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RESEARCH ARTICLE

Assessment of Topographical Factor (LS-Factor) Estimation Procedures in a Gently Sloping Terrain

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Abstract

The major uncertainty in soil erosion assessment studies is derived from LS-factor constituting slope length and slope steepness factors. Empirical soil erosion models employing different algorithms for estimation of LS-factor using raster-based digital elevation models (DEMs). Different algorithms have been adopted for LS-factor determination in soil erosion studies without proper justification for their selection according to the terrain characteristics; a few among them addressed suitability of the algorithms on hilly terrains. The present study focused on the performance of LS-factor estimation methods involving specific contributing area (SCA) method and cumulative slope length method for slope length factor and USLE, RUSLE and USPED algorithms for slope steepness factor in a gently sloping terrain. The results showed that SCA method is the best performing method in gently sloping terrain since the effect of contour length exponent get minimized since there are less influence from diagonal flow direction. The pixel-to-pixel-based slope length exponent may result in more appropriate estimation of slope length factor in gently sloping terrains. The SCA-based slope length estimation along with USLE S-factor algorithm was found to perform well under different elevation classes and slope classes in both SRTM DEM and ASTER DEM. The results from the study may be helpful in appropriate prediction of soil erosion in gently sloping terrains.

Keywords Soil erosion · Slope length factor · SRTM · ASTER · SCA · CSL

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Introduction

The largest uncertainty in prediction of soil loss comes from the combined topographical factor (LS-factor) (Wang et al. 2001). LS-factor constituting slope steepness factor (S-factor) and slope length factor (L-factor) is commonly determined through raster-based digital elevation models (DEMs) in soil erosion studies supported by GIS. The LS-factor subjected to revisions after the introduction of GIS and remote sensing in the field of soil loss estimation. The implementation of the concept of slope length in a raster environment with the use of DEMs as well as adjustments and verification of slope length can be considered as the major insights into the past research era. Though there are vast number of studies on soil loss assessment adopting recommendation of either Universal Soil Loss Equation (USLE)/Revised Universal Soil Loss Equation (RUSLE)/Unit Stream power Erosion and Deposition (USPED) erosion models, proper justifications in the area of LS-factor determination are lacking in spite of its most sensitive nature toward the final predictions. Based on the literature description, two methods were employed for L-factor estimation, viz., (1) cumulative slope length (CSL) method (Hickey 2000) and (2) specific contributing area (SCA) method (Desmet and Govers 1996). The S-factor was determined through USLE, RUSLE and USPED model S-factor algorithms.

The basic form of slope length factor L in USLE and its revised models is defined as follows (Wischmeier and Smith 1965):

$$L = \left(\frac{\lambda}{\lambda_{\mathrm{u}}}\right)^{m} \quad (1)$$

where λ = horizontal slope length and λ_{u} = length of USLE unit plot, 22.1 m. The recommended values of ‘m’ range from 0.2 to 0.5 as slope steepness increases from 0 to 5%; 0.5 was recommended for all slopes above 5%.

RUSLE model has new relationships for the exponent considering equations for basic erosion processes of rill and interrill erosion and deposition by flow. Value of ‘m’ continues to increase with slope inclination according to Eqs. (2) and (3) (McCool et al. 1987).

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

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

where β is ratio of rill to interrill erosion; and θ is slope angle, degrees. As per USPED model, for situations where the furrow erosion dominates a value of $m = 0.6$ and if the laminar erosion prevails $m = 1$ are suggested. For the influence of both flow types on the erosion and deposition, $m = 0.4$ is recommended. In the present study, $m = 0.4$ and $m = 0.6$ were taken for USPED-based L-factor determination.

Hickey (2000) described a method for calculating cumulative downhill slope length (CSL) for USLE model using regular grid DEMs. The developed methodology involves calculation of slope length from high points (ridges/peaks) along the direction of maximum downhill slope angle (flow direction) accounting converging flows and areas of deposition in the algorithm. Desmet and Govers (1996) automated a two-dimensional formulation of the concept for calculating LS-factor for topographically complex terrain, and it was compared with the manual method. The L-factor for such a slope segment can be calculated as:

$$L_{i,j} = \frac{\left(A_{i,j-in} + D^2\right)^{m+1} - A_{i,j-in}^{m+1}}{(D)^{m+2} x_{i,j}^{m} (22.13)^{m}} \quad (4)$$

where $A_{i,\,j-n}$ = contributing area at the inlet of a grid cell with coordinates (i, j) (m^2); $D_{i,j}$ = the effective contour length (m) which is calculated as follows:

