EFFECT OF VEGETATION ON DEBRIS FLOW INITIATION: CONCEPTUALIZATION AND PARAMETERIZATION OF A DYNAMIC MODEL FOR DEBRIS FLOW INITIATION IN TIKOVIL RIVER BASIN, KERALA, INDIA, USING PCRASTER®

Sekhar Lukose Kuriakose[1*], Cees van Westen[1], Ramesh C. Lakhera[2], L.P.H van Beek[3], G. Sankar[4], Dinand Alkema[1] T.W.J van Asch[3], S.K Jayadev[5**]

[1] Department of Earth Systems Analysis, International Institute for Geo-information Science and Earth Observation, P.O. Box 6, 7500 AA, Enschede, The Netherlands
[2] Geosciences Division, Indian Institute of Remote Sensing (NRSA), 4 Kalidas Road, Dehradun, Uttaranchal, India, Pin – 248 001
[3] Faculty of Geosciences, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands
[4] Geology Division, Center for Earth Science Studies, P.O. Box 7250, Akkulam, Trivandrum, Kerala, India, Pin – 695 031
[5] PhD Scholar in Geography, Kerala University Library, Palayam, University P.O, Trivandrum – 695 034

KEY WORDS: Debris Flow Initiation, Dynamic Modeling, Transient Hydrology, STARWARS, PROBSTAB, PCRaster, Reference Evapotranspiration, MODIS NDVI, Root Induced Cohesion

ABSTRACT:

Debris flows, also referred to as mudflows are a common type of fast-moving landslide that generally occurs during intense rainfall on water saturated soil. Vegetation is an important factor influencing the occurrence of rainfall-triggered landslides. The study attempts to numerically simulate the transient hydrological conditions and resultant slope instability conditions occurring in Tikovil River basin of Kerala, India and thereby quantify the effect of vegetation on the initiation of debris flows in the region. The model used for the study was STARWARS+PROBSTAB (van Beek, 2002) and is realized in a dynamic GIS (PCRaster) environment.. The model was modified and additional parameters such as root induced cohesion and vegetation surcharge were incorporated. Root-induced cohesion was calculated using an empirical equation suggested by researchers from US Geological Survey. Hydrological Effects of vegetation such as interception and bulk throughfall were computed from MODIS-derived 16-day composite NDVI data. Interception was computed for every day using Aston's equation. Reference Evapotranspiration (RET) was computed using Hargreaves method and later adjusted to Actual Evapotranspiration using Crop Factors derived from FAO Database. Calibration was carried out using observed ground water height data for the area. The model simulated transient hydrological and slope stability conditions on a daily time step, with and without considering vegetation effects. A detailed investigation revealed that the hydrological effects of vegetation are crucial for the long term stability of the study area. However, its effects on slope stability during high intensity rainfall are negligible. Mechanical effect of vegetation, especially root induced cohesion is the most significant effect of vegetation on slope stability. The model was also able to capture the relative difference of instability in both the years; year 2000 had less number of slides when compared to year 2001. The research leads to the general conclusion that physically based spatial models are ideal to quantitatively understand the contribution of a specific parameter towards debris flow initiation.

* Corresponding Author
** Presenting Author

Introduction

Debris Flows are destructive events caused when eroded and other loose geological materials are mixed with water to the point where they begin to move down a gradient as one semi-cohesive mass, usually defined where sediment concentrations are greater than 60% by volume or 80% by weight (Vallance and Scott, 1997). Often initiated by shallow landslides, they are the primary agent of landscape evolution and the dominant denudational process in humid forested areas (Iida, 1999). In Kerala they are known as 'Urul Pottal'. The characteristic pattern of these phenomena is the swift and sudden down slope movement of highly water saturated overburden containing a varied assemblage of debris material ranging in size from soil particles to huge boulders destroying and carrying with it every thing that is lying in its path (Sankar, 2005).

The occurrence of debris flows is an increasing concern in Kerala. Much of the increase in debris flow activity is observed in areas with frequent changes in landuse/landcover. Studies on a 40,000 km^2 area in the state estimate that the annual rate of deforestation is 1.16%. (Jha et al., 2000).. The densely populated state is prone to debris flows due to its geomorphic setting as 40% of it lies in the most prominent orographic feature of peninsular India, The Western Ghats. Floods and landslides killed almost a 100 people in different parts of Kerala and caused damages (Figure 1) to the tune of Rs 50 crore in 2005 (Ajith, 2005).

