PORE WATER PRESSURE AS A TRIGGER OF SHALLOW LANDSLIDES IN THE WESTERN GHATS OF KERALA, INDIA: SOME PRELIMINARY OBSERVATIONS FROM AN EXPERIMENTAL CATCHMENT

Sekhar L. Kuriakose, V. G. Jetten, and *C. J. van Westen*
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
7500 AA Enschede, The Netherlands

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

L. P. H. van Beek
Department of Physical Geography
Utrecht University
Utrecht, The Netherlands

Abstract: The Western Ghats mountain chain of Kerala, India, is prone to landslides mainly caused by anthropogenic disturbances and very high rainfall amounts. Here, some initial observations on the apparent relationship among pore water pressure fluctuations, rainfall characteristics, and landslide initiation are presented based on monitoring in an experimental catchment in the upper Tikovil River basin. On June 21 and 22, 2007, continuous rain fell for over 10 hours with a total precipitation of 147 mm, causing three shallow landslides in the catchment. Measurements using piezometers in three hollows of the catchment indicate that the rain spell resulted in the development of high pore water pressure from the beginning of the storm that persisted through the time of occurrence of shallow landslides. The pore water pressure patterns in these monitored hollows are possible representatives of the pore water pressure pattern in the hollows where the landslides initiated. This similarity of response pattern enables such data to be used for the calibration and validation of physically based slope hydrology models coupled with slope stability models. [Key words: shallow landslides, pore water pressure, rainfall intensity, piezometers, The Western Ghats, Kerala, India.]

INTRODUCTION

Pore water pressure is considered an important trigger of landslides (Iverson, 1997). Any physically based slope stability assessment in a spatial or punctual domain cannot ignore issues concerning pore water pressure distribution along the soil profiles (Simoni et al., 2004). Continuous monitoring of pore water pressure at locations of landslides is limited by the fact that the initiation locations of landslides are almost never known prior to the occurrence of the events. This is especially true

Physical Geography, 2008, **29**, 4, pp. 374-386.
 DOI: 10.2747/0272-3646.29.4.374

in the case of shallow landslides such as debris flows that originate in topographic depressions depicted by concave contours called hollows (Melelli and Taramelli, 2004). Researchers circumvent this constraint by monitoring pore water pressure in laboratory scaled models (e.g., Wang and Sassa, 2003), known active and dormant landslides (e.g., Malet et al., 2004), or locations that are hydrologically and topographically similar to those that initiated landslides (e.g., Hengxing et al., 2003). The transient behavior of pore water pressure observed through any of these methods is only an approximation of the expected response at the location of actual failure. Nevertheless such data are crucial for the physical understanding of processes leading to landslides and thus an early and timely reporting of such data for a data-poor region such as the Western Ghats, which regularly experience landslides, is a necessity.

The highlands, foot hills, and uplands of the Western Ghats together experienced a population growth of 1342% in the last 80 years (Nair et al., 1997), making it one of the most densely populated mountain chain in India. The region experiences landslides almost every year. Even though the area is steep, agricultural activities are carried out up to the near vertical cliffs that form the plateau margins in this landscape. The area has a history of disastrous flash floods (Markham, 1866) and landslide activity, partly owing to changes from natural to anthropogenically modified land use/land cover (Jha et al., 2000). Debris flows (locally known as "Urul Pottal") are the most frequent landslide types (Thampi et al., 1998; Kuriakose et al., 2008). Studies conducted in the region point out the importance of intense monsoon rains and associated pore water pressure development as the major cause of shallow landslides (Basak and Narasimha Prasad, 1989; Thampi et al., 1998). Several disastrous landslide events have occurred in this area, of which the most notable recent ones are the Mundakay landslide in July 1984 (Basak and Narasimha Prasad, 1989), the 100 shallow landslides of Adivaram in October 1993 (Thampi et al., 1998), and the Amboori landslide in November 2001 (Muthu and Muraleedharan, 2005). Although several postdisaster assessments and empirical landslide susceptibility analyses have been conducted in the area, no research has been conducted on the hydrological behavior of the slopes that leads to landslides. More than 40 disastrous landslides were reported in the state between June 22 and 23, 2007. This paper presents some initial interpretations of the pore water pressure measurements from three piezometers coupled with the rainfall and rain intensity measurements from an automated weather station established in the upper Tikovil River basin of Kerala. These findings are related to the mass movements that occurred in the experimental catchment and surrounding area on June 22, 2007.

