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Causative factors of landslides 2019: case study in Malappuram and Wayanad districts of Kerala, India

Abstract Several landslides and floods were triggered by unprecedented, incessant heavy monsoon rainfall from 4 August 2019 to 8 August 2019, along the northern slopes, at Kavalappara, in the Malappuram district and Puthumala, in the Wayanad district of Kerala, India. The geological and geomorphological field settings were analyzed within the sub-basin wide catchment areas, for a preliminary evaluation of the causative factors of the landslides. This paper provides insights into the causative factors of landslides, together with suggestions on appropriate land use planning and deployment of real-time flood and landslide monitoring systems, besides building an adaptable community resilience model in high landslide-prone areas. The structurally disturbed weakened bedrocks and generally incompetent residual alteration products, exacerbated by nonchalant human interventions, reduction of cohesive strength, on super-saturation of underlying earth material, were inferred to be the primary causes of major landslides, triggered during 5 days of excessively heavy rainfall (400% over the normal average). Additionally, massive toe erosion was observed by streams gushing with course clastic sediments and debris. The destructive nature of such multi-hazards was evoked by unscientific modifications of slopes, mismanagement of water drainage, unplanned residential developments, across the channel courses and within active floodplain of rivers, and lack of early warning schemes for landslide.

Keywords Landslides · Floods · Multi-hazard · Chaliyar River basin · Kerala

Introduction

The state of Kerala, in southern India, pummeled by rainfall deluge during the monsoon seasons of 2018 and 2019, experienced several landslides and ravaging floods in vulnerable tracts; 65 landslides were reported during the seasonal downpour between June 1 and August 16, 2019 (Chandran (2019); Manorama Online, Aug. 2019).

Huge losses taking a toll of 81 lives and heavy damage to property were reported. Around 8.0 p.m. of 8 August 2019, Kavalappara (site 1, see Fig. 1) in Puthukkad area of Malappuram district suffered multiple hazards of landslide and floods (Shaju Philip, August 2019). The landslide was initiated along the north-facing hill-slopes. The 4th order stream joining the Chaliyar River, flowing west to east, started flooding since the morning of the same day. At 12 noon, the flood level reached more than 2 m above the bridge at Bhoodanam in the Puthukkad area. Similarly, the upper drainage catchment sub-basins, located in Puthumala area (site 2, Fig. 1), in Meppadi region of Wayanad district, were ravaged by multiple hazard floods and landslide events, around 4.0 p.m. of 8 August 2019. Here, the landslides occurred along the north-facing hill-slope in a structurally controlled sub-basin of the Chaliyar River.

A semi-structured interview with the Kavalappara residents settled on the hilly slopes, at site 1 of the landslide area, revealed that they heard cracking sounds of debris flow and uprooting of tall trees. However, they remained trapped, as the only escape route, via the bridge, was inundated with floodwaters. It is a tricky challenge to estimate the actual losses—over 39 houses and a walkover bridge were completely washed away. The main access roads and pathways were unusable, escape routes were blocked, and utility lines were damaged; 69 people lost their lives and more than 150 people were directly affected by the disruptive hazardous incidents. Survivors of the catastrophic incident were traumatized by the widespread destruction and loss of their families and pets. At site 2 (Puthumala), landslides and floods took a toll of 12 human lives and damaged several houses on the affected hill-slopes and active flood plains of the river. The main objective of the current work has been to conduct a field level assessment at these two sites and interpret the causative factors for the major landslides.

The Western Ghats in India has always been a hotspot for landslide research (Kuriakose 2009; Sajin Kumar 2011; Ramesh and Vasudevan 2012). Geological Survey of India's compendium on Landslides of Southern Parts of Western Ghats (GSI, 2016) documents the compiled work done in the area. Landslide-prone sites have been highlighted at several locations (Vijith, 2008), but the information is too gross and is not taken seriously by the concerned disaster management institutions. First-hand reports on landslide provide the ground truth, whereas direct field observations furnish justifications for subsequent detailed investigations (Baroň, 2011, Wadhawan, 2015).

The paper is divided into eight sections. The second section discusses the methodology followed for the research work. Section three describes the geological and tectonic setup of the study area, whereas section four details the geomorphological settings and land cover details. Section five lists the landslide characteristics followed by next section on causative geo-factors that triggered the mass movement. Section seven covers the dynamic variation of hydrological conditions observed in the study area. The last section is the discussion followed by concluding remarks on major causative factors and suggestive remedial measures.

