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Assessing Cohesion, Friction Angle and Slope Instability in the Shivkhola Watershed of Darjiling Himalaya

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Abstract

The study of soil strength properties is of very much important to assess the slope instability in the mountain area. Himalayan mountain range characterized by most fragile lithological composition. This fragile lithology is the outcome of heavy compressive forces resulting from the convergence of two solid slabs i.e. Indian Plate and Eurasian Plate. Hence, the upper part of the slope materials up to the weathered limit or weathered front is of low shear strength and very much prone to failure. Cohesion (c) and friction angle (φ) are the two significant parameters of soil and on the basis of these properties the stability and instability of the slope segment can be assessed. The present study area of the Shivkhola watershed of Darjiling Himalaya is dominated by slope instability. To indentify the potential landslide locations, a landslide inventory map was prepared in consultation with Topo-sheet, Google Earth Image, Satellite image (LISS III 2010) and intensive field investigation with GPS. The soil samples were collected from 50 locations considering 0.25 sq. km surface and tested in the laboratory to estimate cohesion and stress parameters. Based on cohesion and major principal stress and minor principal stress a Mohr Stress Circle was developed to determine friction angle. Finally the spatial distribution of cohesion and friction angle and their integration with landslide distribution was accomplished on GIS platform incorporating pixels affected by landslide and pixels not-affected by landslide in each class of the prepared data layers.

Keywords: Cohesion, friction angle, landslide potentiality, shivkhola watershed.

Introduction

Each and every spatial segment of the earth surface possesses some physiographic aspects and the analysis of all the aspects enables us to predict an interrelationship between physical and cultural phenomena and as a whole. The study area, Shivkhola Watershed comprises a number of diversified physical aspects and there is a great diversity of forms and the complexity of interrelationships. The practical relevance of landslide can be recognized only by the systematic and thorough study of geomorphic attributes such as relief, geology, and soil. A detailed and integrated investigation of the geological structure of the area, the petrographical and physical properties of the rocks and the local hydro-geological conditions with changing slope of the Shivkhola watershed will help to prepare the corrective and preventive measures in a reasonable scheme. Barton and Choubey[1] studied the shear strength of rock joints and its impact on slope stability. The existence of finer to large size soil-rock composition has aggravated the problem of soil erosion and soil slip in the Shivkhola Watershed. Besides the size of the soil particles, the mineralogical composition of the soil changes all the physical and chemical properties within the soil. Keen and Raczkowski[2] propounded the relation between the clay content and certain physical properties of a soil. The amount of sand, silt and clay; porosity, water holding capacity and bulk density; cohesion; and saturated depth of the soil are some of the significant properties which continuously changing the actual nature of the soil-rock properties of the hill slope causing slope failure.

The study of various soil strength parameters such as particles size distribution, cohesion and friction angle plays a significant role in slope instability. Landslide potentiality was estimated incorporating *landslide inventory map* (2) for all the geomorphic attributes by determining class/ranges wise *Landslide Potentiality Index Value* (LPIV) of each factor by means of a ratio between the number of cells/pixels disturbed by landslides and the total number of cells/pixels for that specific class. More details of these procedures were obtained in other studies[3,4]. Topographic Index (TI) Value was calculated in consultation with slope and upslope contributing area. The effectiveness of all these parameters were being influenced by hydrologic conditions and other atmospheric processes. Anderson and Burt[5] presented the role of topography in controlling through flow generation and related landslips. GIS tools were applied for the identification of topographic settings conducive to landslide occurrences[6]. Various geomorphic and hydrologic models were being introduced for understanding slope instability[7,8,9,10].

$$LPIV = (F2 \div F1) \times 100 \quad (1)$$

Where, F1 = number of pixels/cells or grid without landslide.
F2 = number of pixels/cells or grid with landslide.

