2.1 Introduction

Kerala has many interesting geologic features in which exposures of exhumed lower continental crust, amphibolite–granulite transition zone; classical exposures of laterite, etc are important ones. The Tertiaries and the recent sediments of Kerala coasts rest directly upon the Archaean crystalline complex consisting of khondalite, leptynite, Charnockite, and mica-hornblende gneisses. The Tertiary formations include Warakalli deposits of variegated sandstones and clays, white plastic clays, carbonaceous clays, associated seams of lignite, and the Quilon formation consisting fossiliferous limestone intercalated with thick beds of variegated sands and carbonaceous clays (Menon, 1966). Coastal regions are blanketed by the mudflats composed of clays, silty clays, and shell fragments. The most prominent of the mud flat lies in the south eastern side of the Vembanad Lake (Narayana et al., 2008).

The central Kerala region hosts geologic features such as coastal alluvium, Quilon and Warkallai formations, and geomorphic features such as backwater systems backed by lagoons, barrier-island complexes, tidal mudflats etc. The
central coast of Kerala is remarkably straight and is believed to have originated as a result of faulting during the late Pliocene (Krishnan, 1968). The central Kerala coast is considered as the ‘haffnehrung’ type of coast with lagoons and backwaters (Ahmad, 1972). The coast contains vast stretches of sandy flats interspersed with lagoons, estuaries, and low lying reclaimed beds. Forty one west flowing rivers, most of them of the type of mountain streams, flow from Western Ghats into backwaters and lagoon that skirts the coasts. Backwaters connected to the sea inlets, are influenced by the movement of sediment straight trending in a NNW-SSE direction. On the landward side of the coast, there is a series of laterite rocks backed by alluvial deposits (King, 1882; Menon, 1974).

2.2 Geology

Kerala State is an integral part of the peninsular shield bounded by the Western Ghats on the east and Arabian Sea on the west. It is mainly occupied by four major rock units - (i) Precambrian crystalline rocks - which include charnockites, garnet biotite gneisses, hornblende gneisses, khondalites, leptynites, cordierite bearing gneisses and other unclassified gneisses which occupy a considerable area of Kerala. (ii) Tertiary sedimentary rocks – which unconformably overlie the Precambrians which extend as a narrow belt along the major part of Kerala coast, comprises continental (Warkalli beds) and marine (Quilon beds) facies. Carbonaceous clays with lignite / coal seams, china clays and friable sandstones forms the continental facies and the marine facies composed of sandstones and carbonaceous clays with thin bands of fossiliferous limestones (Poulouse and Narayanaswami, 1968) (iii) Laterites – are the third major litho-unit covering about 60 % of the surface of Kerala and (iv) Recent to sub recent sediments extending from Kasaragod in the north to Capecomorin in the south, which include fringes of coast parallel sand bars, sandy flats, alluvial sands and lacustrine deposits (Brunn and Nayak, 1980).
Tertiary rocks in the Quilon-Warkal area are divided into (i) Quilon beds - consisting of limestone and calcareous clay and (ii) Warakalli beds - made of sandstone and clay with lignite (King, 1882). King also states that the Warakalli beds must then be of the same age, or if different conditions of deposition and apparent overlap go for anything, of perhaps a later age. Jacob and Sastri (1952) found that the calcareous beds exposed in Quilon area continue subsurface into Chavara and their age is Burdigalian. Narayanan (1958) opined that the Warkalli and Quilon beds are different facies of rocks but more or less of same age. Desikachar and Subramanyan (1959) suggest that the Quilon and Warakalli beds continue far into the north up to Kainakari and Ambalapuzha based on their reconnaissance geological mapping of the sedimentary terrain and study of shallow boreholes of coastal Kerala.

