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Rainfall-induced landslide hazard analysis of Noonmati-Sunsali hill-series in Guwahati city, Assam: A Physically-based model approach

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Abstract. Hill slopes within the city of Guwahati comprises mostly unsaturated residual soils The assessment of potential susceptibility to rainfall-induced landslide is governed by an effective modelling of the changes in matric suction in response to rainfall infiltration. This study presents the assessment of the rainfall-induced landslide susceptibility and hazard for the Noonmati-Sunsali hills in the Guwahati region, using the physically based model vis., TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model). In-situ and laboratory investigations are conducted to ascertain the hydrological and geotechnical characteristics of the hillslope soils. The rainfall intensity-duration-frequency (I-D-F) relations are evaluated, and are considered as input into TRIGRS simulation, and thereby the Factor of Safety (FoS) maps of the region are generated. The output of TRIGRS are validated based on in-situ observations. FOS distribution maps of the study area were developed for different return periods of rainfall with varying intensity and duration. All the results are combined to produce a landslide hazard map. The rainfall events of longer duration, as well as the antecedent rainfall conditions, are observed more influential in triggering landslides in this area. The gradual degradation of slope stability under such conditions can reasonably be elucidated through such an analysis.

Keywords: Rainfall-Induced Landslide, Hazard Mapping, TRIGRS, Rainfall IDF Curves, Antecedent Rainfall.

1 Introduction

The municipal territories of Guwahati region in Assam, India, have been experiencing an ever-growing recurrence of landslides due to the progressively changing rainfall scenario in the region. All landslides are primarily rain-triggered and are reported to occur when monsoon is at its peak or nearing completion, i.e., by the month of July – August to the end of September to mid-October (Sarma and Bora, 1994). Between 5th and 8th October 2004, as well as in 200 and 2012, several landslides occurred around the urbanized locations of Guwahati city resulting in significant loss of life and economic expense (Bhusan *et al*., 2014). The gradual change in the climatic conditions over the years is resulting in rainfall occurrences of higher intensity and duration. In this context, it becomes imperative to develop an explicit understanding of the rainfall induced landslides and detailed landslide inventory maps to identify the landslide-prone areas in a regional scale based on thorough and intricate studies. It is highly necessary that realistic predictive models be developed considering geological, geotechnical and hydrological inputs to the problem. Geotechnical, geological, and hydrological processes play a major role in influencing the landslide susceptibility of a particular site and there-fore, the first step towards any engineering study is to quantify the various parameters that can be identified to be influencing the stability of the slope. In this process, it willbe possible to model the landslide zone with in-depth understanding and arrive at a better-suited solution concerning the required mitigation measures. Such achievement would finally lead to the development of prediction models for probable future inci- dents, and can pave the way for early-warning systems.

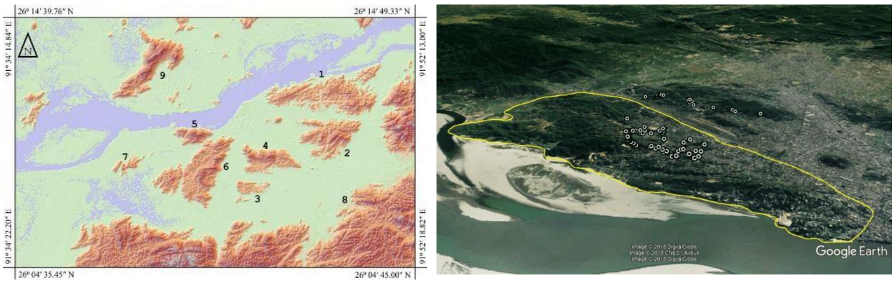
Hill slopes within the city of Guwahati consist of residual soils, in unsaturated condition. Rainfall infiltration results in the increase of water content and decrease in the matric suction, thereby raising the unit weight and reducing the shear strength of soil within the colluvium of the landslide. To assess the potential susceptibility to rainfall-induced landslide, an effective modelling of changes in water content and matric suction in response to rainfall infiltration is essential. Geotechnical slope stability analyses using physically based models are capable of providing the closest possible approximation of potential instability under the impact of rainfall infiltration considering different rainfall scenarios.

