Plant Archives Vol. 25, Special Issue (ICTPAIRS-JAU, Junagadh) Jan. 2025 pp. 137-144
e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives
Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.SP.ICTPAIRS-024

EFFECT OF DEM RESOLUTION ON TOPOGRAPHIC FACTOR OF REVISED UNIVERSAL SOIL LOSS MODEL

A.P. Lakkad*, K.N. Sondarva, M.G. Verma and P.K. Shrivastava

College of Agricultural Engineering & Technology, Navsari Agricultural University, Dediapada, Gujarat, India.
*Corresponding author Email: larunp@nau.in

ABSTRACT

Indiscriminate use and mismanagement led to soil degradation, which is an important global issue that is causing adverse impacts on agricultural productivity, environmental quality, and ultimately quality of human life. Water erosion is the major cause of soil degradation not only for India but for the world. Soil Loss Estimation models *viz*. USLE, RUSLE, and MUSLE can be used to assess the extent of soil erosion. The topographic factor of USLE models plays a major role in gross soil erosion. In the present study, a topographic factor of RUSLE was derived on a sub-watershed basis. The 20 m Digital Elevation Model was prepared by digitization of elevation points, contours, and watershed boundary of selected sub-watershed using the "Topo to Raster" interpolation method of spatial analyst tools into ArcGIS interface. The DEM resolution of 20 m was chosen because this is closest to 22.13 m slope length, which is used for the derivation of model components. USPED Model was used to derive the slope length factor while the slope steepness factor was derived separately for slope gradient < 9 and ≥ 9. The DEM indicates that most of the area has an elevation difference of 125 m which makes the topography highly susceptible to erosion due to overland flow. The reclassified slope length factor indicates that 95.50 % area of the sub-watershed has slope length value < 4, while only 0.50 % area has slope length factor values more than 4 which falls only on high altitudes hilly terrain. It could be inferred from the results that when the value of L was more erosion was more, in steep areas, whereas when it was less, in plain topography, erosion was less. The reclassified slope steepness map indicates that 76.83% of the study area has a slope steepness value less than 1.0 while it is greater than 1.0 only for 23.17% of the study area therefore average gross erosion value of the study area was less. The estimated slope length factor and slope steepness factor of the study area were 1.19 and 0.78 respectively which indicates that the slope length factor is highly responsible for soil erosion in the study region.

Key words: DEM, RUSLE, Slope length factor, Slope steepness factor, USPED Model

Introduction

The world is under the threshold of food insecurity, especially in the developing countries. Food and Agricultural Organization has issued a forecast about rising global hunger, if the global population reaches 9.1 billion by 2050, the FAO says that world food production will need to rise by 70%, and food production in the developing world will need to be doubled. Indiscriminate use and mismanagement led to soil degradation, which is an important global issue causing adverse impact on agricultural productivity and environmental quality. Various forms of land degradation, which affects more than one billion people (Maji *et al.*, 2010), have affected about 33 % of land in the world. Water erosion is the major cause of soil degradation not only for India but also for the world. Soil Loss Estimation models viz. USLE, RUSLE, MUSLE, WEPP, etc. can be used to assess the extent of water erosion. The topographic factor of USLE models plays a major role in gross soil erosion. In the present study, a topographic factor of RUSLE was derived on a sub-watershed basis to analyse the weightage of the topographic factor for gross soil erosion.

