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ORIGINAL ARTICLE

History of landslide susceptibility and a chorology of landslide-prone areas in the Western Ghats of Kerala, India

Sekhar L. Kuriakose · G. Sankar · C. Muraleedharan

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Abstract Kerala is the third most densely populated state in India. It is a narrow strip of land, of which 47% is occupied by the most prominent orographic feature of peninsular India, The Western Ghats mountain chain. The highlands of Kerala experience several types of landslides, of which debris flows are the most common. They are called "Urul Pottal" in the local vernacular. The west-facing Western Ghats scarps that runs the entire extent of the mountain system is the most prone physiographic unit for landslides. The highlands of the region experience an annual average rainfall as high as 500 cm through the South-West, North-East and Pre-Monsoon showers. A survey of ancient documents and early news papers indicates a reduced rate of slope instability in the past. The processes leading to landslides were accelerated by anthropogenic disturbances such as deforestation since the early 18th century, terracing and obstruction of ephemeral streams and cultivation of crops lacking capability to add root cohesion in steep slopes. The events have become more destructive given the increasing vulnerability of population and property. Majority of mass movements have occurred in hill slopes >20° along the Western Ghats scarps, the only exception being the coastal cliffs. Studies conducted in the state indicates that prolonged and intense rainfall or more particularly a combination of the two and the resultant pore pressure variations are the most important trigger of landslides. The initiation zone of most of the landslides was typical hollows generally having degraded natural vegetation. A survey of post-landslide investigation and news paper reports enabled the identification of 29 major landslide events in the state. All except one of the 14 districts in the state are prone to landslides. Wayanad and Kozhikode districts are prone to deep seated landslides, while Idukki and Kottayam are prone to shallow landslides.

Keywords Landslides · The Western Ghats scarps · Kerala · Land use · Debris flows · Rainfall intensity · Pore pressure

S. L. Kuriakose (✉)
United Nations University-ITC School for Disaster Geo-Information Management,
International Institute for Geo-Information Science and Earth Observation (ITC), Hengelosestraat 99,
P.O. Box 6, 7500AA Enschede, The Netherlands
e-mail: sekhar.lk@gmail.com

G. Sankar
Centre for Earth Science Studies (CESS),
Thiruvananthapuram, Kerala, India

C. Muraleedharan
Geological Survey of India (GSI),
Thiruvananthapuram, Kerala, India

Introduction

The Western Ghats, the most prominent orographic feature of peninsular India, occupies 47% of Kerala state. With a total area of 38,863 km^2, it is the third most densely populated (819 people/km^2) state in the country (Census of India 2001). Even though the region once supported typical tropical forests and grasslands, substantially vast area has been cleared and converted into monoculture plantations and agricultural fields from the early 19th century onwards (KSFWD 2004).

All 13 of the 14 districts of Kerala (Fig. 1) except the coastal district of Alappuzha are prone to landslides. About 8% (1,400 km^2) of area in The Western Ghats of Kerala is classified as critical zone for mass movements (Thampi et al. 1995). The region experiences several types of landslides especially during the monsoon seasons. This includes rock falls, rock slips, slumps, creeps, debris flows and in a few cases, rotational types of slides. The most prevalent, recurring and disastrous type of mass movements noted in Kerala are the "debris flows". They are called "*Urul Pottal*" in the local vernacular. The characteristic pattern of this phenomenon is the swift and sudden down slope movement of highly water saturated overburden containing a varied assemblage of debris material ranging in size from soil particles to huge boulders destroying and carrying with it everything that is lying in its path (Thampi et al. 1998). They are confined flows that affects the overburden weathered rock and soil, leaving the much stronger Precambrian crystalline basement intact.

Infiltration and the resultant transient changes in the hydrological systems as proposed by van Asch et al. (1999) is the most common trigger of landslides in the region. The triggering system is related to an increase in pore pressure resulting in a decrease in effective stress and strength, and thus a possible decrease of factor of safety to less than 1. Four sequential phases towards the development of debris flows can be identified, they being (1) movement of water to the site of failure (surface flow, interflow and direct contribution by rainfall), (2) failure of the soil mantle by sliding (loss of cohesion), (3) mobilisation of the material as debris flow and (4) travel of the debris flow (Ellen 1988). A pictorial representation of the processes leading to shallow landslide initiation is provided in Fig. 2. Vegetation exerts a

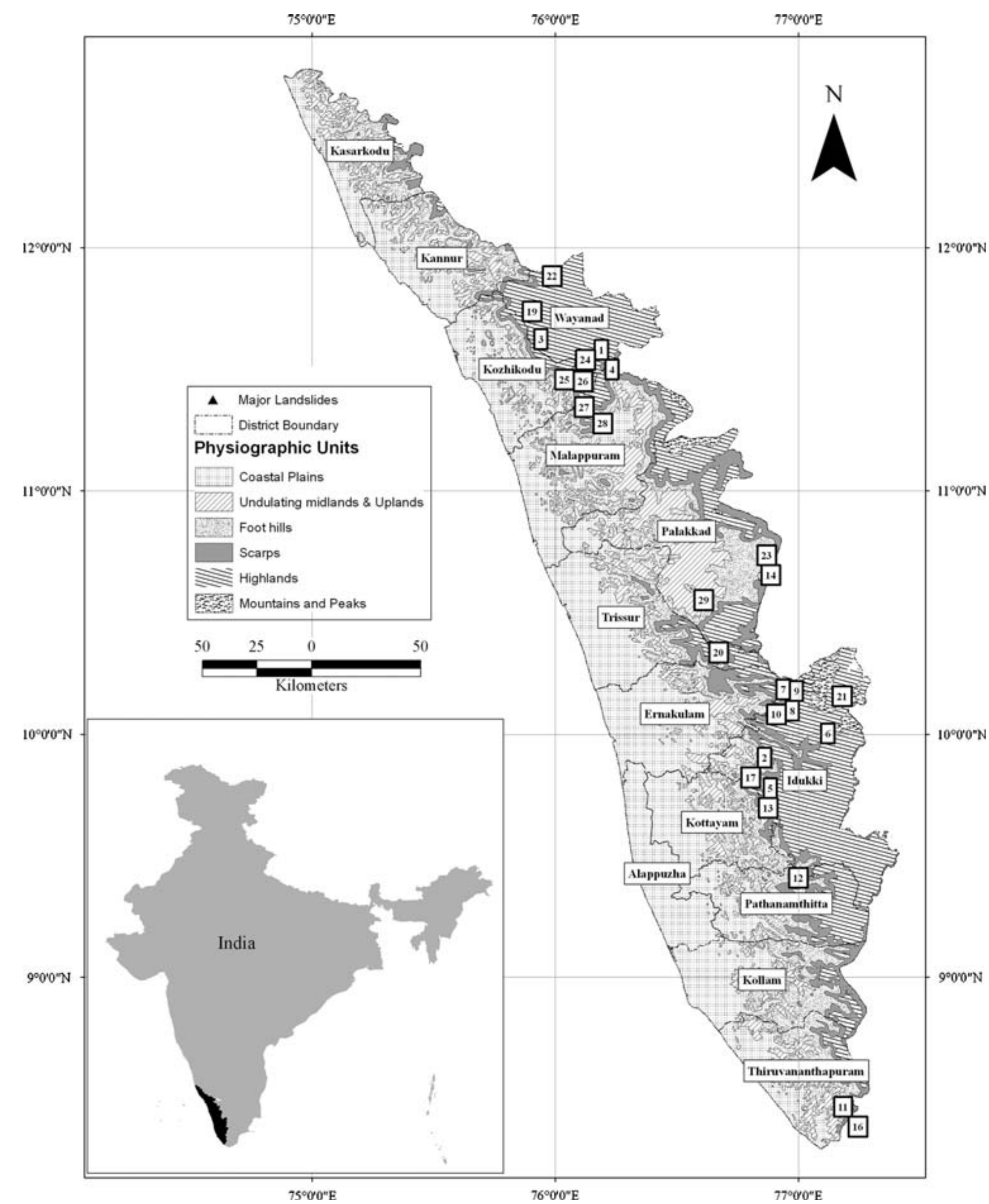

Fig. 1 Physiographic map of Kerala and the major landslides

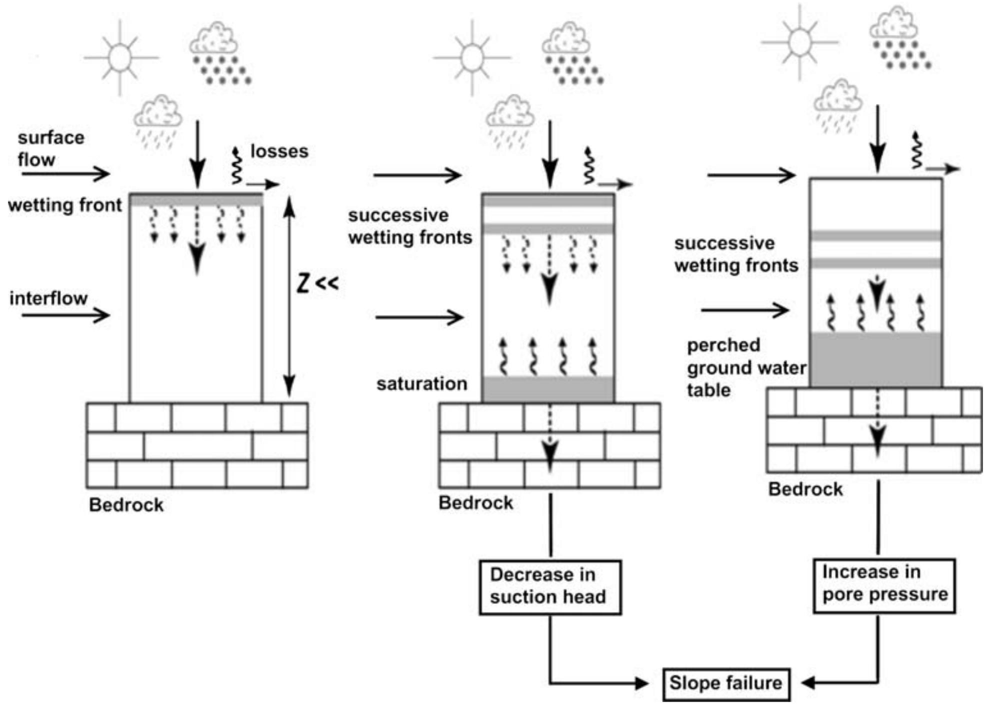

Fig. 2 A sequential schema of shallow landslide initiation (modified after Malet et al. 2005)

significant influence in determining the occurrence of slope failure conditions, by intercepting rainfall, reducing soil moisture through evapotranspiration and increasing the stability by root induced cohesion (Greenway 1987).