Figure 1: Debris Flow havoc in Calicut District, 2005 (Photo by: G. Sankar)

The removal of natural vegetation from the slopes, exposing them to heavy rainfall (annual average of 3000 mm) and inducing monoculture in the extensive rubber, tea and cardamom plantations. The situation is particularly evident in the upper reaches of Idukki and Kottayam districts of Kerala. A study by the Center for Earth Science Studies identified that 'among landuse types the areas with degraded natural vegetation shows maximum slide intensity' (Thampi et al., 1998). This necessitates research to quantify the influence of vegetation on slope stability in the region.

Vegetation effect on slope stability may be broadly classified as either hydrological or mechanical in nature. The mechanical factors arise from the physical interactions of either the foliage or root system of the plant with the slope. The hydrological mechanisms are those intricacies of the hydrological cycle that exist when vegetation is present (Greenway, 1987).

There have been a number of attempts in dynamic spatial modeling of the effects of landuse/landcover on debris flows (van Asch et al., 1999; van Beek, 2002). Most of the studies consider the effect of change in vegetation cover on debris flows and landslides in terms of the effective rainfall that reaches the earth's surface. However, studies elsewhere have identified several other effects of vegetation on soil erosion in general and landsliding in particular (Lancaster and Grant, 1999). Landslide research works in India received deserving attention in the year 1994 through the report presented by the Ministry of Agriculture, Govt. of India, to the world conference on the IDNDR held in Japan. It is seen that considerable work has been done by various national agencies in the Himalayan region, while limited attention has been paid to the Western Ghats region (Thampi et al., 1998). Majority of the work in India was carried out using stochastic models and no work could be identified which tried to utilize a physically based dynamic model for understanding and quantifying the causative parameters.

Aim

The study aims at quantification of the hazard of debris flow initiation considering vegetation effects in the upper catchment of Tikovil River (Figure 2) that flows through Kottayam and Idukki districts of Kerala (India), using a physically based spatial modeling approach.

Methodology

The models used for the study were based on earlier work by Van Beek (2002). The two models (STARWARS and PROBSTAB) are implemented in a raster based GIS with an advanced Environmental Modeling Language, called PCRaster (www.pcraster.nl).

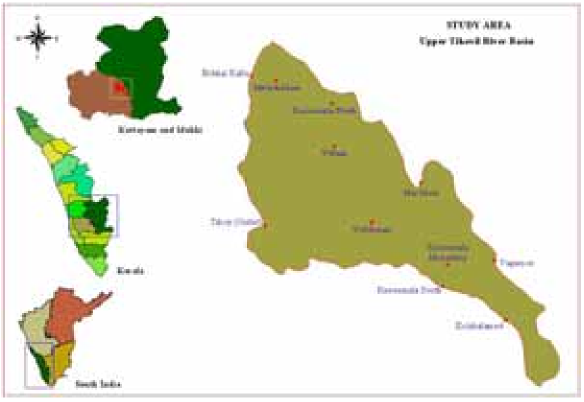

Figure 2: Study Area

The two models are coupled and consider both hydrological and mechanical effects of vegetation on slope instability. The detailed methodology with major input parameters are pictorially represented in Figure 3 and the indicated steps are detailed below.

Due to data deficiency the original coupled model was uncoupled and two more models were integrated. Similarly modifications were made to incorporate new parameters. The procedure is centered on 4 models, namely 1) Aston's model, 2) STARWARS, 3) Effective Degree of Saturation and 4) PROBSTAB. The detailed methodology with major input parameters are pictorially represented in Figure 3 and the indicated steps are detailed below.

Step 1 – Aston's Model: this model computes not only Interception from Aston's equation (Aston, 1979) on a daily time step but also derives Bulk Throughfall, computes the remaining amount of moisture in the soil that is available for evapotranspiration and the effective rainfall that reaches the surface and is available for percolation. The base data for the computation is MODIS NDVI 16 day composite and Rainfall on a daily time step. MODIS NDVI was used to compute Fractional Vegetation Cover using the empirical equation suggested by Walthall et al., (2004). Leaf Area Index was derived using the relationship suggested by Campbell and Norman (1998) (Walthall et al., 2004). Canopy storage was computed from Leaf Area Index (LAI) using the equation proposed by Von Hoyningen-Huene (1981). The bulk throughfall coefficient was computed as suggested by van Beek (2002). The interception deducted rainfall, reaches the surface and is stored as surface detention. The computed outputs of the model are the remaining amount of moisture in the soil that is to be evapotranspired and the effective rainfall that reaches the surface and is available for percolation. These are inputs for the next model: STARWARS.