Methods

Preparatory works for this research included procurement, followed by study of relevant maps and geoscientific and meteorological data. Initially, the reported landslide incidents were collected from news items in the published media (Manorama Online, Aug. 2019; Kuttappan 2019). Landslide locations were roughly marked (1:50000 scale) on Survey of India Topographical sheets (source of data: Survey of India) and reviewed for their accessibility and contextual details. The published District Mineral/Geological Resource maps (Source: Geological Survey of India (GSI)) of the landslide-hit areas were procured from GSI for a preview of their geoscience attributes. General inputs were obtained from the GSI

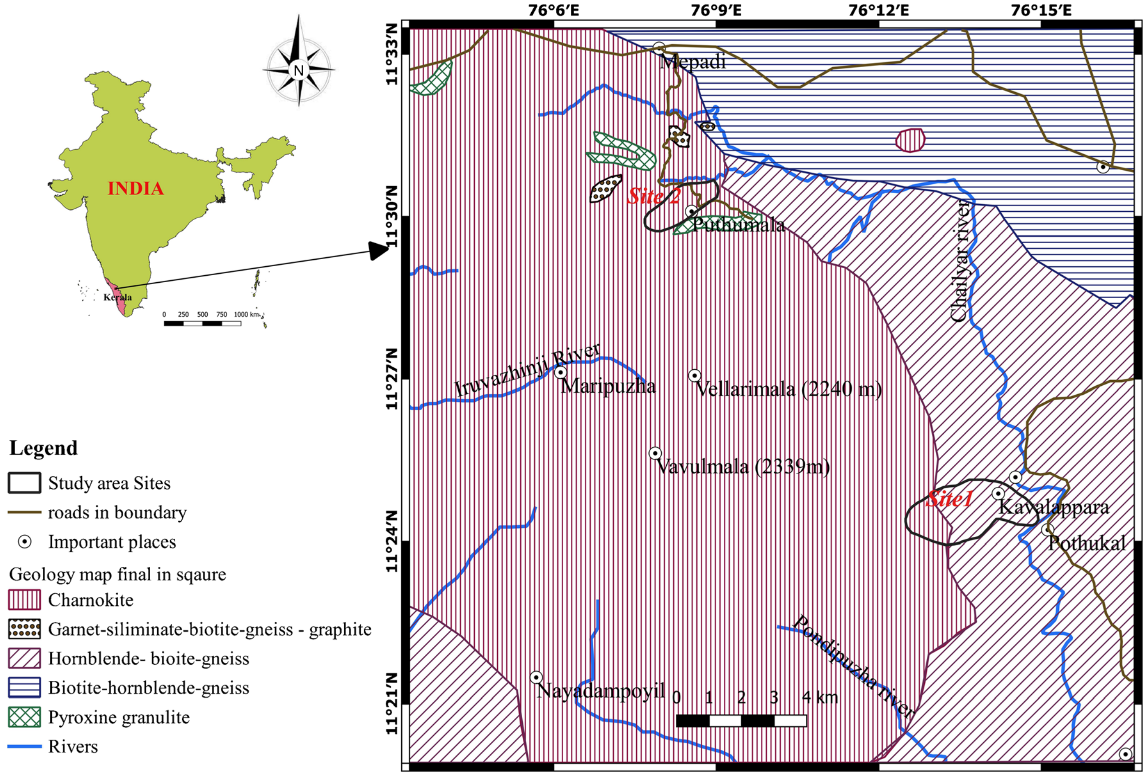

Fig. 1 Generalized map of Geology and Cultural Features of the study area. Source: modified after Geological Survey of India, 2009

office at Thiruvananthapuram, Kerala, who was also involved in the field surveys, at the various landslide-affected sites in Kerala. Based on the preliminary analysis, two major areas, Kavalappara (site 1) and Puthumala (site 2), were shortlisted by our team of experts for the subsequent field investigations. A 5-day field survey was carried out by a group of eight scholars from Amrita Vishwa Vidyapeetham—geologists, landslide monitoring engineers, research scholars, and local coordinators. Mata Amritanandamayi Math, the parent organization of Amrita Vishwa Vidyapeetham, has local youth coordinators in these village regions, which acted as local guides during the field visits. During the preparatory work, geoscientific data sheets were designed as per the attributes listed in Table 8.1 page 154 of Wadhawan (2019). Ground truth surveys were conducted to record the geoscientific data from the geohazard-affected sites. Syntheses and detailed analyses of the collected data were performed on GIS platforms such as Google Earth pro, n.d. (https://www.google.com/intl/en_in/earth/versions/#earth-pro) and Quantum GIS (QGIS) (http://qgis.osgeo.org QGIS Development Team 2018) software. The field photos were edited using Photoshop software (CC 2019, version 20), for depiction of relevant observations and interpretations, from the collected data.

Geological and tectonic setup

The study area is a part of hilly ranges of the Western Ghats, dispersed across four adjoining districts—Wayanad, Kozhikode, and Malappuram districts of Kerala and Nilgiri district of Tamil Nadu—and divided into four major geological units (Fig. 1), noted hereunder:

1. Archaean charnockite, belonging to the Charnockite Group, has a very wide distribution of litho-units such as biotite-hypersthene gneiss and biotite-hornblende-hypersthene gneiss.
2. Pyroxene granulites occur as narrow bands within charnockites.
3. Hornblende-biotite-gneiss and migmatites of the Peninsular Gneissic Complex.
4. Garnet sillimanite-biotite-gneiss, with or without graphite, belongs to the Wayanad Group of supracrustal rocks.>

(Sources: District Mineral Resource Maps of GSI, 2009; District Survey Reports on Minor Minerals 2016 for Wayanad, Kozhikode, 2016 for Malappuram Districts of Kerala, and 2016 Nilgiri District of Tamil Nadu; District Survey Report Coimbatore District 2018; Gunnell and Fleitout 2001)

The formation of residual Laterite Unit, over aforesaid exposed bedrocks, was also observed around mid-slopes of the affected areas, and in many sections exposed along the roads and riverbanks.