Several institutions have conducted landslide research in Kerala including Centre for Earth Science Studies (CESS), Geological Survey of India (GSI), Centre for Water Resources Management and Development (CWRDM), National Transportation Planning and Research Centre (NTPAC) and National Institute of Technology, Calicut (NIT-C). Most of the studies conducted by the institutions are post-event evaluation reports for the Revenue Department of the State Government. (e.g., Sankar 1991; Thampi et al. 1994). One of the phenomenal research works in the region was the "Evaluation study in terms of landslide mitigation in parts of Western Ghats, Kerala" conducted by Thampi et al. (1998). The study evaluates a 750 km^2 area covering the districts of Kottayam and Idukki for landslide susceptibility using weights of evidence method. This being the first of its kind in the state the study was a significant contribution in terms of providing a pragmatic methodology to be later applied in several other regions (e.g., Sankar et al. 2004). Few other research works are also available describing landslide activity in the Western Ghats of Kerala (Basak and Prasad 1989; Chinnamani et al. 1980; Gupta 2001; Kuriakose 2006; Muthu and Muraleedharan 2005; Kumar 2005; Sreekumar and Krishnanath 2000; Vijith and Madhu 2007).

However, a survey of Kerala in terms of historical and present day landslide susceptibility is lacking. Such attempts of building a chronology of landslide susceptibility based on historical documents are a crucial first step towards comprehensive landslide hazard assessment (Guzzetti et al. 2003; Wasowski 1998). In regions where landslide investigation is a young discipline, the analysis of historical documents can provide important information about the type and the temporal and spatial distribution of landslide events (Devoli et al. 2007). This paper presents a brief survey of ancient literature to assess the history of landslide susceptibility and driving forces of landslides in The Western Ghats of Kerala. Attempt was also to present a chorology of landslide prone areas in the state. A district-wise compilation of reported landslides are also attempted. Three major landslide events are described in detail to highlight the intrinsic and extrinsic factors that are crucial to slope instability in the region.

Conducive physiography and climate

Based on distinct biophysical characteristics, the state can be divided into six physiographic units (Fig. 1), namely, the mountains and peaks (>1,800 m), the highlands (600–1,800 m), the foothills (300–600 m), uplands (100–300 m), undulating midlands (20–100 m) and coastal plains (<20 m) (Chattopadhyay and Mahamaya 1995). A major structural discontinuity, named Palakkad Gap with a width of 30 km, divides the Kerala segment of the Western Ghats into two, creating distinct geomorphic units and ecological niches. Five planation surfaces can be identified in the physiographic units, which are grouped into two broad categories, namely the high-level planation surfaces (>700 m) and the low-level planation surfaces (0–300 m). The high-level planation surfaces shows old age characteristics, while slopes bounding them present a youthful topography, consequent of its distinction being the source region of most of the rivers. These plateau margins called the Western Ghats scarps, having a linear extent of approximately 470 km through the entire length of Kerala, present an abrupt rise in topography from an altitude of $\sim$100 m (MSL) creating near vertical scarp faces and amphitheatre-like basins characterised by 70–100% slopes. The Western Ghats scarps are the most susceptible to landslides (Sankar 2007a).

The origin of the scarp face is attributed to the West Coast Faulting in the Cretaceous later modified by Miocene block uplifts. Several nick points along thalwegs of the rivers are an indication of rejuvenation. The evolution and current landscape of the Western Ghats are principally attributed to the scarp retreat along structurally weaker planes (Balakrishnan 2001), neo-tectonics and denudational processes. A detailed description of the scarp lands is available in Chattopadhyay (2004).

The dominant rock unit of the region are Precambrian crystalline rocks such as Charnockites, Khondalites and gneisses, and they underlain most parts of the highlands and the foot hills including the scarps (Soman 2002). It is part of the South Indian Precambrian terrain with sporadic intrusions of later Precambrian, early Paleozoic granites, associated Pegmatites and Meso-Cenozoic dykes. Intensive deformations have occurred to the crystalline rocks in several stages of the orogeny. The general foliation trend is NW-SE and it varies from NNW-SSE to WNW-ESE. Late tertiary sedimentary formations are found along the coast of Kannur and from Kottayam to south of Thiruvananthapuram. Several lineaments manifested through surface features like straight stream channels, distinct vegetation cover and topographic alignments were identified in the region and grouped into three based on their trends (Raj et al. 2001). Almost all major fractures, shears and fault zones of the state align with the NW-SE to WNW-ESE set of lineaments, which appear to be en-echelon in nature. A generalised geology map of the region with major structural discontinuities mapped can be found in Soman (2002).

The state is traversed by 44 rivers, of which only three are east-flowing. The general drainage pattern is dendritic. Most of the streams are structurally controlled and short in length with a steep gradient of 1/250 or more in the highlands. An abrupt change in the gradient is observed along the plateau margins and between the older and the younger planation surfaces indicating active fluvial erosion.

The highlands and foot hills are dominated by lateritic soils and forest loams (SSB and NBSS&LUP 1979). Soil cover in this region is shallow with an average thickness between 1 and 3 m. The profile consists of unconsolidated colluvium, boulders, laterite, saprolite and lithomargic clay resting over the hard Charnokites and Gneisses. Except on plateau surfaces and plateau remnant hills, the soil is transported and constantly disturbed by anthropogenic activity resulting in the lack of cohesion and consolidated profile development. Subsurface pipes are seen to be wide spread along the Western Ghats scarps. Studies conducted on the stress–strain characteristics of the soils along the Western Ghats scarps indicate frictional soils that lack cohesive strength thus being stable in dry conditions but drastically loose shear strength with increasing moisture content (Chandrakaran et al. 1995). Texture analysis indicates that the soils are dominated by sandy clayey loams. Figure 3 shows the textural properties of 21 soil samples from the upper Meenachil River basin along the Western Ghats scarp lands collected and analysed at CESS in 2007.

Kerala has a tropical climate having three distinct seasons namely the south-west monsoon (June–September), north-east (October–November) and pre-monsoon (January–May) influenced by the Indian Monsoon System. The spatial pattern of rainfall in the region is governed principally by the orographic effect of the Western Ghats. The rainfall in the highlands and the Western Ghats scarp faces are generally above 200 cm with some places having more than 500 cm. Analysing the rainfall from 1901 to 1980, Sampath et al. (1995) concludes that SW monsoon rainfall decreases with altitude from west to east up to 600 m (MSL) and then increases up to a height of 1500 m (MSL), beyond which it decreases. The contribution of SW monsoon rainfall increases from south (46%) to north (83%)

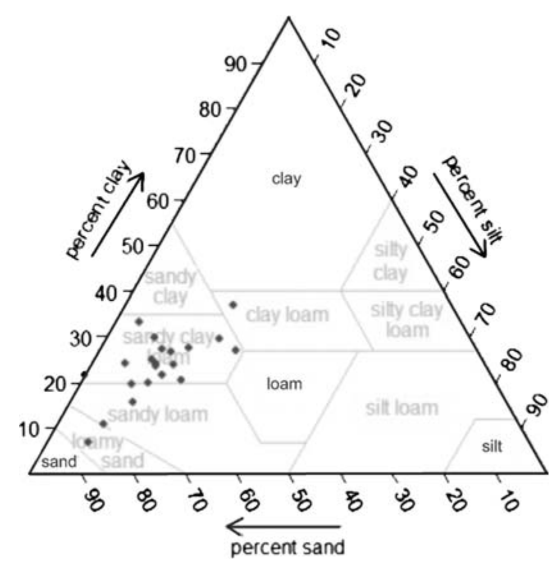

Fig. 3 Textural triangle of soil samples from the upper Meenachil River basin

and is more consistent in the northern part of the state. The NE monsoon contributes 33% of the annual rainfall in the southernmost district of Thiruvananthapuram and 9% in the northernmost district of Kasaragode. Districts south of Ernakulam receive significant amounts of pre-monsoon showers too. Soman et al. (1988) observed a decreasing trend in monsoon rainfall along the highlands, reason for which was attributed to deforestation. A considerable fluctuation in the monsoon system results in increased probability of high intensity rainfall.

Rainfall intensity of the region also has a spatial variation. In the high altitudes (>1,300 m), low-intensity events below 20 mm/h dominate in total contribution (~81%) to the rainfall during the monsoon season. Low altitudes receive only 44% of the monsoon rainfall from low-intensity rainfall (Kumar et al. 2007). Observations also indicate that, in southern Kerala, high-intensity rainfall events are dominated by larger drop sizes in contrast to central Kerala, where high-intensity rainfall events have more number of drops (Harikumar et al. 2007). The former implies higher erosivity associated to such events, while the later favours faster soil saturation. March–May is the hottest period with maximum temperature reaching ~32°C and the minimum nearing 20°C is experienced in December–January. Winds over the state are seasonal; diurnal variation is felt owing to the maritime influence. Wind speeds attain 40–50 km/h during and before the monsoon rains. Relative humidity varies between 80 and 95% during the monsoon and between 70 and 75% during the pre-monsoon (Pisharody 1992).