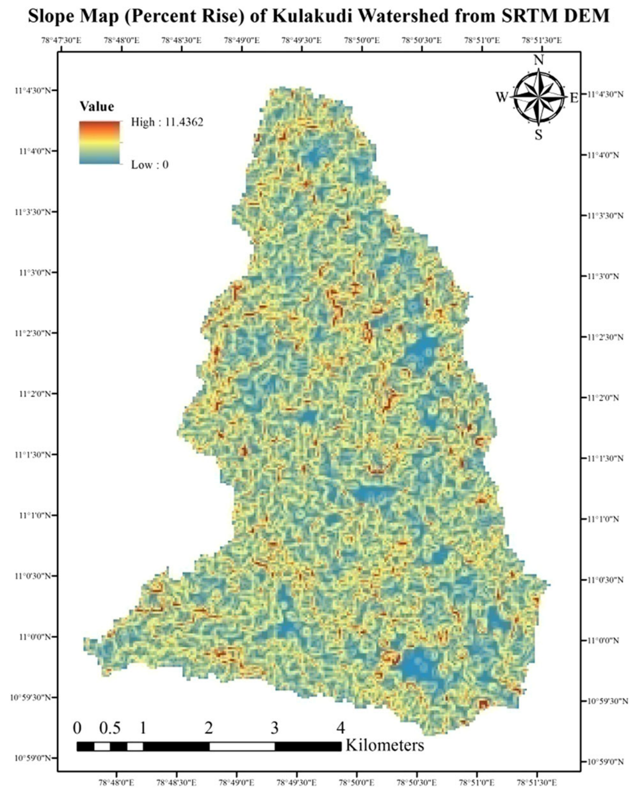


Fig. 1 Slope (percent rise) map from SRTM DEM

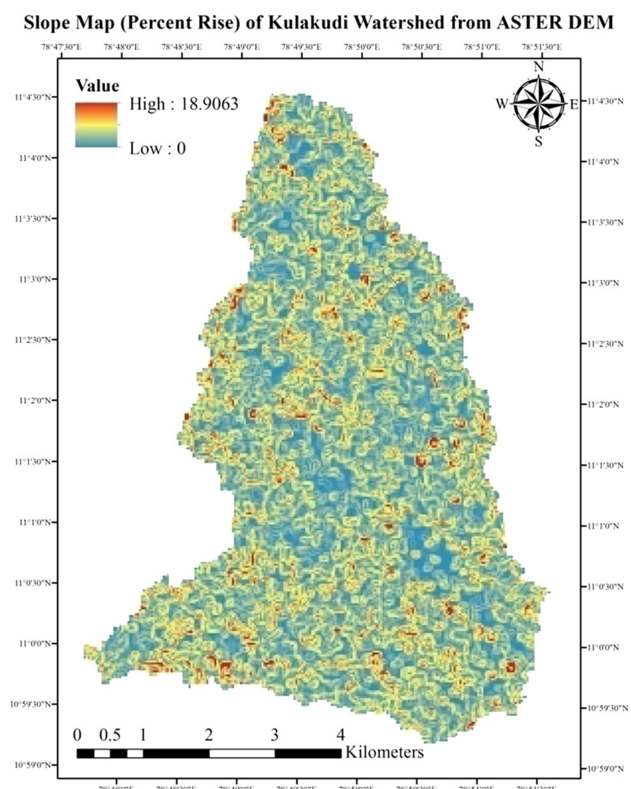


Fig. 2 Slope (percent rise) map from ASTER DEM

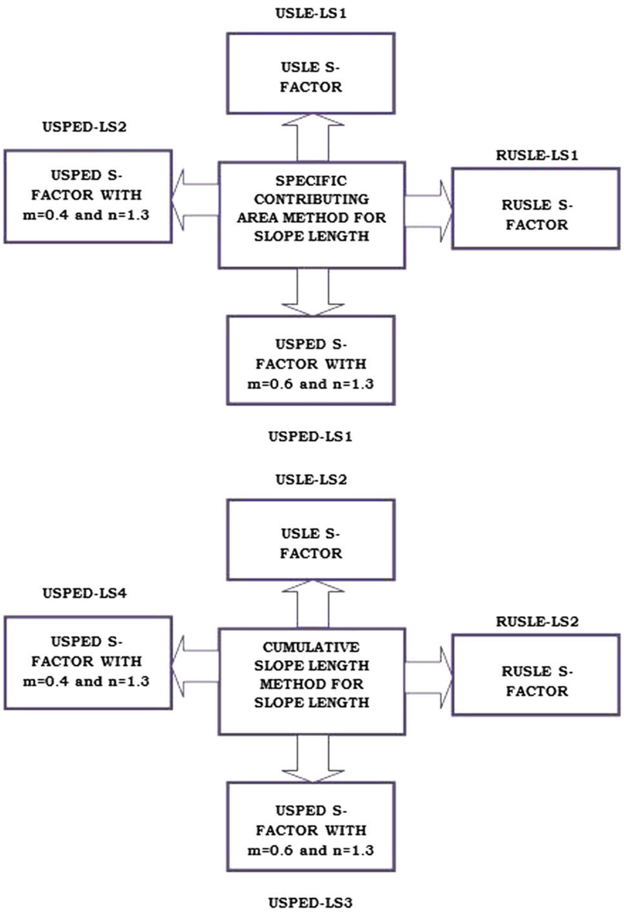


Fig. 3 Selected methods for LS-factor computation and the notations

$$D_{i,j} = D(\sin\alpha_{i,j} + \cos\alpha_{i,j}) = Dx_{i,j} \quad (5)$$

where D = the grid size (m), $\alpha_{i,j}$ = aspect direction for the grid cell with coordinates (i, j). The present study compares the cumulative slope length (CSL) and specific contributing area (SCA) approaches for L-factor estimation using two open-source DEMs-SRTM and ASTER.

