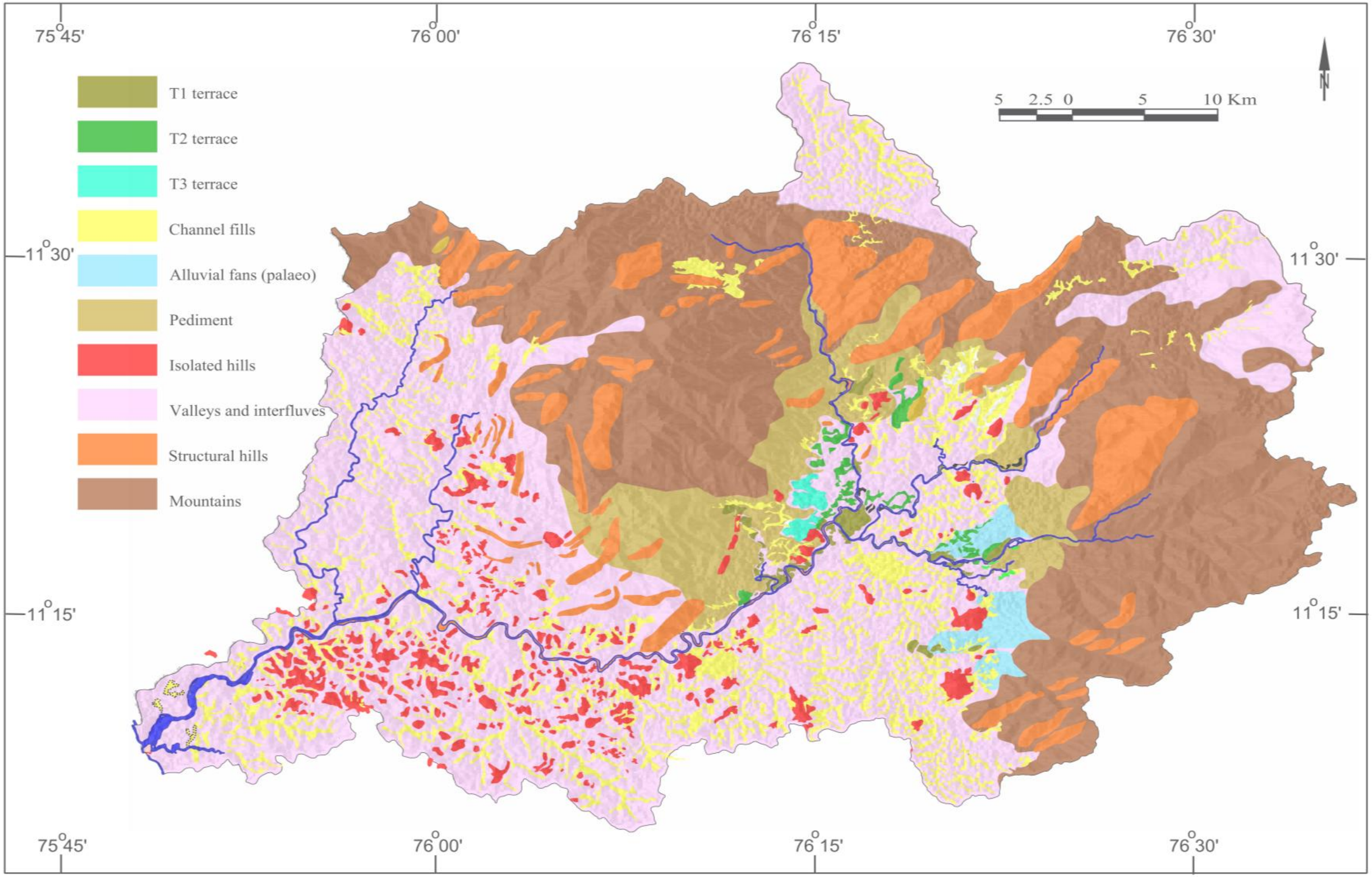


Fig. 3.10 Geomorphological map of Chaliyar River drainage basin derived from the toposheets, aerial photographs and IRS-P6 LISS III imagery.

Point -, Braided- and Channel bars

Bars are exposed sediment laid stream bed within the channel and are major sediment storage places within channels (Hassan, 2005). Point-, braided- and sand bars are observed within the Chaliyar River drainage basin. Maximum elevation of these landforms is 40 m above MSL. Bars are sparsely to moderately vegetated.

Eroded particles settle to the bottom of a water body or left behind in the stream bed as substrate point bar (Schumm, 1977). These are formed due to channel lag on the convex side of the channel bend due to reduced flow velocity. Point bars are very common in the basin. Point bars are made up of sand, silt and gravel bed at the bottom (Fig. 3.11a). The channel bars that typify braided channels are complex features and are modified by the processes of erosion and deposition and evolve over short periods of time. The type of braiding and the number of sub-channels found within the main channel reflect the different environments in which braided channels are found (Charlton, 2007). At the break of slope, almost all the tributaries of Chaliyar River are braided. The stream loses its energy and sheds all the sediments it carried in its course. The stream then flows as braided channel. Along the meander of Karimpuzha tributary gets braided at Karulayi (Fig. 3.11b). Channel bar is an isolated island formed in the river course and is common in Chaliyar River when it attains its higher order towards the lower reaches (Fig. 3.11c).

Channel fills

The channel fills are a significant component of the alluvial plain deposits in the western part of the Chaliyar River basin. These occur as large sediment bodies of broad concave up geometry with low to intermediately sloping channel margins (Fig. 3.11d). The channel fills indicate a much larger river than the present day Chaliyar River. The large channel fill structures are found to occur in isolation and are associated with overbank sediments. Occurrence of large channel fills, adjacent to overbanks strata, and absence of laterally adjacent channel fills indicate mainly a single channel river. It is one of the most widely spread geomorphological feature in the study area (Fig. 3.12). This can also be called as filled-up valley flats where small streams flow through broad valley flats and comprises colluvial materials on the top and sand silt intercalation below.

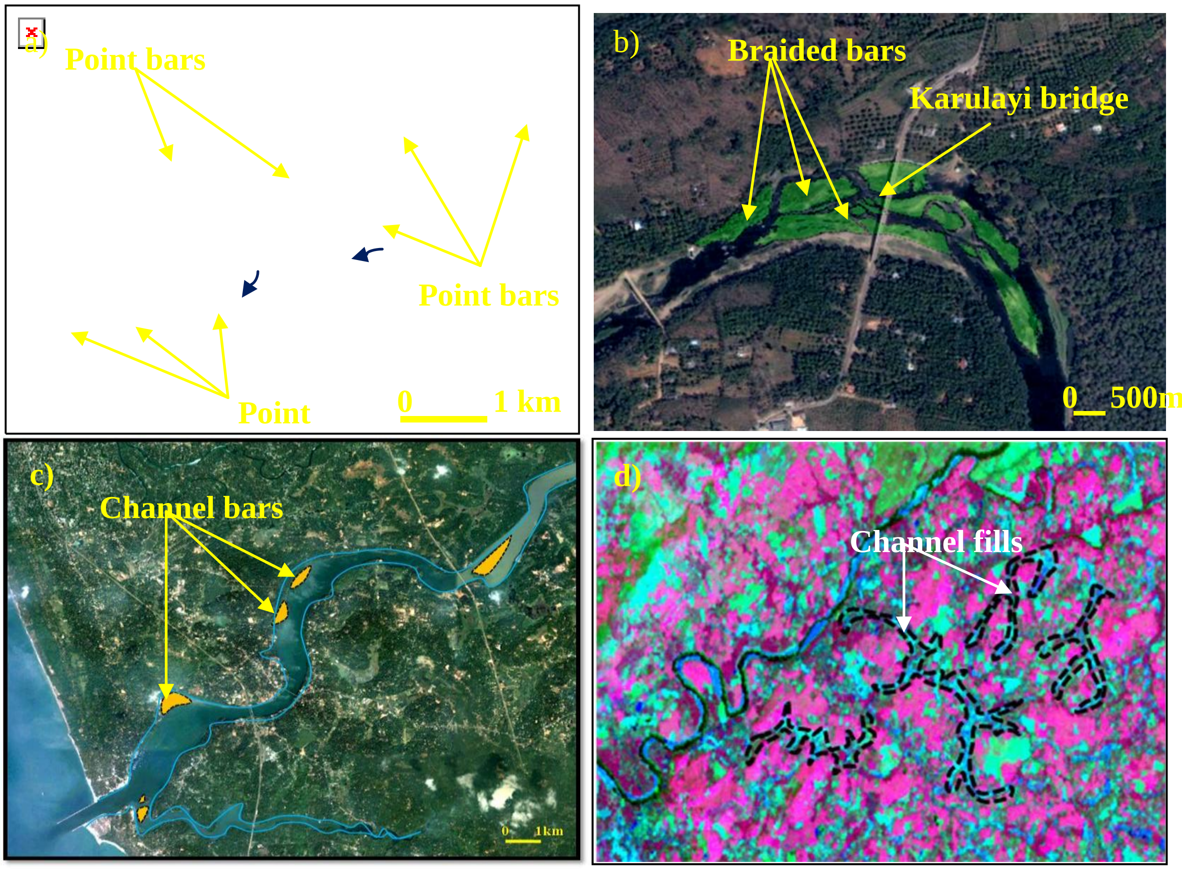


Fig. 3.11 Radiometrically enhanced Google Earth imagery showing (a) point bars in Chaliyar River, (b) braided bars in Karimpuzha River, (c) channel bars in the Chaliyar River as it reaches the river mouth, and (d) channel fills along Chaliyar River delineated from the tassled cap enhanced IRS-P6 LISS III imagery with 4,3,2 band combination.

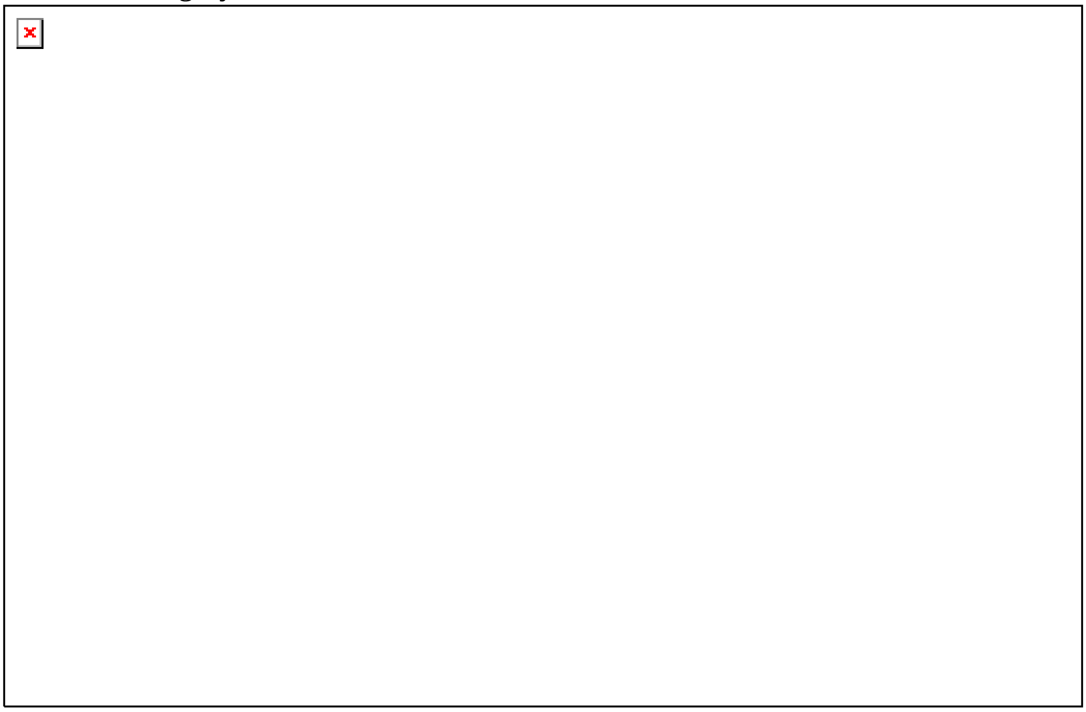


Fig. 3.12 Distribution of channel fills in Chaliyar River drainage basin. Channel fills are more in the low lying areas of the basin where the elevation ranges from 20 to 60 m.

Palaeochannels

Chaliyarpuzha, Punnapuzha and Karimpuzha tributaries have followed courses proximal to the present day channels. Such channels are delineated with the help of aerial photographs, satellite imageries and field observations.

The palaeochannels of Chaliyarpuzha are located in eastern and western part of Chaliyarpuzha (Fig. 3.13a). Palaeochannels of Punnapuzha are observed at many places. Karakkodupuzha flows through a very wide alluvial valley with relicts of palaeochannels, which consists of gravel bed, sand and silt as intercalations. Probably this could be the earlier main course of Punnapuzha (Fig. 3.13b). In Karimpuzha tributary, between Nedungayam and Kurukkankundu, three palaeo-courses trending NE-SW direction are observed (Fig. 3.13c) It appears that Kallanthodu flowing SW might be a palaeochannel of Karimpuzha.

Palaeo-alluvial fans

Fluvial alluvial fans form as rivers exit the topographic front of a mountain belt, migrate laterally in the adjacent basin and deposit the sediments (De Celles and Cavazza, 1999). When a heavily loaded stream emerges from mountains on to lowland, the marked change in gradient results in the deposition of alluvial material in the lowland. Alluvial fans are best developed in areas of sparse vegetation and torrential rainfall (Thornbury, 1969). Alluvial fans are aggrading deposits of alluvium deposited by a stream issuing from a canyon onto a surface or valley floor. Once it reaches the valley, the stream is unconfined and can migrate back and forth, depositing alluvial sediments across a broad area. The development of pediments and alluvial fans is progressive with the uplift of mountains and subsidence of adjacent basins. Downstream of a mountain front, streams deposit sediments on alluvial fans, and in the more upland areas, the channels on the upper alluvial fan may go through periods of down cutting, infilling, and channel migration. Broad fan shaped deposit, consisting of sediments ranging in size from boulders to silty clay, that forms when a stream leaving a narrow mountain valley and dumps onto an open plain especially where there is a high topographic relief, such as along the front of a mountain range or a fault scarp. The first-deposited sediments form a small, steep fan of coarse sediments (boulders, gravel). It plays an integral role in the dispersal and deposition of sediment in tectonic active areas. The deposits of these features serve as primary repositories for information on climatic conditions and rates of tectonic uplift and erosion in both young and ancient mountain belts (Leier et al., 2005).

Alluvial fans are characteristic of tectonically active regions and most of the fans occur either close to the mountain front or in the area of deposition that has moved down fan. The deposits serve as primary repositories for information on climatic conditions and rates of tectonic uplift and erosion in both young and ancient mountain belts (Leier et al., 2005).

Alluvial fans are observed at the break of a slope in the Chaliyar River drainage basin where the tributaries of Chaliyar River debouch into the Nilambur valley (Fig. 3.14a). Most widespread alluvial fan deposit is observed in the Chekuthankundu - Kurukkankundu - Nedungayam area with an areal extent of about 40 km^2 and is covered by thick canopy of vegetation. The expression of these alluvial fans in satellite imagery could not be delineated due to the thick vegetation cover. During field checks these features could be identified and the geomorphic expression and vegetation pattern in the imagery was then studied. Spatial distribution of similar pattern of vegetation is considered for delineation of palaeo-alluvial fans in other localities and was later confirmed in the field (*See Chapter IV for details*).

Terraces

Terraces form when streams carve downward into their floodplains, leaving discontinuous remnants of older floodplain surfaces as step-like benches along the sides of the valley. The formation of terrace sequences requires uplift and cyclic climate fluctuation which provides the trigger for fluvial aggradation and incision events that lead to terrace formation (Bridgland and Allen, 1996; Maddy, 1997; 2002). Paired terraces are the result of stage by stage degradation, while unpaired terraces are the result of sequential degradation by the alternating sweeps of a meandering stream. Cotton (1948) classified terraces into strath and valley terraces of sediments. Strath terraces are rock cut terraces and valley plain terraces are cut and fill terraces formed by the scouring of sediments from the valley and deposited by the stream downstream. Unpaired strath terraces are formed in response to coeval continuous vertical incision and lateral erosion of the river, controlled by episodic tectonic uplifts (Necea et al., 2005). Causative factors for the formation of terraces are (i) eustatic sea level change, (ii) tectonic uplift and (iii) climate change. Local uplift results in the formation of terraces that converges the stream bed after a few kilometers. Terraces are mainly correlated based on the continuity and relative elevation. Convergence of terrace downstream suggests progressive rejuvenation of the headwaters perhaps by continuing tectonic uplift (Bloom, 1992).

In the Chaliyar River drainage basin three terraces have been demarcated from the aerial photographs and satellite images, which are later verified and studied in the field (*See Chapter IV for details*). Chaliyarpuzha, Punnapuzha and Karimpuzha tributaries exhibit remarkable fluvial terraces mainly near the meandering courses. Based on the relative height and age of formation, these terraces are classified as T_1, T_2 and T_3. These terraces can also be classified as erosional, cut and fill unpaired terraces as suggested are commonly the products of tectonism or sudden change in the climatic regime. Most of these terraces are unpaired suggesting that rejuvenation took place continuously (Encyclopedia of Geology, 1968 pp.1120). There is no evidence of still stands of the stream during deepening of the valley. The staggered elevation of the terraces below the original stream valley floor suggest that lateral abrasion was accompanied by down cutting as the stream wandered from one valley side to the other. Such continuous incision or rejuvenation commonly results from secular tectonic uplift, gradual tilting, climatic change or change in load volume relation of stream. Terraces - $T_{1,}$ T_2 and T_3 are well developed along Punnapuzha tributary are located between Edakkara and Chungathara villages.

Upstream of the Chaliyar River and its nine tributaries, erosion prevails over accumulation and strath terraces predominate; whereas in the Nilambur valley area and in the downstream, fill terraces have developed. In the Nilambur valley area, the fill terraces are again incised exposing the pebble beds of the older terrace along the present day river bed. The T_1 terraces are the youngest low-level terraces of low relief and are particularly concentrated along the meandering courses and sharp bends of the stream. They lie at a much lower physiographic levels between 10-20 m above MSL (Fig. 3.14b). The middle level terrace (T_2) is seen along the edges and lower levels of the mounts flanking the alluvial valleys (Fig. 3.14c). T_3 terraces have been identified in Nilambur valley along and between the Chaliyarpuzha and Punnapuzha Rivers (Fig. 3.14d). Terraces of three generations terrace are well exposed in Nilambur valley area (Fig. 3.14f).

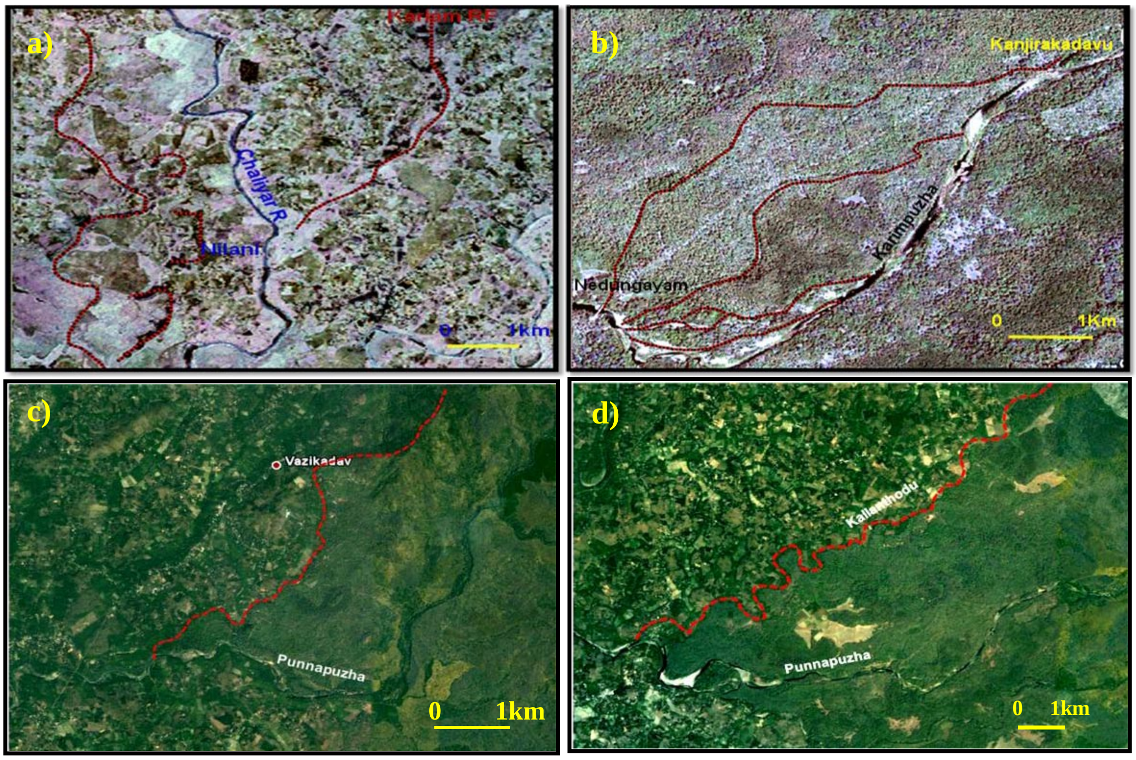


Fig. 3.13 Palaeochannels delineated from the radiometrically enhanced Google Earth imagery. (a) Abandoned palaeochannels of Chaliyar River at Nilani-Kaippini area, (b) palaeochannels of Karimpuzha tributary between Nedungayam and Karadikundu, (c) palaeochannel in Athithodu stream of Punnapuzha tributary, and (d) palaeochannel in Kallanthodu stream of Punnapuzha tributary .

Marshes and back swamps

Marshes and swamps delineated are distributed all along the Chaliyar River (Fig. 3.14e). These are areas of periodical inundation of water and get flooded during monsoon. The low-lying areas of the floodplain beyond the natural levee are known as back swamps or flood basins over which the finer materials are deposited during overbank floods. These low-lying areas are naturally waterlogged and marshy areas, serving as regulators of hydrologic regimes. Most these marshes in this area are abandoned channel scattered all over the active flood plain.

Erosional landforms

The landforms that are carved by denudational processes, either by physical or chemical weathering of structural or depositional landforms are grouped into erosional landforms. Erosional landforms in Chaliyar River drainage basin are denudational and residual hills, valleys and interfluves and pediments.

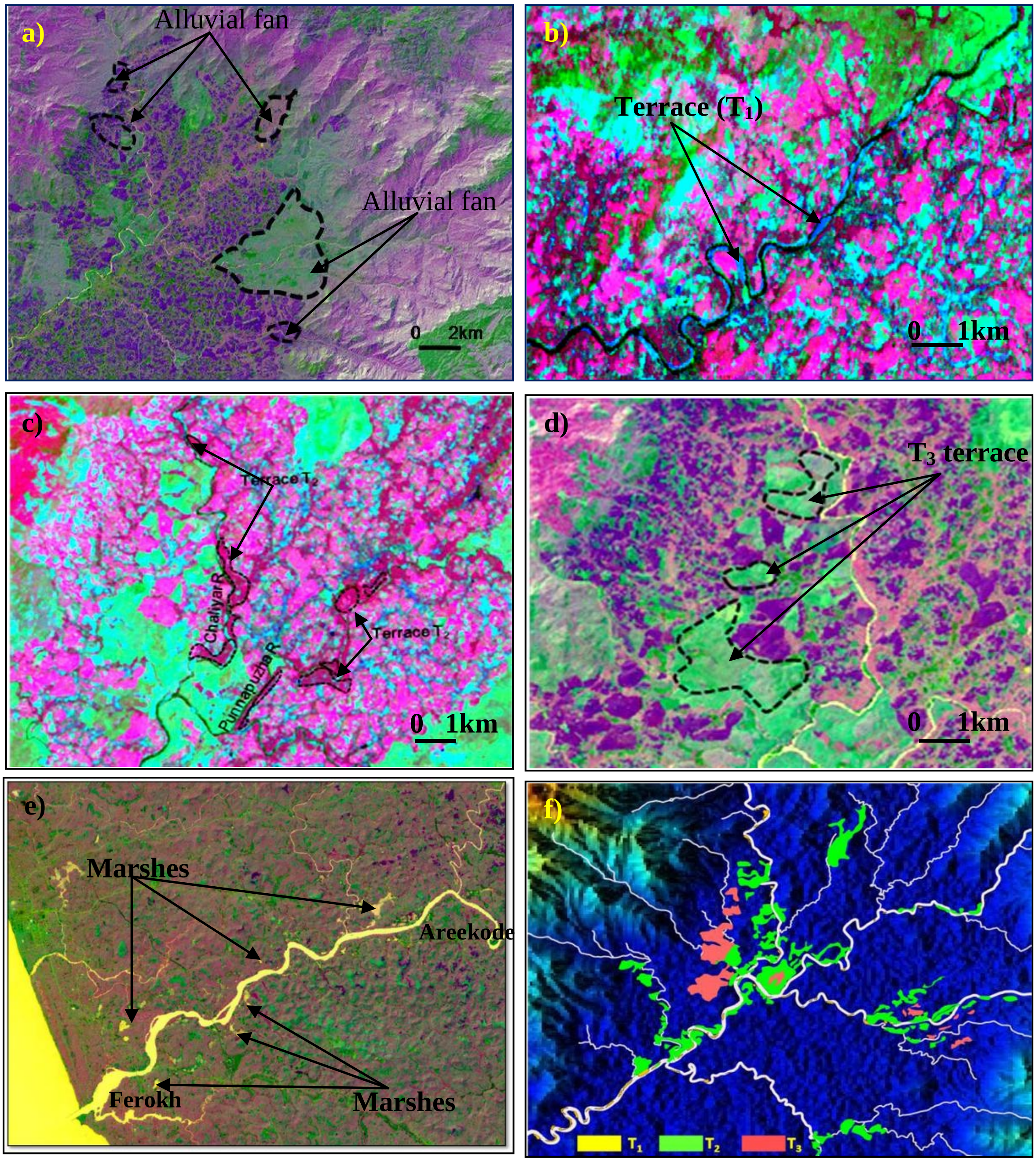


Fig. 3.14 Radiometrically enhanced IRS-P6 LISS III imagery showing (a) alluvial fans in Chaliyar River drainage basin, (b) well developed T_1 terrace along the Chaliyar River, (c) T_2 terraces of Chaliyarpuzha and Punnapuzha, (d) T_3 terrace developed on the left bank of Chaliyarpuzha, (e) marsh and swamps observed all along the Chaliyar River, and (f) DEM of Nilambur valley showing well-developed T_1, T_2 and T_3 terraces.

Denudational and residual hills

Denudation hills can be structural in origin but may not preserve the structural identity due to the strong erosional activity. These are areas of medium to high relief with altitude ranging from 100 to 600 m above MSL. Residual hills are low relief mounts, and are remnants of structural hills, terraces or pediments with an elevation ranging from 40 m to 100 m above MSL in the study area. In the study area these occur as isolated hills surrounded by flat topography. This geomorphic surface is well developed in Kurathi Mala and Mysore mala (Fig. 3.15a; b).

Valleys and interfluves

Incised valleys bordered locally by cliffs and separated by interfluves that are at a higher elevation for inundation by the present day stream and form the erosional valleys and interfluves. In the upper reaches, valleys are bordered by 10 to 20 m cliff where the Precambrian rocks (Fig. 3.15c) are well exposed. The intervening area between two stream channel courses in the upper Western Ghats region, the lower lateritic plains and planar floodplain surfaces with thin soil cover are considered as interfluves.

Pediment

Hills of planation cut across the upturned edges of tilted beds are referred to as pediment. In the study area, the slopes of the pediments are gentle and have a thin veneer of gravel. The pediment in the Chaliyar River drainage basin exhibits a considerable degree of dissection and can be considered as the product of the second cycle erosion of earlier or older flat pediments as suggested by Thornbury (1969). These pediments after dissection give rise to valleys and interfluves. In the upper reaches, pediments are characterized by soil cover and forest vegetation (Fig. 3.15d).

Structural landforms

Structural hills and valleys

A number of hills and valleys of the area owe their configuration to structural deformation (Fig. 3.15e; f). Linear sharp crested folded hills and hogbacks are observed in the study area especially in the upper reaches of (Western Ghats and Wayanad Plateau). A number of parallel hogbacks are observed at Wandur. These hogback crested hills are found folded in the west of Polakkad. Sudden change in the valley trend from NE to SW direction indicates the rapid change in the direction of valley development due to the strong tectonic activity. This tectonic activity might have also contributed to the development of Nilambur valley. The high mountains in the NE, SE and NW are rocky cliffs with steep valleys. The summits of the mountains are rocky and escarpment slopes are its characteristic feature of these mountains. Well-developed talus scree slopes are observed at some places and are characterized by exfoliated rocky outcrop.

3.4 Summary

The relationship between tectonics and drainage network geometry in the Chaliyar River drainage basin is brought out with the help of remote sensing studies, and the deformative events in the Chaliyar River drainage basin have been reconstructed. High hill ranges of Chaliyar River basin are dominated by dendritic pattern but rectangular pattern also form a major drainage pattern. Trellis pattern is mainly observed in the sub-basin - 7 drained by Punnapuzha tributary. Radial patterns of drainage are observed around isolated hills. Sub-basins 1 and 2 exhibit deranged drainage pattern, where the streams flow through plains. A relationship between lineaments and drainage network is reflected in the rectangular, trellis and parallel drainage patterns, this relationship is also observed in the lower order streams that flow perpendicular to the main river stem and to the lineaments. Heterogeneity in the distribution of drainage patterns in the basin itself is a cue to the role of tectonism and is strictly dependent on the substratum anisotropy.

Overall, the Rosgen Stream classification suits with the drainages of Chaliyar River. Based on Rosgen classification, the 17 segments of Chaliyar River are classified into A, B, C, D, E and F type streams. ‘A’ type streams are seen in the upper reaches, which flow through steep V-shaped valleys without well-developed flood plain and are fairly straight. Chaliyar River takes the form of types ‘B’ and ‘C’ when it starts flowing through the broad Nilambur valley. ‘B’ type streams are moderately entrenched with moderate to steep slopes. The high values of width/depth ratios and moderate entrenchment ratios make ‘B’ type stream quite resilient to moderate values of watershed changes. The ‘C’ type streams are moderately entrenched, and therefore, use their floodplain during large discharges. ‘D’ type stream is usually found in well-defined alluvial valleys. But in Chaliyar River it occurs on the upper reaches of the stream as the river debouches into the Nilambur valley where there is sudden break in

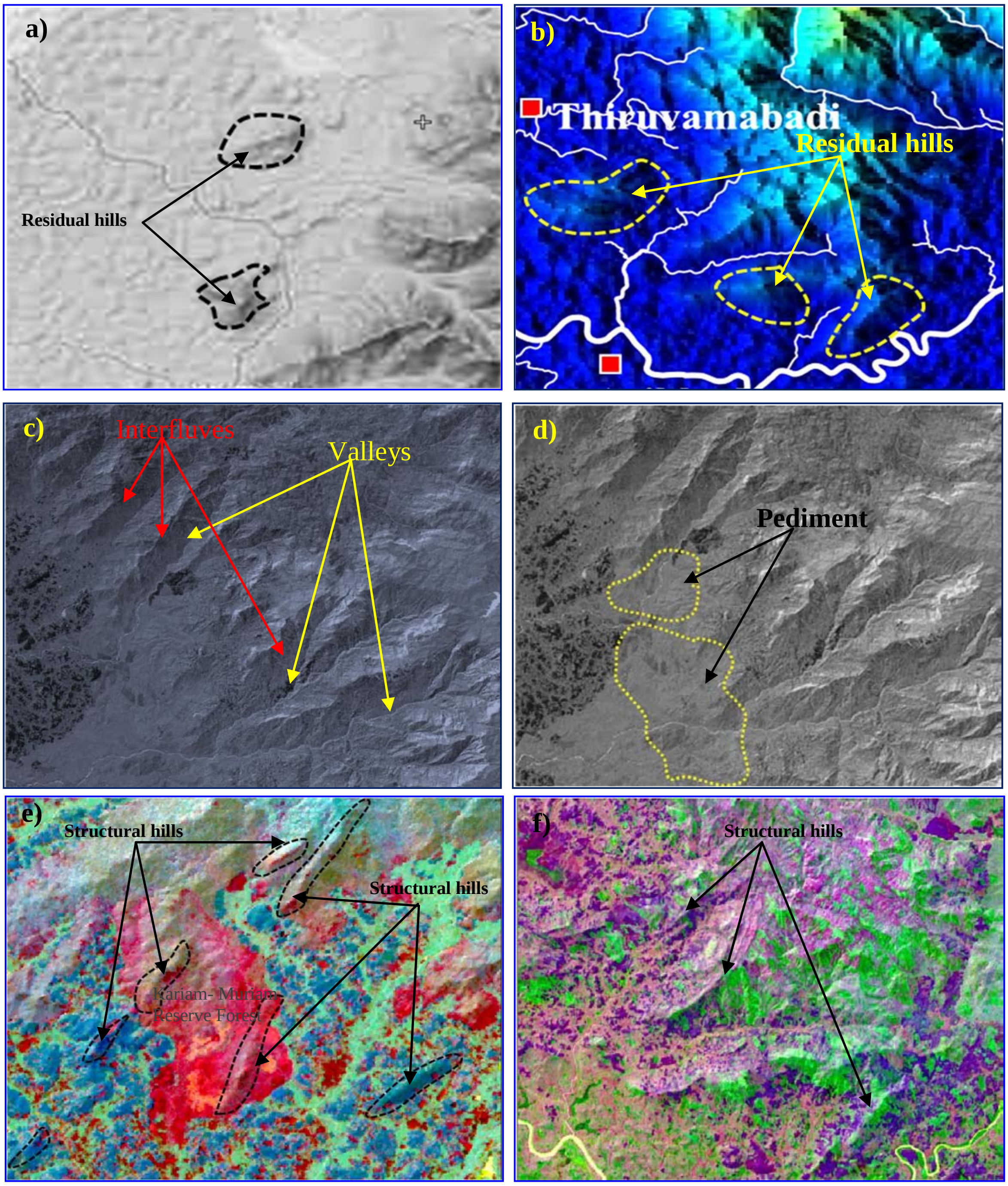


Fig. 3.15 Enhanced IRS-P6 LISS III images showing (a) & (b) residual hills located north of Wandur and north of Arikkod, (c) Valleys and interfluves in the eastern margin of Chaliyar Basin, (d) Pediments at the foothills of Nilgiri hill ranges, (e) NE-SW trending linear structural hills in Chaliyar Basin, (f) Structural hills in the western part of the Nilambur valley. Broad swerve of the ridge crest can be observed on the high hills ranges of Nilambur Kovilakom Forest.

the physiographic slope. Braided channels are characterized by moderate to high bank erosion and frequent shifts in bedforms. The gradient of channels is similar to that of valleys. The anomalous behaviour of the river by the development of D type stream in the upper reaches can only be explained by the localized tectonic activity along the stream course. ‘E’ stream types are generally found in wide alluvial valleys, ranging from mountain meadows to the coastal plain. The stream takes its type ‘E’ form at two levels, just after the break in slope where it debouches into the Nilambur valley as well as at its lower reaches. The ‘E’ stream type is slightly entrenched with low width/depth ratios and moderate to high sinuosity and the bedform features exhibit consistent riffle/pool sequences. The ‘F’ stream types are deeply entrenched, often meandered with a high width/depth ratio and are typically working to create a new floodplain at a lower elevation and will often evolve into ‘C’ and then ‘E’ stream types. This evolutionary process leads to extensive bank erosion, bar development, and sediment transport and are observed along the Chaliyar trunk system.

Landforms delineated from satellite images and aerial photographs can be broadly classified into erosional, depositional and structural landforms. The geomorphological map thus has been prepared and is used as the base map further field studies. Landforms that exhibit characteristic geomorphic features of tectonic activity have been discussed in detail in Chapters IV and V.

Chapter IV

FIELD GEOLOGY AND GEOMORPHOLOGY

4.1 Introduction

Field observations of lithological and structural features are vital for the preparation of geological maps that shows the areal distribution of geologic units and orientation of structural features like foliation, lineaments etc.. Field studies play an important role in understanding the dynamics and evolutionary processes that carved the present day landscape and the complexities in the evolution of a drainage basin.

Extensive field work is carried at different locations in the study area. Each lithological, structural and morphological unit is inspected and recorded the details. The geomorphic expressions observed in the field are incorporated in the final geomorphologic map. The selected geomorphic features such as terraces, braids, strath terraces are mapped. In order to identify ideal stream profile sections, feasible transverse profiles along the Chaliyar River are mapped after taking consideration of the objective of the study.

4.2 Lithology

Chaliyar River drainage basin forms part of the Precambrian Peninsular Shield of India. The area is mainly represented by the Archaean high grade metamorphic rocks like charnockite and its gneissic form. Charnockite Group of rocks makes up the high hills and steep slopes flanking the undulating plains in the east and west. Enclaves of amphibolite, metapyroxenite, talc-tremolite-actinolite schist, metagabbro, banded magnetite quartzite, grunerite schist, quartz- sericite schist and fuchsite quartzite within the migmatite represent the vestiges of the Archaean Wayanad Supracrustals (Pillay and Koshy, 2002). These enclaves vary in size from very small bodies measuring a few centimeters to large bodies of several metres across. Dolerite is the younger basic intrusives and the younger acid intrusive is pegmatite and quartz veins. Innumerable quartz veins occur all over the area and they are the major source for the primary and placer gold. Towards the Nilambur valley, lithology changes to Archaean migmatites with hornblende-biotite gneiss constituting the major rock type. Local variations of hornblende - biotite gneiss to biotite gneiss and hornblende gneiss with or without garnet are also common. Two to three meter thick laterite capping is present over the gneiss in the southern plain areas and thick soil cover encompasses most of the remaining area. Two generations of alluvium are observed, the older one occupying the higher levels of the flood plain, is indurate and partially lateritized, and the younger one is found in the present day river channels. The rugged terrains of the north, east, west and south of the study area are under thick forest cover. The midland of the drainage basin has been lateritized extensively resulting in the limitation of lithologic exposures to the river sections, road cuttings and well sections.

Wayanad Supracrustals

Wayanad Supracrustals are the oldest rock units, observed as enclaves within the Charnockite Group of rocks and migmatites. Wayanad Supracrustals comprise talc-tremolite-actinolite schist, amphibolite, magnetite quartzite, fuchsite quartzite and quartz-mica schist. Talc-tremolite-actinolite schist rock is well exposed on the right bank of Punnapuzha north of Konnamannu (Fig. 4.1a). Another band of talc-tremolite schist was observed at 2 km north of Vazhikadavu, extending in a NE-SW direction from Manalpadam along the northwestern side of Karakodupuzha. Magnetite quartzite veins are ubiquitous in the northern, southern and northeastern part of the Chaliyar River drainage basin. These impersistent bands vary in thickness from few metres to about 20 metres with strike length varying from few metres to about 3.5 km. The most prominent one is the Kurathimala ridge, 3 km north of Chungathara with NE-SW trend. This ridge contains several parallel bands of magnetite quartzite interspersed with quartz veins. Magnetite quartzite veins occur in association with talc-tremolite-actinolite schist at many places. At Tumbimala (Fig. 4.1b) and Aruvakkod areas, magnetite quartzite veins trend NW-SE. Width of these bands varies from a few metres to over 30 m and length a few tens of metres to hundreds of metres. Large bands of amphibolites are observed in the Maruda - Mannuchini, Kariam - Muriam and Munderi areas (Fig. 4.1c). Amphibolite exhibits various stages of migmatization - from amphibolite to migmatised amphibolite to hornblende gneiss. Amphibolite also occurs as enclaves within the migmatitic rocks (Fig. 4.1d).

Charnockite Group

Charnockite Group of rocks are the most wide spread rock units with charnockite, charnockite gneiss and pyroxene granulite members. The peaks, high hill ranges (Fig. 4.2a) gorges and valleys expose massive charnockite, which are presently quarried out (Fig. 4.2b). Charnockite gneiss is restricted to the steep slopes of high hills (Fig. 4.2c). It is extensively migmatised to hornblende-biotite gneiss and biotite gneiss in the low-lying areas flanking these high hills. Exposures of these rocks are observed at Korampuzha and Ayirani areas. Pyroxene granulite occurs as enclaves, lenses and bands with the charnockite and charnockite gneiss (Fig. 4.2d).

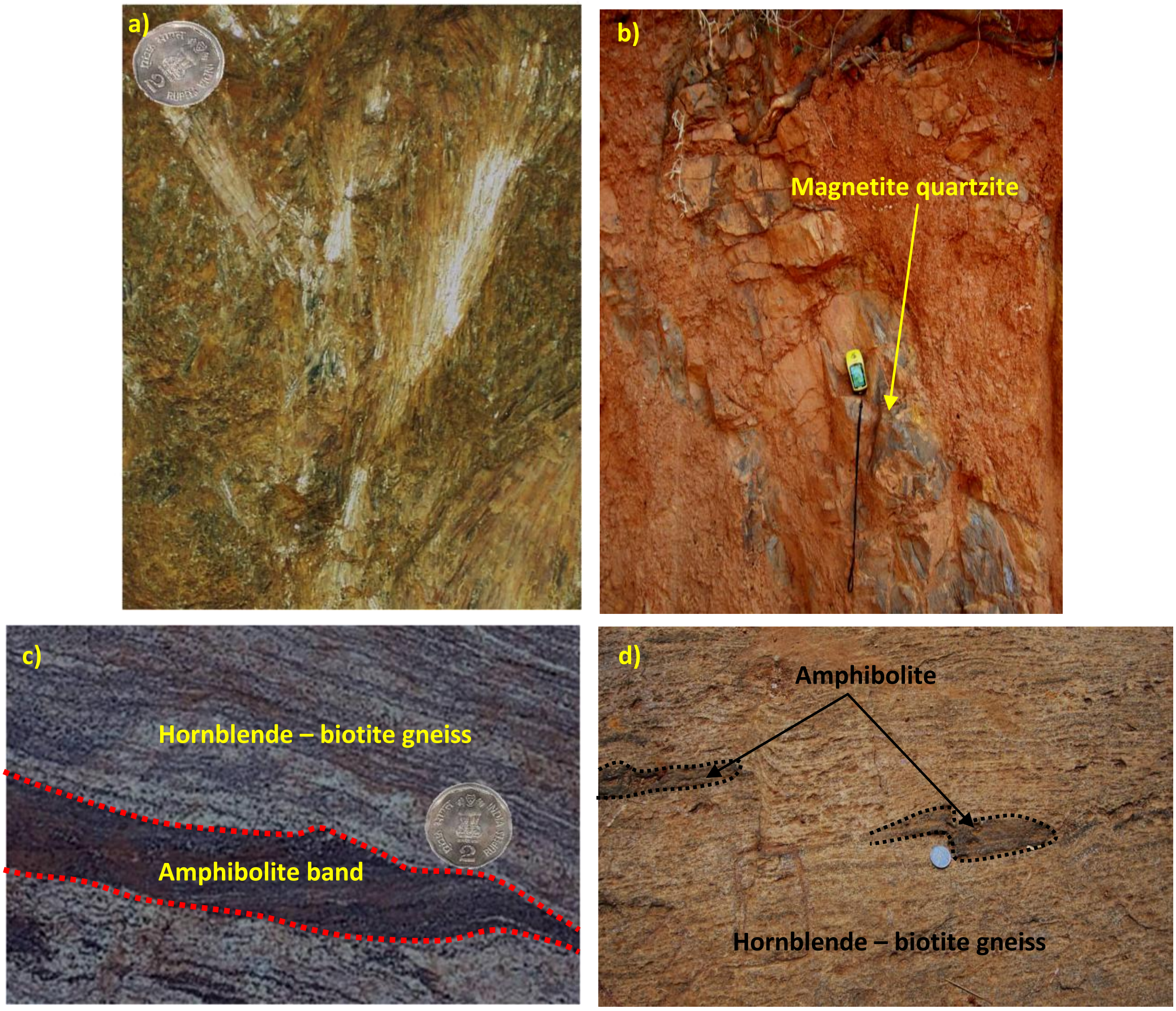


Fig. 4.1 Wayanad Supracrustals of Chaliyar River drainage basin. (a) Talc-tremolite-actinolite schist (Location: north of Konnamannu); (b) highly fractured magnetite quartzite bands. Intense lateritization in the terrain has obliterated the physical characteristics of the rock (Location: Tumbimala); (c) amphibolite band in the hornblende-biotite gneiss (Location: Kariam - Muriam Reserve Forest); (d) enclaves of amphibolite in the hornblende - biotite gneiss (Location: Manali).

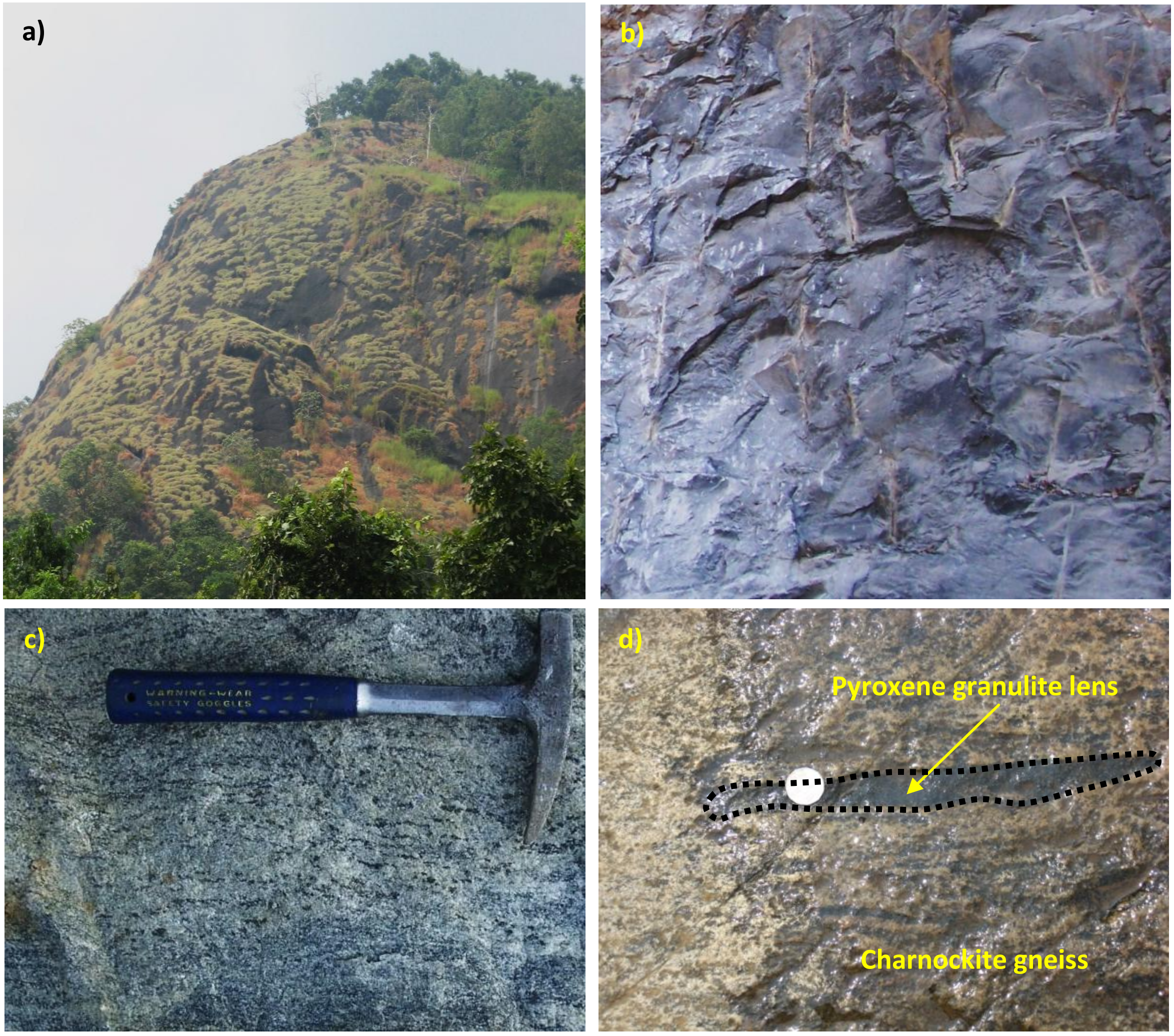


Fig. 4.2 Charnockite Group of rocks in Chaliyar River drainage basin. (a) Charnockite hill (Location: Adyanpara); (b) massive charnockite exposed in a quarry (Location: north of Nellikkaparamba); (c) charnockite gneiss (Location: Arikkod); (d) Pyroxene granulite lens in the charnockite gneiss. (Location: Ayirani).

Migmatites

Migmatitic rocks occupy major part of the Nilambur valley comprising hornblende-biotite gneiss, biotite gneiss and hornblende gneiss. Hornblende-biotite gneiss and biotite gneiss (with or without garnet) are the dominant unit in the central and eastern part of the Nilambur valley (Fig. 4.3a,b). Biotite gneiss is also observed in the western part flanking the charnockite hills. Hornblende-biotite gneiss is observed in the northern part of the terrain and contains enclaves of amphibolite, magnetite quartzite, fuchsite quartzite and meta-ultramafics.

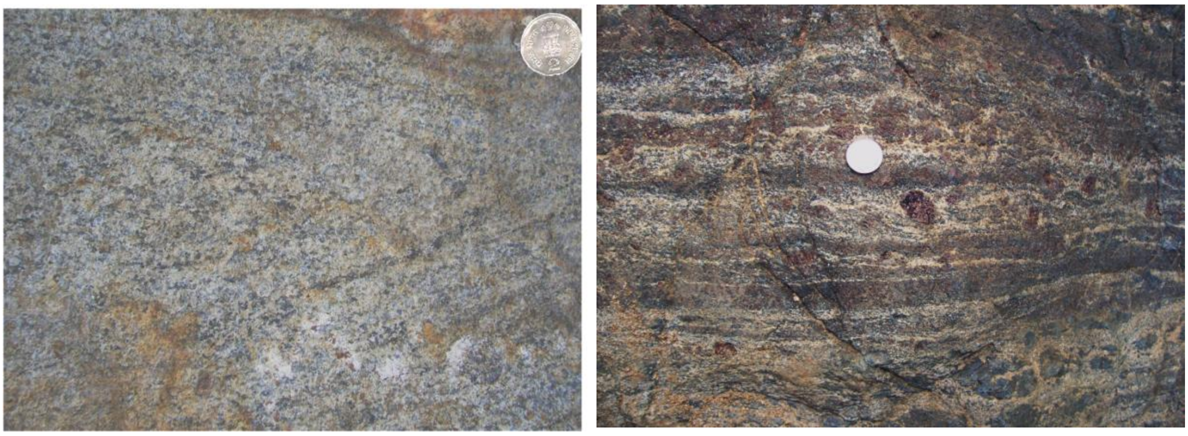


Fig. 4.3 Migmatitic rocks in Chaliyar River drainage basin. (a) Hornblende-biotite gneiss (Location: Kurumbalkotta), and (b) Garnet-biotite gneiss (Location: Kodinji).

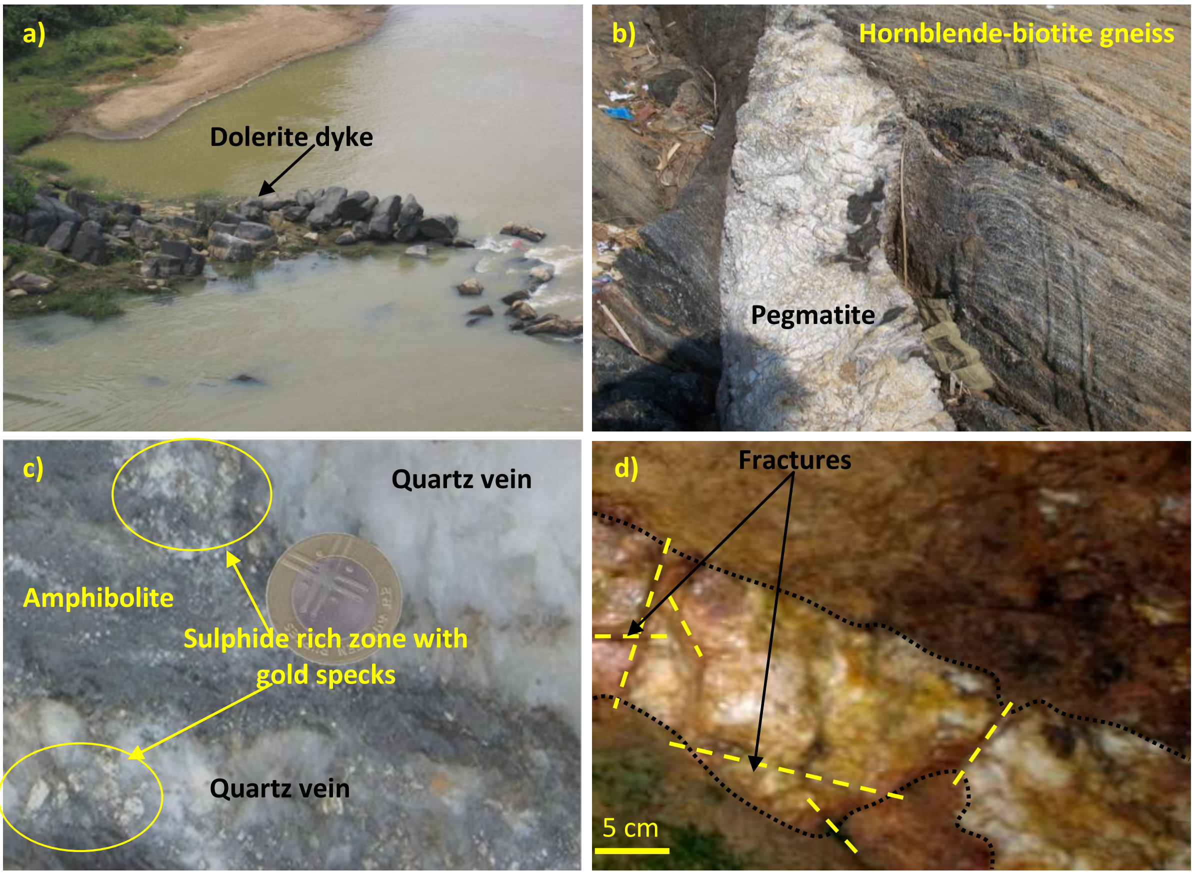


Fig. 4.4 Younger intrusive rocks in Chaliyar River drainage basin. (a) Dolerite dyke cutting across the Chaliyar River course trending NE-SW; (b) Pegmatite vein in hornblende-biotite gneiss (Location: Kunnathupoyi); (c) sulphide rich quartz vein in the amphibolite country rock. This quartz vein form the of host rock for primary gold (Location: Devala); and (d) Quartz veins within the lateritized country rock. Fractures in the quartz vein are with limonitic stain (Location: Chungathara).

Younger intrusives

Basic intrusive in the Chaliyar basin is mainly dolerite (Pillay and Koshy, 2002). Boulders of dolerite are observed in the western part of the basin suggesting intense fracturing and weathering. Dolerite dykes are seen in the river course, cross cutting the Chaliyar River, west of Kunnathupoyi (Fig. 4.4a). These are exposed during the summer i.e., in the non-monsoon season when the river has meager flows. Acid intrusives in the basin are mainly pegmatite and quartz veins. Pegmatite veins cross-cut the migmatitic rocks along joint and fracture planes (Fig. 4.4b). Quartz veins are found abundantly in the migmatitic terrain and constitute the most important host rock for gold (Fig. 4.4c). Veins are emplaced along pre-existing fracture and joint planes without any preferred orientation. Quartz veins also exhibit fracturing (Fig. 4.4d).

Laterite

Intense lateritization has been observed in the midland and lowland zones of the drainage basin. Two to four meter thick laterite capping is present over the gneiss in the southern plain areas of the Chaliyar River drainage basin (Fig. 4.5). Intervening areas between stream courses in the lower plains are capped by laterite. At places it forms hard duricrust occurring on the top of flat-topped mounds.

4.3 Structure

The rocks of the area display three-phases of deformation. Evidences of the first phase of deformation (D_1) are seen as tightly appressed intrafolial isoclinal folds (F_1) as observed in hornblende-biotite gneiss at Vazhikadavu (Fig. 4.6a). At the left bank of Chaliyar River at Canoli, F_1 folds are well exposed in the hornblende-biotite gneiss (Fig. 4.6b). The second phase of deformation (D_2) also is represented by moderately tight to open folds (F_2) with its axial trace in a NE - SW direction. Axial planes of F_1 and F_2 folds are co-parallel and a number of antiformal and synformal folds have been found in the NE parts Nilambur valley, after F_2 folding. Fig. 4.6c shows tight- to open-fold (F_2) in hornblende-biotite gneiss at Nilambur. Tight- to open-folds observed in hornblende gneiss represent the second phase deformation (Fig. 4.6d). The third phase of deformation (D_3) had given rise to broad open warps with axial trace trending NW-SE to N-S. The dominant foliation trend is NE-SW, parallel to the axial trace of F_1/F_2 folds. The dip of foliation is nearly vertical or steep, towards NW or SE.

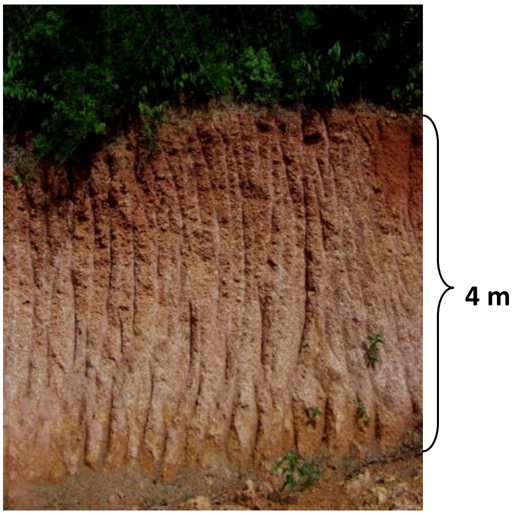


Fig. 4.5 Laterite profile of about 4 m thick. The top portion has a thin layer of regolith (~3 cm) and is underlain by the charnockitic bedrock (Location: West of Edakkara).

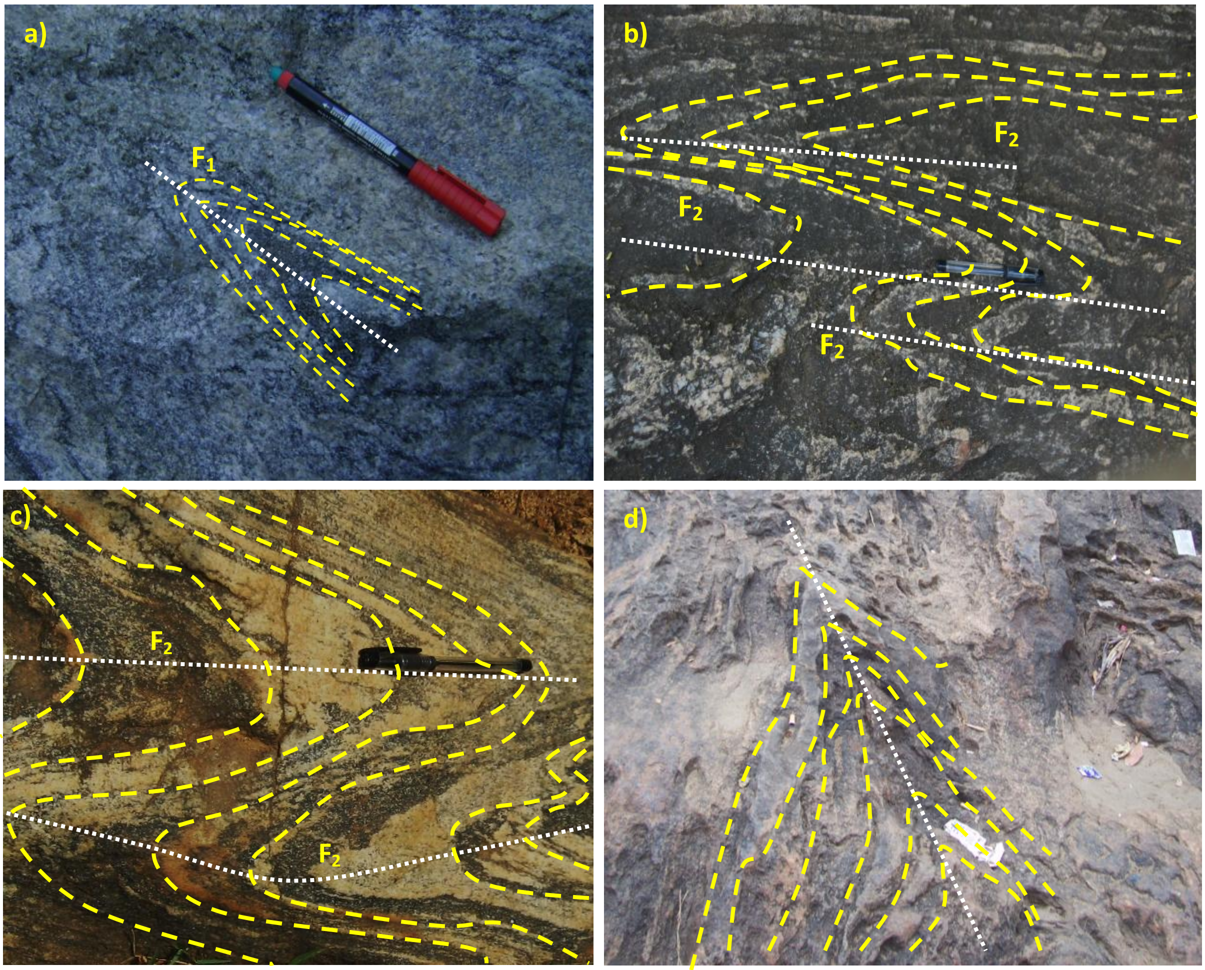


Fig. 4.6 Foldings in the migmatitic rocks in Chaliyar River drainage basin. (a) Tight appressed intrafolial fold (F_1) in hornblende-biotite gneiss; (b) Tight to open folds (F_2) in hornblende-biotite gneiss (Location: left bank of Chaliyar River at Canoli); (c) F_2 fold in the hornblende- biotite gneiss at Nilambur; (d) folding in the sheared hornblende gneiss at Edavanna. Brocken lines show the folded bands.