STUDY AREA

The study area comprises Aruvikkal catchment, a 9.5 km^2 sub-basin of the Tikovil River, which is a tributary of the Meenachil River (Fig. 1). The region is part of the Western Ghats scarp lands (CESS, 1984); a detailed description can be found in Chattopadhyay (2004). The area is underlain by Precambrian crystalline rocks such as charnockites, which weather very slowly, leading to rather shallow sandy soils over a thin layer of saprolite interbedded by lithomargic clay (Chandrakaran et al., 1995). The predominant land use is rubber (*Hevea Brasiliensis*) plantations,

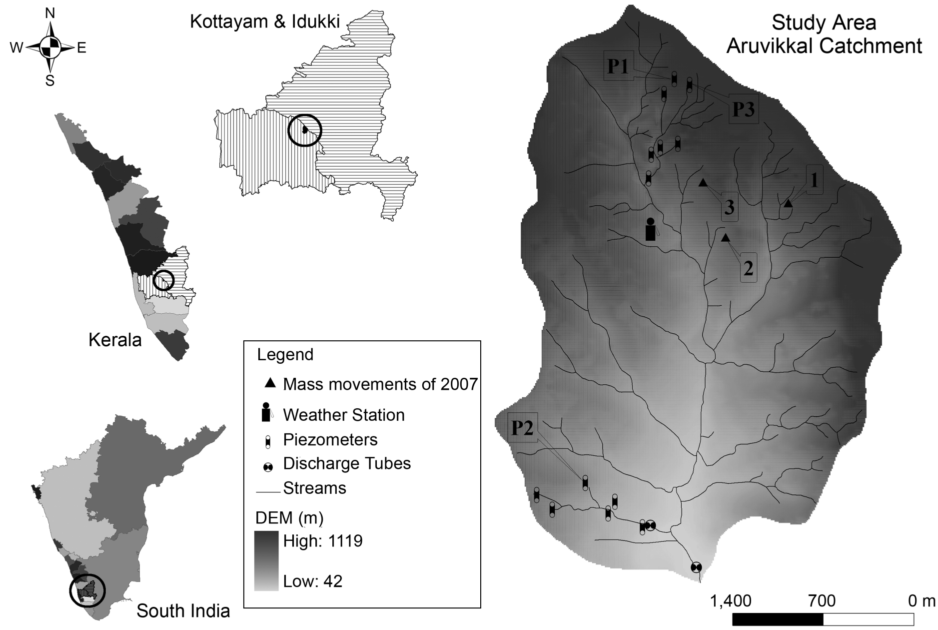

Fig. 1. Relative location of the Aruvikkal basin which is administratively part of the Kottayam and Idukki districts of Kerala state, South India (location of the three piezometers and three landslides indicated by callouts).

which have to be cleared after 20 years, thus exposing the land to high-intensity rainfall until a new set of saplings are planted and achieve significant canopy cover. The upper slopes are used for planting various hill crops, such as cassava, which contributes to soil erosion (Putthacharoen et al., 1998). To plant cassava and rubber, slopes are terraced, often disregarding ephemeral streams, and thereby obstructing natural drainage channels (Thampi et al., 1998). The plateau tops of the Aruvikkal catchment are covered by tea plantations.

Rainfall measurements from the Pullikanam Tea Estate, which is the closest long-term recording rainfall station near Aruvikkal catchment (0.5 km from the southeast boundary of the catchment), show that the area experienced an average annual rainfall of 5182 mm during the period from 1952 to 2006. Average seasonal rainfall is highest in the southwest monsoon (June–September, 3732 mm), followed by the northeast monsoon (October–December, 888 mm) and pre-monsoon (January–May, 562 mm) seasons. The upper catchment of Meenachil River was affected by more than 100 shallow landslides on October 6, 1993, including 11 shallow landslides in the Aruvikkal catchment (Thampi et al., 1998; Vijith and Madhu, 2008).

On June 22, 2007, Kottayam and Idukki districts experienced about 20 landslides, most of which were shallow landslides, such as debris flows. Aruvikkal catchment also experienced two soil slips and a debris flow on June 22 (Fig. 1). Most of the debris flows in the region originate in typical hollows that are concave depressions having a dimension of not more than 10 m × 10 m and with a soil thickness of about 1–1.5 m. An earlier physically based modeling attempt (Kuriakose,

Table 1. Location Characteristics of the Mass Movements of 2007

Mass movements	Altitude (m)	Slope (°)	Soil depth (m)	LU/LC[a]	Ksat (m/hr)	Cohesion (kPa)
1	680	25.8	1.2	MC	0.12	14.90
2	524	39.3	0.9	G & R	0.003*	0.90[b]
3	676	49.9	0.5	MC	0.02*	0.50[b]

[a]LU/LC = land use/land cover (MC = mixed crops, G & R = grass and rock); Ksat = saturated hydraulic conductivity.

[b]Interpolated cohesion values.

2006) showed that slope stability of the area is highly sensitive to soil depth. Field investigations and discussions with local residents indicate that reactivation of the same landslide scarps are rare, implying that supply-limited landslides may be less frequent compared to event-limited landslides.

Table 1 provides the topographic characteristics of the three landslide locations. The occurrence of multiple landslides on a single day in a topographically, geologically, and climatically similar region cannot be coincidental and thus it necessitates further enquiry into the triggering mechanism. Figure 2 shows the initiation and run out zones of the debris flow that occurred in the Aruvikkal catchment on June 22, 2007.

