

# Relationships among remotely sensed soil moisture, precipitation and landslide events

Ram L. Ray · Jennifer M. Jacobs

Received: 23 August 2006 / Accepted: 7 November 2006 / Published online: 2 March 2007  
© Springer Science+Business Media B.V. 2007

**Abstract** Landslides are triggered by earthquakes, volcanoes, floods, and heavy continuous rainfall. For most types of slope failure, soil moisture plays a critical role because increased pore water pressure reduces the soil strength and increases stress. However, in-situ soil moisture profiles are rarely measured. To establish the soil moisture and landslide relationship, a qualitative comparison among soil moisture derived from AMSR-E, precipitation from TRMM and major landslide events was conducted. This study shows that it is possible to estimate antecedent soil moisture conditions using AMSR-E and TRMM satellite data in landslide prone areas. AMSR-E data show distinct annual patterns of soil moisture that reflect observed rainfall patterns from TRMM. Results also show enhanced AMSR-E soil moisture and TRMM rainfall prior to major landslide events in landslide prone regions of California, U.S.; Leyte, Philippines; and Dhading, Nepal.

**Keywords** Landslides · Soil moisture · AMSR-E · TRMM · Rainfall

## 1 Introduction

Numerous natural factors, earthquakes, concentrated rainfall events, and undercutting of banks by flood, as well as anthropogenic factors, including deforestation and slope excavation, contribute to slope failures by decreasing shear strength or increasing shear stress of the soil mass (Abramson et al. 1996). However, most of the slope failures coincide with intensive rainfall (Anderson and Sitar 1995; Iverson 2000). Landslides are frequently a combined effect of intense rainfall and wet antecedent soil moisture conditions that cause landslides. For these slope failures, soil moisture plays a vital role because water both reduces the soil strength and increases the stress (Ray 2004).

---

R. L. Ray (✉) · J. M. Jacobs  
Department of Civil Engineering, University of New Hampshire,  
35 Colovos Rd, Gregg Hall, Durham, NH 03824, USA  
e-mail: rlj3@cisunix.unh.edu

Soil moisture surrogates have been used extensively in slope stability analyses. Montgomery and Dietrich (1994), Van Westen and Trelirn (1996), de Vleeschauwer and De Smedt (2002), and Acharya et al. (2006) analyzed slope stability using wetness indices calculated by the TOPOG model (O'Loughlin 1986). As pointed out by Rosso et al. (2006), Montgomery and Dietrich's (1994) model neglects the presence of soil moisture in the upper soil layer above the groundwater table. They presented a modified model in order to consider soil moisture in the upper soil layer. Anderson and Sitar (1995), Iverson (2000), D'Odorico and Fagherazzi (2003), and Collins and Znidarcic (2004) showed that slope failures are primarily caused by infiltration of rainfall into the sub-surface layer resulting in increased pore water pressure. These studies focus on saturation level soil moisture contents as they relate to landslides. However, these studies have indirectly estimated the soil moisture or pore water pressure based on rainfall and do not directly account for the highly variable soil moisture prior to and during rainfall events.

Antecedent soil moisture can be obtained by in-situ measurements. However, such measurements are time consuming and require complex data collection efforts even for local scales. As a result, there are very few in-situ observing systems to measure soil moisture at regional or continental scales (Gao et al. 2006). An alternative approach is to obtain surface soil moisture from satellite remote sensing at national and global scales.

Surface soil moisture can be observed (measured) using microwave remote sensing (Jackson 1982; Teng et al. 1993; Schmugge and Jackson 1994; Kerr et al. 2001; Jackson 2002; Moran et al. 2004; Loew et al. 2006; de Rosney et al. 2006). Typically remote sensing instruments can only provide the soil moisture information from the surface soil depth down to 1–5 cm. Numerous studies (e.g., Njoku et al. 2003; Walker et al. 2004; Lacava et al. 2005; Njoku and Chan 2006; Gao et al. 2006) point out that microwave remote sensing measurements are affected by surface roughness, topographic features, dense vegetation and, soil texture. This indicates that soil moisture data may have limited value on steep topography (Njoku et al. 2000). However, no validation experiments have been conducted on such terrain. As landslides mainly occur on steep slopes, a preliminary challenge is to determine if satellites can provide a signal in landslide prone areas.

Landslides are not triggered only due to surface layer saturation; rather, it is the combined effect of surface and sub-surface saturation that is critical. Therefore, it is necessary to be able to link the surface soil moisture to the sub-surface layer. A series of studies have established a link between surface soil moisture and groundwater. Choi and Jacobs's (in Press) soil moisture patterns on the surface were strongly related to those in the root zone. With an assumption of hydraulic potential equilibrium, Jackson (1980) developed a complete soil moisture profile based on surface soil moisture measurements. Arya et al. (1983) developed two approaches, regression and water budget approach, to establish the correlation between surface and sub-surface soil moisture. Reutov and Shutko (1991, 1992) explored a technique to measure the depth of a shallow groundwater table based on microwave remote sensing data that uses the capillary rise above the water table to estimate the water table depth.