Given the current trend of climate change in India, the probability of extreme rainfall events during the monsoon is expected to increase (Lal et al. 2000). The south-west monsoon rainfall of 2007 was in excess of 30% from the long period average over the state (IMD 2007). Thus, Kerala possesses all topographical and climatic conditions necessary for frequent slope failures.

Several natural symptoms are known to be indicative of impending landslides in the region, most notable of them being (1) the development of new cracks or unusual bulges in the probable crown area, (2) the development of springs, seepages or saturated ground in the toe areas that have not been typically wet before, (3) a change in position, amount of discharge and amount of turbidity of the springs, (4) tilting of electric poles, trees, fence, rods, etc., (5) sinking of roads or ground surfaces, (6) cracking of floors, foundations or compound walls and (7) decrease in the population of burrowing animals (Thigale and Khandge 2005).

A regional assessment indicates that the major parameters affecting slope stability in the region are critical slope, overburden (soil) thickness, soil moisture, drainage characteristics and land use/landcover (Thampi et al. 1998). Studies conducted in the state indicates that prolonged and intense rainfall or more particularly a combination of the two and the resultant pore pressure variations are the most important trigger of landslides (e.g., Basak and Prasad 1989; Muraleedharan 1995; Thampi et al. 1998). The time of landslide initiation is suspected to be determined by persistence of critical pore pressure conditions for a prolonged period (Kuriakose 2006). So far, no evidences supporting the role of seismic activity in landslide triggering is obtained from Kerala (Kusala and Rajendran 1995).

Even though the state has physical and climatic settings conducive for the natural occurrence of instability, the intensity of these events are not the same as in the historic past. Many researchers suspect an increase in the rate of landslide frequency (e.g. Chattopadhyay 1985; Jha et al. 2000). Increased landslide frequency is suspected to be a consequence of the increased population pressure and unsustainable land use practises on the physiographic units naturally susceptible to landslides. This demands a detailed review of historical documents to assess the rate of landslide activity in the recorded history of the region.

A survey of history

An investigation into the oldest known historical document of the region, the Sangham Literature, did not yield any description of landslides. The Sangham literature is a collective set of documents authored by the Sangham School of scholars and poets who lived from the third century BC to third century AD. None of the Arab travellers to the state from the ninth century AD, namely Sulaiman (841 AD), Al Idrisi (1154 AD), Rashiduddin (1273–1331 AD) or Ibn Batuta (1342–1347 AD), describes landslides in the region. Iban Batuta's travelogue especially has ample descriptions of sudden natural phenomena in the region such as the unprecedented storms that turns calm seas to rough, sudden floods in the rivers and the lightning that are associated with the pre-monsoon convective clouds. There was hardly a chance that these scholars miss any such phenomena as landslides given the details in their descriptions of the climate, geography, demography and economics of the region. If wide spread, the possibility of these events going unnoticed as they occur deep inside the Western Ghats, which was then largely desolated, can also be ruled out given the fact that all the then trade routes connecting to the present Tamil Nadu crisscrossed the forests of the Western Ghats. These were busy routes with spices being a major agricultural commodity mostly collected from the forested Western Ghats and traded across.

The early Portuguese travellers and the Dutch scholars also miss any description of such events. Mr. Francis

Buchanan-Hamilton is known for his detailed descriptions of the Malabar region (northern Kerala); however, he also does not describe any landslides in the region (Buchanan-Hamilton 1807). The Logan's Manual (also known as the Malabar Manual) (Logan 1887) and The Travancore Manual (Aiya 1906) describes various flood events in the rivers of the region, but they also miss details of any landslide events.

However, a keen geomorphologist can easily identify many rainfall extremes in these descriptions, two of which deserves particular interest, they being the description of the 371 AD and the 1341 AD floods in the Periyar River. The fourth century flood severely damaged the areas along the Periyar and the people living there had to escape to safer locations, abandoning their homes and livelihoods. The later flood lead to the filling up of the historically important Muziris port mentioned by Pliny the Elder in his *Natural History* (NH 6.26) as *primum emporium Indiae*, the most important trade centre of India. Available descriptions state that the flood in 1341 AD resulted in splitting of the left branch of the river into two just before Aluva. The flood silted the right branch (known as River Changala) and the natural harbour at the mouth of the river, and resulted in the creation of a new harbour at Kochi. An Island was formed during the flood (Logan 1887) named Putu-Vaipu. The infilling of the Muziris port and the splitting up of the river is beyond any doubt associated to some massive landslides that yielded much more sediments than the current average rate of $1{,}261 \times 10^3$ mt/year sediment load (Ittekkot and Subramanian 2001) in the rivers of Kerala. The natural dam like confinement of Periyar River near Bhoothathankettu reservoir by two gigantic boulders is supposed to have been the after-effect of this landslide (Staff Reporter 2001). The description of these floods thus can be considered as an indirect reference to the landslides in the highlands of Kerala, implying that the processes that are in play today were also in action in the past, though at a much lesser rate. Given the scanty reference of debris flows and landslides in the historic documents, it could be concluded that, in the past, they were isolated events having no hazardous consequences. It is thus necessary to understand the driving forces that changed this evolutionary earth surface process into hazardous events with disastrous consequences.

The driving force

Hilly regions of Kerala experienced anthropogenic disturbances right from the start of the colonial era in the late 1700s. Timber from the Malabar region (northern Kerala) was unscrupulous exploited by the Imperial Government for the construction of the Naval Dockyard in Bombay since early 1730s (KSFWD 2004). This rampant deforestation resulted in reduced surface water availability and frequent disastrous flash floods along the Western Ghats from the mid-19th century (Markham 1866). Though measures to control deforestation were brought in by various British India executives such as Mr. Canolley (1880) and Col. Munroe (1812), the rate of deforestation only increased from the late 19th century. This increase was as a consequence of four state initiatives, they being (1) the late 19th century Royal Proclamation encouraging plantations, (2) the mid-1940's "Grow More Food" campaign, (3) the colonisation program of the state government prior to the reorganization of the states in 1950s and (4) the major hydro-electric and irrigation projects (George and Chattopadhyay 2001). An estimated 44.4% declared forest in 1905 (Chattopadhyay 1985) declined to 28.99% in 2003 (FSI 2003).

The lumberers and the migrant settlers seeking better fortunes cleared most of the natural forest cover, originally for cassava and other hill crops cultivated together with coconut palms only to be later replaced by rubber (*Hevea Brasiliensis*) plantations (Kumar 2005). Cassava cultivation is known to accelerate soil erosion (Putthacharoen et al. 1998) and the land-use practises associated with it are deemed to act as a catalyst to slope failures in the region (Government of India 1956). Cobble-packed slope-terracing ignoring the natural drainage is a prevalent practise among the farmers in the region, which was identified as a reason to have increased the susceptibility to landslides (Fig. 4). Rubber has a crop life of approximately 20 years. As plantations pass their optimal crop life, they are felled, exposing the soil to high-intensity rainfall. Depending on the slope conditions of the rubber fallows, farmers either excavate the rubber root system destroying the inherent stability of the soil or leave the roots to decay over time forming macropores that increases infiltration. As a result of these unsustainable practises, the shallow soils on the steep slopes loose natural and root-induced cohesion, and when coupled with high-intensity rainfall, it results in the activation of intensive and extensive land degradation processes such as soil erosion and debris flows. The current rate of soil loss in Kerala is estimated to be 53 mt km^{-2} $year^{-1}$ (Ittekkot and Subramanian 2001).

According to the systematically recorded climatic history of the state, 1,881 experienced a catastrophic flood as a result of 487.68 cm rainfall. However, reports of landslides were not to be found in news papers of the time. A survey of newspapers namely *Deepika* (1887 onwards) and *Malayala manorama* (1888 onwards) also did not yield references to landslides or debris flows in the region till the mid-20th century. Gopinath (1985) reports that *Urul Pottal* became a popular term in the mass media during the monsoon seasons only after the 1949 debris flow in the Kodiyathoor hill of Thodupuzha taluk, Idukki district.

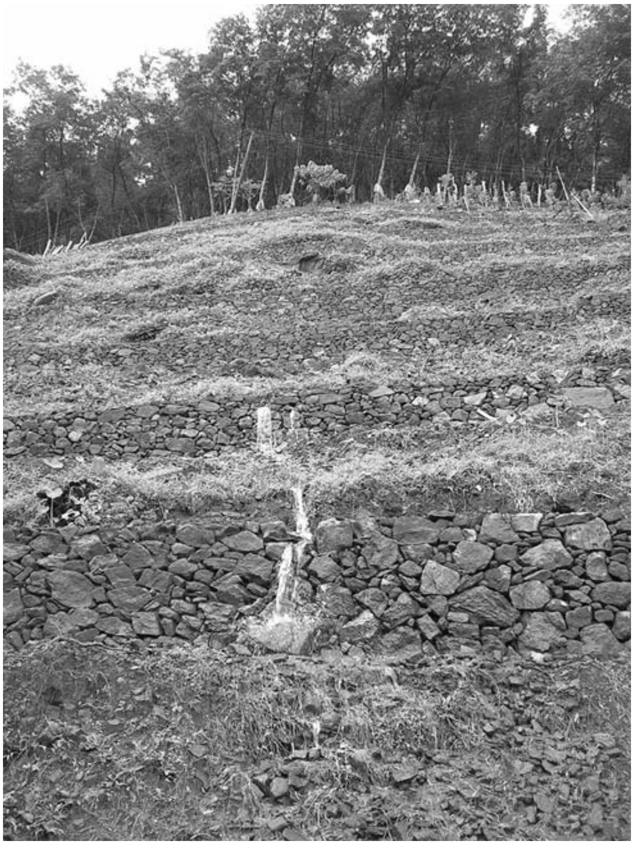

Fig. 4 Terracing and drainage alteration

A study conducted on migration suggested that, in the past 80 years, the coastal plains recorded a population growth of 306%, whereas the highlands, foot hills and uplands together experienced a growth of 1,342% (Nair et al. 1997). The development activities usually associated with the growing population such as building of roads, railway and infrastructure and blasting and quarrying are important drivers of land degradation processes. The growth of population and the consequent demand for land are very high in Kerala, as per capita availability of land is only 0.012 ha as on 2001. This warrants the identification of landslide-susceptible areas, a first step towards which is the compilation of available records.