Varadarajan and Balakrishnan (1976) suggested that the laterite along the coastal area formed part of the continental shelf and their occurrence as terraces of different elevations could be due to Neogene and Quaternary uplift. Desikachar (1976) identified four formations as (i) Mayyanad Formation, (ii) Azheekal Formation, (iii) Ambalapuzha Formation and (iv) Kainakari Formation. Azheekal and Ambalapuzha formations are roughly equivalent to Quilon and Warkalli beds. Desikachar (1976) highlighted the hydrocarbon prospects of offshore Kerala Basin. Murty et al. (1976) had the opinion of greater sedimentary thickness in northwest of Alleppey and Ponnani on account of the extension of the Achankovil shear zone and Palghat gap faults into the basin. Bose et al. (1976) suggested that the deepest part of the sedimentary basin is between Chellanam and Chavara, and around Alleppey the thickness of sediments may be about 600 m. Rao and Datta (1976) opined that the Wrakalli beds could be the continental equivalents of Quilon beds, a view expressed earlier by Narayanan (1958) and doubted by King (1882).

Lineaments and fractures are the major features cutting across the Precambrian terrains of Kerala through which major rivers of Kerala like
Periyar, Achankovil, Pamba are flowing. Nair (1987) reports that among lineaments identified over the Kerala region, the fault lineament parallel to the coast, as well as at right angle to it is found to be neotectonically active and are controlling the configuration of shoreline primarily. The major shearzones of Kerala region are: E-NE trending Nilambur-Attapady-Kozhikode shearzone, E-W trending Achankovil shearzone, Periyar-Thamraparni shearzone, NNW trending Edamalayar shearzone, and SE trending Moyar-Bavali-Mercara shearzone. Minor fracture zones are widely reported all over the state by Geological Survey of India (1995). Central Kerala region consists of basic intrusive rocks, charnockites, khondalites, meta-sediments, Quilon and warakalli formations, laterites, and alluvium (Fig 2.1).

![Figure 2.1: Map showing the geology of central Kerala region, and the rivers debouching into the lagoon and the adjoining continental shelf. R1, R2, R3, R4, R5, R6, R7 and R8 represent the rivers Bharatapuzha, Chalakudi, Periyar, Muvattupuzha, Minachil, Manimala, Pamba and Achankovil respectively. Inset shows the map area with reference to its location in India](image-url)
2.3 Geomorphology and Coastal landforms

Highly irregular, cliffed and wave eroded (Ahmad, 1972) terrains are the geomorphic character of Western Ghats. Kerala has width from 35 to 120 kms with an average of 65 km. Within this small width, the physiographical and topographical features change considerably. It is divided into three geographical regions (1) Highlands (2) Midlands and (3) Lowlands. The Highlands slope down from the Western Ghats which rise to an average height of 900 m with a number of peaks well over 1,800 m in height. The Midlands lying in between the mountains and lowlands too made up of undulating hills and valleys. The lowland or coastal area is made up of river deltas, backwaters and the shore of Arabian Sea.

The characteristic landforms of Kerala coast are the backwaters, lagoons, barrier islands, beach ridges and swales, tidal flats/mudflats, strandlines and floodplains (Narayana and Priju, 2006). They also include lakes (kayals) and inlets, which stretch irregularly along the coast (Joseph and Thrivikramaji, 2002). The biggest one is the Vembanad Lake, with about 230 km² in area, opens into the Arabian Sea at Fort Cochin. The other important backwaters are Ashtamudi, Veli, Kadhinam-Kulam, Anjego, Edava, Nadayara, Paravur, Kayamkulam, Kodungallur and Chetuva. Coastal inlets play an important role in the exchange of water between bays/lagoons and ocean. There are about 48 inlets in Kerala, out of which 20 shows permanent nature of opening, whereas the remaining 28 open only during the monsoon season (Nair et al., 1993). Munambam inlet is a major permanent inlet just north of Cochin inlet, through which Periyar River joins into the sea. Islands and inlets are major landforms that occur along the lagoon.
Kerala Coastline is 560 kms long in which a cumulative 360 km length of coastline is very dynamic and fluctuates seasonally experiencing a moderate energy with monsoonal-storm-dominated wave climate. Based on vulnerability and dynamism, the shoreline is divided into (1) permeable, gently sloping sandy shoreline (2) semi permeable, cliffed, sedimentary shoreline and (3) impermeable crystalline shoreline arranged in order of intensity of erosion.