This study seeks to determine: (1) can remotely sensed soil moisture provide information in landslides prone regions? and (2) is there a qualitative relationship among landslides, rainfall (TRMM), and AMSR-E soil moisture? To answer these questions, the daily and seasonal variations of remotely sensed soil moisture from

the Advanced Microwave Scanning Radiometer (AMSR-E) on the Earth Observing System (EOS) and rainfall from the Tropical Rainfall Measuring Mission (TRMM) are quantified in three landslide prone regions: Cleveland Corral, El Dorado County, CA, U.S.; Guinsaugon, Southern Leyte, Philippines; and Krishnabhir, Dhading Nepal.

The article presents an overview of the remote sensing technologies available to measure soil moisture and a brief review of the TRMM rainfall measurements. The soil moisture retrieval algorithm is also discussed. Details on the study sites as well as the rainfall and soil moisture data used in this study are provided. This article compares and analyzes the AMSR-E soil moisture and TRMM rainfall daily data from January 2005 to May 2006 at the three landslide prone regions.

## 2 Relationship between water and slope failure

A landslide is a sudden failure of slope with or without the influence of water. Landslides that result in disasters are more commonly known as landslide disasters. Prior to slope failure, there is a slope movement. Sometimes slope movement results in a landslide and sometimes it does not. Most of the slope failures are caused by soil moisture or groundwater that increases pore water pressure and decreases shear strength.

Safety factors (FS) are used to characterize slope stability. Slopes having safety factors smaller than one are considered unstable. A relationship can be established between soil moisture and slope failure for cohesive or cohesionless soil. Sidle and Ochiai (2006) developed a safety factor equation for any combination of soil and soil moisture, as

$$FS = \frac{c_s}{W \sin \theta} + \frac{\tan \phi}{\tan \theta} - \frac{u \tan \phi}{W \sin \theta} \quad (1)$$

$$W = [\gamma_t(H - h) + \gamma_{sat}h] \cos \theta \quad (2)$$

$$u = \gamma_w h \cos^2 \theta \quad (3)$$

where, FS is the safety factor,  $c_s$  is the effective soil cohesion [ $\text{kN/m}^2$ ],  $u$  is the pore water pressure [ $\text{kN/m}^2$ ],  $H$  and  $h$  are the depth of the soil and water above failure plain, respectively [m],  $\phi$  is the angle of internal friction and  $\theta$  is slope angle [ $^\circ$ ],  $\gamma_t$  is the unit moist (but not saturated) weight of the soil [ $\text{kN/m}^3$ ],  $\gamma_{sat}$  the saturated unit weight of the soil [ $\text{kN/m}^3$ ], and  $\gamma_w$  the unit weight of water [ $\text{kN/m}^3$ ].

Equation 1 shows that increasing the soil slope decreases the safety factor. Similarly, increasing the soil moisture/water increases pore water pressure ( $u$ ), effectively decreases the safety factor. Landslides occur when the safety factor reduces to less than one.

## 3 Remote sensing products

### 3.1 Remotely sensed soil moisture

Soil moisture can be measured with passive or active microwave sensors. Although the active and passive sensors observe different parameters, brightness temperatures, and backscattering coefficients, respectively, (Jackson 2002), both sensors

provide information about surface reflectivity. Based on surface reflectivity, the dielectric constant necessary to derive surface soil moisture is estimated (Jackson, 2002). However, vegetation and roughness reduce the sensitivity of the microwave observations to soil moisture (Njoku et al. 2003).

Lower frequencies, L band (1–2 GHz), are more sensitive to soil moisture. The higher frequency C (6.9 GHz) and X (10.65 GHz) bands can be used to retrieve soil moisture (Jackson et al. 2005) because these higher frequency bands are less susceptible to radio frequency interference (RFI). At present there are several satellite systems that are capable of observing surface soil moisture (Cashion et al. 2005). The systems include the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) at 10.65 GHz, (Jackson and Hsu 2001), and the Advanced Microwave Scanning Radiometer (AMSR) on the Earth Observing System (Njoku et al. 2003). Soil Moisture and Ocean Salinity (SMOS) (Kerr et al. 2001) is expected to launch by 2007 (Hoffmann 2005; Scipal et al. 2005). This study uses the AMSR-E satellite data.

AMSR-E was developed by the National Space Development Agency of Japan (NASDA) and launched on Aqua satellite by the National Aeronautics and Space Administration (NASA) on May 4, 2002 (Njoku et al. 2003; Li et al. 2004). AMSR-E measures brightness temperature at six frequencies in the range 6.9–89 GHz (Njoku et al. 2003). Soil moisture is retrieved using a microwave radiative transfer (RT) model that links surface geophysical variables to the observed brightness temperature (Jackson 1993; Njoku et al. 2003). AMSR-E produces soil moisture (product level 3) at 56 km spatial resolution and provides re-sampled products at a 25 km grid scale. AMSR-E data are available from June 18, 2002 to present on a daily basis. However, data are missing on a number of days.

