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Original Paper

DEM Spatial Resolution Impact On Hillslope Erosion and Deposition Modeling, an Application On Lebanese Watersheds

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Abstract

Geographic Information Systems analysis based on Digital Elevation Models (DEMs) vary with spatial resolution and datasets production method. DEMs with different spatial resolutions can lead to several analysis results. This study investigates the effects of DEMs on predicting soil erosion and deposition modeling on Lebanese river basins. Two DEMs at different spatial resolutions from two sources were used to calculate topographic and hydrological parameters for the prediction of the Sediment Transport Index (STI), the erosion-deposition based on Unit Stream Power Erosion and the Deposition Model (USPED) taking into account only the topography factors expressed in DEMs.

This paper analyzes hillslope erosion and deposition rates in a GIS to estimate patterns sheet and rill erosion in 13 Lebanese river basins. A correlation analysis applied to test the degree of similarity between the datasets and the effect of erosion deposition with spatial resolution.

Results indicate that rill erosion and deposition have an influence on high spatial resolution DEMs, due to the good terrain representation especially the concave forms of deposition.

This result shows the increased rill erosivity of channel flow in the downstream, and sediment deposition in concave areas.

Keywords

spatial resolution, DEM, USPED, STI, erosion, deposition

1. Introduction

Digital Elevation Models (DEM) represent terrain topography in Geographic Information Systems (GIS) and they can vary in resolution and accuracy. This directly moderates water flow over the Earth's surface and in turn moderates the potential of soil erosion (Hutchinson, 1996).

Geomorphometry is the sciences of extracting topographic and hydrological features from DEMs while terrain analysis has been studied extensively over the last two decades (Mark, 1983; Doumit, 2017; Jenson, 1991; Moore et al., 1993; Florinsky, 1998).

The main purpose of this study was to assess the topography effects of two DEM resolutions on erosion deposition for 13 watersheds in Lebanon. Since there exist open source multiple types of DEMs with different spatial resolutions, it makes easy the evaluation of DEM impact on soil erosion and deposition prediction modeling.

Topographic attributes have, therefore, been used to describe spatial soil elevation, slope, and aspect (Moore et al., 1991). Scientists proposed many hydrologic and topographic indices to map hills slope erosion, soil sediments, and moisture based on field models (Grunwald, 2006), expressing the properties of their maps by numbers of pixels; this approach has been supported by the development of GIS, and remote sensing technologies (Moore et al., 1991; Moore, 1996; Murphy et al., 2009).

Erosion patterns and deposition are results of rainfall, topography, groundwater flow, vegetation cover and growth, and soil detachment. This paper only focused on the main factors influencing on erosion, topography excluding other geographical factors. Here, terrain analyses the mathematical representation of sediment transport and erosion-deposition processes.

The fast evolution of GIS erosion modeling workflows made the data processing and analysis very fast and easy by applying scripts and model builders.

The goal of this project was to assess the impacts of DEM spatial resolution on sheet and rill erosion and deposition in watershed basins. The paper addresses the quantitative estimation of soil erosion to better understand the overall connectivity between erosion type and terrain scale represented by DEM, using a soil erosion and transport model implemented in a Geographical Information System.

Thus, the model focuses on the complex interaction between topography affecting the potential for soil erosion and on how the spatial distribution of these factors leads to variations in sheet and rill erosion and deposition within a watershed based on pixel size.

This paper attempts to identify and predict the spatial patterns of soil rill and sheet erosion with sediment deposition inside the Lebanese watersheds based on MERIT and ALOS DEMS.

2. Materials and Methods

GIS and Digital Elevation Models (DEM) can be used to perform watershed delineation. In our study for delineating watersheds, we used the ArcHydro GIS algorithm developed for building hydrologic information systems. Lebanon includes 16 river basins in which 13 of them flows in the Mediterranean Sea, moving a huge quantity of sediments and constitute the study area of our research Figure 1.