MATERIALS AND METHODS

Two microcatchments of the Aruvikkal catchment were instrumented with 15 self-recording piezometers in the period from June to September 2007 as part of an ongoing research project on slope stability of the region. Three of the 15 piezometers were installed before the onset of the monsoon. The Keller DCX-22 AA piezometers measure and record ground water levels using a two sensor technology. The submersible depth sensor measures the water level. Barometric pressure variations are measured and compensated with the built-in waterproof air pressure sensor mounted in the electronics housing at the top of the borehole (www.keller-druck.com). Of the 15 piezometers, 4 were installed in hollows, with at least 0.7 m of overburden thickness, 7 were installed in rubber planted insloping terraces, 2 were installed in other landuse types, and 2 were installed at drainage outlets. Boreholes of 50 mm diameter were made to the bed rock and PVC standpipes (25 mm diameter and 0.25 m longer than the borehole) were installed. The tube was perforated over 0.5 m at the end of the submersible depth sensor and fixed with a nylon filter to avoid clogging of the sensor with clay. The borehole was then filled with assorted river sand to ensure continuous and near natural conductivity adjacent to the sensor. The submersible sensor was immersed into the borehole and the barometric sensor fixed at the ground surface. This installation was further enclosed in a galvanized iron casing to ensure security. All piezometers were programmed to record the average pore water pressure at an interval of nine minutes so as to minimize the number of visits to the instrument in a year.

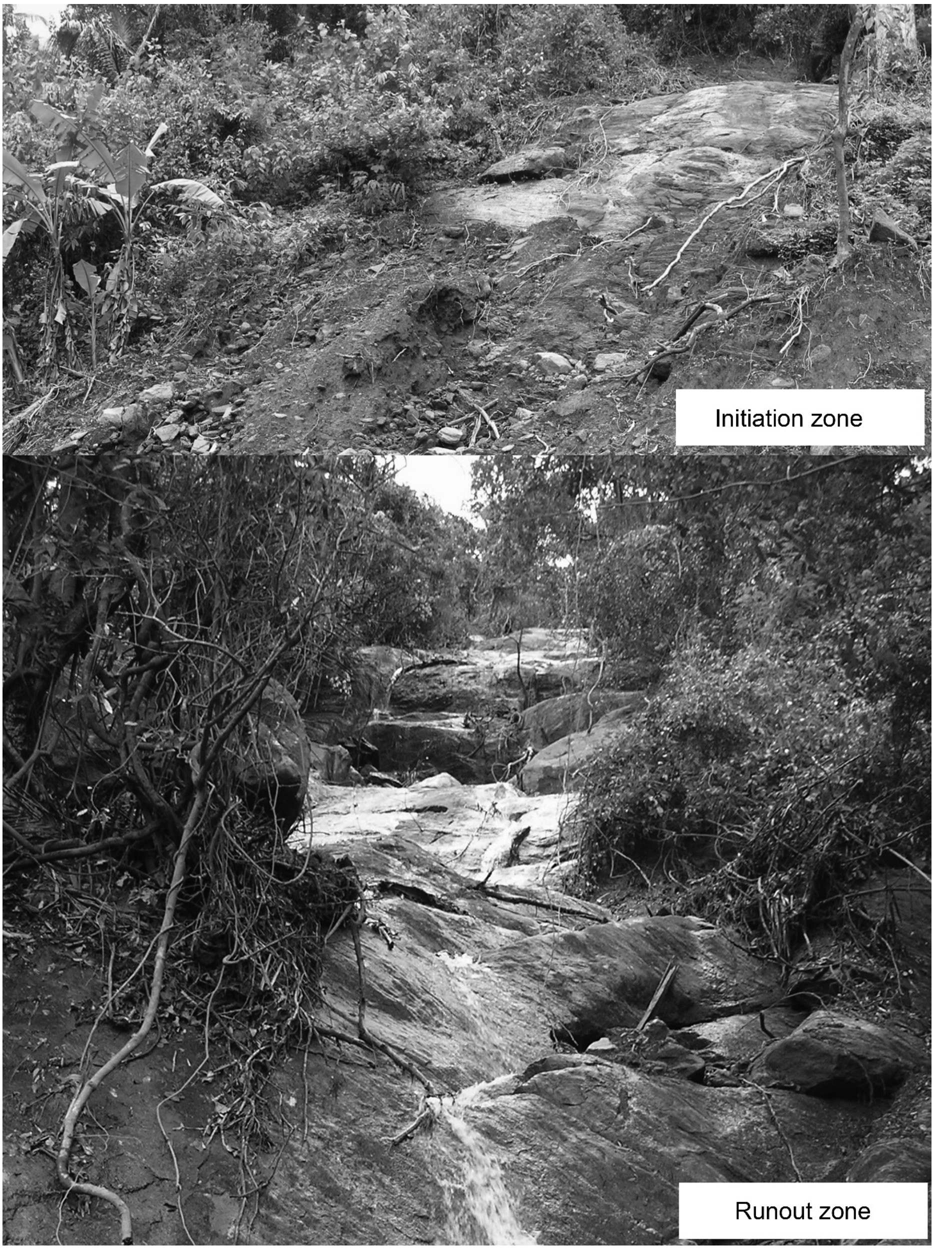

Fig. 2. Initiation and runout zones of a 2007 shallow landslide in the Aruvikkal catchment (Location 1 in Fig. 1).