Step 2 – STARWARS: this is an acronym for Storage and Redistribution of Water on Agricultural and Re-vegetated Slopes. The model simulates the spatial and temporal dynamics of moisture content and perched water levels in response to gross rainfall and evapotranspiration. Both interception and surface detention are subjected to evaporation.

The evapotranspiration is accounted using Hargreaves equation, instead of the original Penman's equation used by the model designer (van Beek, 2002). The model predicts percolation through the unsaturated zone and lateral saturated flow over a semi-pervious bedrock contact. The outputs of the model are Water Level from the bed rock on a daily time step and Volumetric Moisture Content. Calibration of the model was carried out based on available water level data for the study area.

Step 3 – Effective Degree of Saturation: To facilitate the calculation of the unsaturated hydraulic conductivity and to check on the available water, all storages are expressed as

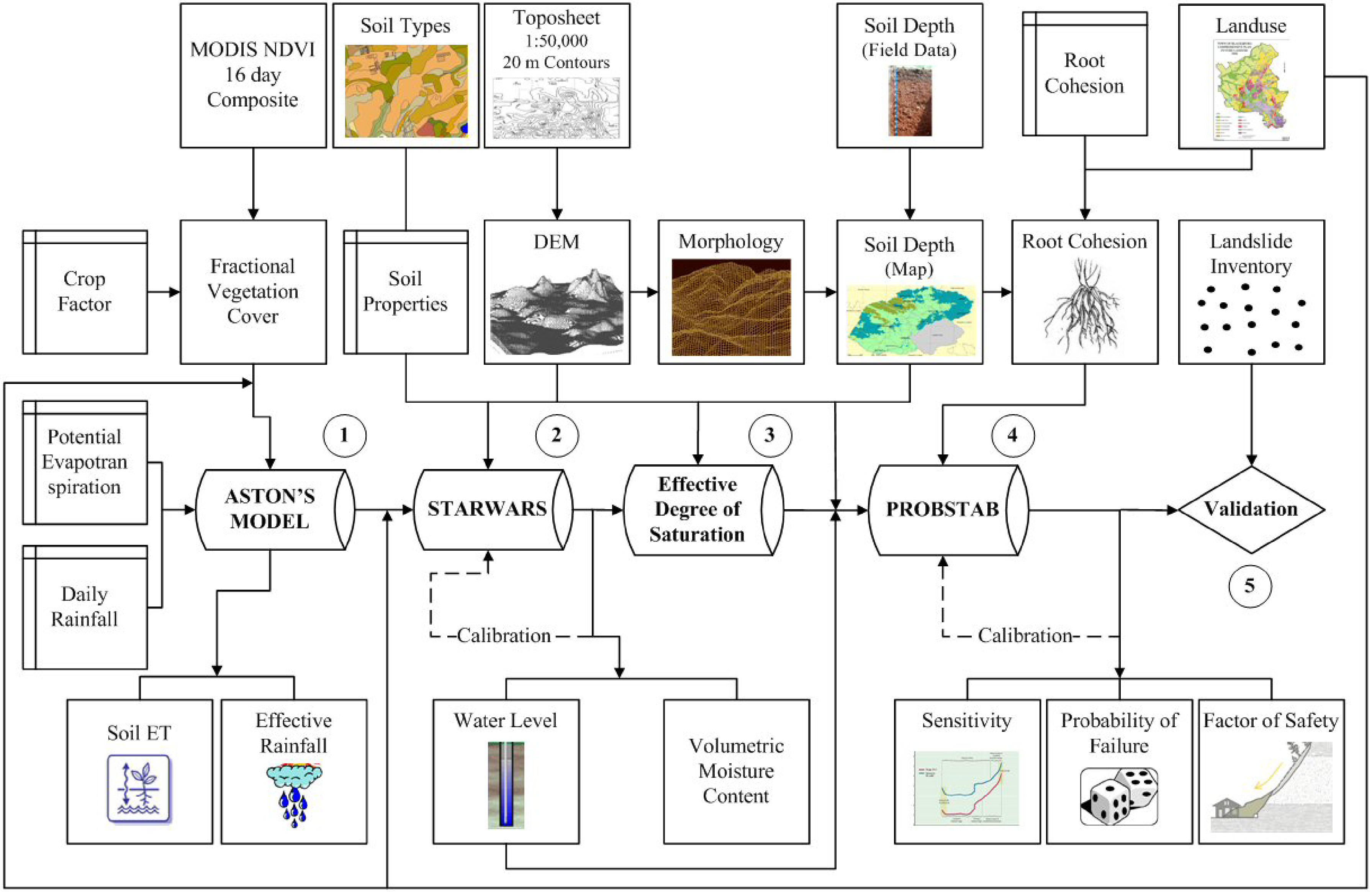

Figure 3: Methodology Flow Chart

water slices and the volumetric moisture content is converted to the relative degree of saturation. This is converted to effective degree of saturation, thus facilitating the computation of unsaturated bulk unit weight of the soil mass in a given time step.

Step 4 – PROBSTAB: this is an acronym for Probability of Stability. The model receives its dynamic inputs, namely water level from step 2 and effective degree of saturation from step 3. Static inputs are soil types defining soil properties, slope angles derived from the DEM (Figure 4), root cohesion as estimated in the field using the method from Schmidt et al., (2001), surcharge estimated in the field, and soil