The shoreline of Kerala is generally straight, trending NNW-SSE, with minor variations. Even though a straight-line configuration is apparent in a synoptic view, the shoreline is highly irregular and indented especially around promontories comprising of crystallines and sedimentaries. Stretches of shoreline between promontories are usually depositional in nature with sandy beaches and are locally straight. Long shore drift deposits straighten out the shore features over long stretches (Nair, 1987).

The central Kerala coast is described as a submerged coast, falling under the terrigenous coast of primary morphologic disequilibrium. Accordingly the long-term tendency of coastal evolution is to increase the linear extent of erosional coastal segments at the expense of intervening depositional areas and when the process goes to completion, a coast of equilibrium results. The coastal features include beaches, beach cliffs, stacks, islands, shore platforms, spits, bars, beach ridges, estuaries, lagoons, mud flats, tidal flats and deltaic plains (Nair, 1987; Thrivikramaji, 1987). Some of them are briefly described here:

**Barrier islands**

Several barrier islands occur along the central Kerala coast of which Vypin island is a significant one. It is about 25 km long and acts as a barrier between the Vembanad lagoon and the Arabian Sea. Another wide shore-
connected barrier island, separating the lagoon from the Arabian Sea, extends from Cochin to Cherthala.

**Beach Ridges and Swales**

A number of parallel beach ridges (also called as strandlines) alternating with swales are observed at many places (Nair, 1987). The width of ridges varies from 50 to 150 m and the height varies from 0.5 to 200 m. The width of the swales varies from 50 m to 200 m. These beach ridges represent successive still-stand positions of an advancing shoreline in relation to the sea. Occurrence of strandlines suggests that the coast has undergone a series of marine transgressions and regressions during the Late Quaternary. Significant changes were brought in the coastal configuration and associated landforms since mid-Holocene period. A number of strandlines, running parallel to the coast for a distance of 15 to 25 km occur up to 15 km inland from the present shoreline and about 2-5 m above sea level in the central Kerala region. Width of the strandline varies from 100 to 200m. These strandlines are present on either side of the Vembanad lagoon. Narayana and Priju (2006) have discussed about total obliteration of geomorphic features and sudden abutments of dune ridges with interdunal depressions near Parur, as reached from the tonal differences in the satellite imageries.

The occurrence of these paleo-beach ridges discussed above suggests the progradation of coastal land. This may be either due to fall in sea level or rise in the level of land or both. It is possible that both fall in sea level and uplift of the coast have influenced the formation of cheniers/strandlines along central Kerala coast. The sea level was higher during 3000 yr BP than the present day along this coast (Narayanan and Anirudhan, 2003).
Estuaries and Lagoons

Estuaries and lagoons (also known as kayals) are high in frequency on Kerala’s landscape (Narayan and Anirudhan, 2003). These kayals are classified into two types as Type I and Type II. North of Kollam, Kayamkulam Kayal, and Vembanad lagoon, the largest coastal landform of the Holocene on the west coast, are Type I Kayals. The average length to width ratio of type I class kayals is 4.5. Among these kayals, Vembanad lagoon is the largest with a length of about 110 km and the width varies from a few hundred meters to 4.5 km. Depth varies from less than 1 m to 13 m. Type II kayals include kayals of Thiruvananthpuram-Kollam coastal stretch e.g. Vellayani Kayal, Veli Kayal, Kadinamkulam Kayal, Nadayara Kayal, Paravur Kayal, and Asthamudi Kayal. The average length to width ratio of Type II kayals is ~6.5. The evolution of the coastal lagoons has been influenced by the geological and geomorphological history of the coastal area and the sequence of changes in the levels of land and sea, which have resulted in coastal submergence and the formation of inlets and embayments (Bird, 2000). Subsidence of coastal regions may deepen and maintain coastal lagoons, delaying their infilling. The greater depth of the lagoon in the southern part, near Vaikom may indicate subsidence. The shallower depth in the northern part may be related to uplift. The morphology of the lagoon suggests that en-echelon faulting has played a role in its evolution (Valdiya and Narayana, 2007). The Vembanad lagoon at many places runs across the strandlines affecting their continuity.