This article highlights the applicability of a physically-based model, TRIGRS (Transient Rainfall Infiltration and Grid based Regional Slope-stability) (Savage et al., 2004; Baum et al., 2008) to illustrate the landslide hazard scenario of the Noonmati-Sunsali hill series of Guwahati city. TRIGRS takes into account the geotechnical and hydrological aspect of the study area. ALOS World 3D-30m (AW3D30) dataset, with a resolution of 1 arc sec. latitude and longitude, is used to produce the digital elevation map (DEM) for the study from which the slope and the aspect map is derived. Rainfall Intensity - Duration – Frequency (IDF) curves is developed for this region. Based on the available literature and laboratory investigations, the soil shear strength properties (c and φ), the soil water characteristic curve (SWCC) and the saturated hydraulic conductivity have been considered. Based on available literature and additional data from in-situ boreholes all across the Guwahati city, a model for determining the thickness of residual soil formation as a function of the slope angle is proposed. Selected rainfall intensity – duration is then used as input into TRIGRS simulation and the corresponding Factor of Safety (FoS) maps of the region are generates as a response to different rainfall scenarios.

2 Study Area: Noonmati-Sunsali Hill Series, Guwahati City

2.1 Geographical and Geological Setting

The city of Guwahati is located approximately within latitude (91°33' – 91°52'6") E and longitude (26°4'45" – 26°14') N covering an area of approximately 328 sq. km across both banks of the river Brahmaputra (Fig. 1a). The hills, the low–lying alluvial plains and the marshy wetlands are three prominently observable geomorphological features of Guwahati City precinct. Sunsali-Noonmati hill series (Fig. 1b) fall within the municipal boundary of Guwahati city. The hillslope angles vary from gentle slopes to as steep as 60°. The hills are composed of the granite and gneiss as basal rocks affected by several sets of joints, intruded by quartz and quartz–feldsphetic veins, aplite and pegmatite. Quartzite, amphibolites and biotite schists, occur as thin bands or lenses parallel to the foliation (Shukla, 1989). Thick residual soil formation (up to depth of 30 m) (Das and Saikia, 2011) can be observed in zones of well-drained regions. Varying thicknesses of overburden are encountered in zones of moderate to imperfectly drained regions. Exposed basal rock, formation of etchforms and inselbergs due to erosion in zones of poor drainage are also observed from the geomorphology of the area.



(a) (b)

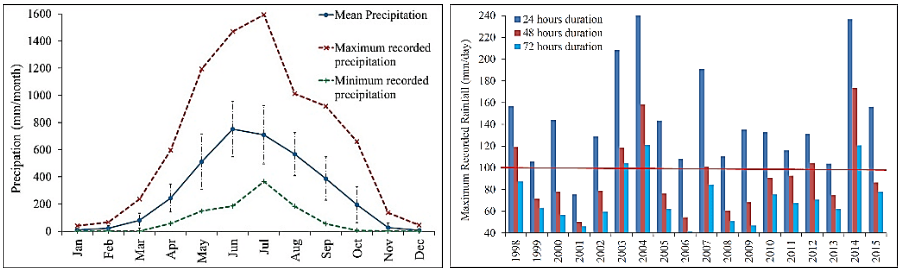
Fig. 1. (a) Geomorphological features and seven hill series of Guwahati city (b) Noonmati-Sunsali hill series (Google Earth Image)

Fig. 2. Cut-slopes at Nabagraha-Sunsali-Noonmati hill series

Hill slopes within the city of Guwahati consist of geological stratification, that characterize progressive stages of residual weathering, which can be categorized as basal rock, decomposed granitic rock and corestones, saprolitic and lateritic residual overburden. From the observation of cut slopes and sub soil investigation, two layers of overburden residual soils can be easily identified. Figure 2 shows the general hillslope soil stratification of this region. A top laterite formation of reddish residual silty clay, of thickness varying from few centimeters to few meters which is then underlain by a saprolite formation of pale yellowish residual soil which can be classified as a poorly graded silty sand.