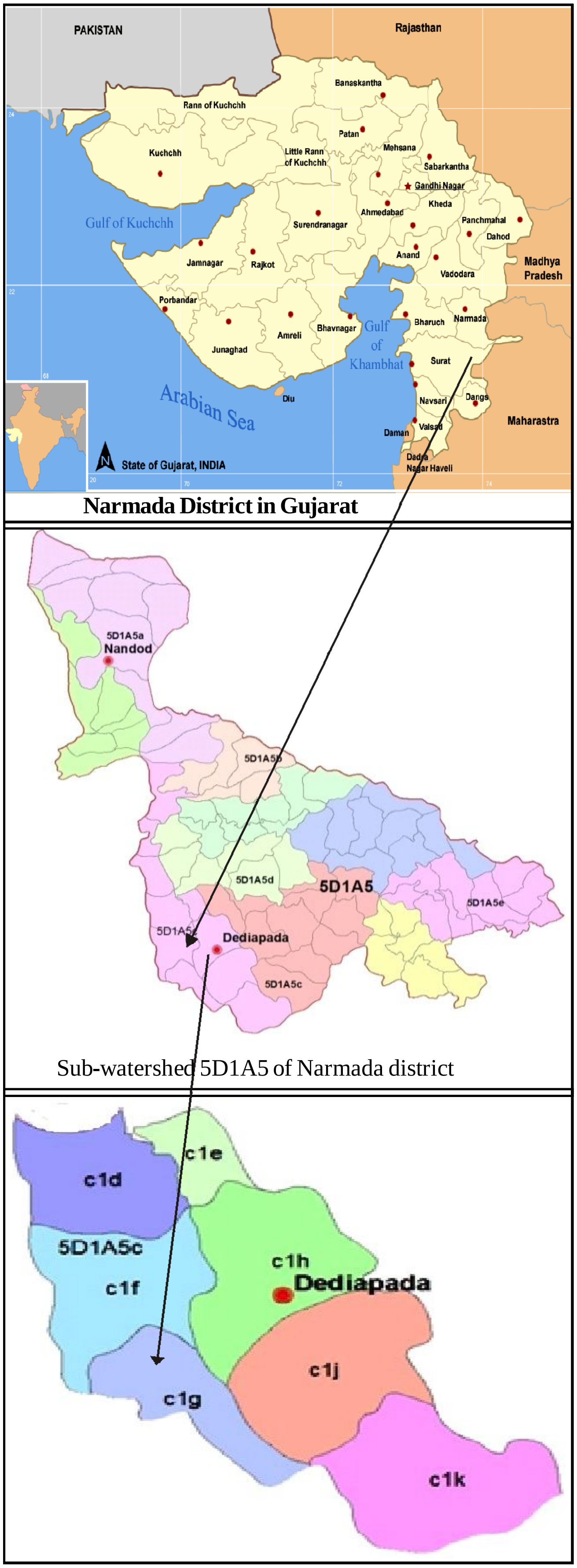

Fig. 1: Location map of selected sub-watershed 5D1A5c.

Material and Methods

Location

Sub watershed that catches water from the mainstream of the Dediapada region (Dist.-Narmada) was selected for the study purpose. The sub watershed lies between 730 31' 52.63" and 730 38' 58.02" East longitude and 210 33' 23.83" and 210 40' 14.18" North latitude. The sub-watershed is located in the Survey of India toposheet no. F43N10. The study area covers 7710.64 ha. The location map of the sub-watershed is shown in Fig. 1. Based hierarchical system of watershed delineation, the selected sub-watershed is given the number as 5D1A5c (Anonymous, 2014).

Slope Length Factor (L)

The L factor is the ratio of the actual horizontal slope length to the experimentally measured slope length of 22.13 m. Slope length is the distance from the point of origin of overland flow to either the point where the slope decreases to the extent that deposition begins or the point where runoff enters well-defined channels (Wischmeier and Smith, 1978).

Unit stream power erosion and deposition (usped) model

In the USLE and RUSLE, L is dependent on linear distance λ which is the horizontal length from the start of sediment transport to any point on the slope. Thus, they are inherently a single-dimensional function while in the USPED model; the topographic factor represents the change in the transport capacity of the flow direction, being positive for areas with topographic potential for deposition and negative for areas with erosion potential (Mitasova *et al.*, 1996). The USPED uses the area of upland contributing flow at any point of distance. In this study, the USPED Model was used to derive the slope length factor.

The L calculation on a slope is shown in Equation 1

$$\mathrm{L} = (m+1)\left(\frac{\lambda_A}{22.13}\right)^m \quad (1)$$

Where,

L is the slope length factor

λ_A is the area of upland flow,

22.13 is the unit plot length.

m is a variable exponent calculated from the ratio of rill-to-inter rill erosion, as described in Equation 2.

$$m = \frac{\beta}{1+\beta} \quad (2)$$

Where, β dependent on slope, It was computes using formula no. 3.

$$\beta = \frac{\sin\theta}{0.0896\,[3\,(\sin\theta)^{0.8} + 0.56\,]} \quad (3)$$

The $m + 1$ comes from the fact that, in order to get a value for $L = \left(\frac{\lambda}{22.13}\right)^{m}$ that is considerate of the area of contributing upland flow on the slope up to any point *i*, we must integrate over the interval . The Digital Elevation Model (DEM) is required to analyse the topographic properties of study area in order to estimate the slope length and slope steepness factor.

Digital Elevation Model (DEM)

Digital Elevation Model (DEM) represents the topography of an area using GIS and since erosion is highly related to topography, by using DEM models, flow direction, flow accumulation; slope steepness; slope direction; flow length and flow pattern could be defined. The geo-morphological and hydrological consistency of a DEM is reached when the matrix image exactly represents the relief features, such as the hydrographic basin watershed, thalwegs, and concave and convex elements, and it assures the convergence of the surface runoff for the mapped drainage network. Topo to Raster interpolation method generates a hydrologically correct DEM so it was used to generate the DEM of 20 m resolution.–The DEM was prepared by adopting the following procedure:

1. Topo-sheet “F43N10” was scanned using Colortrac Smartlf Gx+42 scanner.
2. Toposheet was geo-referenced into ArcGIS interface using latitude and longitude of the Toposheet by geo-referencing tools (Fig. 2).
3. For the digitization of elevation points, contours, and watershed boundaries into the ArcGIS catalogue, respective three shape files of points, polylines, and polygons were prepared using the Arc catalogue.
4. Then using the editor tool, digitization of 20 m contours and elevation points from Toposheet was done (Fig. 3).
5. Shape file of sub-watershed area “5D1A5c” under study was procured from BISAG, Gandhinagar.
6. Using “Topo to Raster” interpolation method of spatial analyst tools into ArcGIS interface, DEM of 20 m resolution was created using all three shape files, *viz.* contour, elevation points, and watershed boundary. The DEM resolution of 20 m was selected because this is closest to 22.13 m slope length, which is used for the derivation of model relations.