Paleodelta

A paleodelta feature in the northern part of the study area extending from the present shoreline for about 11 km into inland region along the mouth of Periyar river is evident from satellite imagery (Fig. 2.2). The dull matground
terrain devoid of any geomorphic feature is considered as a paleodelta (Narayana et al. 2001a), which encompasses an area of about 50 km$^2$. Older deltaic plains, formed as a result of coalescence of two deltas of Manimala and Pamba river extend from the coastal sandy plain to the western margin of the lowland region with an elevation of 10-300 m (Narayanan and Anirudhan, 2003).

**Figure 2.2:** Satellite imagery showing the Munambam paleodelta and the associated coastal geomorphic features (from IRS 1B LISS II FCC bands 2,3, and 4 March 1995). New delta ‘N’ being built up by Periyar river (after Narayana et al., 2001 a)

**Mudflats, Tidal Flats and Mangrove Swamps**

Extensive tidal and mudflats are observed in the eastern part of Vembanad lagoon, particularly near the mouth of the southern branch of the
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Periyar river and in the ChithiraPuzha river mouth area. Most of the mud/tidal flats are covered with mangrove vegetation.

**Flood plains**

Extensive floodplains are seen in the lower reaches of Periyar and Muvattupuzha rivers. The eastern part of the Vembanad lagoon is covered with floodplains.

2.4 Rivers and Drainage system of Central Kerala

The State of Kerala gets drained by 44 rivers out of which 3 flow eastward. The streams originating from the Western Ghats are short and swift flowing, showing various stages of gradation. Forty-one west flowing rivers drain across Kerala, with innumerable tributaries and branches, but these rivers are comparatively small and being entirely monsoon fed, practically turn into rivulets in summer, especially in the upper areas (*cf.* Resource Atlas of Kerala, 1984). These streams are marked by cascades and waterfalls in the upper reaches, although in the plains they show evidences of maturity of development. Some of these rivers have steep gradients (1/250 or more) in their initial reaches. In the case of Periyar and Chalakudi rivers, this extends for three-fourths of their course, while such gradients are also discernible in the upper reaches of Chaliyar, Valapattanam river, Vamanapuram Ar. Karamana Ar etc. suggesting their youthful stages of development (*cf.* Resource Atlas of Kerala, 1984). West coast faulting and later adjustments could be understood as the main evidence for the youthful behaviour of the rivers in region, while high energy shoreline might have prevented delta formation in the river mouths.

The general drainage pattern observed for the rivers of central Kerala is dendritic. However, trellis, sub-parallel and radial patterns are also noticeable in some places. River courses are mainly straight, indicating structural control due
to prominent lineament directions (NW-SE and NE-SW) (Valdiya & Narayana, 2007). Among all the rivers, the Periyar, Pamba and Chalakudi rivers are conspicuous by their length and size of the area they drain.

Periyar is the longest river in Kerala with a length of 244 km and with drainage area of 5398 km² (cf. Water Resource of Kerala, 1974). The catchment area spreads over the districts of Idukki and Ernakulam. The river originates and flows through a metamorphic terrain consisting of charnockites, garnet-sillimanite-gneiss, garnet-biotite and hornblende-biotite gneiss, besides migmatite and granite. Periyar river branches off into northern and southern arms (Narayana et al., 2001a). The northern arm turns to the northwest and has an almost straight channel, suggestive of its more youthful character, and enters its own palaeodelta located in the south of Krishnankotta and further cuts across palaeodelta to enter directly to the Arabian Sea. The southern arm meanders westward and enters the yazoo zone which is the hydrographic regime connecting Vembanad lake at Elur. At Elur, it branches southwestward into a number of small distibutaries which suggest the existence of remnant deltaic regions named as Varapuzha palaeodelta. Details of the rivers discharging into the Vembanad lagoon is given in Table 2.1