2.2 Climatic Setting

The North Eastern territories of India experiences heavy rainfall during the monsoon season spread across the month of April to September. The wetting cycle starts from the month of April to mid of October and drying cycle starts from of November up to March, March being the hottest and driest month of the year. Figure 3a gives the Mean Monthly Rainfall and the Standard deviation (in form of error bars) for a period of 1901 – 2002, along with the maximum and minimum-recorded rainfall, in the district of Kamrup within which lies the city of Guwahati. The data represents the area average rainfall for the whole district for this period. It can be observed that the extreme rainfall events can be occasionally of intensity twice as much the mean of the recorded data. The rainfall data is being adopted from the Tropical Rainfall Measuring Mission (TRMM) 3-hourly rainfall estimate and daily (24–hour) data set, obtained from Goddard Earth Sciences Data and Information Services Center (GES DISC) maintained web portal Giovanni (http://disc.sci.gsfc.nasa.gov/giovanni). Figure 3 gives the maxi- mum rainfall intensity for the period 1998 – 2015, of duration 24 hours, 48 hours and 72 hours. Several landslide events were reported in the year 1998, 2004, 2007, 2012 and 2014. An approximate threshold of rainfall intensity of 100 mm/day for a duration48 hours can be inferred from Figure 3b.



(a) (b)

Fig. 3. (a) Monthly mean rainfall (for a period of 1901 – 2002) in the district of Kamrup (b) Maximum rainfall intensity for the period 1998 – 2015

3 Characteristics of Hillslope Materials

Typical representative and undisturbed samples of soil are collected from slopes of different hill series in the Guwahati city. Sieve analysis (IS 2720-4: 1985) is conducted on the representative samples to determine the particle size distribution, supplemented by the Atterberg's index tests (IS 2720-5: 1985) and determination of specific gravity (IS 2720-3: 1980). In-situ dry density and water content are determined from the undisturbed samples. The shear strength parameters are ascertained with the aid of Triaxial and Direct Shear tests conducted on saturated soil specimens. Figure 4a shows some typical sheared samples obtained after the triaxial test. The failure type can be observed to be predominantly shear failure with some bulging, which is a prevalent characteristic of the granular soils having fine content, as commonly obtained in this region. The samples behaved as normally consolidated specimen, with the pore pressure build up during undrained shearing and volume compression during drained shearing. This is a very important phenomenon influential during the occurrence of landslide. As the shearing starts, the soil compresses with a buildup of positive pore pressure leading to a reduction of the effective confining stresses, thus inducing progressive decrement of the soil shear strength.

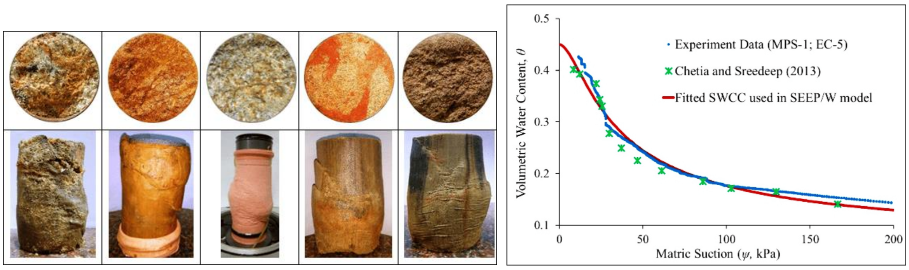


Fig. 4. (a) Cross section of typical undisturbed samples (top) and the sheared samples obtained after triaxial test (bottom) (b) Typical soil water characteristic curve of Guwahati hillslope soils

In-situ infiltration tests, using Mini-disk infiltrometer and Guelph Permeameter, have also been conducted for the identification of in-situ saturated permeability. The surface infiltration varied between 2×10^{-7} m/s to 9×10^{-6} m/s, at various hill sites of Guwahati city. Samples were collected from different depths of cut slopes (0.3 - 2.5 m), and the saturated permeability of the specimens was determined by laboratory permeability tests conducted on soil specimens compacted to in-situ density. The tests revealed that the saprolitic soil strata at lower depth is more permeable than the overlying mature lateritic soil. The permeability of the soil layers varied from 10^{-6} m/s approximately at the surface layers to 10^{-5} m/s at the lower layers.