At site 2, the topsoil in the area is about 1.5 to 2 m thick, covering a thicker weathered zone over the Achaean crystalline rocks, the charnockite, gneisses, and pyroxene granulites that produced several clayey weathered products. Once saturated with water, these metamorphic rocks and their variably weathered alterations facilitated the mass movement of overlying debris and loose overburden. The landslides in their wake dislodged the bedrock blocks, along the steeply dipping and vertical structural discontinuities and joint planes. The two prominent recorded joint sets were trending along the N-S and NW-SE directions, dipping steeply towards east and northeast, respectively; another joint set was trending along the northeast-to-southwest direction, steeply dipping towards the northwest direction. It is further observed that the landslide debris and earth flows were mostly influenced and failed along the joint sets that are dipping towards northeast.

At site 1, on the other hand, the topsoil in the area is 15 to 20 m thick, covering a thickly weathered zone, developed above the Achaean crystalline rocks (Peninsular Gneissic Complex: Hornblende-Biotite Gneiss/Migmatite Complex). These rocks have subject to prolonged weathering in tropical climate that produced several irregularly distributed clayey alteration products. This phenomenon ominously facilitated the mass wasting of overlying debris overburden and the dislodged rock blocks. In addition to east-west trending fault, two vertically dipping joint sets, E-W (N 85 E) and N-S (N 350 E), were recorded in the bedrocks. Formation of several waterfalls and rapids along drainage courses in the upstream parts of the Chaliyar River was also observed in the area. Presence of waterfalls and sub-parallel drainage pattern in the study area indicates the structural control over evolution of drainage and the landscape.

Geomorphology and land cover

Upper catchment sub-basins of the Chaliyar River, affected by the recent devastating floods and landslides, dominantly drain from west to east. Landslides occurred on the northerly facing hill-slopes at both the locations under study, essentially along the 1st and 2nd order drainage courses at Puthumala (Wayanad district) and Kavalappara (Malappuram district), respectively. However, owing to continuous and excessive rainfall in these areas, the easterly flowing higher order channel also received larger discharge of rock debris and earth materials. The high structural and denudation-ravaged hills, with sub-rounded, dome-shaped, and rugged peaks, were moderate to intensely dissected and form narrow V-shaped valleys in the area (Fig. 2).

There were various waterfalls along drainage courses, ranging from heights of 20 to 86 m, in the upper catchment of the Chaliyar River (the Chalipuza, Kaladipuza, Minutipuza, which are tributary streams of the Chaliyar River). The main Chaliyar River (Fig. 2a) shows straight courses with sharp turnings at nearly 90 degree that imply direct structural control on evolution of drainage pattern. The river flows in the north to south direction, with repeated abrupt changes in the flow direction, particularly near Bhoodanam (Fig. 2c) colony. The slopes of both the landslides in the affected areas are moderate to steep (up to 40 degrees from horizontal surface).

Landslide characteristics

The nature and type of landslides at site 1 (Kavalappara) were unique, as it occurred along trifurcated downslope segments. The consequent three steep 1st order drainage courses acted as the rejuvenated favorable carriers for the discharge of large water-saturated material and rocky debris. The lengths of trapeze-shaped landslides are roughly 300 m, 400 m, and 380 m, respectively (from left to right in Fig. 3), narrow at the top and widening downslope at the base. The dimensions of the major landslide were 80 m wide at the top, 100 m in the middle, and 300 m wide at the bottom. Other associated downslope routes of landslides were approximately 50 to 60 m wide. All the landslides were of the type of debris and earth flow. The runoff material extended over a distance of 250 m that transgressed the channel course and temporarily blocked the southerly flowing river, at the base (Fig. 3).

In the case of site 2, Puthumala (Wayanad district), there were multiple landslides, more than five on the northern- and north-eastern-facing hill-slopes, within the delineated sub-basin of the Chaliyar River. However, only three of them were accessible for detailed field investigations. The types of materials were muddy debris and rock in all the investigated landslides, at all the sites (Fig. 4 and Fig. 8: d, f). All the landslides surveyed were reported to be rapid and sudden, depriving the affected inhabitants of sufficient time to escape to safer places. At the time of field investigation, the landslide masses, i.e., the debris and rock materials, were loose to poorly consolidate and appeared to be precariously perched along mid-slopes. These landslide incidences were located all along the active slopes that were confined to the first-order drainage courses. Besides, the landslide mass had been worked up by excavators for retrieval of buried human bodies, resulted in further loosening and shifting of the muck. These disturbed slopes at a later date need to be stabilized through afforestation etc. to prevent re-initiation of landslide.

Field observations at the site 1, Kavalappara, revealed that the mass wasting must have initially started as shallow planar failure at the hill top, evolving to curvy-planar and rotational failure, further downslope. However, at Puthumala, the landslides were comparatively of smaller dimensions and rapid and shallow planar slope failures. These divergent phenomena could be attributed to the presence of larger soil thickness upheld by a marked interface between the weathered bedrocks and the overlying soils at Kavalappara, thereby yielding a larger volume of mass wasting, whereas at Puthumala, the shallower thickness of soil and closely jointed bedrocks were affected by torrential rains that resulted in discrete and widely scattered events of mass wasting and flash flooding in the upper catchment of the Chaliyar River.