depth. The model was calibrated with root cohesion parameter and bulk density parameters. Probability of Failure is calculated using a First Order Second Moment method. The model is designed to also provide an understanding of the sensitivity of each of the input parameters. Sensitivity maps are derived as byproduct of the process.

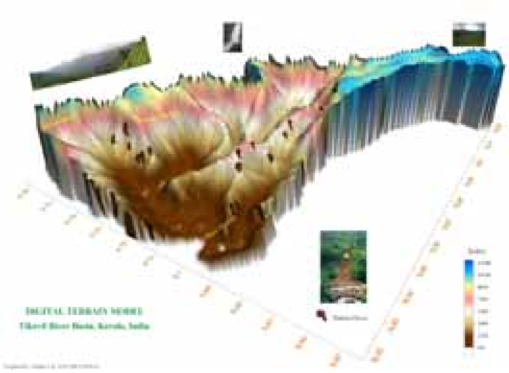

Figure 4: DEM of the study area

Step 5 – Validation: Both temporal and spatial validation was carried out for the factor of safety results, using slide event dates and slide initiation locations, respectively.

A detailed explanation of the methods can be found in Lukose Kuriakose (2006).

Results & Conclusions

The model simulated transient hydrological and slope stability conditions on a daily time step (Figure 5), with and without considering vegetation effects, providing different outputs, indicating the effect of vegetation. A detailed investigation revealed that:

- Hydrological effects of vegetation are crucial for the long term stability of the study area. However, its effects on slope stability during high intensity rainfall are negligible.
- Mechanical effect of vegetation, especially root induced cohesion is the most significant effect of vegetation on slope stability.

The unstable area as calculated by the model, considering vegetation effects was 2.54 km^2 in 2000 and 5.52 km^2 in 2001 (Figure 6); without considering vegetation effects the area was 7.12 km^2 in 2000 and 10.64 km^2 in 2001 (Figure 7).

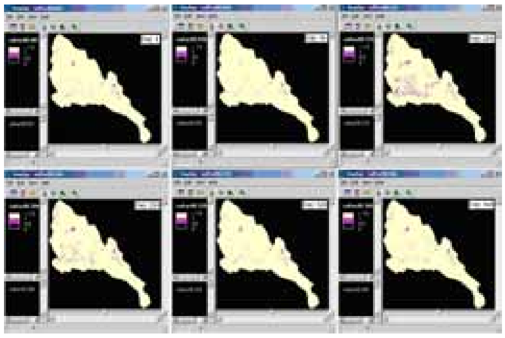

Figure 5: Daily Variations of Safety Factor in 2000 as visualized in PCRaster

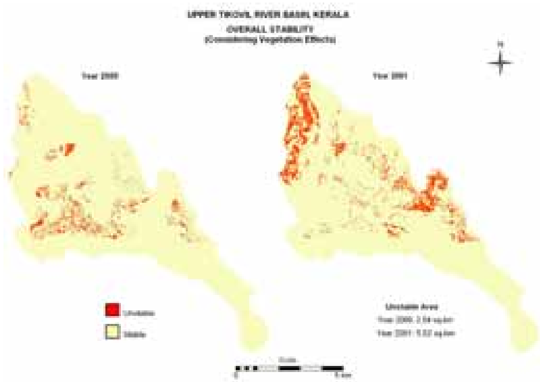

Figure 6: Overall stability of the study for 2000 & 2001, considering vegetation effects