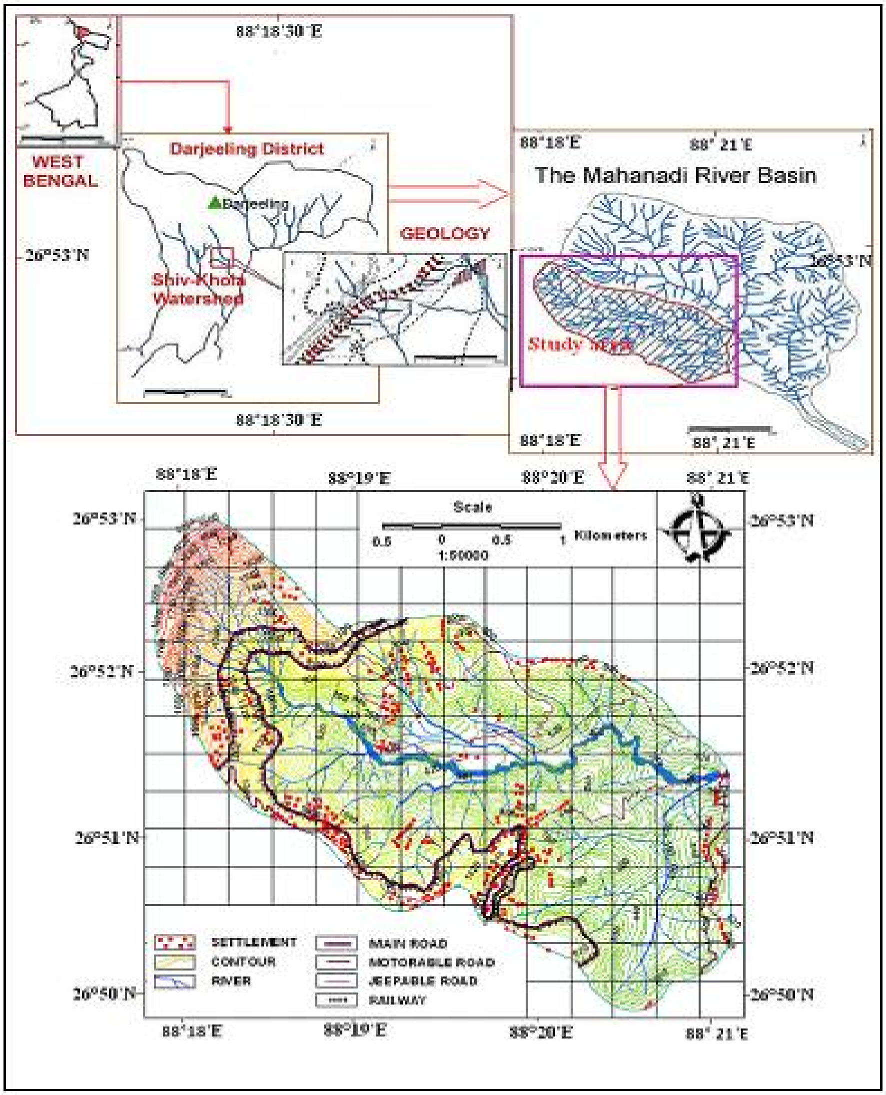

Figure-1
Location of the Shivkhola Watershed

The present study is dealt with the preparation of two important thematic data layers i.e. *cohesion* and *friction angle* as well as to find out the relationship between these two parameters and *landslide potentiality*. This objective was accomplished incorporating pixels affected by landslide and pixels not-affected by landslide in each class of two thematic data layers on GIS platform. The present study area shown in figure 1, the Shivkhola watershed of Darjiling Himalaya is characterized by fragile lithology, steep valley side slope, continuous branching of the drainage network and their branching, prominence of high positive and negative slope curvature, and slope modification by human intervention. The prevalence of all these characters in a mountain basin provides the fabourable condition to reduce soil cohesion and friction angle of the slope materials. The present established the distributional pattern of cohesion and friction angle and their relation with landslide phenomena.