Over the period of 1975–1995, it is estimated that about 100 people have been killed by landslides and about 600 families rendered homeless along the Western Ghats (Thakur 1996). The total number of landslides was nearly 40 in the south-west monsoon season of 2007, with all districts except Alappuzha having reported at least one debris flow. Thus, one could infer a relative increase in the rate of landslide activity and the associated risk along the Western Ghats compared to the historic past due to the increased anthropogenic pressure on slopes as a result of upland migration and deforestation in the late 19th and 20th century. The damages due to floods and landslides in Kerala was estimated to be 12×10^8 Euros in 2007 (Kumar 2007). The losses due to landslides and other hydro-meteorological hazards are only to increase given the current annual rate of deforestation along the Western Ghats pitched at 1.16% of the forest cover of a given year (Jha et al. 2000).

Landslide-prone areas

Given the lack of a systematic database of landslide occurrence, investigation reports from various research institutions and news paper reports are used to build a district-wise inventory of landslides and identify the most prone regions. From south to north, all the 13 districts that are known to be susceptible are covered. Table 1 shows a list of the major landslides that occurred in the state from 1984.

Thiruvananthapuram

The upslope of Neyyar river catchment is identified as the most landslide-prone region in the district with Amboori landslide (see Table 1; Fig. 6) being the most significant of them. Other regions of the district namely Anachari and Mooppanmala experienced rock falls and Venkulam, Mattikettukunnu and Akamala experienced soil creep. These are areas in the thick naturally forested Neyyar Wildlife Sanctuary (Babu et al. 2000). The Pappara reservoir catchment is another region susceptible to landslides with a major landslide event reported in 1992 (Santhi 2004), which reduced the reservoir capacity considerably. Another important region that experiences slope instability is the coastal cliffs of Varkalai (Radhakrishnan 2006). These are tertiary sedimentary formations made up of inherently cohesion-less material that experienced uplift during the Holocene era (Babu et al. 2007) susceptible to retrogressive debris falls as a result of wave and wind action. Few landslides were also reported from Peringamala (9.10.1992) and Thennur (11.11.1992) of Nedumangadu taluk.

Kollam

Landslides were reported from Pathanapuram taluk of the district. A landslide occurred in 1992 near Pandavanpara at Ottakkal in Pathanapuram taluk of the district (Thampi et al. 1992b). Kollam–Shenkottah railway line that passes through the highlands of the district is a major landslide-prone region. One of the earliest reported landslides in the segment was soon after the commissioning of the railway line on 1st June 1904 (Harikumar 2004). Landslides have been reported in Channapetta (9.10.1992), Edamon (9.10.1992) and Thenmala (14.11.1992) also.

Table 1 Major landslides in Kerala

S. no.	Location	Type	Taluk	District	DD/MM/YY	Deaths
1	Mundakay	C	Vythiri	Wayanad	01-7-84	14
2	Kumpanpara (Moolamattom)	DF	Thodupuzha	Idukki	26-6-85	9
3	Koodaranji	DF	Koyilandi	Kozhikode	01-7-91	4
4	Kappikalam (Padinjarethara)	DF	Vythiri	Wayanad	19-6-92	11
5	Adivaram (∼100 slides)	DF	Meenachil	Kottayam	06-10-93	1
6	Bison valley	DF	Udumbanchola	Idukki	14-7-94	7
7	Pazhampallichal	DF	Devikolam	Idukki	21-7-97	9
8	Ozhuvathadam	DF	Devikolam	Idukki	21-7-97	2
9	Valara	RS	Devikolam	Idukki	21-7-97	1
10	Cheeyappara	DF	Devikolam	Idukki	21-7-97	1
11	Idichakkaplamoodu (Trivandrum–Nagercoil railway line)	RS	Neyyattinkara	Trivandrum	15-11-98	3
12	Pamba	RS	Adoor	Pathanamthitta	15-1-99	25
13	Periyanmala	DF	Meenachil	Kottayam	99	
14	Chundakkadu (Nelliyampathi)	DF	Chittur	Palakkad	25-8-00	1
15	Cheenikuzhi	DF	Thodupuzha	Idukki	09-7-01	3
16	Amboori	DF	Neyyattinkara	Trivandrum	09-11-01	39
17	Venniyani mala	DF	Thodukuzha	Idukki	09-7-02	1
18	Kaithapadam Thooveri Parambil (Pottammel–Palazhi road)	DF	Kozhikode	Kozhikode	06-6-04	2
19	Nittukottamala	DF	Vadakara	Kozhikode	10-8-04	10
20	Vellikulangara	DF	Mukundapuram	Thrissur	14-7-05	2
21	Anthoniar Colony (Munnar)	C	Devikolam	Idukki	25-7-05	4
22	Vallamthodu	DF	Manathavady	Wayanad	23-6-07	4
23	Kairadi	DF	Chittur	Palakkad	17-7-07	1
24	Mysoorpetta–Thottamukam	Sl	Kozhikode	Kozhikode	17-7-07	1
25	Panakkachal	DF	Kozhikode	Kozhikode	17-7-07	1
26	Anayode	DF	Kozhikode	Kozhikode	17-7-07	1
27	Alappara	DF	Eranadu	Malappuram	17-7-07	1
28	Edavanna	RS	Eranadu	Malappuram	17-7-07	2
29	Kavalupara	RS	Alathur	Palakkad	17-7-07	1

Trivandrum is Thiruvananthapuram; DD/MM/YY is the date

DF debris flow, *Sl* slump, *C* complex slide, *RS* rotational slide, Trivandrum is Thiruvananthapuram Date: dd/mm/yy

Pathanamthitta

Other than the landslide at Pamba (see Table 1) (ENS and Agencies 1999), a major landslide was reported from Sithathodu in Rani taluk of the district in 1992, which caused extensive damage to agricultural land. The cause of Pamba landslide was the congregation of immense number of pilgrims in a precarious slope.

Kottayam

The highlands and the Western Ghats scarps of Kottayam experiences numerous debris flows every year. They are shallow landslides that cause relatively less damage when compared to those that occur in Idukki, Kozhikode and Wayanad districts, but the cumulative damage surpassing most other districts. Meenachil and Kanjirapalli taluks are the most landslide-prone regions of the district. The district is bordered to the east by the Peerimedu plateau margin, which has all the prerequisites of an active erosion zone, where the natural terrain setup is conducive to slope failure/mass movements. The region became an abode of landslide researchers (e.g., Kuriakose et al. 2006; Thampi et al. 1998; Vijith and Madhu 2007) with the 1993 Adivaram landslides (see Table 1). Some of the recent debris flows in the region are Elavumpara landslide (29.7.1995) (Harikrishnan et al. 1995), Kattupara mala, Mar mala, Chonna mala and Kalakoodu in 2001, Adivaram and Tikoy landslides (05.7.2005), Uluppoonni and Vellikulam landslides (31.7.2005) (Staff Reporter 2005b) and the Meladukkam landslides on 22nd and 23rd June 2007 (Sankar 2007b). The first weeks of south-west monsoon in the region initiates rock slips and falls leading to suspect the action of swelling clays. Thampi et al. (1998) concluded that the region can experience debris flows if it receives 300 mm of rainfall in 2 days period. This is by far the only available rainfall threshold for debris flow initiation in the whole state. In addition to high-intensity rainfall, high velocity wind is also strongly suspected to be a trigger by local inhabitants. Meladukkam landslide (23.7.2007) provided initial evidences of wind-loading effects. A tree was uprooted at the initiation zone in a wind velocity of 6.4 m/s immediately followed by a high-intensity rainfall of 123 mm/h resulting in a huge boulder to dislodge initiating a debris flow (Sankar 2007b). An intensive research work measuring pore pressures and rainfall intensities is ongoing in Meladukkam region under the auspices of UNU-ITC School for DiGM and CESS. Expectations are to arrive at relationships between slope instability, critical pore pressure fluxes and associated rainfall intensities.

Idukki

The highland region covers majority of Idukki district making it inherently prone to landslides. Periyar River originates in this district and thus the 1341 AD flood and landslides may have had its origin in the upslope of this district. Several major and minor lineaments crisscross the district. The most famous landslide of the district occurred in Venniyani mala (9.7.2002) that killed Mr. Victor George, a maverick press photographer who ventured to capture the photograph of a debris flow (Aravind 2003). Some landslides that caused significant damage to property in the district are the Kumpanpara landslide (26.6.1985) (Rajagopalan et al. 1985); Perumala landslide on November 1992 (Thampi et al. 1993); Bison Valley village landslide (14.7.1994) (Thampi et al. 1994) and Munnar slides on 25th and 26th July 2005 (Ramalingam et al. 2006); Kozhippalli, Velliyani mala and Methotti mala (31.7.2005) (Staff Reporter 2005b); Edamuttam, Churuli, Dyemukku-Vandiperiyar and Chelachuvadu landslides (22.6.2007); Periyar Valley landslide, Kudikayathil, Rajapuram, Konnathadi and Muthanmudi landslides on (01.7.2007) (Muraleedharan and Muraleedharan 2007a). The slope stability on the flanks of Kottayam–Kumali road was also investigated in detail by various scholars. Seventy landslides and slips occurred along the Kattapana–Thodupuzha route between 20th and 25th August 2000 (Staff Reporter 2000). A 4.4 ha forest land in Mankulam experienced rotational slumping along arcuate fractures creating a displacement of 10–15 m. The land was cleared of tropical hardwood trees and replanted with softwood Acacia trees. The Acacia trees were removed in the recent past (Sankar 2007b).