### 3.2 Remotely sensed rainfall

The Tropical Rainfall Measuring Mission (TRMM) instrument was launched on November 27, 1997 as joint effort by NASA and the Japanese Space Agency (JAXA) (Kummerow et al. 1998; Gao et al. 2006). TRMM provides precipitation data from 1997 to present (<http://trmm.gsfc.nasa.gov>). The primary instruments are the Precipitation Radar (PR), the first rain radar in space (13.8 GHz), and the TRMM Microwave Imager (TMI), a multi-channel (5 bands from 10.7 GHz to 85.5 GHz) passive microwave radiometer. In addition, the Visible Infrared Scanner (VIRS) instrument is used to image clouds to determine precipitation structure. TRMM provides data from 50° S and 180° W to 50° N and 180° E. This study uses the TRMM precipitation 3B42 3-h product at a  $0.25^\circ \times 0.25^\circ$  (27.5 km<sup>2</sup>) resolution.

### 3.3 Study data sets

For this study, AMSR-E soil moisture data were obtained from NASA Earth Observing System Data Gateway through National Snow and Ice Data Center (NSIDC). The TRMM rainfall 3B42 3-h product was obtained from Goddard Distributed Active Archive Center (DAAC). Both TRMM rainfall and AMSR-E soil moisture data are for the period January 1, 2005 to May 31, 2006. Daily rainfall totals were calculated from the TRMM 3-h product. AMSR-E soil moisture and

TRMM rainfall values were analyzed and compared with landslide events to establish relationships among them.

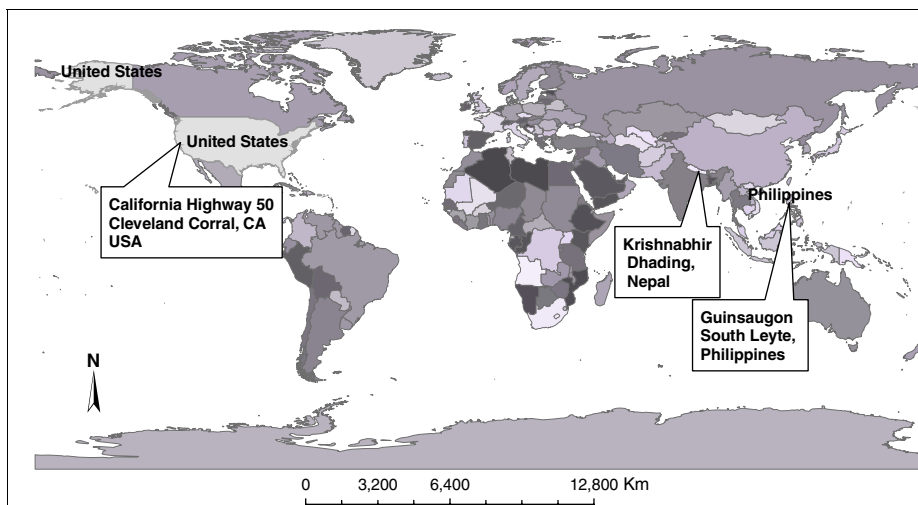
In order to consider the response of soil moisture and rainfall, active landslide locations were selected for the three regions. These landslide areas are on the order of 1 km<sup>2</sup>. Compared to the study areas, both the TRMM and the AMSR-E pixels are much larger. Therefore, one satellite pixel was obtained and analyzed for each site's soil moisture and rainfall.

## 4 Study areas

Three study regions, which are highly prone to landslides, were selected for analysis. The study regions are Highway 50 at Cleveland Corral, El Dorado County, CA, US; Guinsaugon, Southern Leyte, Philippines; and Prithivi highway at Krishnabhir, Dhading, Nepal (Fig. 1). Since 1996, landslides and slope movements are very common in the Highway 50 corridor (Reid et al. 2003). In Guinsaugon, Southern Leyte, Philippines, a major landslide disaster occurred on February 17, 2006. This rainfall-induced landslide crushed a village where 122 people were confirmed dead, hundreds of people were still missing, and thousands of people were left homeless (Lagmay et al. 2006). In Krishnabhir Dhading Nepal, landslides have continuously occurred for four consecutive years starting from 2000 (Ray 2004). Along the Prithivi highway corridor, landslides are very common during every monsoon.

### 4.1 Cleveland Corral, CA, USA

The Cleveland Corral landslide study region in Highway 50 corridor is located in the Sierra Mountains, California, USA (Reid et al. 2003). Highway 50 is a major road located between Sacramento and South Lake Tahoe in California (Spittler and Wagner 1998). The study area is located between 120°17'42" W to 120° 32'42" W and 38° 39'12" N to 38° 54'12" N. Altitudes range from about 30–3140 m. Since



**Fig. 1** Locations of the three study regions

1996, slope movement and landslides occur infrequently during winter season. Additionally, one major catastrophic landslide occurred in 1983 in this region (Spittler and Wagner, 1998). Since 1997 the USGS has monitored this region using real time data acquisition systems (Reid et al. 2003). They found elevated pore-water pressures and abundant soil moisture during periods with slope movement and landslides in the winter (rainy) season.