Methodology

Friction angle (φ) and Cohesion (c): Slope materials are always characterized by three types of stress i.e. *major principal stress, minor principal stress* and *intermediate stress* which act on three mutually perpendicular principal axis revealed in figure 2. The shear strength of the soil is described as the function of normal stress on the slip surface, cohesion, and angle of internal friction. The angle of internal friction (ϕ) and cohesion are the two important physical properties of the soil which determines angle of rupture, shearing strength, safety factor as well as stability condition of the slope materials. A Mohr Stress Circle was developed to obtain angle of internal friction and angle of rupture through confining pressure (σ_3) and compressive stress (σ_1) with the centre on the horizontal axis; the centre of the circle was obviously $(\sigma_1 + \sigma_3)/2$ and the radius was $(\sigma_1 - \sigma_3)/2$. The values of confining pressure, σ_3, and compressive stress, σ_1

were plotted on horizontal axis where stress difference is $\sigma_1 - \sigma_3$. On a plane, the normal stress was σ_3 and the shearing stress was 0. If the plane makes an angle of 45^0 with the greatest principal stress axis (2α=90), the shearing stress is at a maximum and the normal stress is $(\sigma_1 + \sigma_3)/2$. If the plane makes an angle of 90^0 with the greatest principal stress axis ($2\sigma = 180^0$), the shearing stress is 0 and the normal stress is σ_1

Mohr's circle represents the graphical presentation of the failure parameters of soil that is depicted in Figure-3. In the present work, analyzing the stress circle and analyzing the stress parameters the critical stress and critical angle of failure were estimated.

critical stress $(\tau\, cr) = C + \sigma \tan$ (eq.2) (2)

critical angle of failure $(cr) = 45^0 + \frac{\varphi}{2}$ (eq.3) (3)

Where φ = angle of internal friction angle and C = cohesion.