Materials and Methods

Study Area

The study area, named as Kulakudi watershed, is located within Pullambadi taluk of Tiruchirappalli district in Tamil Nadu state, India, with an area of 3656.83 hectares and 34.07897 km perimeter. The study area falls between 10°59′11.9″N to 11°4′32.7″N Latitude and 78°47′43.87″E to 78°51′35.95″E Longitude. The open-source high-resolution (30 m pixel size) DEMs-Shuttle Radar Topography Mission (SRTM) and Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), obtained from US Geological Survey (USGS) online source, are used in the present study for L-factor and S-factor estimation. DEM, being an important geospatial data, can contribute errors to the derived parameters due to different sources of uncertainty (e.g., positional inaccuracy, calculation error and interpolation error). The stream network derived from the DEMs was verified with the actual stream network in the field with the help of GPS survey conducted using a handheld Garmin 60CSx GPS with ± 3 m accuracy. The locations of existing structures such as check dam and culvert were identified, and the same was imported into the stream network obtained from DEM within ArcGIS environment. GPS survey serves as the better ground truth verification tool in larger spatial scale studies. The information of elevation details from the DEMs is verified by total station survey within a small area in the watershed. Total station-based elevation details are considered to be superior to GPS as well as remote sensing data from DEMs among the scientific community due to the high accuracy of elevation measurements. The slope maps of the study area derived from SRTM and ASTER DEMs are shown in Figs. 1 and 2.

Table 1 MAE and RMSE from different LS-factor methods in SRTM DEM under criteria-I

Method	Test sites from criteria-I											
	Class I (77–91 m)			Class II (91–101 m)			Class III (101–112 m)			Class IV (above 112 m)		
	SP	MAE	RMSE	SP	MAE	RMSE	SP	MAE	RMSE	SP	MAE	RMSE
USLE LS-1	33	0.080	0.123	53	0.088	0.168	48	0.080	0.162	38	0.382	1.356
USLE LS-2	33	0.770	1.222	53	0.577	0.927	48	0.372	0.530	38	1.076	1.948
RUSLE LS-1	33	0.258	0.403	53	0.218	0.395	48	0.147	0.226	38	0.295	0.467
RUSLE LS-2	33	0.718	1.158	53	0.57509	0.905	48	0.394	0.561	38	0.859	1.359
USPED LS-1	33	1.909	7.724	53	0.747	2.329	48	1.039	2.290	38	3.811	15.364
USPED LS-2	33	0.451	0.996	53	0.282	0.489	48	0.232	0.368	38	0.484	0.792
USPED LS-3	33	3.323	6.304	53	2.45	5.273	48	1.771	3.760	38	6.580	16.975
USPED LS-4	33	1.005	1.521	53	0.760	1.217	48	0.580	0.888	38	1.227	1.821

MAE mean absolute error, *RMSE* root mean square error, *SP* no. of sample points

Table 2 MAE and RMSE from different LS-factor methods in ASTER DEM under criteria-I

Method	Test sites from criteria-I											
	Class I (77–91 m)			Class II (91–101 m)			Class III (101–112 m)			Class IV (above 112 m)		
	SP	MAE	RMSE	Sp	MAE	RMSE	SP	MAE	RMSE	SP	MAE	RMSE
USLE LS-1	33	0.811	1.691	53	0.483	0.912	48	0.791	1.627	38	1.453	4.32
USLE LS-2	33	1.627	3.466	53	0.950	2.18	48	1.740	3.863	38	2.306	5.44
RUSLE LS-1	33	0.758	1.616	53	0.5268	0.945	48	0.807	1.544	38	1.47	4.26
RUSLE LS-2	33	1.560	3.46	53	0.9611	2.098	48	1.754	4.001	38	2.234	5.12
USPED LS-1	33	5.802	17.55	53	1.788	4.049	48	2.021	4.219	38	2.624	5.85
USPED LS-2	33	1.221	2.462	53	0.707	1.251	48	0.939	1.62	38	1.558	4.26
USPED LS-3	33	7.596	15.419	53	4.200	8.818	48	5.827	11.307	38	6.375	13.83
USPED LS-4	33	1.892	3.375	53	1.227	2.287	48	1.842	3.339	38	2.35	4.88