Spatial Analyst extension of ArcGIS interface was used to derive the 20 m resolution DEM in order to estimate slope length factor as described below.

1. Depression less DEM was prepared using the “Hydrology-Fill” tool of Spatial Analyst extension.

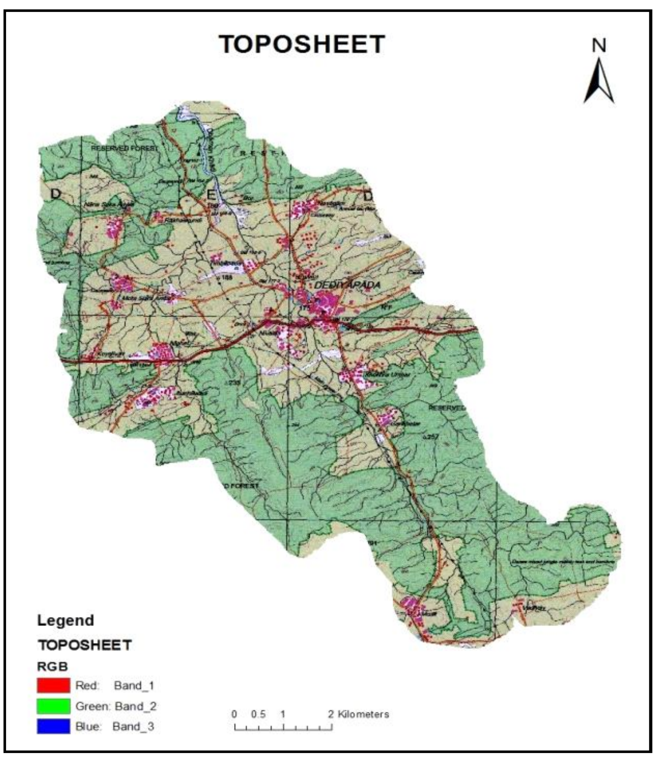

Fig. 2: Toposheet portion of study area.

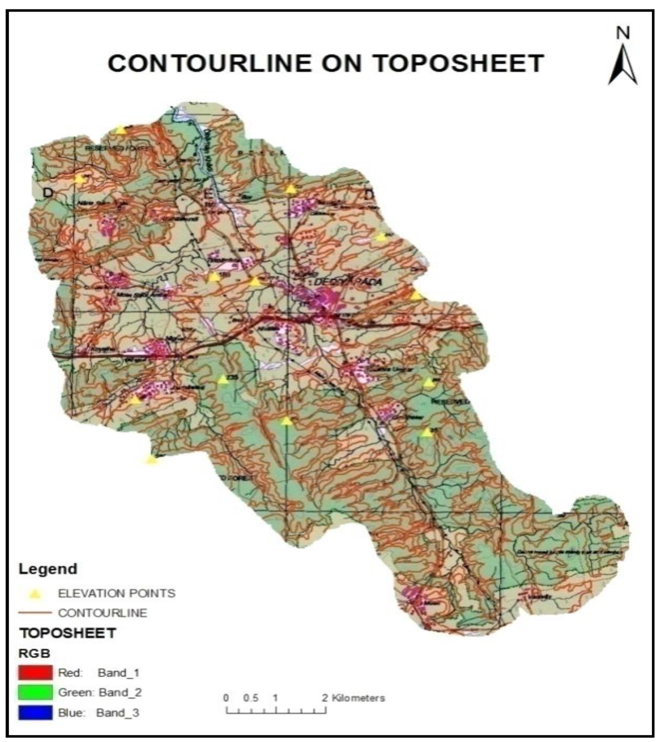

Fig. 3: Contour digitization on toposheet.

2. Flow direction map from depression less DEM was prepared using the "Hydrology – Flow Direction" tool of Spatial Analyst extension.
3. Flow accumulation map from flow direction map was prepared using the "Hydrology – Flow Accumulation" tool of Spatial Analyst extension.
4. Slope map (in degree) was prepared from DEM using the "Surface – Slope" tool of Spatial Analyst extension.
5. The raster layer for the β component of exponent m was derived using Eq. 3 by following algorithm using "Map Algebra - Raster Calculator" tool of Spatial Analyst extension.

   β = Float (sin (slope in degree)) / Float (0.0896*(3*Power (sin (slope in degree), 0.8 + 0.56))).
6. Exponent 'm' (*i.e.* rill to inter-rill erosion ratio) was derived with the help of Eq. 2 using following algorithm and "Map Algebra - Raster Calculator" tool of Spatial Analyst extension.

   m_raster = Float (β_raster / (1+ β_raster))
7. Slope length factor 'L' was prepared using the following algorithm and the "Map Algebra - Raster Calculator" tool of Spatial Analyst extension.

   L = Float (m_raster+1) · Power (flow accumulation * DEM cell size/ 22.13, m_ raster).