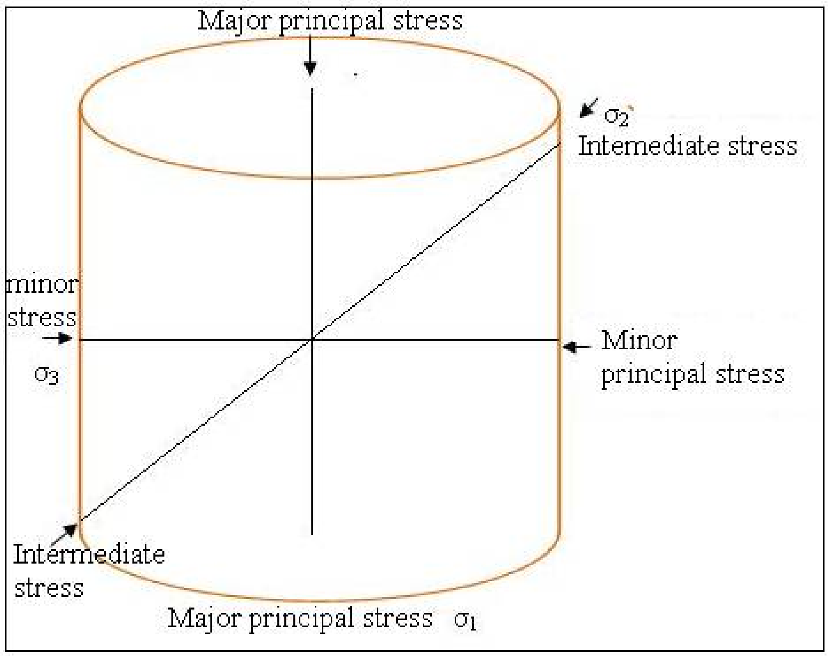

Figure-2
Stresses acting on three mutually perpendicular principal axis

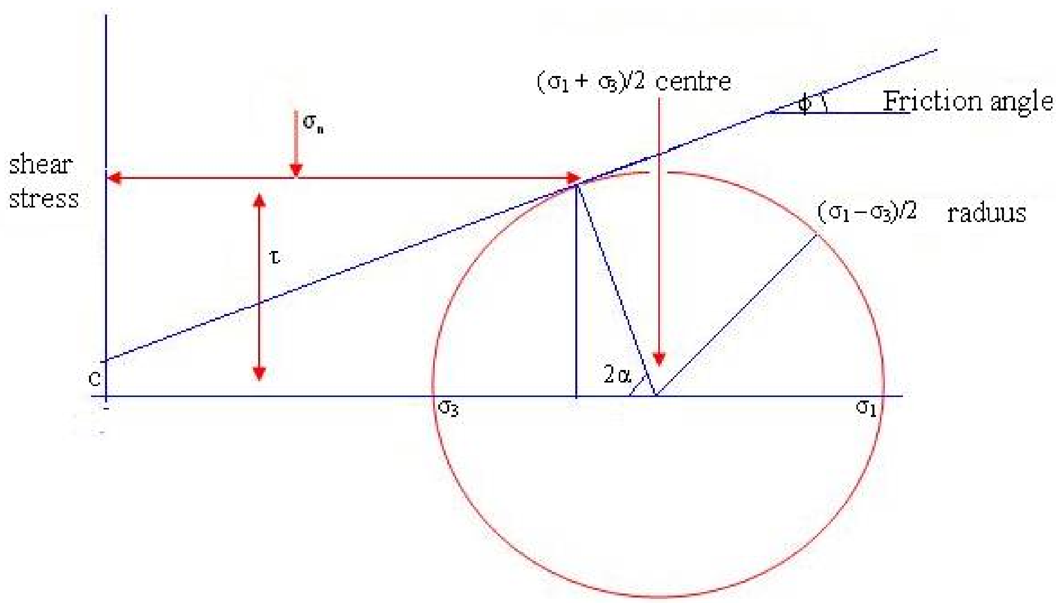

Figure-3
Mohr Stress Circle describing various soil strength parameters

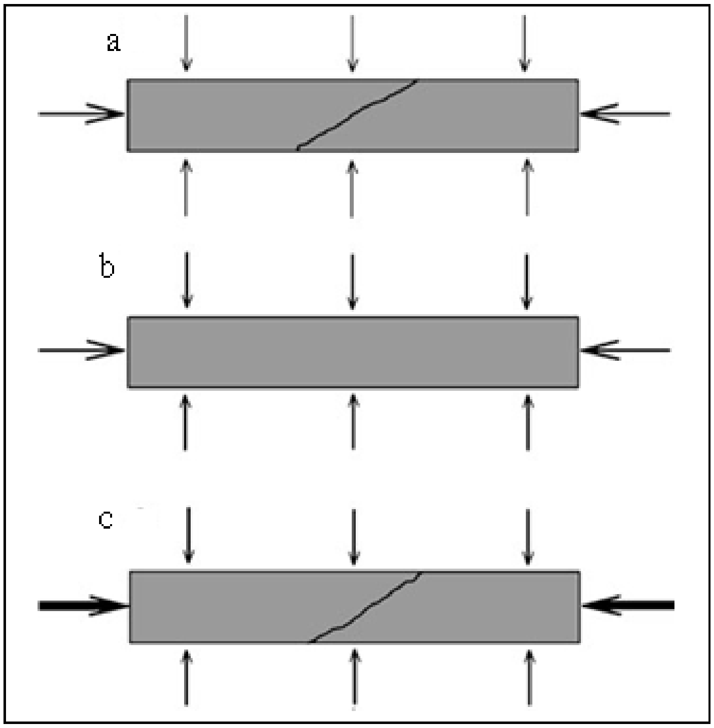

Figure-4
Confining pressure (a), compressive stress (b) and materials failure (c)

If a sample of frictional-cohesive rock or soil is subjected to constant confining pressure (vertical arrows) and compressive stress (horizontal arrows), it typically fails at an angle greater than 45^0 depicted in figure-4. If the confining pressure is increased (4b), a point is reached where the material will not fail for the same compressive stress. The compressive stress must be increased for failure to occur (4c).

Cohesion (C) is the attraction of particles to each other which is not directly governed by a friction law but does provide a measure of strength of a material. Thus sands do not exhibit cohesion, while soil which contains clay show cohesion. It can be measured, as in soil mechanics, by the Mohr-Coulomb Equation.

$$\text{cohesion (c)} = \frac{(\sigma 1 - \sigma 3)\tan^2(45^0 + \frac{\varphi}{2})}{2 + \tan(45^0 + \frac{\varphi}{2})} \text{ (eq.4)} \quad (4)$$