A low-cost wireless automated weather station (AWS; Vantage Pro2) capable of measuring all standard weather variables and solar radiation was established on May 28, 2007, atop Meladukkam CSI church (Fig. 1), located almost in the center of the area at an altitude of 460 m. The logger of the AWS was programmed to

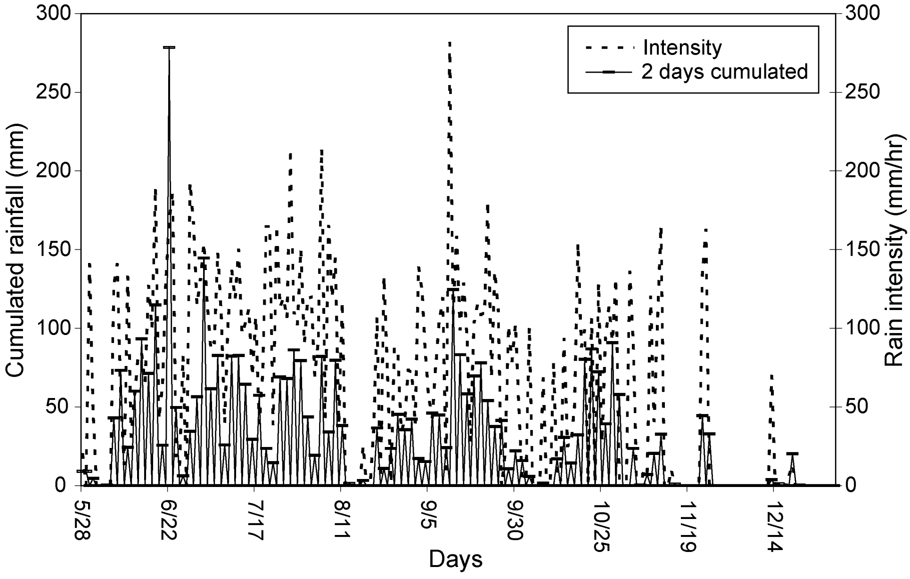

Fig. 3. The 2-day cumulative rainfall and maximum daily rainfall intensity in the Aruvikkal catchment during the southwest and northeast monsoon seasons of 2007 (note the highest 2 days cumulative rainfall on June 22, 2007).

record data at an interval of 15 minutes, and could store data for about 45 days given this interval. The rainfall intensity reported by the instrument is the average received in the recording interval. The data from the three piezometers that were installed before June 2007 were analyzed in combination with the climate data.

RESULTS AND DISCUSSION

The southwest monsoon rainfall of 2007 started in Kerala 4 days prior (May 28) to its long period average (LPA). From June 1 to September 30, Kerala state as a whole received a total rainfall of 2784 mm, while the LPA is 2143 mm, 30% higher. However, based on the rainfall data from the study area during the same period, Aruvikkal catchment received only 3123 mm rainfall, which was 16.3% less than the seasonal LPA rainfall of the area. Thus, though the state received excess rainfall, the study area received relatively less rainfall.

Figure 3 shows the maximum daily rainfall intensity and 2-day cumulative rainfall recorded by the AWS during the 2007 southwest and northeast monsoon seasons. The average maximum rainfall intensity during the southwest monsoon season was 87.7 mm/hr, while during the northeast monsoon season was 28.3 mm/hr. On June 22, 2007, Aruvikkal catchment experienced a debris flow and two soil slips between 6:00 and 10:30 a.m. From the start of the monsoon on May 28 to June 22, the catchment received 997 mm rainfall.

On the day of the mass wasting events, the region received about 200 mm rainfall and the 2-day cumulative rainfall was 278.4 mm. The 2-day cumulative rainfall