Faults, fractures and brittle shearing are ubiquitous in the drainage basin. Faults of mega-scale, meso-scale and micro-scale are omnipresent in the rocks exposed in Chaliyar River drainage basin (Fig. 4.7). Fractures and joints are very commonly observed in the area. These fracture planes and joint planes trigger slumping and landslides, probably due to tropical humid climate and intense monsoonal rainfall.

Brittle shearing trending N-S is traced at Adyanpara falls (Fig. 4.8a) and that of ductile shearing represented by mylonites at Arimbrakattumala (Fig. 4.8b).

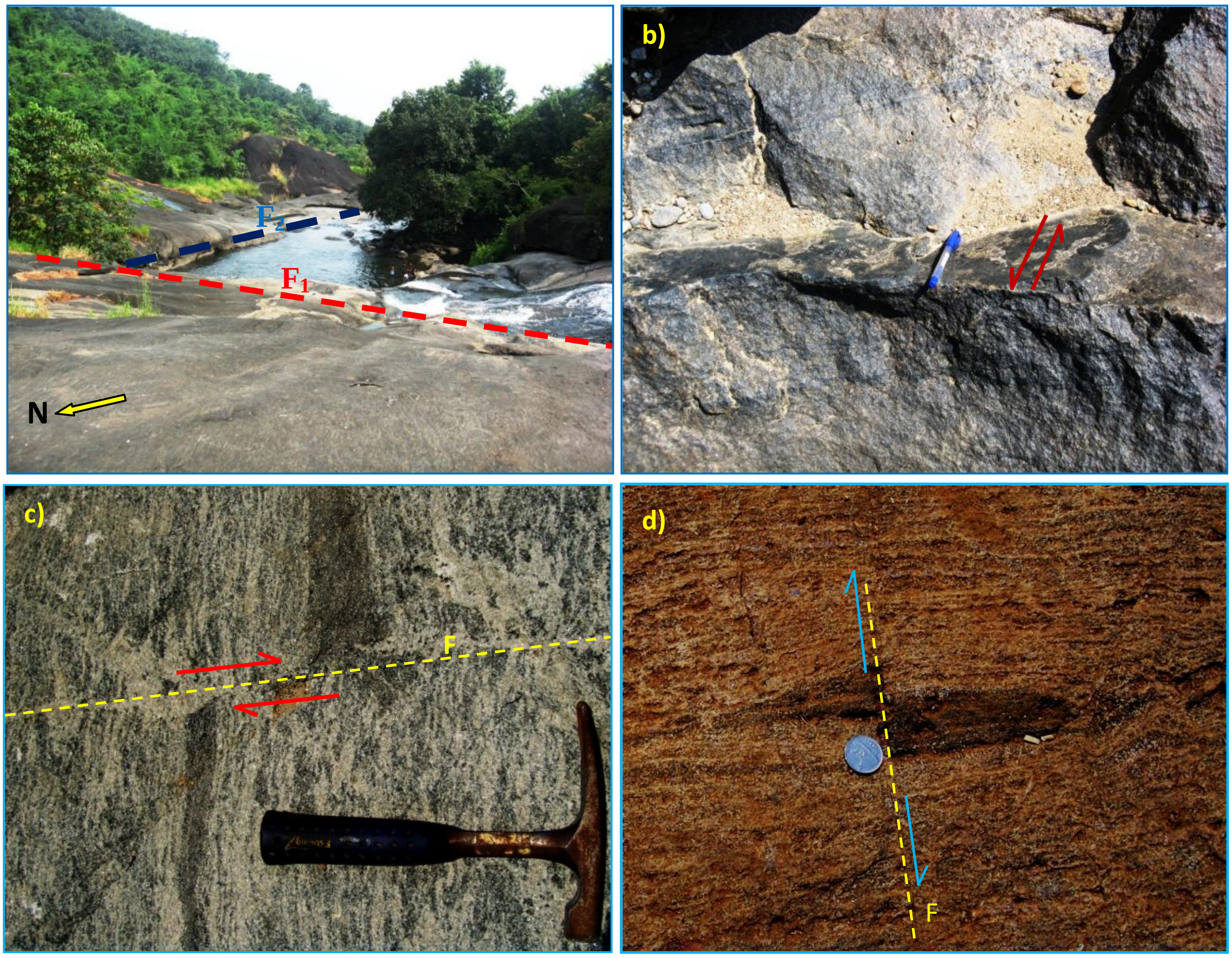


Fig. 4.7 Faults observed in Chaliyar River drainage basin. (a) Mega-scale faults at Adyanapara falls. E - W trending younger fault (F_1) cut across the N - S trending F_2 fault; (b) Meso-scale fault in the charnockite gneiss at the left bank of Karimpuzha (Location: Nedungayam); (c) Meso-scale fault in the biotite gneiss (Location: Chattallur); (d) Micro-scale fault in the hornblende-biotite gneiss. Location: Manali

Fig. 4.8 Shearing observed in the rocks of Chaliyar River drainage basin. (a) Brittle shearing with N-S trend in charnockite (Location: Adyanpara waterfalls); (b) Mylonite developed in a ductile shear zone (Location: Arimbrakuttumala).

Fig. 4.9 Different erosional landforms in the study area. (a) Residual hill (Location: Kurathimala); (b) structural hill (Location: Polakkod); (c) denudational hills seen in the upper reaches of Punnapuzha River; (d) vertical cliffs where the Precambrain rocks are well exposed (Location: Adyanpara).

4.4 Landforms

Fluvial geomorphology in each drainage system reflects a unique adjustment of the river to physical, climatic, tectonic and anthropogenic processes. Fluvial landforms in the study area can be broadly classified into erosional and depositional landforms. Erosional landforms are characterized by landforms like strath terrace, pediment, valleys and interfluves, hills and mountain ridges and depositional landforms like bars, depositional terraces, braids, valley fills/channel fills are observed.

4.4.1 Erosional landforms in the upper reaches of the Chaliyar River drainage basin

Erosional landforms in the Chaliyar drainage basin are mainly observed in the upper reaches as structural hills and valleys, denudational and residual hills, and valleys and interfluves.

Structural hills and valleys

A number of hills and valleys of the area owe their configuration to structural deformation. Linear sharp crested folded hills and hogbacks are observed in the study area especially in the upper reaches i.e., in the Western Ghats and Wayanad Plateau. West of Palakkod (Fig. 4.9b), hogback crested hills are found folded. Sudden change in the valley trend from NE to SW direction indicates the drastic change in the direction of valley development suggesting the strong tectonic domain which contributed to the development of Nilambur valley.

Denudational hills

Denudation hills can be structural in origin but may not preserve the structural identity due the strong erosional activity. These are areas of medium to high relief with altitude ranging from 100 to 600 m above MSL (Fig. 4.9c).

Residual hills

These are low relief mounts with an elevation ranging from 40 m to 100 m above MSL. These are remnant of structural hills, terraces or pediments. In most of the area it occurs as isolated hills in plain. The well developed residual hill is observed at Kurathi Mala (Fig. 4.9a).

Valleys and interfluves

Incised valleys bordered locally by cliffs and separated by interfluves that are too elevated for inundation by the present day stream. In the upper reaches, valleys are bordered by 10 to 20 m cliff where the Precambrian rocks are well exposed (Fig. 4.9d). The intervening area, between two stream channel courses in the upper Western Ghats region, the lower lateritic plains and planar floodplain surfaces with thin soil cover are considered as interfluves. Here the interfluves are just a few feet higher than the valley floor.

4.4.2 Fluvial landforms

Fluvial landforms identified during field studies are terraces - strath terraces, fill terraces of different levels, and terraces developed within the alluvial fan deposit, palaeochannels, palaeo-alluvial fans, pebble beds, present day stream bed, sand-, braided- and point bars, channel fills, and alluvial river and active flood plain.

Terraces

In the Chaliyar river basin, three terraces have been demarcated from the aerial photographs and satellite imagery and were subsequently verified during field checks. Chaliyarpuzha, Punnapuzha and Karimpuzha have very remarkable fluvial terraces mainly aligned along the meandering courses. Most of these terraces are unpaired suggesting that rejuvenation took place continuously (Fig. 4.10a,b). There is no evidence of still - stands of the stream during deepening of the valley. The staggered elevation of the terraces below the original stream valley floor suggest that lateral abrasion was accompanied by down cutting as the stream wandered from one valley side to the other. Such continuous incision or rejuvenation commonly results from localized tectonic uplift, gradual tilting, climatic change or change in load volume relation of the streams. Based on the relative height and age of formation, these terraces are classified into T_1, T_2 and T_3. These terraces can be classified as erosional, cut and fill unpaired terraces, and are commonly the products of tectonism or sudden change in the climatic regime.

In the upstream direction of the Chaliyar River and its tributaries erosional activity prevails over accumulation and strath terraces predominate; whereas when the stream reaches Nilambur valley area, the fill terraces preponderate. Strath terraces are also observed in the downstream part of the tributary streams of Chaliyar River predominantly along the left bank of the streams (Fig. 4.10).

In the Nilambur valley area, the fill terraces are again incised exposing the pebble beds of the older terrace, along the present day river course as observed in

Ambalappoyi area (Fig. 4.11a). Chaliyar River has incised through the bedrock along a fault plane trending NE-SW adjacent to the Manavedan School at Nilambur (Fig. 4.11b). Here the upthrown part of the bedrock forms the T_1 terrace and lateritized sandy horizon further east forms the T_2 terrace. Interestingly, T_1 terrace is unpaired whereas T_2 terrace is paired. River incision along the fault plane is also observed at Nedungayam in Karimpuzha River (Fig. 4.11c). Here the bedrock is exposed along the river bed. The left bank of this stream forms strath terrace (T_2) which is about 12 m thick, while the right bank of the river is only half a meter above the present stream bed. This clearly indicates normal faulting with E – W trend, where the southern block has been up thrown and northern block has been down thrown. The present day Karimpuzha is flowing along the E – W fault plane of this normal fault. At Canoli Teak Garden, T_2 terrace is about 10 m thick on the right bank of Chaliyar River (Fig. 4.11d). Absence of T_1 terrace and scouring away of the T_2 terrace in the right bank of Chaliyar River indicates the river incision through well developed T_2 terrace. Terrace seen on the left bank in this area is strath terrace mantled by thin layer of clayey sand and quartz pebbles. At Tana, along the left bank T_1 terrace is being developed by migrating of the stream towards the right bank by scouring away the T_2 terrace (Fig. 4.11e, f).

Younger terrace (T_1)

The T_1 terraces are recent low-level terraces of low relief and are particularly concentrated along the meandering courses and sharp bends of the streams. They lie at a much lower physiographic levels i.e., between 10 - 20 m above MSL and are composed mostly of unconsolidated to slightly consolidated river sand, silt and clay intercalation with a thickness varying from 1 to 4 m. Well developed T_1 terraces are observed at Edavanna, Panankayam, and Nilambur areas (Fig. 4.12).

T_1 terraces of Chaliyar River and its tributaries are well developed and stabilized by thick vegetation (Fig. 4.12 a, b). At places these terraces are paired while becomes unpaired at some other locations. It can be inferred that localized tectonic activity has influenced in the development of unpaired T_1 terraces at places.

Older terrace (T_2)

The middle level terraces (T_2) are about 1 to 7 m thick and are seen along the edges and lower levels of the mount flanking the alluvial valleys as well as in the valley flats proximal to the present day river system. In Punnapuzha River, T_2 terrace is found perched at a height of 6 m from the channel near Nallathanni, which has been recently artificially terraced for construction purpose (Fig. 4.12d). In the Chaliyar River, east of Bhudan Colony and in Ambalappoyi area, T_2 terrace is found developed to a height of 5 m from the present day river level on the right bank (Fig. 4.12e). T_2 terrace is also well developed along the left bank of Chaliyar River ranging in thickness from 3 to 10 m (Fig. 4.11d). Near Mannathi temple, the surface expression exhibits scattered pebble of quartz over the ferruginous matrix (Fig. 4.12f).

T_2 terraces of Chaliyar River and its tributaries are well developed and stabilized with a thick canopy of vegetation, particularly teak forest (Fig. 4.13a), coconut and arecanut cultivation. They are composed of semi-consolidated fine- to coarse-grained sand (Fig. 4.13b) and ferruginous at places (Fig. 4.14a). Alternate bands of ferruginous sandy layer in these terraces indicate a series of deposition of sediment and subsequent exposure of the sediment to then existing atmospheric condition. In one of the vertical sections of T_2 at Tana, graded bedding and cross-bedding could be observed (Fig. 4.14b).

Oldest terrace (T_3)

In the Nilambur valley, along and between the Chaliyar River and Punnapuzha River, the oldest terraces (T_3) have been observed. These terraces occur as small hillocks and mounts and consist of lateritized and matured oligomictic gravel bed. In many places these are overlain by soil cover and secondary laterite of 0.5 to 1 m thickness. These terraces can be classified as the depositional terraces of Chaliyar and Punnapuzha. They are not preserved well due to intense anthropogenic activity and erosion, but are clearly seen when pits are taken for agricultural purposes (Fig. 4.15a) and also in some well sections (Fig. 4.15b). On the left bank of Chaliyar, west of Chungathara, T_3 terrace is exposed and extends to a few hundreds of metres in N-S direction and is about 80 m wide. The gravel bed with thickness ranging from 0.5 to 8 m, is composed mainly of quartz cobbles of about 50 cm diameter and smaller amount of quartz pebbles. The gravels are sub-rounded to rounded and elongated (Fig. 4.15c). The gravels are cemented in lateritized ferrugeneous matrix showing no preferred orientation or imbrications and are ill-sorted (Fig. 4.15d,e,f). The gravel bed is composed mainly of quartz cobbles with subordinate amount of quartz pebbles.

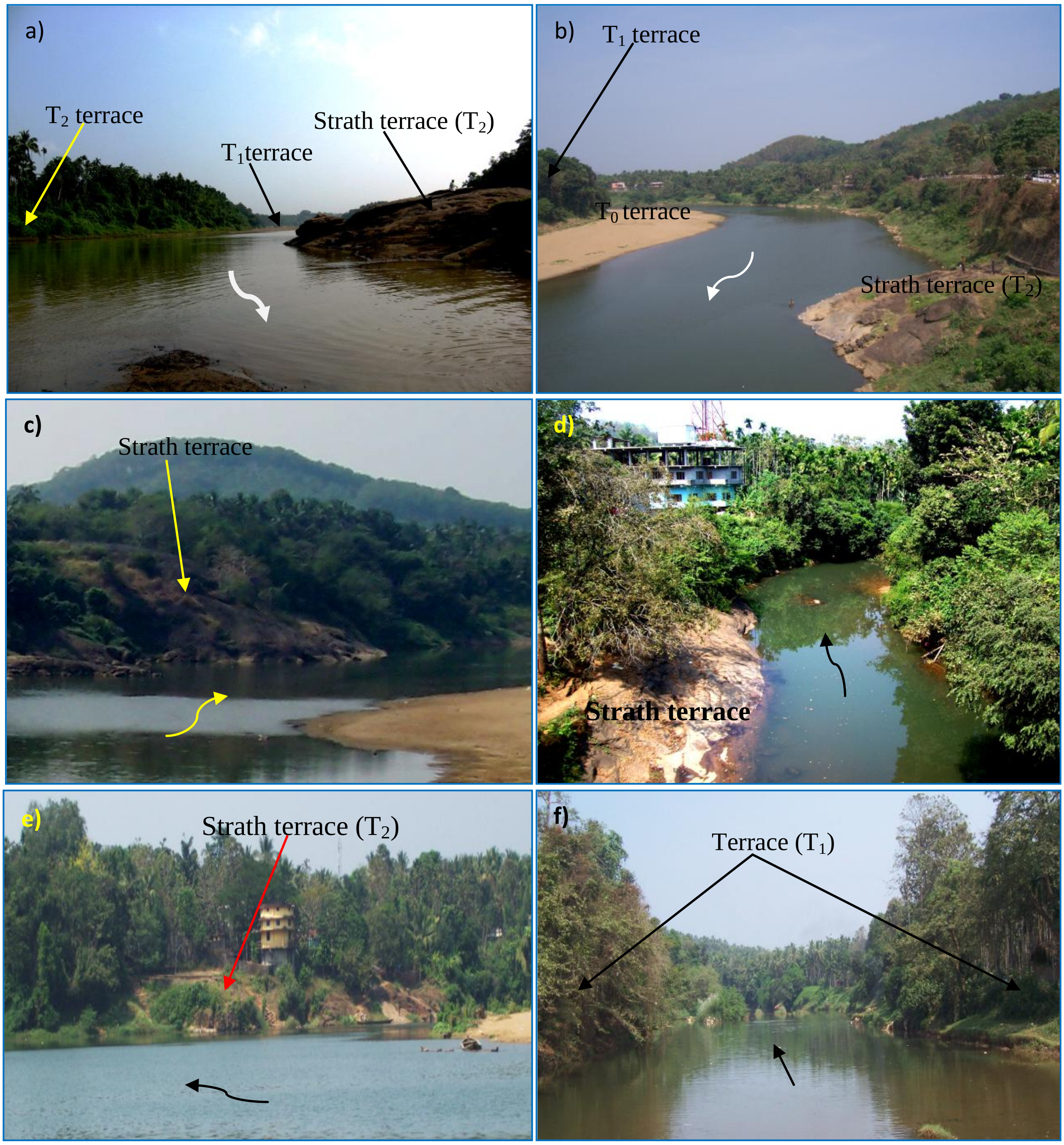


Fig. 4.10 Types of terraces in Chaliyar River drainage basin. (a) Unpaired terrace of Chaliyar River at Mambad. The left bank terrace (T_1) is 1 m thick and is rock cut, while the right bank terrace (T_1) is almost at the level of present day stream bed. T_2 terrace is about 5 m thick and covered by thick vegetation; (b) unpaired terrace of Chaliyar River at Arikkod. T_1 terrace on the right bank is depositional while the left bank is erosional terrace (T_2). Variation in the elevation of terraces is clearly observed; (c) Strath terrace observed along the left bank of Chaliyar River at Edavanna; (d) Strath terrace observed along the left bank Kuthirapuzha at Vadapuram; (e) Strath terrace observed along the right bank Chaliyar River at Mambad, and (f) paired terrace (T_1) of Iruvahnipuzha at Mukkam.

Fig. 4.11 River incision in Chaliyar River drainage basin. (a) Filled terrace (T_1) which have been re-incised as seen on the left bank of Chaliyarpuzha at Ambalappoyi area. Pebble bed at the bottom is overlain by a layer of silty sand and clay; (b) Chaliyar River getting incised along a fault plane in the bedrock. Lateritized older terrace (T_2) can be seen on the right (eastern) side of the photograph (Location: near Manavedan School, Nilambur); (c) bed rock incision along the fault plane at Nedungayam in Karimpuzha River. Here strath terrace has a thickness of 12 m from the water surface at the time of photo capturing (15/05/2007); (d) Well developed T_2 terrace of about 10 m thickness on the right bank of Chaliyar River at Canoli Teak Garden. The thickness of T_2 and absence of T_1 terrace signifies the incision of the river through T_2 terrace; (e) T_2 terrace on the right bank being incised by the Chaliyar River at Tana; (f) Erosion of T_2 terrace on the right bank and development of T_1 terrace on the left bank of Chaliyar river at Tana.

Fig. 4.12 Depositional terraces of Chaliyar River and its tributaries. (a) Thickly vegetated well - developed T_1 terrace along Chaliyar River at Edavanna; (b) T_1 terrace developed on the left bank of Chaliyar River at Panankayam; (c) T_1 terrace on the left bank of Chaliyar River near Nilambur; (d) stabilized T_2 terrace of Punnapuzha River near Nallathanni; (e) slumped T_2 terrace of Chaliyar River near Bhudan Colony. Here the thickness of terrace is about 6 m and is mainly composed of semi-consolidated fine grained sand; (f) loosely scattered quartz pebbles of T_2 terrace over the laterite near to the temple at Mannathi. This pebble bed extends over an area of about 2 km^2 from the present day Chaliyar River to the west.

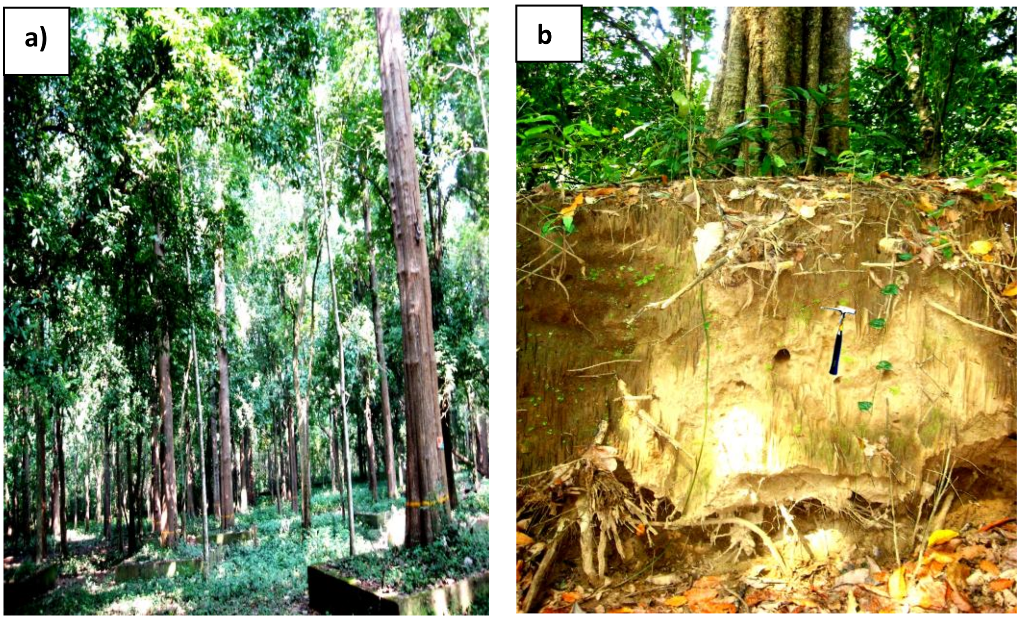


Fig. 4.13 (a) Canopy of teak plantation over the T_2 terrace at Canoli Forest area. (b) Upper part of the vertical profile (top 1m) of the T_2 terrace shows thick column of fine sand stabilized but not oxidized.

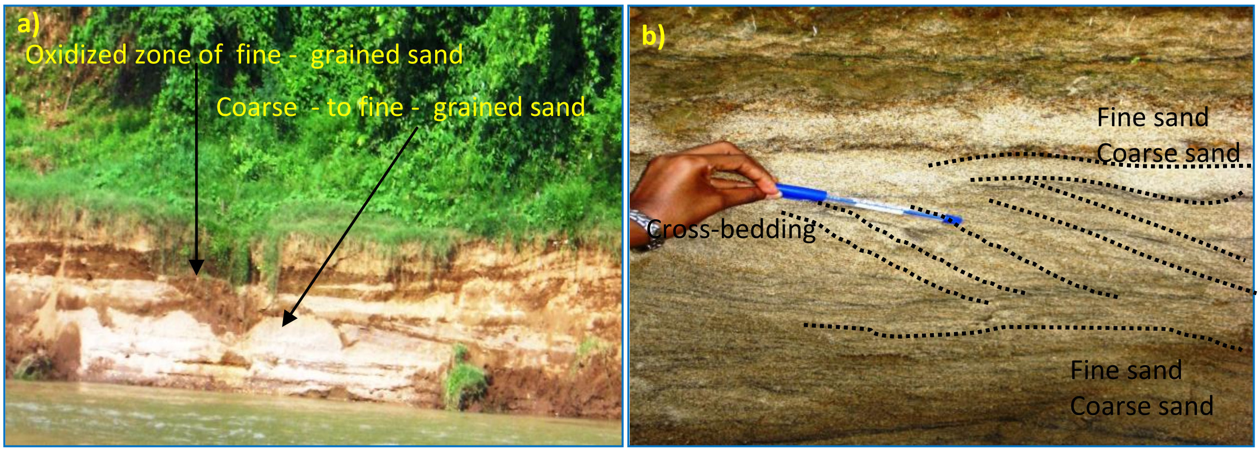


Fig. 4.14 (a) T_2 terrace of Chaliyar River along the right bank consisting coarse- to fine-grained sand. At places the sand horizons are oxidized; (b) vertical section of T_2 terrace on the right bank of Chaliyar River. Below a thin layer of soil coarse-grained to fine grained sand is seen which shows graded bedding. Below the graded bedded sandy horizon, cross-bedding is seen which is further followed by graded bedded sandy horizon (Location: Tana).

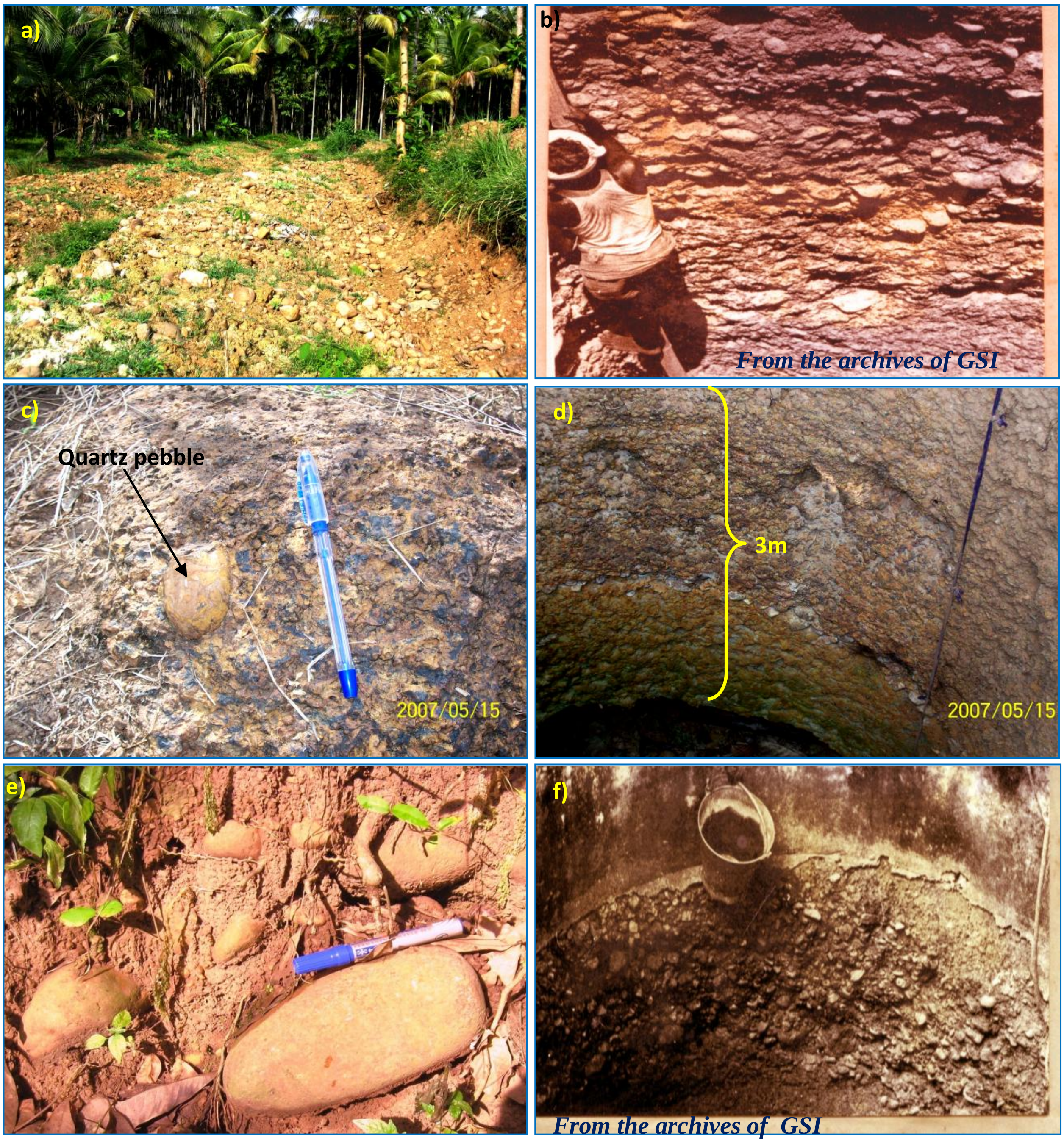


Fig. 4.15 Oldest terraces of Chaliyar River. (a) T_3 terrace of Chaliyar River well exposed when excavated for agricultural activity (Location: Kaippini); (b) T_3 terrace exposed in a well section. The 7 m thick pebble bed is very compact and lateritized; (c) Quartz pebble in the lateritized T_3 terrace exposed at Patiripadam; (d) Lateritized quartz pebble bed well - exposed in a well-section at Patiripadam; (e) sub-rounded to rounded pebbles seen in the T_3 terrace exposed along a road cutting at Nilani; (f) Gravel bed exposed in a well section at Nilani. Gravels vary in size from few cm to 45 cm.

Terraces within the alluvial fan

These terraces are cut in the alluvial fan material and are erosional terraces. Four such terraces are identified at Vellimaittam where the alluvial fan is cut by Ezhuvithodu stream (Fig. 4.16a). This type of terraces is characterized by polymictic pebble beds with hornblende–biotite gneiss, biotite gneiss, amphibolite and quartz as pebbles overlain by a thin sandy horizon (Fig. 4.16b).

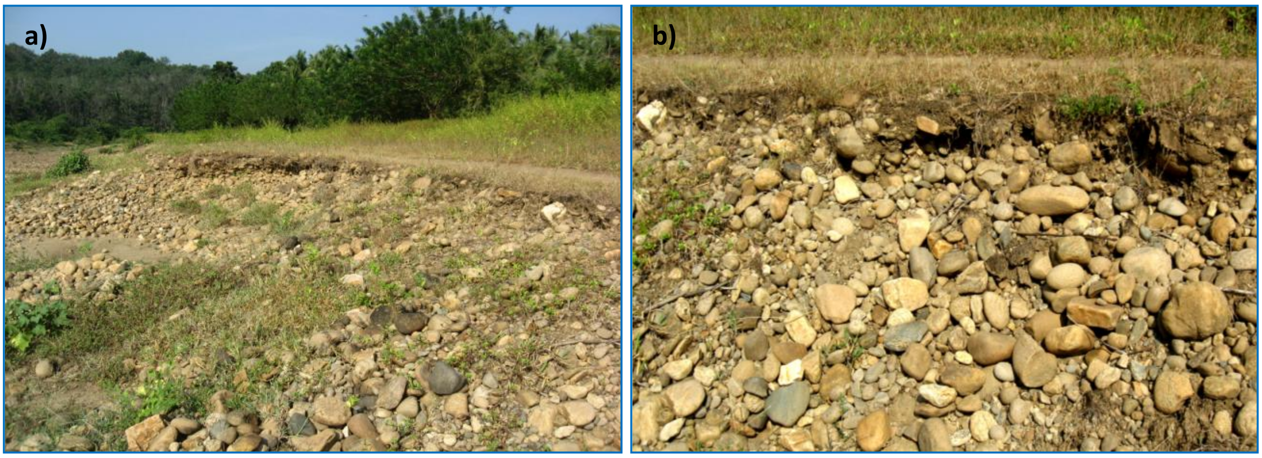


Fig. 4.16 Erosional terraces in Chaliyar River drainage basin. (a) Erosional terrace developed along Ezhuvathodu stream which flows through alluvial fan deposit; (b) polymictic pebble beds in the terrace within the alluvial fan (Location: Vellimattom).

Palaeochannels

Karimpuzha tributary has three palaeo-courses trending in the NE-SW direction for a stretch extending from Nedungayam to Chekuthankundu (Fig. 4.17a). Kallanthodu tributary with SW flow direction is supposed to be the palaeochannel of Karimpuzha (Fig. 4.17b). This stream is presently active only in the rainy season. Palaeochannels along Punnapuzha River are observed near Edakkara, Valluvasseri (Fig. 4.17c), Chungathara (Fig. 4.17d) and Manali. Karakkodupuzha River flows through a very wide alluvial valley with thick sequence of gravel bed, sand and silt layer appears as a miss-fit river for such a broad alluvial valley. So this SW flowing stream is considered as the earlier main course of Punnapuzha. The palaeochannels of Chaliyar River are seen at several places (Fig. 4.17e, f).

The sediment in the palaeochannels varies in size from cobbles to pebbles and from fine sand to silt (Fig. 4.18a). Cobbles and pebbles are mainly of quartz. At places it is highly oxidized resulting in the formation of limonitic oozes (Fig. 4.18b). This thick sedimentary layer is mined out for the manufacture of bricks.

Fig. 4.17 Palaeochannels at different locations in Chaliyar River drainage basin. (a) Palaeochannel of Karimpuzha stream at Karappuram and (b) at Kallanthodu, palaeochannel of Karimpuzha flowing southwest is active only during rainy season; (c) palaeochannel of Punnapuzha at Valluvasseri Reserve Forest; (d) palaeochannel of Punnapuzha at Chungathara. Presently silty clay is mined for tile and brick manufacturing; (e) palaeochannel of Chaliyar River at Kurathipadam; f) palaeochannel of Chaliyar River at Ichambatur - Ramachampadam area.

Fig. 4.18 Vertical cross - sections showing sediment deposit in a palaeochannel. (a) Sediment is made up of assorted pebbles, gravel, sand and silt; (b) sediment composed of quartz pebbles, sand and silt. Oxidized sand/silt and limonitic oozes are prominent in this vertical profile (Location: Valluvasseri Reserve Forest). Graded bedding is observed with sediment grading from pebbles to fine sand.

Fig. 4.19 Sediment deposits of alluvial fans. (a) Vegetation seen over the palaeo-alluvial fan at Nedungayam; (b) sub-rounded to rounded pebbles and boulders exposed in a trench at Nedungayam; (c) rounded to sub-rounded boulders and pebbles that have been excavated from the pit. Size of the boulders varies from few cm to 1 m (Location: Nedungayam); (d) rounded to sub-rounded pebbles exposed in pits dug for rubber plantation at Kaippini.

Palaeo-alluvial fans

Alluvial fans are aggrading deposits of alluvium deposited by a stream debouching from a canyon onto a surface or valley floor. Once in the valley, the stream is unconfined and can migrate back and forth, depositing alluvial sediments across a broad area. An individual deposit looks like an open fan with the apex being at the valley mouth, when viewed from above. The development of pediments and alluvial fans is progressive with the uplift of mountains and subsidence of adjacent basins (http://pubs.usgs.gov.,2004). In the present study, alluvial fans are observed in Karakkodu, Nedungayam, Vellimattam, Pattakarimaba and Kolikkadavu areas.

The Nedungayam alluvial fan developed by the Karimpuzha River covers an area of about 40 km^2. These alluvial fans comprise materials ranging in size from boulders to pebbles, sand and silt. They have a gentle slope and elevation ranges between 20 and 60 m. A number of alluvial fans are identified at Nedungayam, Pattakarimba, Karakkodu, Vellimattam and Kolikkadavu. All these fans located at the foothills at the break of slope with an elevation ranging from 10 to 60 m. They assume very gentle slope with traces of channel ways and hold luxuriant vegetation as observed at Chekuthankundu (Fig. 4.19a).

The surface of the fan deposit is sandy followed by ill-sorted and unconsolidated sediment comprising pebbles, cobbles and boulders. The alluvial fan is characterised by sub-rounded to rounded clasts varying in size from pebbles to boulders (Fig. 4.19b,c,d). These boulders and pebbles are mainly hornblende-biotite gneiss, charnockite gneiss, amphibolite, biotite gneiss and quartz veins. The rounding is due to the elongated catchment area upstream of the fan apex, as clasts are rounded during prolonged bed load transport and are temporarily arrested upstream of the fan apex as channel bars. The fan material comprises unsorted debris flow deposit and sandy layer. These clasts are remobilized and entrained in debris-flows on the fan during events of anomalous discharge (storm events). The clasts are mainly gneissic and show a progressive fall in maximum clast size from 60 cm to 10 cm away from the fan apex.

Pebble beds

Older lateritised gravel beds on the Chaliyar River course are well exposed in NW of Mannathi and south of Kaippini (Fig. 4.20a), SW of Pookkottumannu, Pongallur and near the confluence of Karimpuzha and Chaliyar Rivers. These gravel beds are also observed at Pattiripadam and east and north of Yutirkulam in Pandipuzha stream (Fig. 4.20b). Lateritized gravel beds occur as flat topped mounds consisting of pebbles, cobbles and boulders of vein quartz (80%), amphibolites, gneisses, magnetite quartzite etc. embedded in laterite matrix. These pebbles are rounded to well-rounded and spheroidal to discoidal in shape. The sphericity, roundness and sorting of the pebbles increases downstream but size decreases.

Lateritized older gravel beds are well exposed on the western side of Punnapuzha River. It occurs as detached gravel bed extending from east of Sankarankulam to the point where Punnapuzha joins Chaliyar River. At Palunda and Perunkulam also detached outcrops of lateritised gravel beds are observed. North of Maruda, gravels bed with huge boulders of quartz and magnetite quartzite is well exposed. The gravel bed at Nilani - Kaippini area abruptly ends on the edge of a paddy field (younger alluvium) and again exposed in some of the wells further south at a distance of about 150 m as explained by Cvetkovik, 1980. In Manali area, this lateritized gravel bed consists of cobbles of smaller sizes (< 15cm) and the matrix content is of equal volume to that of its gravel content. Around Kuttimunda, gravel beds are exposed on the lower slope of a mound but have only small areal extent.

Younger pebble beds are part of the younger terraces or palaeochannels and are not lateritized (Fig. 4.20c). Minor oxidation at places is observed as seen in Valluvasseri Reserve Forest (Fig. 4.20d).

Streambed

Chaliyar River has a streambed of non-uniform width and the tributaries show braiding and meandering even in the upper reaches. In the upper reaches stream bed is very active with waterfalls and rapids (Fig. 4.21a,b). Stream bed consists of sediments of varying size ranging from boulders to clay. Lower order streams (1^{st}, 2^{nd} and 3^{rd}) flow through a bed with angular to sub-rounded boulder beds (Fig. 4.21b). When the stream reaches 4^{th} to 6^{th} order, the stream bed is mainly composed of pebbles (Fig. 4.21c) and at its highest order (7^{th} order), the bed is mainly composed of sand (Fig. 4.21d).

Fig. 4.20 a) Pebble beds beneath the thick vegetation exposed along a road cutting (Location: South of Kaippini); b) older pebble bed seen east of Yutirkulam. Quartz pebbles are embedded in compact and highly ferruginous matrix; (c) Younger pebble bed in a palaeochannel of Karimpuzha near Nedungayam; (d) Slightly oxidized pebble beds in a vertical section palaeochannel at Valluvasseri Reserve Forest.

Sand bars, braided bars and point bars

Sand bars are common along the stream and are sparsely to moderately vegetated. Materials in the bars vary from fine sand to pebbles to cobbles. Sand bars of Chaliyarpuzha and Punnapuzha tributaries at places are moderately vegetated as observed in Ambalppoyi and Nellukuthu Reserve Forest (Fig. 4.22a,b).

At the break of hill slope, almost all the tributaries of Chaliyar River get braided, and are stabilized with thick vegetation cover. The Karimpuzha tributary shows strong braiding in its course from Chekuthankundu to Cherupuzha (Fig. 4.23a). In these areas, the stream loses its energy and sheds all the sediment it carried during its course and causes to develop braided channels. At Karulayi, the braided bars are partially stabilized with moderate vegetation (Fig. 4.23b). Similarly, braided bars of Punnapuzha tributary are prominent and stabilized as in Karandakundu area and at Palakkalpara, near Edakkara (Fig. 4.23c,d).

Point bars, formed due to channel lag deposits are observed in the Chaliyar River at many places Kizhuparambu, Chikkod, Puttalam, Vadasseri and Edavanna and are made up of sand, silt and gravel bed (Fig. 4.24a,b).

Channel fills

Channel fill is one of the most widely spread geomorphological feature in the study area (Fig. 4.25a,b). Occurrence of large channel fills adjacent to overbank strata and absence of laterally adjacent channel fills in the drainage basin indicates mainly a single channel river. This can also be called as filled-up valley flats where small streams flow through broad valley flats and comprise colluvial materials on the top and sand-silt intercalation below.

Alluvial river and active floodplain

Alluvial rivers flow between banks and on a bed of sediment that is transported by the river (Schumm, 1986). These rivers are sensitive to changes of sediment load, water discharge and variations of valley floor slope and therefore deformation of the valley floor by active tectonics can cause pattern change, aggradation and degradation (Schumm, 1986). Higher order (7^{th} order) stream of Chaliyar River can be considered as alluvial river and flows through thick bed of sediment towards downstream (Fig. 4.26a). Active flood plain occurs adjacent to the present day active channel and defines the geomorphic unit that is continuously modified by the overbank flow (Fig. 4.26b).

4.5 Field evidences of active tectonism

Tectonic deformation modifies the relief of a terrain, whereas topography gives the first and indispensable indication of the distribution and arrangement of morphological structures. Several present-day tectonic landforms have been used to indicate the activeness of crustal structures (Keller and Pinter, 1996). Globally significant interactions between surface processes, tectonics and climate have been proposed to explain structure of mountain areas (Bishop et al., 2003).

Fig 4.21 Stream bed characteristics from the upstream to downstream portion of rivers in the Chaliyar River drainage basin. (a) Rapids in a sub-tributary of Chaliyar River (Location: Thusharagiri); (b) waterfall in one of the tributaries of Chaliyar River (Location: Adyanpara); (c) boulder stream bed of Karimpuzha (Location: Chekuthankundu; (d) sub-angular to sub-rounded pebble bed in the upper reaches of Chaliyarpuzha (Location: Nilambur Kovilakam Forest); (e) sub-angular to sub-rounded gravel beds of Chaliyar River; (f) Sandy stream bed of Punnapuzha stream in its lower reach (Location: Edakkara).

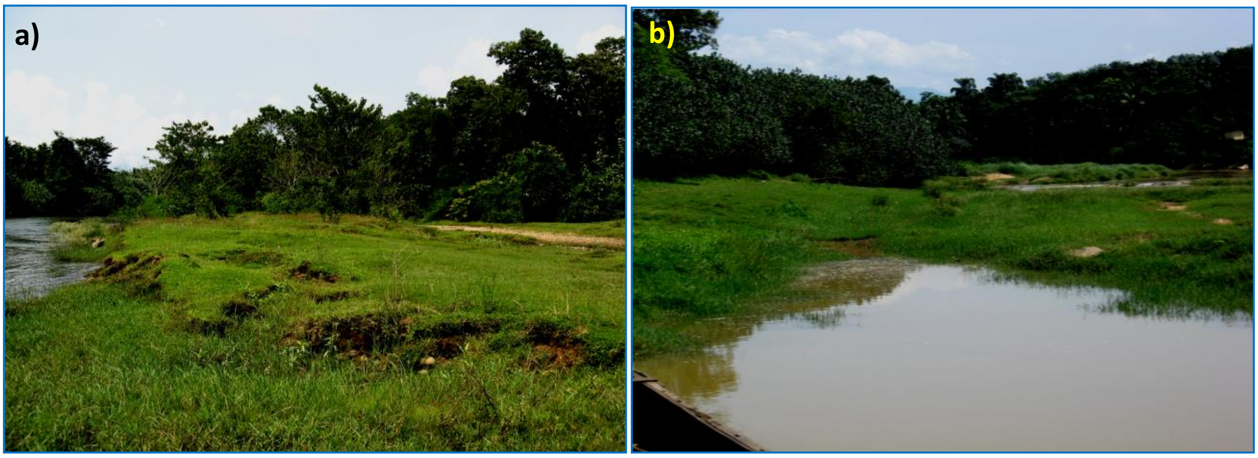


Fig. 4.22 Sand bars with moderate vegetation cover (a) in Chaliyarpuzha stream at Ambalappoyi area; (b) in Punnapuzha stream in Nellukuthu Reserve Forest. Vegetation type and density indicates the stability of the bars.

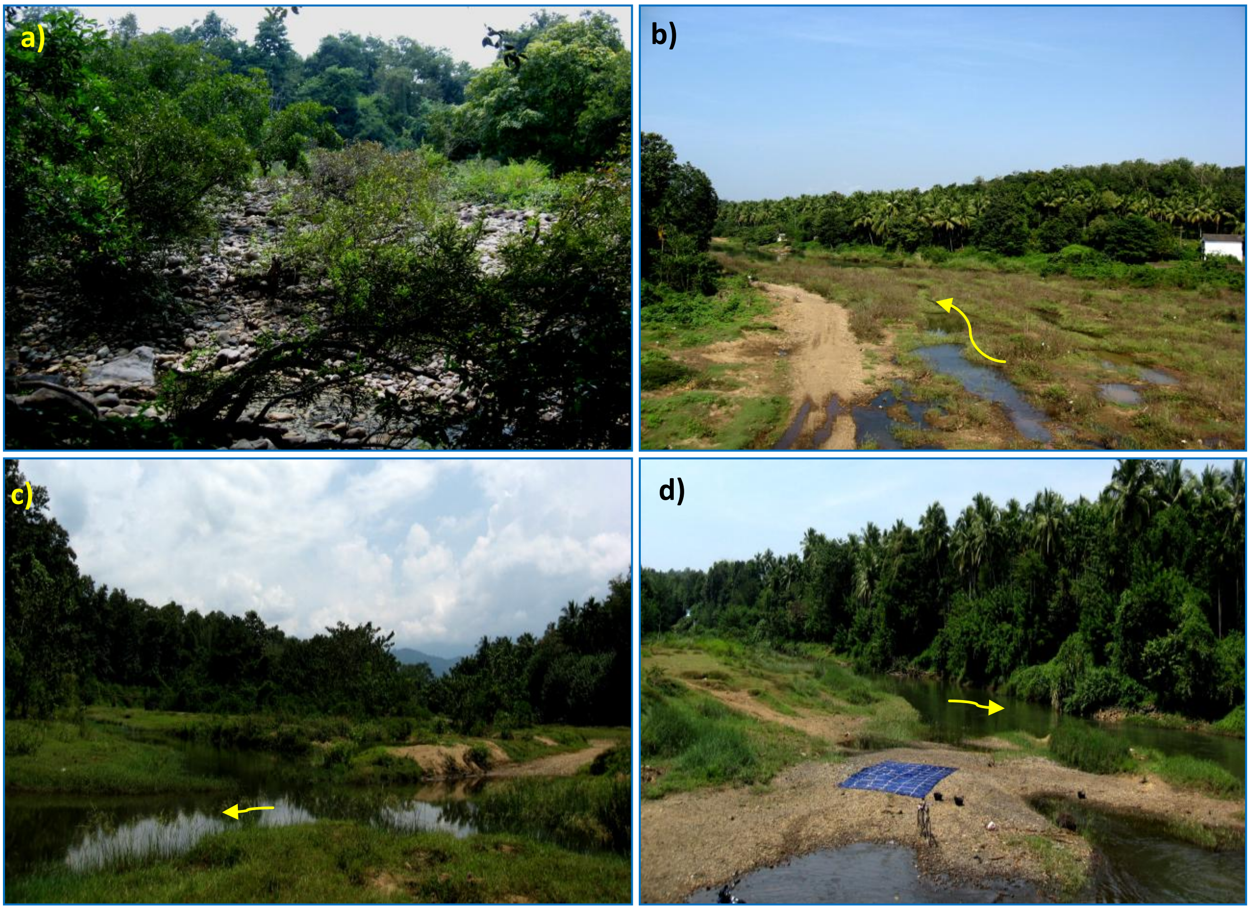


Fig. 4.23 Braiding observed in the river channel at different places in the Chaliyar River drainage basin. (a) Karimpuzha stream west of Chekuthankudu (stabilized braided deposit by thick vegetation); (b) at Karulayi (partially stabilized braided deposit; (c) & (d) Punnapuzha River observed at Karandakundu (stabilized) and near Edakkara respectively. Both braided deposits are stabilized.

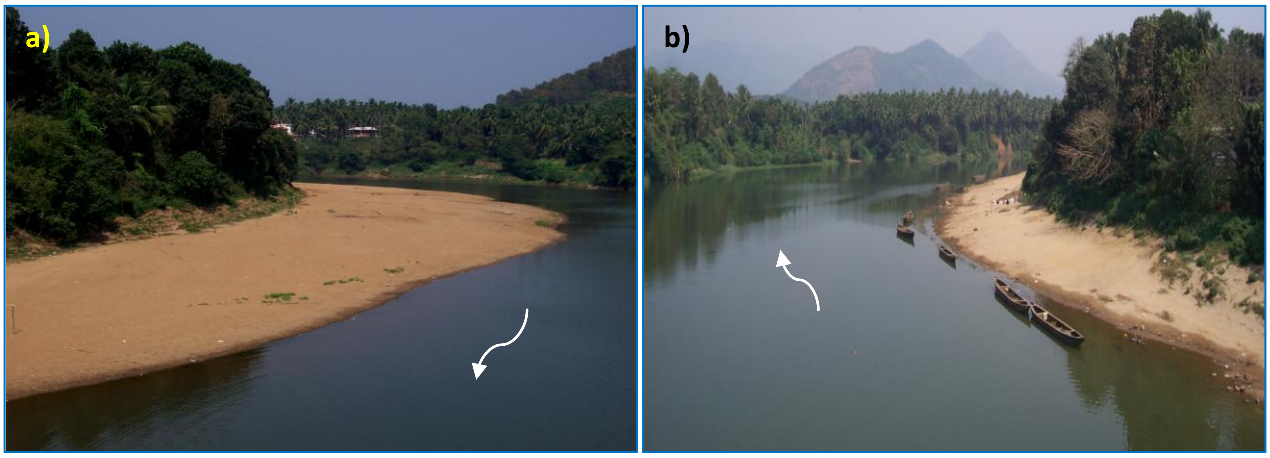


Fig. 4.24 Meandering and point bar deposit in Chaliyar River at a) Arikkod and (b) Edavanna. These point bar deposits are composed of medium- to coarse-grained sand. At places alternate bands of sand and silt are also observed.

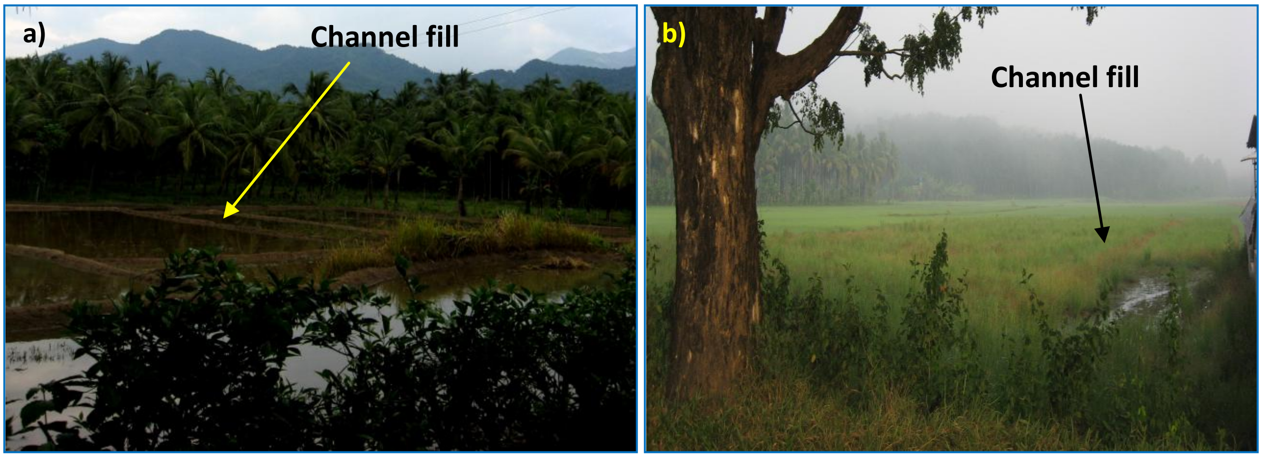


Fig. 4.25 Channel fills observed in the Chaliyar River sub-basin at (a) Enanti and at (b) Muthedam. Channel fills consist of medium to coarse-grained and silty clay admixture. Most these channel fills in the study area are used for paddy cultivation.

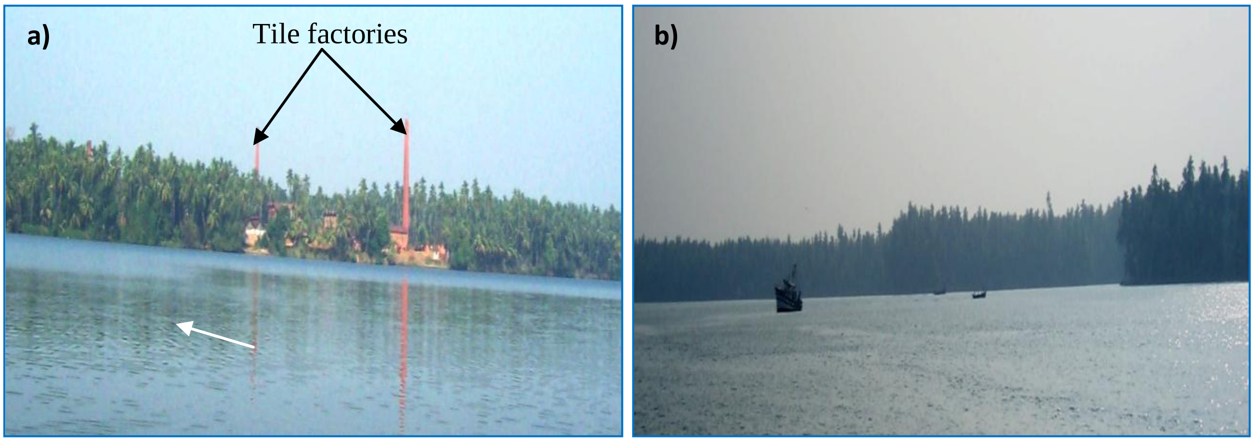


Fig. 4.26 a) Chaliyar River close to its mouth. The river banks comprise thick layer of sediments (sand, silt, clay intercalation). A number of tile factories are located along the river banks; b) Chaliyar River mouth with broad flood plain at Beypore.

Streams play an important role in the evolution of a landscape and can give us valuable information with respect to erosion rates and tectonic movements. Since rivers respond rapidly to tectonic changes they are a prospective instrument to modern geomorphology (Gloaguen, 2008). Influence of active tectonism on the development of landforms expressed in the form of various tectono-geomorphic features like change in drainage patterns, discontinuities in stream courses, deformation in river terraces, morphology of active mountain fronts, landslides within the drainage basins (Ouchi, 1985; Keller and Pinter, 1996; Schumm et al, 2000; Burbank and Anderson, 2001). More details are dicussed in the next chapter (*Chapter V*).

The presence of some landforms gives evidences for the control exerted by structures on the fluvial geomorphology of Chaliyar River drainage basin. Some of the landforms identified in the basin are unpaired terraces, offset streams and shutter ridges, alluvial fans, deflected streams, landslide, fluvial capture due to headwall erosion and anabranching streams. Field relations of some of these landforms are discussed in the foregoing sections.

4.5.1 Unpaired terraces

Unpaired strath terraces are very common in the middle reaches of all the tributaries as observed in Edakkara, Edavanna, Arikkod etc. (Fig. 4.27) and are formed in response to coeval continuous vertical incision and lateral erosion of the river, controlled by episodic tectonic uplifts. Differential deposition is evident from the unequal height of the terraces. Unpaired strath terrace reflects river incision along fault planes, where the strath terrace forms the upthrown part of the normal fault.

4.5.2 Deflected stream

Channel deflection along fault axis is a very common phenomenon in the Chaliyar River drainage basin. Strath terraces with slicken slide faces and sudden deflection of streams are observed in Chaliyar river near Kurathi Mala and in Punnapuzha at Chungathara (Fig. 4.28a,b).

4.5.3 Palaeo-alluvial fans

Reactivation or movements along normal faults during Quaternary Period in the Western Ghat can be determined from the alluvial fan deposits (Fig. 4.19b,c,d). Assorted loose sediments varying in size from boulders to fine sand could be identified in the fan deposit. Alluvial fan deposits are seen in Karakkodu, Nedungayam, Vellimattam, Pattakarimaba and Kolikkadavau. In most places these alluvial fan deposits are incised by streamlets which later join downstream. This appears like a braided stream or can be called as anabranching stream.

4.5.4 Landslides

Evidences of palaeo-landslide are well preserved in the study area. In SOI toposheets of 1971 edition the landslide prone areas are documented. From the inventory of records of Geological Survey of India, it is understood that recurring of landslide in the same area is a common phenomenon.

Remnants of Palaeo-landslides could be traced at Anappara near Sankara Mala and Mamankara near Karuppumpatti. In Anappara area, angular rock fragments within sticky yellowish lateritic soil overlained by sandy layer was observed in an abandoned well-section (Fig. 4.29a). Along a road cutting at Mankara below thickly vegetated area angular and assorted rock fragments embedded in a matrix of lateritic material (muddy and black in colour at the bottom part) was observed (Fig. 4.29b). Further down slope, large boulders of massive charnockite embedded in fine and medium grained sandy horizon also could be traced (Fig. 4.30). All the formations/deposits suggest that landslides are taking place in the study area for a long time. Slumping/land sliding on a small scale is continuously taking place in this area. Scars of recent landslide also could be traced all along the upper reaches of the Chaliyar River drainage basin (Fig. 4.31).

4.5.5 Faults

Evidences of faults in the field include faulted scarp, presence of slicken slides on rock faces, vertical cliffs, pseudotachylite veins etc. Such evidences are recorded in the Chaliyar River drainage basin (Fig. 4.32). Formation of pseudotachylite is associated with seismic activity and are observes as veins cutting through the fault planes as observed in Adyanpara (Fig. 4.33).

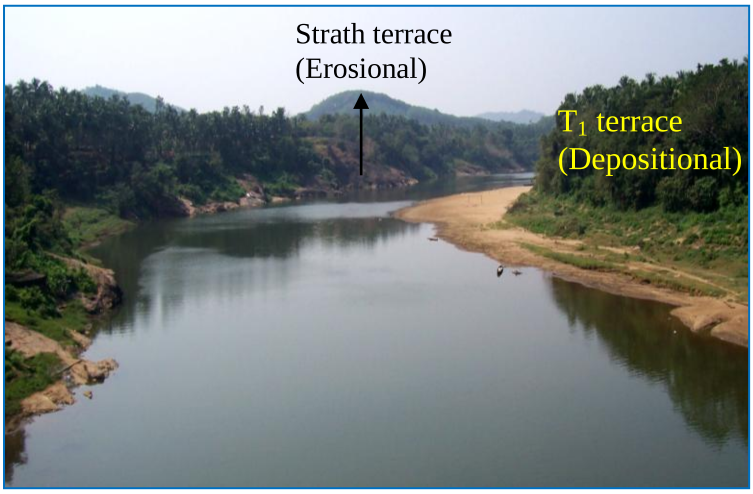
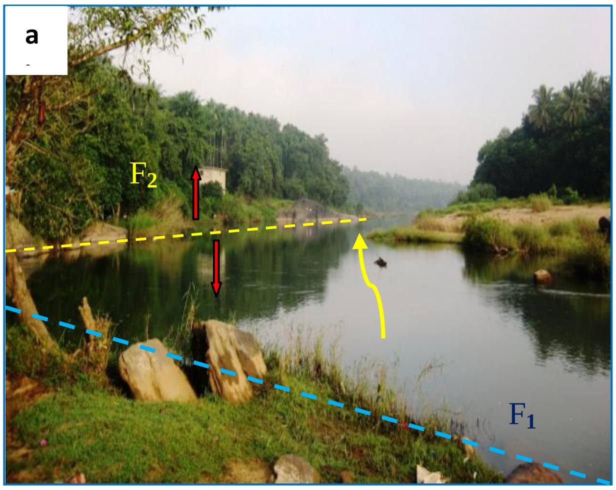


Fig. 4.27 Unpaired terrace of Chaliyar River at Edavanna.



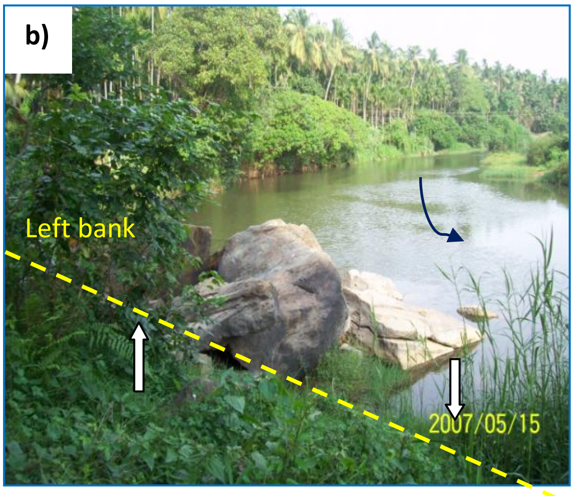


Fig. 4.28 a) Chaliyar River showing deflection in the river profile north of Kurathimala. The stream takes right angle bend at the junction of the two normal fault axes. Left bank is the upthrown part of the faults. Fault F_1 is older to F_2 fault; b) highly fractured rock along the fault plane along Punnapuzha. Deviation in the channel course along the fault zone and ponding are clearly seen.