Results and Discussion

The cohesion of the soil varies from place to place due to variation in the presence of cementing materials which helps to combine soil particles tightly. This is the bonding of the particles with each other. The natural bonding of the soil particles are influenced and loosened by the presence of lubricating agent (water and ice particles) and ensure the materials to collapse. The friction angle of sandstone under dry condition varies from 26^0-35^0 and under wet condition 25^0-34^0. Fine-grained granite provides the friction angle of 31^0-35^0 and 29^0-31^0 for dry and wet condition respectively. In case of gneiss, friction angle is 26^0-29^0 for dry and 23^0-26^0 for wet condition[1]. The spatial distribution of friction angle in the watershed ranges from 18^0 to 32^0 which are described in Table-1. The study revealed that the areas having low friction angle value is dominated by high landslide frequency. So there is a negative correlation between friction angle and landslide potentiality. Figure-5 described the major landslide locations such as Paglajhora, Tindharia, 14 Miles bustee, Gayabari and Gitingia which are registered with low friction angle and high landslide potentiality.

The derived landslide potentiality index value reveals that the area having friction angle of less than 20^0 are registered with high LPIV. The low LPIV is observed at the places where the friction angle is greater than 25^0. The spatial distribution of *cohesion* in the Shivkhola Watershed reveals that Paglajhora, 14 Miles Bustee, Tindharia, Shiviter are characterized by very low cohesive strength of soil that are elaborated in figure 6 and table 2. The range of cohesion is between 0.01 and 0.90. The places of Gayabari and its adjoining areas, Sepoydhura, middle section of the watershed and extreme north-eastern part are dominated by moderate to high cohesive strength of the soil, varying from 0.35 to 0.90. The estimated cohesion of all the 50 locations shows that the cohesion in the Shivkhola watershed is very less, that is less than 0.90. The study indicates that there is an inverse relationship between cohesion and LPIV. The region of low cohesion of less than 0.29, showed the LPIV of more than 15.