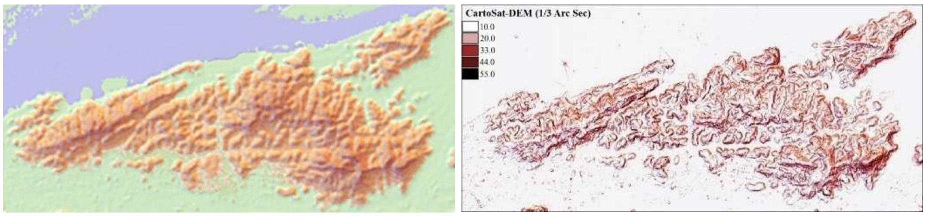
Soil-Water Characteristic Curve (SWCC) is the relationship between the water content and matric suction, which can be utilized to quantify unsaturated shear strength and assessment of unsaturated hydraulic conductivity. The SWCC for the soil specimen was determined using Dielectric Water Potential Sensor (Manifold Pressure Sensor MPS-1, Decagon Devices, Pullman, WA, USA) in combination with volumetric water content sensor (EC–5). Figure 4b gives the relation between the volumetric water content (θ) and the matric suction (ψ). The experimental data obtained from the present study is compared with that available in the literature for similar soil of the region obtained through similar experimental procedure (Chetia and Sreedeep, 2013). van Genuchten (1980) model for describing the soil water characteristics is fitted to the experimental data obtained from the present study, and the fitting parameters are determined.

4 Physically-based Model: TRIGRS

4.1 TRIGRS simulation and its input parameters

TRIGRS (Transient Rainfall Infiltration and Grid-based Regional Slope-stability) is a FORTRAN code developed for the purpose of evaluating the transient pore pressure response to rainfall infiltration, and thereby, simulate the temporal and spatial distribution of shallow, rainfall-induced landslides expressed as decrease in the factor of safety values (Savage *et al.*, 2004; Baum *et al.*, 2008). Further working details of TRIGRS can be obtained in Sarma et al. (2020). Input data required for TRIGRS simulation includes the Digital Elevation Model (DEM) of the study area, the slope map and the aspect map derived from the DEM, and the depth of basal-boundary map generated from the slope map. The soil parameters include Mohr-Coulomb shear strength parameters (cohesion – c and angle of internal friction – φ), soil unit weight (γ), saturated hydraulic conductivity (k_s), saturated and residual volumetric water content (θ_s and θ_r) and soil diffusivity (D_o, assumed to be 10 times the saturated permeability). The values of these parameters are determined through a parametric study involving a SEEP/W model, along with a representative single cell simulation and the entire study area DEM and slope map simulation in TRIGRS, such that the values of these parameters fit within the range of the experimentally determined soil parameters

Digital Elevation Model (DEM), Slope Map and Depth of Basal-Boundary Map. ALOS World 3D-30 m (AW3D30), developed by Japan Aerospace Exploration Agency (JAXA), having a horizontal resolution of approximately 30-meter mesh (1-arc second latitude and longitude), is used as the DEM and the base map for all analysis. The developed digital 3D maps can represent land terrains with 5 m in height accuracy (standard deviation). Fig. 5a shows the 3D-DEM of the Noonmati-Sunsali hill series. Topographic input parameter vis., the slope map (Fig 5b) and the aspect map, required as input for the analysis, are extracted from the DEM. The slope and the aspect map is obtained using the SAGA-GIS (Conrad et al., 2015) by applying the Zevenbergen and Thorne (1987) method.