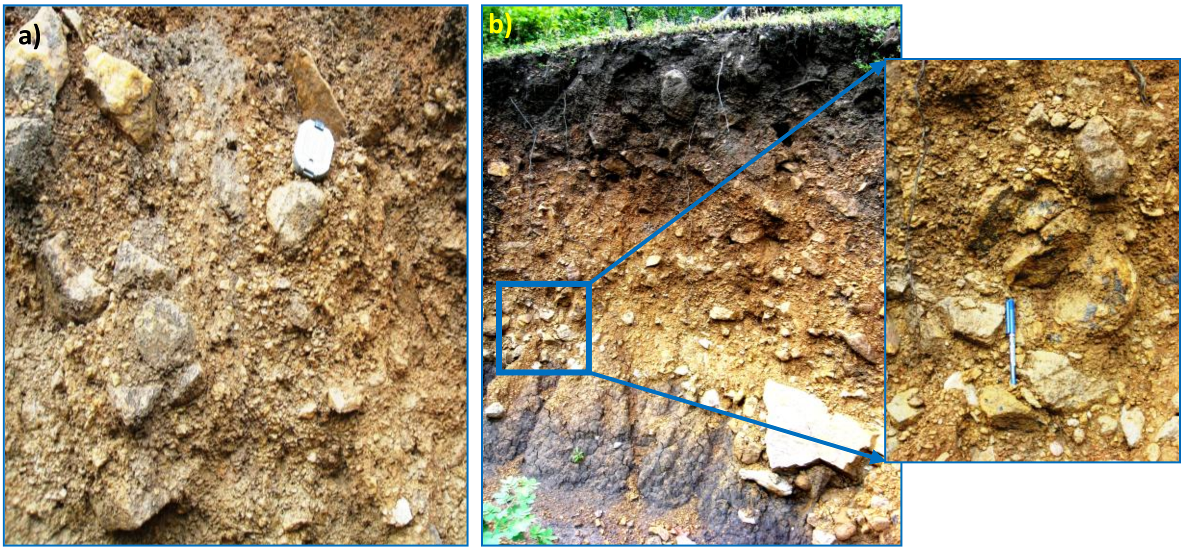


Fig. 4.29 (a) Angular rock fragments (quartz, charnockite and hornblende gneiss) seen in an abandoned well-section at Anappara; (b) angular assorted rock fragments of quartz, charnockite and hornblende gneiss seen along a road cutting at Mamankara. Inset figure shows the close shot of the angular fragments.

Fig. 4.30 Large boulders of charnockite embedded in the fine to medium grained sand horizon. These boulders are rootless and are distributed in the downstream part of Karakkodupuzha suggesting a rolled down-mass during landslides.

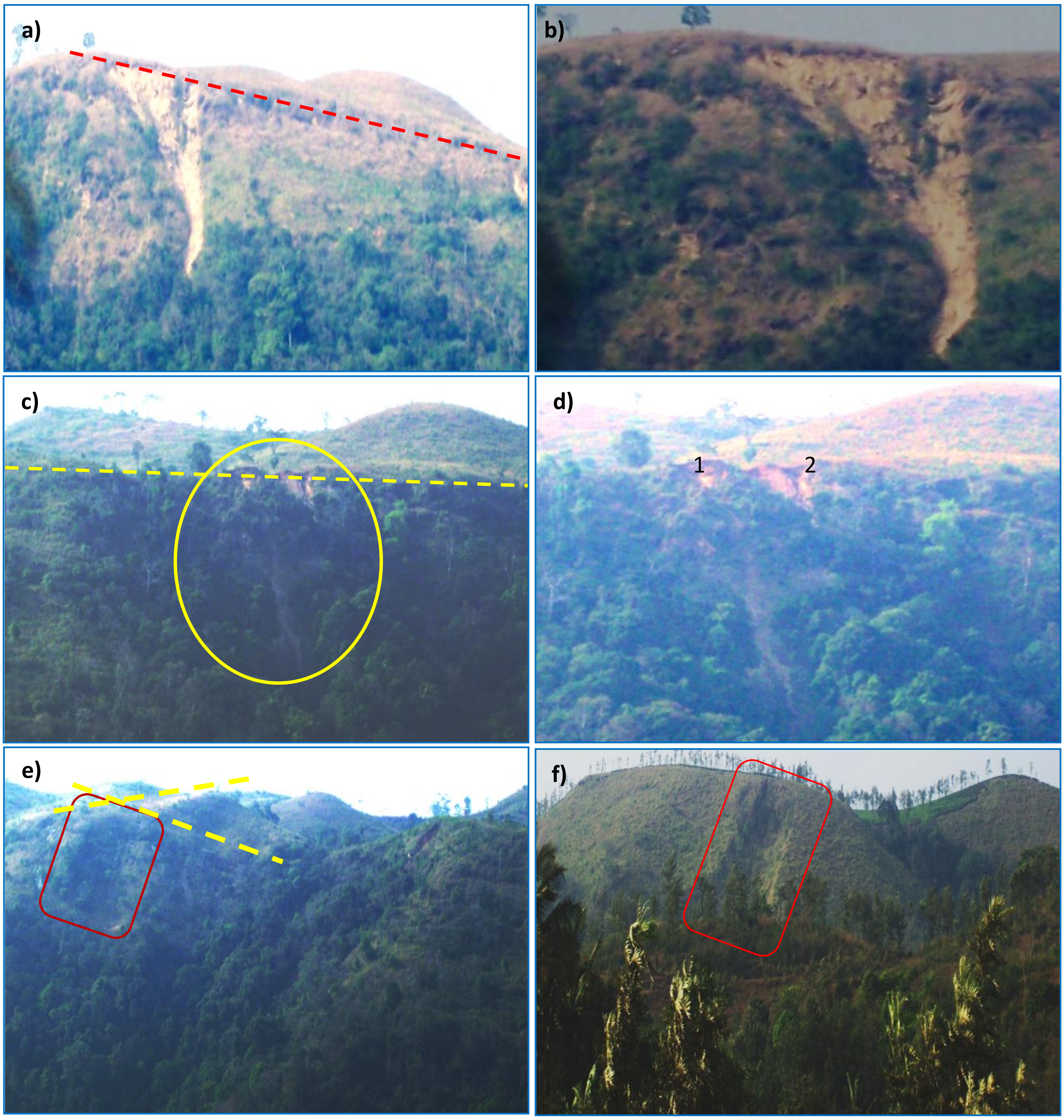


Fig. 4.31 Features of landslides observed in Chaliyar River drainage basin (a) Scar of the landslide seen on the ridge, west of Nadugani; (b) close-up view of the landslide scar of Fig. 4.31a; (c) scars of the landslide seen on a ridge northwest of Nadugani. Broken line indicates the lineament trends and the circle portion shows two adjacent scars of landslides that took place at two different period; (d) Close up view of the scars of two landslides shown in Fig. 4.31c; (e) Scar of an palaeo-landslide observed on a ridge, NW of Nadugani. Broken lines indicate the trend of lineaments; (f) scar of palaeo-landslide, north of Nadugani.

Fig. 4.32 Evidences of faulting in Nilambur valley. (a) Vertical fault scarp face on the western side of Adyanpara waterfalls The fault zone has N-S general trend; (b) fault zone appears to be a horst and graben (microtopography) type multiple faults; (c) & (d) slicken slide faces along a fault zone in charnockite gneiss at Vellimattam and Nedungayam respectively. Arrow indicates the direction of movement.

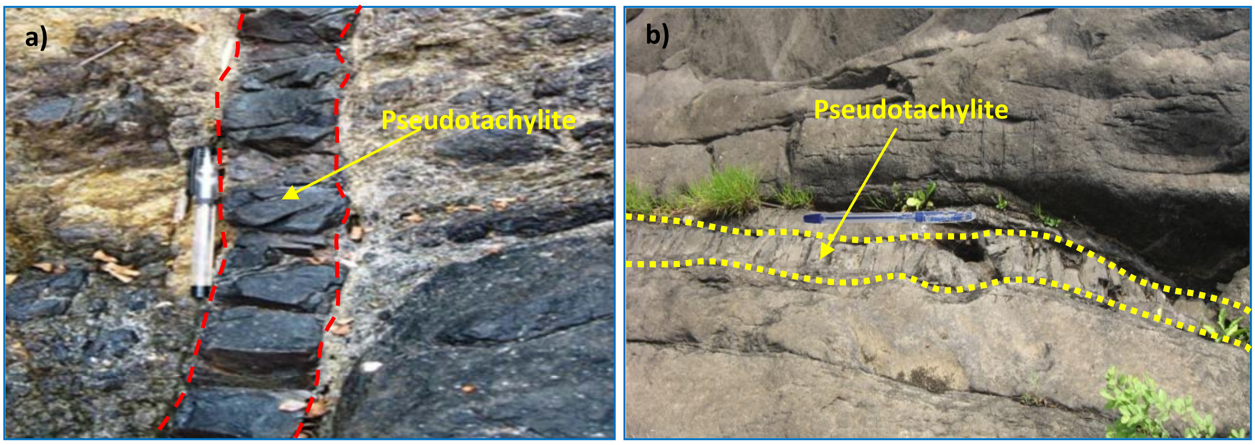


Fig. 4.33 (a) Pseudotachylite vein within the brittle shear zone at Adyanpara waterfalls. Pseudotachylite otherwise known as *fault rock* is an evidence of frictional melting of the wall rocks during rapid fault movement associated with a seismic event; (b) pseudotachylite where parallel fractures/joints are observed. Broken line indicates the contact zone of the pseudotachylite with country rock.

4.6. Summary

Chaliyar River drainage basin forms part of the Southern Granulite Terrane with within the Charnockite and Migmatitic Group of rocks. Charnockite is the most extensive rock type followed by the migmatitic rocks. Younger acid and basic intrusive cut across the older rocks but are highly fractured. Quartz veins in this area are the primary source of gold. The geological milieu of Chaliyar River drainage basin is comparable with any other part of the SGT. Extensive lateritization in the mid-land part of the study area has obliterated the general characteristics of the rock types.

Field relationship of structural aspects of the Chaliyar River drainage basin represents three phases of deformation. The first deformation (D_1) synchronous with ultrahigh temperature metamorphism resulted in the gneissic layering in NNW-SSE direction. The secondary compositional banding of the gneisses and the migmatites is a transposition structure and are represented by tightly appressed rootless isoclinals folds (F_1). Second stage of deformation (D_2) includes small-scale appressed near isoclinal folds with thickened hinges, defined by the NNW-SSE planar fabrics. Planar surfaces of the first two deformation structures are further folded during the stage of deformation (D_3) represented by open folds. These three stages of deformation has been well studied in other parts of Kerala by Narayanaswamy (1976); Sinha-Roy (1980); Nair and Nair (1980); Nambiar (1982); Soman et al., (1990). In Precambrian granulite terrain, field identification of shear zones is difficult as the high grade metamorphism causing the brittle nature of the rocks tend to underplay the evidences of block movements, brecciation etc. (Soman, 2002). However field evidences that support shearing and faulting such as slicken-slides, mylonitization, lineation, scarp lines, pseudotachylite veins etc. could be traced out during the field studies.

Landforms viz., in the Chaliyar River drainage basin were closely studied during the field work. Gradational variation in the grain size of sediments could be identified from the dead to the river mouth. Chaliyar River attains its 7th order at a distance of 45 km from the source where as the total length of the stream is 169 km.

Field evidences like strath terraces, unpaired terraces, palaeochannels, palaeo-alluvial fans, landslides and fault scarps very well support the influence of active tectonism in the development and carving of present day Chaliyar River drainage basin. Development of strath terraces all along the left bank of the Chaliyar River course indicate that the river is flowing through fault plane with upthrown block forming the left bank and the downthrown part forming the right bank. Strath terraces and exposure of T_2 terraces on the left bank of Chaliyar River affirms river incision along fault/fracture planes. Well developed T_1 terrace on the right bank and scouring of T_2 terrace in the right bank reflects the channel migration towards the left bank. Palaeochannels of Karimpuzha, Punnapuzha and Chaliyarpuzha also support the channel migration towards the left banks. Lateral migration of SW flowing Kallanthodu resulted in the present day west flowing Karimpuzha leaving behind a thick pebble bed. Karakodupuzha is a misfit stream flowing through a wide alluvial plane and is considered as the palaeochannel of Punnapuzha.

Palaeo-alluvial fan deposit with a thick boulder bed overlain by sandy horizon now under a thick canopy of teak plantation can be explained by the reactivation of faults along the Western Ghat scarp. The streams were then over-loaded with sediments and resulted in the development of anabranches and braids in the upper reaches. Evidences of palaeo-landslides and scars of recent landslides indicate tectonically active nature of the basin. Pseudotachylite veins observed in one of the fault zone indicates a seismic activity resulted in landslides. Pseudotachylite is observed at the base of some large landslides in the study area, which suggests the movement of large coherent blocks as observed in the Arequipa volcanic landslide, Peru by Legros et al. (2000).

Chapter V
TECTONIC GEOMORPHOLOGY

5.1 Introduction

Tectonic deformation modifies the relief of a terrain; topography gives the first and indispensable indication of the distribution and arrangement of morphological structures. Tectonic activity plays an important part in developing drainage pattern and controlling river behaviour (Vaidyanathan, 1971; Radhakrishna, 1992; Sinha Roy, 2001; Valdiya and Narayana, 2007). Several present-day tectonic land forms have been used to indicate the activeness of crustal structures (Keller and Pinter, 1996). Globally significant interactions between surface processes, tectonics and climate have been proposed to explain structure of mountain areas (Bishop et al., 2005). Tectonism constructs landscapes through uplift and subsidence; climate affects the degradation of the landscapes by physical and chemical erosion (Ouchi, 1985; Keller, 1986; Keller and Pinter, 2002).

Fluvial geomorphology is intrinsically linked to tectonics. Rivers are sensitive to changes in tectonic deformation, adjusting over different periods of time depending on the physical properties of the host rocks, climatic effects and tectonic activity. Thus, the drainage system of a region records the evolution of tectonic deformation (Ouchi, 1985; Schumm, 1986; Holbrook and Schumm, 1999; Peters and Van Balen, 2007; Gloaguen, 2008). Primarily by altering the base level of erosion, tectonic activity will change stream flow characteristics by altering incision rates or by causing diversion. If tectonically-forced incision is preserved and diversion has not occurred, analysis of stream characteristics can be used to infer the tectonic activity that caused the incision.

Rivers play an important role due to their ability to incise, which ultimately sets the rate of lowering of landscape and mass removal in actively rising mountain regions (Snyder et al., 2000). Development of topography results from an adjustment between processes of erosion as streams and rivers flow over rocks and soils of variable strength (Hack, 1973). The adjustment eventually reaches a dynamic equilibrium (El Hamdouni et al., 2007). Evolution of landscape in tectonically active mountain regions is intrinsically related to the combination of endogenic and exogenic processes (Tyagi et al., 2009).

The linear steep scarps of the Western Ghats together with a steep gradient off the west coast has led to a suggestion that these features have evolved through coast parallel faulting (Radhakrishna, 1967). The Western Ghat uplift in the Miocene and related tectonic activity accompanied by a steep westerly gradient of the west coast triggered high fluvial activity and massive accumulation of sediments.

The Quaternary period was characterised by eustatic sea level changes, which continuously changed the shoreline. Marine shell fragments and strand lines observed at a height of 150 m from MSL (Nair et al., 1988), suggest regression and uplift of the west coast. The tectonic activity continued after the uplift of Western Ghats and the resultant coastal subsidence (Rao, 1976; Soman, 2002; Suresh et al., 2007). The beginning of the Quaternary was marked by an uplift of the coastal plain followed by stages of lateritization, elevation and erosion, resulting in large scale sediment flux to the sea (Suresh et al., 2007). The river courses in the headland were raised resulting in the rejuvenation of fluvial activity in early Pleistocene (Rao and Wagle, 1997). Late Pleistocene was characterised by marine transgression and change in the river activity and drowning of valley and deposition of sediments within the valleys.

The lineament tectonics played a major role in the Cenozoic sedimentation (Suresh et al., 2000). Three sets of lineaments are identified trending in NW-SE, NNW-SSE, ENE-WSW and N-S direction. The NNW-SSE and NW-SE trending lineaments are of early Cenozoic origin and mainly controlled the continental margin configuration and sedimentation pattern (Suresh et al., 2000). The NNW-SSE and ENE-WSW trending lineaments are observed to be tectonically active to this day (Nair, 1990). The epicentres of earthquakes and magnetic discontinuities show a preferential alignment in these two directions. During the end of Pliocene the basin has undergone a phase of uplift and erosion. The transgression towards the early part of Late Pleistocene coinciding with the third interglacial age formed the Quaternary sediments (Suresh et al., 2000). Late Quaternary horizontal strike-slip and oblique-slip displacements resulted in river blockages for temporary periods in south eastern Karnataka and adjoining Tamilnadu and Kerala and in western Karnataka (Valdiya, 1998, 2001a, 2001b). The northerly trending faults have caused not only pronounced deflection of rivers and streams and developments of loops and hairpin geometry of drainage but also present day ponding (Valdiya and Narayana, 2007). Three levels of terraces in the

Nilambur valley area are identified (Lower Level Terrace, Middle Level Terrace and High Level Terrace) and studied in detail for the occurrence of placer gold by Sawarkar (1976). Block faultings sequel to the Western Ghat evolution have attributed to the development of amphitheatre like Nilambur valley within the Chaliyar basin (Nair, 1985). Influence of tectonics in the evolution and shaping up of the present day Chaliyar River drainage basin using geomorphic indices and markers are attempted in the present study.

5.2 Methodology

The imprint of tectonic activity on the morphology and the drainage system of Chaliyar River drainage basin is now investigated in order to determine the location of fault scarps and tectonically influenced parts of the drainage basin. Stream profiles are drawn and its characteristic features like knickpoints, concavity and deviation of the profiles are studied. Various geomorphic markers and indices of active tectonics are inferred and presented.

5.2.1 Stream profile analysis

Channel longitudinal profiles result from the interaction between fluvial incision, lithology, tectonics and base level change (Sklar and Dietrich, 1998; Snyder et al., 2000; Kirby and Whipple, 2001; Brocard, 2003; Larue, 2008).

Digitized drainage and contours (20 m interval) are used for drawing the longitudinal profile. Longitudinal profile of nine tributaries of Chaliyar River is made from the SOI toposheets on 1:50,000 scale and knick points/knickzones are marked and compared with the underlying lithology and its influence in the break of physiographic slope in the profile. The longitudinal profile of a river can be represented by a power law function in which the local channel slope (S) of a stream is a function of the stream drainage area (A) (Hack, 1957) and can be represented as

$$S = k_s A^{-\theta} \qquad \text{(i)}$$

Here k_s is the steepness index and θ is the concavity which ranges from 0.2 to 1 (Hack, 1957; Flint, 1974; Slingerland et al., 1998; Snyder et al., 2000; Kirby and Whipple, 2001). The concavity of the profile was determined as the ratio of the measured areas on the profile graph,

$$\Theta = A_1/A_2 \qquad \text{(ii)}$$

where A_1 is the numerically integrated area between the curve of the profile and a straight line uniting its ends and A_2 is the triangulated area created by that straight line, the horizontal axis traversing the head of the profile (Snyder, 2000). The regression analysis of log (S) vs log (A) provides the value of concavity index and steepness index (k_{s}). It permits the quantitative estimation of the folding degree of the profile. If the concavity index value is close to 0, the form of the profile is close to a straight line; if its value is close to 1.0, the profile is L-shaped. If there is no differential uplift, the value of k_s should remain constant for a given stream. However, if the river basin is undergoing differential uplift, k_s may change from one segment to another (Slingerland et al., 1998; Snyder et al., 2000). Considering that the channel slope is inversely proportional to drainage basin area, therefore, as the drainage area increases, the slope of the river profile decreases. However, in areas where differential uplift is going on, the proportionality of drainage area and slope does not hold. The areas where differential uplift is higher, over steepening of the river profiles should occur, and can be ascertained by changes in k_s. Using the method of Goldrick and Bishop (1995), from the semi-logarithmic plot of the longitudinal profiles of the river, amount of deviation (D) was measured by the projection of the upstream equilibrium profile and subtraction of actual stream elevation from the projected elevation, and the results are presented in Tables 5.1 and 5.2, and Fig. 5.1 to 5.5.

The dimensionless curve H/H_0 vs L/L_0 was plotted which allow superposition and comparison of profiles of different river lengths as suggested by Radoane et al. (2003) and Larue (2008). H denotes the stream altitude at the point of measurement, H_0 represents the stream altitude from the mouth of the headwaters, L is the stream distance at the point of measurement and L_0 is the stream distance from the river mouth at the head waters. The catchment area and slope for each stream are calculated using the equation (i), and regression analysis of log (S) vs log (A) (see Fig. 5.2).

A segment of a river longitudinal profile that is steeper than the adjacent segment is commonly referred to as knickzone or knickpoints, if it is visibly steeper than the trend of the longitudinal profile. Knickzones are extracted from the DEM using ArcGIS software. Knickzones have been methodologically recorded with their altitude above base level, gradient, lithology and presence of fault (Table 5.2 and Fig. 5.6a,b).

Stream gradient, as a function of length measurement is computed as given in equation (iii) SL index allows detection of the least knickpoint and very high or very low values that can reveal tectonic distortions if there is no correlation with lithologic factors (Hack, 1973; Keller and Pinter, 1996 and Larue, 2008). Using the method of Goldrick and Bishop (1995), the semi-logarithmic profiles of the river allows measurement of the deviation from the straight line which represents the equilibrium river longitudinal profile. In a semi-logarithmic plot of longitudinal profiles, the amount of deviation is measured by projection of the upstream equilibrium profile and subtraction of the actual stream elevation from the projected elevation. The results are represented in Table 5.3 and Fig. 5.6a,b

Concavity and steepness indices and deviation

Concavity index and steepness index are computed and deviation is measured to study the longitudinal profile and is represented in Fig. 5.4 and Table 5.1.

Evolution of the commonly observed river profile concavity has traditionally been explained through the conceptual notion of a ‘graded’ landform system, in which slope declines downstream as a joint interplay between discharge, bed material size, sediment load, and channel morphological characteristics (Mackin, 1948; Harmar and Clifford, 2007). Concavity index (Langbein, 1964) is used to compare profile concavities. The smoothness of the landscape under small concavity index (θ) is a direct reflection of the near linearity of channel profiles, which facilitates stream capture and integration.

In order to estimate steepness index (k_s), the calculated value of θ which was obtained from the log (S) vs log (A) regression analysis corresponding to each river profile is used. If there is no differential uplift, the value of steepness index (ks) should remain constant for a given stream. However, if the river basin is undergoing differential uplift, ks may change from one segment to another (Hack, 1973). Considering that the channel slope is inversely proportional to drainage basin area, therefore, as the drainage area increases, the slope of the river profile decreases. In areas where differential uplift is going on, the proportionality of drainage area and slope does not hold. The areas where differential uplift is higher, over steepening of the river profiles should occur, and can be ascertained by changes in ks (Tyagi et al., 2009).

The semi-logarithmic profiles of rivers allow measurement of the deviation from a straight line which represents the equilibrium river longitudinal profiles. The amount of deviation (D) is measured by projection of the upstream equilibrium profile and subtraction of the actual stream elevation from the projected elevation (Larue, 2008).

5.2.2 Quantification of geomorphic indices

To describe the interplay of tectonics and geomorphology and to identify the response of the drainage basin morphologies, quantitative measurements of various geomorphic indices are commonly used as reconnaissance tool in tectonic geomorphology (Bull and Mc Fadden, 1977; Burbank and Anderson, 2001). The study of geomorphic index aims to quantify the present day landscape shape and to characterize the balance between erosion and tectonics of the landscape. Since rivers are sensitive to tectonic deformation resulting in changes in slope and base level, the stream-length and gradient index, and the ratio of valley floor width to valley height are calculated on the river profiles and valleys, to detect the changes in the shape of the landscape. Shape of the mountain front is described by mountain front sinuosity and lateral shifting of the drainage basin explained by asymmetry factor (A_f) and transverse topographic symmetry factor (TTSF), even the effects of subtle tectonic activity in an area can be determined (Ribolini et al., 2008).

Geomorphic indices - stream length-gradient index (SL), mountain front sinuosity (S_{mf}), valley floor width to valley height ratio (V_f), asymmetry factor (AF) and transverse topographic symmetry factor (TTSF) are computed to understand the degree of tectonic activity in the Chaliyar River drainage basin.

Stream length-gradient index (SL)

Stream-length gradient ratio is defined as the channel gradient of the reach to the distance of the reach from the fan-head (Hack, 1973). The SL index is defined as the product of channel slope at a given point and the channel length to the source of the stream

$$SL = (\Delta H/\Delta L)L \qquad \text{(iii)}$$

where L is the total upstream channel length from the interest point to the highest point of the channel and $\Delta H/\Delta L$ is the channel gradient or slope of the reach, H is the height of segment investigated (Hack, 1973). In this study, a contour interval H of 100 m is used and L is the horizontal distance of the same 100 m contour interval segment.

In the present study the first derivative of SL and slope gradient index (S) are also computed. Slope gradient index (S) describes the change in SL between segments and shows where the highest rates of SL changes are located (Peters and Van Balen, 2007). Slope gradient index S is defined as

$$S = \left(\frac{\Delta slope}{\Delta L} \right) L \quad \text{.....................................(iv)}$$

where Δslope is the difference in slope between two adjacent segments. ΔL is the mid-point between the lengths of two segments. L is the length of the channel from the point of interest where the slope gradient index is calculated to the source of the channel. The dimensionless values of S can be positive or negative. Positive values indicate change from a steep to less steep segment and negative values indicate an increase in segment steepness for a constant gradient S=0.

Mountain front sinuosity (S_{mf})

Mountain front sinuosity characterizes the morphology of the mountain fronts along the faults. The geomorphologic analysis of mountain fronts, related drainage networks and alluvial fan systems, would provide valuable information about the recorded tectonic history. This index is frequently applied in the regional studies of active tectonics and reflects the balance between mountain front faulting and activity of the transverse stream (Burbank and Anderson, 2001; Cuong and Zuchiewicz, 2001; Silva et al., 2003). Mountain front sinuosity is defined as

$$S_{mf} = L_{mf}/L_r \text{..(v)}$$

where, L_{mf} is the length of the mountain front from a point and L_r is the length of the straight line from the same point to the same end point (Burbank and Anderson, 2001).

Valley floor width to valley height ratio (V_f)

The cross-sectional shape of the valleys can reflect the rate of incision and indicate actively incising streams in areas of recent uplift. Quantification of valley floor width to valley height ratio proved to be a useful tool to evaluate fluvial incision in uplifted areas (Bull and McFadden, 1977; Marple and Talwani, 1993; Cuong and Zuchiewicz, 2001; Azor et al., 2002; Silva et al., 2003). Width to height ratio of valley is the ratio of the width of the valley floor to the height of the valley and is computed as:

$$V_f = 2V_{fw} / [(E_{ld} - Esc) + (E_{rd} - E_{sc})] \text{..(vi)}$$

where, V_{fw} is the width of the valley floor, E_{ld} and E_{rd} are the elevations of the left and right valley divides respectively and E_{sc} is the elevation of the valley floor (Silva et al., 2003). High V_f indicates broad valleys and low uplift rates and low V_f ($V_f < 1$) is for V-shaped valleys, actively incising and high uplift rates. In addition to uplift, the shape of the cross-section of the valley depends on the lithology of the bedrock and the erosive ability of the river (Peters and Van Balen, 2007).

Asymmetry factor (AF)

Asymmetry factor is defined as

$$AF= 100\ (A_r/A_t)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(vii)}$$

where A_r is the area of the basin to the right (facing downstream) of the trunk stream and A_t is the total area of the drainage basin (Guarnieri and Pirrotta, 2007). Asymmetry factor permits to establish lateral tilting with respect to the main water course, which may be associated with the activity of normal fault with a direction parallel to the main water course (Hare and Gardner, 1985; Cox, 1994; Guarnieri and Pirrotta, 2007).

Transverse Topographic Symmetry Factor (TTSF)

The Transverse Topographic Symmetry Factor is calculated as:

$$TTSF = D_a/D_d\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(viii)}$$

where D_a is the distance from the channel to the basin midline and D_d is the distance from the lateral basin margin to the basin midline. TTSF can detect areas of lateral tilting (Ribolini et al, 2008).

5.2.3 Delineation of geomorphic markers

Geomorphic markers provide a reference frame against which to gauge differential or absolute deformation. Geomorphic markers like river terraces, alluvial fans, beheaded rivers, erosional surface and landslide vulnerable areas are delineated with the help of SOI toposheets, aerial photographs and satellite imageries.

5.2.4 Morphostructural analysis

The planar geometry of the present day fluvial network leads many times to the identification of the past drainage characteristics that can help in the reconstruction of different episodes of deformation that have determined the topographic growth of a mountain region. Rose diagrams are prepared for each sub-basin for lower order streams (1^{st}, 2^{nd}, 3^{rd} and 4^{th} orders) and for the lineaments within the sub-basin to evaluate the relationship between the geometry of the drainage network and trend of lineaments. The analysis was performed separately for each zone considering the whole network then the channels of each stream order, since it is likely that streams of different orders are controlled by tectonics in different ways.

5.3 Results and Discussion

Streams play an important role in the evolution of a landscape and can give us valuable information with respect to erosion rates and tectonic movements. Since rivers respond rapidly to tectonic changes they are a prospective instrument to modern geomorphology (Gloaguen, 2008).

The primary response of rivers to tectonics is manifested as change in channel slope, while secondary changes are reflected in aggradation/degradation and variations in channel morphology (Jain and Sinha, 2005). The aggradation/ degradation process disturbs the existing equilibrium of the discharge-sediment load, which is further extended in the downstream reaches as secondary effects (Schumm et al., 2002). Uplift regions are characterized by river entrenchment, low width/depth ratio and degradation processes, while subsidence causes shallow channel, aggradation, frequent flooding and presence of marshy lands (Ouchi, 1985, Valdiya and Rajagopalan, 2000).

5.3.1 River profiles

Rivers and river profiles reflect the integration of multiple forces and processes like climate, bedrock resistance to erosion and river incision due to tectonism. The geometry of the river profile is a proxy for identifying spatial patterns of rock uplift (Seeber and Gornitz, 1983; Merritts and Vincent, 1989; Hurtrez, et al., 1999; Snyder et al., 2000; Kirby and Whipple, 2001; Van Laningham, 2006). Longitudinal profile development depends on the variability of lithology (Gilbert, 1877; Duvall et al., 2004; Stock and Montgomery, 1999).

In a steady state condition, when the rate of uplift is equal to the rate of incision with a stabilized climatic condition where the long-term sediment supply and transport capacity is balanced, the longitudinal profile of a river would be graded (Seeber and Gornitz, 1983). When the uplift rate of the river bed is higher than the incision capability, then a convex longitudinal profile develops (Whittaker et al., 2007). To ascertain the fluvial response to terrain instability, longitudinal profile provides a first order approximation towards the role of exogenic and endogenic processes (Tyagi et al, 2009).

Plotting of longitudinal profiles results in a curve, more or less regular, the concavity of which increases towards the headwater area. The customary theoretical models of longitudinal profile is like that, older the river, concavity should be more towards headwater area and should asymptotically approach a longitudinal equilibrium profile or grade (Alexandrowicz, 1994). According to Gilbert (1877), the slope of the longitudinal profile is inversely proportional to the discharge. The variations of discharge, diameter of river and sediment load are the most important factors that explain the shape of the profile. Vertical section of the longitudinal profile record spatial and temporal changes in the fluvial incision of the landscape (Pazzaglia et al., 1998). Other factors such as lithology, tributaries, and neotectonism account for the deviation from the general form of the profile without fundamentally modifying it (Alexandrowicz, 1994; Radoane et al., 2003). The breaks in the profile are dominantly related to active tectonics and to the nature of the bed rock.

Longitudinal profiles of nine tributaries of Chaliyar River show variable curves, gradient and knickpoints and knickzones (Fig. 5.1). Drainage area as function of downstream distance for the entire nine tributaries plot gave regression coefficient for the tributaries (Table 5.1). Moderate values of regression coefficient for Cherupuzha, Iruvahnipuzha, Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha, Karakodupuzha, Karimpuzha and Kuthirapuzha signify that the longitudinal profiles experience differential uplift. Regression coefficient for Punnapuzha is 0.23 explains the comparatively uniform uplift of the longitudinal profile (Fig. 5.2).

Plots of log (drainage area) versus log (channel slope) show typical inverse trend and wide scatter. Power law regressions of each river profile indicate concavity index (Θ) values of 0.23 to 0.63 (Table. 5.1). R^2 values range from 0.23 to 0.68 (narrow range) indicating substantial consistency to these relationship.

Concavity index (Θ)

Concavity index of river profiles are calculated in order to quantitatively compare longitudinal profile forms in different rock types in the sub-basins which are undergoing differential amount of rock uplift and eroding various rock types. In an active orogen, concavity index varies between 0.35 and 0.60 (Snyder et al., 2000; Kirby and Whipple, 2001; Roe et al., 2002) and under normal condition, the concavities of river profiles range from 0.3 to 0.6 (Hack, 1957; Flint, 1974; Moglen and Bras, 1995; Slingerland et al., 1998 and Snyder et al., 2004). The extreme roughness and network tortuosity of the simulated terrain under Θ=1 reflects a strong sensitivity to initial conditions with low amplitude and uncorrelated random noise as in Fig. 5.3 (Tucker and Whipple, 2002).

Concavity indices for nine tributaries of Chaliyar River are given in Table 5.1. Concavity index shows marked variation for the streams and ranges from 0.23 to 0.63. Average concavity index for Cherupuzha, Iruvahnipuzha, Kurumanpuzha, Chaliyarpuzha and Karimpuzha falls within the range of 0.35 and 0.60 as observed in an active orogen. Kanjirapuzha and Kuthirapuzha has Θ greater than 0.60 (Θ = 0.63) while for Karakodupuzha (Θ = 0.25) and Punnapuzha (Θ = *0.*23) concavity indices are less than 0.3

High concavity index of the large rivers can be explained by a downstream decrease in grain size, the concavity index for smaller rivers are not controlled by this factor because bed-loads of these streams do not vary much downstream (Larue, 2008). The tributaries of Chaliyar River drainage basin do not show much variation in the grain size of the bed load from the upper reaches to the confluence of 4th, 5th and 6th order streams. The differences in base level and tectonics may be the causative factors for high concavity index values.

Steepness index (k_s)

Several studies have found steepness index to approximate rock uplift (Snyder et al., 2000; Kirby and Whipple, 2001). Homogeneous substrate properties are required to derive meaningful comparison of k_s with rock uplift (Van Laningham, 2006). Very high and low values can reveal tectonic distortions if there is no correlation with lithological factors. Steepness index values computed for the nine tributaries of Chaliyar river ranges from 240 to 1960 (Table 5.1).

Steepness index for rivers flowing through uniform lithology (Cherupuzha, Kurumanpuzha, Kanjirapuzha, Karimpuzha, Punnapuzha and Kuthirapuzha) varies from 530 to 1120. Steepness index for rivers flowing through varying lithology (Iruvahnipuzha, Chaliyarpuzha and Karakodupuzha) also varies from 240 to 1960. This

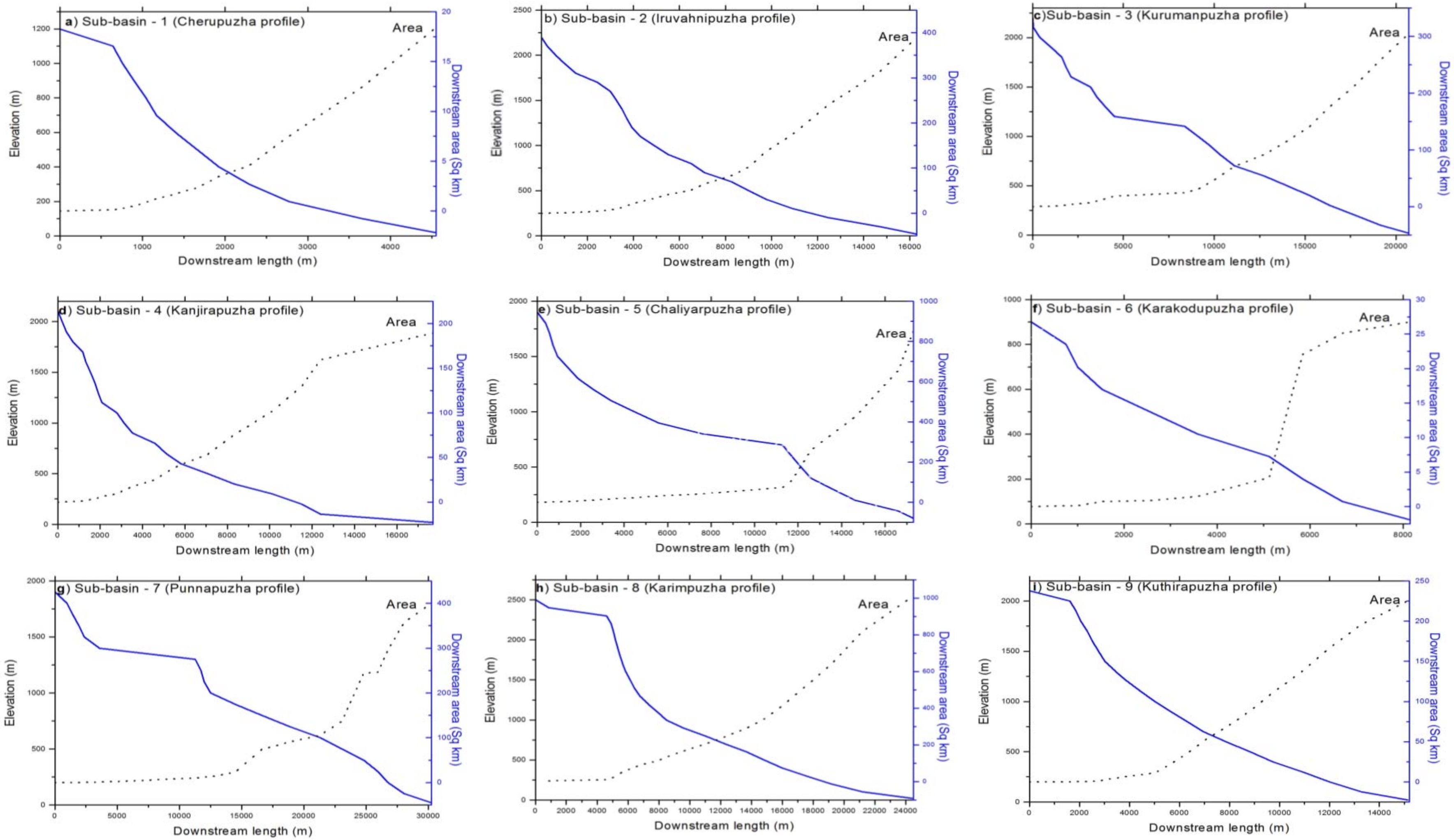


Fig. 5.1 Longitudinal profiles of nine tributaries of Chaliyar River derived from Digital elevation Model of SRTM data (a) Cherupuzha, (b) Iruvahnipuzha, (c) Kurumanpuzha, (d) Kanjirapuzha, (e) Chaliyarpuzha, (f) Karakodupuzha, (g) Punnapuzha, (h) Karimpuzha and (i) Kuthirapuzha. Bold line indicates the stream profile and dotted line indicates the drainage area as a function of downstream distance.

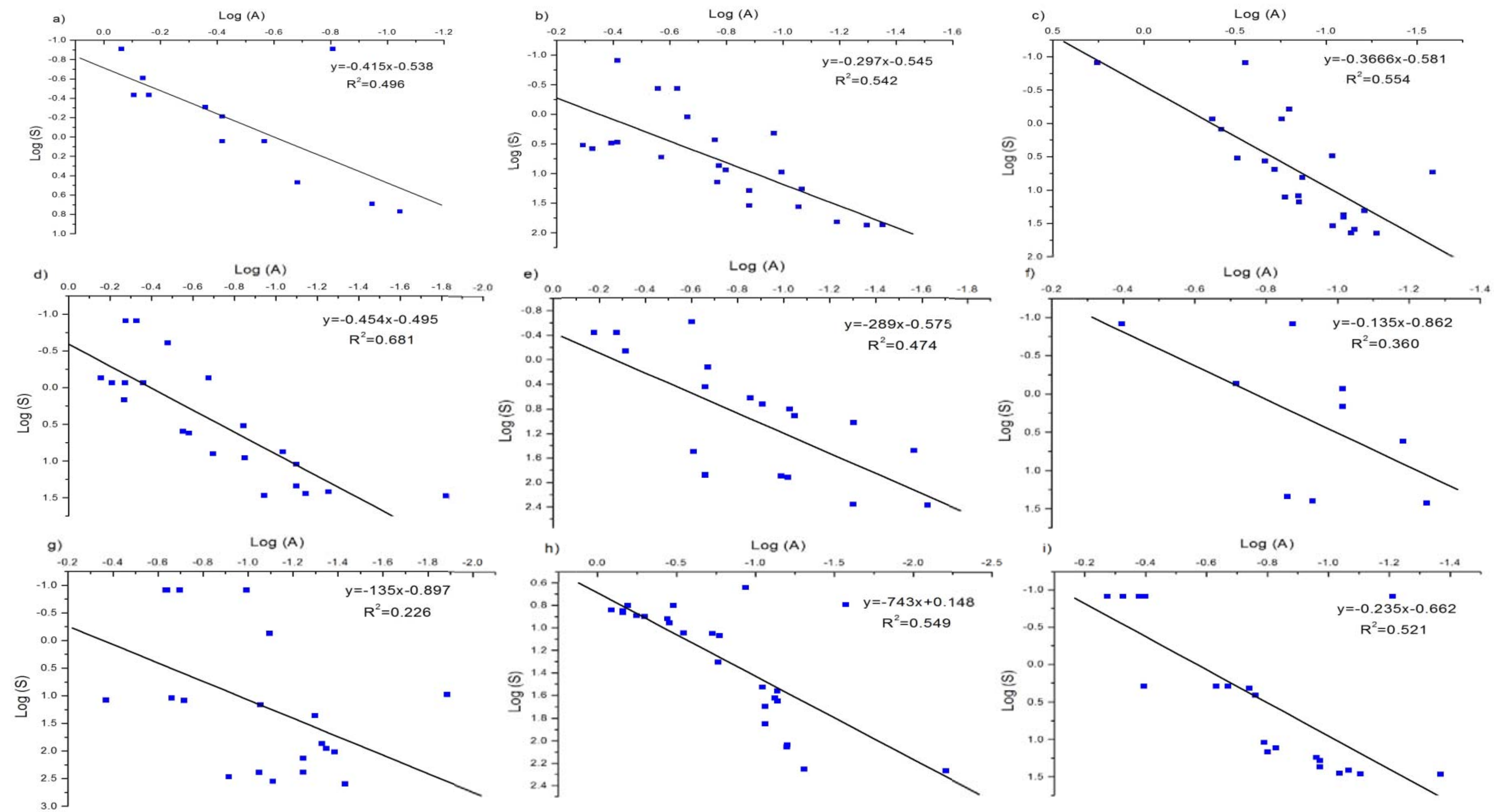


Fig. 5.2 Regression analysis for nine tributaries of the Chaliyar River. (a) Cherupuzha (0.496) (b) Iruvahnipuzha (0.542), (c) Kurumanpuzha (0.554) (d) Kanjirapuzha (0.681), (e) Chaliyarpuzha (0.474), (f) Karakodupuzha (0.360), (g) Punnapuzha (0.226), (h) Karimpuzha (0.549) and (i) Kuthirapuzha (0.521). R^2 value for each tributary is given in the parenthesis.

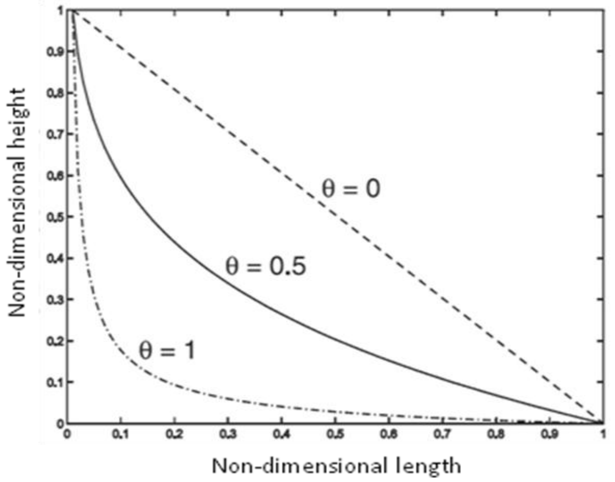


Fig. 5.3 Stream profile concavity as a function of θ. Curves are normalized by their maximum height at $x=x_c=0.01$ (after Tucker and Whipple, 2002).

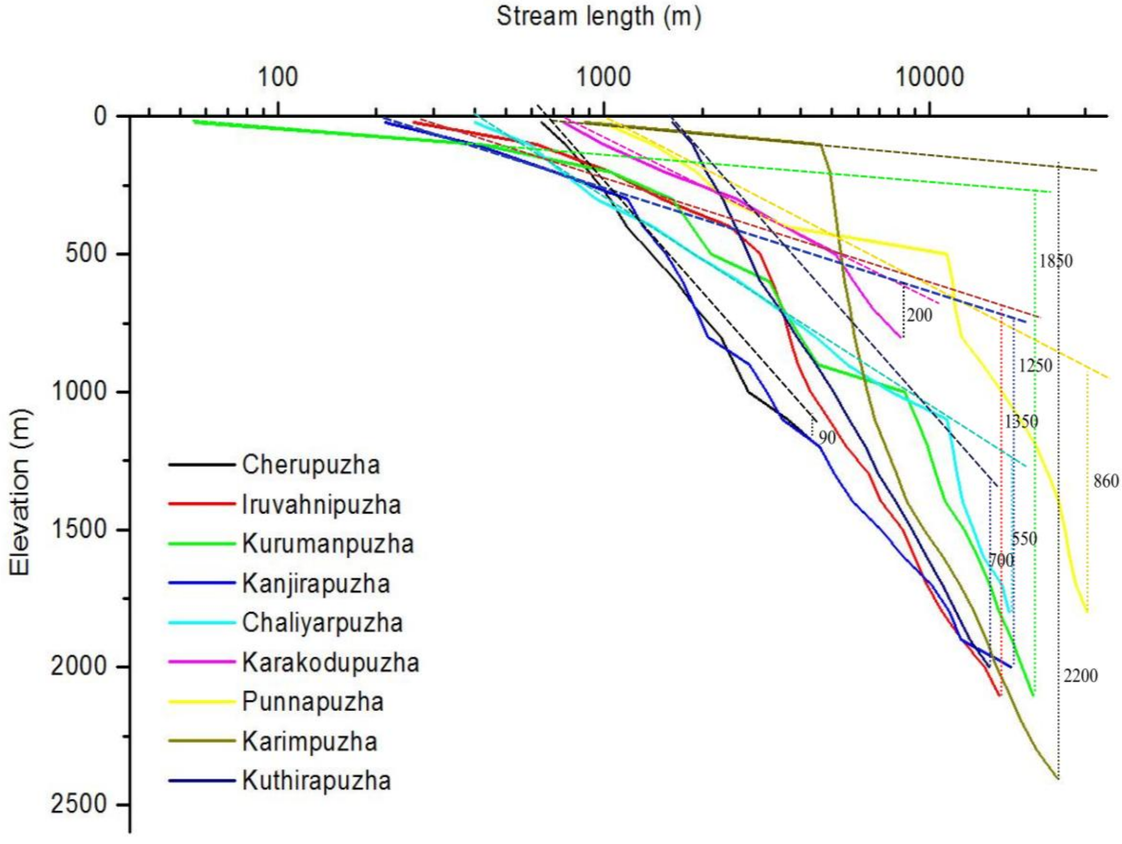


Fig. 5.4 Longitudinal profiles for the nine tributaries of Chaliyar River on a semi-logarithmic scale. Numbers in the figure denote deviation values (D) in metres. Karimpuzha has deviated maximum from the normal profile (2200 m) whereas Cherupuzha has minimum deviation from normal profile of about 90 m. Rivers flowing through uniform lithology (Kurumanpuzha (1850 m), Kanjirapuzha (1250 m), Karimpuzha (2200 m), Punnapuzha (860 m) and Kuthirapuzha (700 m)) exhibits more deviation than the rivers through varying lithology (Chaliyar (550 m), Karakodupuzha (200 m) except for Iruvahnipuzha (1350 m).

Table 5.1 Power law relationships between drainage area and slopes for the 9 tributaries of Chaliyar River

Sub-basin	River	k_s	θ	R^2
1	Cherupuzha	530	0.51	0.50
2	Iruvahnipuzha	980	0.53	0.54
3	Kurumanpuzha	610	0.37	0.55
4	Kanjirapuzha	1120	0.63	0.68
5	Chaliyarpuzha	1960	0.59	0.47
6	Karakodupuzha	240	0.25	0.36
7	Punnapuzha	350	0.23	0.23
8	Karimpuzha	225	0.58	0.55
9	Kuthirapuzha	970	0.63	0.52

Table 5.2 Relationship of knick points observed in the river profiles and underlying lithology.

Sub-basin	Tributary streams	Knick point Elevation (m)	Downstream length (m)	Lithology
1	Cherupuzha	1000	1619	Charnockite
		100	4984	Charnockite
2	Iruvahnipuzha	1800	1515	Charnockite
		1600	3025	Charnockite
		1200	3945	Charnockite
		800	6529	Charnockite
3	Kurumanpuzha	1800	1621	Charnockite
		1500	3190	Charnockite
		1200	4537	Charnockite
		1100	8373	Charnockite
		700	11135	Charnockite
4	Kanjirapuzha	1700	1183	Charnockite
		1200	2088	Charnockite
		1100	2788	Charnockite
		800	4599	Charnockite
5	Chaliyarpuzha	1800	405	Charnockite
		1500	931	Charnockite
		900	5615	Charnockite
		700	11272	Charnockite
6	Karakodu puzha	800	750	Ultramafics
		700	995	Ultramafics
		600	1531	Ultramafics
		300	2272	Biotite gneiss
7	Punnapuzha	1800	1021	Charnockite
		1500	2392	Charnockite
		1400	3596	Charnockite
		1300	11275	Charnockite
8	Karimpuzha	2300	4585	Charnockite
9	Kuthirapuzha	2000	1621	Charnockite

clearly indicates that lithology is not only the criteria for variation in the steepness index for the tributaries of Chaliyar River.

Deviation (D)

According to Hack (1973), the equilibrium river profile on a single lithology is a straight line when plotted semi-logarithmically. High values of D indicate disequilibrium caused by base level lowering, tectonics and bedrock lithology. Cherupuzha has deviated about 90 m from the equilibrium longitudinal profile while Karimpuzha has deviated to about 2200 m from the equilibrium profile (Fig. 5.4). Karakodupuzha has deviated 200 m, Chaliyar about 550 m, Kuthirapuzha about 700 m, Punnapuzha for 860 m. Kanjirapuzha, Iruvahnipuzha and Kurumanpuzha have deviated 1250, 1350 and 1850 m respectively from their respective equilibrium longitudinal profile. All the rivers show abnormally high values. The highest D values are shown by the tributary rivers Karimpuzha, Kurumanpuzha, Iruvahnipuzha, Kanjirapuzha that flows through the resistant charnockite massifs (Fig. 5.4).

The normalized longitudinal profile or the dimensionless curves H/H_0 vs L/L_0 (Fig. 5.5) reveal that the maximum concavity is located between 10 and 70% of the normalized distance for all the tributaries of Chaliyar River. These normalized profiles are marked by the C-shape with a short steep upper segment representing the Ghat zone and a moderately gently sloping segment downstream. Few inflection points are observed in the profiles of Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha, Punnapuzha and Karakodupuzha. Differential deepening in the middle portion of these rivers is suggested by the shape of the longitudinal profile. Towards the downstream end the rivers have reached the base level of erosion.

The normalized longitudinal profiles and stream length gradient index (SL) values show remarkable similarity in the general characteristics of the rivers in Chaliyar River drainage basin. The morphological response of these rivers can be correlated with the concavity index and SL index values. The major breaks in the profile are very well associated with the normal faults across the river profile (Fig. 5.6a).

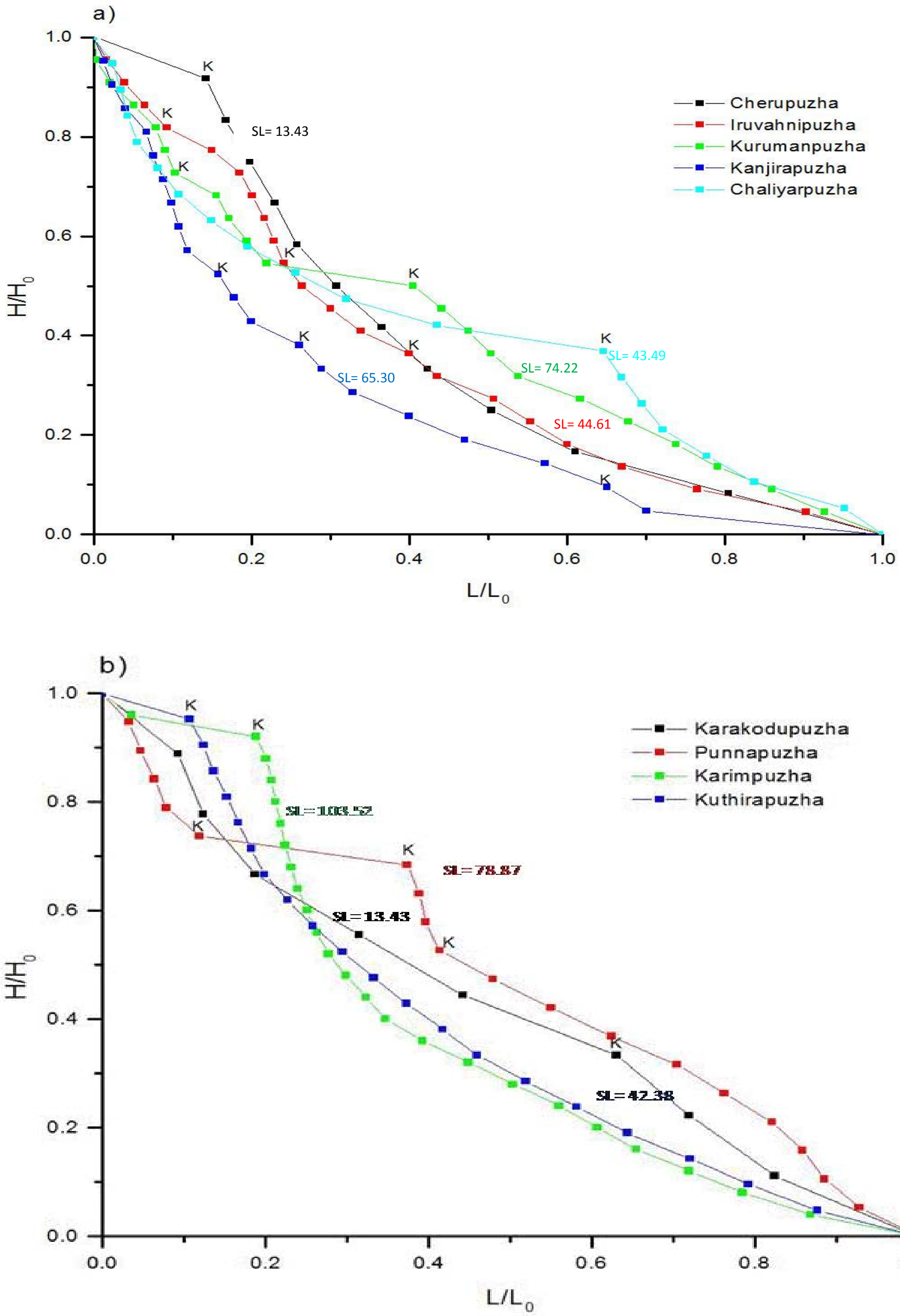


Fig. 5.5 Normalized stream profiles/dimensionless curves H/H_0 vs. L/L_0 (ratio of elevation vs. ratio of distance). Cherupuzha (13.43), Iruvahnipuzha (44.61), Kurumanpuzha (74.22), Kanjirapuzha (65.30) and Chaliyarpuzha (43.49). b) Karakodupuzha (13.43), Punnapuzha (76.87), Karimpuzha (103.52) and Kuthirapuzha (42.38). K in the figure indicates knickpoints and SL indicates stream-length gradient index. Values given in the parenthesis indicate SL i.e. stream-length gradient index.

Knickpoints

Knickpoints, the steep reaches in the longitudinal profile, can be caused by more resistant lithology, or by an increase in shear stress, or by surface uplift (Bishop et al., 2005). These anomalies in profiles can indicate either a stream in equilibrium where the upstream retreat communicates changes in base level to upstream valley (Bishop et al., 2005), or in some cases a dynamic equilibrium between fluvial processes and tectonic movements (Snow and Slingerland, 1990). Knickzones are supposed to be a response to base-level changes (Lewis, 1945) or to alternations in local lithology (Miller, 1991; Alexandrowicz, 1994). Upstream migration of knickzones cause rapid river incision resulting in the formation of terraces and instability of valley-side slopes (Okunishi, 1974; Yanagida, 1991; Shaktivel et al., 1999; Reneau, 2000; Hayakawa and Matsukura, 2002; 2003). Unrejuvenated upper valleys (that are located upstream the main knick points) cannot be used for the reconstruction of tectonic uplift (Starkel, 2003).

Knickpoints observed in the longitudinal profiles of Chaliyar River and its tributaries show that lithology has no influence (Table. 5.2). Knickpoints identified along the longitudinal profiles of each tributary of Chaliyar River with lithologic information and SL indices as the function of downstream length are shown in the Fig. 5.6

Longitudinal profile of Cherupuzha shows two knickpoints at 1000 m and 100 m elevation (Fig. 5.6a). The upper part of the stream has steep gradient of 40.9 m/km and the lower reaches have an average gradient of 6.45 m/km. Iruvahnipuzha indicates an upper reach, having a moderate gradient of 21.05 m/km and a lower reach with an average gradient of 9.56 m/km. Four knickpoints at 1800 m, 1600 m, 1200 m and 800 m elevation with downstream length of 1515 m, 30129 m, 3945 m, 6529 m respectively are observed (Fig. 5.6b). Kurumanpuzha has five knickpoints at elevations 1800 m, 1500 m, 1200 m, 1100 m and 700 m at downstream lengths 1620 m, 3190 m, 4537 m, 8373 m, 11139 m respectively (Fig. 5.6c). Two well distinct reaches with moderate gradient of 22.83 m/km is seen in the upper reaches and middle and lower reaches is with very low gradient of 4.5 m/km and is graded. Kanjirapuzha also has two well distinct reaches with steep gradient of 34.9 m/km in the upper reaches and moderate gradient of 6.48 m/km in the lower reaches of the stream. Four knickpoints could be identified in the profile at elevations 1700 m, 1200 m, 1100 m and 800 m at downstream lengths 1183 m, 2088 m, 2788 m and 4599 m respectively (Fig. 5.6d). Longitudinal profile of Chaliyar River indicates two well distinct reaches, with an upper part having a steep gradient of 27.89 m/km until it comes down to an altitude of 1300 m, and the lower reaches with well-graded profile having an average gradient of 2.86 m/km. The profile shows four knickpoints at 1800 m, 1500 m, 900 m and 700 m altitude represented by rapids at 405 m, 931 m, 5615 m, 11272 m downstream length respectively (Fig. 5.6e). Karakodupuzha indicated by two reaches in the profile with a gradient of 21.79 m/km in the upper reaches and with a low gradient of 3.21 m/km in the lower reach when the elevation comes down below 100 m. Knick points are observed at an altitude of 800 m, 700 m, 600 m and 300 m where the downstream lengths of the river are 750 m, 995 m, 1531 m, 3272 m respectively (Fig. 5.6f). At an elevation of 200 m also a minor break in the slope along the profile is observed. Punnapuzha has a steep gradient in the upper reaches with a break in slope in the middle reaches and has a gradational profile in the lower reaches. Knickpoints are observed at 1800 m, 1500 m, 1400 m and 1300 m at downstream lengths 1021 m, 2392 m, 3596 m and 11275 m respectively (Fig. 5.6g). At an elevation of 300 m also a break in slope is observed below which the stream has a gradational profile. Longitudinal profile of Karimpuzha shows steep gradient of 32.69 m/km in the upper reaches at 2300 m contour elevation and at the lower reaches, the stream gradient is very gentle (1.4 m/km) and has a gradational profile (Fig. 5.6h). Kuthirapuzha also has a gradational stream profile with a steep to moderate gradient (22 m/km in the upper reaches and gentle gradient of 4.4 m/km in the lower reaches). Knickpoint is observed at an elevation of 200 m at a downstream length of 1621 m (Fig. 5.6i).

The tributaries of Chaliyar River have one or more knick points. These knick points are not corresponding to the lithologic variation and hence considered to be the result of tectonism (faulting). Since the relief of all the knickzones is > 200 m, these are considered as major knickzones. Present longitudinal profiles of streams indicate that knickpoints are not controlled by the lithology or confluence impacts but by active tectonism.