#### 4.2 Guinsaugon, Leyte, Philippines

The Philippines is an island country located in South East Asia between latitude  $4^{\circ}23' \text{ N}$  and  $21^{\circ}25' \text{ N}$  and longitude  $116^{\circ} \text{ E}$  and  $127^{\circ} \text{ E}$  with a 1850 km length and a 965 km width. The country's topography is characterized by alluvial plains to high mountains with an elevation to 3144 m. The Guinsaugon study region, municipality of St. Bernard, is located in Southern Leyte Province, Philippines. The Guinsaugon village, the site of the 2006 landslide disaster, is located at the foot of the slope (Lagmay et al. 2006). The study area is centered at  $10^{\circ}21'3'' \text{ N}$ ,  $125^{\circ}64'33'' \text{ E}$  latitude and longitude, respectively, with a maximum elevation of 675 m (Lagmay et al. 2006). The authors indicate that the February 2006 landslide's cause was a weeklong intensive rainfall in the Southern Leyte region.

#### 4.3 Krishnabhir, Dhading, Nepal

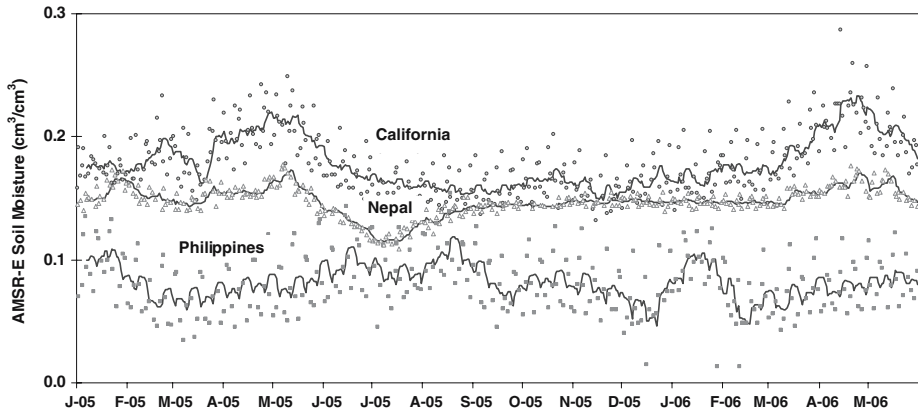
Nepal consists of about 83% mountainous terrain, and the remaining 17% in the southern alluvial plains. The country extends from  $80^{\circ}04' \text{ E}$  longitude and  $26^{\circ} 22' \text{ to } 30^{\circ}27' \text{ N}$  latitude and spans approximately 885 km in the east–west direction and varies from 130 to 255 km in north–south direction. The altitude ranges from 70 m at Kanchan Kalan to 8850 m at the top of the Mount Everest within a very short distance. The relatively high landslide frequency in Nepal, as compared with mountain ranges of other countries, may be because Nepalese Mountains are geographically younger (Ray 2004).

The Krishnabhir study region lies in the Dhusa Village Development Committee (VDC) in Dhading district, Nepal along the Prithvi Highway. The highway connects the Western and Eastern parts of the country to Kathmandu, the national capital. The area is situated within the  $27^{\circ}45' \text{ to } 27^{\circ}52'30'' \text{ N}$  latitude and  $84^{\circ}37'30'' \text{ to } 84^{\circ}52'30'' \text{ E}$  longitude. Altitudes range from about 242 to 1922 m above the sea level. One of the major landslide areas is located at Krishnabhir of Dhusa VDC along the Prithivi Highway. Since 2000, landslides occur annually during the rainy season along the Prithivi Highway.

## 5 Results and Discussion

### 5.1 Intercomparison

Figure 2 shows daily and weekly moving average values of AMSR-E soil moisture for one and half years (January 1, 2005 to May 31, 2006). As daily soil moisture values are highly variable, a weekly moving average soil moisture was calculated for each date by averaging that day's soil moisture with that of the six preceding days. This plot clearly shows daily and seasonal variations for each study region.



**Fig. 2** A comparison of soil moisture and rainfall in the three study regions (January 2005–May 2006). Daily values are indicated with circles, triangles, and squares for California, Nepal, and Philippines, respectively. Solid lines correspond to the 1-week moving average

The period having the wettest soil moisture differs by region. For example, California’s highest soil moisture occurs in the spring season. Nepal’s soils are very wet shortly before and after the monsoon. The Philippines has the highest soil moisture value in the winter and late summer. Weekly moving average soil moisture values vary gradually in CA, USA, and Dhading, Nepal, but oscillate in Leyte, Philippines.