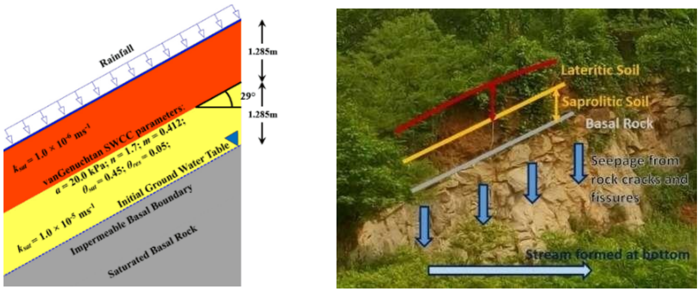
(a) (b)

Fig. 5. (a) ALOS World 3D – 30m (AW3D30) DEM of Noonmati-Sunsali hill (b) Slope map (in degrees) of Noonmati-Sunsali hill series

The weathered soil thickness is affected by many factors including the vegetation cover, the underlying lithology, the climate, rainfall, the angle and curvature of slope, and land use. However, it is very difficult to quantify the relation among so many variables. From available literature, it is observed that the slope angle is the prime factor affecting the thickness of residual soil formation, and, therefore, it is more convenient to assume a simple exponential relationship between the soil thickness and the slope angle (Tan *et al*., 2008). Based on the borehole reports obtained across Guwahati city, the soil thickness (z) and slope angle (β) is related as: $z = 22.0e^{-0.074\beta}$

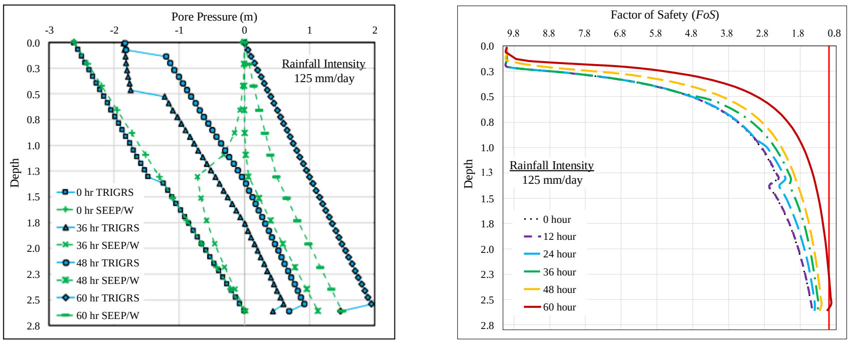
Ground Water Table. The alluvial plains of this region remain saturated all year round, owing to the ground water table (GWT) being controlled by the mighty Brahmaputra River flowing through the city. However, detailed data on the ground water table in the hills of the study area does not exist. Observing the wells dug for obtaining drinking water and from the few in-situ borehole investigation data, it is reasonably assumed that the basal rock strata remain saturated at all times. Thus, in the TRIGRS analysis, the initial ground water table is considered same as the depth of the basal rock. Finite depth basal boundary is considered and the ground water table is allowed to rise due to the rainwater infiltration.

Calibration of Soil Parameters. In order to successfully apply TRIGRS that uses a single layered soil model over the basal bedrock, it is necessary to calibrate the associated soil parameters in lieu of the actual multilayered scenario observed in the field. In this regard, a model of a typical slope was created in SEEP/W as shown in Figure 6. Rainfall infiltration was applied and pore pressure profiles were obtained. The slope angle and depth of basal boundary was input into TRIGRS model, and considering an identical intensity of rainfall, the pore pressures obtained from TRIGRS were compared with that obtained from GeoStudio SEEP/W Finite element model, as shown in Fig. 8. The values of the hydraulic parameters for TRIGRS were determined through a parametric study. For a particular slope angle and soil cover depth, a set of parameters (Gardner fitting parameter α and the saturated permeability, k_s) were assigned to the entire study area (in TRIGRS model) as well as to a representative single cell (in SEEP/W model). The parameters were so adjusted that the rise in water table and the corresponding location of slope instability, along with its time of occurrence, matched with that of in-situ conditions, while the values of the parameters themselves being consistent with that of experimentally observed values. The pore pressure variation with the depth obtained from SEEP/W is observed to be more realistic than that obtained with TRIGRS, which is attributed to the fact that SEEP/W model comprises two soil layers with different permeability giving a much closer approximation to the in-situ condition. The TRIGRS parameters are so considered so that the temporal rise in water table is in close resemblance to that obtained from SEEP/W. The rise in water table is the triggering factor for slope failure as can be observed from Figure 7. Thus, for the present study, instead of focusing on the pore pressure profile itself, emphasis is given on the time of occurrence and location of the initiation of slope failure due to rising water table. Table 1 gives the values of the soil parameters eventually decided for conducting the rainfall induced landslide hazard analysis of the Noonmati-Sunsali hill series area.