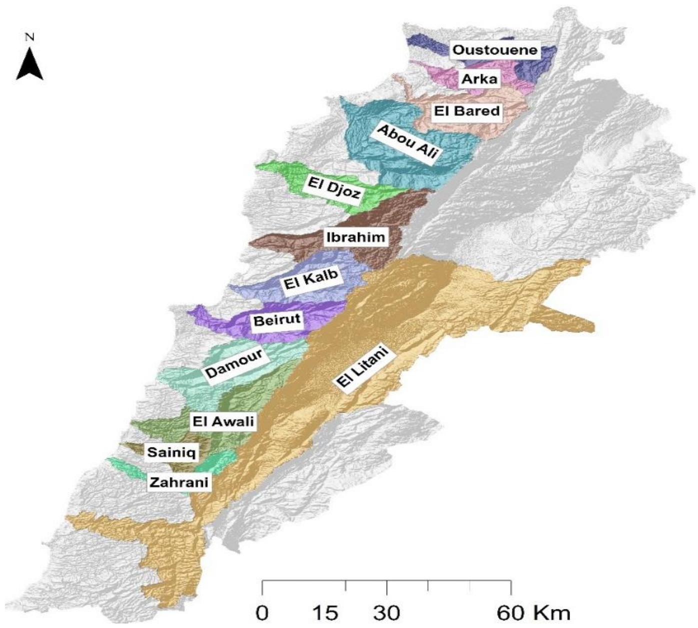

Figure 1. River Basins of the Study Area Draped on the Hill Shade Map of Lebanon

The two different DEM "MERIT and ALOS" used in this study show different spatial resolution datasets. The MERIT DEM of 90-meter spatial resolution made from the existing free of charges SRTM and AW3D with correction of components error (Yamazaki et al., 2017).

The second DEM, ALOS from the Japan Aerospace Exploration Agency (JAXA) dataset is considered to be with a spatial resolution of 30-meter (Takaku et al., 2016).

According to Kothyari et al. (2002), there are many methods to estimate sediment transport, they reported that the best GIS suited method is the one proposed by Moore and Wilson (1992), based on unit stream power theory and called Sediment Transport Index (STI). It is a non-linear function of specific discharge and slope and it is derived by considering the transport capacity limiting sediment flux and catchment evolution erosion theories (Moore & Wilson, 1992). This index is a fundamental factor in the Universal Soil Loss Equation (USLE). It calculates sediment transport capacity and may be better suited to landscape assessments of erosion than the USLE because it takes into accounts the flow convergence and divergence (Moore & Wilson, 1992; Desmet & Govers, 1996).

$$\mathrm{STI} = \left[(m+1).\left(\frac{A_s}{22.13}\right)^m.\left(\frac{\sin\beta}{0.0896}\right)^n\right] \quad (1)$$

Where, "As" is the flow accumulation, "β" is the slope. The flow accumulation determines water accumulation from upstream areas and identifies areas that contribute to overland flow. The exponents m and n control the relative impact of water and slope terms and reflect different erosion patterns, higher values reflecting the pattern for prevailing rill erosion and lower exponent values close to 1 reflect the pattern of both rill and sheet erosion, previous studies have used the recommended m = 1.6 and n = 1.3 for rill erosion and m = 1.0 and n = 1.0 for sheet erosion (Garcia, & Gimenez, 2012; Liu et al., 2003;

Warren et al., 2000).

The model applied for this paper is a modified version of the USPED (Unit Stream Power based Erosion Deposition) which calculates sediment erosion and deposition in the hillslope erosion processes and it is similar to the USLE but calculated based on upslope contributing area (Liu et al., 2007; Mitasova et al., 1996). Therefore, the sediment transport capacity (T) is defined in the following equation (2):

$$T = R \times K \times C \times P \times A^{m} \times (\sin\beta)^{n} \tag{2}$$

where R is the rainfall, K is the soil erodibility, C is the cover and management factor, P is the conservation practice factor, A is the upslope contributing area, and β is the slope inclination angle in degrees (Leh et al., 2011; Mitasova & Mitas, 2001; Mitasova et al., 1999).