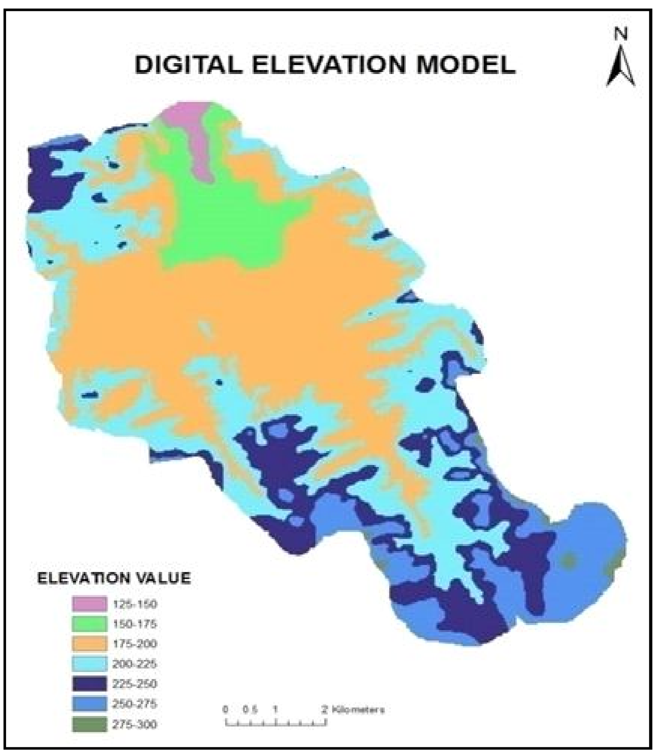

Fig. 4: Digital Elevation Model (DEM).

Slope Steepness Factor (S)

On steep slopes, the flow velocity is high, which causes scouring and cutting of soil. In addition, the soil erosion due to splash is high because splashed particles on steep slopes are thrown to larger distances down the slope on an inclined plane and the damage due to raindrop impact is greater on the crust. The slope steepness factor expresses the ratio of soil loss from a plot of known slope to soil loss from a unit plot under identical conditions. Equations no. 4 and 5 given by Mc Cool *et al.*, (1987) has been used to estimate and prepare the thematic map on the slope steepness factor in the ArcGIS interface.

$S = 10.8 \sin\theta + 0.03$ for slope gradient < 9% (4)

$S = 16.8 \sin\theta - 0.50$ for slope gradient $\geq$ 9% (5)

Where, S is the slope steepness factor

θ is the slope in degrees.

The slope steepness factor S map was prepared by adopting following procedure.

1. Two different maps of slope steepness factor were prepared from slope map (in degree) by following algorithms using "Map Algebra - Raster Calculator" tool of Spatial Analyst extension for the area having < 9 % and ≥ 9% percent slope.

   Float (10.8*sin (slope_degree*0.01745) + 0.03) for slope gradient < 9 %

   Float (16.8*sin (slope_degree*0.01745) – 0.50) for slope gradient ≥ 9 %
2. Then, the slope map (in percent) was prepared from DEM using "Surface-slope" tool of Spatial Analyst extension.
3. Both slope steepness factor maps and slope map (in percent) were converted from raster to vector using "Raster to Polygon" tool of Conversion extension.
4. Then, the Attribute tables of the above three maps were copied to three different Excel sheets.
5. The value of the cell having < 9% was replaced with slope steepness factor value of < 9% and the cell having ≥ 9% slope was replaced with slope steepness factor value of ≥ 9% in the attribute table of slope (in percent) map and sheet was saved in the .csv format.
6. The slope (in percent) vector map prepared in step 3 is joined with table prepared in step 5 by using 'Join and Relates' tool of ArcGIS interface.
7. The slope steepness raster map was prepared by converting the slope map from vector to raster

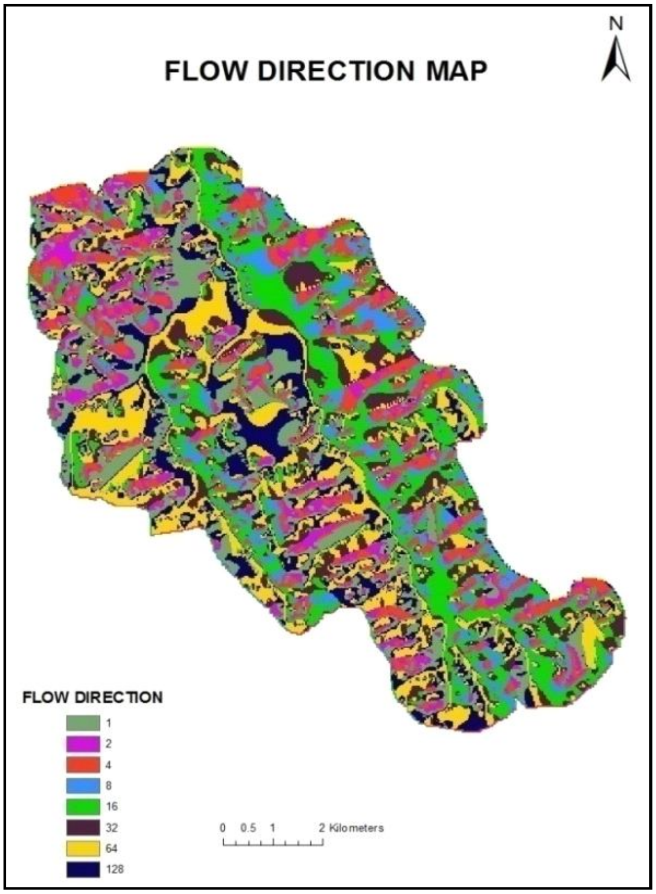

Fig. 5: Flow Directions Map.