Table 1 presents summary statistics that characterize soil moisture variations by study region. The highest soil moisture values, observed in California, US, are twice those reported for Leyte, Philippines. Based on the standard deviation of daily values, Nepal has much lower variability than either California or Leyte. Soil moisture ranges are smaller than expected, particularly for Nepal. Overall, these results indicate that even in steep terrain or landslide prone regions AMSR-E soil

**Table 1** Statistical analysis of AMSR-E soil moisture from January 2005 to May 2006 in three study regions

Descriptions	California, USA		Leyte, Philippines		Dhading, Nepal	
	Soil moisture (cm <sup>3</sup> /cm <sup>3</sup> )	Date	Soil moisture (cm <sup>3</sup> /cm <sup>3</sup> )	Date	Soil moisture (cm <sup>3</sup> /cm <sup>3</sup> )	Date
<i>2005</i>						
Mean	0.175		0.084		0.145	
Range	0.117		0.139		0.068	
Std. Dev	0.023		0.025		0.013	
Min	0.132	November 15	0.015	December 17	0.109	July 17
Max	0.249	May 10	0.154	August 19	0.177	May 7
Count (Days)	271		225		232	
<i>2006 (Jan–May)</i>						
Mean	0.191		0.079		0.153	
Range	0.147		0.112		0.035	
Std. Dev	0.027		0.023		0.008	
Min	0.14	January 2	0.013	February 11	0.141	February 7
Max	0.287	April 14	0.125	January 25	0.176	April 19
Count (Days)	113		92		101	

moisture can provide relevant information by capturing mean values and the timing and duration of wet periods.

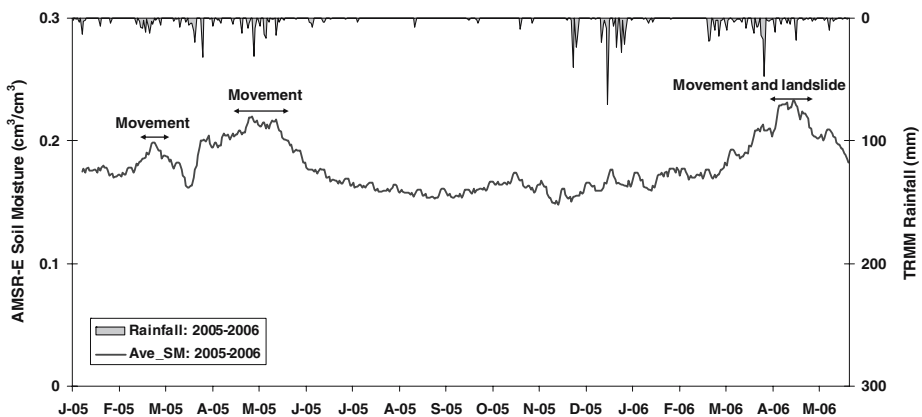
## 5.2 Cleveland Corral, CA, USA

Figure 3 shows the weekly moving average AMSR-E volumetric soil moisture values from January 2005 to May 2006 as well as the daily TRMM rainfall data in the Cleveland Corral, California study region. While the results show only a 12% range in the soil moisture variations annually, the observed variations are adequate to identify the timing of relatively high soil moisture. Seasonal trends show that soil moisture increases from March to late May each year. This rising trend in soil moisture corresponds to a period of high rainfall. Soil moisture peaks occurred in April and May for both 2005 and 2006. However, peaks on 10 May, 2005 (24.9%) and on 14 April, 2006 (28.7%) do not coincide with rainfall peak events on 1 May, 2005 (31 mm) and on 5 April, 2006 (47.8 mm), respectively. This may reflect the lag time between the rainfall event and the satellite measurement. Thus, soil moisture may better characterized using total accumulated rainfall rather than brief intense rainfall events.

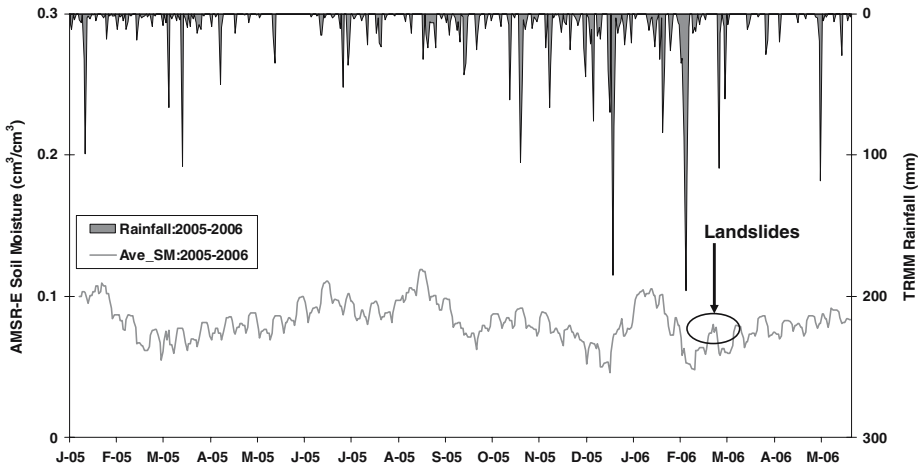
Soil moisture and rainfall trends were compared to slope movements and landslide events. Reported slope movement began in late February 2005. Also, slope movements were observed throughout May 2005 (<http://landslides.usgs.gov/monitoring/hwy50>). Two landslides were observed in 2006, one on April 3rd near Whitehall and another on May 7 near Kyburz. All of the slope movements and landslides coincide with periods of enhanced surface soil moisture and rainfall in this region. Interestingly, the peak precipitation days did not necessarily match the dates of observed movements and landslides.