Two approaches for slope length factor estimation and three approaches for slope steepness factor estimation were adopted in the study. From the estimated factors, combined LS-factors were derived. Figure 3 shows the L-factor and S-factor algorithms employed in the study and the corresponding LS-factors with the notations used. The flow length tool in hydrology Tool set is used for L-factor determination through CSL method. The SCA method is based on unit catchment area concept in place of slope length. The L-factor for the grid cell coordinates (i, j) may then be written as:

$$L_{i,j} = \frac{\left(A_{i,j-in} + D^2\right)^{m+1} - A_{i,j-in}^{m+1}}{(D)^{m+2} x_{i,j}^{m} (22.13)^{m}} \tag{6}$$

where $A_{i,j-n}$ = contributing area at the inlet of a grid cell with coordinates (i, j) (m^2); D = the grid size (m) being calculated as given below:

$$D_{i,j} = D\left(\sin \alpha_{i,j} + \cos \alpha_{i,j}\right) = Dx_{i,j} \tag{7}$$

The LS-factor algorithms were compared on different sample locations pertaining to different elevation classes and different slope classes.

Results and Discussion

Based on the selected L-factor and S-factor algorithms, under each DEM dataset eight LS-factor maps were obtained. The mean absolute error (MAE) and root mean square error (RMSE) values obtained under the eight methods in SRTM and ASTER DEMs are shown in Tables 1 and 2 under criteria-I, Tables 3 and 4 under criteria-II. From MAE and RMSE values computed for the eight methods, it was found that the USLE LS1 method (SCA method for L-factor and USLE algorithm for S-factor), RUSLE LS1 (SCA method for L-factor and RUSLE algorithm for S-factor) and USPED LS-2 (SCA method for L-factor with 0.4 as slope length exponent and USPED algorithm for S-factor) are the best-performed algorithms in both the DEMs. The result indicates that while adopting USPED model in flat terrains, 0.4 is the

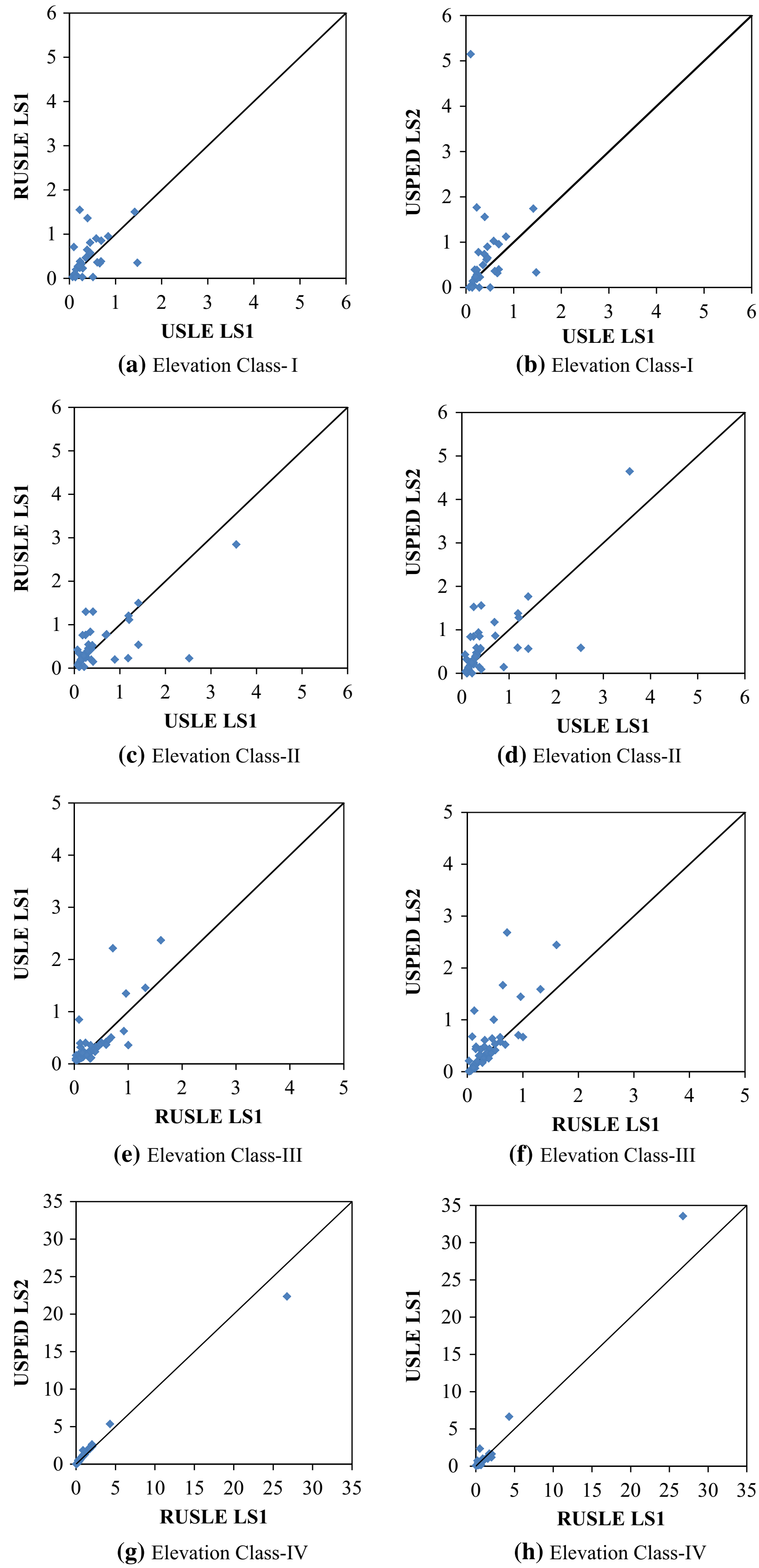
Table 3 MAE and RMSE from different LS-factor methods in SRTM DEM under criteria-II