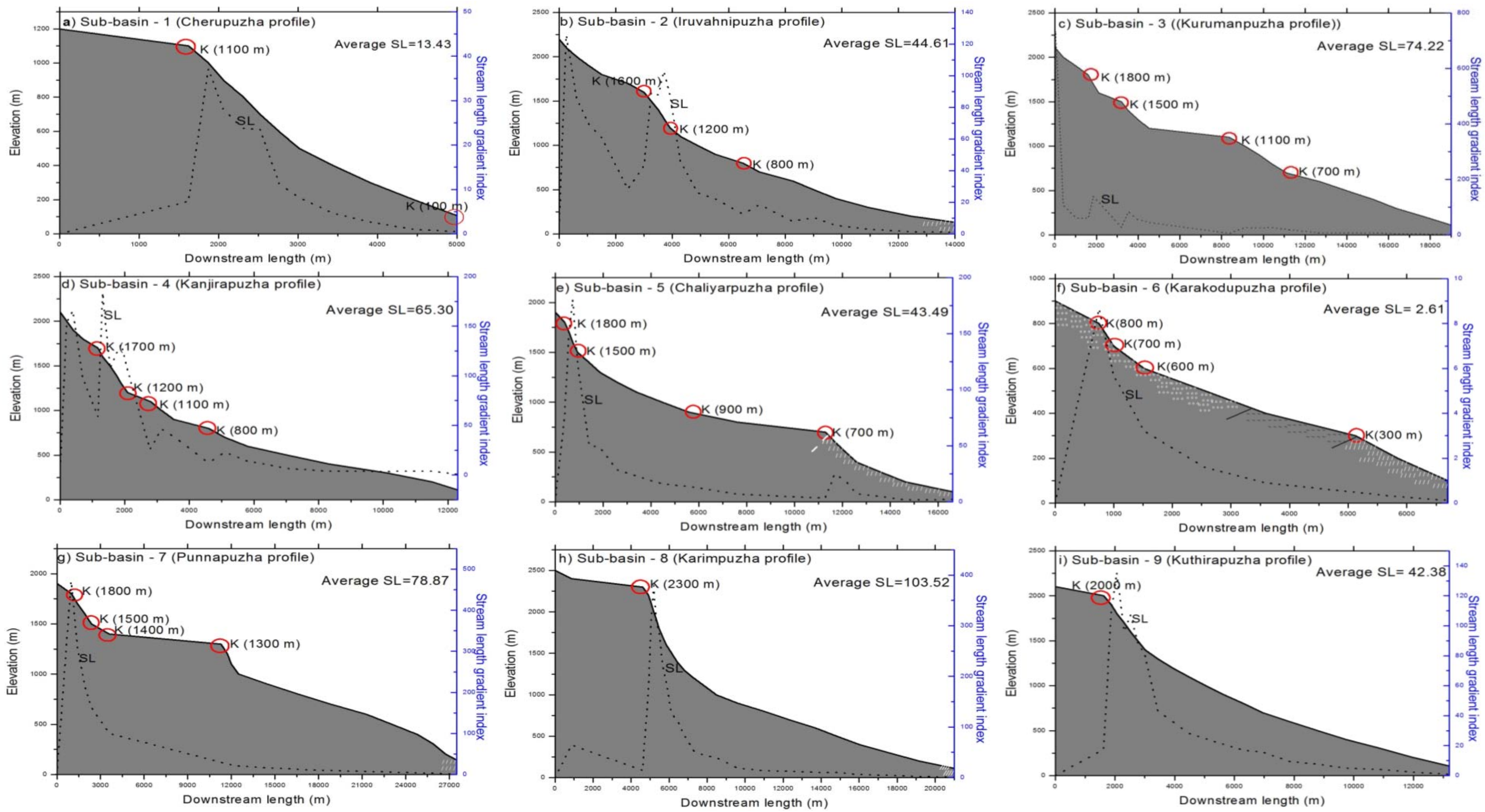


Fig. 5.6 Longitudinal profiles of the nine tributaries of Chaliyar River along with the geological cross-section and plot of SL index as a function of stream length downstream.(a) Cherupuzha, (b) Iruvahnipuzha, (c) Kurumanpuzha, (d) Kanjirapuzha, (e) Chaliyarpuzha, (f) Karakodupuzha, (g) Punnapuzha, (h) Karimpuzha and (d) Red circle represents the knickpoints in the profile. SL=Average SL index values and K = knickpoint and values in parenthesis is the elevation above MSL at which knickpoint occurs.

5.3.2 Geomorphic indices of active tectonics

Geomorphic indices are useful for identifying particular level of tectonic activity (Sinha, 2006), and can be used as a tool for analysing the landforms and evaluating the degree of tectonic activity in a given area (Keller, 1986). Quantitative measurements of geomorphic indices are commonly used as a reconnaissance tool in tectonic geomorphology studies to identify areas experiencing tectonic deformation (Burbank and Anderson, 2001). All geomorphic indices are influenced by the physical and mechanical properties of the bedrock. These tools allow the quantification of surface deformation both on maps and on stream profiles. Indices of active tectonics may detect anomalies in the fluvial system or along mountain fronts. These anomalies may be produced by local changes from tectonic activity resulting from uplift or subsidence (El Hamdouni et al., 2007). In order to estimate the relative variations of tectonic activity in a study area, we propose to use the combination of different geomorphic indices. Morphotectonic parameters viz., mountain front sinuosity index (S_{mf}), stream length gradient index (S_L), valley floor width to valley height ratio (V_f), transverse topographic symmetry factor (TTSF) and asymmetry factor (AF) are studied to understand the tectonic activity in the Chaliyar River drainage basin.

Stream length-gradient index (SL)

Stream length-gradient ratio is sensitive to change in channel slope and correlates to stream power, which is proportional to slope and discharge. It can be considered as the function of tectonics, rock resistance and topography and can be used to evaluate relative tectonic activity (El Hamdouni, et al., 2007).

First derivative of the stream length - gradient index (SL), slope gradient index (S) computed will describe the changes in SL and indicates the rate of change in SL from one segment to the other. The change from positive to negative value and vice-versa helps to identify very subtle gradient change which is not easy with SL. Values of SL and S computed for nine tributaries of Chaliyar River representing the nine sub-basins of the Chaliyar River drainage basin are presented in Table 5.3.

Anomalous values of stream length-gradient index indicate tectonic activity (Sinha, 2006) or can be due to the activity of structures that dislocate the bedrock (Hack, 1973). It is sensitive to changes in slope and lithology and this sensitivity allows the evaluation of the relationship between lithologic resistance and possible tectonic activity. This means the values of SL index are high in areas where the rocks are significantly resistant or where active tectonics prevails. Therefore anomalously high SL values or fluctuation of the SL values in rock of uniform resistance is a possible indicator of active tectonics (Keller, 1986). SL indices can detect areas of anomalous uplift within a landscape (Pinter, 1996). The stream-length index will increase in value as river and streams flow over active uplifts and may have lesser values when flowing parallel to features such as valleys produced by strike-slip faulting (Keller and Pinter, 2002). This index can be correlated with the stream power and it is sensitive to variations in gradient.

SL index for Cherupuzha ranges from 0.48 to 37.08 grad m for 11 segments for 100 m contour interval from 1100 to 100 m. SL index values are greater than 2 for all the segments except 200-100 m segment. Average SL index for the stream is 13.43. Slope index S ranges from -11.29 to 2.25 with an average value of -1.98. Iruvahnipuzha has an average SL index of 44.61 grad. m for 21 segments made at 100 m contour interval from 2000 to 1000 m elevation. The SL index ranges from 0.98 to 125.64 grd. m. Average slope gradient index S is -0.94 with values ranging from -14.20 to 5.55. SL index for Kurumanpuzha ranges from 1.28 to 734.82 grad. m with an average value of 74.22 grad. m for 21 segments. S index ranges from -7.89 to 1.80 with an average value of -1.11. Kanjirapuzha has it average SL index of 65.30 grad. m for 20 segments and values ranges from 0.31 to 183.59 grad, m. S index ranges from -16.26 to 2.89 with an average value of -1.72. SL index of Chaliyarpuzha ranges from 1.70 to 180.29 grad. m with an average value of 43.49 grad. m for 18 segments. SL index ranges from -12.34 to 1.80 with an average value of -1.44. Karakodupuzha has an average SL index of 2.61 grad.m for 8 segments with values ranging from 0.12 to 8.65 grad.m. S index ranges from -3.62 to 0.68 and has an average value of -0.89. Punnapuzha has SL index ranging from 0.92 to 470.43 grad.m with an average value of 78.87 grad.m for 18 segments. S index ranges from -46.91 to 20.48 with an average value of -2.76. SL index for Karimpuzha ranges from 0.72 to 378.92 grad.m with an average value of 103.52 grad.m. S index ranges from -20.37 to 21.70 with an average value of -1.86 for 24 segments made with 100 m contour interval from 2400 to 100 m elevation. Kuthirapuzha has an average SL index of 42.38 grad.m for 20 segments from 2000 to 100m. SL index ranges from 0.76 to 135.45 grad.m. S index ranges from -7.53 to 3.37

with an average value of -0.93. Based upon the quantitative SL indices linked to relative rock resistance described suggest that SL index show variable distribution. The highest and the most anomalous values of SL index are along Kurumanpuzha, Karimpuzha and Punnapuzha tributary rivers (SL > 200 grad.m). These high indices are associated with the rock resistance as well as with tectonics.

Mountain front sinuosity (S_{mf})

Mountain front sinuosity index (S_{mf}) represents the balance between erosional forces that tend to cut the embayment into a mountain front and tectonic forces that tend to produce a straight mountain front coincident with an active range-bounding fault (Kaewmuangmoon et al., 2008). Mountain front sinuosity gives the amount of incision at the apex of fans and is a balance between the rock uplift rates in the footwall. It depends on the rates of fluvial erosion in the footwall and variations in sediment supply. The S_{mf} is a measure of the degree of irregularity or sinuosity at the base of a topographic escarpment (Goswami et al., 2009). Active mountain front is generally straight and inactive one is increasingly embayed. More is value of S_{mf}, older is the tectonic event. Mountain front sinuosity is more of an indicator for the long-term level of faulting and erosional activity (Peters and Van Balen, 2007) since it is insensitive to detect short-term or minor fault reactivation that is insufficient to restore a straight front, or changes of the fluvial system due to a single climatic change.

Mountain front sinuosity computed, at places where the stream debouches the mountain, ranges from 1.48 to 2.29, indicating tectonically active to less active fronts (Table 5.3). Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha and Karakodupuzha have less active mountain fronts (S_{mf} > 1.5) while Punnapuzha and Kuthirapuzha have active mountain fronts. Cherupuzha and Karimpuzha have moderately active mountain fronts. Mountain front sinuosity computed at 30 different locations in the basin represented zones that are 17% active, 70% less active and 13% inactive. Since the mountain front sinuosity for Chaliyar River drainage basin falls in the tectonically less active zone, it can be surmised that the tectonic event is not a recent one or the climatic condition that subsisted in the terrain fomented the rate of weathering and erosion attributing to the comparatively high value of sinuosity.

Valley floor width to valley height ratio (V_f)

Valley floor width to valley height ratios quantify the degree to which a drainage system has been integrated into the landscape. This metric shows how a valley or drainage basin has been able to expand as the result of the slowing down or cessation of uplift. Valley floor width to valley height ratios can be used to determine the effect of tectonism on valley geometries (Burbank and Anderson, 2001). High valley floor width to valley height ratios are indicative of a landscape experiencing relatively high rates of uplift, in turn causing streams to continually incise their valleys in an attempt to keep pace with the relative drop in base level. Low valley floor width to valley height ratios indicate the drainages have seen a relatively long period of base level stability, allowing them to stabilize in the landscape and subsequently widen their flood plains and lower their valley walls (Bull and McFadden, 1977; Wells et al., 1988).

Valley floor width to depth ratio computed for the nine rivers within Chaliyar River drainage basin in the upper reaches show wide variation (Table 5.4). Cherupuzha has $V_f < 19$ indicating the V-shaped nature of the valley but are not steeply incised. Localized faults have influenced in the incision stream at places giving values of $V_f <$ 2.2. Average V_f of Iruvahnipuzha is 18.95 and has a slightly broad V-shaped valley without much incision. Localized steepening of the valley also could be noticed. Kurumanpuzha has average V_f of 14.10 with very narrow V-shaped valleys in the upper reaches which have been steeply incised. As moving downstream broadness of the valley increases. Average V_f of Kanjirapuzha River is 17.09 and has broad valleys with no incision as explained by its high value of V_f. Average V_f of Chaliyarpuzha is 15.25 with values ranging from 3.89 to 26.27. Chaliyarpuzha also has broad valleys even in the upper reaches with a very low incision rate. Karakodupuzha has its average V_f of 1.62 and has very narrow V-shaped valleys with steep high rate of incision rate as explained by the low V_f values. Average V_f of Punnapuzha is 26.52 and has very narrow V-shaped valleys in the upper reaches and the valleys get broadened downstream. The V-shaped valleys are steeply incised at places. Karimpuzha has average V_f of about 37.09. Karimpuzha has very narrow V-shaped valleys with steeply incised nature in the upper reaches and the valley gets broadened downstream. Kuthirapuzha has average V_f of 20.39 with very broad valleys even in the upper reaches of the stream.

Random computation of valley width to valley depth ratio covering almost all the parts of the drainage basin was also carried out to understand of the nature and types of valleys along the stream course (Table. 5.6). V_f computed all along Chaliyar River basin have values < 1, while in the Nilambur valley area, the values ranges between 1 and 5. In the lower reaches and at the mouth of Chaliyar, the values range from 4.73 to 128.80 indicating that the valleys are very broad with a very low incision rate. Low width-depth ratio in the upper reaches indicates that the valleys are V-shaped, actively incising with high uplift rates. Comparatively high values of width-depth ratio in the lower reaches and Nilambur valley suggest that the valleys are comparatively broad with lower uplift rates. Low values of V_f in the upper reaches indicate active incision. V_f in the lower reaches are also not so high, indicating the stream still continue to incise but at a lower rate. Towards the river mouth incision has almost ceased.

Asymmetry factor (AF)

Asymmetry factor permits us to establish the lateral tilting of a basin with respect to the main water course, which may be associated with the activity of a normal fault with a direction parallel to the main water course (Hare and Gardner, 1985; Cox, 1994). For a stream network that developed and continues to flow in a stable setting and uniform lithology, asymmetry factor should be equal to about 50, whereas unstable setting would give a deflection from normal value either < 50 or > 50 (Keller and Pinter, 1996). Asymmetry factor was calculated for the sub-basins and for the Chaliyar basin (Table 5.4).

Asymmetry factor (AF) for the Chaliyar basin is 41.88 indicating unstable nature of the basin. Sub-basins 1, 6, 7 and 9 have AF value > 50 and sub-basins 2, 3, 4, 5 and 8 have AF value < 50. Since all the basins show deviation from normal AF, it is concluded that all the sub-basins have a lateral tilting. Sub-basins 1, 6, 7 and 9 drained by Cherupuzha, Karakodupuzha, Punnapuzha and Kuthirapuzha respectively have tilting towards the left and sub-basins 2, 3, 4, 5 and 8 drained by Iruvahnipuzha, Kurumanpuzha, Kanjirapuzha, Chaliyarpuzha and Karimpuzha respectively show tilt towards the right side of the basin in the downstream direction.

Transverse Topographic Symmetry Factor (TTSF)

Transverse Topographic Symmetry Factor can detect areas of lateral tilting. High values indicating areas of potential tilting influence on drainage pattern. Like all geomorphic indices, single values of TTSF have no significance, but broad areas with similar values indicate a possible tectonic signature on the drainage pattern. Transverse Topographic Symmetry Factor, the index includes both a numerical value (asymmetry of the valley) as well as a vector orientation (direction of asymmetry) (Pinter, 2000).

Average Transverse Topographic Symmetry Factor for sub-basins 1, 2, 3, 5, 7, 8 and 9 is < 0.5 where as for sub-basins 4 and 6, the TTSF values are > 0.5 (Table 5.4). Average TTSF for Chaliyar basin is greater than 0.5. It can be inferred that the drainage of the basin is influenced by the tilting of the terrain due to tectonic activity.

Table.5.3 Stream-length – gradient index (SL), Slope index (S) and mountain front sinuosity (S_{mf}) computed for the sub-basins of Chaliyar River.

Stream	**Stream length – gradient index (S_L) (grad. m)**	**Slope index (S)**	**Mountain front sinuosity (S_{mf})**
1. Cherupuzha	13.43	-1.98	1.70
2. Iruvahnipuzha	44.61	-0.94	2.05
3. Kurumanpuzha	74.22	-1.11	2.94
4. Kanjirapuzha	65.30	-1.72	2.97
5. Chaliyarpuzha	43.49	-1.44	2.51
6. Karakodupuzha	13.43	-0.89	2.51
7. Punnapuzha	78.87	-2.76	1.48
8. Karimpuzha	103.52	-1.86	1.78
9. Kuthirapuzha	42.38	-0.93	1.60

Table 5.4 Valley floor width to depth ratio (V_f), Asymmetry factor (AF) and Transverse Topographic Symmetry Factor (TTSF) for the 9 tributaries of Chaliyar River.

Stream	**Valley floor width to depth ratio (V_f)**	**Average V_f**	**Asymmetry Factor (AF)**	**Transverse Topographic Symmetry Factor (TTSF)**	**Average TTSF**
1. Cherupuzha	9.75 5.48 24.22 12.82 1.67 17.39 3.18	10.64	62.00	0.39 0.52 0.36 0.55 0.43 0.63	0.48
2. Iruvahnipuzha	1.93 23.58 37.86 12.41	18.95	42.53	0.17 0.16 0.45 0.43 0.24 0.07 0.42	0.28
3. Kurumanpuzha	-4.27 1.97 17.32 44.77	14.10	42.75	0.34 0.09 0.27 0.25 0.53	0.29
4. Kanjirapuzha	26.10 8.07	17.09	20.80	0.26 0.78 0.61 0.31 0.56	0.50
5. Chaliyarpuzha	3.89 7.27 23.55 26.27	15.25	41.19	0.74 0.57 0.07 0.09 0.08 0.17 0.18 0.31	0.28
6. Karakodupuzha	1.33 1.94	1.62	68.49	0.69 0.84 0.47 0.52 0.38	0.58
7. Punnapuzha	1.94 46.51 31.12	26.52	56.68	0.47 0.53 0.45 0.20 0.42 0.11 0.31 0.29	0.35
8. Karimpuzha	1.85 2.87 59.16	21.30	37.09	0.74 0.82 0.54 0.39 0.28 0.16 0.35 0.76 0.15	0.47
9. Kuthirapuzha	18.11 22.67	20.39	61.39	0.83 0.15 0.26 0.03 0.12 0.49	0.31

5.3.3 Geomorphic markers of active tectonics

The impact of crustal deformation is expressed by various tectono-geomorphic features viz., escarpments, discontinuities along river courses, changes in drainage patterns, channel types, floodplain morphology, deformation of river terraces and the morphology of active mountain fronts (Ouchi, 1985; Schumm et al., 2000; Burbank and Anderson, 2001; Peters and Van Balen, 2007). The intensity of the interplay between tectonic and surface processes which gives impetus to tectonic geomorphology is strongly controlled by climatic conditions (Bull, 1991). Geomorphic markers are identifiable geomorphic features or surfaces that provide a reference frame against which to gauge differential or absolute deformation (Sinha, 2006).

Alluvial rivers and streams are very sensitive to epeirogenic tilting. Anomalous features in alluvial rivers indicating tectonism are local meandering, compressed meanders, pinched valleys, anomalous flares in the valleys, variation in levee width, flying levees etc.

River terraces

It is now recognised that climatic fluctuations are necessary to lead to terrace formation, but the formation of terrace sequences may also require uplift (Bridgland, 2000; Van den Berg and Van Hoof, 2001; Bridgland et al., 2004). Number, altitude and type of the terraces vary downstream and correlating and linking of the fragments is a difficult task. The river response to uplift is reflected in two types of terraces, which have been recognized in the Chaliyar river drainage basin; (i) degradational (strath) terrace and (ii) aggradational (fill) terrace. In the upstream reaches of all the tributaries of Chaliyar River, erosion prevails over the accumulation and strath terrace dominate. Towards the downstream part both strath and fill terraces are observed as in Arikkod (Fig. 5.7b), Edavanna and Puttalam areas. Strath terraces are dominant in the left bank of all the tributaries and fill terraces are commonly seen in the right bank of the streams. Strath terraces are the result of river incision in to the bedrock, typically within or immediately adjacent to tectonically active areas of mountain chains (Burbank and Anderson, 2001). Fill terraces are developed where the river bed is filled with sediments and the river is subsequently incising into this filling, leaving an aggradational abandoned surface at a higher level. The strath terraces are mainly exposed bedrock exhibiting fractures and joints (Fig. 5.7c). Cherupuzha and

Iruvahnipuzha in its downstream part have paired fill terraces. These paired terraces are the result of the episodic vertical incision of the river channel into the valley fill, which implies a regional development and longer-term stable events (Merritts et al. 1994).

The thickness of sediments in a terrace can be controlled by tectonics (Larue, 2008). Thickness of the sediment sequence increases where subsidence occurs. At Tana, the thickness of T_1 terrace sediments on the right bank of Chaliyar River is 7 m (Fig. 5.7d) and at Canoli Teak Garden T_1 on the right bank of Chaliyar River is about 10 m thick (Fig. 4.11d, *Chapter IV*).

At Nedungayam area, parallel step like normal faulting on the left bank of Karimpuzha resulted in the development of strath terrace (Fig. 5.8a). On the right bank T_0 terrace (fill terrace) has developed. T_0 surface is very thin and is comprised of pebble to sand size sediments with bed rock exposed at places.

T_0, T_1, T_2 and T_3 terraces are well developed on the right bank of Chaliyarpuzha at Ambalappoyi (Fig. 5.8b). Degradation of the left bank has resulted in the narrowing down of T_1 terrace. T_2 is well developed having thickness of 7 m. From the T_0 surface it can be inferred that the pebbles on this surface are derived from the T_1 terrace which is presently scoured by the Chaliyarpuzha tributary and get deposited on the other side of the river. After the development of T_2 terrace, a major faulting (F_1) occurred resulting in horst and graben pattern where T_2 terraces became the horst and stream bed the graben. This resulted in the development of a new flood plain which was further uplifted to T_1 terrace by the F_2 faulting (river along faulting) on the left bank. The uplifted terrace on the left bank was incised by the stream on the left bank. Oscillatory movement and channel migration towards north in this part is evident from the transverse profile.

Development of unpaired terraces at Nilani along Chaliyarpuzha signifies the role of localized tectonism and channel migration (Fig. 5.8d). Present channel is getting migrated to the eastern bank resulting in the degradation of T_1 terrace. At some places the width of T_1 terrace has been reduced to about a metre or so. T_0, T_1, T_2 and T_3 are well developed on the western right bank of Chaliyarpuzha.

Climate and tectonism play an important role in the development of fluvial terraces. Climatically induced base level changes, produce terraces that commonly run parallel to the stream bed for tens of kilometres. Localized tectonism also produces terraces that converge within a few kilometres. Eustatic changes, lower base level and cause streams to incise their channels, which begin to degrade them to the new base level.

Field evidences indicate that the terraces developed along the Chaliyar River are developed as a result of localized tectonism, with strike continuity ranging from hundreds of metres to a few kilometres only.

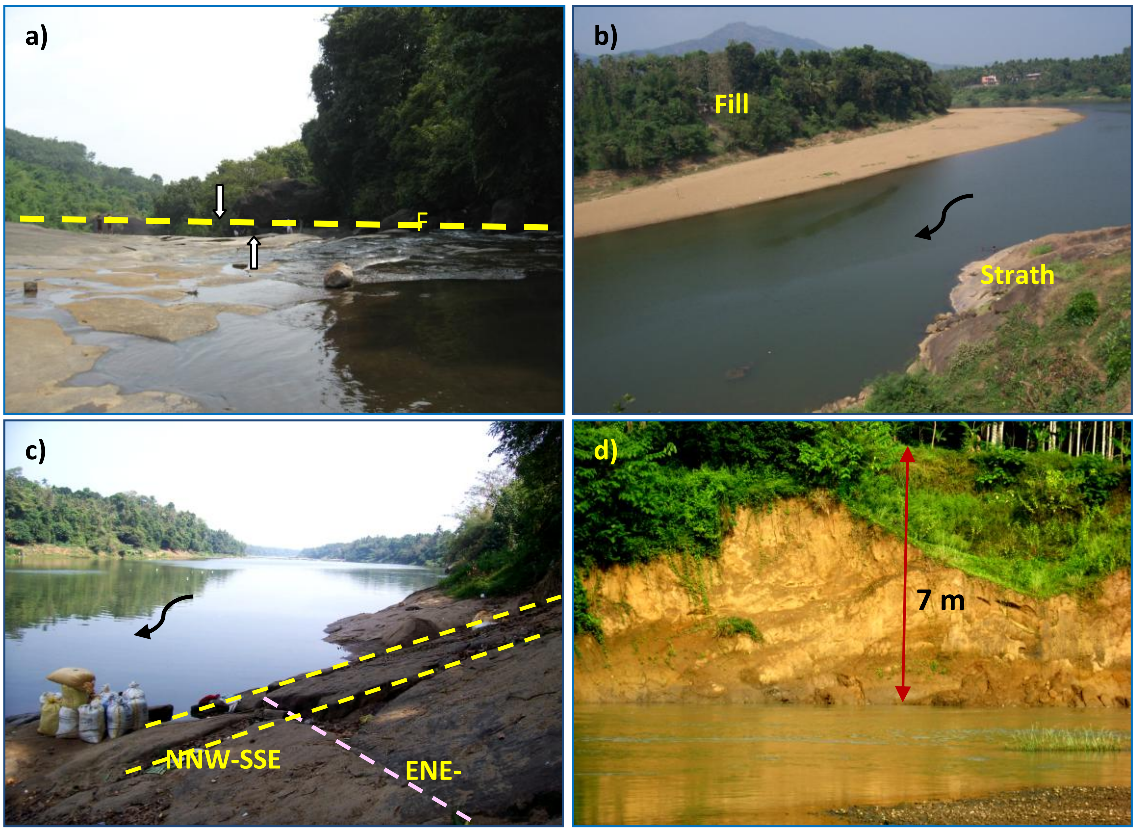


Fig. 5.7 (a) Normal fault across the stream at Adyanpara waterfall. Down throw of the fault is 12 m as observed in the field; (b) strath and fill terrace of Chaliyar River at Arikkod observed on the left and right banks respectively; (c) fractures observed in the strath terrace of Chaliyar River at Puttalam. Two sets of terrace trending NNW-SSE and ENE-WSW are marked with dashed lines of yellow and light pink respectively. The sudden shift in the course of the river from west to NNW is due to the NNW-SSE trending river along normal fault and (d) T_1 terrace on the right bank of Chaliyar River at Tana. Thickness of T_1 is about 7 m.

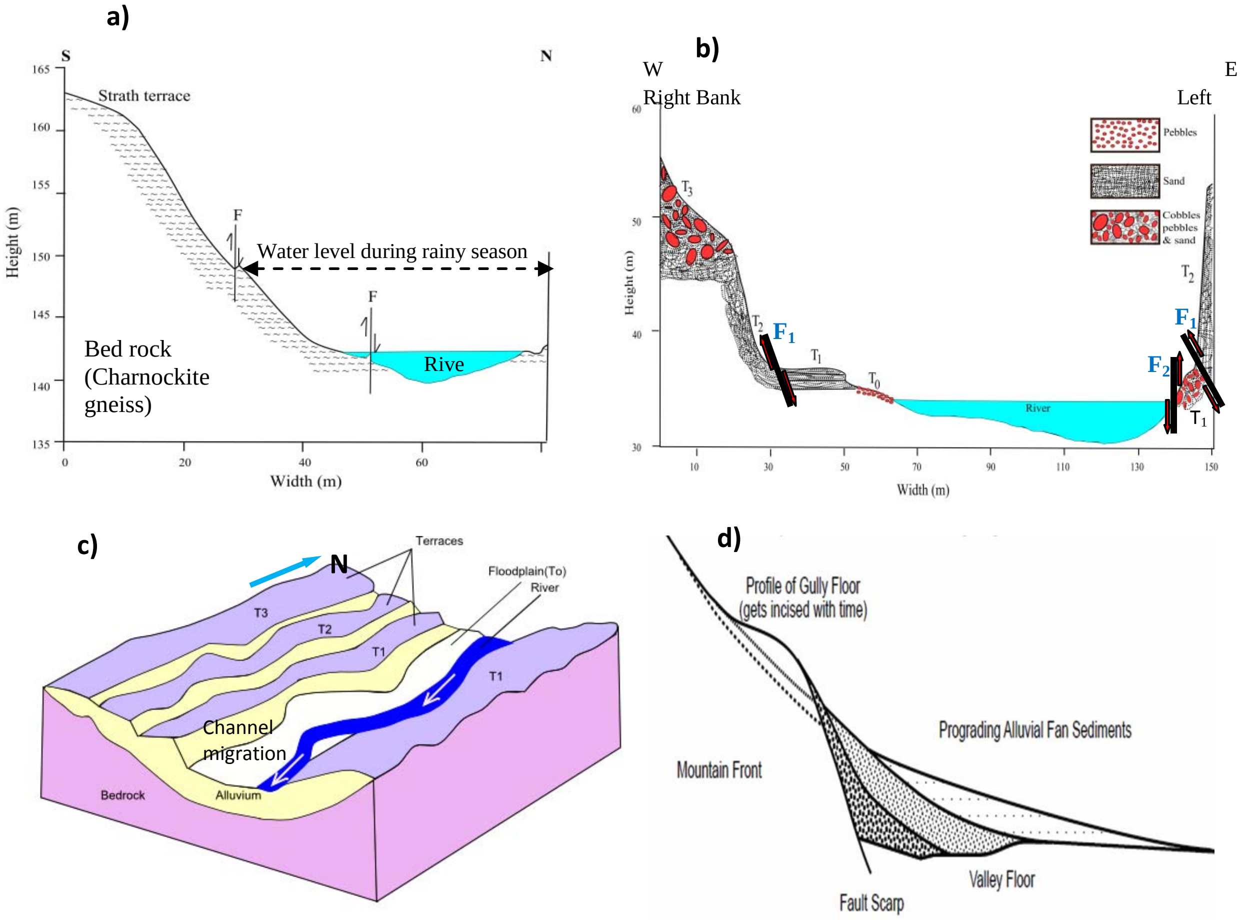


Fig. 5.8 (a) Transverse profile of Karimpuzha at Nedungayam. T_1 terrace is strath terrace with two parallel normal faults; (b) transverse section of Chaliyarpuzha at Ambalappoyi as observed in the field. The profile shows wide valley with unpaired terraces. T_0 and T_1 are well developed on the right bank. T_1 on the right bank composed of sand silt intercalation is well developed while T_1 in the left bank composed of pebbles undergoes erosion (degradation). T_2 is having thickness of ~ 6 m on either bank (paired). T_3 composed of cobbles and pebbles and are lateritized at places; (c) block diagram of the unpaired terraces of Chaliyarpuzha at Nilani. T_0, T_1, T_2 and T_3 are well developed on the western bank. Currently T_1 terrace on the left (eastern) bank is being eroded and (d) schematic diagram of the development of alluvial fan followed by a single movement along a fault.

Alluvial fans

Aggradation can happen when a river debouches from a mountain to the pediment along a fault scarp and builds up an alluvial fan. Rapid hanging wall subsidence and footwall uplift creating a linear range front, large facets, small piedmont fans and proximal axial river. Slower deformation leads to large, low-gradient fans, small facets, entrenched fan heads, and distal axial rivers. Alluvial fan spacing is the ratio of the mean length of the basin to the mean spacing of mouths along the mountain front. Alluvial fan spacing between 1.8 and 4 indicate tectonically active regions and spacing will be 1.2 for complex geological uplift and older mountains (Sinha, 2006).

Alluvial fans in Chaliyar River drainage basin are located at the foothills at the break of slope and can be considered as palaeo-alluvial fans (Fig. 5.8d) and these could not be traced because these alluvial fan deposits are concealed under thick vegetation (Fig. 4.25 *Chapter 4*). They assume very gentle slope with elevation ranging from 40-60 m above MSL. Such alluvial fan deposits are seen in Nedungayam, Bhudan Colony Karakkodu, Vellimattam and Pattakarimba (Fig. 5.9). Alluvial fan at Nedungayam spreads over an area of 40 km^2.

Alluvial fan spacing (AFS) in the Chaliyar River drainage basin ranges from 1.57 to 1.96. Alluvial fans observed at Vellimattam (AFS =1.85) and Pattakarimba (AFS = 1.6) have values > 1.8 indicating tectonically active zone. Alluvial fan spacing (AFS) of alluvial fans at Nedungayam, Bhudan Colony and Karakkodu exhibits values > 1.2 and < 1.8 indicating less active zone.

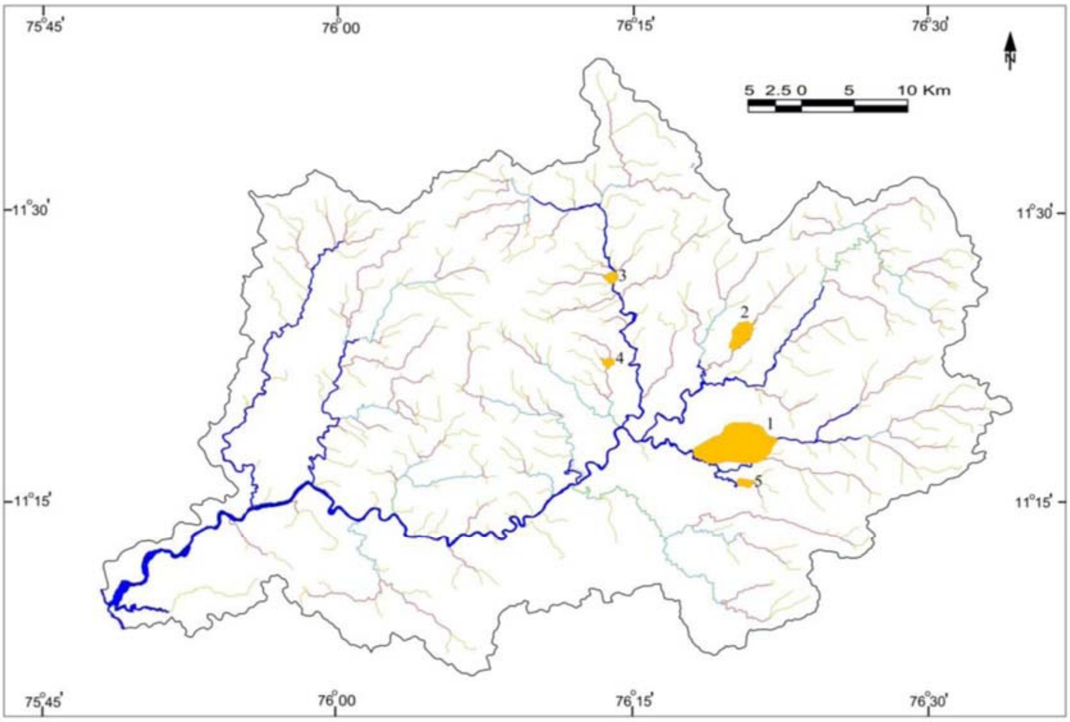


Fig. 5.9 Location of alluvial fan deposits in Chaliyar River drainage basin. (1) Nedungayam, (2) Karakkodu, (3) Bhudan Colony, (4) Vellimattam and (5) Pattakarimba.

Beheaded streams

Streams usually behead due to strike-slip motion. Abandoned streams abruptly terminate as it crosses a fault and is useful in relating the deflection due to a fault. It is easier to identify stream beheading when deflection is against the regional slope. Scraps can be preserved on either side of the fault. Linear features like streams and ridges become offset along the fault and can yield a clear sense of slip direction. When a ridge that has been translated along the fault blocks the drainage is called shutter ridge (Fig. 5.10a). Beheaded streams and shutter ridges are observed at Thamabattimala where streamlets that flow SW gets deflected along the ENE-WSW fracture plane and joins Punnapuzha further east (Fig. 5.10b). ENE-WSW trending ridge at Thambattimala acts as the shutter ridge for the direct flow of the streamlets to join the Karakodupuzha in the south.

Deflected streams

Presence of fluvial elbows and knickpoints in same river is a good indicator of a fluvial capture (Bishop, 1995). In Kurumanpuzha and Kanjirapuzha both elements were found close to one another. It can be inferred that the fluvial reorganization occurred by means of strike-slip fault (Fig. 5.11). The stream flowing south along F_1 fault is deflected by WNW-ESE fault (F_2-F_2') shifting the flow direction to ESE displacing the older (F_1-F_1') fault.

Landslides

Landslides are an important factor in landform evolution. Active landslides are triggered by a) fragmented rock, b) steep slopes, c) supply of sub-surface and surface water by rain or snow melt and d) human impact or combination of these factors (Glade et al, 2009).

Landslides prone areas are observed at the foothills of the mountain scarps. Details of the landslides that occurred in the Chaliyar River drainage basin show repeated landslide and slump in some locations (Table. 5.5). Evidences of palaeo-landslides could be observed during field study (Fig. 4.29, *Chapter IV*). Most of the landslides fall well within 0.55 km and 0.66 km buffer zones of NW-SE and NE-SW trending lineaments respectively (Fig. 5.12). Field study could confirm the reactivation of earlier faults which have triggered recent landslides in the basin in conjunction with heavy rain.

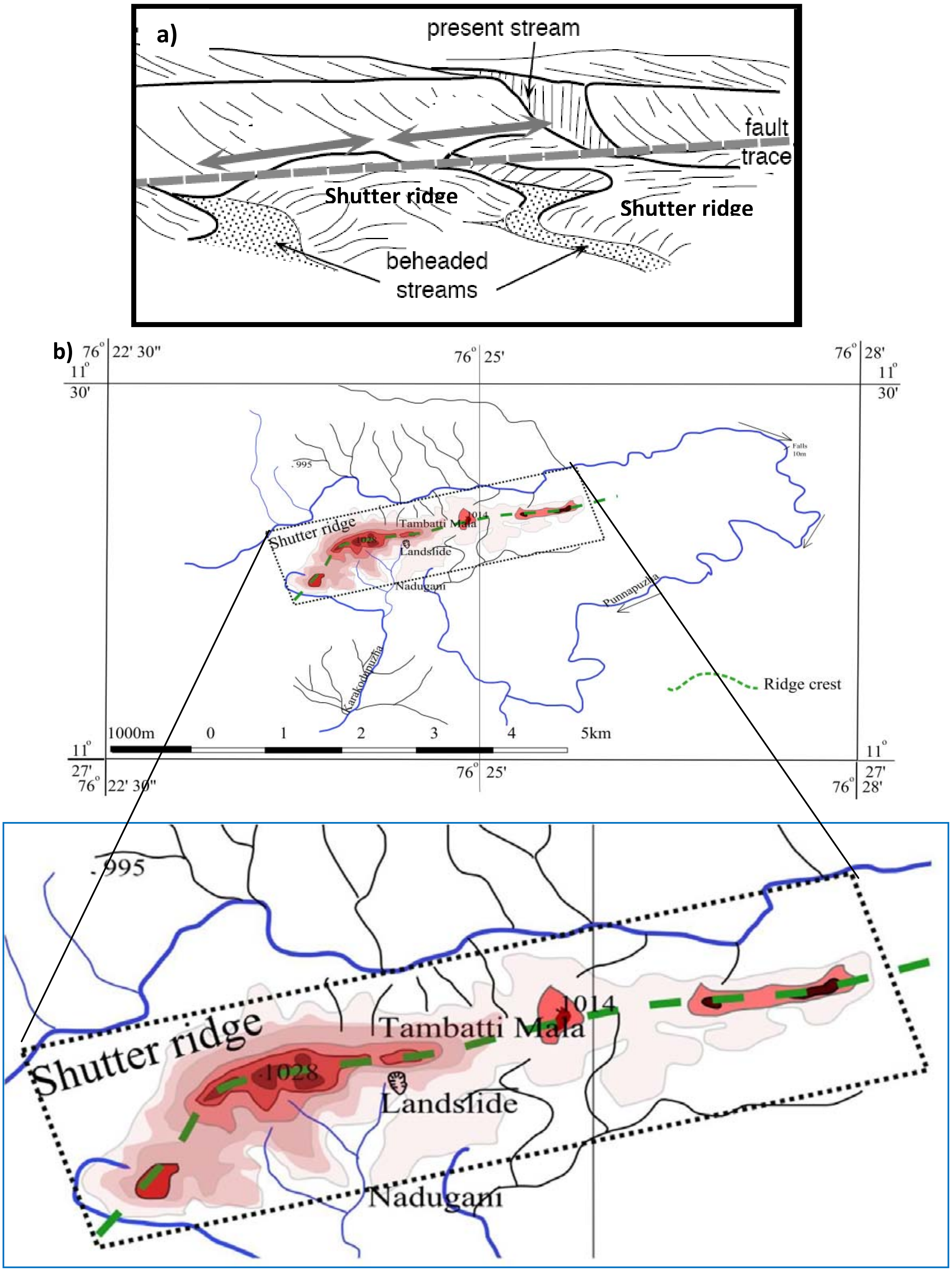


Fig. 5.10 (a) Schematic diagram showing the development of offset streams; (b) beheaded stream and shutter ridge in Chaliyar basin at Tambattimala. The E-W ridge forms the shutter ridge. The stream flows through a normal fault trending ENE-WSW direction and joins Punnapuzha. This normal fault has resulted in the formation of shutter ridge (Tambattimala) which obstructed the southward flow of the streams.

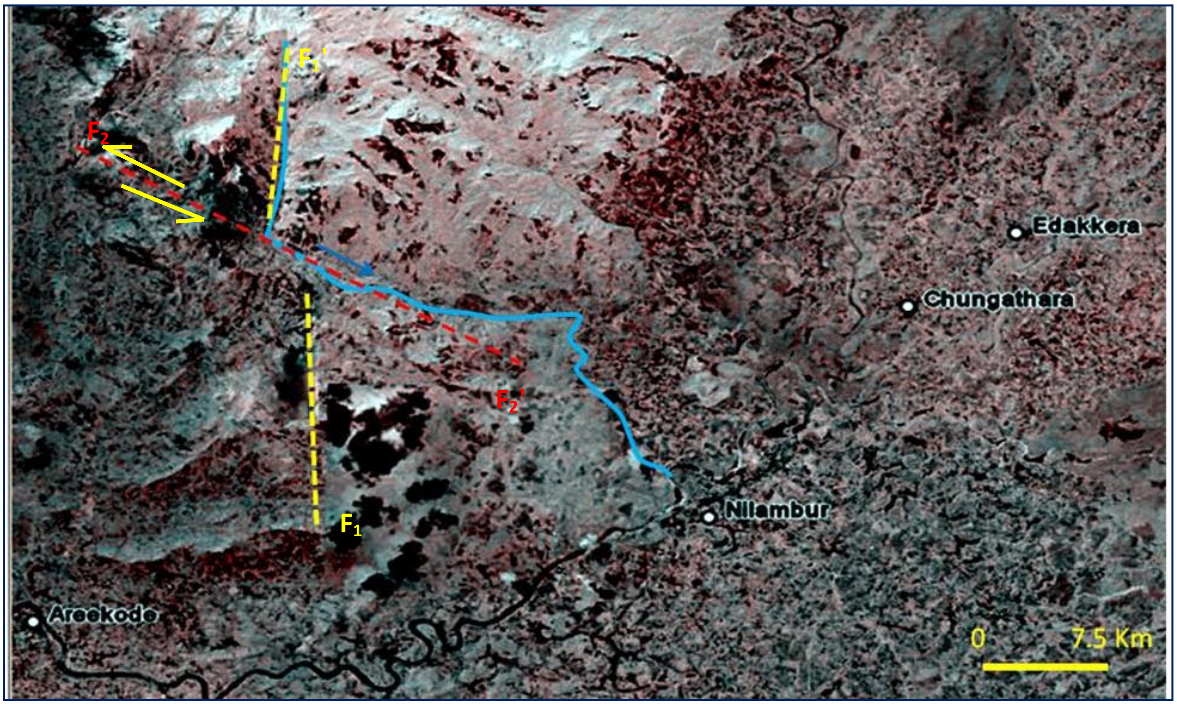


Fig. 5.11 Deflection of stream due to WNW-ESE trending strike-slip fault (F_2-F_2') as observed in the enhanced Google earth map. The fault (F_2-F_2') off-sets the N-S trending (F_1-F_1') fault and deflects the south flowing stream to ESE direction.

Compressed meander

The closely spaced meanders i.e., compressed meanders occur along the upper reaches (as in Punnapuzha SSE of Puliyanparai near the hillock .962 and in Kuthirapuzha, west of Chokkad) as well as along the lower reaches (as in Cherupuzha and Iruvahnipuzha) of the tributaries of Chaliyar River (Fig. 5.13a) and also along the trunk stream of Chaliyar River at Edavanna (Fig. 5.13b). The development of these meanders may not be due to river maturity but may be the result of parallel strike slip faults trending NW-SE which resulted in the shifting of stream course and development of compressed meanders.

Angular drainage

Angular drainage pattern is very common in the Chaliyar River drainage basin. Lower order as well as higher order streams show angular drainage pattern. Cross-cutting of lineaments of different ages has resulted in the angular pattern of the drainage (Fig. 5.14).

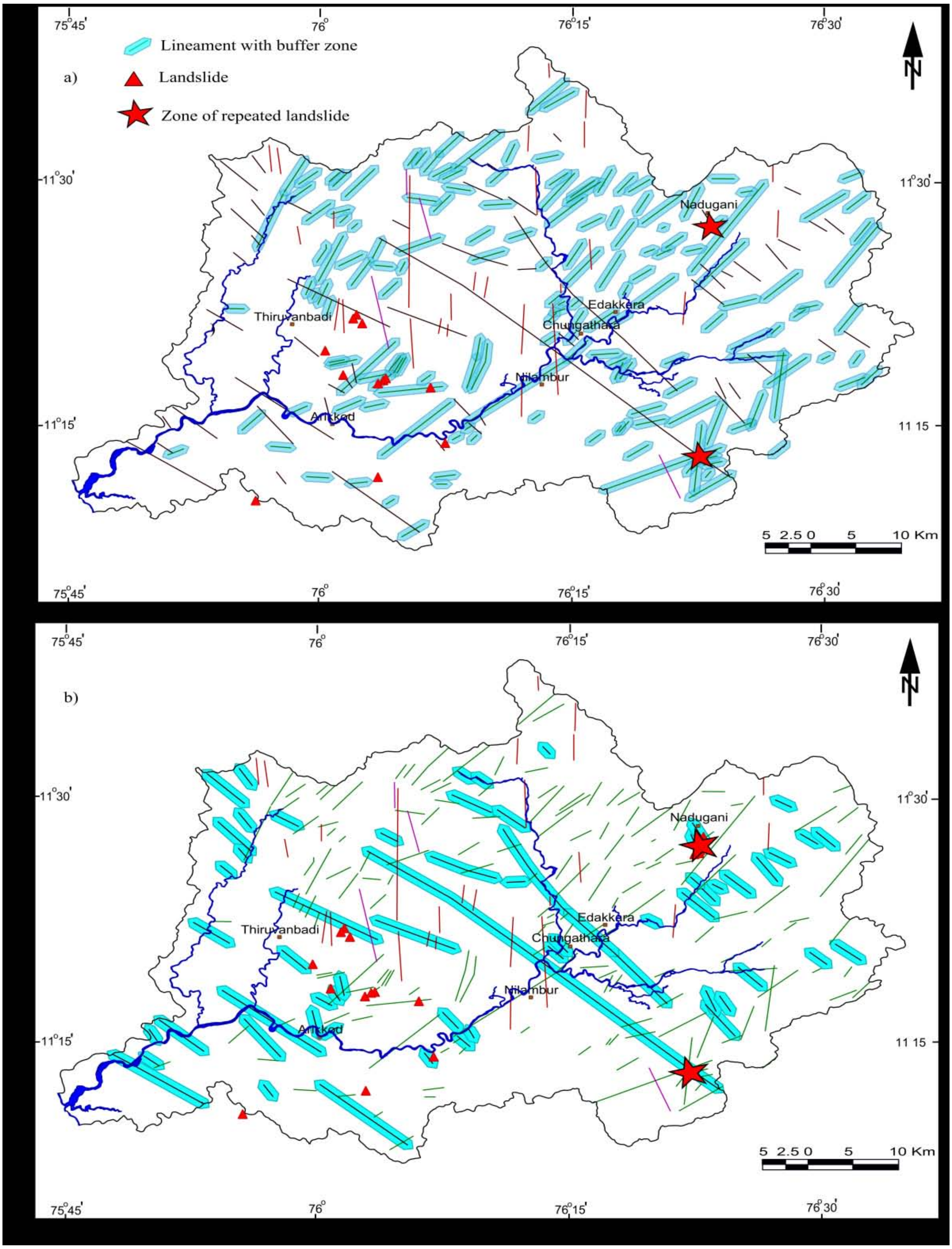


Fig. 5.12 Relationship of lineaments and landslides in the Chaliyar River drainage basin. a) Map showing NE-SW and ENE-WSW lineaments with buffer zone of 0.55 km. Majority (about 70%) of the landslides fall well within the buffer zone. b) Map showing NW-SE lineaments with buffer zone of 0.66 km. About 50% of the landslides fall within the buffer zone.

Table. 5.5 Inventory of the landslides reported in Chaliyar river drainage basin (database from Geological Survey of India (2009), Kerala Unit and archive of Malayala Manorama Daily)

Sl. No.	Location	Types of slides/mode of failure	Geology, Lithology & landuse	Morphometric characters
1	Tinur Valuk village Vadakara Taluk Kozhikode District 11^0 44'52.0"N-75^0 47'26.0"E	Debris flow 5.6.2007 at 1845 to 1900 hours. On 4th June 2007 there was a rock fall reported in the area.	Gneiss/ Charnockite gneiss. Rubber plantation, forest.	Northern slope of a E-W trending ridge with thin lateritic soil and scree materials.
2	Thoradumala Konthaladu village Koilandy Taluk Kozhikode District 11^0 29'33.7"N-75^0 51'59.5"E,	Initiation of a landslide on 17.7.2007 at 0350 hours.	Gneiss/ Charnockite gneiss. Rubber sapling, settlements, new kutchcha road.	Southern slope of a E-W trending ridge with thin lateritic soil and scree materials.
3	Oranjottukunnu Konthaladu village Koilandy Taluk Kozhikode District 11^0 29'37.5"N-75^0 53'24.7"E	Initiation of a landslide on 17.7.2007 at 0350 hours.	Gneiss/ Charnockite gneiss. Rubber sapling, settlements, new kutchcha road.	Northern slope of a E-W trending ridge with thin lateritic soil and scree materials.
4	Periyamala Konthaladu village Koilandy Taluk Kozhikode District 11^0 31'00.9"N-75^0 53'57.2"E,	Initiation of a landslide on 21.7.2007 at 0400 hours.	Gneiss/ Charnockite gneiss. Rubber sapling, settlements..	Northern slope of a E-W trending ridge with thin lateritic soil and scree materials.
5	Mysoorpetta-Thottumukkam Kodiyattur village Koilandy Taluk Kozhikode District 11^0 17'37.6"N-76^0 03'01.5"E,	Debris slide on 17.7.2007 at 0200 hours.	Gneiss/ Charnockite gneiss, settlements.	Northern slope of a E-W trending ridge with thin lateritic soil and scree materials.
6	Thottumukkam Kumaranallur village Kozhikode Taluk Kozhikode District 11^0 18'41.1"N-76^0 02'00.8"E,	Debris avalanche on 17.7.2007 at 0130 hours.	Gneiss/ Charnockite gneiss, settlements.	Northern slope of a E-W trending ridge with thin lateritic soil and scree materials.

Sl. No.	Location	Types of slides/mode of failure	Geology, Lithology & landuse	Morphometric characters
7	Pakakkachal Koodaranji village Kozhikode Taluk Kozhikode District 11^0 20’58.3”N-76^0 03’44.0”E,	Debris flow on 17.7.2007 at 0200 hours.	Gneiss/ Charnockite gneiss, settlements.	Southern slope of a E-W trending ridge with thin lateritic soil and scree materials.
8	Panakkachal 2nd Koodaranji village Kozhikode Taluk Kozhikode District 11^0 20’45.1”N-76^0 03’33.7”E,	Debris flow on 17.7.2007 at 0130 hours.	Gneiss/ Charnockite gneiss, settlements.	Southern slope of a E-W trending ridge with thin lateritic soil and scree materials.
9	Anayode Koodaranji village Kozhikode Taluk Kozhikode District 11^0 20’25.7”N-76^0 04’05.5”E,	Debris slide on 17.7.2007 at 0200 hours.	Gneiss/ Charnockite gneiss, settlements.	Southern slope of a E-W trending ridge with thin lateritic soil and scree materials.
10	Chengara Vettilapara Village Eranadu Taluk Malappuram District $11^0$10’34.6”N- 76^0 04’56.0”E,	Reactivation of an old slump on 17.7.2007 at 0230 hour	Gneiss/ Charnockite gneiss. Rubber plantation, sapling	Southern slope of a E-W trending ridge with thick pile of lateritic soil. Sapling pits helps to infiltration.
11	Alappara Vettilapara Village Eranadu Taluk Malappuram District $11^0$16’33.1”N- 76^0 05’18.1”E	Debris flow 17.7.2007 at 0200 hour	Gneiss/ Charnockite gneiss. Rubber plantation, sapling	Eastern slope of a N-S trending ridge with loose slope forming material. Contour bunding seen the area.
12	Alappara Vettilapara Village Eranadu Taluk Malappuram District $11^0$16’33.1”N- 76^0 05’16”E	Debris flow 17.7.2007 at 0200 hour	Gneiss/ Charnockite gneiss. Rubber plantation, sapling	Eastern slope of a N-S trending ridge with loose slope forming material. Contour bunding seen the area.
13	Alappara Vettilapara Village Eranadu Taluk Malappuram District $11^0$16’33.1”N- 76^0 05’ 14”E	Debris flow 17.7.2007 at 0200 hour	Gneiss/ Charnockite gneiss. Rubber plantation, sapling	Eastern slope of a N-S trending ridge with loose slope forming material. Contour bunding seen the area.

Sl. No.	Location	Types of slides/mode of failure	Geology, Lithology & landuse	Morphometric characters
14	Odakkayam-muppari mala Vettilapara Village Eranadu Taluk Malappuram District $11^0$16’18.5”N- 76^0 07’51.7”E	Debris flow 17.7.2007 at 0700 hour	Gneiss/ Charnockite gneiss. Rubber plantation, agri-land	Western slope of a N-S trending ridge with loose slope forming material. Contour bunding seen the area for rubber plantation.
15	Chepilikunnu Kondotti Village Eranadu Taluk Malappuram District $11^0$09’04.7”N-75^0 58’10.6”E	Debris flow 17.7.2007 at 0200 hour	Gneiss/ Charnockite gneiss, agricultural land.	Western slope of a N-S trending ridge with tick pile of clayey red soil. Three steps of platform were made for house construction. Un lined latrine pit were made on the slope.
16	Edavanna Edavanna Village Eranadu Taluk Malappuram District $11^0$12’47.9”N-76^0 08’42.8”E,	Debris slide 17.7.2007 at 0200 hour	Gneiss/ Charnockite gneiss, agricultural land.	Eastern slope of a N-S trending ridge with tick pile of clayey lateritic soil. Steep slope cutting to height of 8m for house construction. Above slope, rubber sapling pits were seen which direct the water seepage and ultimately lead to toe erosion.
17	Mannarmala Kariyavattom Village Perinthalmanna Taluk Malappuram District 11^0 00’03.2”N-76^0 14’44.0”E	Debris flow 17.7.2007 at 0200 hour	Gneiss/ Charnockite gneiss. Rubber plantation.	Northern slope of a E-W trending ridge with loose slope forming material. Contour bunding seen in the area.
18	Kallala 102/800 Vazhikkadavu Village Nilambur Taluk Malappuram District 11^0 25’53.5”N-76^0 23’20.5”E	Reactivation of an old slump on 2.9.2007	Gneiss/ Charnockite gneiss. Reserve forest, state highway	Western slope of a N-S trending Nadukani ridge with thick pile of screee and lateritic soil.
19	Kallala 101/850 Vazhikkadavu Village Nilambur Taluk Malappuram District 11^0 25’44.8”N-76^0 23’05.8”E	Debris avalanche on 23.6.2008 at 1930 hours.	Gneiss/ Charnockite gneiss. Reserve forest, state highway	Western slope of a N-S trending Nadukani ridge with thick pile of screee and lateritic soil.
20	Kallala 101/900 Vazhikkadavu Village Nilambur Taluk Malappuram District 11^0 25’46.5”N-76^0 23’07.2”E	Debris avalanche on 23.6.2008 at 1930 hours.	Gneiss/ Charnockite gneiss. Reserve forest, state highway	Western slope of a N-S trending Nadukani ridge with thick pile of screee and lateritic soil.

Sl. No.	Location	Types of slides/mode of failure	Geology, Lithology & landuse	Morphometric characters
21	Kallala 102/400 Vazhikkadavu Village Nilambur Taluk Malappuram District 11^0 25’49.5”N-76^0 23’20.3”E	Debris avalanche on 23.6.2008 at 1930 hours.	Gneiss/ Charnockite gneiss. Reserve forest, state highway	Western slope of a N-S trending Nadukani ridge with thick pile of screee and lateritic soil.
22	Kallala 102/450 Vazhikkadavu Village Nilambur Taluk Malappuram District 11^0 25’48.3”N-76^0 23’23.5”E	Debris avalanche on 23.6.2008 1930 hours.	Gneiss/ Charnockite gneiss. Reserve forest, state highway	Western slope of a N-S trending Nadukani ridge with thick pile of screee and lateritic soil.
23	Kallala 102/700 Vazhikkadavu Village Nilambur Taluk Malappuram District 11^0 25’58.4”N-76^0 23’22.1”E	Debris flow on 23.6.2008 1930 hours.	Gneiss/ Charnockite gneiss. Reserve forest, state highway	Western slope of a N-S trending Nadukani ridge with thick pile of screee and lateritic soil.
24	Kallala 103/500 Vazhikkadavu Village Nilambur Taluk Malappuram District 11^0 26’17.8”N-76^0 23’33.9”E	Debris slide on 23.6.2008 1930 hours.	Gneiss/ Charnockite gneiss. Reserve forest, state highway	Western slope of a N-S trending Nadukani ridge with thick pile of screee and lateritic soil.
25	Kerala estate	7-10-1993	Data retrieved from archives of Malayala Manorama Daily Newspaper.	
26	Karuvara kundu	28-5-1993		
27	Karuvara kundu	May 1993		
28	Karumbakongodu	15-07- 1994		
29	Kaliyakavu	7-10-1993		
30	Kaliyakavu	28-05-2003		
31	Kuruvarakundu	07-10-1993		

Sl. No.	**Location**	**Types of slides/mode of failure**	Remarks
32	Kerala Estate	28-05-1997	Data retrieved from archives of Malayala Manorama Daily Newspaper.
33	Poolapadam	15-07-1995	
34	Chengra	17-07-2007	
35	Kodaleri mala	17-07-2007	
36	Chekunni mala	17-07-2007	
37	Odakkayam	17-07-2007	
38	Allappara	17-07-2007	
39	North of .1532 hill 11º17’10”: 76º28’45”	1965	
40	North of Nadugani near Tambattimala 11º 27’ 40”:76º 24’ 30”	1965	Reflected in the first edition of SOI toposheet 58A/7 (1965) on 1:50,000 scale

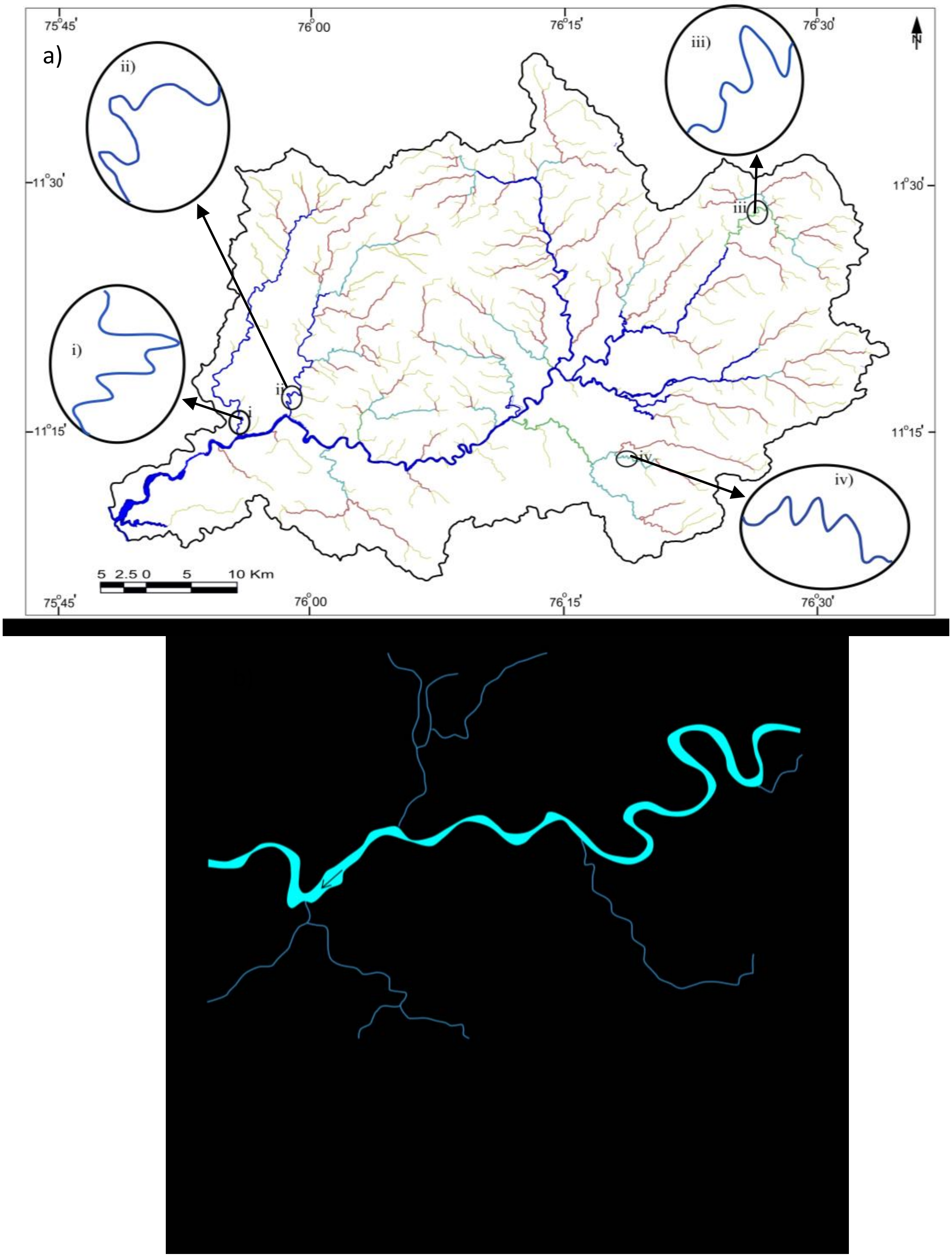


Fig. 5.13 (a) Compressed meandering in i) Cherupuzha, ii) Iruvahnipuzha, iii) Punnapuzha and iv) Kuthirapuzha and (b) Compressed meander loop of Chaliyar River at Edavanna. Compressed meandering has formed as a result of strike-slip faults that enhanced channel migration in the slip direction.