## 5.3 Guinsaugon, Leyte, Philippines

Figure 4 depicts the weekly moving average AMSR-E volumetric soil moisture values and daily TRMM rainfall values from January 2005 to May 2006 in



**Fig. 3** Slope movement/landslides, 1-week moving average AMSR-E soil moisture and daily TRMM rainfall in California, US from January 2005 to May 2006



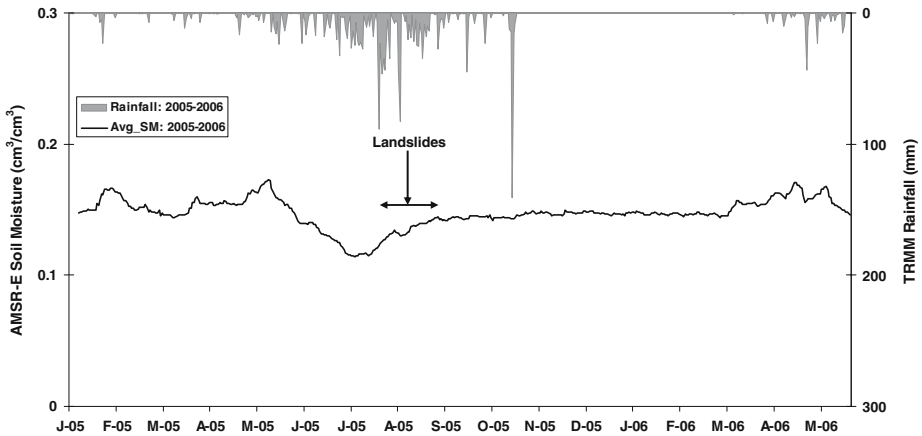
**Fig. 4** Landslides, 1week-moving average AMSR-E soil moisture and daily TRMM rainfall in Leyte, Philippines from January 2005 to May 2006

Guinsaugon, Leyte, Philippines. This study region has a completely different daily and seasonal soil moisture and rainfall temporal pattern than the California site. In this region, frequent rainfall events were observed throughout the year. Figures 2 and 4 show higher daily soil moisture variations than seasonal soil moisture variations. Due to the fairly uniform yearly rainfall distribution, no distinct seasonal soil moisture variations were observed. The seasonal evolution of soil moisture appears to somewhat correspond to the rainfall observations, but a clear relationship is not readily evident.

The soil on the day of landslide disaster, February 17, 2006, was not as wet as that in January 2006. As shown in Fig. 4, this region had received high (375 mm) rainfall from 22 to 26 December in 2005. This rainfall causes gradual increase of soil moisture till mid January. Without rainfall, gradually decreased soil moisture can be observed from mid January to mid February in 2006. A weeklong continuous heavy rainfall (>400 mm) that increased soil moisture/pore water pressure in the sub-surface layer likely caused the landslide disaster. That the landslide occurred during lower than peak soil moisture indicates the importance of rainfall characteristics in addition to antecedent conditions. This site suggests that additional research is needed to estimate soil moisture for landslide hazard prediction that uses both soil moisture and rainfall.

#### 5.4 Krishnabhir, Dhading, Nepal

The one and half year (January 2005–May 2006) moving average AMSR-E soil moisture and daily TRMM rainfall plot for Dhading, Nepal produces a comparatively different pattern than the other two study regions (Fig. 5). This is mainly due to Nepal’s monsoonal (June–September) climate. In this study region, off monsoonal (October–May) season receives a very little rainfall. Dry soil conditions persist until late July. Figures 2 and 5 show higher seasonal soil moisture variations than daily soil moisture variations. Interestingly, the soil moisture values are nearly constant



**Fig. 5** Landslide, 1-week moving average AMSR-E soil moisture and daily TRMM rainfall in Dhading, Nepal from January 2005 to May 2006

from September to February and appear to be insensitive to rainfall. This may indicate a measurement problem. As this period coincides with Nepal's typical late August planting, the potential cause is dense vegetation.