Causative geo-factors that triggered mass movement and floods

According to the Indian Meteorology Department's (IMD's) data, there was a prolonged heavy rainfall from 4 August 2019 onwards, with very heavy torrential downpour on 8 August 2019 (Fig. 5) in most places across the state of Kerala, with exceptionally heavier rainfall at several places. Figure 5 also shows that the rainfall was about 400% in excess of the normal average rainfall, for five consecutive days between 4 and 8 August 2019. The rains reportedly triggered more than 24 small and big landslides across entire Kerala (https://www.downtoearth.org.in/news/india/kerala-rains-24-landslides-in-24-hours-22-killed-22-165-moved-66107).

The anthropogenic activities in these areas reveal interesting details. The hill-slopes were modified to make room for rubber plantation (Fig. 6a), in privately owned forests. Successively leveled terraces were prepared across the slope that created abnormal obstructions to natural drainage system. Several pits, with approximate dimensions of $5 \times 5 \times 2$ ft., were dug-up as reservoirs (Fig. 6), to divert and store seasonal surface runoff leading to increased and sustained infiltration and super saturation of the soil and the lateritic profile overlying the Archaean crystalline rock migmatites.

On the other hand, the Chaliyar River was flooded because of incessant rains for 5 days (starting from 4 August 2019); concurrent heavy torrential rains in the upper catchment of the

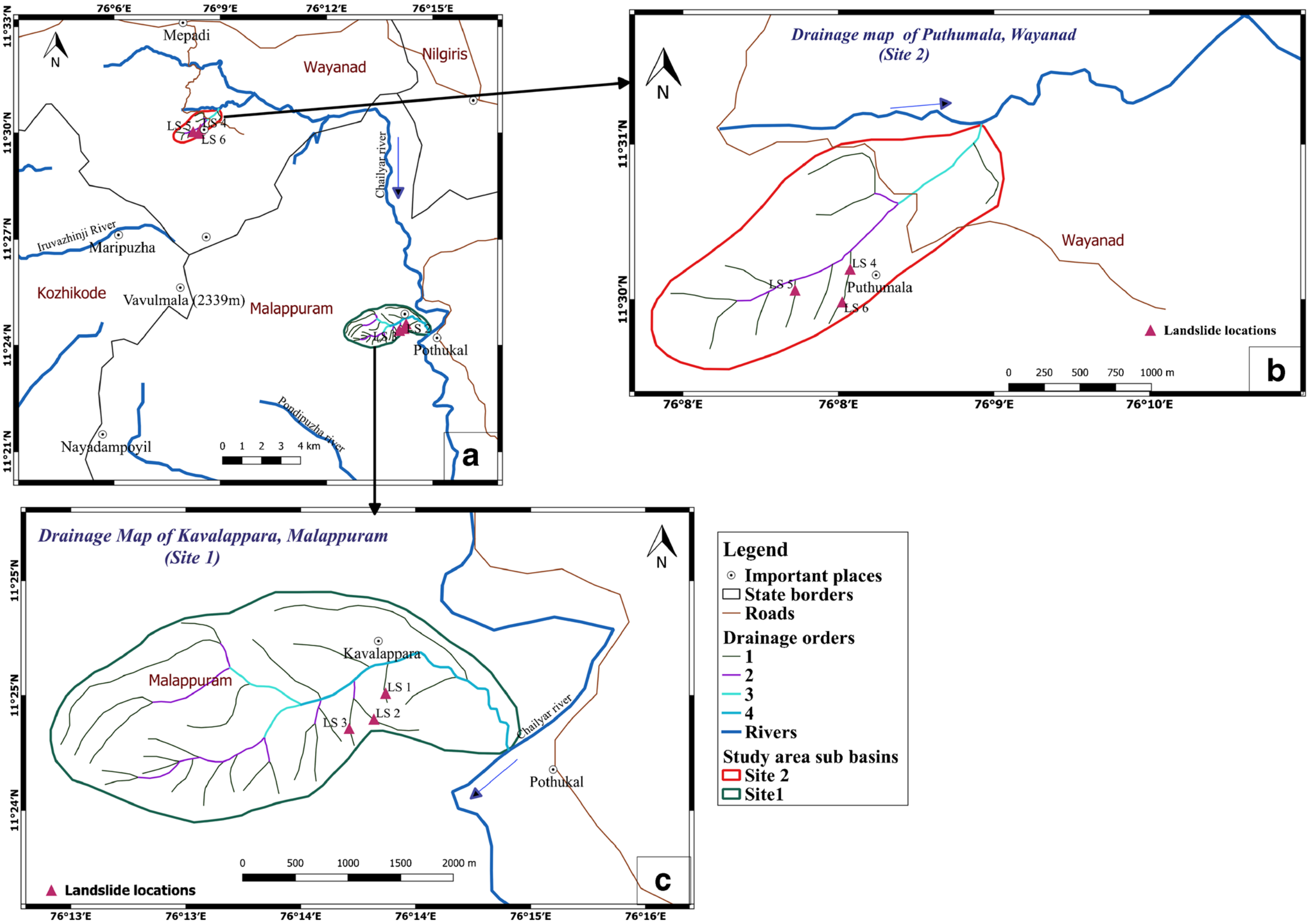

Fig. 2 **a** Drainage map of the study showing catchment affected by major landslides and floods. **b** Site 2: Puthumala catchment area. **c** Site 1: Kavalappara catchment area