Fig. 5.14 Angular drainage pattern in the 3rd, 4th, 5th, 6th and 7th order streams observed Chaliyar River drainage basin. Flow direction of the streams is determined by the lineaments. Younger lineament when cross cuts the older one stream takes the direction of the younger lineament.

River ponding

Strike-slip and oblique-slip displacements results in the blockage in the river resulting in river ponding as explained by Valdiya (1998, 2001) and Valdiya and Narayana (2007). Localized stream ponding along active faults results in still-water bodies (pools) along the faults in the tributaries of Chaliyar River (Fig. 5.15a). South of Chungathara, Punnapuzha tributary shows ponding due to the NW-SE fault (Fig. 5.15b). Ponding in Karimpuzha is observed at Karulayi and it Nedungayam, formed due to the NE-SW trending lineaments (Fig. 5.16a, b).

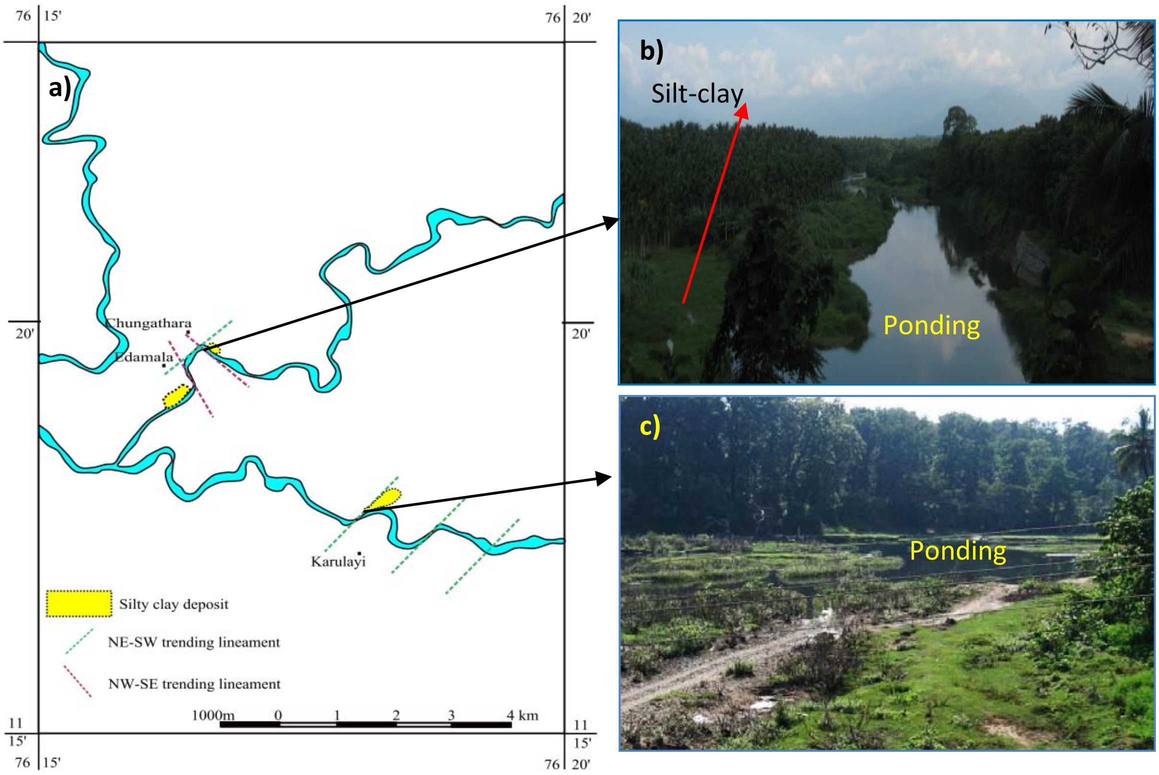


Fig. 5.15 (a) Active faults or lineaments that control the drainage pattern and the present day ponding in Punnapuzha and Karimpuzha Rivers. Vertical or horizontal movements along these faults have changed the gradient of these rivers resulting in the blockage in the flow at Karulayi, (b) River ponding in Punnapuzha at Edamala south of Chungathara and (c) River ponding in Karimpuzha at Karulayi.

Fig. 5.16 Spectrally enhanced Google earth imagery showing river ponding in Karimpuzha stream at (a) Karulayi and (b) Nedungayam.

5.4 Lineaments

Different stages of tectonic evolution for Indian craton by the study of lineament patterns with the help of Landsat imagery have been recognised by Drury and Holt (1980). Five sets of lineaments have been identified in the physiographic province of Kerala with general trends of WNW-ESE, NW-SE, NNW-SSE, NNE-SSW and ENE-WSW (Nair, 1990). Lineaments that are trending NNE-SSW and NE-SW are considered as faults which have disturbed the younger dolerite dykes in southern India (Grady, 1971). Lineaments with NNW-SSE trends are considered as coast parallel lineaments of the west coast. The causative factors observed along the coastal Kerala are traced to the strain factors associated with the transform faults of the Carlsberg ridge (Subrahmanyam and Chand, 2006). Lineaments with NW-SE trend have probably controlled the emplacement of basin dykes associated with Deccan volcanism (Krishnaswamy, 1981: Nair, 1990). Rectilinear valleys, ridges, crests, passes or combination of these features when aligned were drawn as lines over the aspect map of the study area. Aligned features that have been proved to correspond to the intersection between the surface and the main fault or fracture or shear system are called lineaments in the present study.

Lineament data derived from satellite imagery and aerial photographs have been used effectively to characterize regional structural patterns, which in turn may provide better understanding of the structural and tectonic evolution of the region. Extraction of lineaments from the LISS III data revealed the presence of five sets of lineaments trending NW-SE, NNW-SSE, N-S, NE-SW and ENE-WSW directions (Fig. 5.17 and 5.18). Most prominent lineaments in the study area are with NW-SE trend (5.18a). These lineaments extend for few kilometers. Lineament density is high for the features that have ENE-WSW trend but do not have strike extension (Fig. 5.18e).

Cherupuzha in the upstream part flows along the NNE-SSW trending lineament. As it reaches downstream it takes a gentle swerve in SW direction for a few kilometres after reaching the confluence point, it takes a sharp bend in the SE direction and flows southerly when it reaches the trunk stream. The notches in the stream from the upstream to downstream parts are controlled by the NW-SE trending lineaments (Fig. 5.17).

Iruvahnipuzha in the upstream part flows in WSW direction and takes a sudden shift in the flow direction to SSW direction which is controlled by the NNW-SSE trending lineament. It again takes a swerve westerly and then flows NNW with a number of NW-SE trending notches and compressed meandering as it gushes into the trunk stream (Fig. 5.17).

Kurumanpuzha flows southerly in the upstream part. It suddenly takes an ESE deviation and then gently flows easterly and again takes a southerly shift. As it joins the trunk stream it makes a broad n-shape and finally joins the main stream flowing southerly. The ESE deviation of the stream in the upstream is due to the WNW-ESE trending strike-slip fault that has deflected the stream from its original flow direction. Kanjirapuzha, another tributary of Chaliyar River, flows along the major NW-SE trending lineament that almost cut across the Chaliyar River drainage basin (Fig. 5.17).

Chaliyarpuzha in the upstream portion flows westerly and takes a sharp bend along a N-S trending lineament resulting in the southerly flow. A number of shifts and notches are evident in the stream course downstream that are controlled by the NE-SW trending lineaments. At the confluence, it takes right angle bends forming a broad ‘U’. This pattern in the stream course is the outcome of the NW-SE parallel lineaments subsequently cut by a NE-SW lineament (Fig. 5.17).

South westerly flowing Karakodupuzha takes an acute angle swerve and then flows southerly. Again it takes a left turn and flows SW and joins Punnapuzha southerly. All these deviation in the stream course are controlled by the lineaments. Punnapuzha, one of the largest tributaries of Chaliyar River, has a number of angular bends right from the upstream part to the downstream part until it joins the main stream. The stream course follows the NE-SW lineament and the notches and angular bends in the stream course are controlled by the NW-SE trending lineaments (Fig. 5.17).

Karimpuzha tributary is the only river that flows almost westerly to join the trunk system of Chaliyar River. The river follows E-W trending lineaments with sharp bend in its course controlled by the NW-SE trending lineaments. Kuthirapuzha tributary follows the NW-SE trending lineament. These lineaments could not be traced from the imagery or aerial photographs due to thick vegetation.

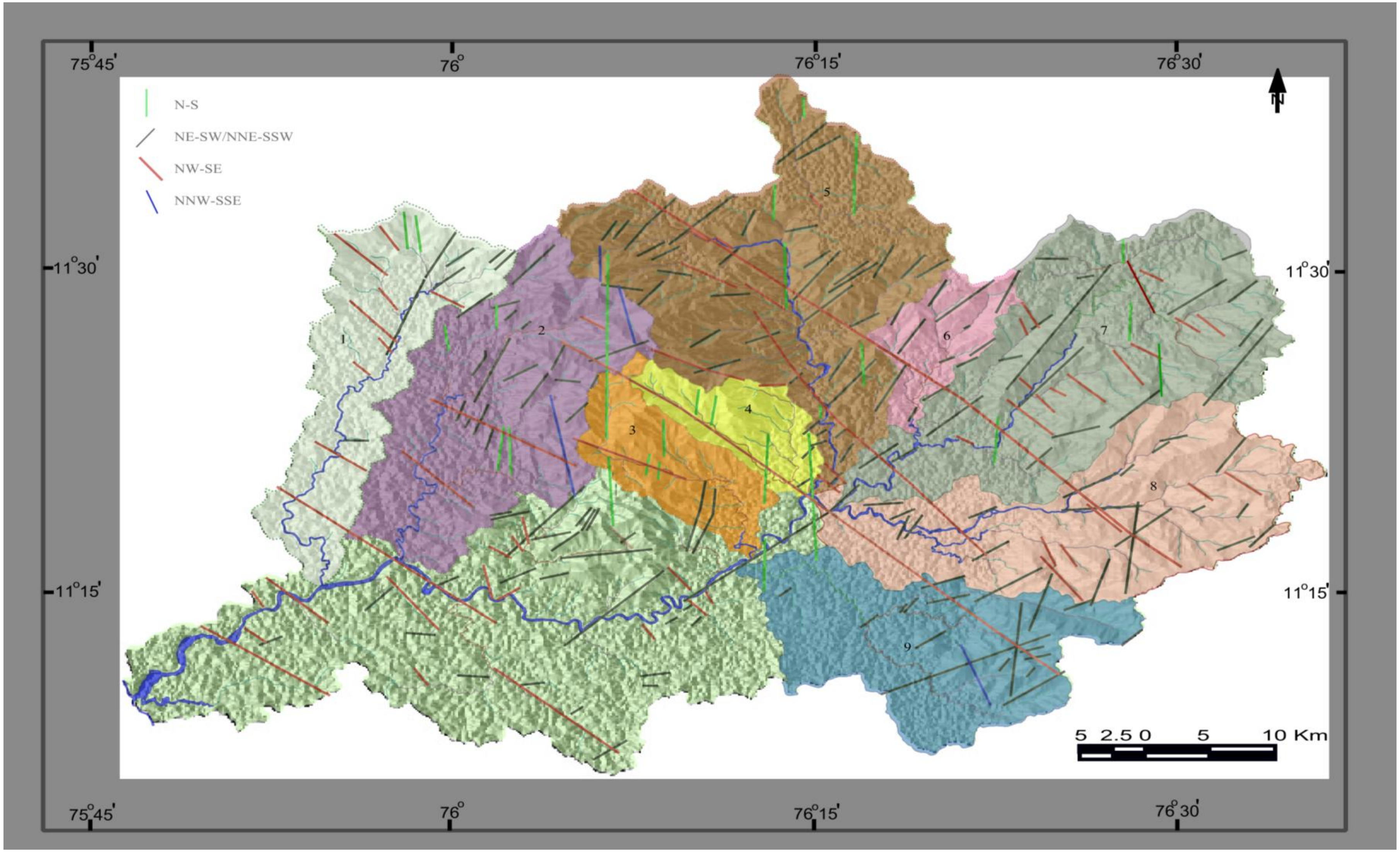


Fig. 5.17 Lineament map of Chaliyar River drainage basin superimposed over SRTM derived aspect map. Five sets of lineaments could be delineated trending NW-SE, NNW-SSE, N-S, NE-SW and ENE-WSW directions. Sub-basins are represented by different colours and numbers.

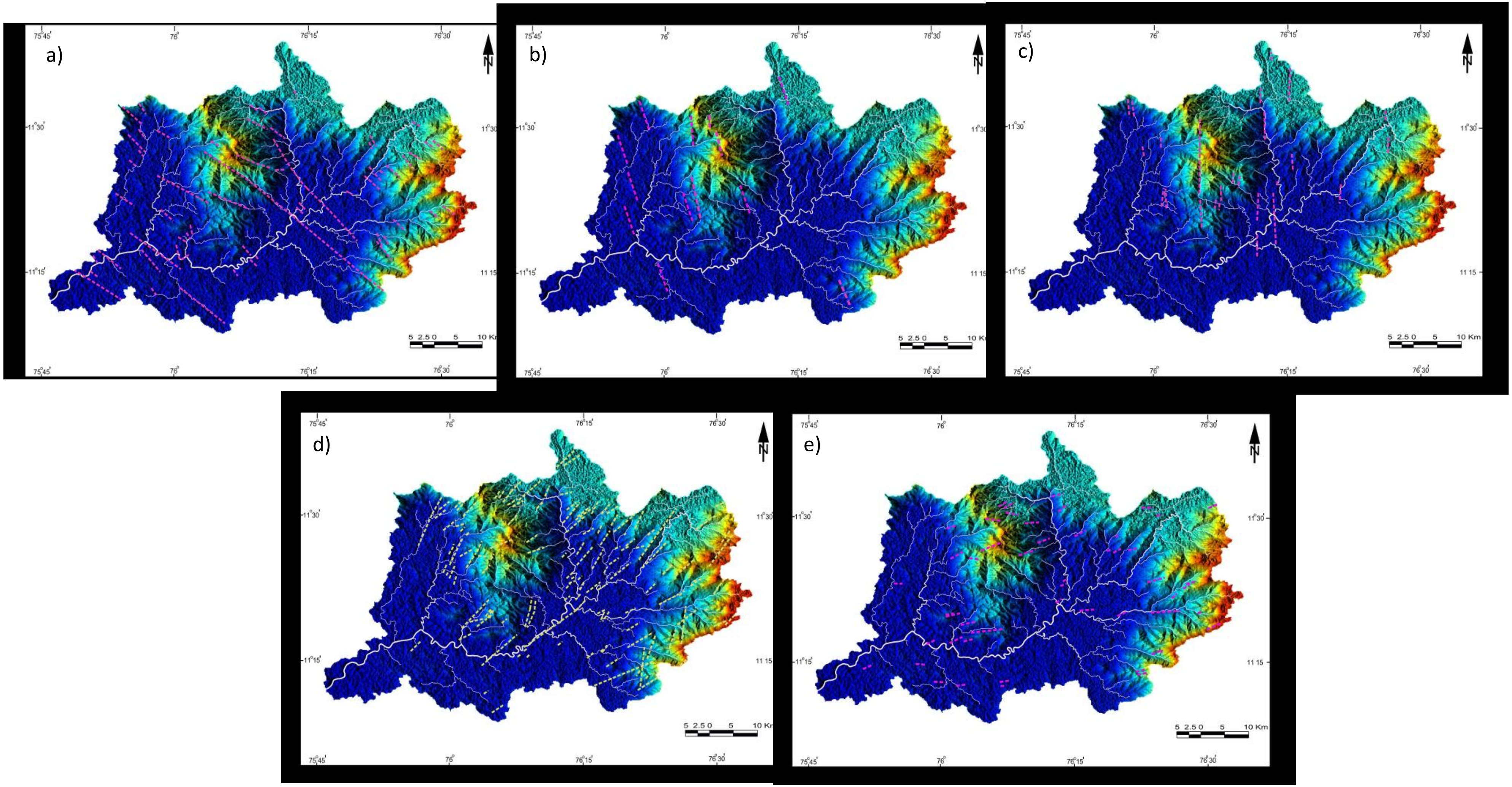


Fig. 5.18 SRTM derived DEM map showing the (a) NW-SE trending lineaments, (b) NNW-SSE trending lineaments, (c) N-S trending lineaments, (d) NE-SW trending lineaments and (e) ENE-WSW trending lineaments

But from the stream line trend, it was assumed that that the stream flows along lineament. Curves and bend in the stream course are the result of NE-SW trending lineaments (Fig. 5.17).

Chaliyar River shows an acute bend in the northwest direction in its course at the mouth before it debouches into the sea (Fig. 5.19). The movement here is supposed to be left lateral and may be the result of the strike-slip movement. In the study area movements along these lineaments resulted in the sudden break in slope and sudden deposition of materials leading to the development of alluvial fans at Nedungayam, Vellimattam, Karakodu, Kolikadavau and Patakarimba.

The major stream courses in Chaliyar River drainage basin is controlled by the lineaments. Chaliyarpuzha in its course takes abrupt change in the flow direction is the result of strike slip faults as observed in Fig. 5.20a. At places older normal faults have been shifted by the younger strike-slip faults thus deflecting the stream flowing through the younger fault as observed at Kakkadampoyil (Fig. 5.11). Along Chaliyarpuzha near Bhudan Colony, N-S trending F_1 fault resulted in the sudden break in slope and fault scarps along the mountain front followed by NW-SE trending F_2 normal faults resulting in the development of shutter ridge which was further shifted by the F_3 fault there by opening up the channel course and sudden inflow of sediments resulted in the braiding of the stream (Fig. 5.20b). Broad valley (Nilambur valley) within the Chaliyar River drainage basin is formed due to the block faulting (Fig. 5.20c, d).

ENE-WSW lineaments are prominent in numbers within the Chaliyar basin and the lower order streams follow this lineament system. High gradients in the upper reaches of Chaliyar and its tributaries are attributed to the uplift. For most of the stream courses in its upper reaches have a gradient a high as 1/250.

5.5 Morphostructures

Morphostructural analysis allows qualitative evaluation of the relationship between the geometry of the hydrographic network and the tectonic structures (Ciccacci et al., 1986; Jackson and Leeder, 1994; Centamore et al., 1996; Delcaillau et al., 1998; Burbank and Anderson, 2001; Van der Beek et al., 2002; Delcaillau et al., 2006). The correspondences between the directions of the drainage and the faults are evaluated by comparing rose diagrams of the different orders of the fluvial channels with the rose diagrams of the trends of the active structures.

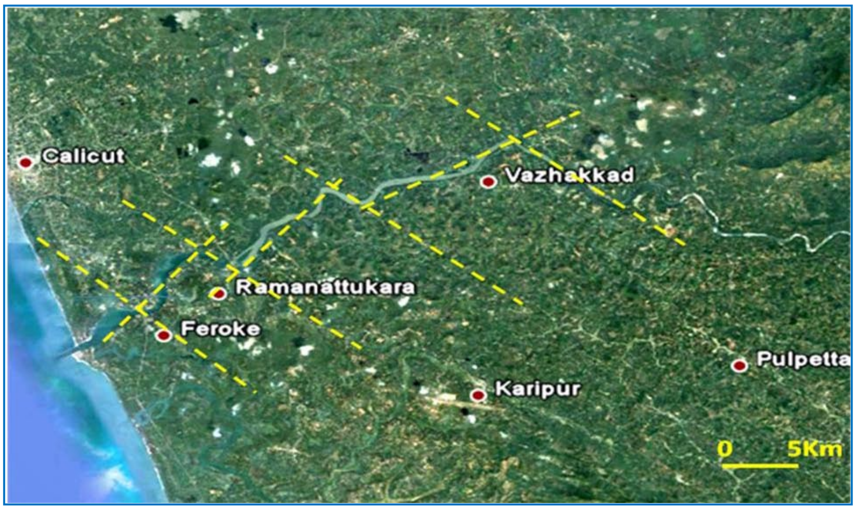


Fig. 5.19 Acute bends in the course of Chaliyar River at its lower reaches as observed in Google Earth Imagery. Westerly flowing river suddenly takes a swerve in the NW direction. At Vazhakkad the stream again takes a right angle bend to flow in ESE direction. The river again takes a shift in NW direction. Deflection of the river in similar pattern is repeated at Ramanattukara and Feroke and finally dedouches into the sea flowing SW.

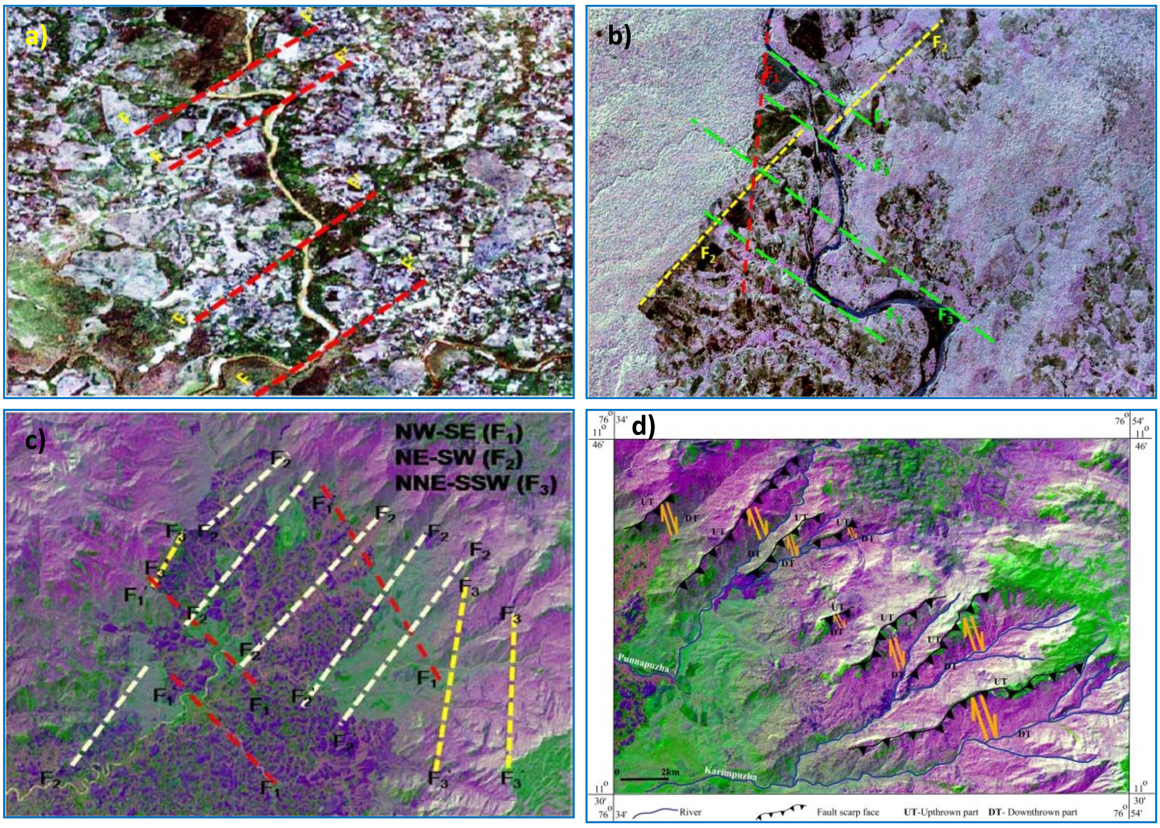


Fig. 5.20 (a) NE-SW trending lineaments that caused channel migration in Chaliyar River, (b) N-S trending normal fault (F_1-F_1') with vertical fault scarp and F_2-F_2' caused the development of shutter ridge which was later off-set by F_3-F_3' faults, (c) and (d) series of fault system (en-echelon faults) resulted in the formation of Nilambur valley within the Chaliyar River drainage basin.

Azimuthal drainage distribution

The planar geometry of the present-day fluvial network sometimes leads to the identification of past drainage characteristics that can greatly improve the reconstruction of the different deformative events that have determined the topographic growth of a mountain region (Harvey and Wells, 1987; Burbank et al., 1999; Friend et al., 1999; Mather, 2000; Jones, 2004; Ribolini and Spagnolo, 2008). Relationship between channel orientation and structures can be used as a tool for reconstructing the deformative events that have occurred in a mountain range (Ribolini and Spagnolo, 2008).

Considering the higher order streams 6th and 7th orders in the Chaliyar basin, the basin is drained by six streams namely Cherupuzha, Iruvahnipuzha, Chaliyar, Punnapuzha and Karimpuzha. Cherupuzha and Iruvahnipuzha flow from NNE to SSW and join the main stream at right angle. Chaliyar flows easterly in the upper reaches and then flows southwards to join the main stream. Punnapuzha in its upper reaches flows south-westerly and then westerly for a short length and swerves down in the SW direction to join the main stream. Westerly flowing Karimpuzha deflects to SW direction for a very short distance and takes a WNW flow direction before joining the stream. The trunk stream flows in the WSW direction when it attains the 7th order status for a long distance and then slightly shifts its flow in the NW direction and then again in the SW direction and debouches in to the Lakshadweep Sea. The main stream reaches the highest order of 7, when the stream flows a short distance of about 45 km whereas the total length of the stream is 169 km.

Statistical analysis of the azimuthal distribution of the drainage network for lower order streams are carried out and the results are expressed in the form of rose diagrams. The main peaks of these rose diagrams show preferred orientation or domains of drainage network (Ciccacci et al., 1986; Centamore et al., 1996). From the lineament map, the influence of lineaments on higher order streams could be interpreted (Fig. 5.21).

Sub-basin - 1 drained by Cherupuzha flows SSW and joins the main stream. 1st order streams in this basin are concentrated in the southern hemisphere of the rose diagram which suggests the gushing of streams towards south. 80% of the 2nd order streams flow southerly and remaining 20% flow WNW direction. Third and 4th order streams have southerly course (Fig. 5.21a).

Drainage basin analysis for sub-basin - 2 for the lower order streams preferably takes westward flow direction (Fig. 5.21b). First order streams are mainly confined in the south and western hemisphere of the rose diagram affirming the southwest flow. Majority of the second order streams flow in SE and SSE direction. 3rd order streams fall in the western hemisphere of the rose diagram with flow direction in NNW, NW, WSW and SW directions. 4th order streams also fall in the western hemisphere with flow direction in NW and SW directions. Higher order streams are having the affinity to flow towards the western part while lower order streams flow southerly.

Sub-basin - 3 drained by Kurumanpuzha has its first order streams flowing in all directions but majority of them flow south westerly (Fig. 5.21c). Majority of the second order stream joins the higher order stream after flowing westerly and few in NW, SE and SW directions. Flow direction of 3rd order streams falls in the southern hemisphere of the rose diagram. 95% of the 4th order streams fall within the western hemisphere with flow in NW, WNW, W and SW directions.

Kanjirapuzha tributary that drains the sub-basin - 4 flows westerly with majority its 1st order streams flowing southerly. Very few streams flow in north direction to join the higher order streams. 2nd order streams also have southern flow trend. 3rd and 4th order streams also fall within the southern hemisphere of the rose diagrams (Fig. 5.21d).

Sub-basin - 5 drained by Chaliyarpuzha flows easterly in the upstream part and takes a southerly swerve and joins the main stream. First order streams of Chaliyarpuzha drains to higher order streams in all direction though majority flow southerly (SSE and SE) (Fig. 5.21e). Majority of the 2nd order streams falls in the southern hemisphere of the rose diagram suggesting SSE and SSW flow direction. 3rd order streams also flow southerly with general flow trend in WSW, SW and SE direction. 4th order streams flow in ENE direction. Few 4th order streams have NE and SE course.

Karakodupuzha tributary drains south westerly through sub-basin - 6. Most of the 1st order streams have its course in the SE and SW directions (Fig. 5.21f). Second order stream courses are mainly in the SSE and SW directions, 3rd order streams are in the southern hemisphere of the rose diagram with WSW, SW and ESE flow directions and 4^{th} order streams flow in S and SSE directions.

Sub-basin - 7 drained by Punnapuzha has its 1^{st} order streams flow in all directions though majority have westerly and southerly flow direction (Fig. 5.21g). Second order streams flow in NW, SSE and N directions whereas third order streams follow NW, SW and SSE directions and 4^{th} order streams follows SW, NW and SE trend.

Sub-basin - 8 drained by west flowing Karimpuzha has its 1^{st} order streams flowing mainly in the SW, WSW, SE, NE and NW directions (Fig. 5.21h); 2^{nd} order stream courses are in SE, SSE, W and NNW directions. Third order streams flow in NNW, WSW and SW trends and 4^{th} order streams flow in NW and SW directions.

Kuthirapuzha flows through sub-basin - 9 with its 1^{st} order course in NNW, NW, SW and SE directions (Fig. 5.21i). Second order streams flow south-westerly and west-north-westerly, while 3^{rd} order steam show SW direction and 4^{th} order streams flow in WNW and WSW directions.

Lineament direction

Direction of the lineaments was quantified for Chaliyar River drainage basin as well as for each sub-basin separately. Rose diagrams prepared for Chaliyar basin explains the pervasive nature of NE-SW trending lineaments (Fig. 5.22a). N-S trending lineaments are also conspicuous. NW-SE trending lineaments are few in numbers but strike length tower other lineaments.

Sub-basin - 1 shows ascendancy of NW-SE trending lineaments though the main stream Cherupuzha flows along the NE-SW trending lineaments (Fig. 5.22b). Dominance of NE-SW trending lineaments in sub-basin - 2 also corresponds with the flow direction of Iruvahnipuzha and its main tributaries (Fig. 5.22c). Sub-basin - 3 exhibits preponderance of NNE-SSW trending lineaments (Fig. 5.22d). WNW-ESE trending lineament has deflected the stream course from south to ESE. Kanjirapuzha tributary flows along the NW-SE trending lineaments but its tributaries follow the NNE-SSW and NE-SW trending lineaments (Fig. 5.22e). Though the main stream course of Chaliyarpuzha is controlled by N-S trending lineaments, density NE-SW trending is more in the sub-basin - 5 (Fig. 5.22f). Sub-basin - 6 dominates with NNE-SSW trending lineaments which mark the flow of Karakodupuzha (Fig. 5.22g). Sub-

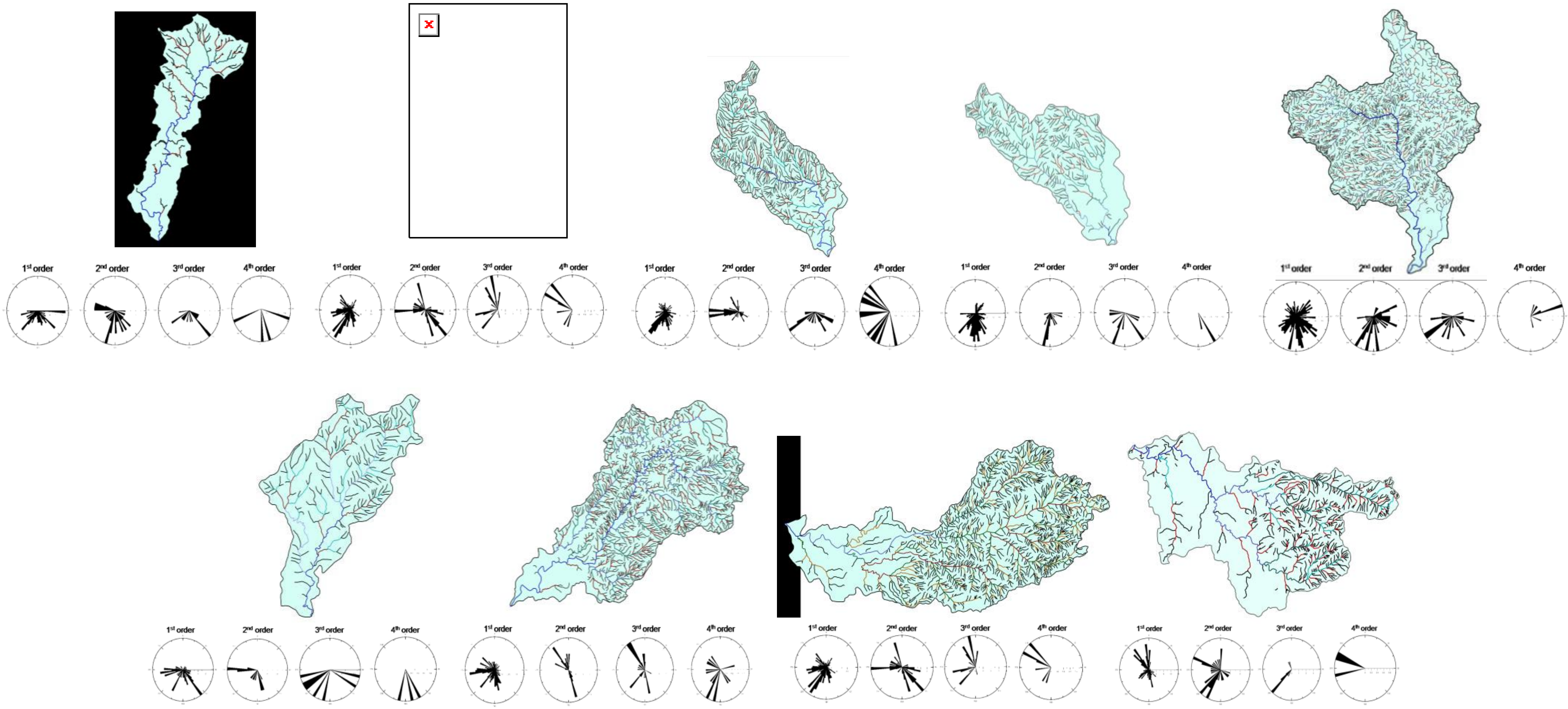


Fig. 5.21 Drainage network of sub-basins of Chaliyar River with the correspondent rose diagrams of the stream directions of 1st, 2nd, 3rd and 4th order streams for a) Sub - basin - 1 (Cherupuzha), b) Sub-basin - 2 (Iruvahnipuzha), c) Sub - basin - 3 (Kurumanpuzha), d) Sub - basin - 4 (Kanjirapuzha), e) Sub - basin - 5 (Chaliyarpuzha), f) Sub - basin - 6 (Karakodupuzha), g) Sub - basin - 7 (Punnapuzha), h) Sub - basin - 8 (Karimpuzha) and i) Sub - basin - 9 (Kuthirapuzha).

basin - 7 through which Punnapuzha drains out has preponderance of NE-SW trending lineaments (Fig. 5.22h). NW-SE lineaments are also very prominent in this sub-basin. Lineament density is high for NE-SW lineaments in sub-basin - 8 (Fig. 5.22i). NW-SE and NNE-SSW trending lineaments also controls the flow direction of tributaries of Karimpuzha. In sub-basin - 9, 90% of the lineaments are restricted to N-S to ENE-WSW trends (Fig. 5.22j). NW-SE trending lineament with extensive strike length which cuts across the Chaliyar River basin controls the main stream drainage direction in the upstream part.

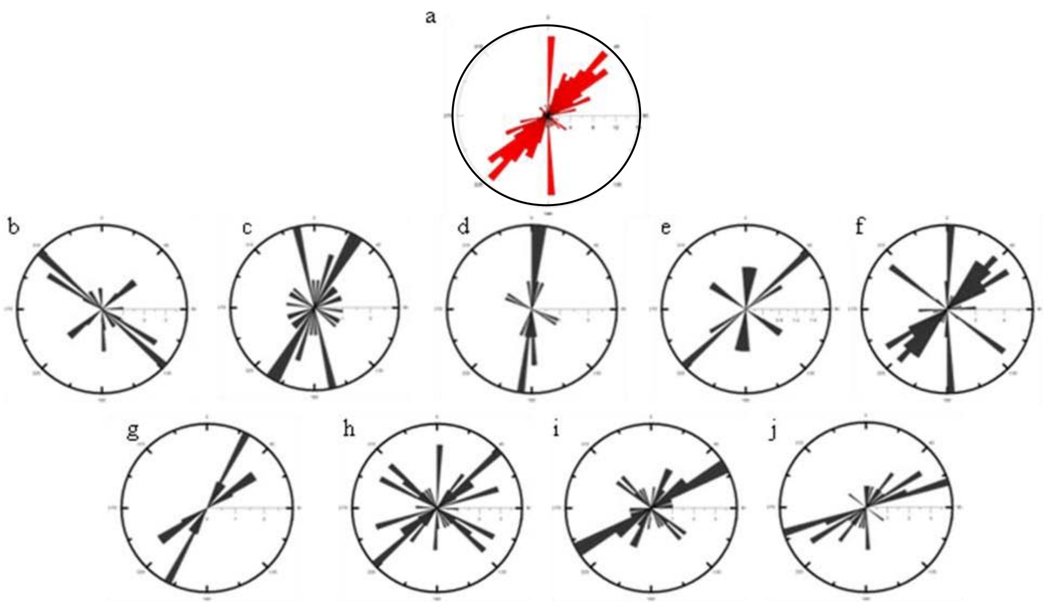
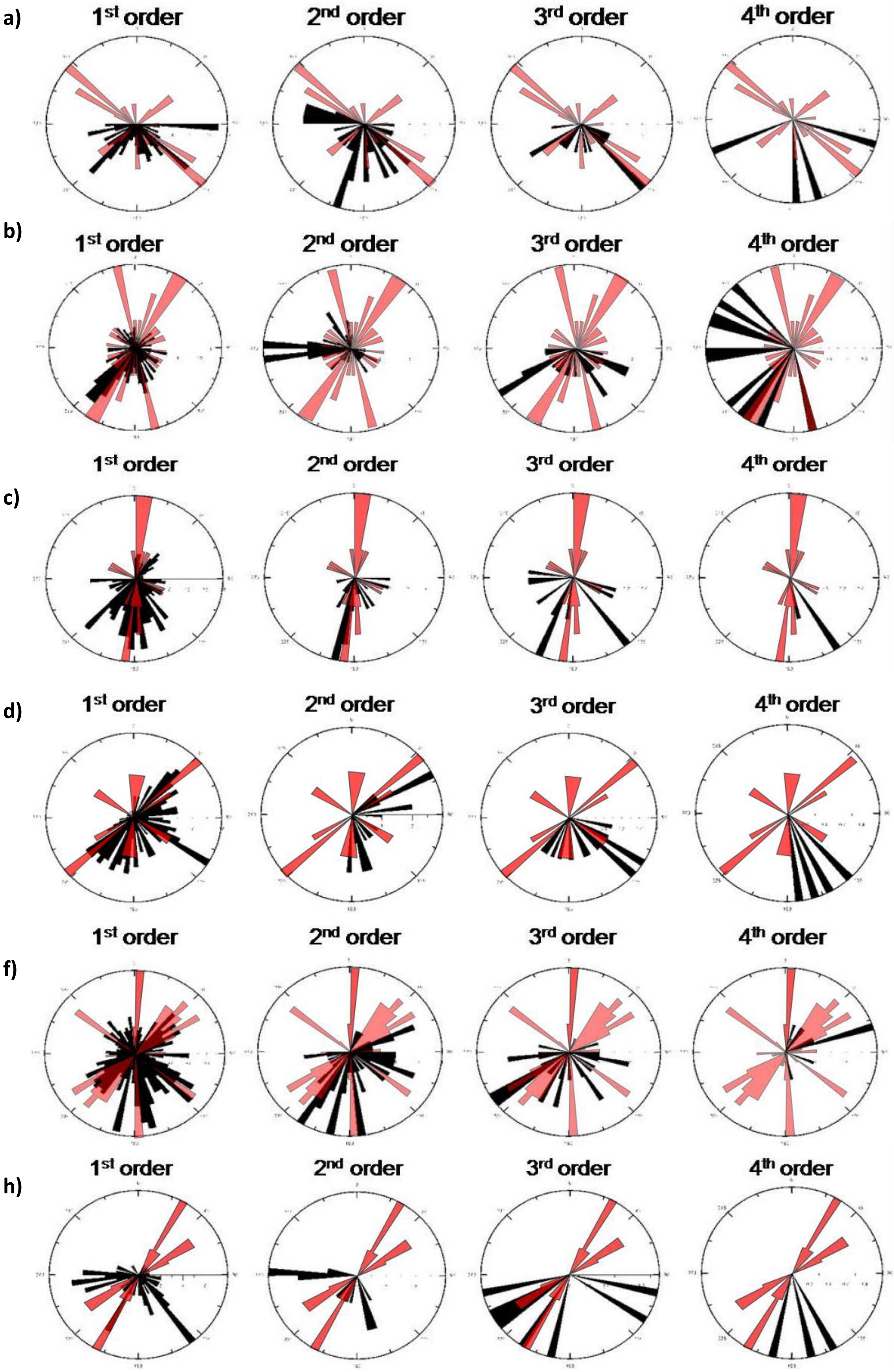


Fig. 5.22 Rose diagram showing the general trend of lineaments in a) Chaliyar River drainage basin, b) Sub-basin - 1 (Cherupuzha), c) Sub-basin - 2 (Iruvahnipuzha), d) Sub-basin - 3 (Kurumanpuzha), e) Sub-basin - 4 (Kanjirapuzha), f) Sub-basin - 5 (Chaliyarpuzha), g) Sub-basin - 6 (Karakodupuzha), h) Sub-basin - 7 (Punnapuzha), i) Sub-basin - 8 (Karimpuzha) and j) Sub-basin - 9 (Kuthirapuzha).

Domain analysis of drainage network and lineaments

Comparison of lineament trends with drainage direction throws light on the relationship between channel orientation and tectonics. The planar geometry of the present day drainage network and trend of lineaments can be used to reconstruct the tectonic activity that has carved out the landscape (Table 5.6 and Fig. 5.21). The


a)
1st order
2nd order
3rd order
4th order
b)
1st order
2nd order
3rd order
4th order
c)
1st order
2nd order
3rd order
4th order
d)
1st order
2nd order
3rd order
4th order
f)
1st order
2nd order
3rd order
4th order
h)
1st order
2nd order
3rd order
4th order

Continued....

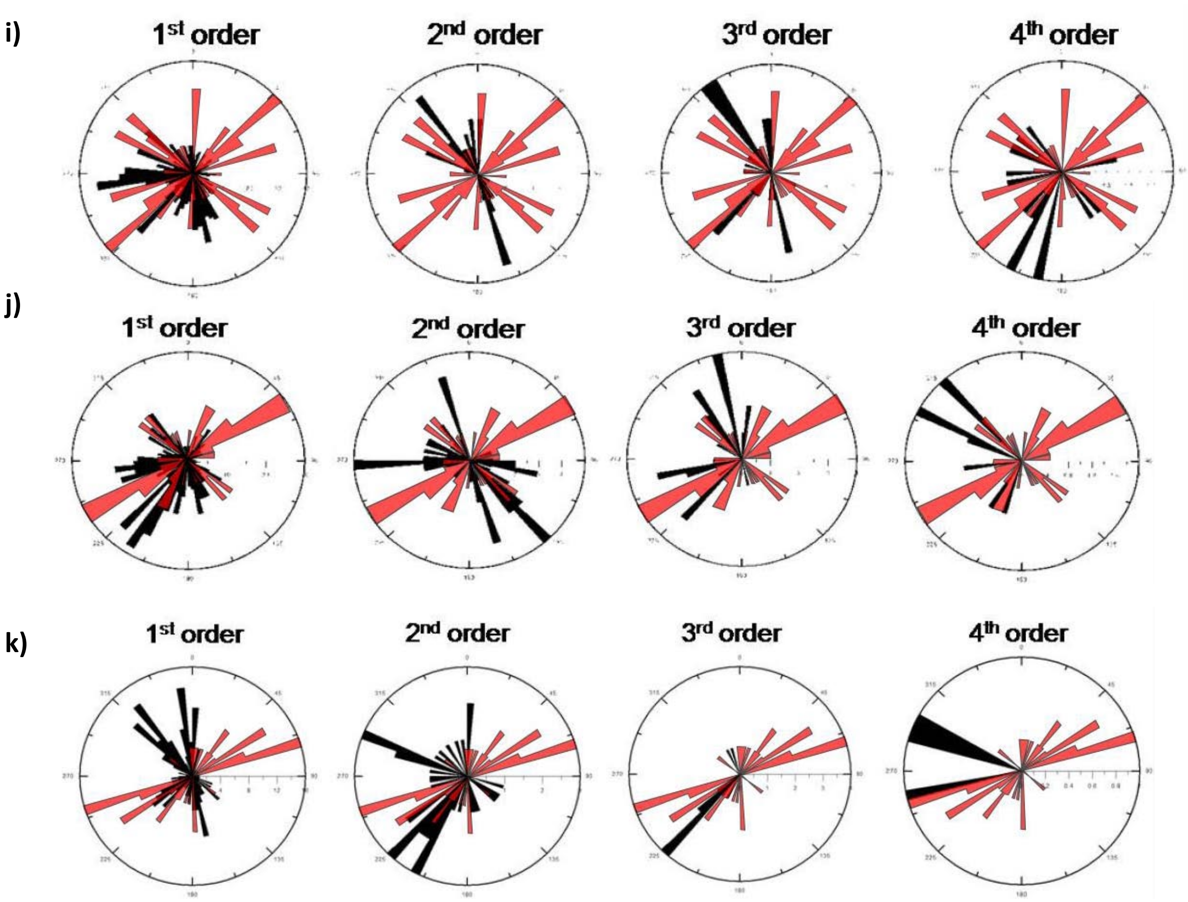


Fig. 5.23 Trend of lineaments superimposed on the stream direction for different orders for (a) Sub - basin – 1; (b) Sub-basin – 2; (c) Sub - basin – 3; (d) Sub - basin – 4; (e) Sub - basin – 5; (f) Sub - basin – 6; (g) Sub - basin – 7; (h) Sub - basin - 8 and (i) Sub - basin - 9. Black shade indicates stream orientation and red colour indicates lineament trend.

analysis of the stream channels and lineaments demonstrate that some preferential orientations exist which are likely to be tectonically controlled.

Fifth order streams in Chaliyar River drainage basin has single out SW as the dominant domain followed by SE and WSW respectively in the order of dominance (Fig. 5. 22a). When compared with the lineament trend analysis the domain with peaks in NE-SW direction in the rose diagram of lineament trends of Chaliyar River drainage basin (Fig. 5.22b) corresponds with the SW domain of stream analysis. Importance of NE-SW domain becomes highlighted when the streams reach 5th order.

Sixth order streams in Chaliyar River drainage basin show its preponderance in SE direction (Fig. 5.22c). But in correspondence to the lineament analysis it can be concluded that streams flowing in SW direction is controlled by the NE-SW trending

Table 5.6 Azimuthal distributions of streams and lineaments in the nine sub-basins of Chaliyar River

Stream Order	Subbasin - 1		Subbasin - 2		Subbasin - 3		Subbasin - 4		Subbasin - 5		Subbasin - 6		Subbasin - 7		Subbasin - 8		Subbasin - 9	
	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction	Stream Direction	Lineament Direction
1st order	ESE **SE** SSE SSW **SW** WSW	NW-SE NE-SW	**SW**	NE-SW	SW	NNE-SSW	S N	NE-SW	SSE SE	NE-SW	SE SW	NNE-SSW	W S	NE-SW NW-SE	SW WSW SE NE NW	NE-SW	NNW NW SW **SE**	NW-SE NNE-SSW N-S ENE-WSW
2nd order	S WNW		SE SSE		W NW SE SW		S		SSE SSW		SSE SW		NW SSE N		SE SSE W NNW		SW WNW	
3rd order	S		NNW NW WSW **SW**		E W		S		WSW **SW** SE		WSW SW ESE		NW SW SSE		NW SW SSE		SW	
4th order	S		NW **SW**		NW WNW W SW		S		ENE NE SE		S SSE		SW NW SE		NW SW		WNW **WSW**	

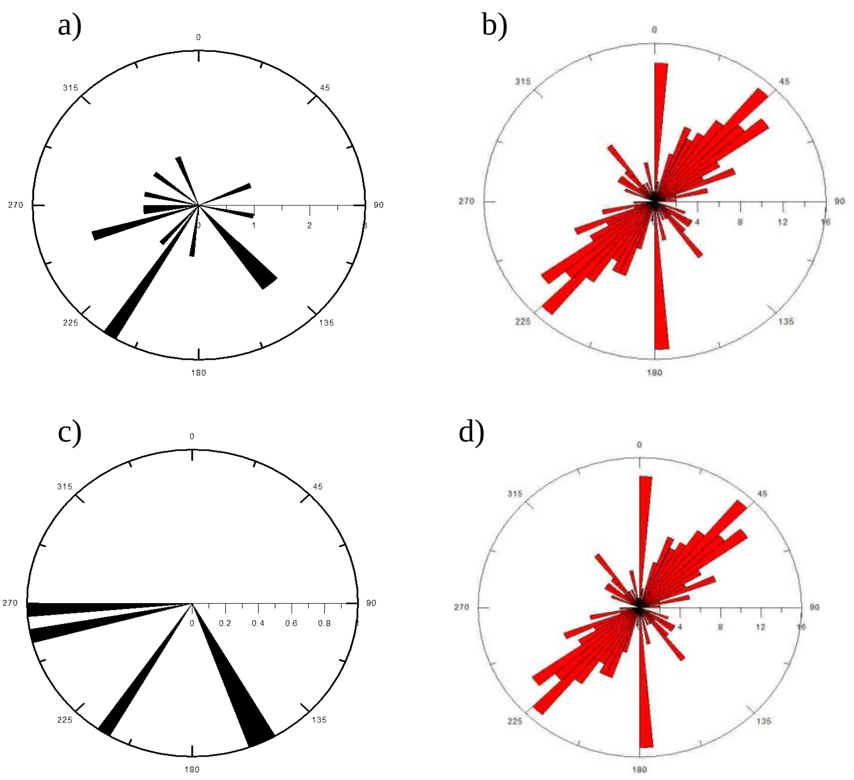


Fig. 5.24 Rose diagram showing (a) the preferred drainage flow direction of 5th order streams in the Chaliyar River drainage basin, (b) lineament trends in the Chaliyar River drainage basin (c) the preferred drainage flow direction of 6th order streams in the Chaliyar River drainage basin and (d) lineament trends in the Chaliyar River drainage basin.

lineaments (Fig. 5.22d). The dominance of NE-SW domain of lineament with 6th order streams is emphasized.

Influence of lineaments in the flow direction of streams increases with the order of the streams. Based on the above inferences, influence of tectonic activities in the terrain has attributed to the drainage network geometry.

Within the nine sub-basins of Chaliyar River drainage system, three main types of geometric relationship between drainage network and lineament exist and are classified as type A, B and C. Type A refers to the domain where the main orientation of the drainage network is the same as the trend of the lineaments. Type B occurs where the orientation of the lower order streams that runs almost perpendicular to the lineaments through which the main streams flow and Type C are the stream channels that occurs parallel to the NW-SE trending lineaments occurring parallel to the coastline.

5.6 Class designation of relative tectonic activity

Two geomorphic indices S_{mf} (mountain front sinuosity) and V_f (Valley floor width to depth ratio) provide semi quantitative information of relative tectonic activity of mountains fronts (Bull and McFadden, 1977; Silva et al., 2003). Active fronts are those with low values of S_{mf} (< 1.6) and V_f (< 0.5) indices, characterised by the occurrence of steep, un-trenched alluvial fans receiving Holocene sediments at the apex, triggered by uplift.

Based on the geomorphic indices of tectonism, Keller and Pinter (1996) classified river basins into four tectonic classes viz., Class 1, Class 2, Class 3 and Class (4 & 5) (Table 5.7). Criteria for Class 1 is that mountain front sinuosity (S_{mf}) and valley floor width to valley floor height (V_f) will be low and stream length-gradient index (S_l) will be high. When the S_{mf} and V_f are high and S_L is low it is classified in class 2 and suggests less tectonic activity. Class 3 basins are the one associated with active tectonics but geomorphic indices suggest less activity than for Class 2. Class 4 & 5 are the group characterised by minimal tectonic activity or those that are now inactive (Keller and Pinter, 1996). The study area exhibits only one class of tectonism i.e., 2 (Table 5.8). All the sub-basins in the Chaliyar River drainage basin are classified into Class 2. These are river basins associated with active tectonics but tectonically less active than Class 1 which is considered as tectonically very active (Table. 5.8).

Relative tectonic activity based on geomorphic indices by El Hamdouni et al, 2007 provide semi-quantitative information of relative degree of tectonic activity in a drainage basin. Various indices are divided into three classes with class 1 being high tectonic activity and class 3 being low activity. Relative tectonic activity index (Iat) is obtained for each sub-basin by the average of different classes of geomorphic indices (S/n) and divided into four classes, where class I is very high tectonic activity with values of S/n between 1 and 1.5; class 2 is high tectonic activity with S/n values > 1.5 but < 2; class 3 is moderately active tectonics with S/n > 2 but < 2.5 and class 4 is low active tectonics with values of S/n > 2.5. Sub-basins of Chaliyar River drainage basins are restricted two classes: Class 2 and 3 with Iat ranging from 1.60 to 2.20 (Table 5.9). Highest Iat is exhibited by the sub-basins 1, 2, 5, 6 and 9 and lowest index is for sub-basin – 4. Sub-basins 3, 4, 7 and 8 belong to class 2 of high tectonic activity while sub-basins 1, 2, 5, 6 and 9 belong to class 3 of moderately active tectonics (Fig. 5.25).

Table 5.7 Relative tectonic activity class designation (after Keller and Pinter, 1996).

Tectonic class	Criteria	Remarks
Class 1	Low mountain front sinuosity (S_{mf}) Low valley floor width to depth ratio (V_f) High stream length - gradient index (SL)	Associated with active tectonics
Class 2	High mountain front sinuosity (S_{mf}) High valley floor width to depth ratio (V_f) Low SL index	Associated with active tectonics but less tectonic activity than class 1.
Class 3	Low mountain front sinuosity (S_{mf}) Low valley floor width to depth ratio (V_f) High stream length - gradient index (SL)	Still associated with active tectonics, but geomorphic indices suggest less activity than for class 2 fronts
Class 4 & 5	Low mountain front sinuosity (S_{mf}) Low valley floor width to depth ratio (V_f) Low stream length - gradient index (SL)	Characterized by minimal tectonic activity or those that are now inactive

Table 5.8 Relative tectonic activity classification for the sub-basins of Chaliyar River drainage basin (after Keller and Pinter, 1996).

Sub-basins	Mountain front Sinuosity (S_{mf})	Valley floor width to depth ratio (V_f)	Stream length - gradient index (SL)	Tectonic class	Remarks
1. Cherupuzha	1.70	10.64	13.43	Class 2	*Associated with tectonically active zone but less active than class I*
2. Iruvahnipuzha	2.05	18.95	44.6	Class 2	
3. Kurumanpuzha	2.94	14.10	74.22	Class 2	
4. Kanjirapuzha	2.97	17.09	65.30	Class 2	
5. Chaliyarpuzha	2.51	15.25	43.49	Class 2	
6. Karakodupuzha	2.51	1.62	2.61	Class 2	
7. Punnapuzha	1.48	26.52	78.87	Class 2	
8. Karimpuzha	1.78	21.30	103.52	Class 2	
9. Kuthirapuzha	1.60	20.39	42.38	Class 2	

Table 5.9 Classification of the Iat (relative tectonic activity index) in the sub-basins of Chaliyar River drainage basin after El Hamdouni et al, 2007. (SL= stream length gradient index; Af= asymmetry factor; Hi= hypsometric integral; Vf= valley floor width to valley height ratio; Smf= index of mountain front sinuosity).

Sl. No	**Sub-basin**	**SL**	**Af**	**H_i**	**V_f**	**Smf**	**S/n**	**Iat class**
1	Sub-basin – 1 Cherupuzha	2	2	2	3	2	2.20	**3**
2	Sub-basin – 2 Iruvahnipuzha	2	2	2	3	2	2.20	**3**
3	Sub-basin – 3 Kurumanpuzha	1	2	2	3	2	2	**2**
4	Sub-basin – 4 Kanjirapuzha	1	1	1	3	2	1.60	**2**
5	Sub-basin – 5 Chaliyarpuzha	2	2	2	3	2	2.20	**3**
6	Sub-basin – 6 Karakodupuzha	3	1	2	3	2	2.20	**3**
7	Sub-basin – 7 Punnapuzha	1	2	2	3	2	2	**2**
8	Sub-basin – 8 Karimpuzha	1	2	1	3	2	1.80	**2**
9	Sub-basin – 9 Kuthirapuzha	2	2	2	3	2	2.20	**3**

5.7 Process Response model of active tectonics

Active strike slip faults produces characteristic assemblage so landform like offset or deflected streams, linear valleys, shutter ridges, pressure ridges, river ponding (sags), fault scraps and small horst and grabens (microtopography) as observed in Fig. 5.10, 11 & 16 . Many of the topographic features associated with active strike-slip faulting like fault scarps, horst and graben, folds can be explained by the simple shear that produces contraction and extension as explained by Sylvester and Smith, 1976; Keller et al., 1982 (Fig. 5.26). Other landforms like sags, pressure ridge and shutter ridge can be explained by extension or contraction associated with releasing or constraining bends or steps of fault traces as explained by Dibblee, 1977; Keller, 2002 (Fig. 5.26c).

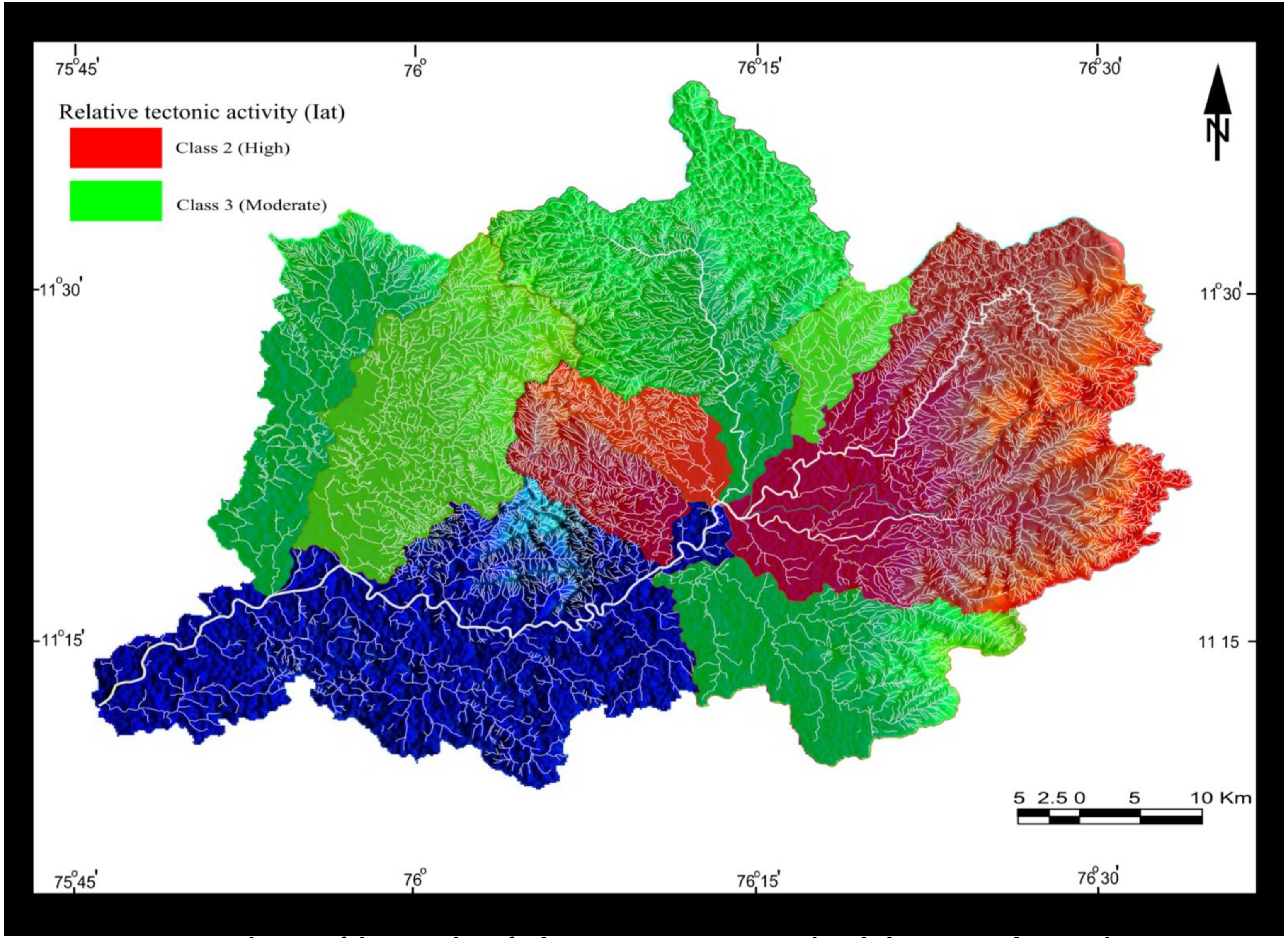


Fig. 5.25 Distribution of the Iat index of relative active tectonics in the Chaliyar River drainage basin.