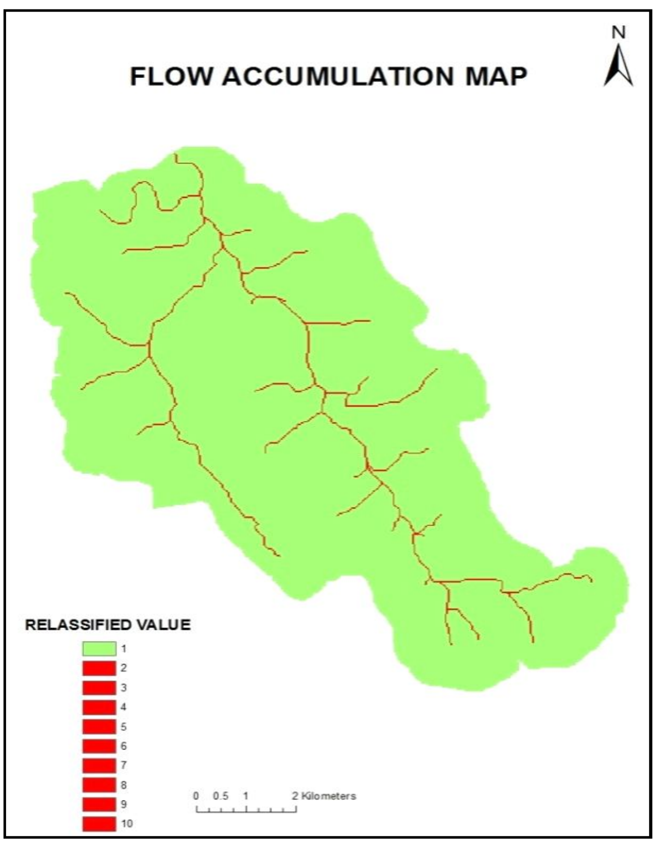

Fig. 6: Flow Accumulation Map.

and selecting slope steepness value as value field from "Polygon to Raster" tool of Arc GIS Conversion tools and saved as "Slope Steepness Factor Map".

Results and Discussion

Digital Elevation Model

Fig. 6 shows the Toposheet with digitized contour lines of 20 m interval and elevation points of the sub-watershed 5D1A5c under study, whereas, Fig. 4 depicts the reclassified DEM of the study area derived from shape files of contour lines, elevation points, and watershed boundary. The reclassified DEM indicates that 98.67 ha (1.28 %) area is covered by more than 275 m altitude and 47.81 ha (0.62 %) area is covered by less than 150 m altitude while 7563.78 ha (98.1 %) area of study area falls between 150 m to 275 m altitudes. The lowest and highest altitude values of the study area are 139.39 m and 288.35 m respectively. It could be inferred that most of the area has an elevation difference of 125 m, which makes the topography highly susceptible to erosion due to overland flow.

Flow Direction and Flow Accumulation

The flow direction map (Fig. 5) shows the direction of flow from one cell to the next cell at a lower elevation, ultimately joining the drainage channel. The flow Accumulation map (Fig. 6) shows the accumulation of runoff water from the individual cell to the drainage channel up to the study area outlet.

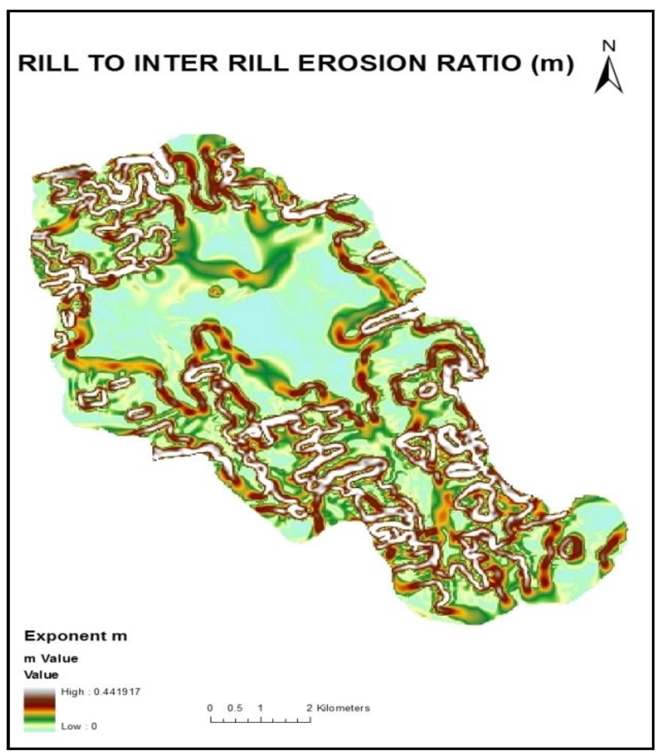

Fig. 7: Exponent m map.