Fig. 3 2019 landslides at site 1: Kavalappara, Malappuram District, Kerala

Fig. 4 Effects of landslides at site 1: Kavalappara. **a** Synoptic view of the major landslide. **b** Prominent dip-slope joints in the bedrock exposed after stripping away of overburden at Kavalappara major landslide. **c** Debris-covered run-out material at middle reaches to downslope. **d** Sediment-charged activated stream dislodging large boulders along the joints and resulted in formation of cascading rapids. **e** Western part of landslide where large blocks of rocks rolled down the slope. **f** Bank erosion and channel bed-load forming a channel bar, thus bifurcating the channel carved during the flooding of the Chaliyar River. (Photo source: author's personal collection at Amrita Vishwa Vidyapeetham, Kerala)

basin charged heavily with huge amounts of debris and rock flow type of downslope mass wasting. The normal width of the river is 10 m wide; during the times of floods (8 August 2019), the width of the river increased up to 130 m (Fig. 7a) at site 2 (Puthumala). The height of water rose up to 2 m above the banks.

Dynamic variation of hydrological conditions

The unprecedented dynamic variations of hydrological conditions at both sites have led to multiple landslides and floods. This section is intended to reveal the impact of changes in the hydrological conditions observed in the study sites during August 2019. The details are given below:

- Site 1: At Kavalappara, the land was wet, with runoff water flowing over in a network of small streams (Fig. 4 d and e). The exceptionally high flood levels in the Chaliyar River resulted in overflows of its own banks and created post-flood braided channels, showing several channel bars of very coarse gravel and boulders.
- Site 2: At Puthumala, drainage courses of the runoff water, flowing through the channel, were obstructed by the human developmental interventions (Fig. 7). People had constructed houses within the active river floodplains (Fig. 7a). Some of the constructed houses were damaged by the onrush of floodwaters (Fig. 7b). The culverts across the road were not properly located, to drain smoothly and discharge effectively (Fig. 8e). Overlying soils and weathered material were observed to have been washed away by the floodwaters, along the banks of the river, exposing the bed rocks (Fig. 8c). The soil cover was approximately 2 m thick over the closely spaced, jointed and weathered bedrocks with one set of the joint planes dipping downslope, along the gradient of the tributary stream.

Discussion and conclusion

Preliminary analyses of the landslides at the two sub-catchments in the Chaliyar River basin, through geoscientific methods, provide insights into their major causative factors and present suggestive remedial measures and the way forward.

a. Causative factors:

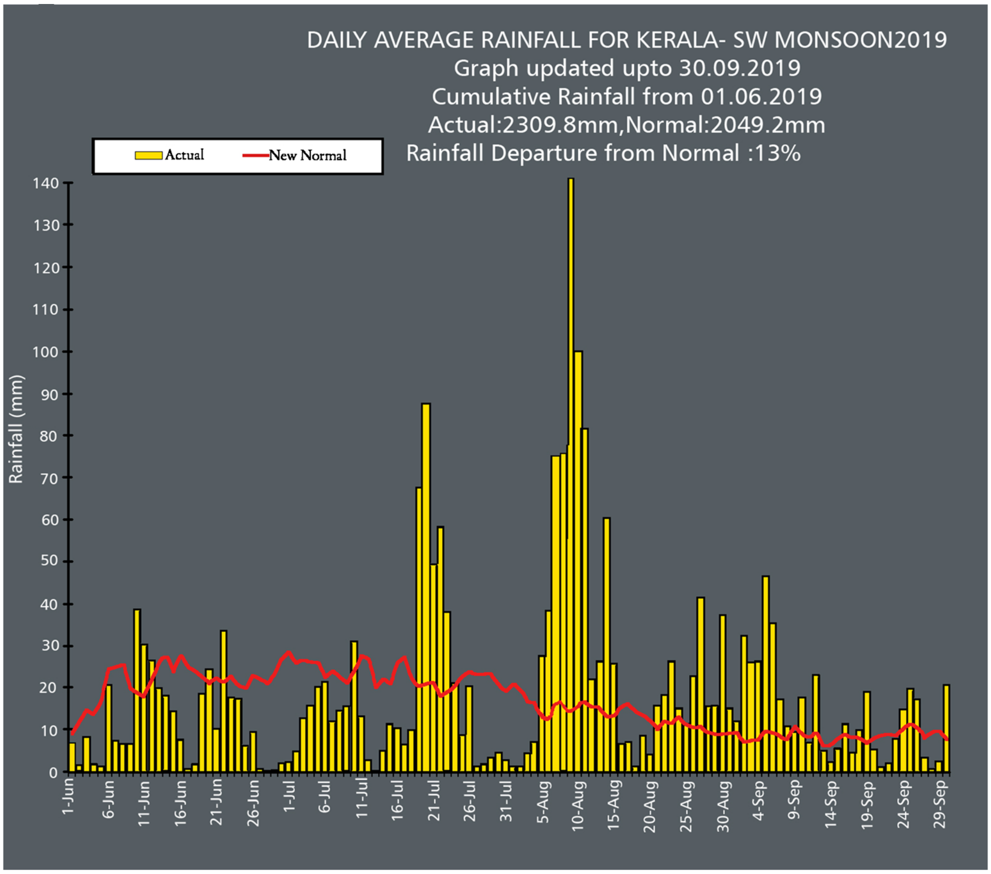

Fig. 5 Daily average rainfall during southwest monsoon season 2019. Modified image, Source: IMD 2019