Method	Test sites from criteria-II					
	Slope class-I (0–5%)			Slope class-II (> 5%)		
	SP	MAE	RMSE	SP	MAE	RMSE
USLE LS-1	85	0.080	0.123	42	0.088	0.168
USLE LS-2	85	0.770	1.222	42	0.577	0.927
RUSLE LS-1	85	0.258	0.403	42	0.218	0.395
RUSLE LS-2	85	0.718	1.158	42	0.575	0.905
USPED LS-1	85	1.909	7.724	42	0.747	2.330
USPED LS-2	85	0.451	0.996	42	0.282	0.489
USPED LS-3	85	3.323	6.304	42	2.450	5.273
USPED LS-4	85	1.00468	1.52114	42	0.76015	1.21671

Table 4 MAE and RMSE from different LS-factor methods in ASTER DEM under criteria-II

Method	Test sites from criteria-II					
	Slope class-I (0–5%)			Slope class-II (> 5%)		
	SP	MAE	RMSE	SP	MAE	RMSE
USLE LS-1	85	0.808	1.691	42	0.483	0.912
USLE LS-2	85	1.627	3.466	42	0.950	2.180
RUSLE LS-1	85	0.758	1.616	42	0.527	0.945
RUSLE LS-2	85	1.560	3.46	42	0.9611	2.098
USPED LS-1	85	5.802	17.551	42	1.788	4.049
USPED LS-2	85	1.221	2.462	42	0.707	1.251
USPED LS-3	85	7.596	15.419	42	4.20	8.818
USPED LS-4	85	1.892	3.375	42	1.227	2.287

Fig. 4 **a** Elevation class-I, **b** elevation class-I, **c** elevation class-II, **d** elevation class-II, **e** elevation class-III, **f** elevation class-III, **g** elevation class-IV, **h** elevation class-IV and **a**–**h** comparison of the best-performed LS-factor methods in SRTM DEM under criteria-I