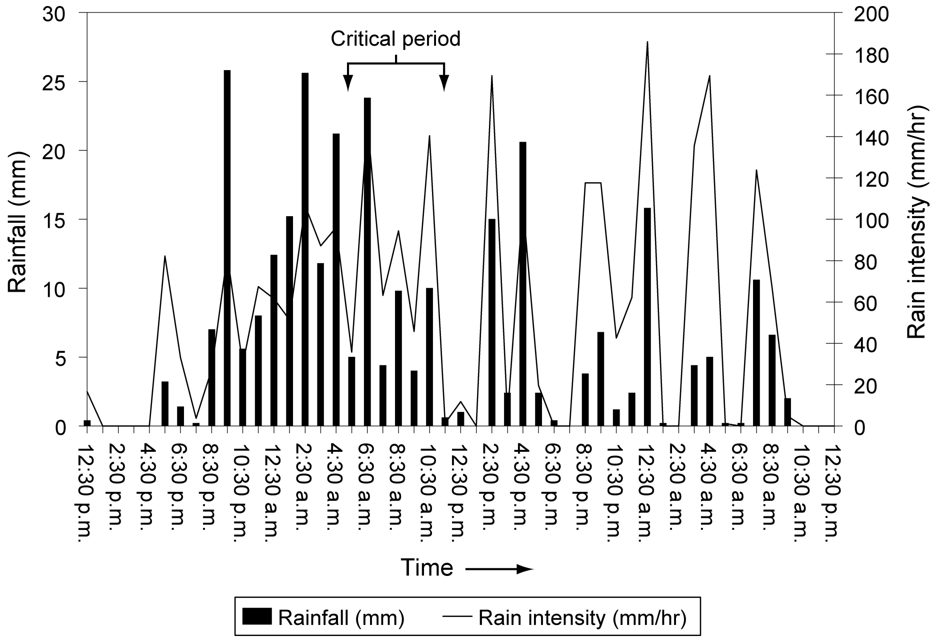

Fig. 4. Hourly rainfall and the hourly maximum rain intensity from June 21, 2007, 12:30 p.m., to June 23, 2007, 12:30 p.m. (note the three rainfall intensity peaks during the critical period and the antecedent rainfall).

explains the relatively lower landslide activity in the region on June 22, 2007, compared to the October 6, 1993, event. In 1993, the 2-day cumulative rainfall coinciding with landslides was 315 mm, and more than 11 landslides occurred in Aruvikkal catchment alone (Thampi et al., 1998). The deviation of the seasonal totals in 1993 (3803 mm) and 2007 (3123 mm) from the LPA seasonal (3723 mm) also explains the lower spatial frequency of landslides in 2007.

The region received 189 mm of continuous rainfall from June 21, 2007, 8:00 p.m. until June 22, 2007, 10:30 a.m. Of this, the catchment received 147 mm from the beginning of the storm till June 22, 6:00 a.m., the beginning of the known critical period. Continuous rainfall is defined as having no rainless periods of at least 45 min. Two rainfall events greater than 100 mm/hr occurred during the known time of mass wasting in the area: (1) between 5:45 and 6:00 a.m., measuring 9.8 mm rainfall and 147.6 mm/hr intensity; and (2) between 9:45 and 10:00 a.m., measuring 7.8 mm rainfall and 140.4 mm/hr intensity. Figure 4 shows the hourly rainfall and the hourly maximum rain intensity from 12:30 p.m. on June 21 to 12:30 p.m. on June 22.

However, such absolute values are only of indicative relevance if the spatio-temporal probability of landslide triggering rainfall is unknown. This necessitates long-term climatic records of the area to be analyzed alongside a temporal landslide inventory. In situations where long-term temporal landslide inventory is unavailable, physically based dynamic models of slope hydrology couple with slope stability are an ideal alternative for hazard quantification (van Westen et al., 2005).

Table 2. Location Characteristics, Maximum Pore Water Pressure Response, and Averages and Standard Deviations of the Maximum Daily Pore Water Pressure Observed at the Three Piezometers During the Southwest and Northeast Monsoon Seasons of 2007

Piezo-meters	Altitude (m)	Slope (º)	Soil depth (m)	Ksat (m/hr)	LU/LC[a]	Pore pressure (kPa)					
						Southwest			Northeast		
						Max.	Avg.	*SD*	Max.	Avg.	*SD*
1	873.7	46.7	2.6	0.11	MC	8.61	1.31	1.92	5.14	0.29	0.81
2	320.5	24.9	1.3	0.14	R	7.46	0.29	1.11	1.38	0.14	0.24
3	915.8	31.7	1.9	0.13	MF	12.33	4.47	3.49	10.29	1.14	2.59

[a]LU/LC = land use/land cover (MC = mixed crops, R = rubber, MF = mixed fallow); Ksat = saturated hydraulic conductivity.

Rainfalls of higher intensities that produced higher quantities of rainfall occurred during the northeast monsoon season of 2007. For example, on October 18, the region experienced a rainfall intensity of 153.6 mm/hr, amounting to 20 mm (Fig. 3). However, this extreme rainfall event during the northeast monsoon failed to initiate any landslides in the Aruvikkal catchment or elsewhere in the state. Figure 3 explains the reason for this clearly. Though rainfall intensities contributing higher quantities of rainfall occurred in the northeast monsoon, the 2-day cumulative rainfall was far less than that during the southwest monsoon. Thus, it could be inferred that, during this period, the antecedent moisture condition was not sufficient to generate a significant response in the soil pores to initiate landslides.