From 2000 to present, landslides were observed annually during the monsoon (Mid August) (Ray 2004) in the Prithivi highway corridor. During the monsoonal rainfall, enhanced soil moisture is shown in Fig. 5. These wetter conditions increase pore water pressures to levels that are sufficient to cause slope failure. Hence in Nepal, the steady rainfall measured by TRMM that causes a continuous increase in soil moisture is closely linked with this region's landslide.

## 6 Conclusion

Soil moisture is an important parameter for landslide studies. As the soil mass's soil moisture increases, pore water pressure rises. Pore water pressure, which increases shear stress and decreases shear strength, is the main cause for many landslides. This soil moisture can be estimated by in-situ measurements, but such measurements are time consuming and cost prohibitive at national and global scale. In contrast, this study shows that AMSR-E can provide surface soil moisture for global scale at a daily temporal resolution.

Each of the three study regions had landslide or slope movement when soil moisture and rainfall showed higher values. These landslide occurrences clearly indicate a strong relationship among landslide events, AMSR-E surface soil moisture and TRMM rainfall. Results show that AMSR-E soil moisture data can be used for landslide studies. However, more intensive research is still necessary to validate soil moisture patterns and implement and include AMSR-E soil moisture in slope stability analysis.

**Acknowledgements** This work was supported by NASA Headquarters under the Earth System Science Fellowship Grant NNG05GP66H.

## References

- Abramson LW, Lee TS, Sharma S, Boyce GM (1996) Slope stability and stabilization methods. A Wiley-Interscience Publication, John Wiley & Sons Inc., NY
- Acharya G, De Smedt F, Long NT (2006) Assessing landslide hazard in GIS: a case study from Rasuwa, Nepal. *Bull Eng Geol Environ* 65(1):99–107
- Anderson SA, Sitar N (1995) Analysis of rainfall induced debris flows. *J Geotech Eng* 121(7):544–552
- Arya LM, Richter JC, Paris JF (1983) Estimating profile water storage from surface zone soil moisture measurements under bare field conditions. *Water Resour Res* 19(2):403–412
- Cashion J, Lakshmi V, Bosch D, Jackson TJ (2005) Microwave remote sensing of soil moisture: evaluation of the TRMM microwave imager (TMI) satellite for little river watershed Tifton, Georgia. *J Hydrol* 307:242–253
- Choi M, Jacobs JM (2007) Soil moisture variability of root zone profiles within SMEX02 remote sensing footprints. *Adv Water Resour* 30:883–896
- Collins BD, Znidarcic D (2004) Stability analysis of rainfall induced landslides. *J Geotechn Environ Eng* 130(4):362–372
- D' Odorico P, Fagherazzi S (2003) A probabilistic model of rainfall-triggered shallow landslides in hollows: A long-term analysis. *Water Resour Res* 39(9):1262, doi:10.1029/2002WR001595
- de Rosney P, Calvet JC, Kerr Y, Wigneron FL, Lemaitre F, Escorihuela MJ, Sabater JM, Saleh K, Barrie J, Bouhours G, Coret L, Cherel G, Dedieu G, Durbe R, Fritz NED, Froissard F, Hoedjes J, Kruszewski A, Lavenu F, Suquia D, Waldteufel P (2006) SMOSREX: A long term field campaign experiment for soil moisture and land surface processes remote sensing. *Remote Sens Environ* 102:377–389
- de Vleeschauwer C, De Smedt F, (2002) Modeling slope stability using GIS on a regional scale. Proceedings of the first Geological Belgica International Meeting, Leuven, 11–15 September 2002. *Aardkundige Mededelingen* 12:253–256
- Gao H, Wood EF, Jackson TJ, Drusch M, Bindlish R (2006) Using TRMM/TMI to retrieve surface soil moisture over the southern United States from 1998 to 2002. *J Hydrometeorol* 7:23–38
- Hoffmann J (2005) The future of satellite remote sensing in hydrogeology. *Hydrogeol J* 13:247–250, doi: 10.1007/s10040-004-0409-2
- Iverson RM (2000) Landslide triggering by rain infiltration. *Water Resour Res* 36(7):1897–1910
- Jackson TJ (1980) Profile soil moisture from surface measurements. *J Irrigation Drainage Div, Am Soc Civil Eng* 106(IR2): 81–92
- Jackson TJ, (1982) Passive microwave sensing of soil moisture under vegetation canopies. *Water Resour Res* 18(4):1137–1142
- Jackson TJ, (1993) III Measuring surface soil moisture using passive microwave remote sensing. *Hydrol process* 7:139–152
- Jackson TJ (2002) Remote sensing of soil moisture: implications for groundwater recharge. *Hydrogeol J* 10:40–51
- Jackson TJ, Bindlish R, Gasiewski AJ, Stankov B, Njoku EG, Bosch D, Coleman TL, Laymon CA, Starks P (2005) Polarimetric scanning radiometer C- and X-band microwave observations during SMEX03. *IEEE Trans Geosci Rem Sens* 43(11):2418–2430
- Jackson TJ, Hsu AY (2001) Soil moisture and TRMM microwave imager relationships in the Southern Great Plains 1999 (SGP99) experiment. *IEEE Trans Geosci Rem Sens* 39(8):1632–1642
- Kerr YH, Waldteufel P, Wigneron JP, Martinuzzi JM, Font J, Berger M (2001) Soil moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) mission. *IEEE Trans Geosci Rem Sens* 30(8):1729–1735
- Kummerow C, Barnes W, Koju T, Shiue J, Simpson J (1998) The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J Atmos Ocean Technol* 15:809–817
- Lacava T, Greco M, Di Leo EV, Martino G, Pergola N, Sannazzaro F, Tramutoli V (2005) Monitoring soil wetness variations by means of satellite passive microwave observations: the HYDROPTIMET study cases. *Nat Hazard Earth Syst Sci* 5:583–592
- Lagmay AMA, Ong JBT, Fernandez DFD, Lapus MR, Rodolfo RS, Tengonciang MP, Soria JLA, Baliatan EG, Quimba ZL, Uichanco CL, Paguican MR, Remedio ARC, Lorenzo GRH, Valdivia W, Avila FB (2006) Scientists investigate recent Philippine Landslide, EOS Transaction, American Geophysical Union, 87(12)
- Li L, Njoku EG, Chang PS, Germain KS (2004) A preliminary survey of radio-frequency interference over the U.S. in Aqua AMSR-E Data. *IEEE Trans Geosci Rem Sens* 42(2):380–390