Ernakulam

The natural dam that got created by the 1341 AD landslide event is in this district. Neriyamangalam village has experienced landslides in the past. Most of the recent landslides in the district are associated with granite quarries and the railway line connecting Kottayam and Kochi. The latest of the incidents were reported from Urakkadu quarry on 17.1.2008 (United News of India 2008), Kuzhoor quarry on 22.12.2007 (United News of India 2007) and Kuruppunthara along the railway line on 14.7.2007 (Indo-Asian News Service 2007).

Thrissur

Landslides were reported from Akamala, Kilimangalam, Chelakkara, Wadakkancherry and Enkakkad in 2000 and 2004. Vellikulangara experienced a significant damage on 14th July 2005 (Staff Reporter 2005a). Two landslides have been reported in Kuthiran (17.7.2007) and one at Vattoly (18.7.2007) (Sankar 2007b). The road connecting Thrissur–Palakkad (National Highway 47) was closed for days together due to the slides at Kuthiran.

Palakkad

The Palghat gap runs through this district. The gap has steep northern and southern faces with the southern having steeper gradient rising from 300 to 1,000 m. The northern face has a more gradual rise (Chattopadhyay 2004). Numerous landslides were reported from various parts of the district, they being the Palakkayam slump, subsidence and creep on 26th and 27th of July 1992, Elachivali landslide (14.11.1992) (Rajagopalan and Pitchaimuthu 1995), Kallumala landslides in Attappady hills (Earnest et al. 1995) and Chundakkadu landslide (25.8.2000) (Staff Reporter 2000). The Chundakkadu landslide was the first of its kind that occurred in the Nelliyampathy hills in the recent history. Environmentalist groups active in the region claimed that the landslide occurred in a region deforested of hardwood tropical trees some years prior to the event. The Palakayam events were identified to be a result of piping (Thampi et al. 1992a). The Nemmara–Nelliyampathy (SH) road was blocked for 2 days due to nine landslides that occurred on 16.7.2007.

Malapuram

Erandu and Perinthalmanna taluks of the district are the most susceptible. Clear evidences of circular deep seated failures are observed in the district. The known reports of landslides in the region are the Alapara, Odakkayam, Edavanna, Mannarmala landslides and Chengara–Kottavumala slump

(17.7.2007) and Chepilikunnu landslide (03.7.2007) (Muraleedharan and John 2007b). Paleo-slide scars are observed along the Vazhikkadav–Nadukani road, which was an active trade route ever since the past. Slumping and creeping owing to drainage obstruction was observed along the route on 6th September 2007 (Muraleedharan and Kurien 2007).

Kozhikode

Kozhikode experiences extremely catastrophic landslides in terms of loss of life unlike other districts. The risk to human life is significantly high with 1,228 people/km^2 (Census of India 2001) making it the second most densely populated district in the state. The Wayanad plateau margins runs through this district creating an abrupt variation in slope and terrain conditions conducive for slope failure. Well-studied landslides that occurred in the region include Chengodumala rockfall in 1989, Koorachundu (13.10.1990), Marudonkara (4.8.2004) (Sankar 2005b) and Nittukottamala (see Table 1) (Raj and Muraleedharan 2004). Orangattukunnu, Periyamala (21.7.2007), Thoradumala (17.7.2007) experienced slumps and Thottumukkom and Anayode (17.7.2007) experienced landslides (Muraleedharan and John 2007a).

Wayanad

The topography of the district is rolling with Wayanad plateau forming most part of it. The altitude of the district varies from 700 to 2,100 m (MSL). The district is bounded to the south-west by the plateau margins and the plateau itself is interspersed with intermitted high rising hills making parts of the district topographically vulnerable to landslides. One of the earliest reported and well-studied landslides in the state occurred in Mundakay in 1984 (see Table 1). For many years since 1984, Wayanad was devoid of landslides. A reactivation of the region was observed in 2007 with many parts of the district reporting landslides and slumps with arcuate cracks running all across the hill slopes, Vallamthodu (see Table 1) being a major one among them. The district was the worst affected in 2007 by mass movements (Muraleedharan and Muraleedharan 2007b; Sankar 2007b).

Kannur

Landslides are usually noticed in the steeply sloping terrain of the Western Ghats. However, their occurrences in the coastal tract of Kannur district reveal the possibility of slope instability outside the highland region also. Mass movements in isolated patches are noticed in Ezhom and Cherukunnu panchayats. Arikkamppara and Chandanakkampara localities of the district are also affected by landslides. Land subsidence occurred in the Chattivayal ward of the Cherupuzha Panchayat in the Taliparamba taluk on September 9, 2005, reason for which was subsurface piping (Sankar 2005a). Ayyankunnu, Parakkamala, Palthukadavu, Santhigiri, Vendakkanchal–Kelakam, Chappan mala–Kottiyur and Kadakampara experienced mass movements such as minor rotational slumps and debris flows in 2007 (Sankar 2007b).

Kasargode

Not many landslides are reported from Kasargode district. Nevertheless, a landslide occurred at Chandragiri on 13.6.1994 and another at Karingode on 6.7.1995 in the district.

Case studies

Three well-studied events are briefly discussed below. The events are the Mundakay landslide, the Amboori landslide and the Adivaram slides (see Table 1). The selection of the events were made in such a way that the intrinsic and extrinsic factors contributing to slope instability in the region is brought out clearly.

Mundakay landslide

The landslide (see Table 1, S. no. 1) initiated in a reserved forest area in the Arunamala hills of Wayanad district at an altitude of 1,240 m (MSL). A rotational landslide that occurred liquefied and changed into a massive debris flow following the path of Arunapuzha stream at around 14.00 h. The debris flow had an average width of 150 m and it travelled 1.5 km from the initiation point to 840 m down hill (Fig. 5). The total area affected by the landslide was 32.3 ha. The volume of material that initiated the debris flow was estimated as 5×10^4 m^3 and the material that was scoured off was 4.5×10^3 m^3 making it the biggest landslide recorded in the state. The area predominantly had gneissic formations. Basak and Prasad (1985) reports that the initiation zone had 3–4 m lateritic deposit overlying micaceous Kaolinitic plastic clay bed of around 3 m thick underlain by a saprolite layer of 10–15 m depth resting over the bed rock. The weathered gneisses were observed to have two sets of joints (vertical and horizontal) and were dipping parallel to the terrain slope of approximately 35°. Rainfall records show that the region received 340 mm rainfall on the day of the landslide, which was the peak rainfall of the year in the middle of an above average south-west monsoon rainfall season. Increase of pore pressure in the already saturated clayey layer as a result of this high-intensity rainfall is considered as the cause of the

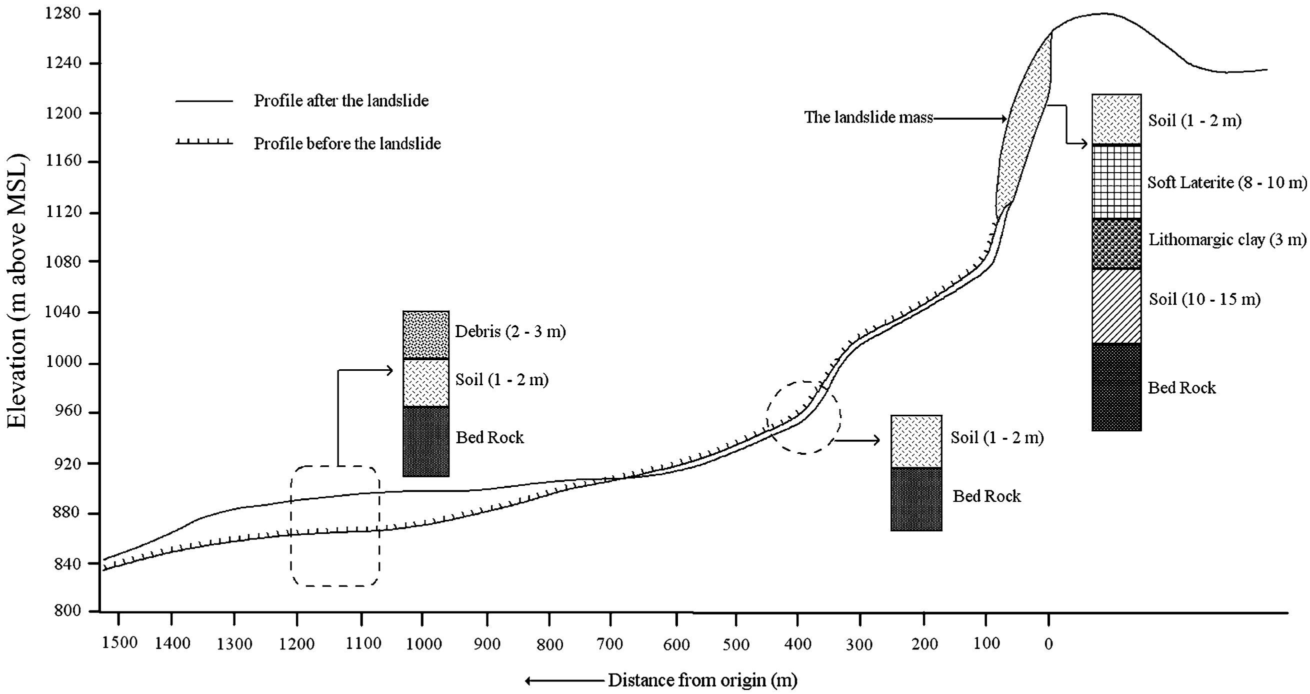

Fig. 5 Cross section of Mundakay landslide (Modified after Basak and Prasad 1985)

landslide. This is supported by evidences from the unconfined compression tests on various layers of overburden sampled from the region that indicated an 84% loss of strength for a 30% increase in moisture content.