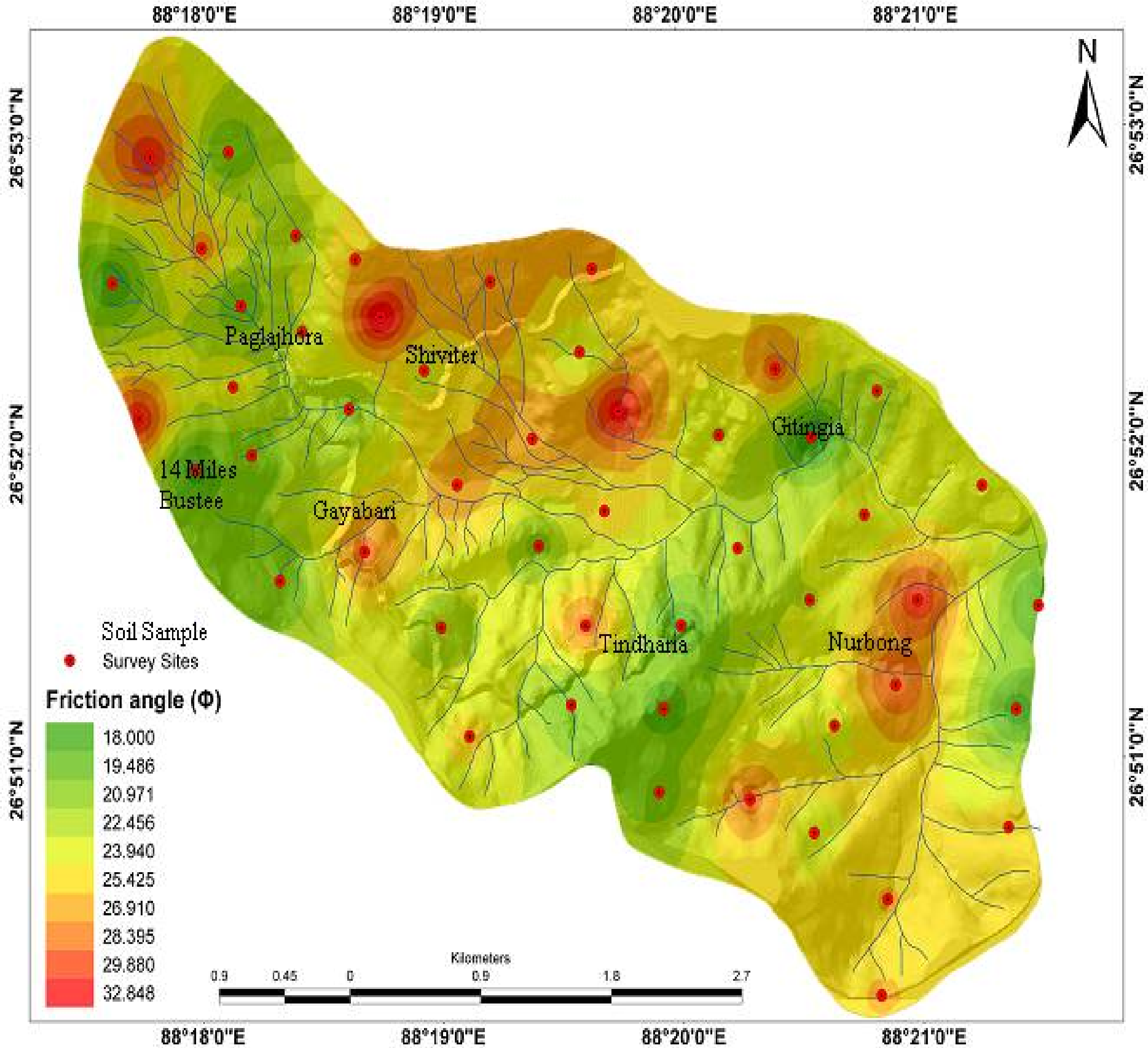

Figure-5
Spatial distribution of Friction angle (φ)

Table-1
Friction angle (φ) and Landslide Potentiality Index (LPIV)

Classes	Number of pixels [F_1]	No. of landslide affected pixels [F_2]	Landslide Potentiality Index (LPI) = [$F_2/F_1 \times 100$]
<18.00	3500	626	17.88
18.00-19.486	3547	523	14.74
19.486-20.971	3266	417	12.77
20.971-22.456	3864	413	10.69
22.456-23.940	2786	329	10.81
23.940-25.425	3545	311	8.77
25.425-26.910	2435	201	8.25
26.910-28.395	3597	211	5.86
28.395-29.880	3248	202	6.21
29.880-32.848	3343	190	5.68

Table-2
Cohesion (c) and Landslide Potentiality Index (LPIV)

Classes	Number of pixels [F_1]	No. of landslide affected pixels [F_2]	Landslide Potentiality Index (LPI) = [$F_2/F_1 \times 100$]
<0.01	3381	691	20.44
0.01-0.11	3786	668	17.64
0.11-0.20	3695	451	12.20
0.20-0.29	3352	522	15.57
0.29-0.38	3899	344	8.82
0.38-0.47	3741	286	7.64
0.47-0.55	2450	110	4.48
0.55-0.64	3987	221	5.54
0.64-0.73	4021	120	2.98
0.73-0.90	1519	60	3.94