As in this paper, we only test the influence of topography factors on hillslope erosion and its relation with DEM spatial resolution we applied Sediment Transport Index (STI) instead of transport capacity (T) in the Erosion Deposition (ED) equation (3) where α reflects the aspect of the elevation surface (Oliveira et al., 2013).

$$ED = \frac{d(T\cos\alpha)}{dx} + \frac{d(T\sin\alpha)}{dy} \tag{3}$$

To make the equation easy to implement in GIS, Mitasova et al. (1996) used the relationship between partial derivatives and surface slope β and aspect α of equation (4), to the ED equation (3) Mitasova et al. (1996).

$$\frac{dz}{dx} = \tan\beta \times \cos\alpha, \frac{dz}{dx} = \tan\beta \times \sin\alpha \tag{4}$$

Simulation results from the USPED model can be positive, indicating soil deposition, or negative, indicating soil erosion.

The topography is only one of many factors that can affect water erosion. DEMs resulted in substantially different resolution leading to different terrain models, which in turn led to different erosion results.

The approach was to compare the spatial distribution of rill and sheet erosion and sediment deposition using MERIT and ALOS DEMs.

The modeled patterns of erosion and deposition rates in the basins were analyzed only based on topographic forcing; the model was run only with the topographic factor present in the calculation of USPED.

3. Discussions and Results

The terrain topography plays the most important role in erosion and deposition of the watershed basins, the increasing of the upslope contributing area values combining with a high slope value of the local slope could lead to a high sediment transport rate same as the areas with concave slope profile of convergent accelerated flow. The areas of high transport rate are also associated with concave slope profiles and valleys because these are areas of convergent accelerated flow, in the areas with high sediment transport the rill erosion is higher than the sheet erosion.

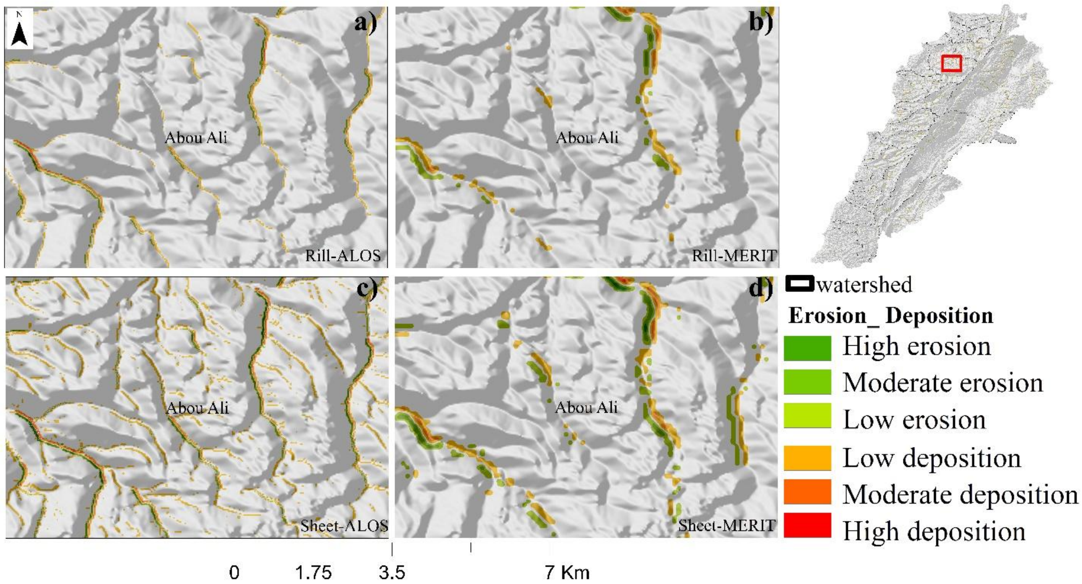

Figure 2. Erosion Deposition Maps of Abou Ali River, a) Rill Erosion and Deposition in ALOS, b) Rill Erosion and Deposition in MERIT, c) Sheet Erosion and Deposition in ALOS, d) Sheet and Deposition Erosion in MERIT

The sediment transport rate expressed in equation 3 identifies areas where the sediment transport rate increases in the upslope contributing area and lead to erosion in ED negative values, and decreases with ED positive values leading to deposition, or stays constant with values near to zero for areas stable no net erosion and deposition.