As was the case with the events of 2007, landslides in the Western Ghats generally occur during the middle and later stages of the southwest monsoon season. However, if the region receives a high pre-monsoon shower, especially during May, landslides can also occur in an early phase of the season. Similarly, if the southwest monsoon rainfall continues uninterrupted without the monsoon breaks, it will lead to landslides in the northeast monsoon season (Sampath et al., 1995). High-intensity rainfall during the northeast monsoon season is generally concentrated to some pockets, thus causing large localized landslide events. For example, on the preceding days, succeeding days, and actual days of the landslides of Adivaram in 1993 (Thampi et al., 1998) and Amboori in 2001 (Muthu and Muraleedharan, 2005), which occurred in October and November, respectively, no landslides were reported from any other part of the state. In contrast, rain spells during the southwest monsoon season generally cause widespread shallow landslides across the Western Ghats scarps.

The pore water pressure responses of the catchment also follow the general trend of the rainfall. The piezometers were located in hollows similar to that of the location of the shallow landslides. These locations exhibit evidences of prior landslides, such as small circular scarp heads, concave curvature, shallow soils, locations below rocky exposures, scrubby vegetation, and most importantly the head of ephemeral streams that activate only during the peak of the monsoon rainfall. The piezometers were located within 1 km from the locations of failure and at similar

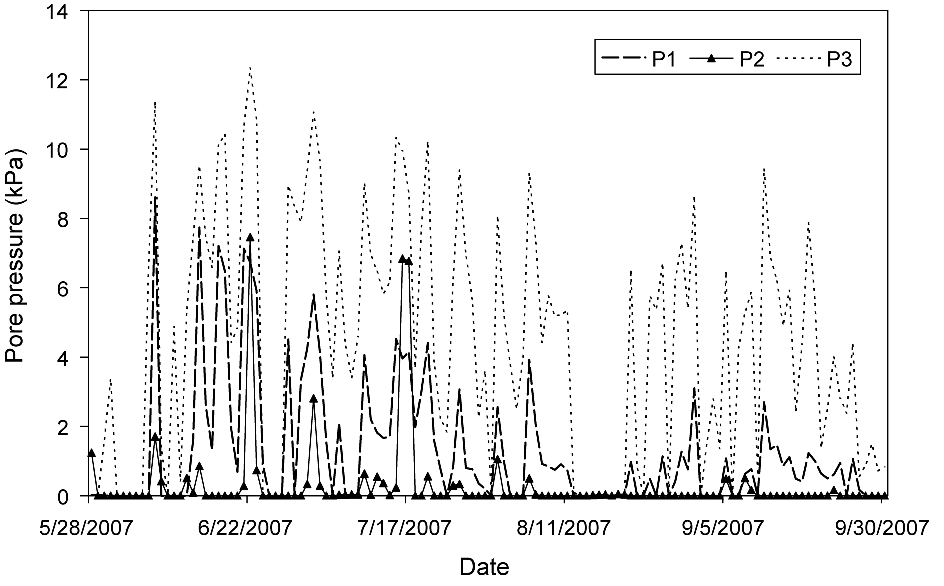

Fig. 5. Daily maximum pore water pressure response at the three representative hollows during the southwest monsoon season of 2007.

altitudes. Table 2 provides the topographic and land-use characteristics of the locations of the three piezometers deployed before the date of occurrence of landslides. It also provides the maximum, average of the maximum daily, and standard deviation of the maximum daily pore water pressure observations of the three piezometers during the southwest and northeast monsoon seasons. As in the case of rainfall, pore water pressure fluctuated during the northeast monsoon season, but for shorter periods, achieving lower absolute maximum values (cf. Table 2). Figure 5 shows the daily maximum pore water pressure response at the three representative hollows from May 28 to September 30, 2007.

It could be seen from the pore water pressure data that the hydrological response of the subsurface also started between 8:00 and 9:00 p.m. on June 21. From the time of the initial hydrological response at around 8:00 p.m. to the beginning of the critical time (6:00 a.m., June 22) 10 hours later, the pore water pressure values remained high. Figure 6 shows the pore water pressure response at each piezometer from June 21, 2007, 11:30 a.m., to June 23, 2007, 1:00 p.m.

A close observation of the continuous response pattern of pressure wave underlines the transient nature of the hydrological response. Piezometers 1 (P1) and 3 (P3) are similar in their response to fluctuations in rainfall, while piezometer 2 (P2) shows a delayed response. P3 showed many more fluctuations than P1, which may be attributed to the local characteristics of the location, such as saturated hydraulic conductivity, soil depth, and slope, which result in the sudden drainage of excess pore water. Though P1 is located in a steeper slope, the high soil depth and the relatively lower hydraulic conductivity could be the reasons for a more stable pattern