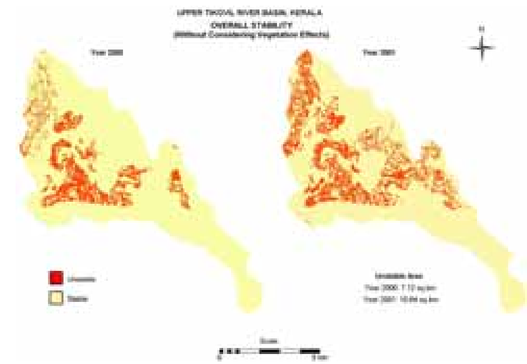

Figure 7: Overall stability of the study for 2000 & 2001, without considering vegetation effects

The model was able to capture the relative difference of instability in both the years; year 2000 had less number of slides when compared to year 2001. However, the overall area figure for both the years as predicted (considering vegetation effects) are overestimations that can be attributed to the data deficiency and the best possible model resolution (20 m X 20 m), given the scale of available datasets.

Physically based spatial models are ideal to quantitatively understand the contribution of a specific parameter towards debris flow initiation, as proven from the study.

References:

1. Ajith, L., 2005. 100 people die in floods, landslides in Kerala. www.indiadisasters.org.
2. Aston, A.R., 1979. Rainfall interception by eight small trees. Journal of Hydrology, 42(3-4): 383-396.
3. Greenway, D.R., 1987. Vegetation and Slope Stability. In: M.G. Anderson and K.S. Richards (Editors), Slope Stability. John Wiley and Sons Ltd.
4. Iida, T., 1999. A stochastic hydro-geomorphological model for shallow landsliding due to rainstorm. Catena, 34: 293-313.
5. Jha, C.S., Dutt, C.B.S. and Bawa, K.S., 2000. Deforestation and landuse changes in Western Ghats, India. Current Science, 79(2): 231-237.
6. Juyal, G.P., 2000. Spurs as Torrents Training Structures with Special Reference to Siwaliks of Doon Valley. In: S.P. Mittal, R.K. Agarwal and J.S. Samra (Editors), Fifty Years of Research on Sustainable Resource Management in Shivaliks. Central Soil and Water Conservation Research and Training Institute, Chandigar, pp. 267-274.
7. Lancaster, S.T. and Grant, G.E., 1999. Modeling the Interaction of Landslides, Debris Flows, and the Channel Network.
8. Lukose Kuriakose, S., 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. M.Sc Thesis, International Institute for Geo-information Science and Earth Observation (ITC)/Indian Institute of Remote Sensing (NRSA), Enschede, The Netherlands/Dehradun, India, 121 pp.
9. Sankar, G., 2005. Landslides of Kerala and their Management. In: G.V. Rajamanickam (Editor), National Seminar on Landslides. SASTRA Deemed University, Thanjavur, pp. 97-106.
10. Schmidt, R.L. et al., 2001. The variability of root cohesion as an influence on shallow landslide susceptability in the Oregon Coast Range. Canadian Geotechnical Journal, 35(5): 995-1024.
11. Thampi, P.K., Mathai, J., Sankar, G. and Sidharthan, S., 1998. Evaluation study in terms of landslide mitigation in parts of Western Ghats, Kerala, Center for Earth Science Studies, Trivandrum.
12. Vallance, J.W. and Scott, K.M., 1997. The Osceola mudflow from Mount Rainier: Sedimentology and hazard implications of a huge clay rich debris flow. Geological Society of America Bulletin, 109: 143-163.
13. van Asch, T.W.J., Buma, J. and van Beek, L.P.H., 1999. A view on some hydrological triggering systems in landslides. Geomorphology, 30: 25-32.
14. van Beek, L.P.H., 2002. Assessment of the Influence of Changes in Landuse and Climate on Landslide Activity in a Mediterranean Environment. PhD Thesis, Utrecht University, Utrecht, 363 pp.
15. Von Hoyningen-Huene, J., 1981. Die Interzeption des Niederschlags in landwirtschaftlichen Pflanzenbeständen, Arbeitsbericht Deutscher Verband für Wasserwirtschaft und Kulturbau, DVWK. 63, Braunschweig.
16. Walthall, C. et al., 2004. A comparison of emperical and neural network approaches for estimating corn and soybean leaf area index from Landsat ETM+ imagery. Remote Sensing of Environment, 92(4): 465-474.