(a) (b)

Fig. 6. (a) Slope model as developed in SEEP/W (b) Cut-slope showing close resemblance to developed model



(a) (b)

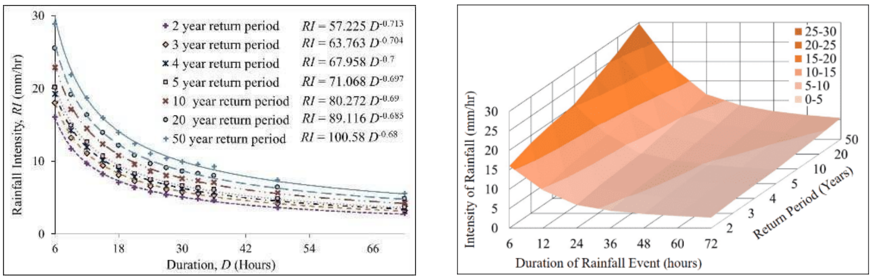
Fig. 7. (a) Slope model as developed in SEEP/W (b) Cut-slope showing close resemblance to developed model

Table 1. Calibrated input parameters to be applied in the TRIGRS simulation.

c' (kPa)	φ' (º)	γ_s (kN/m^3)	k_s (m/s)	D_o (m/s)	θ_s	θ_r	α
10	27º	18.5	2.5×10^{-6}	2.5×10^{-5}	0.45	0.05	0.8

5 Intensity – Duration – Frequency of Rainfall events

For considering the hazard, rainfall events are represented in terms of Intensity–Duration–Frequency (IDF) curve. An IDF curve gives the expected rainfall intensity of a given duration of storm having desired frequency of occurrence. The frequency is expressed in terms of return period (T) which is the average length of time between rainfall events that equal or exceed a particular chosen magnitude. The most commonly used tool for developing IDF relationships is Gumbel's Extreme Value Type-I distribution, and the same is implemented for this study. Based on the rainfall data shown in Fig. 3b, the IDF curves processed for Guwahati city is shown in Fig. 8a. Figure 8b shows the intensity of rainfall (mm/hour) considering the rainfall duration and return period selected for the study. Forty-nine (7-rainfall duration for 7-rainfall return period) rainfall scenarios were taken into consideration to represent the most probable rainfall intensity – durations corresponding to return periods. The rainfall intensities were input into TRIGRS and the *FoS* maps were obtained, which represented the stability condition of the hillslopes of Guwahati for the specified return period. The *FoS* at the RVS – points locations were then extracted out of the maps and the average, maximum and minimum of the data were determined.



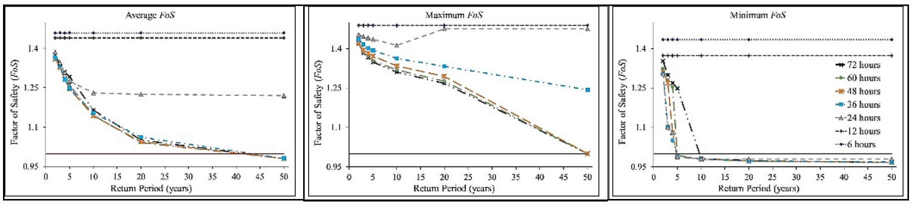
(a) (b)

Fig. 8. (a) Rainfall Intensity–Duration–Frequency (IDF) curve for Guwahati region (b) Rainfall intensity corresponding to return period and rainfall duration selected for the study