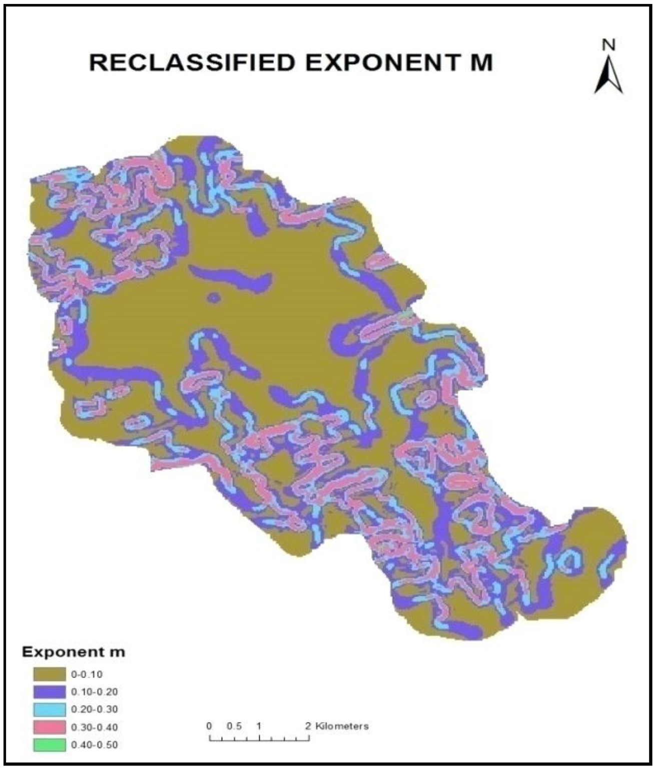

Fig. 8: Reclassified exponent m map.

The map indicates that 7565.42 ha (98.12%) area of the sub-watershed is affected by splash, sheet, and rill erosion while only 145.23 ha. (1.88%) area is covered by drainage channels which are affected by channel erosion. This map gives the drainage pattern of the study area. The drainage pattern closely coincides with the drainage pattern shown in the Toposheet.

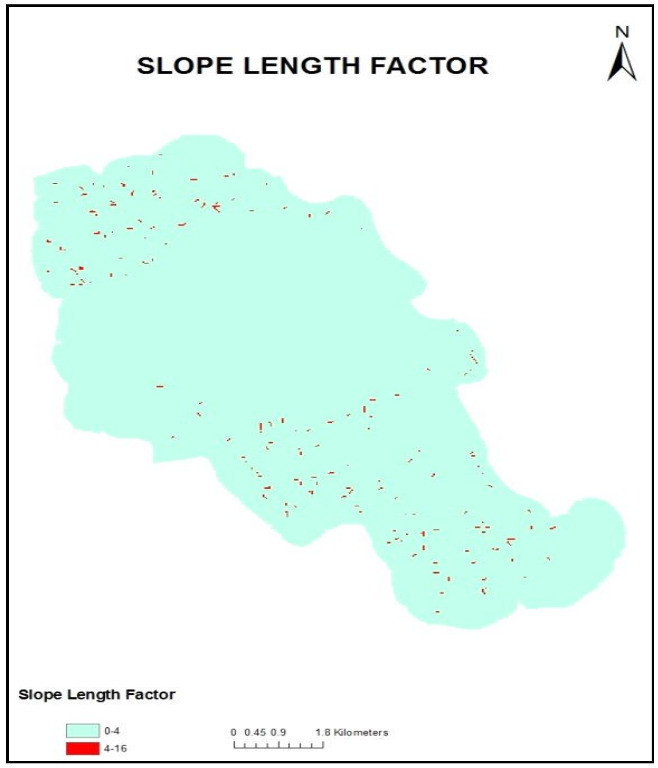

Fig. 10: Reclassified slope length map.

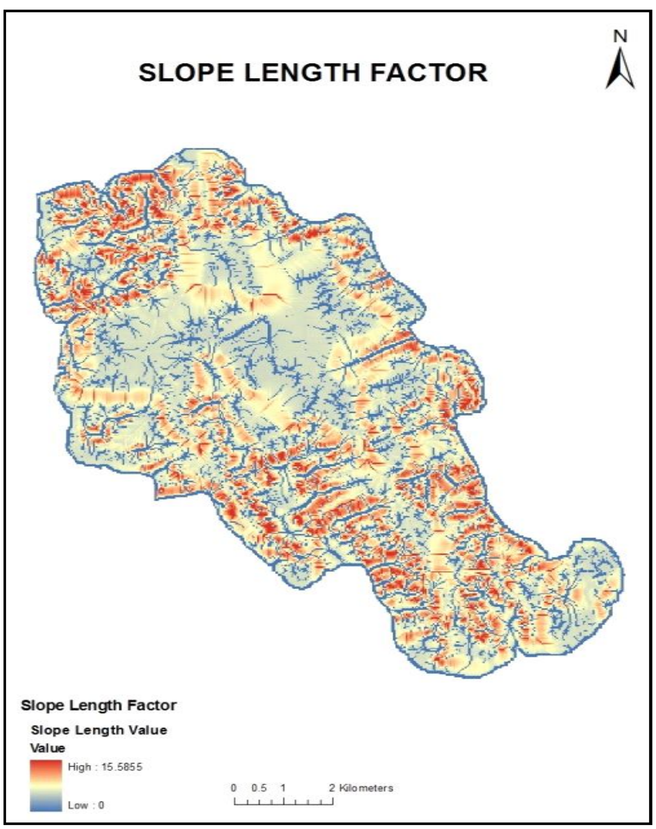

Fig. 9: Slope length factor map.