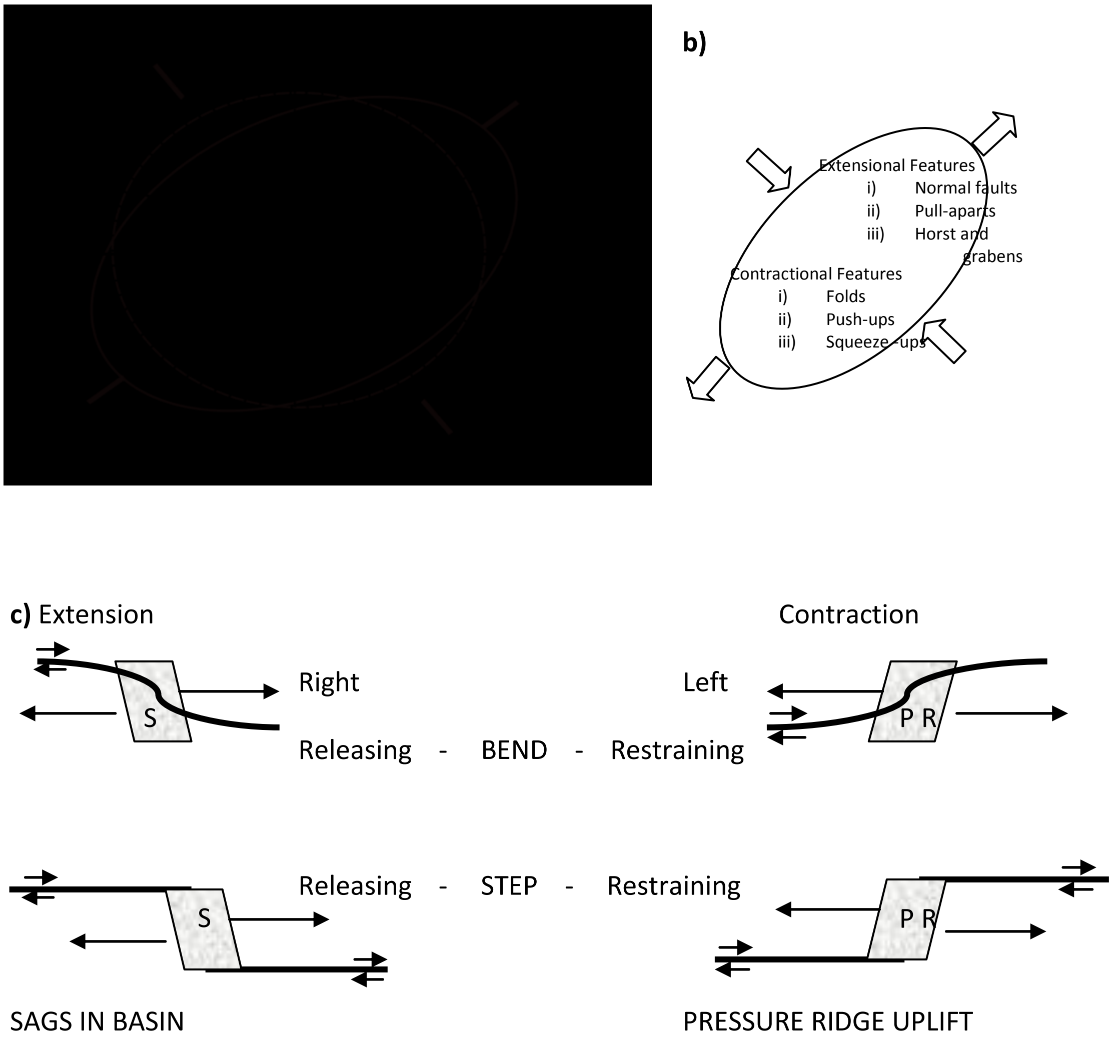


Fig. 5.26 (a) Schematic diagram showing simple shear associated with strike-slip faulting produces preferred orientation of fractures, faults and folds. (b) extensional and contractional landforms developed by simple shear modified after Sylvester and Smith (1976) and Keller et al. (1982); (c) pressure ridges and sags associated with restraining and releasing bends and/or steps along strike-slip faults (after Dibble, 1977; Keller, 2002).

5.8 Summary

In regions of active plate motions, the drainage analysis forms a major tool in identifying the neotectonic movements and also in quantifying the displacements along the faults and fractures. (Ouchi, 1985; Schumm, 1986; Dumont et al., 1991; Deffontaines et al., 1994; Jackson et al., 1996; Audin et al., 2003; Pellegrini et al., 2003). However, in Precambrian terrains with structures resulting from multiple facies of metamorphism and ductile deformation and superimposition of brittle joints and faults, the relationship between drainage and structure is poorly studied.

The tributaries of Chaliyar River do not display smooth concave profiles because of the prevalence of numerous knickpoints. Since most of the streams have uniform lithology along its profile, it can be assumed that these knickpoints are structurally controlled. Steepness index approximates to rock uplift where there is no lithologic variation. In Chaliyar River drainage basin, tributaries that flow through uniform lithology (Cherupuzha, Kurumanpuzha, Kanjirapuzha, Karimpuzha, Punnapuzha and Kuthirapuzha) also have high steepness index values indicating that the rate of uplift is exceeding the rate of incision.

If the fluvial incision rate exceeds the uplift or base level lowering rates, the profile goes to a steady state with a smooth downstream concavity (Hack, 1973). Attaining steady state profile needs a long time and the response time is the order of 1 Ma, in tectonically active under the detachment-limited conditions and during a period of climate stability (Whipple et al., 2001). The rate of uplift for tributaries of Chaliyar River namely Cherupuzha, Kurumanpuzha, Kanjirapuzha, Karimpuzha, Punnapuzha and Kuthirapuzha exceed the rate of incision. Tectonic uplift has been more important than river erosion, so that the tributary rivers could not develop an equilibrium profile. The actual form of the longitudinal profiles of the rivers is the result of continuous adjustment since Pleistocene until the present day.

Since stable base level results in the development of straight profiles, the analysis of longitudinal profiles of the tributaries of Chaliyar River suggest that base level history may affect the evolution of channel profiles. Knick point propagation may be a primary process of bed rock lowering along these streams and reflects the local tectonic events. Based on these studies, it has been hypothesized that the change in the base level due to uplift has resulted in the formation and propagation of the knickpoints.

Stream length-gradient index values of the graded streams are homogenous and relatively high values indicate steepening of the slope. Theoretically, the low stream length-gradient index value (close to 1) and the high stream length-gradient index value (> 200) indicate active tectonic region (Keller & and Pinter, 1996). Value greater than 2 indicates tectonic activity and value less than 2 shows that the area is tectonically inactive. Mountain front sinuosity when the computed value ranges between 1 and 1.6 then the mountain front can be considered as active. When the value is between 1.6 and

3 it shows lesser tectonic activity and values between 1.6 and 5 are tectonically inactive mountain fronts and relatively strong erosional activity.

River responses to active tectonics produce characteristic geomorphological features manifesting surface deformation in any area. River response to active tectonics depends upon the nature and amount of vertical movement in a river basin and the trend of the faults with respect to river flow (Jain and Sinha, 2005). Detection and characterization of geomorphic anomalies in the Chaliyar River drainage basin have provided an additional tool for recognizing the subtle tectonic movements in the region. Such morphologic manifestations identified in the terrain are unpaired river terraces, strath terraces, alluvial fans, beheaded and deflected streams, compressed meanders, landslides angular drainages and river ponding.

The differential movements along the faults have produced tilting that triggered channel avulsion and shifted river flow from W to S and then to SW. In general, longitudinal profile, aggradation–degradation behaviour of channel, channel avulsion, channel planform pattern and cross-section morphology are some of the geomorphic expressions of active tectonics in the Chaliyar River drainage basin. Later transverse faults have also affected the fluvial processes, channel morphology and fluvial avulsion.

Various geomorphic features such as the presence of detached older terraces, unpaired terraces, emergence of a strath terrace in the downstream part of an alluvial channel, hillocks showing cuesta slope, local meandering, compressed meandering, deflected stream, river ponding and the presence of alluvial fan deposit suggest the tectonically active nature of the study area.

The multiple terraces, differential deposition of the terraces and shifting of the stream channels indicate the tectonic instability. Older terraces of the Chaliyar River and its tributaries being composed mainly of larger clasts lacking gradation and sorting, points towards the tectonic activity of the source area as well as to fan sedimentation by the streams. Bigger sizes, the elongated and sub-rounded to sub-angular nature of the grains indicate the shorter distance of transport and exhibit a well-oxidized nature with limonitic oozes and lateritization. The finer materials of younger terraces exhibit an erosive and less destructive nature, with stable energy conditions in the depositing streams, and the sediments are not oxidized. Graded bedding and cross-bedding of sediments in the younger terrace (T_1) throw light on the alternate passive and active nature of depositional environment.

Lineaments trending N-S, NE-SW, ENE-WSW, NNW-SSE and NW-SE marks the major drainage network in Chaliyar River drainage basin. Lower order streams follow the NW-SE lineaments and higher order streams follow NE-SW lineaments. Relicts of palaeo-drainage system observed in the Nilambur valley indicate that the initial SW flowing drainages was characterized by a planar geometry similar to that currently observed in eastern part of the drainage basin suggesting temporal evolution from an initial when the drainage geometry with uplift induced higher relief dendritic drainage system to a later stage drainage system dominated by selectively erosion along geological structures. Displacements of Quaternary deposits (pebble beds) by stream along normal faults reveal the recent tectonic activity, taking place in the study area. Frequent landslides near to the lineament junctions, accelerated by the heavy rainfall, may be related to these movements.

Experimental work by Ouchi (1985) has demonstrated that the alluvial rivers response to vertical deformation in the basin through changes in above-mentioned fluvial characteristics. The tributaries Punnapuzha and Karimpuzha shows the typical characters of a braided and meandering river as explained by Ouchi (Fig. 5.27). The braided river of Punnapuzha is the result of upliftment of the bed-load river and adjustment of the stream resulting in the braiding of bars (aggradation) and formation of terrace (degradation). Karimpuzha River clearly matches with Ouchi's experiment (Fig. 5.28) and can be considered as anticlinal uplift. Due to anticlinal uplift, anastomosing channels are formed in the uplifted zone and downstream channel become sinuous and braided.

Karimpuzha river shows uplift in the upstream part (Fig. 5.28). The area upstream of the uplift axis shows development of anabranching drainage pattern, high width-depth ratio, aggradation, river ponding and flooding as observed in Chekuthankundu - Nedungayam area. The downstream part of the uplift is characterised by low width-depth ratio, high channel sinuosity, degradation and bank erosion. Karimpuzha in the downstream part of the uplift is marked by channel avulsion and development of compressed meanders.

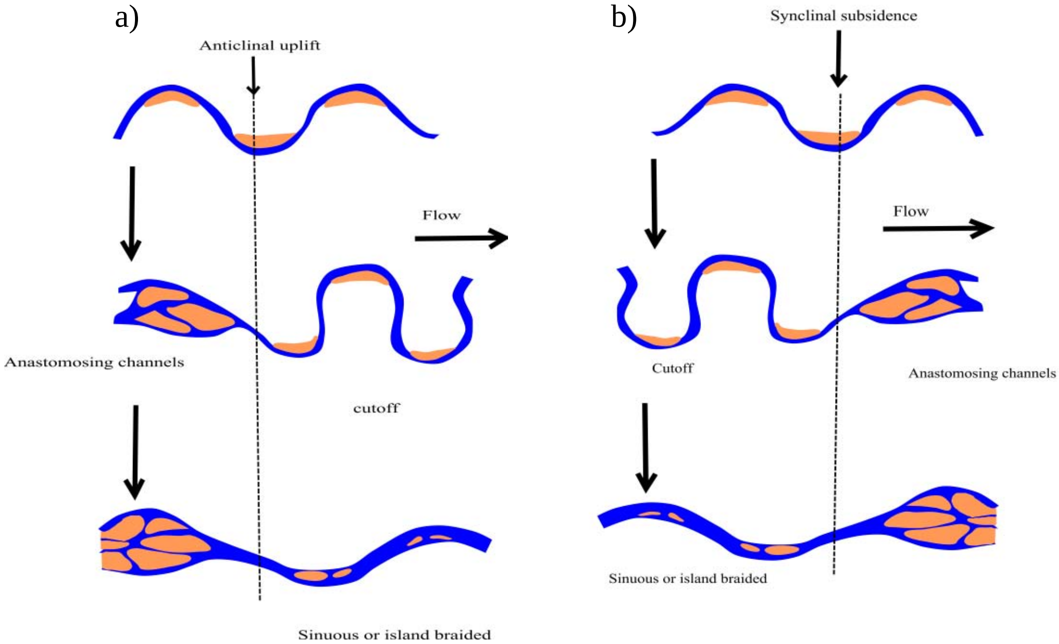


Fig. 5.27 River response to (a) anticlinal uplift and (b) synclinal subsidence as derived from Flume experiment (Ouchi, 1985). Similar scenario is observed in the study area in the Karimpuzha tributary as shown in Fig. 5.28.

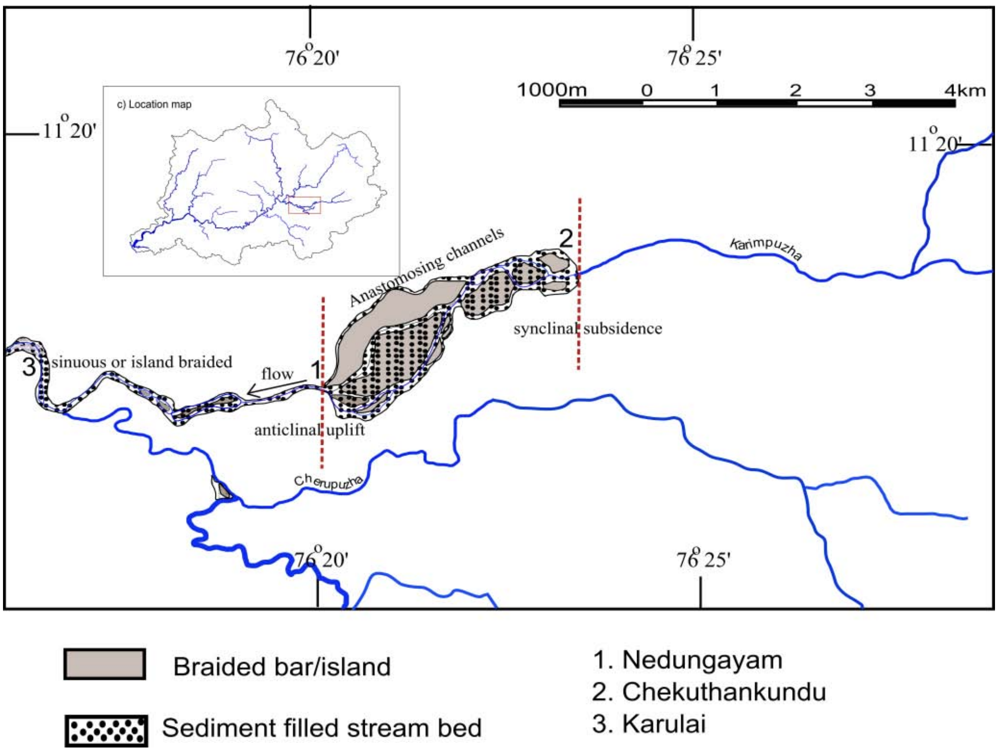


Fig. 5.28 Response of Karimpuzha River (tributary of Chaliyar River) to synclinal subsidence and anticlinal uplift. At Chekuthankundu synclinal subsidence occurred resulting in the formation of anastomosing channels in a stretch between Chekuthankundu and Nedungayam. Anticlinal uplift at Nedungayam resulted in the formation of braiding and meandering in a stretch between Nedungayam and Karulayi.

Based on the tectonic activity classification by Keller and Pinter (1996), drainage basins are classified taking mountain front sinuosity (S_{mf}), valley floor with to depth ratio (V_f) and stream length-gradient index (SL) as parameters. Keller and Pinter's (1996) tectonic classification for the sub – basins of Chaliyar River grouped all the sub-basins into Class 2 sectors, where the drainage basins are tectonically active but not as active as that of Class 1. Relative tectonic activity based on geomorphic indices by El Hamdouni et al., 2007, provide semi-quantitative information of relative degree of tectonic activity in a drainage basin. Highest relative tectonic index (Iat) is exhibited by the sub-basins 1, 2, 5, 6 and 9 and lowest index is for sub-basin - 4. Sub-basins 3, 4, 7 and 8 belong to class 2 of high tectonic activity while sub-basins 1, 2, 5, 6 and 9 belong to class 3 of moderately active tectonics.

Major climatic changes of Pleistocene - Holocene times seem to have affected the sedimentation pattern of the study area in association with proximal tectonism associated with active tectonic activities, which uplifted the Quaternary deposits. The geomorphic and tectonic behaviour of the Chaliyar river drainage basin is connected with the morphologic features and genesis of the structures. Morphological adjustment of stream channels over a short period of time and location of the basin in a tectonically active region have played dominant roles in changing the morphology of Chaliyar River drainage basin.

Active strike slip faulting has produced characteristic geomorphic assemblages in the Chaliyar river drainage basin suggest tectonic creep or moderate earthquake have occurred in the past few thousand years.

CHAPTER VI
SEDIMENTOLOGY

6.1 Introduction

In general, the term texture refers to the size, shape, roundness, grain surface features and fabric of grains. In this chapter, textural studies mainly focused on grain size variations and grain size parameters. The size distribution of sediments mainly reflects the conditions in the depositional environment, processes acting and the energy level of those processes.

As a result of differential erosion, transportation and deposition, sediments laid down in different depositional environments may possess distinctive particle size distributions. By determining these particle size distributions it is therefore, possible to hypothesize about the environment of deposition and so to utilize this technique as a tool for environmental reconstruction (Lario *et al*., 2002). Quantitative analysis of the size distributions of sediments is necessary for detailed comparison between samples and to discover significant relationship between sediment properties and geologic processes or settings (Lewis, 1984).

In interpreting particle-size data, a number of approaches have been utilized. One such example the use of summary statistics (mean grain size, sorting, skewness and kurtosis) of particle size distributions (Folk, 1974; Folk and Ward, 1957). These may then be plotted on bivariate scatterograms, for which a number of workers have identified graphic envelopes within which deposits of particular environments are plotted (Mason and Folk, 1958; Friedman, 1961, 1967, 1979a,b; Moiola and Weiser, 1968; Buller and McManus, 1972; Tanner, 1991; Duck, 1994; Passega, 1957, 1964, 1972, 2006). Many studies have attempted to make environmental sense from bivariate plots of parameters that describe the sample size spectrum (Stewart, 1958; Friedman, 1961; 1967; Buller and McManus, 1972; Friedman and Sanders, 1978; Tanner, 1991) and the success has been varied for several reasons, such as oversimplified discrimination, e.g. beach vs. river where dunes and other depositional settings are ignored (Socci and Tanner, 1980). From these results, it is clear that no universal models exist to distinguish the depositional environments using these graphic approaches (McManus, 1988).

Various statistical approaches, used to explain the grain size characteristics and mode of transport and deposition, have demonstrated that the statistical attributes viz., mean size, standard deviation, skewness and kurtosis either in isolation or in combination serve as an effective indices in differentiating various environments of formation (Friedman, 1961, 1967; Folk, 1966). The mean grain size, sorting and skewness of sediments are dependent on the grain size distribution and the sedimentary processes of erosion, selective deposition of the grain size distribution in transport and total deposition of sediments in transport. Sedimentation in a riverine context is intermittent, it may be variably present in different parts of a catchment, and sediments may be removed by subsequent phases of incision and lateral River reworking. Complexities also arise because of the contrasting styles and rates of sedimentation in different alluvial domains. Even without environmental change, rivers deposit and rework sediments in a localized fashion within systems which have variable internal (autogenic) activities and controls.

The flow regime and sediment transport characteristics of rivers are systematically correlated to temporal and spatial changes in channel geometry and bed material size (Hey, 1987). Alterations to the flow regime often affect sediment production and transport, while altered channel morphology occurs only through mobilization of sediment (Reid and Dunne, 1996). Therefore, an evaluation of sediment in the fluvial system is necessary to determine potential or existing channel responses to different factors.

Based on the type of total sediment load, several methods are available to evaluate the sediment component of a fluvial system. Such evaluations involve the development of particle size distributions, suspended sediment sampling, measurement of bed load transport, and the determination of changes in sediment storage. Numerous methods are available to conduct each of these evaluations. The method or combination of methods is dependent on the channel characterization and specific purpose of sediment evaluation.

6.2 Materials and Methods

6.2.1 Sediment samples

Sediment Sampling was restricted to the Nilambur valley area (Fig. 6.1). Sediment samples were collected from the present day stream channel (T_0), younger terrace (T_1) and older terrace (T_2). Samples from still older terraces were avoided as the terraces have been more or less lateritized.

All the sub samples were dried in hot air oven at 50ºC before they were subjected to textural analysis. The samples represented three domains- stream sediment and terrace samples T_1 and T_2. 32 stream sediment, 47 T_1 and 28 T_2 samples were subjected to textural analysis. The weighed samples (approx. 100g) were treated with 15% H_2O_2 for removal of organic matter. Later the samples were heated up to 70ºC till the effervescence stopped to remove the excess H_2O_2 present in the samples. The treated samples are used for grain size analysis and major elements estimation. In total, 32 stream sediment samples, 47 samples from T_1 terraces and 28 samples from T_2 terrace are collected and analyzed for texture and for major elements.

6.2.2 Textural analysis

The oven-dried samples were sieved through ASTM mesh wet sieves (6" diameter) arranged at 0.5ϕ intervals using mild water jet. Mud was thoroughly washed from each sieve using distilled water. Fractions in the sieves were air-dried, weighed and calculated the weight percentage and other statistical parameters following the standard procedure (Folk and Ward, 1957). The mud (silt and clay) fraction obtained after wet sieving is used for pipette analysis to estimate the silt and clay. The pipette analysis was carried out at 1ϕ interval up to 11ϕ using the procedure as suggested by Galehouse (1971). The sand-silt-clay percentages were plotted on a ternary diagram to obtain different textural classes (Folk et al., 1970).

Generally four grain size parameters are used to describe the grain size distribution. The grain size in phi values of the samples was plotted against the cumulative weight percentage on a probability chart and different percentile values of 5, 16, 25, 50, 75, 84 and 95 (ϕ) were obtained from the graph and grain size parameters viz., mean, standard deviation, skewness and kurtosis are calculated using Folk and Ward's formulae (1957).

Various bivariate plots have been prepared to discriminate different depositional environments for all the sample types (Friedman, 1961; Tanner, 1991a,b). These bivariate plots are prepared to examine their suitability to serve as discriminants for identifying the dominant depositional processes and environment. The bivariate plots

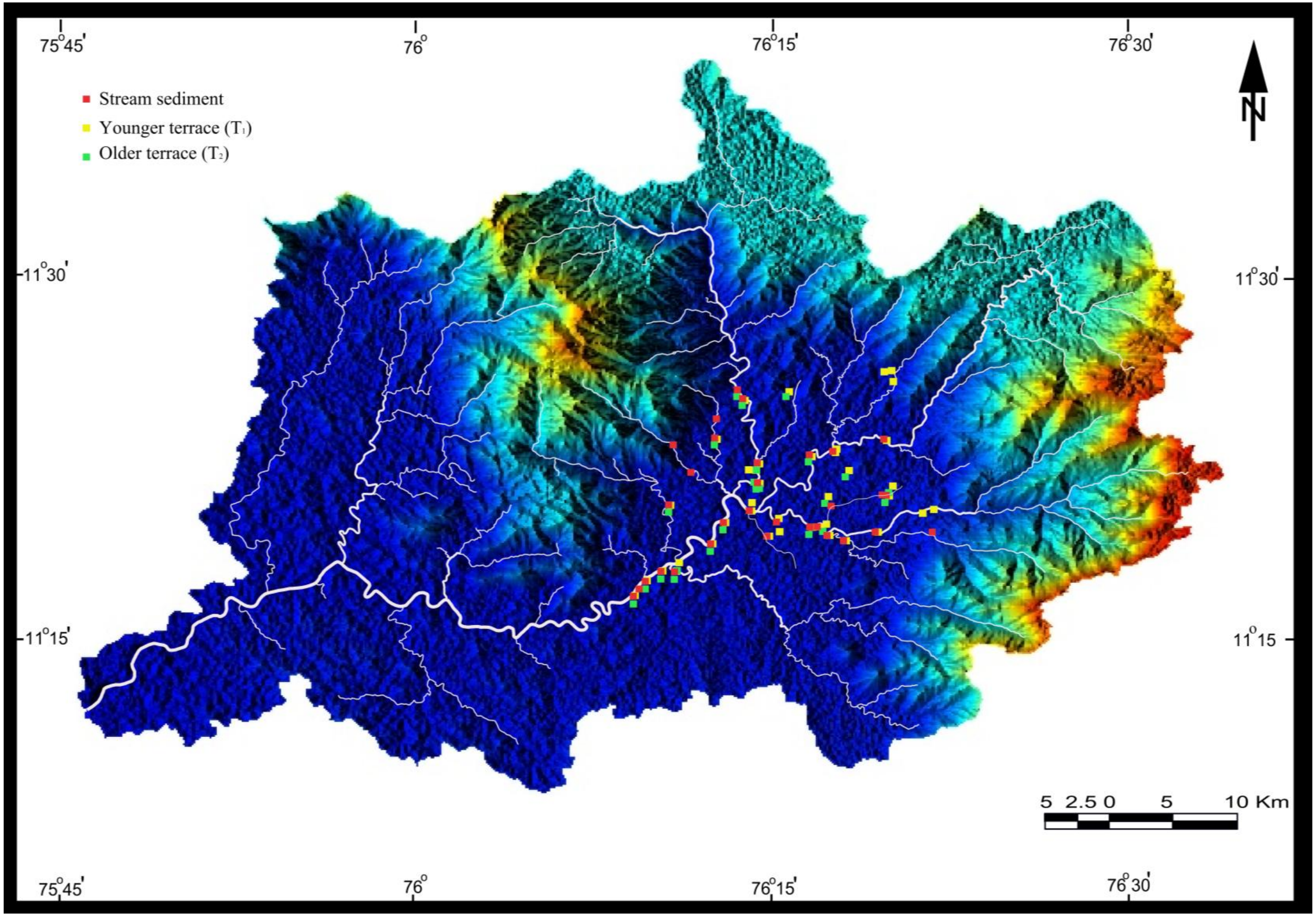


Fig. 6.1 SRTM derived DEM - aspect map of the Chaliyar River drainage basin showing stream sediments and terrace samples location points.

prepared for the stream sediments and T_1 and T_2 terrace samples : Bivariate plots - (i) mean size vs. standard deviation and (ii) standard deviation vs. Skewness iii) mean size vs. skewness. (iv) Friedman's plot, (v) Tanner's plot (mean size vs. sorting) are represented in Fig. 6.5 and 6.6. CM diagram is prepared and represented in Fig. 6.6a.

Friedman's bivariate plot discriminates sands of beach and river environments. Tanner's bivariate plot differentiates the sediments based on the energy zone and environment of deposition. It discriminates sands of fluvial, estuarine or closed basin environment. The CM diagram is prepared (Passega, 1964; 1972) as it offers a platform for the purpose of deducing transportation modes of sediments. The position of the points in a CM diagram depends upon the mode of deposition of the sediments. The CM diagram of the sediment samples were prepared to understand the transportation/deposition processes.

6.2.3 Geochemical analysis

The mineralogical and bulk chemical composition of sedimentary rocks and sediments are used to determine provenance, evaluate palaeoclimate and tectonic activity and study of the evolution of crust (Condie, 1967; Wildeman and Condie, 1973; Pettijohn, 1975; Mac Lennan and Taylor, 1982; Nesbitt and Young, 1982; Cullers et al., 1988; Mac Lennan and Taylor, 1991; Potter, 1994).

Chemical weathering affects plagioclase preferentially, K-feldspar comparatively and quartz least of all (Nesbitt and Young, 1989). The weathered residue of feldspars is clay minerals. Feldspar depletion becomes progressively more pronounced as weathering proceeds and resulting sandy sediment become progressively less representative of the source rock.

The bulk chemical analysis of representative samples from stream (SS) and terraces (T_1 and T_2) is carried by XRF method. In total, 10 stream sediment samples, 7 T_1 terrace samples, and 7 T_2 terrace samples are analyzed.

A-CN-K and A-CNK-FM diagrams

Chemical weathering of silicate rocks result in the rapid and continuous loss of cations like Ca, Na, Mg and K, slow and variable loss of silica and gradual enrichment of Al and Fe. The A-CN-K and A-CNK-FM diagrams are based on the molecular concentration of Al_2O_3, CaO, Na_2O, K_2O, FeO and MgO in the sediment samples. From the same molecular proportions, chemical index of alteration (CIA) is calculated:

$$CIA = \left[Al_2O_3 / (Al_2O_3 + Na_2O + K_2O + CaO) \right] \times 100$$

CIA value for average continental crust is about 50. Gibbsite and kaolinite have CIA values of 100. CIA of sediment samples are good indicators of extent of chemical weathering in the source area and therefore the climate conditions.

6.3 Results and Discussion

6.3.1 Texture

Textural distribution (Sand-silt-clay ratio)

The distribution pattern of the sand-silt-clay ratios of stream sediments, terrace samples (T_1 and T_2) of the Nilambur valley area of the Chaliyar river basin is discussed and compared.

Sand content of stream sediments varies from 76-95% (average 87%), the silt content from 5-23% (average 12.5%) and the clay content ranges from 0-1%. T_1 terrace samples contain 28-48% of sand, 28-50% of silt and 10-35% of clay. Sand content in T_2 terrace samples ranges from 27-43%, silt content from 28-56% and clay content from 16-45% (Table 6.1, 6.2 and 6.3 and Fig.6.2 a, b and c).

The distribution of the sediments in ternary diagram of Sand–Silt–Clay after USDA (Baize, 1988) in which stream sediments fall well within the sand and sandy loam facies (Fig. 6.3). Loam is the dominant textural facies of both the terrace samples.

Grain size parameters

The grain size parameters generally employed for the analysis of sediment size distribution are mean (*Mz*), standard deviation (σ_1), skewness (Sk_1) and kurtosis (K_G). The mean size expresses the force of water, wind or current which can set the sediments in motion. It is the reflection of the overall competency of the transportation dynamic system (Goldbery, 1980). Standard deviation reflects the degree of sorting of the sediment and depends on the range of the size of the sediment, rate of deposition and strength and variation in energy of the agents of deposition. It allows an appreciation of the size grading processes active during transport and deposition and reflects the energy level in the environment of deposition (Lewis, 1984). Skewness indicates the degree of symmetry and is a sensitive indicator of environment of deposition. It is controlled more by the depositional processes than by the transporting conditions (Chamley, 1990). Kurtosis is the degree of peakedness of a grain size frequency curve.

Table. 6.1 Textural parameters of the stream sediment samples of Chaliyar River and for tributaries that flow in Nilambur valley area.

Smpl. No	Latitude (decimal)	Longitude (decimal)	Sand (%)	Silt (%)	Clay (%)	Graphic Mean (ϕ)	Incl.gr. std.dev(ϕ)	Incl.Gra. Skewness(ϕ)	Kurtosis
1	11.31	76.26	84	16	0	0.47	0.98	-0.27	0.90
2	11.34	76.26	79	20	1	1.30	1.15	0.11	0.73
3	11.33	76.26	91	9	0	0.47	0.76	0.21	0.38
4	11.35	76.30	89	11	0	1.33	0.76	0.06	1.00
5	11.35	76.30	84	16	0	0.53	0.91	0.03	0.72
6	11.36	76.35	92	8	0	0.68	1.03	0.11	0.53
7	11.26	76.20	95	5	0	0.63	0.79	0.80	0.46
8	11.26	76.20	93	7	0	0.30	0.64	1.50	0.96
9	11.25	76.19	94	6	0	1.10	0.96	0.09	0.55
10	11.25	76.18	87	13	0	0.97	0.83	-0.01	0.41
11	11.24	76.18	87	13	0	0.67	0.86	0.07	0.76
12	11.28	76.23	78	22	0	0.37	0.55	1.00	1.23
13	11.29	76.27	92	8	0	1.00	0.83	-0.05	0.37
14	11.30	76.27	76	23	1	0.65	0.79	-0.02	0.62
15	11.29	76.30	93	7	0	0.70	0.92	1.00	0.69
16	11.29	76.30	90	10	0	0.04	0.57	2.39	1.38
17	11.29	76.31	88	12	0	0.80	0.84	0.48	0.68
18	11.29	76.32	86	14	0	0.42	0.81	1.49	0.91
19	11.29	76.34	85	15	0	1.73	0.75	0.05	1.02
20	11.31	76.38	84	16	0	0.13	0.27	1.00	9.43
21	11.33	76.31	82	18	0	1.17	0.57	-0.12	1.09
22	11.32	76.35	92	8	0	0.35	0.71	1.50	0.83
23	11.32	76.35	83	17	0	0.21	0.54	1.73	1.01
24	11.32	76.35	81	19	0	0.82	1.15	1.10	0.63
25	11.30	76.24	78	22	0	1.20	0.60	-0.11	1.13
26	11.31	76.20	93	7	0	0.60	0.78	0.80	0.73
27	11.33	76.22	90	10	0	0.43	0.71	1.22	0.79
28	11.35	76.20	91	9	0	0.10	0.29	1.00	-2.38
29	11.36	76.23	89	11	0	0.80	0.83	0.11	0.79
30	11.37	76.23	87	13	0	0.23	0.79	2.00	0.76
31	11.39	76.25	89	11	0	1.11	0.69	-0.09	1.12
32	11.39	76.25	95	5	0	2.14	0.61	0.07	1.08

Table. 6.2 Textural parameters of the younger terrace (T_1) samples of Chaliyar River and for tributaries that flow in Nilambur valley area.

Smpl. No	**Latitude (decimal)**	**Longitude (decimal)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Graphic Mean (ϕ)**	**Incl.gr. std.dev (ϕ)**	**Incl.Gra. Skewness (ϕ)**	**Kurtosis**
1	11.31	76.26	33	43	24	2.70	0.69	0.11	1.13
2	11.31	76.26	45	45	10	1.53	1.22	-0.05	0.91
3	11.31	76.26	43	39	18	1.09	1.36	-0.02	0.70
4	11.34	76.26	39	41	20	1.72	1.34	-0.12	1.05
5	11.34	76.26	36	35	29	1.05	1.36	-0.15	0.77
6	11.34	76.25	48	38	14	1.50	1.29	-0.08	0.75
7	11.33	76.26	37	28	35	2.65	0.73	0.50	1.68
8	11.35	76.30	41	38	21	2.15	0.73	0.17	1.18
9	11.35	76.31	35	36	29	1.78	1.06	-0.06	1.02
10	11.35	76.31	37	39	24	2.53	0.70	-0.06	1.09
11	11.36	76.35	32	38	30	2.98	0.79	0.13	1.17
12	11.36	76.35	37	42	21	2.23	0.70	0.11	1.06
13	11.40	76.35	39	44	17	1.81	1.02	-0.09	1.20
14	11.41	76.35	46	31	23	1.52	1.23	-0.18	0.59
15	11.41	76.34	44	37	19	1.59	1.13	-0.11	0.98
16	11.29	76.27	32	33	35	1.54	1.16	-0.08	0.91
17	11.29	76.27	41	36	23	1.48	1.14	0.06	0.88
18	11.30	76.27	43	34	23	3.33	1.09	0.19	0.83
19	11.29	76.30	36	41	23	2.43	0.60	-0.03	1.12
20	11.29	76.30	39	43	18	2.52	0.68	0.04	1.23
21	11.29	76.30	41	38	21	2.85	0.73	0.23	1.24
22	11.29	76.31	45	40	15	2.93	1.06	-0.29	1.31
23	11.29	76.31	48	38	14	2.23	0.61	0.03	1.06
24	11.28	76.32	39	40	21	2.17	0.77	-0.03	1.12
25	11.29	76.34	36	45	19	1.10	0.81	-0.19	1.38
26	11.29	76.34	33	39	28	2.13	0.80	0.01	1.08
27	11.29	76.34	38	37	25	2.87	0.83	0.12	1.11
28	11.31	76.38	47	39	14	1.47	1.18	-0.03	0.82
29	11.30	76.37	35	42	23	1.53	1.16	-0.03	0.98
30	11.30	76.37	43	32	25	1.70	1.13	0.00	1.04
31	11.30	76.31	43	40	17	2.85	1.27	-0.15	1.19
32	11.32	76.31	46	41	13	2.20	0.86	0.01	1.14
33	11.34	76.32	48	39	13	2.00	0.95	0.09	1.16
34	11.32	76.35	37	43	20	2.65	0.82	0.06	1.23
35	11.32	76.35	39	45	16	2.74	0.68	0.23	1.31
36	11.32	76.35	34	39	27	2.54	0.81	0.03	1.23
37	11.26	76.20	38	46	16	3.03	0.90	-0.14	1.29
38	11.26	76.20	38	47	15	2.78	1.10	-0.33	1.46
39	11.25	76.19	34	44	22	2.99	0.76	0.09	1.01

Table 6.2 continued

Smpl. No	Latitude (decimal)	Longitude (decimal)	Sand (%)	Silt (%)	Clay (%)	Graphic Mean (ϕ)	Incl.gr. std.dev (ϕ)	Incl.Gra. Skewness (ϕ)	Kurtosis
40	11.24	76.18	28	42	30	2.43	0.81	-0.06	2.19
41	11.27	76.21	38	42	20	2.79	0.59	0.18	1.19
42	11.28	76.23	31	49	20	3.63	1.03	-0.11	1.00
43	11.30	76.24	43	42	15	2.83	0.87	0.03	0.93
44	11.31	76.20	46	37	17	2.28	0.95	-0.18	1.90
45	11.36	76.23	45	38	17	2.53	0.70	0.11	1.26
46	11.39	76.28	32	48	20	2.50	0.41	-0.19	0.84
47	11.39	76.25	35	50	15	2.85	0.81	0.08	1.15

Table 6.3 Textural parameters of the older terrace (T_2) samples of Chaliyar River and for tributaries that flow in Nilambur valley area.

Smpl. No	Latitude (decimal)	Longitude (decimal)	Sand (%)	Silt (%)	Clay (%)	Graphic Mean (ϕ)	Incl.gr. std.dev (ϕ)	Incl.Gra. Skewness (ϕ)	Kurtosis
1	11.33	76.26	32	41	27	2.90	1.35	-0.23	1.49
2	11.33	76.26	36	46	18	1.67	1.50	0.10	0.60
3	11.34	76.26	40	41	19	1.55	1.37	-0.05	0.82
4	11.33	76.26	31	44	25	3.04	0.68	0.13	1.06
5	11.35	76.30	29	44	27	2.34	0.69	0.04	1.34
6	11.29	76.30	27	28	45	3.18	0.75	0.00	1.01
7	11.30	76.31	43	32	25	1.76	1.73	0.01	0.67
8	11.26	76.20	32	43	25	2.27	1.00	-0.20	1.20
9	11.31	76.20	37	44	19	2.95	1.09	-0.11	1.16
10	11.39	76.25	32	32	36	3.40	0.82	-0.11	1.56
11	11.39	76.25	35	39	26	2.64	1.44	0.01	0.97
12	11.30	76.31	33	41	26	2.72	0.88	-0.11	1.38
13	11.32	76.31	29	45	26	2.57	1.23	-0.08	1.16
14	11.34	76.32	31	47	22	2.15	1.03	-0.16	1.07
15	11.32	76.35	27	51	22	2.25	1.40	-0.04	1.16
16	11.32	76.35	29	53	18	2.27	1.38	0.07	1.06
17	11.32	76.35	33	32	35	2.10	1.19	-0.07	1.02
18	11.26	76.20	28	56	16	2.22	1.40	0.12	1.04
19	11.26	76.20	29	48	23	2.57	1.46	-0.04	0.93
20	11.25	76.19	28	47	25	2.45	1.36	-0.03	1.14
21	11.24	76.18	32	49	19	2.33	1.16	0.02	1.11
22	11.27	76.21	31	47	22	2.32	1.02	-0.05	1.03
23	11.28	76.23	37	47	16	2.40	1.23	0.07	1.10
24	11.30	76.24	28	44	28	2.23	1.27	0.02	1.22
25	11.31	76.20	34	43	23	1.96	1.34	0.01	1.24
26	11.36	76.23	33	46	21	2.70	1.47	0.06	0.96
27	11.39	76.28	31	49	20	2.15	1.21	0.06	1.45
28	11.39	76.25	32	43	25	2.33	1.41	0.00	1.12

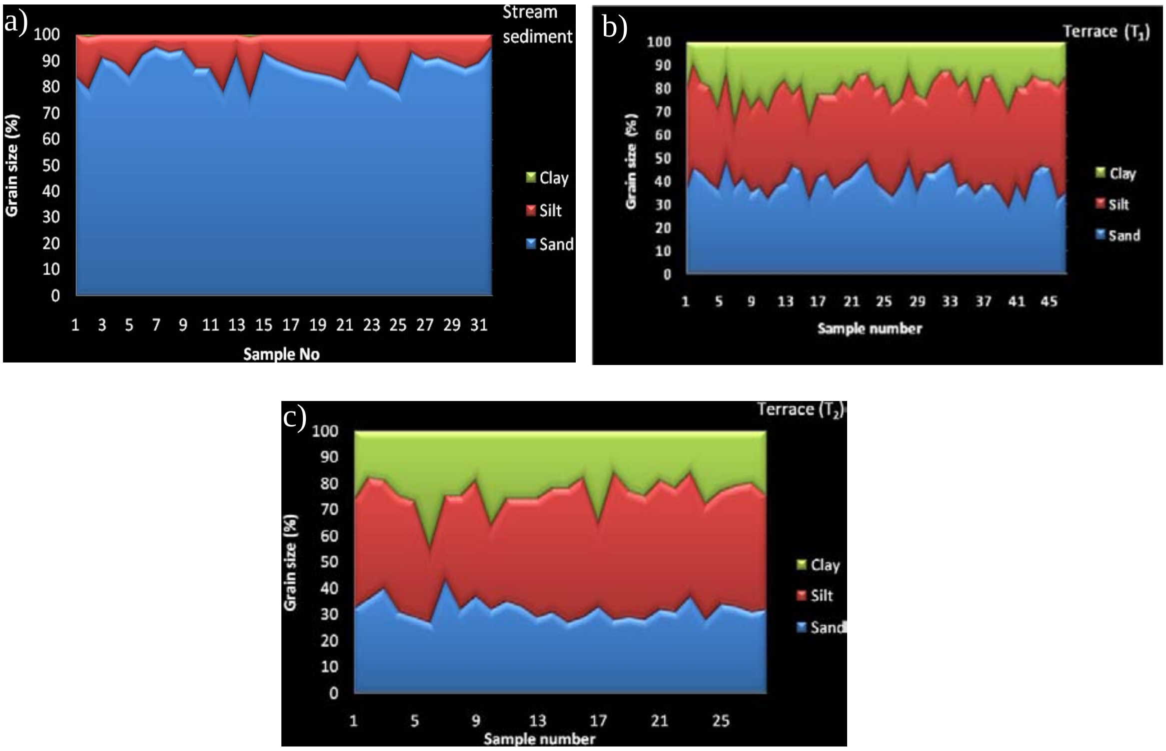


Fig. 6.2 Relative percent of sand-silt-clay of (a) stream sediments (SS); (b) younger terrace samples (T_1); (c) older terrace samples (T_2) in Nilambur valley area of Chaliyar River drainage basin.

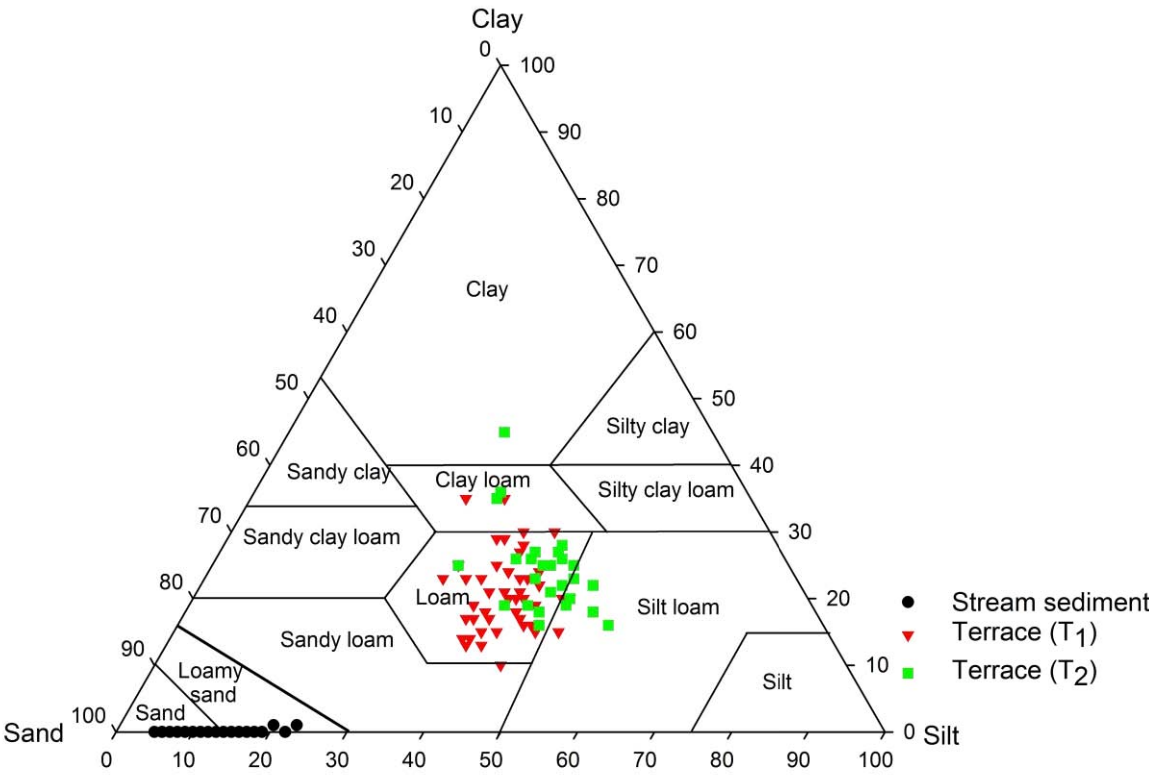


Fig. 6.3 Ternary diagram showing grain size distribution of stream sediments, younger terrace (T_1) and older terrace (T_2) of Nilambur valley of Chaliyar River drainage basin.

The evaluation of various granulometric factors facilitates the identification of ancient depositional environments, when these factors are seen in their sedimentological context as widely as possible and when treated by appropriate statistical methods (Riviere, 1977).

Mean

The grain size of sediment depends on the character of the source rocks, weathering processes, abrasion and selective sorting during transportation. Sediment particles are segregated according to their hydrodynamic behavior and depend mainly on the particle size. Mean grain size is a reflection of the competency of the transporting system.

Mean size of the stream sediments of the Nilambur valley region of Chaliyar River basin varies from 0.04 to 2.14ϕ (coarse sand to fine sand). Only one sample could be categorized as fine sand. Majority of the samples exhibits mean size of 0 to 2 (coarse to medium sand), indicating mature to sub-mature nature of the sediments (Table 6.1 and Fig. 6.4a). Mean size of the T_1 terrace samples ranges from 1.05 to 3.63 ϕ (very fine sand to medium sand). But majority of the samples fall within the range of 1 and 3 ϕ (fine sand to medium sand) depicting the matured nature of the sediments (Table 6.2 and Fig. 6.4a). Mean size of the T_2 terrace samples varies from 1.55 to 3.34 ϕ (very fine sand to medium sand). Majority of the samples fall in the fine sand class and the remaining samples falls in the medium sand and very fine sand (Table 6.3 and Fig. 6.4a).

Sorting (Standard deviation)

Sorting is the measure that depends on the size range of the sediment, rate of deposition and strength and variation in energy of the deposition agent. Poorer sorting indicates variable current velocities and turbulence during deposition, while good sorting indicates smooth, stable currents (Amaral and Pryor, 1977). Most sandy floodplain deposits tend to be less well sorted and to contain some muddy matrix because energy levels in a river system fluctuate and deposits are not continuously reworked.

Grain size characteristics in Nilambur valley sediments suggest moderately sorted to moderately well-sorted nature of stream sediments (Table 6.2 and Fig. 6.3 b). Younger terrace (T_1) samples show moderate to poor sorting (Table 6.2 and Fig. 6.3 b) and majority of the older terrace (T_2) samples exhibit poor sorting (Table 6.2 and Fig. 6.4 b).

Skewness

Skewness gives the degree of symmetry. Samples weighted towards the coarse end-member are said to be positively skewed (lop-sided toward the negative phi values), samples weighted towards the fine end are said to be negatively skewed (lop-sided toward the positive phi values).Variation in the sign of skewness is due to varying energy conditions of the sedimentary environments (Friedman, 1967). The river sediments are usually positively skewed, beaches show a more normal distribution with a slight positive or negative skew, and dune sands are invariably positive (Friedman, 1979). Positive skewness is due to the competency of the unidirectional flow of the transporting media where the coarse end of the size frequency curve is chopped off while negative skewness is caused by the amputation of the fine grained end of the curve due to the winnowing action (Valia and Cameron, 1977). Winnowing action produced by fluid media is the mechanism that gives negative skewness, whereas sediments resulting from accumulation in sheltered environments are dominantly positively skewed (Duane, 1964). Negatively skewed sediments are affected by higher energy depositing agent, and are subjected to transportation for a greater length of time, or the velocity fluctuation toward the higher values occurred more often than normal (Sahu, 1964).

In Nilambur valley, 47% of the stream sediments are strongly positively skewed and 30% of the samples show nearly symmetrical skewness, 4% are fine skewed and only 9% of the samples are negatively skewed. Samples that show negative skewness are from the seventh order main stream. Samples of the T_1 terrace are dominantly near symmetrical (51%). 25% of the samples are negatively skewed, and the remaining 24% are negatively skewed. Majority of the T_2 terrace samples exhibit near symmetrical skewness (68%), 21% of the samples show negative skewness and the remaining 11% are positively skewed (Table 6.2 and Fig. 6.4c).

Kurtosis

Kurtosis is the degree of peakedness of a grain size frequency curve. Curves that are more peaked than normal distribution curve are termed leptokurtic; those which are saggier than the normal are said to be platykurtic.

Stream sediments are mainly platykurtic to very platykurtic (31% and 28% respectively), 25% of the samples are mesokurtic and remaining 16% falls within leptokurtic to very leptokurtic. About 53% of the (T_1) terrace samples are leptokurtic (47%) and very leptokurtic (6%), 30% mesokurtic and 17% platykutic (15%) to very platykurtic (2%). T_2 terrace samples are mainly leptokurtic and mesokurtic (47%), 11% comes within platykurtic to very platykurtic and 4% very leptokurtic (Table 6.2 and Fig. 6.4 d).

6.3.2 Bivariate plots

The bivariate plots of statistical measures and depositional environments of grain size data serve as reliable tools for identifying mechanisms of deposition (Kukal, 1971; Al-Ghadban, 1990). Important and most utilized bivariate plots are mean vs. sorting, mean vs. skewness, sorting vs. skewness as suggested by various researchers (cf. Folk and Ward, 1957; Stewart, 1958; Sahu, 1964; Folk, 1966; Friedman, 1967; Moiola and Weiser, 1968; Siemers, 1976; Chakrabarti, 1977; Erlich, 1983; McLaren and Bowles, 1985). Chakrabarti (1977) has demonstrated the relationship between the mean size and skewness characteristics, which helps in demarcating distinct grouping of sediments. He suggests that the size parameters alone cannot effectively differentiate environments particularly when the sediments are bimodal or polymodal in character. Bivariate plots of mean vs. sorting, mean vs. skewness and sorting vs. skewness for bulk samples of all the sediment samples are shown in Fig. 6.5a, b, c.

Graphic mean (Mz) vs. Inclusive graphic standard deviation (Sorting) (σ_1)

Bivariate plot of mean vs. sorting (after Tanner, 1991) is plotted for stream sediments and T_1 and T_2 terrace samples (Fig. 6.5). Very good positive correlation are observed between mean and sorting for all the samples (R= 0.76 for SS, 0.66 for T_1 and 0.74 for T_2). Stream sediments and terrace samples show Gaussian fit distribution (Fig. 6.5a)

Mean (Mz) vs Skewness (S_k)

Samples from T_1 terrace show slight positive correlation between mean size and skewness. Stream sediments and T_2 terrace samples show negative correlation (Fig. 6.5b). All the samples show polynomial fit sediment distribution (Fig. 6.5 b). Linear

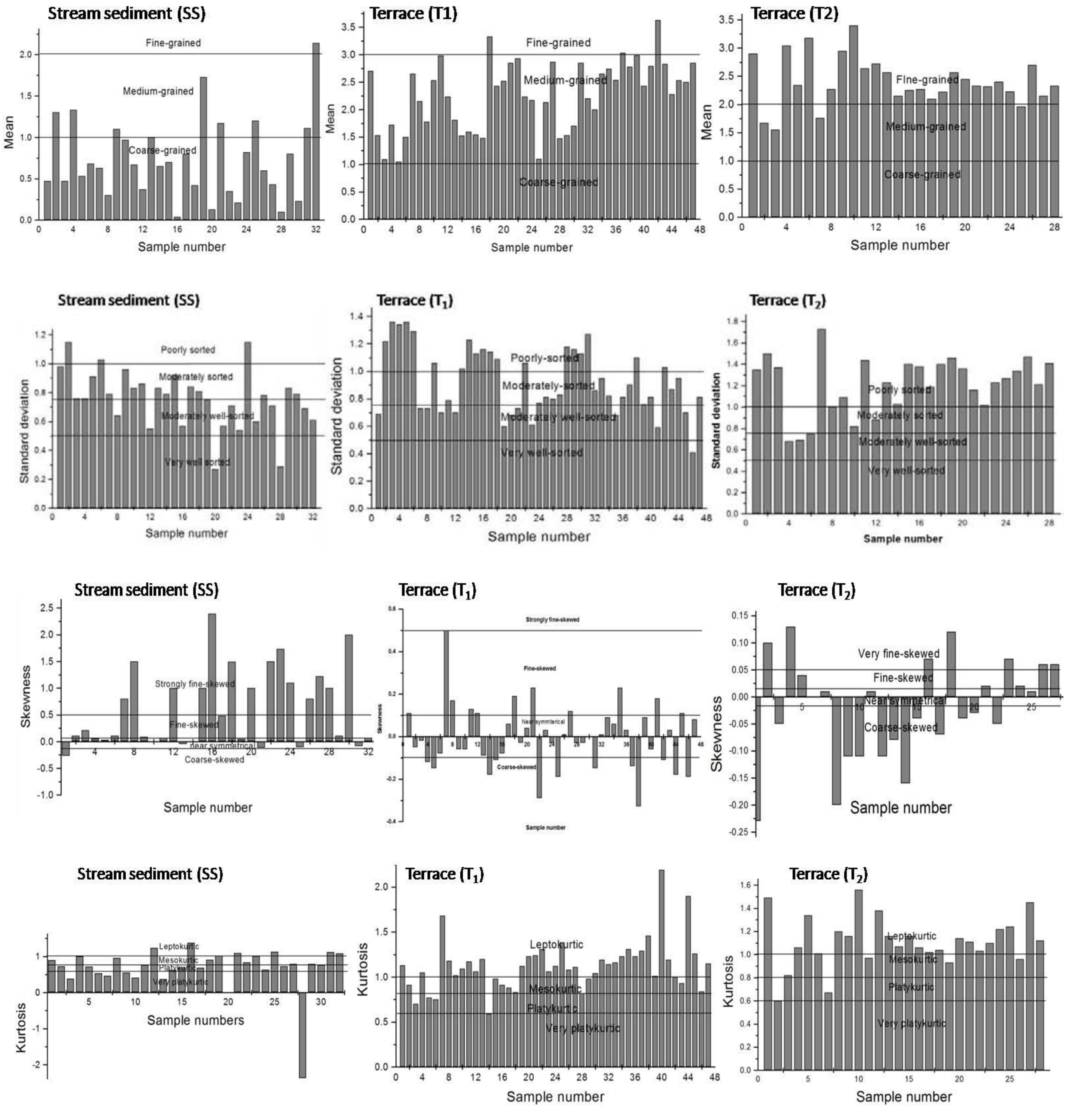


Fig. 6.4 Grain size parameters of the stream sediments (SS), younger terrace (T_1) and older terrace (T_2) of Nilambur valley. (a) Mean size; (b) Sorting; (c) Skewness; (d) Kurtosis.

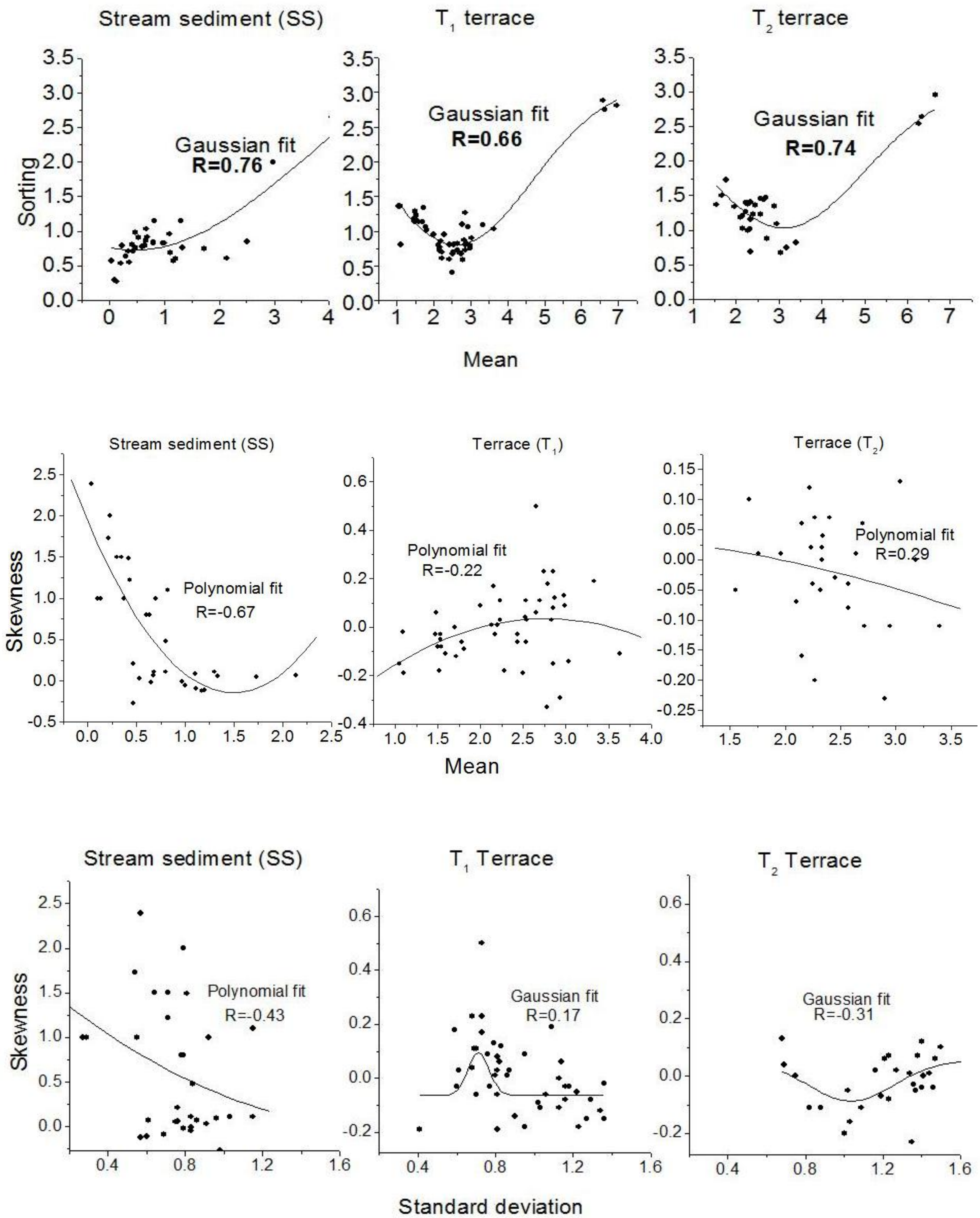


Fig. 6.5 Bivariate plots (a) Mean grain size vs. standard deviation (sorting); (b) Mean grain size vs. skewness; (c) standard deviation (sorting) vs. skewness. R is the linear regression coefficient.

regression coefficient (R) for stream sediment is -0.67 and that for T_1 and T_2 are -0.22 and 0.29 respectively (Fig. 6.5 b).