6 Results and Discussions

In the month of June, 2012, several landslide occurrences were reported in the Guwahati city along with the death of four persons in two separate landslide events. Following the events, the State Government of Assam, India, ordered an official investigation into the occurrences in the month of July, 2012. A visual reconnaissance of the landslide areas was conducted under Assam State Disaster Management Authority (ASDMA). The findings were published in the form of an official report – "Rapid Visual Screening Potential Landslide Areas of Guwahati" (Goswami, 2013). The report presented the location of landslide occurrences in the month of June, 2012 along with landslide prone areas in the form of GPS Latitude-Longitude coordinates, overlaid on top of Google Earth Imagery. Factors such as type of soil comprising the slope, slope inclination, height, land movement, tilting trees, crack in the slope, elevation difference across cracks, seepage of water within the slope, significant change in the water level in the wells were considered for delineating landslide prone areas. Presently, it is the only document publicly available, describing the in-situ landslide scenario of the Guwahati hill slopes. The areas delineated in the report were revisited in-situ, and 347 locations were considered for this study. The locations, henceforth, will be referred as RVS-points.

Figure 9 provides the average, maximum and minimum FoS obtained at the locationsof the RVS points under varying durations of incumbent rainfall. The reduction in average FoS of the RVS-points shows that with the increase in rainfall return period, more areas are exposed towards instability. Shorter duration rainfall (< 24 hours) does not have any effect on the stability condition of the slopes, irrespective of the rainfall intensity, which is attributed to the fact that major portion of the rainwater is lost as runoff and the infiltrated portion is not adequate to raise the level of ground water to trigger landslides. Considering a return period of 40 years, the average *FoS* of the hillslopes drops below 1.0, indicative of rainfall event within this return period which triggers landslides throughout a major portion of the hill slopes of Guwahati, and especially of the Noonmati-Sunsali hill series. It is observed that landslides are mostly triggered by longer duration rainfall. This factor is controlled by the soil permeability and soil water characteristics.



(a) (b) (c)

Fig. 9. Stability at the location of the RVS points (a) Average FoS (b) Maximum FoS (c) Minimum FoS

The difference in the maximum and minimum *FoS* highlights the fact that some areas are highly prone to landslides. Higher slope angle indirectly results in lesser thickness of overburden soil and therefore needs lesser amount of infiltrated water to raise the ground water level. On the other hand, lager upslope catchment area brings in more amount of excess water from runoff of upslope areas. The gully regions, where the slope angle is high and have a larger upslope catchment area, are very much prone to landslides. Those areas are characterized by the minimum *FoS*. The first rainfall parameter having a significant effect on the slope stability is the duration of the rainfall event. It is observed, that only the longer duration rainfall supply enough water so that the ground water level may be raised sufficiently to trigger landslide. The other important parameter is the intensity of rainfall. The critical rainfall intensity required to trigger landslide is considered approximately equal to the saturated permeability of the soil. If the rainfall intensity is significantly lower than the critical intensity, then the infiltrated water will flow out as basal flux through the soil, and the ground water level will not rise. As the intensity increases to the critical intensity, the rate of infiltration will exceed the rate of basal flux and the ground water table will rise quickly. However, beyond the critical rainfall intensity, the rate of infiltration will remain constant at approximately the saturated permeability of the soil, while the excess rainwater will be lost as runoff.