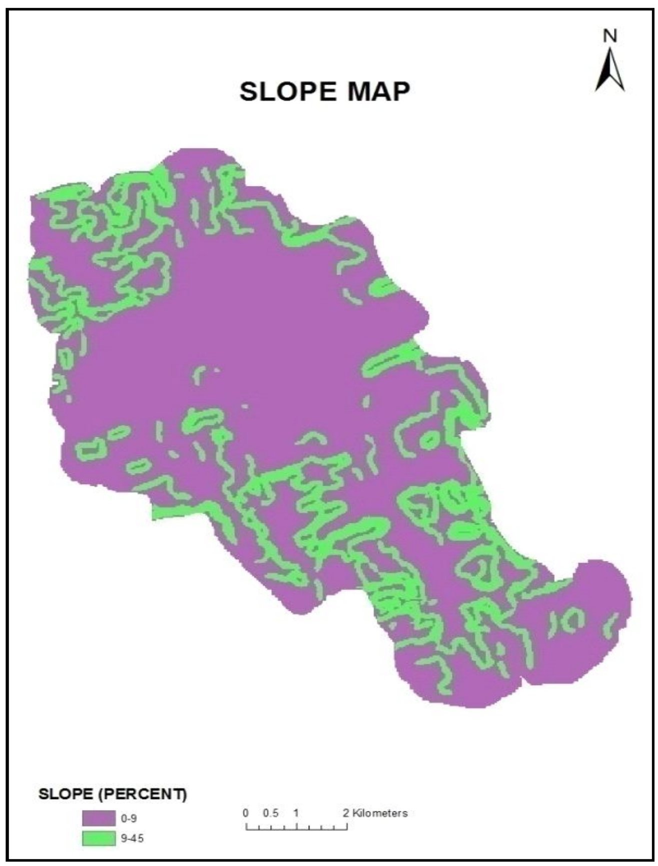

Fig. 11: Slope map in percent.

Rill to Inter Rill Erosion Ratio

The rill to inter rill erosion ratio is used as exponent 'm' to derive the slope length factor. The exponent m value was derived by using Eq. 2 as shown in Fig. 7. The maximum value of exponent m is 0.44. The reclassified exponent m value map (Fig. 8) shows that 51.68% area has a value less than 0.10 while 25.01% area has exponent m values between 0.10 to 0.20. Though the highest value of the exponent is 0.44, it is of a very small area, whereas most of the area (77%) has less than 0.20 values, therefore it shows that erosion susceptibility covers less area (23%).

Slope Length Factor (L)

Fig. 9 describes the slope length factor at each grid cell of the study area. The slope length factor value ranges from 0 to 15.58. The reclassified slope length factor (Fig. 10) indicates that 95.50% (7672.28 ha) area of the sub-watershed has slope length value of less than 4, while only 0.50% (38.35 ha.) area has slope length factor values of more than 4 which falls only on high altitudes hilly terrain. It could be inferred from the above results that when the value of L was more erosion was more, in steep areas, whereas when it was less, in plain topography, erosion was less. In addition, the exponent 'm' plays a major role in affecting the L factor.

Slop Steepness Factor

Fig. 11. Depicts the slope in percent, as shown in the Fig., 5924.27 ha. (76.83%) area has a slope < 9 percent, so Eq. 4 was used to compute the slope steepness for this area while 1786.37 ha. (23.17 %) area has a slope ≥ 9 percent so Eq. 5 was used to compute the slope steepness for that area.

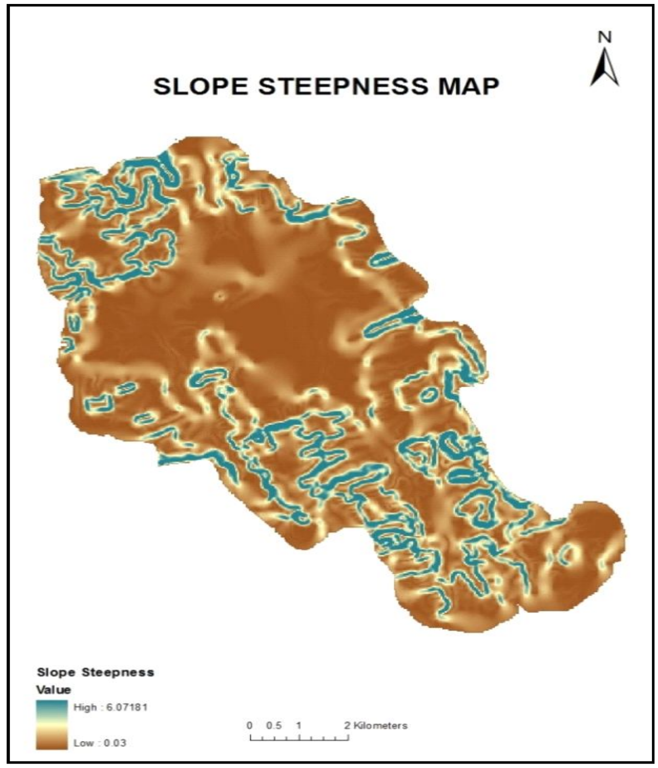

Fig. 13: Slope steepness factor map.