Mundakay is an exceptional landslide in the modern history of Kerala in terms of the extrinsic factors that lead to it. No direct evidences of anthropogenic disturbances could be found from the initiation zone, unlike the numerous landslides that are reported every year from all over the state, including Wayanad district. This landslide thus indicates that landslides may have been occurring in the past at a lower intensity than that at present, as they are principally a landscape evolutionary process.

Adivaram debris flows

Adivaram debris flows are notable for the scientific attention it triggered on understanding the mechanisms of numerous shallow landslides that occur in the region. The cumulative destruction caused by these shallow landslides surpasses most other known natural hazards in the state. These debris flows of 6th October 1993 paved way for developing the regional landslide hazard assessment methodology by Thampi et al. (1998) currently practised in the state. The debris flows of 1993 (see Table 1, S. no. 5) initiated in typical hollows (Fig. 6) with slopes ranging from 16° to 32°. The hollows had degraded natural scrubby vegetation (Harikrishnan et al. 1995). Most of the debris flow initiation zones were located in terraced rubber

Fig. 6 A typical hollow after failure

plantations that obstructed ephemeral streams. Rubber plantations with tree sapling of <7 years of age were also seen to have been subjected to debris flows. The average dimension of the initiation locations was 5–10 m in width and 2–5 m in length, with the runouts reaching to the nearest confluence with a higher order stream. In all the cases, bed rock remained intact constraining instability to the overburden. The rainfall records from nearby Pullikanam show that the 2 day cumulated rainfall on 6th October was 315 mm. The year experienced 5,415 mm rainfall, almost 300 mm more than the mean annual rainfall from 1950–2007 for the region. A significant relationship was observed with the slope length and initiation locations; 157 of 182 surveyed events occurred in slopes of 150–450 m length (Thampi et al. 1998). Overburden of the region was identified as cohesion-less frictional soils having an average depth of 1 m resting over hard crystalline charnokites (Chandrakaran et al. 1995). The major land-use up to

600 m (MSL) was rubber plantations, beyond which hill crops such a cassava and cardamom were grown. Cassava plantation was noticed along the head scarp of several debris flows.

A back analysis was carried out based on infinite slope model to assess the effect of perched water table in determining the failure of 34 of these locations that are in the upper Tikovil river basin (Kuriakose 2006). Scenarios of dryness and half saturation were assessed keeping cohesion at the average reported. The parameter values used (based on Thampi et al. 1998 and Chandrakaran et al. 1995) and the corresponding factor of safety for five landslide locations in Tikovil River basin (a sub-catchment in the area) are shown in Table 2. Among the 34 landslides analysed, three remained stable even under saturated conditions owing to the low slope values (<10°) estimated for the locations; slide 4 in Table 2 is an example. Seven out of 34 remained unstable in dry conditions as well; slide 5 in Table 2 is an example. The reason for this can be attributed to the local variability of the intrinsic parameters that are not captured by the estimates of such variables based on generalised soil units and slope values derived from a coarse resolution digital elevation model of 20 m.

Amboori landslide

Amboori landslide is a classic example of the influence of unsustainable land-use practises, careless developmental activity and unplanned housing on increasing the vulnerability to natural hazards in the state (see Table 1, S. no. 16). It was a debris flow (Fig. 7) that initiated in a convex slope of 38° that had accumulated an overburden of 1–2 m unconsolidated colluvium, boulders, laterite, saprolite and lithomargic clay. The approximate volume of material involved in the slide was 5,000 m^3. Lithology comprises highly migmatised metapelitic sequences banded with charnockites and gneisses. The slope was terraced for rubber plantation and an ephemeral stream was obstructed near the initiation zone. The initiation zone was 245 m above (MSL) and the runout reached 155 m downhill as a confined flow that traced the original path of the ephemeral stream, travelling a distance of ~1 km. Houses constructed in the lower reaches of the obstructed stream and the road that intercepted the slope just below the crown were all destroyed. The exposed bedrock at the hill summit routed significant amounts of water to the failure location. The upslope exposed side of the road, where the slope abruptly ended and created an overhanging phase, acted as a storm water discharge channel resulting in toe erosion of the already precarious slope. High-intensity rainfall of 82.4 mm from 08.30 h to 20.30 h (~time of the event), preceded by an above average seasonal rainfall, was identified as the trigger of the event.

Amboori event is the worst natural disaster that has been reported from Kerala in the recent past excluding the Indian Ocean Tsunami of 2004. It is the only disaster from the state that features in the EM-DAT (2008) with a death toll of 39. Muthu and Muraleedharan (2005) and Sankar (2001) provide a detailed description of the slide, the geotechnical properties of the soil, the vertical and horizontal cross sections and remedial measures.

Table 2 Location characteristics and factor of safety for various soil saturation scenarios of some of the 1993 Adivaram shallow landslide initiation locations

S. no.	Sl (°)	SC (kPa)	SD (m)	AIF (°)	SBUW (kN/m^2)	FS (–)		
						S	HS	D
1	16.2	0.0140	1.75	24.9	13.0	0.32	0.99	1.66
2	21.3	0.0017	1.75	39.9	15.9	0.67	1.46	2.25
3	28.6	0.0066	0.75	30.9	14.7	0.21	0.71	1.21
4	10.7	0.0017	0.75	39.9	15.9	1.61	3.03	4.45
5	39.2	0.0140	1.75	24.9	13.0	0.00	0.32	0.69

Sl Slope, *SC* soil cohesion, *SD* soil depth, *AIF* angle of internal friction, *SBUW* soil bulk unit weight, *FS* factor of safety, *S* saturation, *HS* half saturation, *D* dry

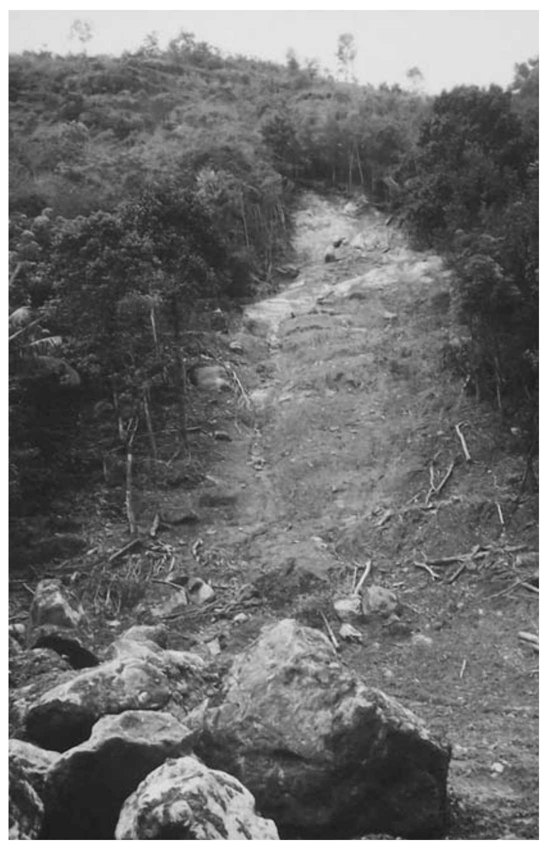

Fig. 7 Amboori landslide

Concluding remarks

Based on the above discussions, it is evident that the physical and climatic setting of Kerala favours slope instability. Majority of mass movements in Kerala occur in hill slopes >20° along the Western Ghats scarps, only exception being the coastal cliffs. Shallow landslides and debris flows are more common than deep seated ones. Debris flows normally result in the development of new lower-order streams, opening up of natural blocked/diverted drainage lines and/or widening of existing lower-order streams. Wayanad and Kozhikode districts located north of Palakkad Gap are more prone to deep-seated landslides, which can be explained by the higher quantities of monsoon rainfall received by this part of the state. Among the districts south of the Palghat Gap, the scarp lands along Idukki and Kottayam are the most susceptible to landslides in general and debris flows in particular. Almost all mass movements occur during monsoons (see Table 1 for dates) indicating that the main triggering mechanism is pore pressure variations as a result of the combination of prolonged and high-intensity rainfall. Piping is also a major intrinsic contributor to landslide initiation in the region.

Ancient documents reveal only indirect indications of landslides in the past, probably confined to rainfall intensities of extreme return intervals. The intensity of landslides is observed to have increased since the population expansion in the late 19th century. The process is accelerated by anthropogenic disturbances such as deforestation, terracing and obstruction of ephemeral streams and cultivation of crops lacking capability to add root cohesion in steep slopes. Invariably, in most of the failed slopes, natural drainage was blocked or modified by terracing without adequate provision for surface drainage of excess storm water during high-intensity rains. Unplanned developmental activities like construction of buildings, road cuttings, cut and fill structures and withdrawal of toe support have also seen to increase the risk to the society from landslides.

Processes that lead to landslides were in action even before human kind evolved on earth’s surface; constant destruction (weathering and erosion) and rebuilding (rejuvenation) are those that have shaped the earth. These geophysical events that were part of the natural evolutionary system of the earth turned into “natural hazards” when the human system started interacting with it. These transformations and their links to the natural system have served as templates of the dynamics of natural hazards and, therefore, of natural disasters (Alcantara-Ayala 2002). The landslide-prone regions of the Kerala segment of Western Ghats are an ideal example of such templates. Considering the ongoing population expansion to landslide-susceptible areas and the lack of long-term data to establish relevant statistical relationships, physically based dynamic models capable of quantifying the nature–human interaction and assessing the spatio-temporal probabilities of landslide initiation is the need of the hour in Kerala.