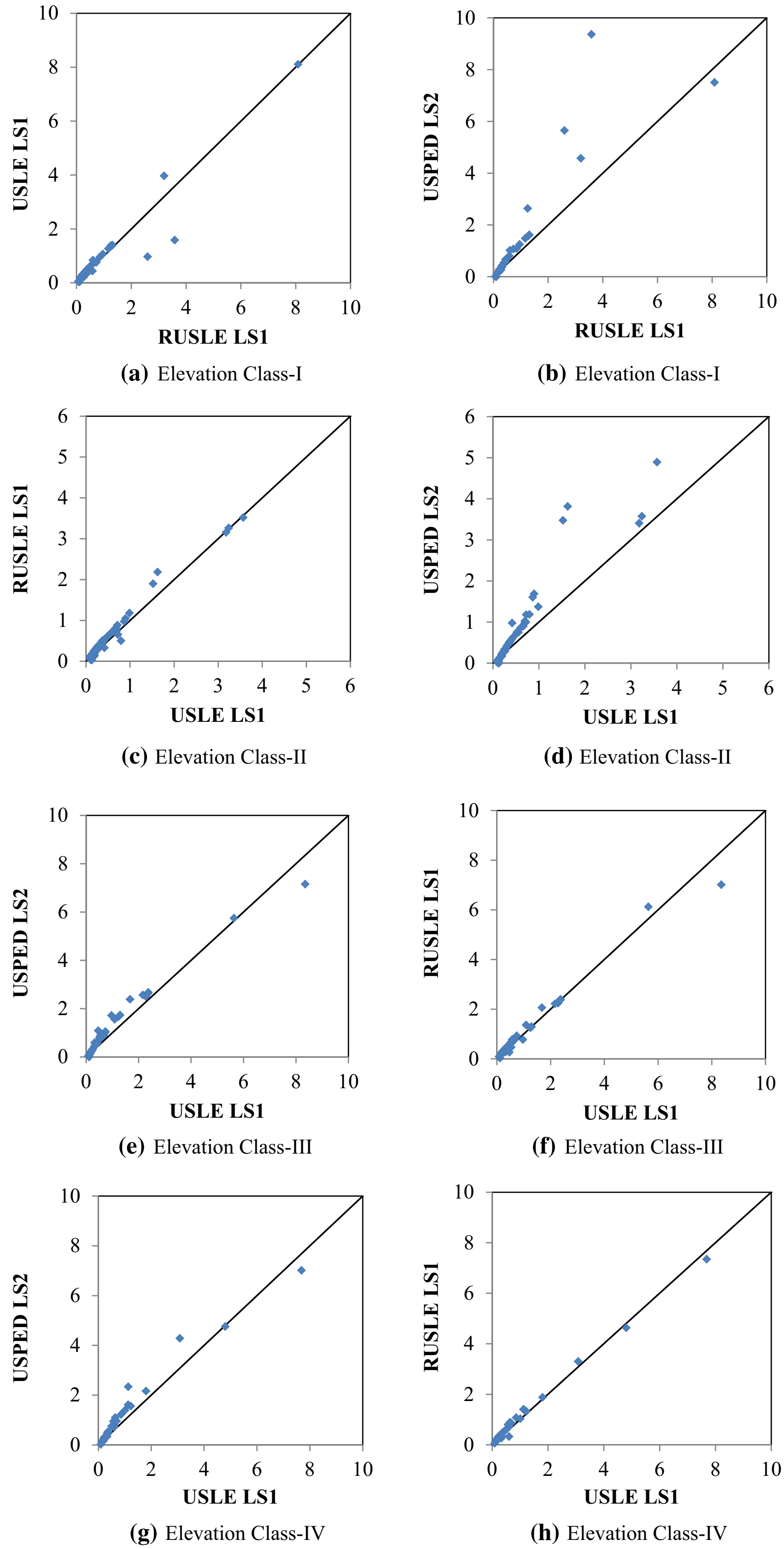
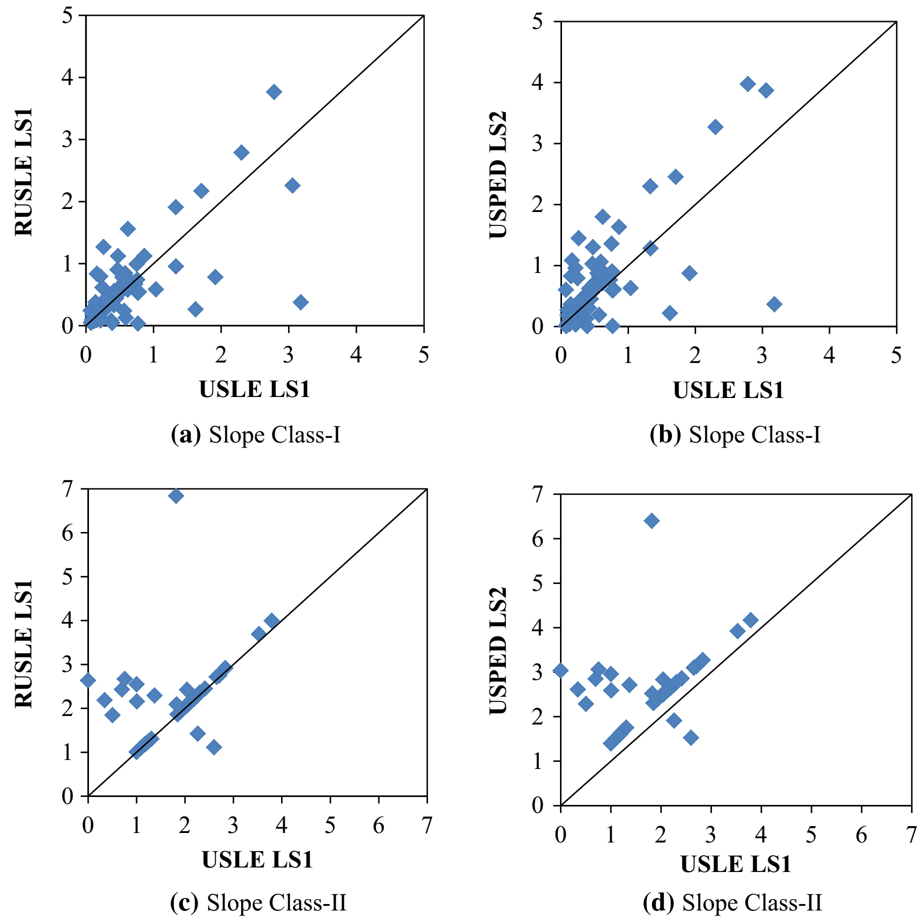