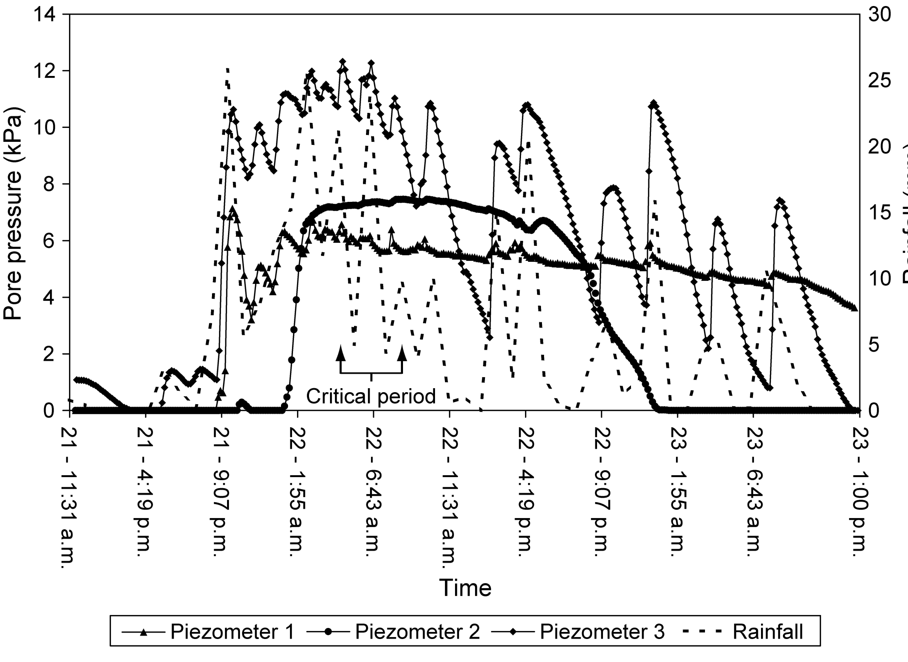

Fig. 6. Pore water pressure response at each piezometer from June 21, 2007, 11:30 a.m., to June 23, 2007, 1:00 p.m.

of pressure waves. The pressure wave at P2 is the most regular of the three. The delayed and more regular trend may be a result of some soil pipes that act as preferential flow paths and drain through the location. Such soil pipes route subsurface water from upstream to hollows, causing rapid soil saturation and pore water pressure fluctuations (Putty and Prasad, 2000; Taro, 2004) and are known to have resulted in landslides in the region (Thampi et al., 1992).

CONCLUSION

The shallow landslides in the Aruvikkal catchment on June 22, 2007, occurred during a continuous rain spell characterized by several high-intensity events. The rain spell resulted in the development of high pore water pressure in the monitored hollows from the beginning of the storm and persisted through the known critical period of occurrence of landslides. These initial results indicate that there exists an evident congruence between the prolonged and high-intensity rainfall leading to the persistence of critical pore water pressure conditions and the occurrence of shallow landslides. This observation is in line with the findings from elsewhere in the world by Crozier (1986) and Nilsen (1986) and agrees with observations by Thampi et al. (1998) for the region.

Thampi et al. (1998) suggested a minimum rainfall of 300 mm in 2 days as needed to initiate landslides in the region. In light of this research, a continuous rain spell lasting 10 hours and producing 147 mm is sufficient to cause landslides. However, it is too far-fetched to say that all such rain spells will cause landslides, as a rainfall characterization analyzed against corresponding temporal landslide inventory is pending for the region. The rainfall thresholds also need to be coupled with pore water pressure thresholds to be useful in an early warning system, as not all rain spells with the same rain intensity and amount cause the persistence of critical pore water pressure that leads to landslides. To know the pore water pressure thresholds applicable in the region, physically based modeling of the slope hydrology coupled with slope stability needs to be conducted. Continuous monitoring of climatic data in a catchment scale and the monitoring of corresponding pore water pressure data in hydrologically and topographically representative hollows, in fine temporal resolution, such as that reported herein are a necessity for the calibration and validation of such complex models.

Acknowledgment: We are thankful to Mr. P. C. George, Member of the Legislative Assembly, Poonjar Constituency, for his constant support and help in carrying out the research. We thank Dr. M. Baba, Director, CESS for his continuing support in this research. We thank Mr. Jaibi (Vagamon) and Mr. Binoy (Kottayam) for the upkeep of the instruments and the timely retrieval of data. Thanks are owed to the Members and the Secretary of the Tikoy Panchayath and the Parish Priest of the CSI Church, Meladukkam. We also thank the efforts of the reviewers for helping us improve the article to its present form.

REFERENCES

Basak, P. and Narasimha Prasad, N. B., 1989, Recurring landslides in the Western Ghats—An environmental hazard. *Environmental Conservation*, Vol. 16, No. 2, 169–172.

CESS, 1984, *Resource Atlas of Kerala*. Kerala, India: Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram.

Chandrakaran, S., Paul, K. V., and Nambiar, M. R. M., 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, August 29th–30th*. Kerala, India: Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram.

Chattopadhyay, S., 2004, Landforms of Kerala: An overview. In G. R. Ravindra Kumar and N. Subhash, editors, *Earth System Science and Natural Resources Management, Silver Jubilee Compendium*. Kerala, India: Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, 211–288.