<table>
<thead>
<tr>
<th>River</th>
<th>Length (Km)</th>
<th>Catchment Area (Km²)</th>
<th>Annual Run-off (1000 MC ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalakudi</td>
<td>130</td>
<td>1704</td>
<td>42.00</td>
</tr>
<tr>
<td>Periyar</td>
<td>244</td>
<td>5398</td>
<td>434.00</td>
</tr>
<tr>
<td>Muvattupuzha</td>
<td>121</td>
<td>1554</td>
<td>93.68</td>
</tr>
<tr>
<td>Minachil</td>
<td>78</td>
<td>1272</td>
<td>96.27</td>
</tr>
<tr>
<td>Manimala</td>
<td>90</td>
<td>847</td>
<td>72.67</td>
</tr>
<tr>
<td>Pamba</td>
<td>176</td>
<td>2235</td>
<td>222.80</td>
</tr>
<tr>
<td>Achankovil</td>
<td>128</td>
<td>1484</td>
<td>76.00</td>
</tr>
</tbody>
</table>
Muvattupuzha is one among the perennial rivers of central Kerala with a length of about 120 km and a catchment area of about 1,554 km² (cf. Water Resource of Kerala, 1974) and debouches into Vembanad lagoon. The river originates from the Western Ghats and drains mainly through highly lateritised crystalline rocks and finally ends into the Vembanad lagoon near Vaikom. Two major tributaries namely Thodupuzha and Kaliyar join the Muvattupuzha river near Muvattupuzha town. After flowing as a single stream upto Vettukattumukku, the river branches into two distributaries namely Ittupuzha and Murinjapuzha. The river exhibits dendrite drainage pattern. The river discharge ranges from 50 m³/sec (premonsoon) to 400 m³/sec (monsoon). Peak discharge is recorded during June to October. Considerable changes have taken place in the flow characteristics of the Muvattupuzha river after the commissioning of the Idukki hydroelectric project in 1976, across the adjoining Periyar river. The tailrace water (19.83-78.5 m³/sec) was directed into the Thodupuzha tributary from Moolamattom power station. This tailrace water (almost constant) plus surface run-off have not only altered the morphological characteristics of the river considerably but also the sediment dynamics and ecological habitat of the river basin as well.

Pamba is the third longest river (176 km) in Kerala having the fourth largest catchment area of 2235 km². It rises in the hill ranges of Pathanamthitta district and the adjoining Pirmed plateau, and is formed by the confluence of Pambiyar Ar, Kakki Ar, Arudai Ar, Kakkad Ar and Kal Ar. Pamba and Kakki are the major reservoirs in the basin. Flowing through the crystalline rocks (pyroxene granulites, charnockite gneiss, khondalites and associated calc-granulite bands), the basin displays dendritic to sub-dendritic and rarely rectangular and trellis drainage patterns.
The river Chalakudy has a length of 130 km and a drainage area of 1704 km². Five streams – Parambikulam, Kuriakutty, Sholayar, Karapara and Anakkayam form the Chalakudy river. Of these, Parambikulam and Sholayar rise in the Anaimalai hills at elevations above 1733 m and 1332 m, respectively. The river flows through thick forests and the channel has many waterfalls until it reaches the plains at Kanjirapally. The river debouches into the right arm of the Periyar at Puthenvelikkara. Poringalkutu, Sholayar and Parambikulam are the major reservoirs in the basin. Charnockites and migmatitic gneisses are encountered along the river course.

Achankovil is also one of the main river of the Kerala with a length of 128 km and a catchment area of 1484 km². Achankovil river joins with the river Pamba before entering into the Vembanad lagoon. The Manimala river has a length of 90 km and has a catchment area of 847 km² and Minachil river has a length of 78 km and a catchment area of 1272 km².