Fig. 5 **a** Elevation class-I, **b** elevation class-I, **c** elevation class-II, **d** elevation class-II, **e** elevation class-III, **f** elevation class-III, **g** elevation class-IV, **h** elevation class-IV and **a**–**h** comparison of the best-performed methods in ASTER DEM under criteria-I

Fig. 6 **a** Slope class-I, **b** slope class-I, **c** slope class-II, **d** slope class-II and **a–d** comparison of the best-performed methods in SRTM DEM under criteria-II



reasonable value for LS-factor estimation, if there is no information on the flow dynamics in the area. The value 0.4 or 0.6 may be sufficient for complex terrains. In other conditions, field-level investigation can provide the best option other than 0.4. In order to rank the algorithms, relative error between pair of algorithms was plotted for different classes under criteria-I and criteria-II. The comparison of the best-performed methods is shown in Fig. 4 under criteria-I in SRTM DEM, Fig. 5 under criteria-I in ASTER DEM, Fig. 6 under criteria-II in SRTM DEM and Fig. 7 under in criteria-II ASTER DEM.

With reference to the statistical comparison of selected methods in terms of MAE and RMSE and relative error diagrams, the best-performed algorithms can be ranked and are given in Table 5. The USLE-LS1 shows dominance among other selected methods irrespective of the terrain characteristics. The RUSLE-based S-factor algorithm and USPED-based S-factor algorithms are theoretically proposed for higher slope segments. The clear demarcation regarding adoption of the methods in terms of slope range limits is mentioned nowhere in the previous studies. With respect to the unit plot condition, USLE method is treated to be good for uniform slopes using data from runoff plot with gradients varying from 2 to 18%. But, still USLE S-factor algorithm was applied in studies for soil loss estimation on mountain terrains without any justification (Abdul Rahaman et al. 2015; Vikhe and Patil 2016).

The RUSLE S-factor algorithm considered dataset under simulated rainfall condition with slope gradient ranging from 0.1 to 3% and data from natural rainfall for slopes of 9–55%. The USPED S-factor was developed by combining research findings of Musgrave (1947), Smith and Whitt (1948) and Wischmeier and Smith (1965). All the linear relationships are statistically more accurate within the limits of slope steepness accounted for their derivation, but under predicts beyond the limits (Mulengera 2008). The USPED algorithm is widely used in soil erosion studies for all ranges of slope gradients (Ouyng and Bartholic 2001; Tirkey et al. 2013). Hence, the three selected algorithms are expected to give almost similar results in the study area. The variation in LS-factor values among the methods can be attributed to the influence of slope length factor.

Except USPED LS1 (SCA-based L-factor with 0.6 as slope length exponent) and USPED LS3 (CSL-based