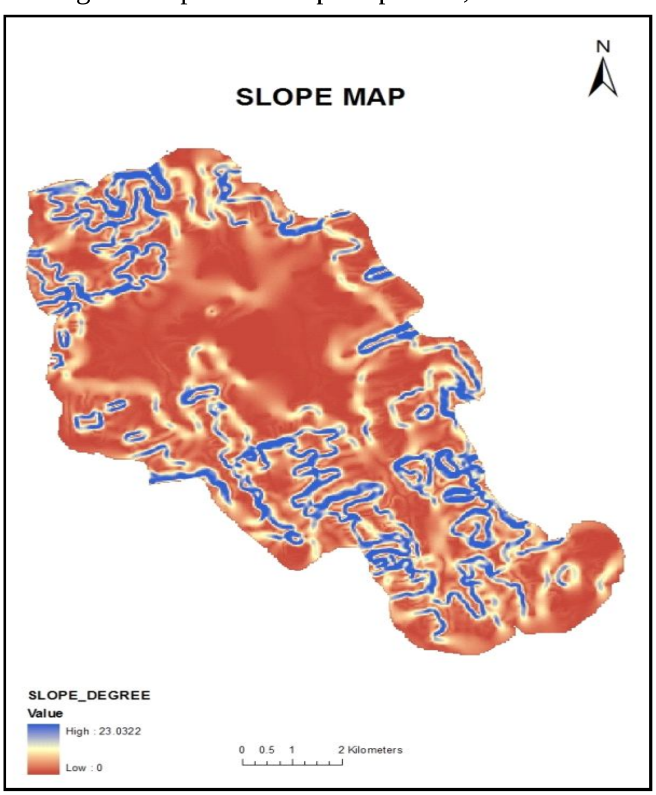

Fig. 12: Slope map in degree.

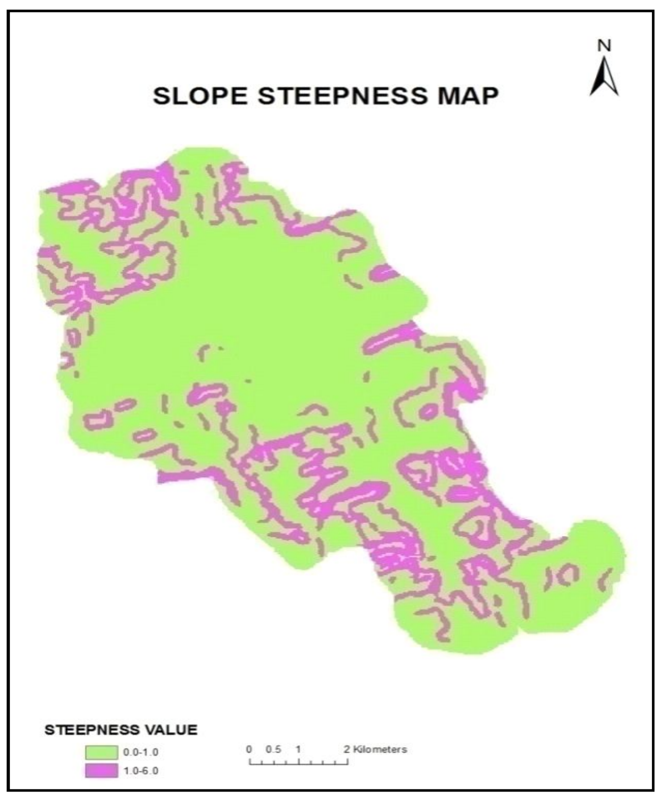

Fig. 14: Reclassified slope steepness map.

The raster layer of the slope map (in degree) as shown in Fig. 12 was used to calculate the slope steepness by using both the formula (Eq. 4 and 5) separately. The attribute value of slope steepness for the resulting raster layer was transferred to the raster layer of Fig. 12 to get the final slope steepness map as shown in Fig. 13. Reclassified slope steepness map (Fig. 14) indicates that 76.83 % of the study area has slope steepness value less than 1.0 while it is greater than 1.0 only for 23.17 % of study area therefore average gross erosion value of study area was less.

Conclusion

The 20 m DEM indicates that 98.67 ha (1.28%) area was covered by more than 275 m altitude and 47.81 ha (0.62%) area was covered by less than 150 m altitude while 7563.78 ha (98.1%) area of study area falls between 150 m to 275 m altitudes. The lowest and highest altitude values of the study area are 139.39 m and 288.35 m respectively. The slope length factor value ranges from 0 to 15.58. The reclassified slope length factor indicates that 95.50% (7672.28 ha) area of the sub-watershed has a slope length value of less than 4, while only 0.50 % (38.35 ha.) area has slope length factor values of more than 4 which falls only on high altitudes hilly terrain. The reclassified slope steepness map indicates that 76.83 % of the study area has a slope steepness value less than 1.0 while it is greater than 1.0 only for 23.17 % of the study area therefore average gross erosion value of the study area was less.

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