i. The catchment approach: The Chaliyar River was flooded because of incessant rains for four consecutive days, followed by heavy torrential rains on the fifth day, on 8 August 2019, at both Kavalappara (site 1) and Puthumala (site 2). Both the sites fell within the same drainage basin of the Chaliyar River, in parts of Malappuram and Wayanad districts of Kerala (Fig. 2). In addition to the rising levels of floodwaters, the river was simultaneously charged heavily with huge amount of debris and loose earth materials. These materials were mainly sourced from the downslope mass wasting, in the upper catchment of the drainage basin (from Puthumala region in the north). The Archaean rocks, exposed in the riverbed, were easily erodible along the structurally weak planes, joint sets, and fractures. The riverbed was loaded with very large boulders, indicative of excessive discharge and high stream

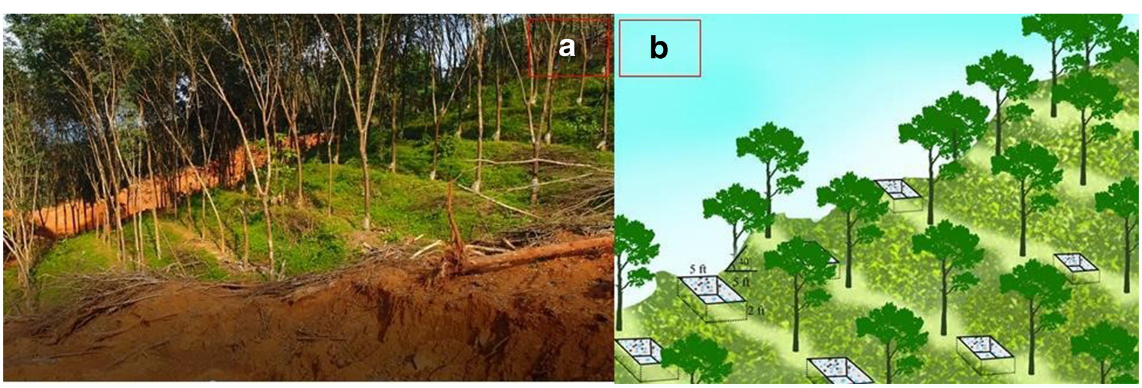

Fig. 6 Devastated plantations in Kavalappara area. **a** Photo from the landslide-affected field. **b** Schematic sketch showing replacement of natural vegetation, modification of slope and dug-up soak pits along the terraces, and rubber tree plantations for recharging ground water and for domestic water supply, thereby obliterating the natural course of drainages in the area. Photo source: Authors