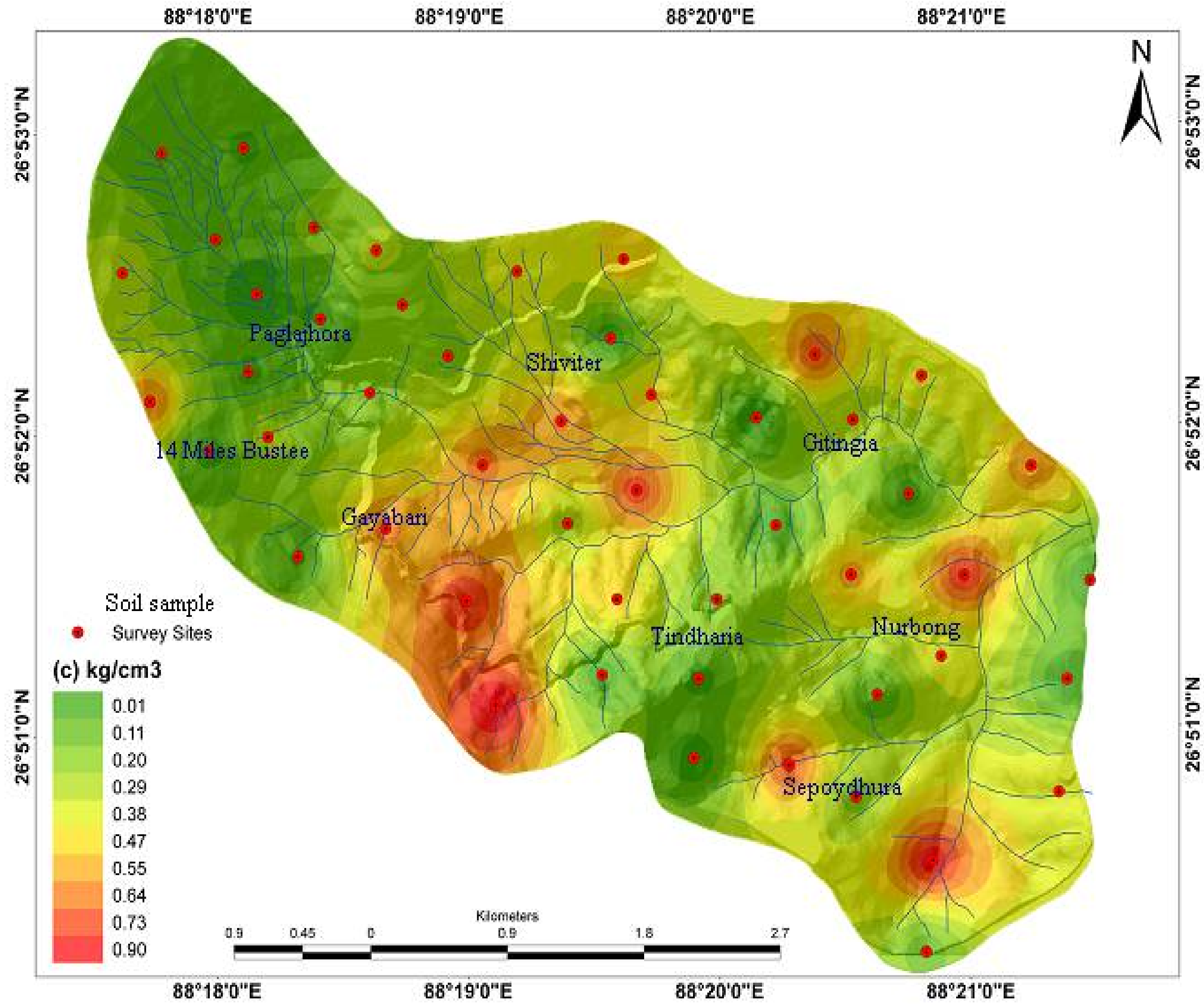

Figure-6
Spatial distribution of Cohesion (c)

Conclusion

The study area Shivkhola watershed possesses a wide range of elevation between 300 m in the south-east and 2040 m in the north. A large part of the watershed is lying between the altitude of 400 m and 600 m. The steepness of the slope varies significantly from place to place and its characteristics mostly depend on the drainage density. The study area is composed mainly of the Darjiling Gneiss, Daling formation composed of Chungtung formation, Lingtse Granite, Garubathan formation and Ryang formation. Gondwana formation, the most fragile one due to the presence of carboniferous rocks is located along a narrow belt being sandwiched between Daling to the north and siwalik to the south. The structural-cum stratigraphic succession can be observed as a traverse across Tindharia-Kurseong region. The concerned study area is structurally instable as most of the unconformities are lying across the drainage lines and so subsidence zones are developed at the junctions of the drainage lines with the structural discontinuities and lineaments. At the sub-surface layer of the soil percentage of pore space is high but at greater depth pore space decreases because of the existence of large percentage of finer particles. The reduction of pore space at greater depth results in the increase of water holding capacity and volumetric expansion at the sub-surface soil which increases the pore-water pressure and reduces cohesion and finally invites slope soil failure at most of the places of the Shivkhola Watershed.

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