2.5 Climate and Rainfall

Kerala state is diverse which causes the diversity in its climate too. Monsoon is the main feature of tropical climate experienced in Kerala. Subtropical type of climatic regime is seen in certain areas in the eastern part of the state due to the high variation in relief from west coast to the hilly regions of the Western Ghats in the east. Heat waves from the plain of Tamil Nadu enter in Kerala through Palghat Gap and Ariankavu pass. India Meteorological Department has grouped the seasons in Kerala into four seasons:

1. Hot weather period (the pre-monsoon season): March - May
2. Southwest monsoon: June - September
3. Retreating southwest monsoon (i.e., onset of northeast monsoon): October – November


The atmospheric temperature reaches a maximum of 37\(^\circ\)C during the pre-monsoon period and from June onwards it gradually comes down due to heavy rainfall. Land and sea breezes influence the coastal area and here the seasonal and diurnal variations of temperature and almost of the same range (5 - 7\(^\circ\)C). Kerala experiences two monsoons, namely the Southwest (June to September) and northeast (October – December) seasons. The Kerala state receives the highest annual rainfall among the other states of India, which is three times the average rainfall of India. The average annual rainfall varies from 100-400 cm with an average of about 300cm. The northeast monsoon is generally weak along the West Coast and the average annual rainfall is about 60 cm (Pisharody, 1992; Sampath and Vinayak, 1989).

2.6 Waves, Currents and Tides

West coast of India is experiences SW monsoon (rough weather season) between June and September. The wave activity becomes very strong during June and July and low in August and September. The sea remains relatively calm during October to May which is considered as fair weather season. During fair weather season, long swells often mixed with the local wind-seas prevail along the coast. Central Kerala coast is a micro-tidal zone, and falls under the major tectonic and morphologic class of the ‘Amerotailing’ edge coast (Inman and Nordstrom, 1971). The dominant energy in the nearshore is composed of gravity waves and mean currents or circulation. Far infra-gravity wave energy is about two orders of magnitude larger than that of gravity waves and evidence of edge waves in the infra-gravity band was demonstrated by Tatavarti \textit{et al.}
Far infra-gravity waves may be a common feature in the nearshore oceans in the presence of longshore currents (Bowen and Holman, 1989).

The wind and current systems along the coast play an important role in the dynamics of mudbanks of the southwest coast of India. The important feature of the wind system in the Indian seas is a seasonal reversal of direction associated with two monsoons. Along the west coast of India, during the southwest monsoon the winds blow southwards from May to September and attain a northerly direction during the northeastern monsoon. Thus, the seasonally reversing wind pattern influences the southward littoral drift during the southwest monsoon, while a northward drift occurs during the northeastern monsoon. By the middle of May, the southwest monsoonal winds of oceanic origin are established. These winds continue to increase gradually until June when there is a ‘burst’ or sudden strengthening of the southwest winds. During July and August, the winds have their highest strength, and in September the wind force decreases ahead of the fall transition, which lasts through October and November (Sharma, 1978).

Estuarine hydrography plays an important role in the sedimentation and geochemical processes of this environment. The quantum, duration, transport and settlement of the particulate sediments depend directly on estuarine hydrography. The hydrography of the Vembanad estuary has been investigated by several researchers (Quasim and Reddy, 1967; Quasim et al., 1968; Sankaranarayanan et al., 1986; Anirudhan, 1988; Rasheed et al., 1995). The distribution of the temperature in the estuary is a function of the input of freshwater from rivers as well as the intrusion of salt water from Lakshadweep sea. Processes like exchange of heat with atmosphere and other localised phenomena are also likely to influence the hydrographic conditions of the system. The temperature of the water in the lagoon varies between 25-31°C.
Low salinity values ranging from 0 to $10 \times 10^{-3}$ at the surface and 0 to $12 \times 10^{-3}$ at the bottom were observed during monsoon. This was brought about by the combined effect of land drainage from the prevailing monsoonal rains causing high freshwater discharge from the river and intrusion of saltwater from the sea. As the season advances to post and premonsoon, higher salinity values ranging from 10 to $22 \times 10^{-3}$ at the surface and 12 to $24 \times 10^{-3}$ at the bottom were observed (Anirudhan, 1988). The estuarine waters considerably get diluted near the Muvattupuzha river confluence. The pH values of the surface and bottom water vary from 6.6 to 7.4 and slight increase is observed seasonally up to postmonsoon period.

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