Crozier, M. J., 1986, *Landslides: Causes, Consequences and Environment*. London, UK: Croom Helm.

Hengxing, L., Chenghu, Z., Lee, C. F., Sijing, W., and Faquan, W., 2003, Rainfall-induced landslide stability analysis in response to transient pore pressure—A case study of natural terrain landslide in Hong Kong. *Science in China Series E: Technological Sciences*, Vol. 46, 52–68.

Iverson, R. M., 1997, The physics of debris flow. *Reviews of Geophysics*, Vol. 35, No. 3, 245–296.

Jha, C. S., Dutt, C. B. S., and Bawa, K. S., 2000, Deforestation and landuse changes in Western Ghats, India. *Current Science*, Vol. 79, No. 2, 231–237.

Kuriakose, S. L., 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. Unpublished M.Sc. thesis, International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands, and Indian Institute of Remote Sensing, Dehradun, India. Available from http://www.itc.nl/library/papers_2006/msc/iirs/sekhar.pdf

Kuriakose, S. L., Sankar, G., and Muraleedharan, C., 2008, History of landslide susceptibility and a chorology of landslide prone areas in the Western Ghats of Kerala, India. *Environmental Geology*. DOI: 10.1007/s00254-008-1431-9.

Malet, J. P., Laigleb, D., Remaitrea, A., and Maquaire, O., 2004, Triggering conditions and mobility of debris flows associated to complex earthflows. *Geomorphology*, Vol. 66, Nos. 1–4, 215–235.

Markham, C. R., 1866, On the effects of the destruction of forests in the Western Ghats of India on the water-supply. *Journal of the Royal Geographical Society of London*, Vol. 36, 180–195.

Melelli, L. and Taramelli, A., 2004, An example of debris flows hazard modeling using GIS. *Natural Hazards and Earth System Sciences*, Vol. 4, No. 3, 347–358.

Muthu, R. P. and Muraleedharan, C., 2005, Causes and mechanism of Amboori landslide of 9th November, 2001, Thiruvananthapuram district, Kerala. *Journal of the Geological Society of India*, Vol. 66, No. 2, 203–208.

Nair, K. M., Chattopadhyay, S., and Sasidharan, C. K., 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.

Nilsen, T. H., 1986, Relative slope stability mapping and landuse planning in San Francisco Bay region, California. In A. D. Abraham, editor, *Hillslope Processes*. London, UK: Allen and Unwin Inc., 389–413.

Putthacharoen, S., Howeler, R. H., Jantawat, S., and Vichukit, V., 1998, Nutrient uptake and soil erosion losses in cassava and six other crops in a Psamment in eastern Thailand. *Field Crops Research*, Vol. 57, No. 1, 113–126.

Putty, M. R. Y. and Prasad, R., 2000, Understanding runoff processes using a watershed model—A case study in the Western Ghats in South India. *Journal of Hydrology*, Vol. 228, 215–227.

Sampath, S., Vinayak, P. V. S. S. K., and Sasi Kumar, V., 1995, *Rainfall—A Trigger for Landslides, Abstracts of the National Seminar on Landslides in Western Ghats, August 29th–30th*. Kerala, India: Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram.

Simoni, A., Berti, M., Generali, M., Elmi, C., and Ghirotti, M., 2004, Preliminary result from pore pressure monitoring on an unstable clay slope. *Engineering Geology*, Vol. 73, 117–128.

Taro, U., 2004, Clarifying the role of pipe flow on shallow landslide initiation. *Hydrological Processes*, Vol. 18, No. 2, 375–378.

Thampi, P. K., Mathai, J., and Sankar, G., 1992, Evaluation of Slope Failures and Subsidence Phenomenon Around Palakkayam Village, Mannarghat Taluk, Palghat District Kerala. Unpublished investigation report, Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India.

Thampi, P. K., Mathai, J., Sankar, G., and Sidharthan, S., 1998, Evaluation Study in Terms of Landslide Mitigation in Parts of Western Ghats, Kerala. Unpublished research report submitted to the Ministry of Agriculture, Government of India, Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India.

van Westen, C. J., van Asch, T. W. J., and Soeters, R., 2005, Landslide hazard and risk zonation: Why is it still so difficult? *Bulletin of Engineering Geology and Environment*, Vol. 65, No. 2, 167–184.

Vijith, H. and Madhu, G., 2008, Estimating potential landslide sites of an upland sub-watershed in Western Ghat's of Kerala (India) through frequency ratio and GIS. *Environmental Geology*, Vol. 55, No. 7, 1397–1405. DOI: 10.1007/s00254-007-1090-2.

Wang, G. and Sassa, K., 2003, Pore-pressure generation and movement of rainfall-induced landslides: Effects of grain size and fine-particle content. *Engineering Geology*, Vol. 69, Nos. 1–2, 109–125.