The resulting ED maps of Lebanese watershed basins topography based on ALOS and MERIT DEMs shows that estimated high erosion and deposition areas located on the North of Lebanon in El Bared and Abou Ali basins Figure 3.

Figure 2 shows the Sheet and Rill ED maps of Abou Ali basin generated from ALOS and MERIT datasets, Figure 2a of the Rill ED ALOS map shows a low rate of erosion and deposition contrary to Figure 2b the Rill ED generated from MERIT dataset with high rate of erosion and deposition due to the high spatial resolution.

The ALOS sheet ED of Figure 2c shows a scattered spatial distribution of sheet erosion and deposition in most of the concave areas unlike the sheet ED the concentration of sheet deposition and erosion in deep valleys Figure 2d.

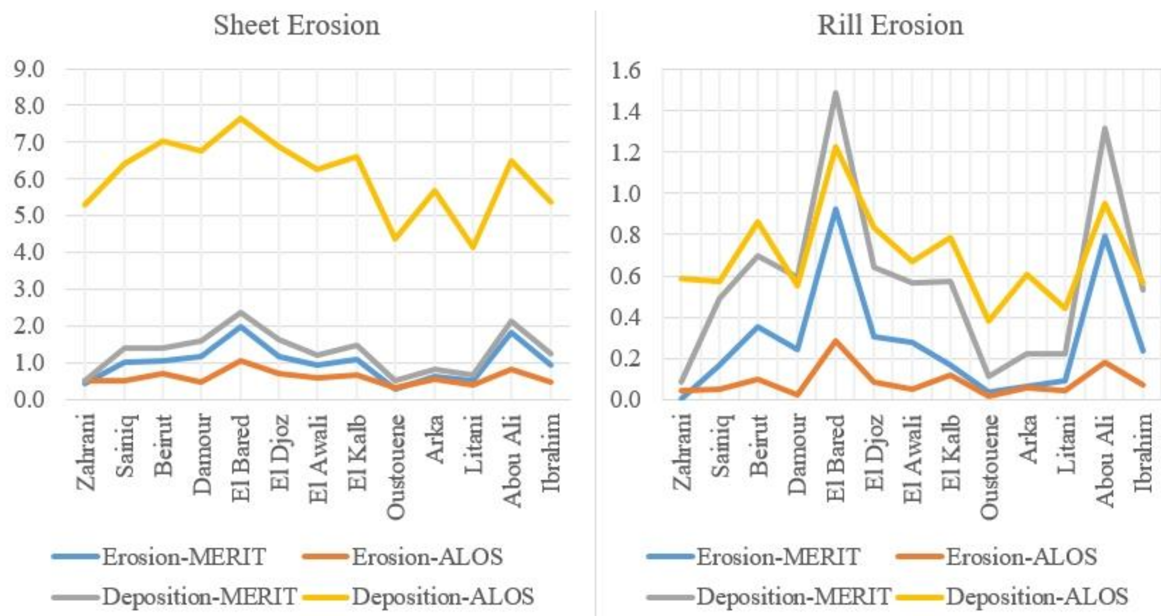

Figure 3. Diagrams of Rill and Sheet Erosions Areas in Lebanese Watershed Basins

The graphs of Figure 3 of Sheet and Rill Erosions with percentage of areas (Y axes) in each basin shows a very high percentage of areas for deposition in ALOS datasets for all Lebanese watershed with very high values for El Bared and Abou Ali basins and a very low percentage of area for Oustouene and Damour basins.

The comparison between elevation data sets for sheet erosion gives a proportional percentage of areas between erosion and deposition of MERIT datasets, otherwise a heterogeneity in the percentage of areas between Erosion and Deposition in ALOS datasets when deposition occupied big areas against erosion with a lower percentage of areas.

In the diagram of rill erosion of Figure 3 we can see very similar graph for all basins with some exceptions in Zahrani basin the Erosion in ALOS datasets have a higher percentage of erosion than Erosion in MERIT datasets, the Deposition of ALOS datasets is lower than deposition in MERIT datasets in Damour, El Bared and Abou Ali basins.

Due to the unexpected rill erosion and deposition results of difference in the percentage of areas between ALOS and MERIT datasets we calculated the percentage of areas of the classified erosion and deposition in MERIT and ALOS datasets Figure 4, and Figure 6.