Sorting (σ_1) vs Skewness (S_k)

Bivariate plot shows that there is no correlation between these two parameters (σ_1 and S_k) for any of the samples. Linear regression coefficient for stream sediment is 0.43, T_1 is 0.17 and T_2 is 0.31. Terrace samples (T_1 and T_2) show Gaussian distribution while stream sediments show polynomial distribution (Fig. 6.5c).

6.4 Geochemistry

Most primary minerals become thermodynamically unstable during the process of weathering, erosion and transportation and alter to new stable secondary minerals by physical disintegration and chemical weathering. Rock weathering process results in grain size reduction, loss of soluble elements, enrichment of water insoluble elements resulting in the formation of clay minerals. It is a continuous process, the rate and intensity of which depend on the intensity of the physical variables on the surface, topography, relief, structure, texture and geochemistry of the exposed rocks and time. Geochemistry of the sediments helps to evaluate the nature of the provenance and tectonic history of the provenance during sedimentation.

In this study, sediment samples from present day stream bed and terraces are studied to understand the rate of weathering and thereby the chronological order of deposition.

Major elements

Clastic sediments derived from the provenance area undergoing chemical weathering of rocks show a similar compositional trend in the A-CN-K space. Some chemical fractionation could occur during transport of sediment particles due to the transportation of fine colloidal clay as suspended load. The extent of the transport related geochemical fractionation depends on the extent of chemical weathering in the provenance area. Any post depositional geochemical changes associated with diagenesis/metasomatism of sediments can also be evaluated from these plots.

During the early stage of uplift of a terrain sediment supply become very significant because of mass wasting and erosion. The sediments are physically and chemically immature. As the net uplift rate decreases the degree of chemical weathering increases and sediments become chemically evolved. However, the sediment deposited finally bears the cumulative effect of tectonics and weathering history of the provenance as well as reworking history during transit.

Major element concentration of the stream sediments and terrace samples (T_1 and T_2) are given in the Table. 6.5. A-CN-K diagram represents the molar proportion of Al_2O_3, CaO+ Na_2O and CaO, where CaO represents the part that has been derived from the silicate minerals (Nesbitt and Young, 1984; 1989). Within the A-CN-K compositional space the plots of SS, T_1 and T_2 are close to the (A) Al_2O_3 apex showing the concentration of alumina and potash (Fig. 6.6 a_1, b_1, c_1). The sediments might have derived from the charnockite and gneisses that form the hilly terrains of Chaliyar River drainage basin. A-CN-K diagram for stream sediment shows highest concentration of illite that has been derived from the K-feldspar. The preponderance of K-feldspar over plagioclase also indicates the intensity of chemical weathering and alteration of plagioclase to clay mineral (kaolinite).

A-CNK-FM plots show the molecular proportion of Al_2O_3, $CaO+Na_2O+K_2O$ and FeO (total) + MgO. Within the compositional space of A-CNK-FM diagram, the plots for stream sediment samples and terrace samples are close to the feldspar A-CNK zone close to feldspar apex (Fig. 6.6 a_2, b_2, c_2). The plots of SS show their concentration very close to the A apex indicating very high rate of chemical weathering. T_1 and T_2 terrace samples show almost similar characteristics and are concentrated towards the feldspar apex. Intensity of chemical weathering is high in stream sediments than in terrace sediments. The younger and older terraces (T_1 and T_2) do not show much variation in the chemical characteristics as shown in plots of A-CN-K and A-CNK-FM diagrams (Fig. 6.7). This suggests that the rate of chemical weathering is almost uniform in both the deposits and the formation of these two terraces occurred within a short span of time. However, formation of two levels of terraces within a short period of time can only be explained by the signatures of tectonism.

The chemical index of alteration (CIA) has been widely used as a proxy for chemical weathering in sediment source area (Nebitts and Young, 1982). It is commonly used for characterizing weathering profiles. Chemical weathering indices incorporate bulk major element oxide chemistry into a single value for each sample.

Fig. 6.4 Major element concentration of the stream sediments (SS), younger terrace (T_1) and older terrace (T_2) samples of Chaliyar River from Nilambur valley (all the values are in wt%).

Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	MnO	Na_2O	K_2O	P_2O_5
Stream sediment										
SS-33	37.06	24.36	15.6	1.85	0.44	0.44	0.08	0.09	0.49	0.3
SS34	37.83	24.43	14.71	1.84	0.74	0.65	0.07	0.21	0.80	0.38
SS35	44.62	23.18	13.39	1.85	1.36	0.59	0.08	0.56	0.52	0.24
SS36	56.24	19.36	8.65	1.16	0.89	0.42	0.10	0.38	0.48	0.21
SS37	68.94	15.46	4.93	1.20	0.52	0.34	0.05	0.15	0.35	0.20
SS38	52.05	20.63	10.20	1.62	1.44	0.74	0.79	0.66	0.72	0.28
SS39	42.86	24.03	11.44	1.43	0.88	0.6	0.12	0.22	0.6	0.22
SS40	54.99	21.09	7.24	1.47	2.65	0.8	0.09	1.67	0.74	0.16
SS41	55.52	18.76	8.82	1.43	1.35	0.55	0.09	0.67	0.34	0.2
SS42	57.57	17.97	7.66	1.26	0.56	0.34	0.08	0.16	0.55	0.28
Terrace (T_1)										
TS13	58.46	13.52	10.46	2.42	3.07	2.36	0.14	1.68	0.41	1.26
TS15	56.93	14.32	10.58	2.42	2.87	2.11	0.15	1.43	0.36	0.91
TS19	76.51	6.79	5.98	2.42	1.26	0.64	0.08	0.72	0.11	1.14
TS32	48.87	14.95	16.91	2.42	3.71	5.28	0.2	1.79	0.71	0.89
TS34	50.84	14.49	10.48	1.02	3.06	2.68	0.2	1.74	0.77	2.81
TS45	56.96	16.94	9.29	1.45	3.08	2.55	0.11	1.74	0.74	0.95
TS46	53.7	17.71	9.09	1.34	3.71	3.03	0.12	2.08	0.65	0.87
TS47	54.76	16.14	10.58	1.61	3.37	2.72	0.12	1.85	0.66	0.8
TS51	57.38	14.99	9.4	1.77	4.28	3.33	0.13	2.07	0.51	1.22
Terrace (T_2)										
TS4	62.88	14.99	6.06	0.96	3.64	2.15	0.09	2.46	0.45	0.7
TS5	71.52	10.15	6.37	1.77	0.89	0.58	0.11	0.61	0.24	1.15
TS8	52.98	19.19	9.21	0.91	2.75	2.4	0.11	1.97	0.46	1.24
TS11	55.95	16.92	8.93	1.12	4.5	3.53	0.12	2.35	0.45	1.37
TS12	53.99	15.99	12.09	3.01	3.28	2.28	0.16	1.81	0.35	0.42
TS25	51.04	18.16	10.46	0.95	3.23	3.31	0.13	1.92	0.79	0.92
TS38	69.89	11.51	5.69	0.95	1.50	0.82	0.09	1.26	1.35	0.78
TS55	50.67	20.61	7.47	0.91	2.93	1.84	0.08	2.04	0.91	0.98
TS58	52.78	18.22	10.79	0.86	2.61	3.93	0.12	2.64	0.65	1.17
TS60	46.98	20.72	10.32	0.86	4.52	2.19	0.12	1.62	0.38	0.79

Fig. 6.5 Chemical index of actuation computed for the stream sediments (SS) and terraces samples (T_1 and T_2).

Sl. No	**Chemical Index of Alteration (CIA)**		
	Stream Sediment (SS)	**Terrace (T_1)**	**Terrace (T_2)**
1	95.98	72.38	69.59
2	93.32	75.45	85.37
3	90.48	76.46	78.74
4	91.71	70.65	69.86
5	93.81	72.23	74.62
6	87.97	75.29	75.35
7	93.39	73.33	73.69
8	80.65	73.30	77.80
9	88.83	68.60	75.54
10	93.40		76.06

CIA is interpreted as a measure of the extent of conversion of feldspars (which dominate the upper crust) to clays such as kaolinite (Nesbitt and Young, 1984, 1989; Fedo et al., 1995). Chemical index of alteration computed for stream sediments and terraces samples show that the values are higher than 50 which are considered as the average CIA for the crust. Stream sediments have CIA values ranging from 80.65 to 95.98 with an average of 91. Younger terrace (T_1) has an average CIA value as 73 with values ranging from 69 to 77. CIA of older terrace ranges from 70 to 85 with an average value of 76. This indicates high degree of alteration of sediments. Alteration is more for the stream sediments when compared to the terraces samples.

6.5 Depositional environment

The use of size parameters in various combinations as environmental indicators has been advocated by various researchers across the world (Mason and Folk, 1958; Sahu, 1964; Doeglas, 1968; Solohub and Klovan, 1970; Buller and McManus, 1972; Valia and Cameron, 1977; Goldbery, 1980). The mean grain-size and sorting are hydraulically controlled (Griffiths, 1967), and these parameters can be positively correlated with the energy of the environment and the degree of sediment processing (Tanner, 1991; Long *et al.*, 1996; Lario et al., 2000).

CM diagram

Discussions of parameters C (first percentile of the size distribution) and M (median of the size distribution in microns) showed that these parameters are indicators of hydraulic conditions under which sediments were deposited (Passega, 2006). The C-M plot (Passega, 1972) is used to understand the dominant mode of transportation and the environment of deposition. C-M diagrams in which C is the one-percentile, M the median of the grain-size distribution, characterize the coarsest fractions of the samples (Passega et al., 2006). CM diagram gives the relationships which exist between certain sizes of clastic grains and the most probable deposition mechanism are used to classify clastic sediments by subdividing them into types indicative of their genesis.

First percentile of the size distribution (C) in microns was plotted against the median of the size distribution in microns (M) for the stream sediments (SS) and T_1 and T_2 terraces sediments (Fig. 6.6 a). It is observed that stream sediments are characterized by the rolling process of deposition. T_1 terrace samples are mainly deposited under graded suspension and maximum grain size was transported by uniform suspension. T_2 terrace samples are deposited by suspension with rolling process. Maximum grain size of this terrace deposit was transported by graded suspension.

Friedman's plot (Phi Sorting vs. Skewness)

In Friedman's plot, standard deviation (sorting) is plotted against skewness as suggested by Friedman (1961, 1967) to discriminate the sands of beach and river environments (Fig. 6.6 b). About 90% of the terraces samples fall well within the fluvial regime of the plot indicating the riverine origin of the terraces. Few stream sediments fall within the beach profile (20%) and this may be due to the winnowing action of the stream and variable current velocities in the higher order streams.

Tanner's bivariate plot

Tanner (1991) proposed a bivariate plot of mean against standard deviation (sorting) showing the high and low energy zones and fluvial and estuarine zones of deposition. In this study, the parameter mean size of the sand fraction of the sediments was plotted against sorting values (Fig. 6.6c). It shows that all the stream sediments and majority of the terrace samples fall well within the fluvial and stream episode zone. About 7% of the terrace samples fall in the fluvial estuarine/closed basin boundary.

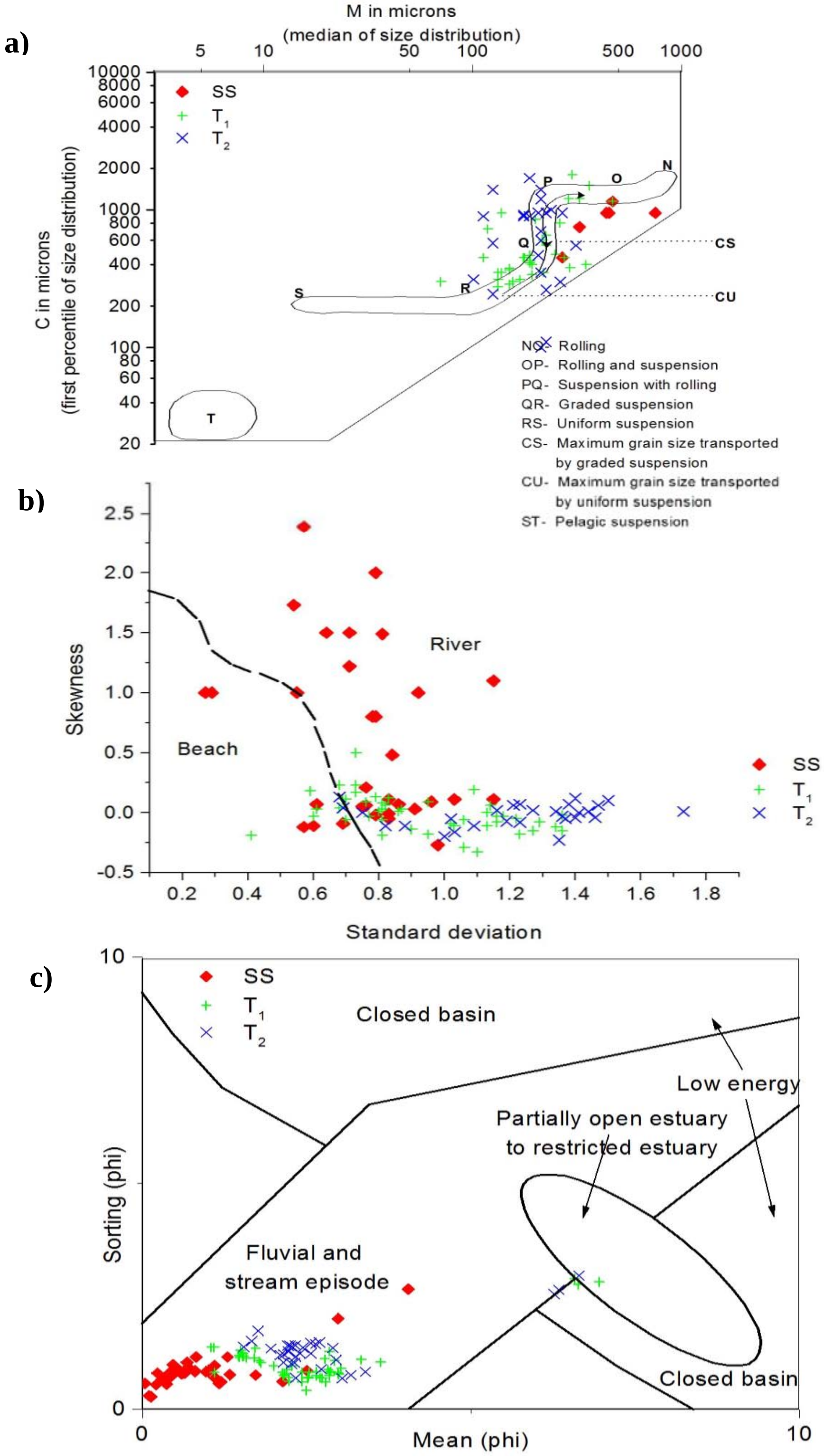


Fig. 6.6 Plots of grain size parameters. (a) Depositional processes derived from CM diagram for stream sediments, and T_1 and T_2 terrace samples (after Passega, 1972); (b) Friedman's (1961) bivariate plot of standard deviation (sorting) vs. skewness applied for the sand fractions of the samples from the stream sediment (SS), and terraces of two levels (T_1 and T_2) of Chaliyar river; (c) Bivariate plot of mean size vs. sorting after Tanner, 1991) for stream sediments and terrace samples of Chaliyar River from Nilambur valley.

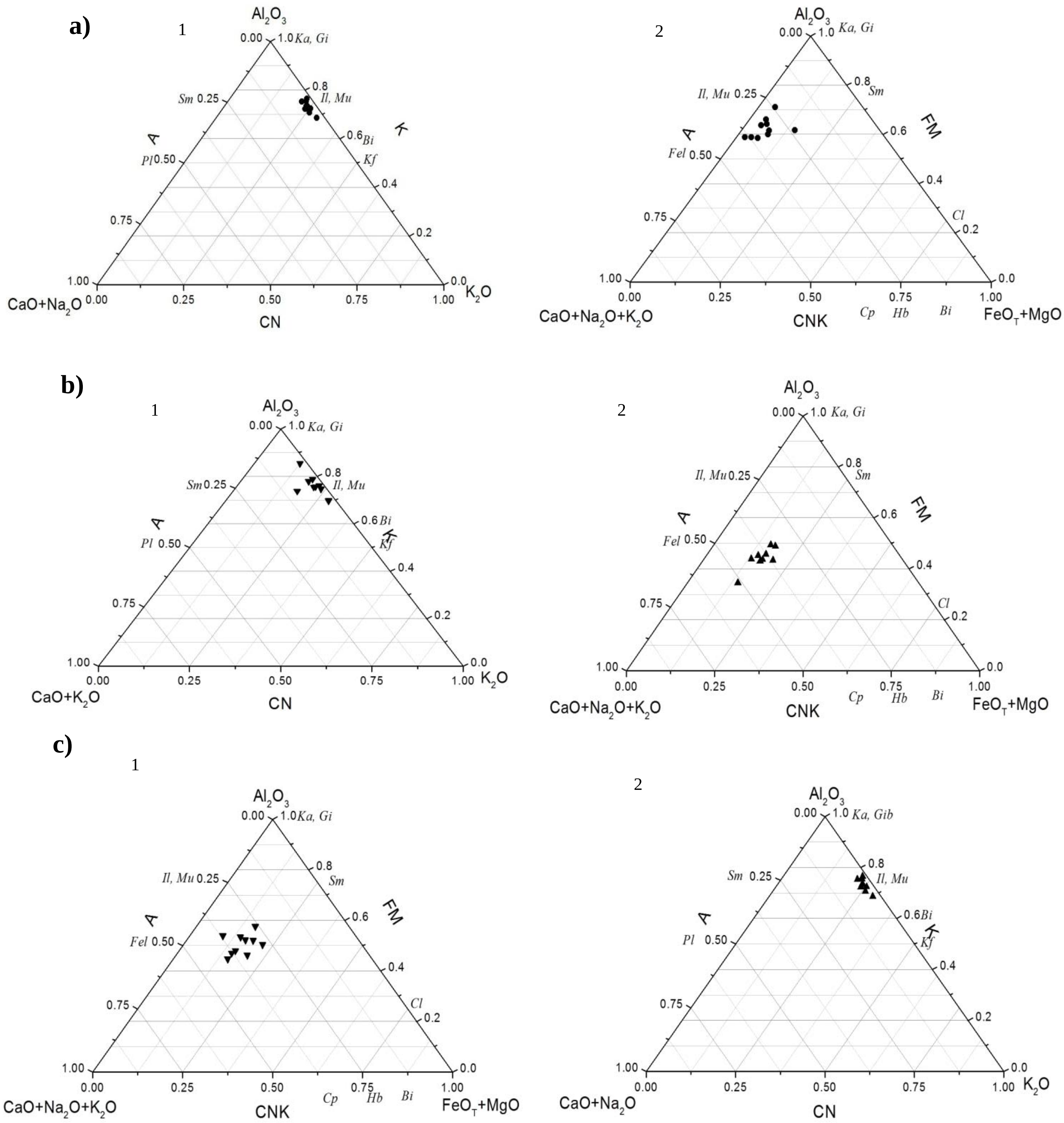


Fig. 6.7 Weathering trends of the sediments of Chaliyar River in Nilambur valley. A-CN-K and A-CNK-FM diagrams of (a) stream sediments; (b) younger terrace (T_1) (c) older terrace (T_2) samples. Ka=kaolinite; Chl=chlorite; Gi=gibbsite; Sm=smectite; Il=illite; Pl=plagioclase; Kf=K-feldspar; Bi=biotite; Mu=Muscovite; A= Al_2O_3; K= K_2O, CN= $CaO+Na_2O$.

6.6 Summary

Stream sediments of the Chaliyar River and its tributaries in the Nilambur valley area texturally consists of sand and sandy loam facies. Sandy sediments are moderately well-sorted, matured to sub-matured, coarse- to medium grained. Loam is the dominant textural facies for both younger and older terraces. Younger T_1 terrace consists of matured fine- to medium-grained sand that is moderate to poorly sorted. Older terrace (T_2) sediments are medium to fine- grained sand but are poorly sorted.

Statistical analysis of the grain size parameters are used to interpret depositional environment and describe the changes in the environmental settings. Stream sediments are positively skewed and its bivariate plot (M_z vs. σ_1) suggests the flowing water regime, exhibits polynomial fit. Plots of mean size against skewness also shows polynomial fit for stream sediments. Sorting coefficient plotted against skewness for T_1 and T_2 terraces shows Gaussian fit. Mean grain size when plotted against skewness shows positive correlation with polynomial fit for T_1 samples and negative correlation for T_2 samples with polynomial fit.

From the bivariate plots of Tanner (1991) and Friedman (1961; 1967), it is observed that the depositional environment of the stream sediments and terrace samples is of episodic fluvial and stream regimes. Few T_2 samples fall within the closed basin or partially opened estuarine condition which can be explained by the localized ponding that might have occurred during the time of deposition. CM plot (Passega, 1972) for stream sediments typify the rolling of sediments during the depositional process. Younger terrace samples (T_1) were transported by uniform suspension and deposited by graded suspension, while older T_2 terrace samples were transported by rolling process and deposited by suspension.

Geochemical data have helped in ascertaining the weathering trends of the sediments. The chemical index of alteration (CIA) has been used to quantify the degree of weathering of stream sediments and terraces samples. CIA values range between 68 and 96 on a scale of 40-100, indicating a high degree of alteration (stream sediments seem to be more altered). Similar geochemical properties and rate of weathering of the younger and older terraces indicate that there was no time gap between the time of deposition of these two formations. It is understood that the formation of two levels of terraces can take place at the same time due to tectonism.

Chapter VII

SUMMARY AND CONCLUSION

Drainage basins are durable geomorphic features that provide insights into the long term evolution of the landscape. River basin geometry develop response to the nature and distribution of uplift and subsidence, the spatial arrangement of lineaments (faults and joints), the relative resistance of different rock types and to climatically influenced hydrological parameters (Burbank and Anderson, 2001). For developing a drainage basin evolution history, it is necessary to understand physiography, drainage patterns, geomorphic features and its structural control and erosion status.

The present study records evidences for active tectonic activities which were found to be responsible for the present day geomorphic set up of the study area since the Western Ghat evolution. A model was developed to explain the evolution of Chaliar River drainage basin based on detailed interpretation of morphometry and genesis of landforms with special emphasis on tectonic geomorphic indices and markers.

7.1 Summary and Conclusion

This thesis integrates morphometric analyses, drainage and morphostructural analyses, geomorphic studies, quantitative tectonic geomorphology and sedimentology to arrive at a conclusion for the evolution of Chaliyar River drainage basin and Nilambur valley.

In the present study, the role of linear, areal and relief aspects and development of drainage system are revealed through the geomorphic processes on the basis of morphometric analysis. Spatial analysis of the morphometric parameters has provided the topographic expression and has represented the interim phase during the quantification of morphology and tectonics of Chaliyar River drainage basin.

Sub-basins of Chaliyar River drainage basin have moderate to high channel dimension and stream discharge. Well developed lower order streams might have reduced the sheet flow and about 100 km^2 drainage area is sufficient to main 265 km of channel in the basin. Low drainage density and stream frequency indicate high precipitation, low runoff and low incidence of flooding. Average size, irregular and elongated nature of the sub-basins and that of Chaliyar River drainage basin also shows that the basins have longer lag time and low peak flow.

Comparatively higher values of bifurcation ratio, low values of elongation ratio, form factor, compactness factor and circularity index of the sub-basins and that of Chaliyar River drainage basin as a whole reflects the elongated nature of the basins and points to the role of younger tectonic activity that controls the drainage architecture of the basins. Mean length of the lower order streams are higher than the next higher order in sub-basins 4, 5, 7 and 8 indicating the change in stream gradient due to tectonic uplifting and tilting of the drainage basins.

Highly dissected nature, high relief and steep slopes as explained by the relief aspects of Chaliyar River drainage basin and its sub-basins reflect the active nature of the upland zone of the drainage basins. It also indicates that the upper reaches of the basin is structurally complex mountain landscape. Hypsometric analysis of the sub-basins suggests variation in the evolutionary history. Hypsometric curve of these sub-basins show that the streams have attained its old age of evolutionary history while the hypsometric integral computed for these sub-basins shows matured stage of evolution. This variation can be attributed to the concurrent tectonism and high rate of erosional activities within the drainage basins.

A brief study on the drainage characteristics and geomorphologic set up of the Chaliyar River drainage basin is attempted in the present study. Chaliyar River drainage basin is marked by geomorphological diversity manifested in terms of morphological and hydrological characteristics. Chaliyar River flows 169 km before it debouches into Lakshadweep Sea and attains its 7^{th} order when it flows 45 km from its source. Chaliyar River generally exhibits dendritic, sub-dendritic and rectangular drainage patterns. Trellis pattern is observed in the sub-basin of Punnapuzha tributary. 3^{rd} and 4^{th} order streams follow the general structural trend and exhibit rectangular pattern. Overprint of rectangular drainage pattern over dendritic pattern is quite common in the northern part of Nilambur valley and can be attributed to the right angle fault system. Deranged or contorted drainage pattern is observed in the Cherupuzha and Iruvahnipuzha sub-basins. Radial pattern is observed around isolated hills. Parallel drainage pattern is observed in the northern part of Iruvahnipuzha and Cherupuzha sub-basins. Anabranching drainage pattern observed in the middle reaches of Punnapuzha and Karimpuzha throw light on the upliftment and subsidence of river profiles due to block faulting.

Classification of streams based on stream behaviour and source area is attempted during the present study. Based on the proxies like valley slope, sinuosity, valley width to depth ratio, median size of the stream bed material and entrenchment ratio 10 km long, 17 segments of Chaliyar River from the source to river mouth is classified into A, B, C, E and F type (after Rosgen, 1994). Based on source area (after Sinha and Friend, 1996), Chaliyar River and its tributaries are classified into (i) mountain-fed, (ii) foot hill-fed, (iii) plain-fed and (iv) mixed-fed streams.

Geomorphological map of the Chaliyar River drainage basin is prepared depicting the spatial distribution of various landforms. Different geomorphic units are delineated on the basis of observation made from Survey of India toposheets, aerial photographs and satellite imagery and field observations. Geomoprhic units thus delineated are grouped based on the geomorphic processes into (i) depositional landforms, (ii) erosional landforms and (iii) structural landforms. Depositional landforms delineated from the study area are active channel belt with point bars, braided bars and channel bars, channel fills, palaeochannels, palaeo-alluvial fans, terraces of different levels (T_0, T_1, T_2 and T_3), and marshes and back swamps. Erosional landforms in the study area include denudational and residual hills, valleys and interfluves, and pediments. Structural landforms include structural hills and valleys.

Extensive field work was carried out and the observations of lithological, structural and geomorphological features in the study area ise explained. Evidences of active tectonism observed during field studies have been specially recorded.

Geological milieu of Chaliyar River drainage basin is comparable with any other parts of the Southern Granulite Terrane (SGT). Charnockite Group of rocks makes up the high hills and slopes and is the most widely distributed rock type of the study area. Wayanad Supracrustals represented by amphibolite, fuchsite quartzite, magnetite quartzite, are the oldest rock types and occurs as enclaves within the Charnockite and Migmatite Group of rocks. Migmatites are represented by hornblende-biotite gneiss, biotite gneiss and garnet-biotite gneiss. Younger acid and basic intrusive cut across the older rocks and are highly fractured. Quartz veins in the Chaliyar river basin are the primary source for gold and contribute to the alluvial placer gold deposit of Nilambur valley. Extensive lateritization has obliterated the general lithologic characteristics.

Field relationship of structural aspects of the Chaliyar River drainage basin represents three phases of deformation. Gneissosity with a general trend in NNW-SSE direction is the result of first stage of deformation (D_1). The secondary composition banding in gneisses and migmatites is a transposition structure represented by rootless tight isoclinal folds (F_1). Small scale appressed near isoclinal folds with thickened hinges (F_2) with NNW-SSE planar fabric represents the second stage of deformation (D_2). Open folds or warps represent the third stage of deformation (D_3) where the first two deformation structures get refolded. Field evidences supporting shearing (ductile and brittle) such as mylonites, lineation, slicken-slides, scarp lines, pseudotachylite veins could be traced out.

Field evidences that support the role of active tectonics in carving out the present day Chaliyar River drainage basin are unpaired terraces, strath terraces, channel migration and river incision, palaeochannels and palaeo-alluvial fans. Scars of palaeo-landslides and recent landslides indicates the reactivation of lineaments. Reactivation of lineaments with pseudotachylite veins along the fault scarp throw light on the seismic activity that occurred within the drainage basin.

Palaeo alluvial fan morphology acts as an indicator of active tectonics as it reflects varying rate of tectonic processes such as uplift of the source mountain along a range-bounding fault or tilting of the fan surface. Westward tilting and normal faulting produced segmented alluvial fan at Karadikundu - Chekuthankundu area. On the western side of Nilambur valley, alluvial fans are relatively small and steep. Active normal faulting produces straight mountain front with single fan head.

Stream profile analysis of Chaliyar River and its tributaries display uneven longitudinal profiles with numerous knickpoints along the profiles. Analysis of river concavity and river morphology has been carried out to better understand the influence of tectonics and rock uplift on the fluvial and topographic system in Chaliyar River drainage basin. Concavity derived from the river longitudinal profiles is independent of lithology of the study area. Wide variability in the concavity index of the tributaries of Chaliyar River reflects the role of tectonism in carving the present river profiles and is inconsistent with the findings of Whipple and Tucker (2002). Steepness indices and concavity indices computed for the longitudinal profiles show that the rate of uplift is higher than the rate of incision.

River incision is not uniform in Chaliyar River. It varies from 2 m to 20 m. Terraces are discontinuous, and number and altitude of terraces vary downstream and linking of different terrace fragments is difficult. From the field studies, it is clear that uplift has triggered river incision and lateral migration of stream channels at many places especially within the Nilambur valley. Simultaneous occurrence of tectonism and incision in which valley depth is equal to the amount of uplift can be compared with the suggestions made by Meritts et al., 1994; Bonnet et al., 1998; Bull, 1999 and Hovius (2000).

Morphotectonic parameters viz., mountain front sinuosity, stream length-gradient index and valley floor width to height ratio allow the quantification of tectonic deformation along the river profile. Anomalous stream length gradient index observed along the river profiles of Kurumanpuzha, Punnapuzha and Karimpuzha are attributed to the rock resistance and tectonics. Mountain front sinuosity computed indicates tectonically active to less active mountain fronts reflecting the comparatively older tectonic event in the drainage basin. Valley floor width to valley height ratio shows wide variation in the upper reaches of Chaliyar River and its tributaries. Low width to depth ratio in the upper reaches of Chaliyar River shows that the valleys are narrow and V-shaped, actively incising with high uplift rates. High values of valley floor width to height ratio in the lower reaches and in Nilambur valley is manifested in the broad U-shaped nature of the valleys.

Asymmetry Factor and Transverse Topographic Symmetry Factor could establish the lateral tilting of the drainage basins with respect to the main water course. Sub- basin 1 (Cherupuzha basin) has tilted towards east while sub-basins 2 and 5 (Iruvahnipuzha and Chaliyarpuzha basins) have tilted towards west. Sub-basins 3 and 4 (Kurumanpuzha and Kanjirapuzha basins) have tilted towards south while sub-basin 8 (Karimpuzha) has tilted towards north. Sub-basins 6 and 7 (Karakodupuzha and Punnapuzha basins) have tilted towards southeast and sub-basin 9 (Kuthirapuzha basin) has tilted towards NE. Considering Chaliyar River drainage basin as a single unit, the lateral tilting of the basin is towards south.

River response to active tectonics produces geomorphic anomalies within the drainage basin and are known as geomorphic markers of active tectonics. Such morphologic manifestations observed in Chaliyar River drainage basins are unpaired terraces, palaeo-alluvial fans, beheaded and deflected streams, compressed meanders, angular drainages, landslides and river ponding.

Based on the values of geomorphic indices of active tectonics, classification of sub-basins of Chaliyar River drainage basin is attempted as applied by Keller and Pinter, 1996 and El Hamdouni et al, 2007. As per Keller and Pinter's classification the sub-basins 2, 7, 8 and 9 belong to class 2, where the sub-basins are tectonically active. Sub-basins 1, 3, 4, 5, 6 belong to class 3 and are less tectonically active. According to the classification method of El Hamdouni et al., 2007, the sub-basins 3, 4, 7 and 8 belongs to class 2 of high tectonic activity and sub-basins 1, 2, 5, 6 and 9 belongs to moderate active tectonics.

The imprints of tectonic features are delineated in the form of lineaments and verified during field studies. Morphostructural analysis of drainage network and lineaments show that N-S, NE-SW, ENE-WSW, NNW-SSE and NW-SE trending lineaments mark the major drainage network of Chaliyar River drainage basin. Lower order streams generally follow NE-SW and NNW-SSE trending lineaments and higher order streams follow NW-SE trending lineaments.

Sedimentological aspects of the Quaternary fluvial sediments deposited in the Nilambur valley are studied to determine the depositional environment and rate of weathering. Sediment samples collected from the present day stream beds of Chaliyar River and its tributaries and from younger (T_1) and older terraces (T_2) are used to represent the sedimentological and geochemical characteristics of sediments of Nilambur valley. Texturally, the stream sediments from Nilambur valley belong to sand and sandy facies while the terraces are represented by the loam facies. Sandy stream sediments are well-sorted, matured to sub-matured, and coarse- to medium-grained. Younger T_1 terrace consists of matured, fine- to medium-grained, moderate to poorly sorted sand. Older terrace (T_2) consists of fine- to medium-grained poorly sorted sand. From the bivariate plots of Tanner (1991) and Friedman (1961; 1967), it is observed that the depositional environment of the stream sediments and terrace samples generally show episodic fluvial and stream regimes. CM plot (Passega, 1972) for stream sediments characterize the rolling of sediments during the depositional process. Younger terrace samples (T_1) were transported by uniform suspension and deposited by graded suspension, while older T_2 terrace samples were transported by rolling process and deposited by suspension. The chemical index of alteration (CIA) has been used to quantify the degree of weathering of stream sediments and terrace samples and the values range between 68 and 96 on a scale of 40-100, indicating a high degree of alteration. Similar geochemical properties and CIA values of T_1 and T_2 terrace samples indicate that there is no time gap between the development of these two terraces. Formation of two levels of terraces simultaneously can occur only due to tectonism.

The Chaliyar River drainage basin is in a transient state of response to regional Quaternary exhumation. The examination of morphological evidence of tectonics and morphometric and morphostructural characteristics shows that the geomorphological evolution of the Chaliyar River drainage basin is strongly affected by active tectonics.

- Two different regional hydrographic domains have been distinguished on the basis of the geometry of the drainage network located roughly to the north and south of the drainage basin. Almost all the main tributaries of Chaliyar River belong to the northern domain, where the stream flow is generally oriented southwards cross cutting the regional structural trend of different lithofacies. The southern domain is characterized by a river network being drained to N and NNW and is almost parallel to the general structural trend. The drainage network of Chaliyar River drainage basin is tectonically controlled and frequent knickpoints along the longitudinal stream profiles of uniform lithology indicate neotectonic activity along lineaments. Active tectonic movements have been determining river segment development patterns or drainage network, in which correlation between river segment azimuth and lineament azimuth significantly confirms this process.

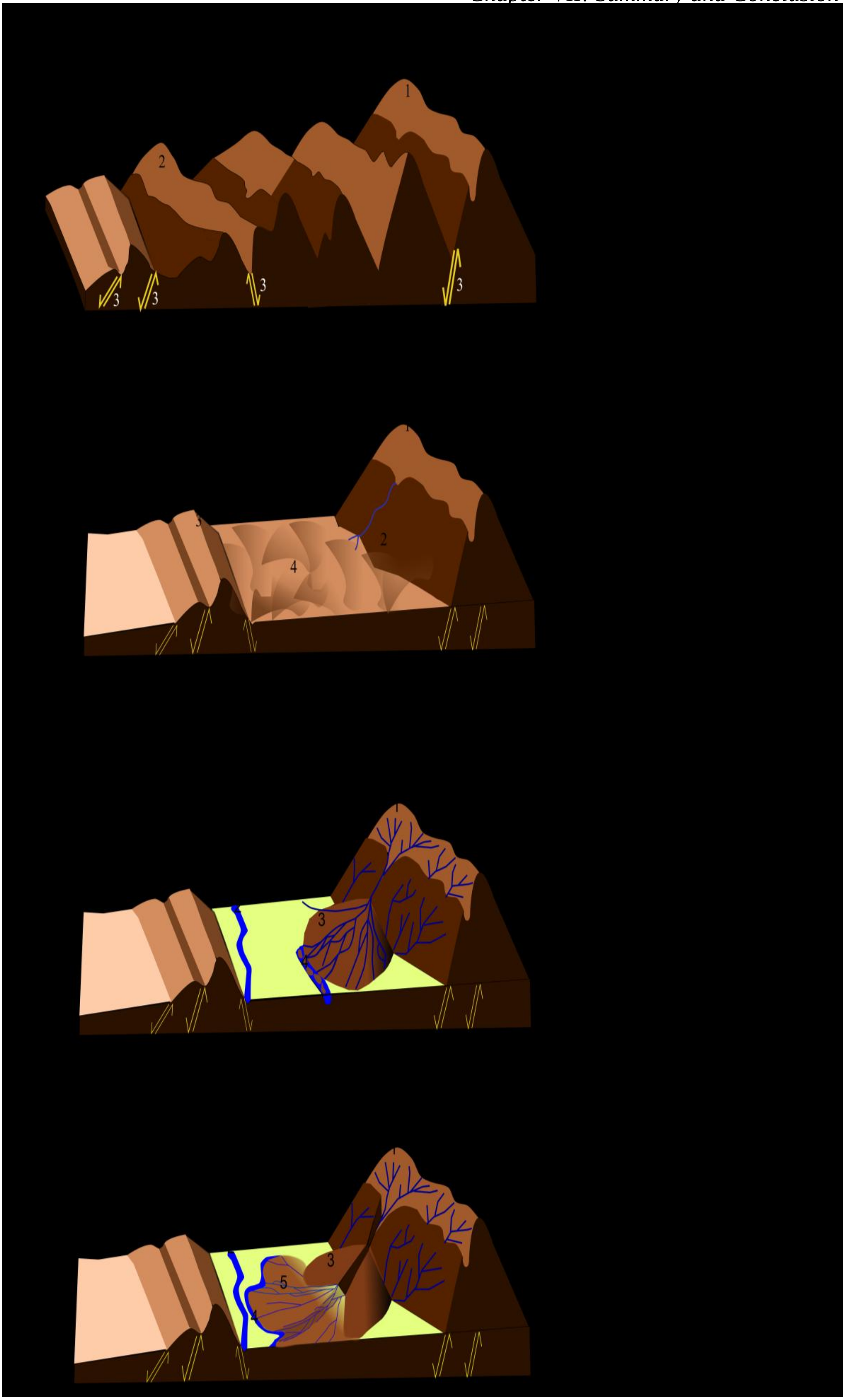
- V-shaped valleys with low valley floor width to depth ratio develops in the upper reaches of Chaliyar River and its tributaries in response to active uplift and broad U-shaped valleys in the lower reaches and in Nilambur valley indicate major lateral erosion due to the stability of base level or to tectonic quiescence.

- Down cutting induced by faulting has left the older channel remnants much higher than the present day channel. This explains the displacement of Quaternary pebble beds and reveals recent tectonic activity along normal faults. Frequent and recurring landslides at lineament junctions can be related to the reactivation of lineaments accelerated by heavy rain. River adjustment to active uplift on the river flanks are reflected in the formation of different levels of terraces like unpaired strath terraces, paired and unpaired fill terraces. The differential movements along the faults have resulted in the tilting of the basin that triggered channel avulsion and shifted the river flow from west to south and then to southwest direction.

- Active strike-slip faulting in Chaliyar River drainage basin produced characteristic assemblages of landforms that are considered as geomorphic markers of active tectonism like deflected and beheaded streams, shutter ridges, river ponding (sag pond), faults scarps, small horst and graben (microtopography). Presences of these geomorphic markers give strong evidence for tectonic creep or moderate earthquakes to have occurred in the past few thousand years. There have been no large earthquakes in historical time (few hundred years) but the morphostructural features in the basin suggests that earthquakes are likely to be generated.

- Many of the topographic features associated with active strike-slip faulting like fault scarp, river ponding can be explained by the simple shear that produced contraction and extension or can be explained by extension and contraction associated with releasing or restraining bends or step fault traces (after Sylvester and Smith, 1976; Dibble, 1977; Keller, 1996). Thus it is assumed that two tectonic phase existed in the study area. The first phase was compressive in nature and occurred on a regional scale. This phase was responsible for the development of folded structures, over thrust, reverse faults and strike slip faults. The second, a neotectonic phase related with general uplift produced normal faults which displaced the geological structures formed during the compressive tectonic phase. These later structures have displaced the fluvial terraces and are responsible for the sharp fluvial channel deviation within the basin.

- From the foregoing geomorphic and tectonic setting, a model of evolution of Nilambur valley is proposed (Fig. 7.1). Block faulting sequel to the evolution of Western Ghat escarpment initiated in the evolution of Nilambur Valley. Block faulting resulted in the development of horst and graben. Initiation of the development of drainage system along the fault scarps and sudden deposition of boulders and gravels into the graben resulted in the formation of alluvial fan. Development of drainage systems in the Wayanad plateau resulted in Chaliyarpuzha flowing south and antecedent stream developed along the margin of the alluvial fan. Fan growth shifted the antecedent stream further west with a number of streamlets through the fan joining the main stream. Normal faulting almost perpendicular to the earlier fault scarp faces resulted in the upliftment of part of the alluvial fan deposit there by detaching the massive alluvial deposit. The antecedent river shifted the flow direction from south to WSW direction long the fault plane. New drainage systems were developed from the upthrown block in the south eroding Quaternary alluvial deposits there by exposing the bedrock. These streamlets have combined together and resulted in the development of the Karimpuzha River and the earlier antecedent river formed the Punnapuzha tributary. Localized normal faults within the valley resulted in the development of terraces and channel migration. These faulted blocks have been evolved and modified to present form by subsequent denudational processes.


1
2
3
3
3
3
1
2
3
4
3
1
5
3

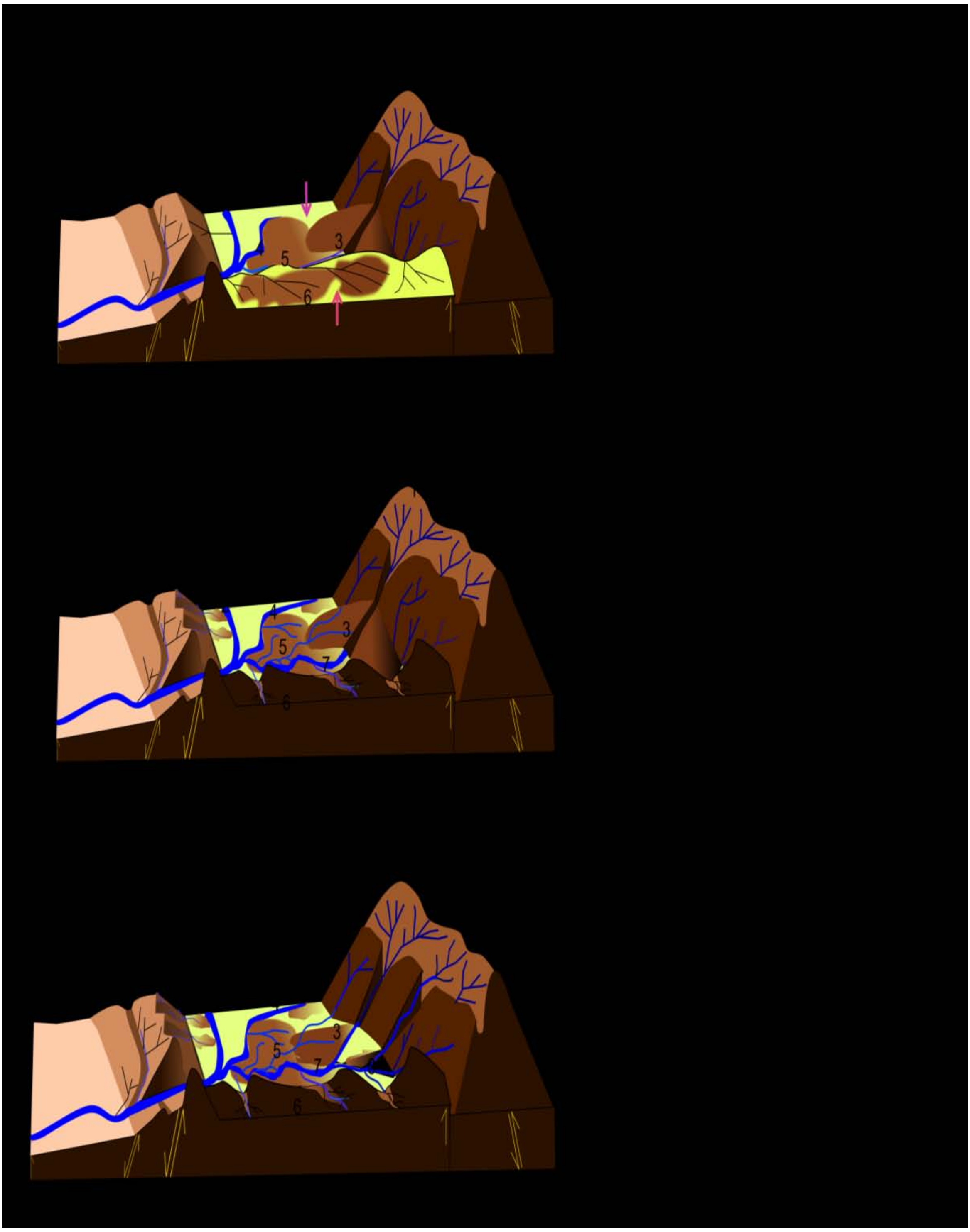


Fig. 7.1 Schematic block diagram showing the evolution of Nilambur valley (a) Western Ghat escarpment, (b) Step faulting that resulted in the development of horst and graben, and fault scarp faces, (c) Development of drainages and alluvial fan, (d) Reactivation of the alluvial and development of antecedent river, (e) ENE-WSW trending normal faulting resulting the upliftment of fan materials and development of streams through the uplifted part of the fan, (f) Erosion and development new river system and the antecedent river joining south flowing Chaliyar River and (g) Present day Nilambur valley with remnants of alluvial fan deposit and numerous rivers and streamlets and thick layer of alluvium.

7.2 Recommendations

This comprehensive study has provided the necessary foundation and paved the way for taking up further research on a wide range of applied aspects involving geomorphology. Some of the aspects that has not been dwelt upon in the present study can be pursued in the future to build up on the existing knowledge gained from this study,

- In the present study, dating of the terraces of different levels is not attempted. Thermoluminiscence dating can provide an excellent relative chronology of the terrace sediments. It enables to establish a correlation between sedimentation episodes of fluvial systems and can throw light on the climatic cycles in the Quaternary age.

- To understand the tectonic evolution and palaeo-seismicity of the study area, dating ($^{40}Ar/^{39}Ar$) of pseudotachylite is very useful since it is fault-related rock composed of friction-derived melt material interspersed with clasts and crystals from the host rock and is thought to be formed in response to seismic activity, meteoric impact, rapid tectonic faulting or landslides.

REFERENCES

Adiga K.S., 1979. Report on the structural geological mapping in the eastern parts of Kasaragod Taluk. Unpub. GSI report.

Alexandrowicz, Z., 1994. Geologically controlled waterfall types in the outer Carpathians, Geomorphology, V.9, pp.155-165.

Al-Ghadban, A.N. (1990). Holocene sediments in a shallow bay, southern coast of Kuwait, Arabian Gulf. Mar. Geol., V.92, pp.237-254.

Alvarez, W., 1999. Drainage on evolving fold-thrust belts: a study of transverse canyons in the Apennines. Basin Research 11, 267–284.

Amaral, E.J. and Pryor, W.A., 1977. Depositional Environment of the St. Peter sandstone deduced by textural analysis. Journ. Sed. Petrol., V.47, no.1, pp. 32-52.

Ananthakrishnan, R., Parthasarathy, B. and Pathan, J.M., (1979) Meteorology of Kerala. Bull. Dept. of Mar. Sci., V.10, pp.123- 125.

Anilkumar P.S., Varma A.D.K. and Nair M.M., 1993. Detailed studies on acid intrusives of Kerala, Part-B; Ambalavayal and Kalpatta. Unpub. GSI report.

Anu, S. and Mohankumar, K. (2004) Spatial variability and rainfall characteristics of Kerala. Proc. Indian Acad. Sci. (Earth Planet. Sci.), V.113, pp.211-221.

Audin, L., Herail, G., Riquelme, R., Darrozes, J., Martinod, J. and Font, E., 2003. Geomorphological markers of faulting and neotectonic activity along the western Andean margin, northern Chile. Journ. of Quaternary Science V. 18(8), pp.681-694

Avena, G.C., Giuliano, G., Palmieri, E.L., 1967. Quantitative evaluation of the hierachization and evolution of drainage networks. Bull Soc Geol Italy 86. pp. 781–796.

Azor, A., Keller, E.A., and Yeats, R.S., 2002. Geomorphic indicators of active fold growth: South Mountain – Oak Ridge anticline, Ventura basin, southern California, GSA Bull. V. 114(6), pp. 745-753.

Baize, D., 1988. Soil Science Analyses: A guide to current use. Wiley, Chichester, 192p

Balakrishnan, T.S., 2001, Tectonics of Western India inferred from gravity patterns and geophysical exploration. In Gunnell, Y and Radhakrishna, B.P. (eds.). Sahyadri - The Great Escarpment of Indian Sub-continent. Memoir 47(1), Geol. Soc. Ind, pp.271-277.

Bannister, E. and Arbor, A., 1980. Joint and drainage orientation of SW Pennsylvania. Zeitschrift fur Geomorphologie Neuefolge, V.24., pp. 273-286.

Bishop, M.P., Shroder, J.F. and Colby, J.D. 2003. Remote Sensing and geomorphometry for studying relief production in high mountains. Geomorphology, V. 55(1-4), pp. 345-361.

Bishop, P. and Hoey, T. B. and Jansen, J. D. and Artza, I. L., 2005. Knickpoint recession rate and catchment area: the case of uplifted rivers in Eastern Scotland. Earth Surface Processes and Landforms 30(6):pp. 767-778.

Bishop, P., 1995. Drainage rearrangement by river, beheading and diversion. Progress in Physical Geography, 19, 449-473.

Blatt, Harvey, Middleton, Gerard, and Murray, Raymond, 1972, Origin of Sedimentary Rocks: Englewood Cliffs, New Jersey, Prentice-Hall, p. 634.

Bloom, A.L., 1991. Geomorphology: A systematic analysis of Late Cenozoic Landforms (2nd ed.). Prentice-Hall Pvt. Ltd.

Bonnet, S. and Crave, A., 2003, Landscape response to climate change: Insights from experimental modelling and implications for tectonic versus climatic uplift of topography, Geology, v. 31, p. 123–126.

Brice, J.C., 1982. Stream channel stability assessment. U.S. dept. Of Transportation, FHWA/RD-821021.

Brice, J.C., 1984. Planform properties of meandering rivers. In.Elliot, C.M. (eds.), Proceedings of the conference-Rivers, ’83. Amer. Soc. of Civil Eng. Pp. 1-15.

Bridgland, D.R. and Allen, P., 1996. A revised model for terrace formation and its significance for the early Middle Pleistocene terrace aggradations of north-east Essex, England. In. Turner, C. (eds.): The early Middle Pleistocene in Europe. Balkema, pp. 121-134.

Bridgland, D.R., 2000. The characteristics variation and likely origin of the Buchan Ridge Gravel. In: Merrit, J.W., Connell, E.R. & Bridgland, D.R. The Quaternary of the Banffshire coast and Buchan. Quarternary Research Association, pp.139-143.

Bridgland, D.R., Maddy, D. & Bates, M., 2004. River terrace sequences: templates for Quaternary geochronology and marine-terrestrial correlation. Journal of Quaternary Science.V.19, pp. 203-218.

Brocard, G.Y., P.A. van der Beek, D.L. Bourlès, L.L. Siame, and J.L. Mugnier., 2003. Long-term fluvial incision rates and postglacial river relaxation time in the French Western Alps from ^{10}Be dating of alluvial terraces with assessment of inheritance, soil development and wind ablation effects, Earth and Planetary Science Letters, v-209, pp.197-214.

Bull, W. and McFadden, L., 1977. Tectonic geomorphology north and south of the Garlock Fault, California, Geomorphology in Arid regions, Doehring, D.O., (eds.) Publ. In Geomorphology, pp.115-138.

Bull, W.B., 1962. Relation of textural (CM) patterns to depositional environment of alluvial fan deposits: Journ. Sed. Petrology, V. 32, pp. 211-217.

Bull, W.B., 1997, Discontinuous ephemeral streams: Geomorphology, V. 19, p. 227–276.

Bull, W.B. and McFadden, L.D., 1977, Tectonic geomorphology north and south of the Garlock fault, California, *in* Doehring, D.O., ed., Geomorphology in arid regions: Proceedings, Eighth Annual Geomorphology Symposium: New York, State University of New York at Binghamton, pp. 115–138.

Bull, W.L. and Knuepfer, P.L.K. 1987. Adjustment by the Charwell River, New Zealand, to uplift and climatic changes. Geomorphology, 1, pp. 15-32.

Buller, A.T. and McManus, J., 1972. Simple metric sedimentary statistics used to recognize different environments. Sedimentology, V.18, pp. 1-21.

Burbank, D.W. and Anderson, R.S., 2001. Tectonic Geomorphology. Blackwell Scientific, Oxford. 270 pp.

Burbank, D.W., Leland, J., Fielding, E., Anderson, R.S., Brozovic, N., Reid, M.R., and Duncan, C., 1996, Bedrock incision, rock uplift and threshold hill slopes in the northwestern Himalayas: Nature, V. 379, p. 505–510.

Burbank, D.W., Leland, J., Fielding, E., Anderson, R.S., Brozovic, N., Reid, M.R., and Duncan, C., 1996, Bedrock incision, rock uplift and threshold hill slopes in the northwestern Himalayas: Nature, V. 379, pp. 505–510.

Burbank, D.W., McLean, J.K., Bullen, M., Abdrakhmatov, K.Y., and Miller, M.M., 1999, Partitioning of intermontane basins by thrust related folding, Tien Shan, Kyrgyzstan: Basin Research, V. 11, pp. 75–92.

Centamore, E., Ciccacci, S., Del Monte, M., Fredi, P., Lupia, and Pelmieri, E., 1996. Morphological and morphometric approach to the study of the structural arrangement of the North-Eastern Abruzzo (Central Italy), Geomorphology, V.16, pp.127-137.

Chakrabarti, A. (1977). Polymodal composition of beach sands from the east coast of India., Journ. Sed. Petrol., V.47, no.2, pp. 634-641.

Chamley, H., 1990. Sedimentology. Springer-Verlag, Berlin, Heidelberg. 285p.

Chamyal, L.S., Khadkikar, A.S., Malik, J.N., and Maurya, D.M. 1997. Sedimentology of the Narmada alluvial fan, western India, Sedimentary Geology, V.107, pp.263-279.

Charlton, R., 2007. Fundamentals of fluvial geomorphology, Routledge Pub. P.138.

Chattopadhyay, S. and Chattopadhyay, M., 2007. Geomorphology of Kerala: An overview, Field workshop-IGCP 514, pp. 64-71.

Chattopadhyay, S., 2002, Emergence of Central Kerala coastal plain: A geomorphic analysis. In S.K. Tandon and B. Takur (eds.). Recent Advances in Geomorphology, Quaternary Geology and Environmental Geosciences: Indian case studies, Manisha Publ. New Delhi, pp.287-298.

Cheetham, M.D., Keene, A.F., Erskine, W.D., Bushi, R.T. and Jacobsen. G., 2008. Connecting and disconnected: Longitudinal correlation of river terrace remnants, Sediment Dynamics in Changing Environments, IAHS Proceedings, Publ.325, pp. 123-129.

Chen, V.E., Quocheng, S. and Cheng, K.Y., 2003. Along-strike variations of morphometric features in the Western foothills of Taiwan: Tectonic implication based on stream-gradient and hypsometric analysis. Geomorphology, V.56, pp. 109-137.

Chetty, T.R.K. 2006. Contrasting deformational systems and associated seismic patterns in Precambrian Peninsular India, Curr. Sci., V.90 (7), pp. 942-951.

Church, M., 1992. Channel morphology and typology. In. The rivers handbook, P. Calow and G.E. Petts (eds.) Blackwell Scientific, Oxford, U.K. V.1, pp. 126-143.

Ciccacci, S., Fredi, P., Lupia Palmieri, E., Pugliese, F. 1986. Indirect evaluation of erosion entity in drainage basins through geomorphic, climatic and hydrological parameters. International Geomorphology, 2: 33–48.

Condie, K.C., 1967. Composition of the ancient North American crust, Nature, V-150, pp. 1013-1015.

Cotton, C.A., 1948. Landscape as developed by the processes of normal erosion: Whitcombe and Tombs Ltd., Wellington, New Zealand, pp.500-510.

Cox, R.T., 1994. Analysis of drainage basin asymmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: An example from the Mississippi Embayment. Geol. Soc. of Amer. Bull. V. 106, pp. 571-581.

Cullers, R.L., Basu, A., and Suttner, L.J., 1988. Geochemical signature of the provenance in sand size materials in soils and stream sediments in the Tobacco Root Batholith, Montana, USA, Chemical Geology, V-70, pp. 335-348.

Cuong, N,Q., and Zuchiewicz. 2001. Morphotectonic properties of the Lo River Fault near Tam Dao in north Vietnam, Natural Hazards and Erath System Sciences, V.1, pp. 15-22.

Cvetkovik, D., 1980, Investigation of gold occurrences in Nilambur valley area. Interim technical report EG-2, KMEDP.

Das, A.K. and Mukherjee, S., 2005. Drainage morphometry using satellite data and GIS in Raigad district, Maharashtra, Journ. Geological Society of India, V.65, pp. 577-586.

Das, D. (1985). Remote sensing application for landform studies and environmental appraisal: A case study.

Davay, D.R., 1975, Preliminary exploration for gold in the Nilambur area, Malappuram District, Kerala State, Unpublished progress report, GSI

Davis, M.W. and Erlich, 1970. Relationship between measures of sediment-size-frequency distributions and the nature of sediments. Geol. Soc. America Bull., V.81, pp. 3537-3548.

Davis, W.M., 1889. The geographical cycle. Geographical Journal, V. 14, pp. 481–504.

De Celles, P.G., and Cavazza, W., 1999, A comparison of fluvial megafans in the Cordilleran (Upper Cretaceous) and modern Himalayan foreland basin systems: Geological Society of America Bulletin, V. 111, p. 1315–1334.

DeCelles, P.G. and Cavazza, W., 1999, A comparison of fluvial megafans in the Cordilleran (Upper Cretaceous) and modern Himalayan foreland basin systems: Geological Society of America Bulletin, V. 111, pp. 1315–1334.

DeCelles, P.G., Gehrels, G.E., Quade, J., Kapp, P.A., Ojha, T.P. and Upreti, B.N., 1998, Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal: Geological Society of America Bulletin, V.110, pp. 2–21.

Deffontaines, B. and Chorowicz, J., 1991. Principles of drainage basin analysis from multisource data: application to the structural analysis of the Zaire basin. Tectonophysics, V.194, pp. 237-263.

Deffontaines, B., Lee, J.C., Angelier, J., Carvalho, J. and Rudant, J.P., 1994. New geomorphic data on Taiwan active orogen: a multisource approach. Journ. Geophys. Res., V.99, pp. 20243-20266.

Dehbozorgi, M., Pourkermani, M., Arian, M., Matkan, A.A., Motamedi, H. and Hosseiniasl, A., 2010. Quantitative analysis of relative tectonic activity in the Sarvestan area, central Zagros, Iran. Geomorphology, V.30. (doi: 10.1016/j.geomorph.2010.05.002, 13p.)

Delcaillau, B., Carozza, J.M. and Laville, E., 2006. Recent fold growth and drainage development: the Janauri and Chandigarh anticlines in the Siwalik foothills, northwest India. Geomorphology, V.76, 241–256.

Delcaillau, B., Deffontaines, B., Floissac, L., Angelier, J., Deramond, J., Souquet, P., Chu, H.T. and Lee, J.F., 1998. Morphotectonic evidence from lateral propagation of active frontal fold; Pakuashan anticline, foothills of Taiwan. Geomorphology 24, pp.263–290.

Dettinger, M.D and Diaz, H.F., 2000. Global characteristics of stream flow seasonality and variability, Journ. Hydromet.,V.1, pp.289-310.

Devi, R.K.M., 2008. Geomorphic appraisals of active tectonics associated with the uplift of the Gohpur-Ganga section in Itanagar, Arunachal Pradesh, India. Geomorphology, V-99, pp.76-89.

Dibblee, T.W., 1977. Strike-slip tectonics of the San Andreas Fault and its role in Cenozoin basin evolvement. In. Late Mesozoic and Cenozoic Sedimentation and Tectonics in California, San Joaquin Geol. Soc. short course, pp. 26-38.

Dinesh, S., 2008. Computation and characterization of basic morphometric measures of catchments extracted from Digital Elevation Models, Journal of Applied Sciences Research, 4(11), pp. 1488-1495.