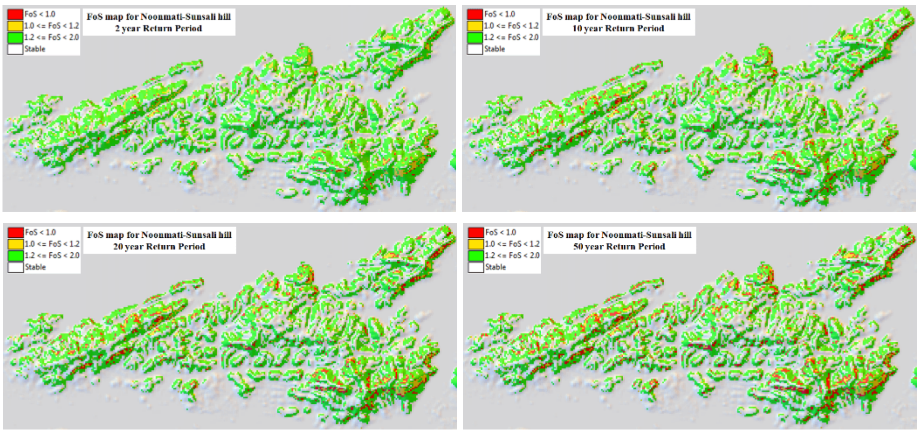


Fig. 10. FoS maps for Noonmati-Sunsali hill series for various return periods

Figure 10 presents the FoS maps for some typical rainfall scenarios with 2, 10, 20 and 50 year return periods. However, presenting the FoS maps for each and every rainfall scenario is not feasible, and, thus, the results are combined in the form of landslide hazard map, which gives the location of probable landsliding in terms of return period. Figure 11 gives the return period of rainfall induced landslide occurrences or the Landslide Hazard Map of Guwahati city, with demarcation of the Noonmati-Sunsali hill series.

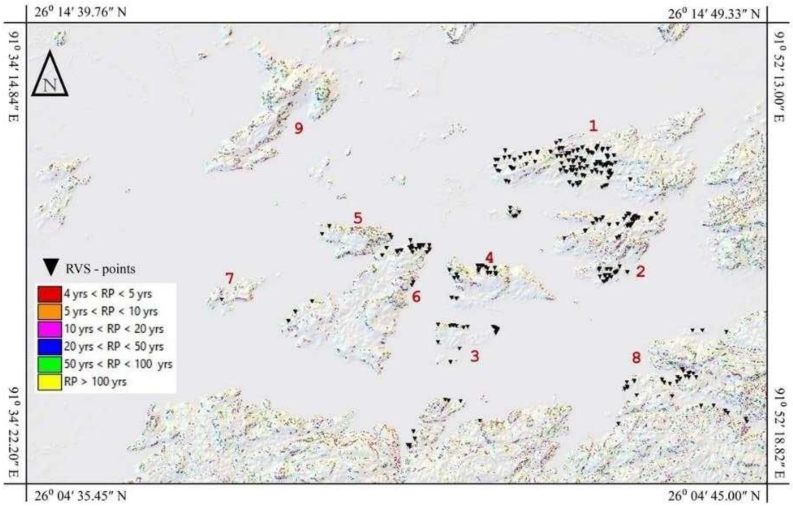


Fig. 11. Landslide Hazard Map of Guwahati city

7 Conclusions

The research reported herein highlights the effectiveness of the spatiotemporal predictability of rainfall induced landslide occurrences in the Noonmati-Sunsali hill series of Guwahati city using the TRIGRS model for regional landslide hazard assessment. Based on extensive field reconnaissance, it can be concluded that the hillslopes in and around Guwahati city mostly comprise of lateritic soil strata overlying a saprolitic layer followed by a basal rock stratum, with embedded corestones in the upper soil strata. The 100-year rainfall data indicate that the months of April to September experiences the most intense rainfall, during which the highest number of landslides are also recorded in the urban precinct of Guwahati. Based on the extensive laboratory investigations, the soils of the hillslopes have been characterized for their shear strength parameters, hydraulic conductivity and soil-water characteristic curves. With the aid of ALOS World 3D-30 (AW3D30) DEM, the slope map and aspect maps are extracted. Further, expression for the depth of soil cover in relation to the slope angle for Guwahati city has been developed, and the basal boundary map are formed which are used as input to TRIGRS model. Based on the field experimentations, the GWT has been ascertained at the soil-rock interface. Limit equilibrium models developed in Geostudio aided in ascertaining input parameters to be used in TRIGRS model. IDF curves are developed for Guwahati city area, and the same is used in assessing the depletion in FoS for the Noonmati-Sunsali hill series. FoS maps are produced for different return periods for the area highlighting the growing vulnerability of rainfall induced landsliding in the area with the increase in the return periods of the incident rainfall.

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