- Loew A, Ludwig R, Mauser W (2006) Derivation of surface soil moisture from ENVISAT ASAR wide swath and image mode data in agricultural areas. *IEEE Trans Geosci Rem Sens* 44(4):889–899
- Montgomery DR, Dietrich WE (1994) A physically based model for the topographic control on shallow landsliding. *Water Resour Res* 30(4):1153–1171
- Moran MS, Peters-Lidard CD, Watts JM, McElroy S (2004) Estimating soil moisture at the watershed scale with satellite-based radar and land surface models. *Can J Rem Sens* 30(5):808–826
- Njoku EG, Chan SK (2006) Vegetation and surface roughness effects on AMSR-E land observations. *Rem Sens Environ* 100:190–199
- Njoku EG, Jackson TJ, Koike T (2000) AMSR-E Science Data Validation Plan, version 2, 7/00. 76 pp
- Njoku EG, Jackson TJ, Lakshmi V, Chan TK, Nghiem SV (2003) Soil moisture retrieval from AMSR-E. *IEEE Trans Geosci Remote Sens* 41(2):215–229
- O'Loughlin EM (1986) Prediction of surface saturation zones in natural catchments by topographic analysis. *Water Resour Res* 22:794–804
- Ray RL (2004) Slope stability analysis using GIS on a Regional Scale: a case study from Dhading, Nepal. MSc. thesis in Physical Land Resources, Vrije Universiteit Brussel, 98 pp
- Reid ME, Brien DL, LaHusen RG, Roering JJ, de la Fuente J, Ellen SD (2003) Debris-flow initiation from large, slow-moving landslides. In: Rickenmann D, Chen CL (eds) *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment* Millpress, Rotterdam, ISBN 90 77017 78X
- Reutov EA, Shutko AM (1991) Estimation of the water table using remote microwave radiometer measurements. *Soviet J Rem Sens* 9(2):315–327
- Reutov EA, Shutko AM (1992) Estimation of the depth to a shallow water table using microwave radiometry. *Int J Remote Sens* 13:2223–2232
- Rosso R, Rulli MC, Vannucchi G (2006) A physically based model for the hydrologic control on shallow landsliding. *Water Resour Res* 42: W06410, doi:10.1029/2005WR004369
- Schmugge T, Jackson TJ (1994) Mapping surface soil moisture with microwave radiometers. *Meteorol Atmos Phys* 54:213–223
- Scipal K, Scheffler C, Wagner W (2005) Soil moisture runoff relation at the catchment scale as observed with coarse resolution microwave remote sensing. *Hydrol Earth Syst Sci* 9:173–183
- Sidle RC, Ochiai H, (2006) *Landslides: Processes, Prediction, and Land Use*. American Geophysical Union, *Water Resources Monograph* 18, 312 pp
- Spittler TE, Wagner DL, (1998) Geology and slope stability along highway 50. *Califor Geol* 51(3):3–14
- Teng WL, Wang JR, Doraiswamy PC (1993) Relationship between microwave radiometric data, antecedent precipitation index, and regional soil moisture. *Int J Remote Sens* 14(13):2483–2500
- Van Westen CJ, Trelirn TJ (1996) An approach towards deterministic landslide hazard analysis in GIS: a case study from Manizales (Colombia). *Earth Surf Process Landforms* 21:853–868
- Walker JP, Houser PR, Willgoose GR (2004) Active microwave remote sensing for soil moisture measurement: a field evaluation using ERS-2. *Hydrol Process* 18:1975–1997