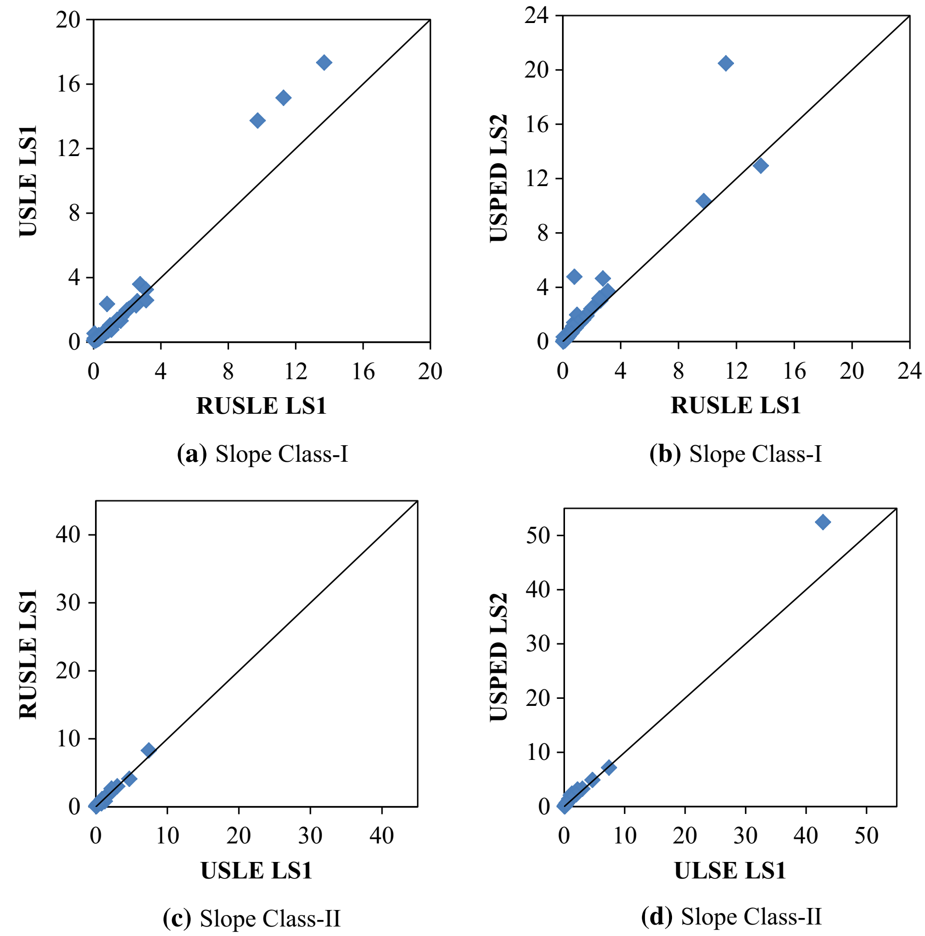


Fig. 7 **a** Slope class-I, **b** slope class-I, **c** slope class-II, **d** slope class-II and **a–d** comparison of the best-performed Methods in ASTER DEM under criteria-II

L-factor with 0.6 as slope length exponent), all other methods showed comparable LS-factor values and lower error estimates (RMSE and MAE). It suggests non-adaptability of slope length value of 0.6 in USPED model in the study area, which is mainly recommended under conditions where furrow erosion dominates. Also those L-factor values may finally lead to unjustifiable predictions of soil loss. Based on the literature recommendations, m value of 0.4 may be considered for calculations as it can give average satisfactory results by balancing impact of laminar and turbulent flow (Mitasova et al. 1996). Considering criteria-I, in SRTM DEM dataset, both SCA-based LS-factors and CSL-based LS-factors showing a decreasing error between first and third (on an average 40% reduction in error) class and from the third class to fourth class, there is a sudden increment in error (about 194% increase). The error changes are more pronounced in the case of slope length predictions with exponent value of 0.6. Within ASTER DEM dataset, between first and second class, there is a gradual decrease in error (about 11%); and then toward the last class, error values are considerably increasing (about 45%). Considering criteria-II under both SRTM and ASTER DEM dataset, the error values are steadily decreasing from the first slope class to the last slope class (about 25% and 43% in SRTM and ASTER, respectively). The similar trend in error variation shows that both SCA- and CSL-based methods respond to terrain variation. The exceptional case occurs in 0.6 m-value-based LS-factor methods, where under SRTM dataset error values at the last class are higher than the first class in criteria-I. But in ASTER dataset, the first class error value is found to be higher compared to error in fourth class. On comparing all the methods, USLE LS1 is the least error method under almost all criteria considered. The RUSLE LS1 method dominated other methods in performance in elevation class-III and elevation class-IV in SRTM DEM and in elevation class-I of ASTER DEM.

Conclusions

The study takes into account CSL and SCA methods for slope length determination, both of which are superior to the method proposed by Wischmeier and Smith (1978) in

Table 5 Ranking of the best-performed methods

Criteria	Best-performed methods		
	Rank	SRTM	ASTER
Elevation class-I	1	USLE-LS1	RUSLE-LS1
	2	RUSLE-LS1	USLE-LS1
	3	USPED-LS2	USPED-LS2
Elevation class-II	1	USLE-LS1	USLE-LS1
	2	RUSLE-LS1	RUSLE-LS1
	3	USPED-LS2	USPED-LS2
Elevation class-III	1	RUSLE-LS1	USLE-LS1
	2	USLE-LS1	RUSLE-LS1
	3	USPED-LS2	USPED-LS2
Elevation class-IV	1	RUSLE-LS1	USLE-LS1
	2	USPED-LS2	RUSLE-LS1
	3	USLE-LS1	USPED-LS2
Slope class-I	1	USLE-LS1	RUSLE-LS1
	2	RUSLE-LS1	USLE-LS1
	3	USPED-LS2	USPED-LS2
Slope class-II	1	USLE-LS1	USLE-LS1
	2	RUSLE-LS1	RUSLE-LS1
	3	USPED-LS2	USPED-LS2

terms of consideration of terrain concavity and convexity. The slope steepness factor (S-factor) was determined through USLE, Revised USLE (RUSLE) and Unit Stream Power Erosion and Deposition (USPED) algorithms. The USLE LS-1 method (SCA-based slope length + USLE S-factor algorithm) was found to perform well under different elevation classes and slope classes in both SRTM DEM and ASTER DEM. The minimum diagonal flows within the watershed contribute to better performance of SCA method. While adopting USPED model for LS-factor predictions within lower slope areas, 0.4 is the recommended value of slope length exponent with the value of constant, $n = 1.6$, if the flow dynamics in the area is unknown since the value balances the impact of both laminar and turbulent flow. A better value to be chosen with proper justification may need detailed research involving flow dynamics and its interactions with soil loss processes.

The difference in terrain characteristic is the key parameter in the selection of the algorithm for estimation of terrain parameters. Soil erosion studies predict reliable estimates depending on the accuracy related to the topographical factor. Selection of appropriate algorithm is thus important. The results of the study may be specific to gently sloping terrains. The studies of similar nature are conducted nowhere before.

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