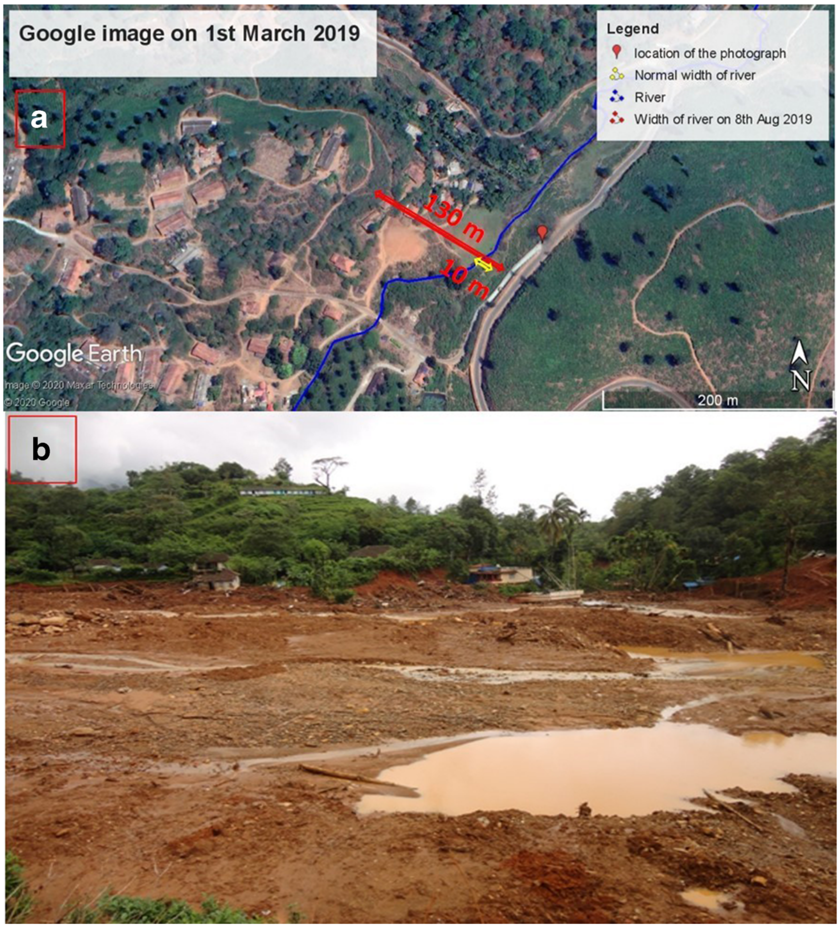

Fig. 7 Comparing Google image as before flooding event and the field photograph taken after hazardous flooding event at Puthumala, Wayanad 7. **a** Shows the width of river flood plain that was covered by sediment-charged water during the floods that spread out from normal 10 to 130 m in the flood plain. Photo sources: **a** Google image and **b** authors

power of the deluge. Angularity of well-cut large blocks of rocks indicates original structural influence on dislodgement and transport of rock boulders, under rapid, forceful flow of water. The presence of large boulders, seen as rolling and traction load, had the potential to down-cut slopes during sheet wash, and ferociously erode the stream banks causing aggravated devastation in the floodplains, further down-stream (Fig. 8).

ii. The extreme weather event: High floods were very sudden and unprecedented in the study area. Human settlements along the path of the river were vulnerable to perilous living. Other houses constructed closer to the riverbanks were also damaged during the deluge of the extreme weather events in August 2019. In some places, the slopes were abruptly truncated, possibly because of road widening; few shallow slumps and earth flows were noticed along the major transport corridors in the area.

iii. The structural control: Structurally, the upper catchment sections of the landslide-affected area were predisposed to mass-failure hazards. They were contributed by factors such as the originally steep natural topography, relatively deep weathering, and incompetent residual alteration products that envelop around the cores of unaltered Archaean rocks. Additionally, the existence of structural discontinuities, such as faults and closely spaced joint sets, master fractures, and large lineaments, has made the area, dissected terrain, susceptible to mass movements during the excessive rains.

iv. Enhanced erosive power of flooded river: The river bank and toe erosion were enhanced by the flooding of higher order Chaliyar River, flowing down-stream near Kavalappara (site 1). Loading of coarse clastic sediments and debris-charged high velocity flowing water, received from the upper catchment of the river in Wayanad region to the north, intensified their erosive powers in the adjoining Puthumala (site 2). Other geoscientific factors included degraded cohesive strength of the super-saturated soil and weathered zone that accentuated the flowage and toe erosion, by naturally organized but anthropogenically disrupted network of streams.

v. Human interventions: Degrading anthropogenic activities, such as unplanned tree-cutting, high bench terracing, adverse modification of slope, and indiscriminate construction of houses, across the active first-order channel courses and

Fig. 8 The landslide and floods at Puthumala, Wayanad (site 2). **a** The damages due the flood in the tributary of the Chaliyar River. **b** Rain water draining downslope carved its own new consequent course along the leveled and stone paved path resulting in the caving-in or sinking of path in the middle. **c** Large boulder blocks of freshly cut rocks transported as rolling bed-load by floodwaters in the river. **d** One of the landslides at Puthumala, showing rolled boulder and exposed bedrock after stripped-off of its overlying weathered zone and soil cover. **e** Improper hill-side drainage of storm/rainwater and improperly placed culvert. **f** View from downslope of a landslide at Puthumala that washed away houses built within the channel course. Photo source: Authors

within active floodplain of higher order streams, were vulnerable to natural processes of erosion and destruction, precipitated by heavy downpour. At Kavalappara (site 1), the land was observed to be wet, with surface runoffs flowing in a network of small streams (Fig. 4d, e). The exceptionally high flood levels in the river resulted in cutting through its own banks and creation of post-flood braided channels that course through several channel bars of the bed-load of very coarse gravel and boulders. At the Puthumala (site 2), the water flows through the channel, where the drainage courses were obstructed by careless human interventions. The houses constructed within the active river floodplain were dislodged by the onrush of floodwaters; the drainage culverts across the road were not properly located to drain effectively (Fig. 8e). Therefore, a lot of damage to property could have been avoided by proper application of sound civil geotechnical engineering. Secondly, plenty of rainwater was observed running over the sloping mountainous roads due to lack of properly engineered drainage system which is needed to be laid through well-maintained hill-side trenches so that surface runoff water is suitably channelized and outlet is created at appropriate sites by considering the geomorphology and discharge characteristics of the area.

b. Suggested remedial measures

i. Remedial measures in human settlements and crucial installations susceptible to landslides include adoption of scientific land use practices and regular scrutiny of geoscientific and meteorological machine data essential for making informed decisions.
ii. Natural drainage courses need to be kept clear of slope modifications, leveling, improper terracing, and alternate land uses. All drainage channels need to be cleared of the runoff debris to enable smooth channelized flow of surface water.
iii. Construction of houses along hazardous zones prone to flooding must be strictly avoided.
iv. Natural afforestation should be taken up for stabilization of the slopes and restoration of ecological balance.

v. Monitoring of rivers for floods in the area should be considered for prediction of multiple hazards and disaster risk reduction.