References

Aiya VN (1906) The Travancore State Manual I, II & III (1906, 1st edn, and 1999, new edn). Kerala Council for Historical Research, Thiruvananthapuram, India

Alcantara-Ayala I (2002) Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. Geomorphology 47(2–4):107–124

Aravind N (reporter) (2003) Light, shade and rain, The Hindu news paper, 6 July 2003, Thiruvananthapuram, India, Online edition. http://www.hindu.com/thehindu/mag/2003/07/06/stories/2003070600230400.htm. Accessed 7 Jan 2007

Babu DSS, Nair AG, Jayaprasad BK (2007) Evolution of Kerala coast during Cenozoic and evidences of Holocene tectonism, extended abstracts of the international workshop on fluvial and marine processes of Cenozoic and Placer formation, 1–10 November 2007. Centre for Earth Science Studies, Thiruvananthapuram, and National Institute of Oceanography, Goa, India

Babu DSS, Nandakumar V, John B, Jayaprasad BK, Pramod SV (2000) Siltation analysis in the Neyyar reservoir and forest degradation in its catchment: a study from Kerala state, India. Environ Geol 39(3):390–397

Balakrishnan TS (2001) Tectonics of Western India inferred from gravity patterns and geophysical exploration. In: Gunnell Y, Radhakrishna BP (eds) Sahyadri—the great escarpment of the Indian subcontinent (patterns of landscape development in the Western Ghats). Geological Society of India, Bangalore, India, pp 271–277

Basak P, Prasad NBN (1985) Landslides in the Western Ghats. In: Proceedings of the workshop on landslides in Western Ghats, 30–31 July 1985, Kozhikode, India. Kerala State Committee on Science, Technology and Environment

Basak P, Prasad NBN (1989) Recurring landslides in the Western Ghats—an environmental hazard. Environ Conserv 16(2):169–172

Buchanan-Hamilton F (1807) A journey from Madras through the countries of Mysore, Canara and Malabar for the express purpose of investigating the state of agriculture, arts and commerce; the religion, manners and customs; the history natural and civil and antiquites I, II & III (reprinted in 1988). Asian Educational Services India Ltd, New Delhi, India

Census of India (2001) Population distribution, percentage decadel growth rate, sex ratio and population density of Kerala, 2001. Government of India. http://kerala.gov.in/statistical/vitalstatistics/1.02.pdf. Accessed 16 Mar 2007

Chandrakaran S, Paul KV, Nambiar MRM (1995) Geotechnical characteristics of landslide prone areas of Idukki and Kottayam districts of Kerala. In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Chattopadhyay S (1985) Deforestation in parts of Western Ghats region (Kerala), India. Int J Environ Manag 20:219–230

Chattopadhyay S (2004) Landforms of Kerala: an overview. In: Kumar GRR, Subhash N (eds) Earth system science and natural resources management, silver jubilee compendium. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India, pp 211–288

Chattopadhyay S, Mahamaya C (1995) Terrain analysis of Kerala, technical monograph 1/95. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, Kerala

Chinnamani S, Venkataraman C, Tejwani KG (1980) Landslides and landslips in Peninsular India. Bull Central Soil Water Conserv Res Train Inst 4

Devoli G, Morales A, Hoeg K (2007) Historical landslides in Nicaragua—collection and analysis of data. Landslides 4(1):5–18

Earnest A, Khan A, Nair GD (1995) Role of groundwater in landslide initiation on Western Ghats, new case histories from Palakkad district, Kerala. In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Ellen SD (1988) Description and mechanics of soil slip/debris flows in the storm. In: Ellen SD, Wieczorek GF (eds) Proceedings of the conference on landslides, floods and marine effects of the storm of January 3–5, 1982, in the San Francisco Bay Region, California, Washington, USA, USGS professional paper 1434

EM-DAT (2008) Emergency disasters data base. Center for Research on the Epidemiology of Disasters, Université Catholique de Louvain—Ecole de Santé Publique. http://www.em-dat.net/disasters/Visualisation/emdat_display_list.php. Accessed 12 Jan 2008

ENS and Agencies (reporter) (1999) Over 25 pilgrims killed in landslide at Pamba, The Indian Express news paper, 15 Jan 1999. Thiruvananthapuram, India, Online edition. http://www.indianexpress.com/res/web/pIe/ie/daily/19990115/01550755.html. Accessed 5 July 2001

FSI (2003) State of the forests report—Kerala, Forest Survey of India, Ministry of Environment and Forests, Dehradun, India. http://www.fsi.nic.in/sfr2003/kerala.pdf. Accessed 14 Mar 2006

George PS, Chattopadhyay S (2001) Population and land use in Kerala. In: Wolman MG (ed) Growing populations changing landscapes: studies from India, China, and the United States. National Academy Press, Washington, DC, pp 79–106

Gopinath CI (1985) Debris Flows in the Western Ghats [*Urulpottal Paschimaghattathil* (in Malayalam)]. In: Workshop on landslides in Western Ghats, 30–31 July 1985. Kerala State Committee on Science, Technology and Environment, Kozhikode, India

Government of India (1956) Forests and soil conservation, second 5 year plan. Department of Education, Ministry of Human Resource Development and National Informatics Centre, New Delhi, India. http://www.education.nic.in/cd50years/15/8P/8A/8P8A0G01.htm. Accessed 8 May 2007

Greenway DR (1987) Chapter 6: vegetation and slope stability. In: Anderson MG, Richards KS (eds) Slope stability. Wiley, West Sussex

Gupta HS (2001) Terrain evaluation for eco-restoration using remote sensing and GIS. In: Proceedings of the 4th AGILE conference on GIScience, 19–21 April 2001, Brno, Czech Republic. Association of Geographic Information Laboratories, Europe (AGILE). http://plone.itc.nl/agile_old/Conference/brno2001/proceedings/50.pdf. Accessed 14 April 2006

Guzzetti F, Reichenbach P, Cardinal M, Ardizzone F, Galli M (2003) The impact of landslides in the Umbria region, central Italy. Nat Hazards Earth Syst Sci 3(5):469–486

Harikrishnan K, Manoj B, Dinakar VS, Nair NH, Sankar G, Mathai J, Thampi PK (1995) Proper landuse practice—an effective mitigation measure for landslide. In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Harikumar B (2004) A passage to the past: an engineering sage in which each and every event has a magical charm. Kerala calling. http://kerala.gov.in/keralcalnov04/p24-25.pdf

Harikumar R, Kumar VS, Sampath S, Vinayak PVSSK (2007) Comparison of drop size distribution between stations in Eastern and Western coasts of India. J Indian Geophys Union 11(2):111–116

IMD (2007) South-west monsoon 2007: end of season report, Indian Meteorological Department, Government of India. http://www.imd.gov.in/section/nhac/dynamic/endmonsoonreport2007.htm. Accessed 1 Jan 2008

Indo-Asian News Service (reporter) (2007) Rains subside but Kerala continues to suffer, Latest News India, 19 July 2007. Kochi, India, Online edition. http://www.freshnews.in/rains-subside-but-kerala-continues-to-suffer-13494. Accessed 10 Aug 2007

Ittekkot V, Subramanian V (2001) Nature of organic carbon in rivers of Kerala. ENVIS Newsletter 7(3): special abstract volume of the international workshop on ecohydrology (Theme: Western Ghats in Kerala). http://envisjnu.tripod.com/newslet/newslet-framev7n3.html. Accessed 14 Dec 2007

Jha CS, Dutt CBS, Bawa KS (2000) Deforestation and landuse changes in Western Ghats, India. Curr Sci 79(2):231–237

KSFWD (2004) History of Kerala forestry. Kerala Forests and Wildlife Department. http://www.keralaforest.org/html/general/index.htm. Accessed 12 Jan 2008

Kumar BM (2005a) Land use in Kerala: changing scenarios and shifting paradigms. J Trop Agric 42(1/2):1–12

Kumar BM (2007) Flood situation report—2007 (No. 137/2007, 1700 hours, LAST SITREP). Disaster Management Division, Ministry of Home Affairs, Government of India. http://www.ndmindia.nic.in/flood-2007/floods2007.htm. Accessed 12 Jan 2008

Kumar KSS (2005) Geo-informatics in landslide risk assessment and management in parts of Western Ghats, Central Kerala, South India. PhD Thesis, Indian Institute of Technology Bombay, Mumbai, India

Kumar VS, Sampath S, Vinayak PVSSK, Harikumar R (2007) Rainfall intensity characteristics at coastal and high altitude stations in Kerala. J Earth Syst Sci 116(5):451–463

Kuriakose SL (2006) Effect of vegetation on debris flow initiation: conceptualisation and parameterisation of a dynamic model for debris flow initiation in Tikovil River Basin, Kerala, India, using PCRaster. MSc Thesis, International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands, and Indian Institute of Remote Sensing, Dehradun, India, p 133. http://www.itc.nl/library/Academic_output/AcademicOutput.aspx?p=1&y=6&l=20

Kuriakose SL, van Westen CJ, Lakhera RC, van Beek LPH, Sankar G, Alkema D, van Asch TWJ, Jayadev SK (2006) Effect of vegetation on debris flow initiation—conceptualisation and parameterisation of a dynamic model for debris flow initiation in Tikovil River Basin, Kerala, India, using PCRaster. In: Proceedings of the 2nd international symposium on geo-information for disaster management (Gi4DM)—remote sensing and GIS techniques for monitoring and prediction of disasters, Goa, India, 25–26 Sept 2006. International Society for Photogrammetry and Remote Sensing

Kusala R, Rajendran CP (1995) Occurrences of micro-earthquakes and landslides in Kerala: are they related? In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India.