Doeglas, D.J., 1968. Grain-size indices, classification and environment, Journ. Sed. Petrology, V.10, pp. 83-100.

Doornkamp, J.C. and Cuchlaine, A.M.K., 1971. Numerical Analysis in Geomorphology - An introduction. Edward Arnold, London.

Dowling, T.I., Richardson, D.P., O'Sullivan, A., Summerell, G.K. and Walker, J., 1998. Application of the hypsometric integral and other terrain based metrics as indicators of catchment health: A preliminary analysis, CSIRO Land and Water, Tech. Rep. No. 20/98, 52 p.

Drury, S. A., and Holt, R.W., 1980. The tectonic framework of the south Indian craton: reconnaissance involving Landsat imagery. Tectonophysics, V.65. pp. T1-T15.

Duane, D.B., 1964. Significance of skewness in Recent sediments, western Palmico Sound, N. Carolina. Journ. Sed. Petrol., V.34, pp. 864-874.

Duck, R.W., 1994. Application of the Qda-Md method of environmental discrimination to particle size analyses of fine sediments by pipette and sedigraph methods: a comparative study. Earth Surf. Processes & Landforms, V.19, pp. 525-529.

Dument, J.F., Deza, E and Garcia, F., 1991. Morphostructural provinces and neotectonics in the Amazonian lowlands of Peru. Journ. of S. Amer. Earth Sci., V.4, pp. 373-381.

Duvall, A., Kirby, E. and Burbank, D., 2004. Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California, Journ. of Geophys. Res., V.109, F03002, doi: 10.1029/2003JF000086.

El Hamdouni, R., Irigaray, C., Fernadez, T., Chacon, J., Keller, E, A., 2007. Assessment of relative active tectonics, southwest border of Sierra Nevada, southern Spain, Geomorphology, V.96, pp. 150-173.

Erlich, R., 1983. Size analysis wears no cloths, or have moments come and gone. Journ. Sed. Petrol., V.53, pp. 1-31.

Erlich, R., Brown, P.J., Yarus, J.M and Przygocki, R.S., 1980. The origin of shape frequency distributions and the relationship between size and shape. Journ. Sed. Petrol., V.50, pp. 475-484.

Fairbridge, R.W., 1968. Terraces, fluvial-environmental controls. Encyclopedia of Geomorphology. Reinhold, New York, pp.1124-1138.

Fedo, C.M., Nesbitt, H.W. and Young, G.M., 1995. Unraveling the effects of potassium metasomatism in sedimentary rock and paleosols, with implications for paleoweathering condition and provenance. Geology, V. 23, pp. 921-924.

Flint J.J., 1974. Stream gradient as a function of order, magnitude and discharge. Water Resource Research 10, pp. 969-973.

Folk, R.L. and Ward, W.C., 1957. Brazos River bar: A study in the significance of grain size parameters. Journ. Sed. Petrol., V.27, pp. 3-26.

Folk, R.L., 1965. Petrology of Sedimentary rocks: Hemphills Book Store, Austin, Texas, 159p.

Folk, R.L., 1966. A review of grainsize parameters. Sedimentology, V.6, pp.73-94.

Folk, R.L., 1974. Petrology of Sedimentary Rocks. Hemphill, Austin.

Folk, R.L., Andrews, P.B. and Lewis, D.W., 1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. New Zealand Journ. of Geol. and Geophys., V. 13, pp. 937-968.

Friedman, G.M., 1961. Distribution between dune, beach, and river sands from their textural characteristics: Journ. Sed. Petrology, V.31, pp. 514-529

Friedman, G.M., 1962. On sorting, sorting coefficients, and the log-normality of the grain-size distribution of clastic sandstones: Journ. Geol., V.70, pp. 737-753.

Friedman, G.M., 1967. Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands: Journ. Sed. Petrology, V.37, pp. 327-354.

Friedman, G.M., 1979a. Address of the retiring President of the International Association of Sedimentologists: differences in size distributions of populations of particles among sands of various origins. Sedimentology, V.26, pp. 3-32.

Friedman, G.M., 1979b. Differences in the size distributions of populations of particles among sands of various origins: addendum to IAS Presidential Address. Sedimentology, V.26, pp. 851-861.

Friedman, G.M., and Sanders, J.E., 1978. Principles of Sedimentology. New York, John Wiley & Sons, p. 792 .

Friend, P. and Sinha, R., 1994, in Braided Rivers, Eds. Best, J. L. And Bristow, C. S., Geological Society Special Publication, London, 1993, pp. 105–111.

Friend, P.F., Jones, N.E., Vincent, S.J., 1999. Drainage evolution in active mountain belts: extrapolation backwards from present day Himalayan River patterns. Special Publication of the international Association of Sedimentologists, 28, pp.305-313.

Gale, S.J., Hoare, P.G., 1991. Quaternary Sediments—Petrographic Methods for the Study of Unlithified Rocks. Belhaven Press, London, 323 pp.

Galehouse, J.S., 1971. Point counting. In. Carver, R.e (eds.) Procedures in sedimentary petrology, Wiley Interscience, New York, pp.385-407.

Gardiner, V., 1980. Drainage basin morphometry: Quantitative analysis of drainage basin form. In H.S. Sharma (eds.). Prospective in geomorphology, V.2, pp 107-142.

Gelabert, B., Fornos, J.J., Pardo, J.E., Rosello, V.M., and Segura, F., 2005. Structurally controlled drainage basin development in the south of Menorca (Western Mediterranean, Spain). Geomorphology, V.65, pp. 147-170.

Ghassemi, M.R., 2005. Drainage evolution in response to fold growth in the hanging-wall of the Khazar fault, north-eastern Alborz, Iran. Basin Research V.17, pp. 425–436.

Giamboni, M., Wetzel, A. and Schneider, B., 2005. Geomorphic response of alluvial rivers to active tectonics: An example from the southern Rhine graben, Australian Journ. of Earth Sciences, V-97, pp. 24-37.

Gilbert, G.K., Report on the geology of the Henry Mountains (Utah), USGS, Washington DC.

Gilchrist, A.R. and Summerfield, M.A., 1994, Tectonic models of passive margin evolution and their implications for theories of long-term landscape evolution, *in* Kirkby, M.J., ed., Process models and theoretical geomorphology.

Glade, T., Crozier, M., 2009. Landslide geomorphology in changing environment, Geomorphology V-2010, doi:10.1016/j.

Gloaguen, R., 2008. Remote Sensing analysis of crustal deformation using river networks. http://www. igarsso8.org/abstracts/pdfs/3197.pdf

Goldbery, R., 1980. Use of grain-size frequency data to interpret the depositional environment of the Pliocene Pleshet formation, Beer Sheva, Israel. Journ. Sed. Petrol., V.50, no.3, pp.843-856.

Goldrick, G, and Bishop, P. 1995. Distinguishing the roles of lithology and uplift in the steepening of bedrock river long profiles: An example from southeastern Australia. *Journal of Geology* **103**: 227–231.

Goswami, P. K., Pant, C.C., Pandey, S., 2009. Tectonic control on the geomorphic evolution of alluvial fans in the piedmont zone of Ganga Plain, Uttarakhand, India. J. Earth Syst. Sci. 118, No. 3, pp. 245–259

Grady, J.L., 1971. Deep main faults in south India. Journ. Geol. Soc. India, V.12, pp.56-62.

Gregory, K.J. and Walling, D.E., 1985, Drainage basin form and process; A geomorphological approach, pp.47-54.

Griffiths, J.C., 1967. Scientific Methods in the Analysis of Sediments. McGraw-Hill, New York, McGraw Hill, p.508.

Guarnieri, P. and Pirotta, C., 2008. The response of drainage basins to the late Quaternary tectonics in the Sicilian side of the Messina Strait (NE Sicily). Geomorphology, V-95, pp. 260-273.

Guisti, E.V. and Schnieder, W.J., 1965. The distribution of branches in river networks, USGS professional paper, 422 G, US Geol survey.

Gupta, A. and Liew, S.C., 2007. The Mekong from satellite imagery: A quick look at a large river. Geomorphology, V. 85, pp.259-274.

Gupta, A., Lim, H., Huang, X. and Chen, P., 2002. Evaluation of part of the Mekong River using satellite imagery, Geomorphology, V.44, pp. 221-239.

Gupta, B.L., 1999, Engineering Hydrology, 3rd Ed. Runoff, pp. 46-56.

Gupta, S., 1997. Himalayan drainage patterns and the origin of fluvial megafans in Ganges foreland basin. Geology, V-25, pp 11-14.

Hack, J.T., 1957. Studies of longitudinal stream profiles in Virginia and Maryland. USGS Professional Paper, pp. 45-97.

Hack, J.T., 1960, Interpretation of erosional topography in humid temperate regions, American Journal of Science, v. 258, p. 80–97.

Hack, J.T., 1973. Stream profile analysis and stream gradient index. U.S. Geol. Surv. Journ. Res., V.1(4), pp. 421-429.

Hadley, R.F. and Schumm, S, A., 1961. Hydrology of the upper Cheyenne River basin. USGS Water Supply paper, 1531-B, pp. 186-198.

Hallet, B. and Molnar, P., 2001. Distorted drainage basins as markers of crustal strain east of the Himalaya. Journal of Geophysical Results, V.106, 13697–13709.

Hare, P. W. and Gardner, T. W., 1985.Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica, In: Tectonic Geomorphology: Proceedings of the 15th Annual Binghamton Geomorphology Symposium, (Eds) Morisawa, M. and Hack, J. T., September 1984, Allen and Unwin, Boston, 90–104.

Harlin, J.M., 1984. Watershed morphometry and time to hydrograph peak, Journ. Hydrology, V.67, pp.141-154.

Harman, W.H., Jennings, G.D., Patterson, J.M., Clinton, D.R., Slate, L.O., Jessup, A.G., Everhart, J.R. and Smith, R.E., 1999. Bankfull hydraulic geometry relationships for North Carolina streams, In. Olsen, D.S. and Potyondy, J.P. (eds.), Proceedings Wildland hydrology symposium, AWRA, Bozeman.

Harmar, O.P. and Clifford, N.J., 2007. Geomorphological explanation of the long profile of the lower Mississippi River. Geomorphology, V-84, pp. 222-240.

Harvey, A.M., Wells, S.G., 1987. Response of Quaternary fluvial system to differential epeirogenic uplift: Aguas and Feos river systems, southeast Spain. Geology V-15, pp. 83-109.

Hasbargen, L.E., Paola, C., 2000. Landscape instability in an experimental drainage basin. Geology, V. 28, pp.1067–1070.

Hassan, M.A., 2005, Characteristics of Gravel Bars in Ephemeral Streams, Journal of Sedimentary Research, V. 75; no. 1; p. 29-42.

Hayakava, Y. and Oguchi, T., 2006. DEM based identification of fluvial knickzones and its application in Japanese mountain rivers. Geomorphology, V. 78, pp. 90-106.

Hayden, R.S., Blair, R.W., Garvin, J. and Short, M.M., 1986. Future outlook; Geomorphology from Space. A global overview from regional landforms. http://daac.gsfc.nasa.gov/DAAC DOC/geomorphology/GEO HOME PAGE.html.

Hey, R.D., 1987. River dynamics, flow regime and sediment transport: Sediment transport in gravel-bed rivers. New York, John Wiley & Sons, 23 p.

Holbrook, J. and Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers of tectonic deformation; a brief review and critique of a tool recognizing subtle epirogenic deformation of modern and ancient settings. Tectonophysics, V.305, pp. 287-306.

Horton, R.E., 1932, Drainage basin characteristics. Transaction of American Geological Union,13, pp. 350-361.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Bull. Geol. Soc. Amer.,V.56, pp.275-370.

Hovius, N., 2000. Macroscale process systems of mountain belt erosion: In. M.A. Summerfield (eds.) Geomorphology and global tectonics, John-Wiley, New York, pp. 77-105

Howard, A.D., 1964. Drainage analysis in Geological interpretation : a summation. Bulletin of the American Association of Petroleum Geologists. V. 56 , pp. 275-370.

Howard, A.D., Dietrich, W.E. and Seidl, M.A., 1994. Modeling fluvial erosion on regional to continental scales. Journ. of Geophys. Res. V.99, pp. 13971-13986.

http://pubs.usgs.gov., 2004. Pediments and Alluvial Fans.

Hurtrez J.E., Lucazeau, F., Lave, J., Avouac, J.P., 1999. Investigation of the relationships between basin morphology, tectonic uplift and denudation from the study of an active fold belt in the Siwalik Hills, central Nepal, Journ. Of Geophysical Research, V-104, pp. 12779-12796.

Hurtrez, J.E, Sol, C., Lucazeau, F., 1999. Effect of drainage area on hypsometry from an analysis of small scale drainage basins in the Siwalik hills (Central Nepal) Earth Surface Processes & Landform V-24, pp. 799-808.

Iware Matsuda, 2004. River morphology and channel processes, in Fresh surface water, (Ed. James C. I. Dooge), in Encyclopedia of Life Support Systems, Eolss Pub. Oxford, U.K. (http://www.eolss.net).

Jackson, J., Norris, R. and Youngson, J., 1996. The structural evolution of active fault and fold systems in central Otago, New Zealand: Evidence revealed by drainage patterns. Journ. of Structural Geology, V.18, pp.217-234.

Jackson, J., Van Dissen, R. and Berryman, K., 1998. Tilting of active faults and folds in the Manawatu Region, New Zealand: evidence from surface drainage patterns, Journ. of geology and Geophysics, V.41, pp. 377-385.

Jackson. J. and Leeder, M., 1994. Drainage development of normal faults: An example from Pleasnt valley, Nevada. Journ. of Structural Geology, V.16 (8), pp. 1041-1059.

Jain, V. and Sinha, R., 2003. Hyperavulsive-anabranching Bhagmati river system, north Bihar plains, eastern India. Geomorphology., V.47(1), pp.101-116.

Jain, V. and Sinha, R., 2004. Fluvial dynamics of an anabranching river system in Himalayan foreland basin, Baghmati river, north Bihar plains, India., Geomorphology, V.60, pp.147-170.

Jones, S.J., 2004. Tectonic controls on drainage evolution and development of terminal alluvial fans, southern Pyrenees, Spain. Terra Nova, V-16, pp. 121-127.

Kaewmuangmoon, S., Thipyopass, S., Kosuwan, S., Daorerk, V. and Charusiri, P., 2008. Investigations on tectonic geomorphology along the Khlong Maruti Fault, Kao Phanom area, Southern Thailand: Application of ArcGIS approach. Proceeding of the International Symposia on Geoscience Resources and Environments of Asian Terranes, Thailand.

Kale, V. S., 1999. Long period fluctuations in monsoon floods in the Deccan Peninsula, India, Journ, Geol. Soc. India, V.53, pp 5-15.

Kale, V. S., 2002. Fluvial geomorphology of Indian rivers-An overview-Progress in Physical Geography, V-26, pp.400-433.

Kale, V.S and Gupta, A., 2001. Introduction to geomorphology, pp. 84-86.

Keller, E.A. and Pinter, N. 1996. Active tectonics: Earthquakes, Uplift and Landscape. Prentice Hall, New Jersey.

Keller, E.A., 1986. Investigation of active tectonics: use of surficial earth processes. In Wallace, R.E. (eds.), Actice Tectonics. Studies in geophysiscs. Nat. Acad.Press, Washington, pp. 136-147.

Keller, E.A., and Pinter, N., 2002. Active tectonics: Earthquakes, Uplift and Landscape-Second Edition. Prentice Hall, New Jersey.

Kellerhals, R.M., Chruch, and Bray, D.I., 1976. Classification and analysis of river processes. Journ. Hydrual. DiV. Amer. Soc. Civil Eng. V. 102, pp. 813-829.

Khayari, R., Arian, M. and Ghorasi, M., 2009. Neotectonics of the south central Alborz drainage basin in NW Tehran, N. Iran. Journ. Applied Sciences, V. 9, pp. 4115-4126.

King, W., 1882. General sketch of the geology of Travancore State, Rec. Geol. Surv. India, V.15, part 2, pp. 93-102.

Kirby, E., Whipple, K.X., Tang, W. and Chen, Z., 2003, Distribution of active rock uplift along the eastern margin of the Tibetan Plateau: Inferences from bedrock channel longitudinal profiles: Journal of Geophysical Research, v. 108, no. B4, 2217 (doi: 10.1029/2001JB000861).

Kirby, L.C., Whipple, K.X., 2001. Quantifying differential rock uplift rates via stream profile analysis. Geology, V-29, pp. 415-418.

Knighton, D., 1998. Fluvial forms and processes, a new perspective. New York, Oxford University Press Inc.

Kolduk, W.S., 1968. On environment-sensitive grain-size parameters. Sedimentology, V.10, pp. 57-69.

Krishnaswamy, V, S., 1981. Status report of the work carried out by GSI in the framework of the International Geodynamic Project. In. Gupta, H.K., Delany, F.M., (eds.), Zagros-Hindu Kush-Himalaya Geodynamic Evolution. Amer. Geophys. Union, Washington DC., pp. 169-188.

Kukal, Z. (1971). Geology of Recent Sediments. Academic Press, London, 490p.

Langbein, W.B. 1964. Geometry of River channels. American Society of Civil Engineers, Proceedings, V.90, pp. 301 – 312.

Langbein, W.B., 1947. Topographic characteristics of drainage basins. USGS Water supply paper 968C , pp.127-157.

Lario, J., Spencer, C., Plater, A.J., Zazo, C., Goy, J.L. and Dabrio, C.J. (2002). Particle size characterisation of Holocene back-barrier sequences from North Atlantic coasts (SW Spain and SE England). Geomorphology, V.42, pp. 25-42.

Lario, J., Zazo, C., Plater, A.J., Goy, J.L., Dabrio, C., Borja, F, Sierro, F.J., Luque, L. (2000). Particle size and magnetic properties of Holocene estuarine deposits from the Donana National Park (SW Iberia): Evidence of gradual and abrupt coastal sedimentation, Z. Geomorphology., V.45 (1), pp. 33-54.

Larue, J.P., 2008. Effects of tectonics and lithology on long profiles of 16 rivers of the southern Central Massif border between the Aude and the Orb (France). Geomorphology 93, 343–367.

Lave´, J., and Avouac, J.P., 2001, Fluvial incision and tectonic uplift across the Himalayas of central Nepal: Journal of Geophys. Res., V. 106, pp. 26,561–26,591.

Legros, F., Cantagrel, J-M. and Devouard, B., 2000. Pseudotachylyte (Frictionite) at the Base of the Arequipa Volcanic Landslide Deposit (Peru): Implications for Emplacement Mechanisms. The Journ. of Geol., V. 108, pp. 601 – 611.

Leier, A.L, De Celles, P.G., and Pelletier, J.D., 2005, Mountains, monsoons and megafans, *Geology;* April 2005; V. 33; no. 4; p. 289–292.

Leonard, E.M., 2002, Geomorphic and tectonic forcing of late Cenozoic warping of the Colorado Piedmont: Geology, v. 30, p. 595–598.

Leopold, L.B, Wolman, M.G and Miller, J.P., 1964 Fluvial processes in geomorphology, W.H. Freeman & Co., London.

Lewis, D.W. 1984. Practical Sedimentology, Hutchinson Ross Publishing Company. Stoudsburg.

Lewis, W.V., 1945. Nickpoints and the curve of water erosion, Geological Magazine, V.82, pp. 256-266.

Long, A., Plater, A.J, Waller, M.P. and Innes, J.B. (1996). Holocene coastal sedimentation in the Eastern English channel: new data from the Romney Marsh region, United Kingdom. Mar. Geol., V.136, pp. 97-120.

Luo,W., 1998. Hypsometric analysis with GIS. Computers and Geosciences 24(8), pp.815-821.

Lykoudi, E. and Angelaki, M., 2004. The contribution of the morphometric parameters of a hydrographic network to the investigation of the neotectonic activity: An application to the upper Acheloos River. Bull. Geol. Soc. of Greece, V.35, pp. 1054-1092.

Mack, G. H., and Leeder, M. R., 1999. Climatic and tectonic controls on alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half graben, southern Rio Grande Rift , Journ. Sedimentary Research, V.69, pp. 635-652.

Mackin, J.H., 1948. Concept of a graded river. Geol. Soc. of America Bull. 59, pp.463-511.

Maddy, D., 1997. Uplift-driven valley incision and terrace formation in south England. Journ. of Quaternary Science, V.12, pp. 539-545.

Maddy, D., 2002. An evaluation of climate, crustal movement and base level controls on the Middle-Late Pleistocene development of the river Severn, U.K., Netherlands Journ. of Geosciences, V.81, pp. 329-338.

Manu, M.S. and Anirudhan, S., 2008. Drainage characteristics of Achenkovil River Basin, Kerala. Journ. Geol. Soc. India, V. 71, pp. 841-850.

Marple, R.T. and Talwani, P., 2003. Evidence of possible tectonic upwarping along the southern Carolina coastal planes from an examination of river morphology and elevation data. Geology, V.21, pp.651-654.

Mason, C.C. and Folk, R.L. (1958). Differentiation of beach, dune and aeolian flat environments by size analyses, Mustang Island, Texas, Journ. Sed. Petrology, V.28, pp. 211-226.

Mather, A.E., 2000. Adjustment of drainage network to capture induced base-level change: an example from the Sorbas basin, SE Spain. Geomorphology, V-34, pp. 271-289.

Mather, A.E., Stokes, M. and Griffiths, J.S., 2002. Quaternary landscape evolution: a framework for understanding contemporary erosion, SE Spain. Land Degradation and Management 13, pp.1-21.

Mather, P. and Doornkamp, J.C., 1970. Multivariate analysis in geography with particular reference to drainage basin morphometry. Transactions of the Institute of British Geographers, 51, pp. 163-187.

Maurya, D.M., Thakkar, M.G., Chamyal, L.S., 2003. Implications of transverse fault system on tectonic evolution of Mainland, Kachchh, western India, Current Science, V-85, No.5, pp. 661-667.

McCave, I.N. and Syvitski, J.P.M., 1991, Principles and methods of particle size analysis, In J.P.M. Syvitski (eds.), Principles, Methods, and Applications of Particle Size Analysis, New York, Cambridge University Press, p. 3-21.

McLaren, P. and Bowles, D., 1985. The effects of sediment transport on grain-size distributions. Journ. Sed. Petrol., V.55, pp. 457-470.

McLaren, P., 1981. An interpretation of trends in grain size measures. Journ. Sed. Petrol., V.51, no.2, pp. 611-624.

McLennan, S.M., and Taylor, S.R., 1982. Geochemical constraints on the growth of the continental crsut. Journ. Geology, V-90, pp. 347-361.

McManus, J. (1988). Grain size determination and interpretation. In: Tucker, M. (eds.), Techniques in Sedimentology. Blackwell, UK, pp. 63-85.

Melton, M.A., 1965. The geomorphic and palaeoclimatic significance of alluvial deposits in Southern Arizona. Journal of Geology, 73, pp. 1-38.

Merrits, D. and Vincent, K.R., 1989. Geomorphic response to coastal streams to low, intermediate and high rates of uplift, Mendocino triple junction region, northern California, Geol. Soc. of America Bull., V. 101, pp. 1373-1388.

Merritts, D.J., Vincent, K.R., Wohl, E.E., 1994. Long river profiles, tectonism and eustasy: a guide to interpreting fluvial terraces. Journ. Geophys.Res. V.99 (B7), pp. 14031-14050.

Mesa, L.M., 2006. Morphometric analysis of a subtropical Andean basin (Tucuman, Argentina). Environmental Geology, 50, pp. 1235-1242.

Miller JR., 1991. The influence of bedrock geology on knickpoint development and channel-bed degradation along down-cutting streams in south-central Indiana. Journal of Geology, V.9, pp. 591–605.

Miller, A.J. and Gupta, A., 1999. Varieties of fluvial form. Wiley, New York, p.521.

Miller, J.R., 1991. The influence of bedrock geology on knick point development and channel bed degradation along down-cutting streams in south central Indiana, Journal of Geology, V.99, pp.591-605.

Miller, V.C., 1953. A quantitative geomorphic study of drainage basin characteristics in the Clinch mountain area, Virginia and Tennessee. Technical report 3. Columbia University, New York: Office of Naval Research, Department of Geology.

Moglen GE, Bras R.L., 1995. The importance of spatially heterogeneous erosivity and the cumulative area distribution within a basin evolution model. Geomorphology 12:173–185.

Moglen, G. E., and Bras, R. L., 1995, The effect of spatial heterogeneities on geomorphic expression in a model of basin evolution: Water Resources Research, V. 31, p. 2613-2623.

Moiola, R.J. and Weiser, D. (1968). Textural parameters: an evaluation: Journ. Sed. Petrology, V.38, pp.45-53.

Montgomery, D.R., 1994, Valley incision and the uplift of mountain peaks: Journal of Geophysical Research, v. 99, pp. 13,913–13,921.

Morisawa, M E., 1959. Relation of morphometric properties to runoff in the Little Mill Creek, Ohio, drainge basin. Tech. rep. 17. Columbia University, Department of Geology, ONR, New York.

Morris, P.H., Williams, D.J., 1999. Worldwide correlations for aerial aqueous flows with exponential longitudinal profiles. Earth Surface Processes and Landforms, V-24, pp. 867-879.

Muller, K. and Talling, P.J., 1997. Geomorphic evidence for tear faults accommodating lateral propagation of an active fault-bend fold, Wheeler Ridge, California. Journal of Structural Geology 19, 397–411.

Muraleedharan, M.P. and Raman, M.S. (1989) Studies on the origin of the Palghat gap, GSI Unpub. Prog. Rep., F.S. 1983-86 Unpub. GSI report.

Mustafa, S. and Yusuf, M.I., 1999. A text book of hydrology and water resources (1st ed.). Abuja: Jenas Printing and Pub.Comp., chapter. 5.

Nag, S.K. and Chakraborty, S., 2003. Influence of rock types and structures in the development of drainage network in hard rock area. Journal of the Indian Society of Remote Sensing, 31 (1), pp. 25-35.

Nagender,N,B., Kunzendorf**,** H., and Plüger W.L., 2000. Influence of provenance, weathering, and sedimentary processes on the elemental ratios of the fine-grained fraction of the bedload sediments from the Vembanad Lake and the adjoining continental shelf, southwest coast of India. Journ. of Sed. Res. V.70 (5), pp.1081-1094.

Nair, K.K., 2007. Quaternary geology and geomorphology of coastal plains of Kerala, GSI, Geol. Surv. India., Spl. Pub. No.88. p.74.

Nair, M. M. N. and Ramachandran, K. K., 2000. Textural and trace elemental distribution in sediments of the Beypore estuary (SW coast of India) and adjoining innershelf. Indian Journ. Mar. Sci., V.3 (4), pp. 295-304.

Nair, M.M., 1885. Report on the photogeomorphological mapping of Nilambur valley, Malappuram district, Kerala, Unpub. Prog. Rep., Geol. Surv. of India.

Nair, M.M., 1990. Structural trendline patterns and lineaments of the Western Ghat, south of 13º latitude. Journ. Geol. Soc. India, V.35, pp. 99-105.

Nair, M.M., and Rao, M.R., 1980, Stratigraphic analysis of Kerala basin, GSI, Special Publication No.5, Geology and Geomorphology of Kerala.

Nair, M.M., and Rao, M.R., 1980, Stratigraphic analysis of Kerala basin, GSI, Special Publication No.5, Geology and Geomorphology of Kerala.

Nair, M.M., Vidyadharan, K.T., Pawar, S.D., Sukumaran, P.V. and Murthy, Y.G.K., 1975.The structural and stratigraphic relationship of the schistose rocks and associated igneous rocks of the Tellicherry - Manantoddy area, Cannanore district, Kerala, Ind. Mineralogist, V.16, pp. 89-100.

Nair, P.K.R. and Nair, E.V., 1980. Superimposed folding of Precambrian rocks around Ottappalam, Palghat district, Kerala, Proc. Sem. on Geology and Geomorphology of Kerala (Abstr.), Spec. Publ. No.5, Geol. Surv. of India, pp.15 – 18.

Nambiar, A.R., 1982. Report on the geological mapping and geochemical exploration for precious metals in parts of Attapadi area, Palghat district, Kerala. Unpub. Prog. Rep., Geol. Surv. of India.

Nanson, G.C. and Knighton, A.D., 1996. Anabranching rivers: Their cause, character and classification: Erath surface Process and Landforms, V.21, pp. 217-239.

Narayana, A.C. 2006. Rainfall variability and its impact on sediment discharge from the rivers of Kerala region, southwestern India. J. Geol. Soc. India., v. 68, pp. 549-558.

Narayanaswamy, S., 1976. Structure and tectonics of the Archaean crystalline rocks of Kerala. Proc. Sem. on Geology and Geomorphology of Kerala (Abstr.), Geol. Surv. of India, pp. 68-70.

Necea, D., Fielitz, W. and Matenco, L., 2005. Late Pliocene- Quaternary tectonics in the frontal part of the SE Carpathians: Insights from Tectonic Geomorphology, Tectonophysics, V.410, pp. 137-156.

Nesbitt, H.W., and Young, G.M. 1989. Formation and diagenesis of weathered profiles. Journ. Geology, V. 97 (2), pp. 129-147.

Nesbitt, H.W., Young, G.M., McLennan, S.M., and Reays, R.R., 1996. Effects of chemical weathering and sorting on the petrogenesis of siliciclastic sediments implication for provenance studies, Journ. Geology, V.104(5), pp. 525-542.

Newman, D.R, Vivoni, E.R and Groffman, A.R., 2006. Surface water–groundwater interactions in semiarid drainages of the American southwest, Hydrol. Process. V.20, pp.3371–3394.

Oguchi, T., 1997. Drainage density and relative relief in humid steep mountains with frequent slope failure. Earth Surface Processes and Landforms, V-22, pp. 107-120.

Ohmori, H., 1991. Change in the mathematical function type describing the longitudinal profile of a river through an evolutionary process, Journal of Geology, V.99, pp.97-110.

Ohmori, H., 1993. Morphometric evolution of Japan., in Geomorphology and Global Tectonics, Summerfield, M.A., (eds.) John Wiley, New York, pp. 147-166.

Okunishi, K., 1974. Characteristic erosional processes in granitic drainage basins as found in Tanakami mountain range, Shiga Prefecture, Japan, Bull. of Disaster Prevention Research Institute, Kyoto University, V.24, pp. 233-261.

Ollier, C., 1981. Tectonics and Landforms. Longman, London, p.321.

Ouchi, S., 1985. Response of alluvial rivers to slow active tectonics movement. Geological Society of American Bulletin, V. 96, 504–515.

Ouchi, S., 1985. Response of alluvial rivers to slow active tectonics movement. Geological Society of American Bulletin 96, pp. 504–515.

Passega, R., 1957. Texture as a characteristic of clastic deposition: Bull. Amer. Assoc. Petrol. Geol., V. 41, pp. 1952-1984.

Passega, R., 1964. Grain size representation by CM patterns as a geological tool: Journ. Sed. Petrology, V.34, pp. 830-847.

Passega, R., 1972. Significance of CM diagrams of sediments deposited by suspension, Sedimentology, V.24, pp. 723-733.

Passega, R., 2006, Significance of CM diagrams of sediments deposited by suspensions, Sedimentology, V.24, Issue.5, pp. 723-733.

Passega, R., and Byramjee, R., 2006, Grain-size image of clastic deposits, Sedimentology, V. 13, Issue. 3-4, pp.233-252.

Paul, A.W., 2002. Neotectonic deformation of alluvial valleys in Southern Arkansas and northern Louisiana, Gulf Coast Association of Geological Societies Transactions, V.52, pp.991-1002.

Pazzaglia, F.J., Gardner, T.W. and Merritts D.J., 1998. Bedrock fluvial incision and longitudinal profile development over geological timescales determined by fluvial terraces. In Rivers over Rock : Fluvial processes in bedrock channels, Tinkler and Wohl (Eds.). American Gephysical Union, Washington, pp. 207-236.

Pellegrini, L., Boni, P. and Carton, A., 2003. Hydrographic evolution in relation to neotectonics aided by data processing and assessment: some examples from the Northern Apennines (Italy). Quaternary International, 101-102, pp. 211-217

Peters, G. And Van Balen, R.T., 2007. Pleistocene tectonics inferred from the fluvial terraces of the northern Upper Rhine Graben, Germany. Tectonophysics, V.430, pp.41-65.

Petrovszki, J., 2009. Morphometric analysis of the Koros drainage basin (Hungary/Romania) using historical topographic maps. Geophysical Research Abstract V. II.

Pettijohn, F.J., 1975. Sedimentary rocks. New York, Harper & Row, p. 628, 718.

Pike, R.J. and Wilson, S.E., 1971. Elevation- relief ratio, hypsometric integral and geomorphic area-altitude analysis. Geol. Soc. of America Bull., V. 82, pp. 1079-1084.

Pillay, K.R. and Koshy John, 2002. Preliminary investigation to locate gold lodes in the Punnapuzha – Chaliyarpuzha sector of the Nilambur valley, Malappuram District, Kerala, (P-I stage), Unpub. GSI progress report.

Pinter, N., 1986. Applications of tectonic geomorphology for deciphering active deformation in the Pannonian Basin, Hungary, Occasional Papers of the Geological Institute of Hungary, volume 204, pp. 45-51.

Pinter, N., 1996. Exercises in Active tectonics: Earthquakes and landscape. Prentice Hall, New Jersey.

Pohn, H.A., 1983. The relationship of joints and stream drainage in flat lying rock of south central New York and northern Pennsylvania. Zeitschrift fur Geomorphologie Neuefolge, V.27., pp. 375-384.

Price, J.R., and Velbel, M.A., 2003. Chemical weathering indices applied to weathering profiles developed on heterogeneous felsic metamorphic parent rocks, Chemical Geology, V-201, pp. 397-416.

Rachna, R., 2007. Strike-slip faulting inferred from offsetting of drainages: Lower Narmada basin, western India, Journ. Earth Syst. Sci., V.116(5), pp. 413-421.

Rachna, R., Maurya, D.M. and Chamyal, L.S., 1999. Evolution of Mahi drainage basin during quaternary: A morphometric approach, Gondwana Geol. Magz., Spl, V.4, pp.131-139.

Radhakrishna, B.P., 1992. Cauvery: Its geological past, Journ. Geol. Soc. Ind., V.40, p.12.

Radhakrishna,T., Gopakumar, K., Murali, A.V. and Mitchell J.G., 1991. Geochemistry and petrogenesis of Proterozoic mafic dykes in north Kerala, southwestern Indian shield: primary results. Precambrian Research, v. 9, pp. 235-244.

Radhakrishnan, K., 2008, Major thrust areas of Remote Sensing and GIS application in Geosciences-An overview, Journ. Geological Society of India, V.71, pp.153-170.

Radoane, M., Radoane, N and Dumitriu, D, 2003. Geomorphological evolution of longitudinal river profiles in the Carpathians. Geomorphology 50, pp.293-306.

Rajan, T.N. and Anil Kumar, P.S (2005). Geology and Mineral Resources of Kerala, Geol.Surv. Ind. Misc. Pub. No.30 Part. IX, 2nd Revised Edition.

Ramirez-Herrera, M.A., 1998. Geomorphic assessment of active tectonics in the Acambay Graben, Mexican Volcanic Belt. Earth Surface Process and Landforms, V. 23, pp. 317-332.

Ramkumar, M., Sudha Rani, P., Gandhi, M.S., Pattabhi Ramayya, M., Rajani Kumari, V., Bhagavan, K.V.S. and Swamy, A.S.R., 2000. Textural characteristics and depositional sedimentary environments of the modern Godavari Delta. Journ. Geol. Soc. India., V.56, pp.471-487.

Rao, D.P., 1984. Geomorphological techniques in groundwater exploration. Proc. Int. Workshop on rural hydrology and hydraulics in Fissured basement zones, Silver Jubilee Year, Dept. of Erath Sciences, University of Roorkee, pp.29-37.

Rao, VP and Wagle, BG. 1997. Geomorphology and surficial geology of the western continental shelf and slope of India: A review. Current Science, 73, 330- 350.

Reid, L.M. and Dunne, T., 1996. Rapid evaluation of sediment budget. Catena Verlag GMBH, Reiskirchen, Germany.

Reis, S., Yalcin, A., Nisanci, R., and Yomralioglu, T., 2007. Geology and Geomorphology of Gumushane area, Northeatern Turkey using digitally enhanced satellite images and Geographical Information System, Journ. Geological Society of India, V.69, pp. 261-273.

Reneau, S.L., 2000. Stream incision and terrace development in Frijoles Canyon, Bandelier National Monument, New Mexico, and the influence of lithology and climate. Geomorphology 32,171–193.

Rhea, S., 1993. Geomorphic observations of the rivers in the Oregon coast range from a regional reconnaissance perspective. Geomorphology, V-6, pp.135-150.

Ribolini, A. and Spagnolo, M., 2008. Drainage network geometry versus tectonics in the Argentera massif (French-Italian Alps). Geomorphology, V-93, pp. 253-256.

Richardson, W.R. and Thorne, C.R., 2001. Multiple thread flow and channel bifurcation in a braided river: Brahmaputra-Jamuna River, Bengladesh. Geomorphology, V-38, pp.185-196.

Ritter, D.F., Kochel, R.C. and Miller, J.R., 2002. Process Geomorphology (4^{th} Ed.), McGraw-Hill, New York. 560p.

Riviere, A., 1977. Methodes granulometriques. Techniques et interpretations. Masson, Paris, 170p (translated version).

Rockwell, T.K., Keller, E.A. and Johnson, D.L., 1984. Tectonic geomorphology of alluvial fans and mountain front near Ventura, California. In: Morisawa, M., Hack, J.T. (Eds.), Tectonic Geomorphology — Proceedings of the 15th Annual Binghampton Geomorph. Symp. Sep. 1984. Allen and Unwin, Boston, pp. 183–208.

Roe, G.H., Montgomery, D.R., Hallet, B., 2002. Effects of orographic precipitation variations on the concavity of steady state river profiles. Geology, V-30, pp. 143-146.

Rosgen, D., 1994, A Classification of Natural Rivers, Catena, V.22, pp. 169-199.

Rosgen, D., 1996. Applied river morphology. Wildland Hydrology. Pagosa springs, Colarado.

Rosgen, D.L., 1999. Development of a river stability index for clean sediment TMDL's. In. Proceedings of Wildland hydrology, Olsen, D.S. and Potyondy, J.P. (eds.) AWRA, Montanna, pp. 25-36.

Ruhe, R.V., 1975. Geomorphology, geomorphic processes and surficial geology. Houghlam Mifflin Co., pp. 87-97.

Rust, B.R., 1978. Depostional models for braided alluvium, in Miall, A.D., ed., Fluvial sedimentology, Memoir 5. Canadian Society of Petroleum Geologists, pp. 605-625.

Sahu, B.K., 1964. Depositional mechanisms from the size analysis of clastic sediments, Journ. Sed. Petrology, V. 34, pp. 73-83.

Sahu, B.K., 1982. Multigroup discrimination of river, beach and dune sands using roundness statistics. Journ. Sed. Petrology, V.52, no.3, pp.779-784

Sahu, B.K., 1983. Multigroup discrimination of depositional environments using size distribution statistics. Indian Journ. Earth Sci., V.10, pp. 20-29.

Sakthivel. R., Manivel.M., Jawahar-Raj. N., Pugalanthi, V. and KumaranRaju D., 2006. Role of Remote Sensing In Geomorphic Mapping: A Case Study from Kalrayan Hills, Parts of Eastrn Ghats, Tamil Nadu. Indian journal of geomorphology volume 112, pp.101-110.

Salvany, J.M., 2004. Tilting neotectonics of the Guadiamar drainage basin, SW Spain. Earth Surface. Proc. and Landforms, V. 29, pp. 145-160.

Sarangi, A., Bhattacharya, A.K., Singh, A., Singh, A.K., 2001. Use of Geographic Information System (GIS) for determination of erosion status of watersheds. Indian Journ. of Soil Conservation, V.29 (3), pp. 190-195.

Sawarkar, A.R., 1965. Report on the investigation of gold bearing alluvial gravels of Nilambur Valley, Kozhikode district (Wayanad Gold field), Kerala State, Unpub. Prog. Rep. Geol. Surv. of India.

Scheidegger, A.E. and Ai, N.S., 1986. Tectonic processes and geomorphical design. Tectonophysics, V.126, pp. 285-300.

Scheidegger, A.E., 1987. Systematic Geomorphology, Springer-Verlag Pub.

Scheidegger, A.E., 1991. Theoretical geomorphology, Springer, Berlin.

Scheidegger, A.E., 2004. Morphotectonics, Springer-Verlag, Berlin, 197p.

Schlunegger, F. and Hinderer, M., 2001. Crustal uplift in the Alps: why drainage pattern matters. Terra Nova 13 (6), 425–432.

Schumm, S. A., 1981. Evolution and response of fluvial system: Sedimentological implications. Soc. Economic Palaeontologists & Mineralogist Spec. Pub.

Schumm, S.A. and Khan, H.R., 1972. Experimental study of channel patterns. Geol. Soc. of Amer. Bull., V.85, pp.1755-1770.

Schumm, S.A. and Lichty, R.W., 1965. Time, space and causality in geomorphology. Amer. Journ. of Science, V.263, pp.110-119.

Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological Society of America Bulletin, 67, pp. 597-646.

Schumm, S.A., 1963. A tentative classification of river channels. U.S. Geol. SurV. Circular, V.447, 10p.

Schumm, S.A., 1977. Applied fluvial geomorphology. Hails, J.R (Eds.) Applied geomorphology. Elsevier Scientific Publishing Co., pp. 119-156.

Schumm, S.A., 1979. Geomorphic thresholds: the concept and its applications. Transactions of the Institute of British Geographers, New Series 4, pp. 485-515.

Schumm, S.A., 1985. Explanation and extrapolation in geomorphology: seven reasons for geologic uncertainty, Transactions, Japanese Geomorphological Union, V.6(1), pp. 1-18.

Schumm, S.A., 1986. Alluvial river response to active tectonics, Studies in Geophysics:

Schumm, S.A., Dumont, J.F. and Holbrook, J.M., 2000. Active tectonics and alluvial rivers, Cambridge University Press, Cambridge, p.401.

Schumm, S.A., Mosley, M.P., Weaver, W.E., 1987. Experimental fluvial geomorphology, John Wiley and Sons, New York, 413p.

Seeber, L and Gornitz, V., 1983. River profiles along the Himalayan arc as indicators of active tectonics., Tectonophysics, V-92, pp.335-367.

Seidl, M.A., Dietrich, W. and Kirchner, J., 1994. Longitudinal profile development into bedrock: An analysis of Hawaiian channels: Journal of Geology, V. 102, p. 457-474.

Seidl, M.A. and Dietrich, W.E., 1992. The problem of channel erosion into bedrock: Catena Supplement, v. 23, p. 101–124.

Seidl, M.A., and Dietrich, W.E., 1992. The problem of channel erosion into bedrock: Catena Supplement, V. 23, p. 101–124.

Seidl, M.A., Finkel, R.C., Caffee, M.W., Hudson, G.W. and Deitrich, W.E., 1997. V.22, pp 195-209.

Senadeera K.P.G.W., Piyasiri,S and Nandalal, K.D.W (-) The evaluation of morphometric characteristics of Kotmale reservoir catchment using GIS as a tool, Sri Lanka, The Int Arc of Photogrammetry, Remote Sensing and Spatial Information Sciences, V.34, Part XXX.

Seralathan P. and Padmalal, D., 1994. Textural studies of the sediments of Muvattupuzha river and central Vembanad estuary, Kerala, Journ. Geol. Soc. India, V.43, pp.179-190.

Shen, H.W. and Julien, P.Y., 1993. Erosion and sediment transport. Handbook of Hydrology, McGraw-Hill, Inc. Chapter 12.

Sherman, L.K., 1932. The relation of hydrographs of runoff to size and character of drainage basins, Transactions of American Geophysical Union, V.13, pp. 332-339.

Shukla, U.K., Singh, I.B., Sharma, M. and Sharma, S., 2001, A model of alluvial megafan sedimentation: Ganga megafan: Sedimentary Geology, V. 144, pp. 243–262.

Siemers, C.T. (1976). Sedimentology of the Rocktown channel sandstone, upper part of the Dakota Formation (Cretaceous), Central Kansans: Journ. Sed. Petrology, V.46, pp.97-123.

Silva, P.G., Goy, J.L., Zazo, C. and Bardaji, T. 2003. Fault generated mountain fronts in southeast Spain: geomorphologic assessment of tectonic and seismic activity. Geomorphology, V.50, pp. 203-225.

Singh, H., Parkash, B. and Gohain, K., 1993. Facies analysis of the Kosi megafan deposits: Sedimentary Geology, V. 85, pp. 87–113.

Singh, O, Sarangi, A. and Sharma, M.C., 2008. Hypsometric integral estimation methods and its relevance on erosion status of north-western Lesser Himalayan watersheds, Water Resource ManageV-22, pp. 1545-1560.

Sinha R., 2002. Hypsometry and landform evolution: A case study in the Banas drainage basin, Rajasthan with implication for Aravalli uplift, Journ. Geol. Soc. Ind. V.60, pp. 7-27.

Sinha R., Jain V., Prasad Babu G., and Ghosh S., 2005a Geomorphic characterization and diversity of the fluvial systems of the Gangetic plains. Geomorphology, 70/3-4 pp. 207-225.

Sinha R.S, 2002. Hypsometry and landform evolution: A case study in the Banas drainage basin, Rajasthan with implication for Aravalli uplift, Journ. Geol. Soc. Ind. V.60, pp. 7-27.

Sinha-Roy, S and Mathai, T., 1979. Development of western continental margin of India and platform uplift as related to geology and tectonics of Kerala. *In*: Workshop on status, problems and programmes in Indian shield, pp. 235-271.

Sinha-Roy, S., 1980. Structural evolution of the Precambrian crystalline rocks in parts of Trivandrum and Quilon districts, Kerala, Prof. Paper No.7, CESS, p.25.

Sinha-Roy, S., 2001. Neotectonically controlled catchment capture: An example from the Banas and Chambal drainage basins, Rajasthan.Curr. Sci. V. 80 (2), pp. 293-298.

Sinha, R. and Friend, P.F., 1994. River systems and their sediment flux, Indo-Gangetic plains, northern Bahir, India: Sedimentology, V. 41, pp. 825–845.

Sinha, R. and Jain, V., 1998. Flood hazards of north Bihar rivers, Indo-Gangetic plains, In: Kale, V.S (eds.), Flood studies in India, GSI memoir, V.41, pp.27-52.

Sinha, R., Gibling, M.R., Jain, V. & Tandon, S.K., 2005b Sedimentology and avulsion patterns of the anabranching Baghmati river in the Himalayan foreland basin, India. In: Fluvial Sedimentology (eds. Blum, M. and Marriott, S.), Special publication of the International Association of Sedimentologists, 35, 181-196.

Sinha, R., Jain, V., Prasad Babu, G. and Gosh, S., 2005. Geomorphic characterization and diversity of the fluvial systems of the Gangetic plains, Geomorphology, V.70, pp. 207-225.

Sinha, R., Vikrant Jain, Prasad Babu, G. and Gosh, S., 2005. Geomorphic characterization and diversity of the fluvial systems of the Gangetic plains, Geomorphology, V.70, pp. 207-225.

Sinha, S.K. and Parker, G., 1996, Causes of concavity in longitudinal profiles of rivers: Water Resources Research, V. 32, pp. 1417–1428.

Sklar, L. and Dietrich, W.E., 1998. River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply, In: K.J. Tinkler and E.E. Wohl (Eds.), Rivers over Rock: Fluvial Processes in Bedrock Channels, Geophysical monograph, V.107, AGU, Washington, D.C., pp.237-260.

Slingerland, R., Willet, S.D., and Hovius, N., 1998. Slope-area scaling as a test of fluvial bedrock erosion laws: Eos (Transactions, American Geophysical Union), V. 79, Fall meeting supplement, F358.

Slingerland, R.L. and Snow, R.S., 1987. Mathematical modeling of graded river profiles: Journal of Geology, v. 95, p. 15–33.

Smart, J.S and Surkan, A.J., 1967. The relation between mainstream length and area in drainage basins. Water Resource Research. V.3 (4), pp.963-974.

Smith, K.G., 1950. Standards for grading texture of erosional topography. American Journal of Science, 248, pp.655-668.

Snow, R.S. and Slingerland, R.L., 1987. Mathematical modeling of graded river profile. The Journ. of Geology, V. 95(1), pp. 15-33.

Snow, R.S. and Slingerland. R.L., 1990. Stream Profile Adjustment to Crustal Warping: Nonlinear Results from a Simple Model, Geology, 98, pp. 699-708

Snyder, N.P., Whipple, K.X., and Tucker, G.E., Merritts, D.J., 2000. Landscape response to tectonic forcing: DEM analysis of stream profiles in the Mendocino triple junction, northern California, Geol. Soc. Amer. Bull., V-112, pp. 1250-1263.

Snyder, N.P., Whipple, K.X., Tucker, G.E. and Merritts, D.J., 2003, Channel response to tectonic forcing; field analysis of stream morphology and hydrology in the Mendocino triple junction region, northern California: Geomorphology, V. 53, pp. 97-127.

Socci, A. and Tanner, W.F., 1980. Little-known but important papers on grain-size analysis. Sedimentology, V.27, pp. 231-232.

Solohub, J.T. and Klovan, J.E. (1970). Evaluation of grain-size parameters in lacustrine environments: Journ. Sed. Petrology, V.40, pp. 81-101.

Soman, K., 2002, Geology of Kerala, Geol. Soc. India Pub. p. 335.

Soman, K., Thara, K.G., Arakelyants, M.M. and Golubyev, V.N., 1990. Mineral ages of pegmatites from the Palghat Gap region in Kerala and their tectonic significance, Journ. Geol. Soc. India, V.35, pp. 82-86.

Sreedevi, P.D., Owals, S., Khan, H.H. and Ahmed, S., 2009. Morphometric analysis of a watershed of South India using SRTM data and GIS. Journal of Geological Society of India, 73, pp. 543-552.

Sreedevi, P.D., Subrahmanyam, K. and Ahmed, S., 2004. The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. Environmental Geology, 47, pp. 412-420.

Starkel, L., 2003. Younger Dryas-Preboreal transition documented in the fluvial environment of Polish rivers. Global and Planetary Change 35(1-2): 157-167, DOI 10.1016/S0921-8181(02)00133-9.

Stewart, H.B. Jr., 1958. Sedimentary reflections of depositional environment in Sanmiguel lagoon, Baja California, Mexico. Bull. Amer. Assoc. Petrol. Geol., V.42, pp.2567-2618.

Stock, J. D. and Montgomery, D. R., 1999. Geologic constraints on bedrock river incision using the stream power law: Journal of Geophysical Research- Solid Earth, V. 104, no. B3, p. 4983-4993

Stokes, M., Mather, A.E. and Harvey, A.M., 2002. Quantification of river capture induced base-level changes and landscape development, Sorbas Basin, SE Spain. In: S.J. Jones and L.E. Frostick (Editors),Sediment Flux to Basins, Causes, Controls and Consequences. Geological Society, London Special Publication 191, pp. 23-35.

Strahler, A.N., 1952. Hypsometric analysis of erosional topography, Geol. Soc. Amer. Bull. 63, pp. 1117-1142.

Strahler, A.N., 1954. Statistical analysis in geomorphic research. Journal of Geology, 62, pp. 1-25.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Transactions of American Geophysics Union, 38, pp. 913-920.

Strahler, A.N., 1958. Dimensional analysis applied to fluvially eroded landforms. Geological Society of America Bulletin, 69, pp. 279-300.

Strahler, A.N., 1964. Quantitative geomorphology of drainage basin and channel networks. In: V.T. Chow, ed. Handbook of applied hydrology. New York: McGraw Hill Book, pp. 4-76.

Subrahmanyam, C. and Chand, S., 2006. Evolution of the passive continental margins of India- a geophysical appraisal. Gondwana Res., V.10, pp. 167-178.

Sugden, D.E., Summerfield, M.A., and Burt, T., 1997. Linking short-term processes and landscape evolution. Earth Surface Processes and Landforms 22, 193–194.

Summerfield, M.A., 1991. Global geomorphology: An introduction to the study of landforms. Prentice Hall, 537p.

Suresh, N., Bagati, T.N., Kumar, R., Thakur, V.C., 2007. Evolution of Quaternary alluvial fans and terraces in intermontane Pinjaur dune, Sub Himalaya, NW India. Interaction between tectonics and climate change. Sedimentology, 54 (4), doi: 10.111/J.1365 – 3091.2007. 00861. X, 809-833.

Suresh, R., 2000, Soil and water conservation engineering 3rd Ed. 24, Watershed concept and management, pp.785-813.

Sylvester, A.G. and Smith, R.R., 1976. Tectonic tranpression and basement-controlled deformation in San Andreas Fault zone, Salton trough, California. Amer. Assoc. Petrol. Geol. Bull., V.60, pp. 2081-2102.

Tanner, W.F., 1958. The zigzag nature of Type I and Type II curves. Journ. Sed. Petrol., V.28, pp. 372-375.

Tanner, W.F., 1964. Modification of sediment size distributions: Journ. Sed. Petrol., V.34, pp. 156-164.

Tanner, W.F., 1991. Suite statistics: The hydrodynamic evolution of the sediment pool. In: Syvitski, J.P.M. (eds.), Principles, Methods and Applications of Particle Size Analysis. Cambridge Univ. Press, Cambridge, pp. 225-236.

Thomas J., Joseph, S. and Thrivikramaji, K.P. 2010. Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India, International Journ. of Digital Earth,

Thornbury, W.D., 1969, Principles of Geomorphology, John Wiley &Sons, pp. 271-274.

Thorne, C.R., 2002, Geomorphic analysis of large alluvial rivers. Geomorphology, V.44, pp. 203-219

Thrivikramji, K.P., 2008. Western Ghats, neotectonics and Kerala black sand placers: An appraisal. Field workshop, IGCP 514, pp.88-95.

Tooth, S. and McCarthy, T.S., 2004. Anabranching in mixed bed-rock alluvial rivers: the example of the Orange River above Augrabies Falls, North Cape Province, South Africa. Geomorphology, V-57, pp. 235-262.

Tripathi, J.K. and Rajamani, V., 1999. Geochemistry of the loessic sediments on Delhi ridge, eastern Thar desert, Rajasthan: implications for exogenic processes, Chemical Geology, 155 pp. 265-278.

Tucker, G.E. and Slingerland, R., 1997, Drainage basin responses to climate change, Water Resources Research, V. 33, pp. 2031–2047.

Tucker, G.E., Whipple, K.X., 2002. Topographic outcomes predicted by stream erosion models: Sensitivity analysis and intermodal comparison. Journ. Geophysical Reserach, V-107 (B9), pp.2179-2194.

Twidale, C.R., 2004. River patterns and their meaning, Earth Sci. Rev., V.67, pp. 159-218.

Tyagi, A.K., Chaudhary, S., Rana, N., Sati, S.P., Juyal, N., 2009. Identifying areas of differential uplift using steepnex index in the Alaknanda basin, Garhwal Himalaya, Uttarakhand, Current Sci., V-97 (10), pp. 1473-1477.

Vaidyanadhan, R, 1967. An outline of the geomorphic history of India south of N latitude 18º, Seminar on the geomorphological studies in India, Dept. of Applied Geology, University of Saugar., pp. 121-130.

Vaidyanadhan, R., 1977. Recent advances in geomorphic studies – A review, Ind. Journ. Earth Sc., pp. 13-35.

Valdiya and Narayana, A.C., 2007. River response to neotectonics in central and southern Kerala, India, Journ. Geol. Soc. of India, V.70, pp. 427-433.

Valdiya, K.S. and Kotlia, B.S., 2001. Fluvial geomorphic evidence of Late Quaternary reactivation of a synclinally folded nappe in Kumaun Lesser Himalaya. Journ. Geol. Soc. India, V.58, pp. 301-317.

Valdiya, K.S., 1993. Uplift and geomorphic rejuvenation of the Himalaya in the Quaternary Period. Curr. Sc., V.64, pp. 873-885.

Valdiya, K.S., 1998. Late Quaternary movements and landscape rejuvenation in southeastern Karnataka and adjoining Tamilnadu in southern Indian Shield. Journ. Geol. Soc. Ind., V.51, pp. 139-166.

Valdiya, K.S., 2001a. River respone to continuing movements and the scarp development in central Sahyadri and adjoining coastal belt. Journ. Geol. Soc. India, V.51, pp.139-166.

Valdiya, K.S., 2001b. Tectonic resurgence of the Mysore plateau and surrounding regions in cratonic Southern India. Curr. Sci., V.57, pp.13-30.

Valdiya, K.S., and Narayana, A.C., 2007. River response to neotectonic activity: Example from Kerala, India, Journ. Geol. Soc. Ind., V.70, pp. 427-443.

Valdiya, K.S., Rajagopalan, G., 2000. Large palaeolakes in Kaveri basin in Mysore Plateau: Late Quaternary fault reactivation. Current Science, V. 78 (9), pp. 1138– 1142.

Valia, H.S. and Cameron, B., 1977. Skewness as a palaeoenvironmental indicator. Journ. Sed. Petrol., V.47(2), pp. 784-856.

van den Berg, M.W. & Van Hoof, T., 2001. The Maas terrace sequence at Maastricht, SE Netherlands: evidence for 200 m of late Neogene and Quaternary surface uplift. In: Maddy, D., Macklin, M.G. & Woodward, J.C. (eds): River Basin Sediment Systems: Archives of Environmental Change, Balkema (Rotterdam): pp. 45-86.

van der Beek, P., Champel, B. and Mugnier, J.L., 2002. Control of detachment dip on drainage development in regions of active fault propagation folding. Geology V.30, pp.471–474.

van Laningham, S., Meigs A., and Goldfinger C., 2006, The effects of rock uplift and rock resistance on river morphology in a subduction zone forearc, Oregon, USA: Earth Surface Processes and Landforms, V. 31, pp. 1257-1279.

Varadarajan, K., and Nair, M. K., 1978, Stratigraphy and structure of Kerala basin. Journ. Geol. Soc. Ind. V.19, pp. 217-220.

Verstappen, H. Th., 1983. Applied geomorphology - geomorphological surveys for environmental development. New York: Elsevier, pp. 57-83.

Vetel, W., Le Gall, B. and Johnson, C., 2004. Recent tectonics in the Turkana Rift (North Kenya): an integrated approach from drainage network, satellite imagery and reflection seismic analyses. Basin Research, V.16, pp.165–181.

Virdi, N.S., Philip, G. and Bhattacharya, S., 2006. Netectonic activity in the Markanda and Bata river basins, Himachal Pradesh, NW Himalaya: A morphometric approach. Int. Journ. of Remote Sensing, V. 27(10), pp. 2093-2099.

Visher, G.S., 1969. Grain size distributions and depositional processes. Journ. Sed. Petrology, V.39, pp.1074-1106.

Vittala, S.S., Govindaiah, S. and Gowda, H.H., 2004. Morphometric analysis of the sub-watersheds in the Pavagada area of Tumkur district, South India using remote sensing and GIS techniques. Journ. Indian Soc. Remote Sensing, 32 (4), pp.351-361.

Vivoni, E.R., Teles, V., Ivanov, V.Y., Bras, R.L., Entekhabi, D., 2005. Embedding landscape process into triangulated terrain models. International Journ. of Geographical Information Science, V.19, pp. 429-457.

Waugh, D., 1995, Geography: An integrated approach. 2nd Ed. Chapter-3, Morphometry of drainage basins, pp.51-62.

Wells, S., Bullard, T., Menges, T., Drake, P., Karas, P., Kelson, K., Ritter, J. And Wesling, J., 1988. Regional variations in tectonic geomorphology along segmented convergent plate boundary, Pacific Costa Rica. Geomorphology, V.1, pp.239-265.

Whipple, K.X. and Tucker, G.E., 1999. Dynamics of the stream-power river incision model: implications for height limits of mountain ranges, landscape response timescales, and research needs: Journ. of Geophys. Res., V. 104, pp. 17,661–17,674.

Whipple, K.X., 2001. Fluvial landscape response time: How plausible is steady-state denudation. Amer. Journ. of Sci., V. 301, pp. 313–325.

Whipple, K.X., 2004. Bedrock rivers and the geomorphology of active orogens: Annual Reviews of Earth and Planetary Sci., V. 32, pp. 151–185.

Whittaker, A.C., Cowie, P.A., Attal., M., Tucker, G., Roberts, G.P., 2007. Bedrock channel adjustment to tectonics forcing: implication for predicting river incision rates. Geology, V-35, pp.103-106.

Wildeman, T.R. and Condie, K.C., 1973. Rare earths in Precambrian sediments. Geochim, Cosmochim. Acta., V. 37, pp. 439-453.

Wobus, C., K. Whipple, E. Kirby, N. Snyder, J. Johnson, K. Spyropolou, B. Crosby und D. Sheehan., 2006. Tectonics from topography: Procedures, promise and pitfalls. In: Willett, S. D., N. Hovius, M. T. Brandon und D. Fisher (Hrsg.): Tectonics, climate, and landscape evolution: Geological Society of America Special Paper 398, pp. 55-74.

Yanagida, M., 1991. A dynamic approach to the formation of fluvial terraces. Komazawa Journal of Geography 27, pp. 1–75.

Zăvoianu, I., 1985. Morphometry of Drainage Basins. Developments in Water Science 20. Elsevier, Bucharest - Romania, 238 p.

Zernith E.R., 1932. Drainage patterns and their significance. Journ. Geology. V. 40, pp. 498-521.

Zuchiewicz, W., 1991. On different approaches to neotectonics: a Polish Carpathians example. Episodes, V.14, pp. 116–124.