vi. Disaster risk awareness and preparedness by the people in the hazard prone and affected areas are important considerations for hazard management. A participatory approach and community resilience model for risk management need to be implemented in landslide hazard zones.

vii. Effective and accurate exchange of information between the stakeholders; i.e., risk communication is required which is the central part of disaster risk management. This could help in the dissemination of heightened risk awareness and promotion of protective and cooperative behavior. Public preparedness towards a structured, coordinated response fosters credibility among the stake holders, i.e., individuals, community, and institutions. People should be involved in risk management, right from the beginning of risk management, by regular conductance of workshops and community engagement/outreach programs.

viii. Important considerations while designing of hazard risk communication systems are the social and environmental aspects of habitations which may vary in terms of their skill sets, beliefs, financial status, gender, cultural background, likes and dislikes, etc., together with the crucial factors of warning time and the credibility of the alarming system with cooperative but firm civic administration. A collective and collaborative team effort is imperative to avert such disasters in the future.

In this work, we have adopted a deterministic approach where we were recording observations, characterizing parameters, and relating them to actual landslide events, correlating them in order to draw interpretation based on analysis of geo-factors and our understanding of geology, geomorphology, and land use–land cover of the area. The proposed future work includes carrying out similar studies in the other sub-basins and provides a reliable basis for next-stage works, i.e., development and deployment of multi-scale early warning and risk management systems in the region for preparing a resilient and proactively adoptive community.

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References

Baroň I, Řehánek T, Vošmik J, Musel V, Kondrová L (2011) Report on a recent deep-seated landslide at Gírová Mt., Czech Republic, triggered by heavy rainfall: the Gírová Mt., outer West Carpathians; Czech Republic. Landslides 8(3):355–361

Cynthia Chandran (2019) Kavalappara unfit for human settlement DECCAN CHRONICLE. https://www.deccanchronicle.com/nation/current-affairs/010919/kavalappara-unfit-for-human-settlement.html

District Survey Report of Minor Minerals, Wayanad District (2016). www.dmg.kerala.gov.in

District Survey Report of Minor Minerals, Kozhikode District (2016). www.dmg.kerala.gov.in

District Survey Report of Minor Minerals, Malappuram District (2016). www.dmg.kerala.gov.in

District Survey Report Coimbatore District (2018). www.gsi.gov.in

Gunnell Y, Fleitout L (2001) The morphotectonic evolution of the Western Ghats. In: Gunnell Y, Radhakrishna BP (eds) Sahyadri: the great escarpment of the Indian subcontinent. Geological Society of India, Bangalore, pp 581–598

Google Earth pro (https://www.google.com/intl/en_in/earth/versions/#earth-pro)

IMD (2019). https://www.imdtvm.gov.in/images/stories/dwr/swm%20rf%20kerala.jpg)

Kuriakose SL, Sankar G, Muraleedharan C (2009) History of landslide susceptibility and a chorology of landslide-prone areas in the Western Ghats of Kerala, India. Environ Geol 57(7):1553–1568

Geological Survey of India (2016) Landslide compendium of southern parts of Western Ghats. GSI, Kolkata

Geological Survey of India, (2009). District mineral resource maps, Wayanad and Malappuram districts, Kerala GSI, Thiruvananthapuram

Manorama Online (August, 2019) Landslides across Kerala this year so far, Palakkad tops list. https://english.manoramaonline.com/news/kerala/2019/08/18/landslides-kerala-malappuram-kavalappara-search-palakkad.html

Ramesh MV, Vasudevan N (2012) The deployment of deep-earth sensor probes for landslide detection. Landslides 9(4):457–474

Rejimon Kuttappan (9 Aug 2019) Kerala rains: 24 landslides in 24 hours, 22 killed, 22,165 moved https://www.downtoearth.org.in/news/natural-disasters/kerala-rains-24-landslides-in-24-hours-22-killed-22-165-moved-66107

Sajinkumar KS, Anbazhagan S, Pradeepkumar AP, Rani VR (2011) Weathering and landslide occurrences in parts of Western Ghats, Kerala. J Geol Soc India 78(3):249–257

Philip S (Aug 2019) Kavalappara landslide: how a hill in Western Ghats buried part of a village in Kerala. The Indian Express https://indianexpress.com/article/explained/how-a-hill-in-the-western-ghats-buried-a-part-of-a-village-in-kerala-kavalappara-landslide-5903013/

QGIS Development Team (2018). QGIS geographic information system. Open Source Geospatial Foundation Project. http://qgis.osgeo.org

Vijith H, Madhu G (2008) Estimating potential landslide sites of an upland sub-watershed in Western Ghats of Kerala (India) through frequency ratio and GIS. Environ Geol 55(7):1397–1405

Wadhawan SK (2015) Implementation of landslide susceptibility mapping program, vulnerability and risk assessment – a gateway to research and development of early warning system in India. Journal of Engineering Geology XL(1):20–32

Wadhawan, Sudesh Kumar, (2019). Landslide susceptibility mapping, vulnerability and risk assessment for development of Early Warning System in India, pp. 145–172. Springer International Publishing AG, part of Springer Nature 2019. S.P. Pradhan et al. (eds.). Landslides: theory, practice and modeling, advances in natural and technological hazards research 50. https://doi.org/10.1007/978-3-319-77377-3_8

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