Lal M, Meehl GA, Arblaster JM (2000) Simulation of Indian summer monsoon rainfall and its intraseasonal variability in the NCAR climate system model. Reg Environ Change 1(3):163–179

Logan W (1887) The Malabar manual I & II (reprinted in 2000). Asian Educational Services, New Delhi

Malet J-P, van Beek R, Thiery Y, Maquaire O (2005) Distributed physically-based slope stability models as forecasting tools to define hydro-climatic thresholds for rainfall-induced landslides. In: Proceedings of the European Geosciences Union General Assembly 2005, Vienna, Austria, European Geosciences Union, Geophysical Research Abstracts, vol 7. http://www.cosis.net/abstracts/EGU05/02522/EGU05-J-02522.pdf

Markham CR (1866) On the effects of the destruction of forests in the Western Ghauts of India on the water-supply. J R Geogr Soc Lond 36:180–195

Muraleedharan MP (1995) Landslides in Kerala—a drenched state phenomena in regolith. In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Muraleedharan C, John MK (2007a) Report on recent landslides in Koilandy and Kozhikode taluks, Kozhikode district, Kerala. Investigation report. Geological Survey of India, Government of India, Thiruvananthapuram, Kerala

Muraleedharan C, John MK (2007b) Report on the recent landslides in Eranadu and Perinthalmanna taluks, Malappuram district, Kerala. Investigation report. Geological Survey of India, Government of India, Thiruvananthapuram, India

Muraleedharan C, Kurien S (2007) Report on the Kallala 102/800 slump/creep, Vazhikkadavu, Malappuram district, Kerala. Investigation report. Geological Survey of India, Government of India, Thiruvananthapuram, Kerala

Muraleedharan C, Muraleedharan MP (2007a) Report on recent landslides in Thodupuzha, Udumbanchola and Devikulam taluks, Idukki district, Kerala. Geological Survey of India, Government of India, Thiruvananthapuram, India

Muraleedharan C, Muraleedharan MP (2007b) Report on recent landslides in Wayanad district, Kerala. Geological Survey of India, Government of India, Thiruvananthapuram, India

Muthu RP, Muraleedharan C (2005) Causes and Mechanism of Amboori Landslide of 9th November, 2001, Thiruvananthapuram district, Kerala. J Geol Soc India 66(2):203–208

Nair KM, Chattopadhyay S, Sasidharan CK (1997) Analysis of the environmental impact of the lowland to highland migration in the Western Ghats region, Kerala. Technical report submitted to the Ministry of Environment and Forests. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Pisharody PR (1992) Climate of Kerala [*Keralathile Kalavastha* (in Malayalam)]. State Institute of Languages. Government of Kerala, Thiruvananthapuram, India

Putthacharoen S, Howeler RH, Jantawat S, Vichukit V (1998) Nutrient uptake and soil erosion losses in cassava and six other crops in a Psamment in eastern Thailand. Field Crops Res 57(1):113–126

Radhakrishnan SA (reporter) (2006) Cliff at Varkala facing threat of extinction, The Hindu news paper, Varkala, India, Online edition, 14 July 2006. http://www.hindu.com/2006/07/14/stories/2006071423050300.htm. Accessed on 16 June 2006

Raj UD, Muraleedharan C (2004) A geotechnical report on the Nittukottapara landslide of 4th August 2004, Badagara taluk, Kozhikode district, Kerala. Geological Survey of India, Government of India, Chennai, India

Raj KG, Paul MA, Hegde VS, Nilagunappa R (2001) Lineaments and seismicity of Kerala: a remote sensing based analysis. Photonirvachak J Indian Soc Remote Sens 29(4):203–211

Rajagopalan G, Pitchaimuthu R (1995) A geotechnical appraisal of slide at Elachivali village, Mannarkkadu Taluk, Palakkad district, Kerala. In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Rajagopalan SP, Prasad NBN, Nazimuddin M, Basak P (1985) Landslides in the high ranges of Western Ghats within Idukki district—a brief exposition. In: Proceedings of the workshop on landslides in Western Ghats, 30–31 July 1985, Kozhikode, India, Kerala State Committee on Science, Technology and Environment

Ramalingam E, Muraleedharan C, Chandrasekaran S (2006) A geotechnical report on the Munnar landslide of 25th July 2005, Idukki District, Kerala. Engineering Geology Division (Southern Region), Geological Survey of India, Government of India, Chennai, India

Sampath S, Vinayak PVSSK, Kumar VS (1995) Rainfall—a trigger for landslides. In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Sankar G (1991) Landslides in Koodaranji and Koorachundu, Calicut district. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Sankar G (2001) A preliminary report on the November 9th landslide at Amboori Panchayath, Thiruvananthapuram district. Site Investigation report. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Sankar G (2005a) Investigation of the land subsidence in Chattivayal locality of Cherupuzha gram panchayat, Taliparamba taluk, Kannur district. Investigation report. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Sankar G (2005b) Landslides of Kerala and their management. In: Rajamanickam GV (ed) Proceedings of the National Seminar on Landslides, Thanjavur, India, SASTRA Deemed University

Sankar G (2007a) Chapter 1: natural hazards. In: Yesodharan EP, Kokkal K, Harinarayanan P (eds) State of the environment report of Kerala 2007, vol II: natural hazards. Kerala State Council for Science, Technology and Environment, Government of Kerala, Thiruvananthapuram, India

Sankar G (2007b) Landslides in Kerala during the south-west monsoon, 2007. Investigation report. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Sankar G, Mathai J, Sidharthan S (2004) Landslide mitigation study in landslide prone areas of Pathanapuram taluk. CESS-PR-36-2004. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Santhi S (2004) Forests, river valley projects and displacement: a pilot study of the impact of displacement by the Peppara dam on the Kani tribal families in the Vithura panchayath of the Thiruvananthapuram district. Unedited report. Kerala Research Programme on Local Level Development, Centre for Development Studies, Thiruvananthapuram, India. http://www.krpcds.org/report/santh.pdf. Accessed 20 Aug 2006

Soman K (2002) Geology of Kerala. Geological Society of India, Bangalore, India

Soman MK, Krishnakumar K, Singh N (1988) Decreasing trend in the rainfall of Kerala. Curr Sci 57(1):7–12

Sreekumar S, Krishnanath R (2000) Stability of Lateritic profiles in parts of Western Ghats, India. In: Bromhead EN, Dixon N, Ibsen M-L, Sfakianaki E (eds) Landslides in research, theory and practice: proceedings of the 8th international symposium on landslides held in Cardiff, England, June 26th–30th, 2000. Thomas Telford Ltd., London, pp 1395–1400

SSB and NBSS&LUP (1979) Soils of Kerala. Soil Survey Branch, Department of Agriculture, Government of Kerala and National Bureau of Soil Survey and Landuse Planning, Thiruvananthapuram, India

Staff Reporter (2000) Monsoon wreaks havoc in State, The Hindu news paper, 26 Aug 2000. Thiruvananthapuram, India, Online edition. http://www.hinduonnet.com/2000/08/26/stories/0426211t.htm. Accessed 17 May 2001

Staff Reporter (2001) The magic of Bhoothathankettu, The Hindu news paper, 28 Dec 2001. Kochi, Kerala, India, Online edition. http://www.hinduonnet.com/2001/12/29/stories/2001122903250300.htm. Accessed 1 Sept 2003

Staff Reporter (2005a) Landslide in Trichur: two doubted missing [*Trissuril Urul pottal: Randupere kananillannu samshayam* (in Malayalam)], ThatsMalayalam.com, 14 July 2005. Kochi, India, Online edition. http://thatsmalayalam.oneindia.in/news/2005/07/14/kerala-landslide.html. Accessed 7 Jan 2006

Staff Reporter (2005b) Landslides strikes Idukki again [*Idukkiyil veendum mannidichil (in Malayalam)*], ThatsMalayalam.com, 1 Aug 2005. Idukki, India, Online edition. http://thatsmalayalam.oneindia.in/news/2005/08/01/kerala-landslide-idukki.html. Accessed 17 Jan 2006

Thakur VC (1996) Landslide hazard management and control in India. Status report. International Center for Integrated Mountain Development, Kathmandu, Nepal

Thampi PK, Mathai J, Sankar G (1992a) Evaluation of slope failures and subsidence phenomenon around Palakkayam village, Mannarghat taluk, Palghat district Kerala. Investigation report. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Thampi PK, Mathai J, Sankar G (1992b) Land distrubances at Ottakkal area, Quilon district, Kerala. Investigation report. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Thampi PK, Mathai J, Sankar G (1993) Land disturbances at Kandalur area of Devikolam taluk, Idukki district, Kerala. Investigation report. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Thampi PK, Mathai J, Sankar G (1994) Urul pottal (landslides) in the Bison Valley, Idukki district. Investigation report. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Thampi PK, Mathai J, Sankar G (1995) A regional evaluation of landslide prone areas in the Western Ghats of Kerala. In: Abstracts of the national seminar on landslides in Western Ghats, 29–30 Aug 1995. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Thampi PK, Mathai J, Sankar G, Sidharthan S (1998) Evaluation study in terms of landslide mitigation in parts of Western Ghats, Kerala. Research report submitted to the Ministry of Agriculture, Government of India. Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India

Thigale SS, Khandge AS (2005) Coping with landslide disasters in the Western Ghats. In: Valdiya KS (ed) Coping with natural hazards: Indian context. Orient Longman, New Delhi, pp 153–164

United News of India (reporter) (2007) Five labourers killed in quarry landslide, NewKerala.com, 22 Dec 2007. Kochi, India, Online edition. http://www.newkerala.com/one.php?action=fullnews&id=6548. Accessed 18 Jan 2008

United News of India (reporter) (2008) One killed in landslide, WebIndia123.com, 18 Jan 2008. Kochi, India, Online edition. http://news.webindia123.com/news/Articles/India/20080118/871388.html. Accessed 19 Jan 2008

van Asch TWJ, Buma J, van Beek LPH (1999) A view on some hydrological triggering systems in landslides. Geomorphology 30(1/2):25–32

Vijith H, Madhu G (2007) Estimating potential landslide sites of an upland sub-watershed in Western Ghat's of Kerala (India) through frequency ratio and GIS. Environ Geol. doi: 10.1007/s00254-007-1090-2

Wasowski J (1998) Understanding rainfall-landslide relationships in man-modified environments: a case-history from Caramanico Terme, Italy. Environ Geol 35(2–3):197–209