		Sheet Erosion-MERIT %						Sheet Erosion-ALOS %					
		Erosion			Deposition			Erosion			Deposition		
Basin	Area Sq/Km	High	Moderate	Low	Low	Moderate	High	High	Moderate	Low	Low	Moderate	High
Zahrani	102	-	-	0.413	0.518	0.007	-	0.005	0.056	0.445	5.092	0.201	0.014
Sainiq	109	-	0.119	0.903	1.252	0.132	-	0.004	0.072	0.422	6.197	0.194	0.020
Beirut	237	0.033	0.165	0.845	1.187	0.192	0.033	0.013	0.119	0.563	6.660	0.335	0.030
Damour	308	-	0.104	1.061	1.463	0.128	-	0.001	0.039	0.420	6.584	0.174	0.004
El Bared	263	0.040	0.508	1.441	1.806	0.538	0.021	0.084	0.251	0.718	7.013	0.503	0.132
El Djoz	194	0.022	0.183	0.959	1.412	0.183	0.015	0.011	0.110	0.594	6.538	0.311	0.026
El Awali	297	0.012	0.147	0.786	1.032	0.156	0.007	0.003	0.068	0.504	6.030	0.229	0.009
El Kalb	254	-	0.062	1.019	1.386	0.095	-	0.022	0.126	0.515	6.272	0.305	0.044
Oustouene	164	-	0.013	0.279	0.486	0.021	-	0.001	0.027	0.297	4.240	0.130	0.002
Arka	133	-	0.042	0.574	0.775	0.032	-	0.009	0.075	0.455	5.427	0.223	0.015
Litani	2110	-	0.051	0.442	0.596	0.053	0.002	0.006	0.051	0.317	3.964	0.152	0.012
Abou Ali	472	0.146	0.360	1.330	1.631	0.402	0.11	0.040	0.178	0.589	6.056	0.374	0.072
Ibrahim	332	-	0.113	0.813	1.132	0.126	-	0.015	0.078	0.375	5.128	0.213	0.026

Figure 4. Percentage of Sheet Erosion and Deposition Areas of ALOS and MERIT

Figure 4 of the area percentage of the degree of erosion and deposition between MERIT and ALOS of sheet erosion, the highest sheet erosion areas of MERIT datasets are found in Abou Ali basin followed by El Bared basin contrary in ALOS sheet erosion the highest area found in El Bared followed by Abou Ali.

Lower sheet erosion percentage of MERIT and ALOS areas are found in Oustouene basin, a very clear symmetrical percentage of areas between sheet erosion and sheet deposition are found in Beirut basin.

An independent-samples t-test was conducted to compare the two datasets results of MERIT and ALOS in sheet erosion and deposition. There was a significant difference in the scores for low level in sheet erosion ($P<0.05$) Figure 5. The MERIT method which expressed the highest results in a low level of sheet erosion due to gentle terrain slopes and the low spatial resolution of MERIT datasets. Otherwise ALOS datasets showed a highly significant difference ($p<0.01$) comparing with MERIT datasets in a low level of sheet deposition reflecting a decrease of values in low-level erosion of ALOS datasets. These results prove the effect of spatial resolution on sheet erosion and deposition modelling. Specifically, our results suggest that high resolution datasets lead to a better results of modelling erosion and deposition.

		Sheet Erosion/Deposition	
	Level	MERIT	ALOS
Erosion	High	0.019 ± 0.041^a	0.016 ± 0.023^a
	Moderate	0.102 ± 0.139^a	0.096 ± 0.062^a
	Low	0.835 ± 0.345^b	0.478 ± 0.119^a
Deposition	High	0.01477 ± 0.31594^a	0.03123 ± 0.035570^a
	Moderate	0.15885 ± 0.152957^a	0.25723 ± 0.104296^a
	Low	1.12892 ± 0.427406^a	$5.7847 \pm 0. .94704^b$

Figure 5. Statistical Analysis for Results Obtained with MERIT and ALOS Datasets for Sheet Erosion and Deposition

[a,b] Values with different superscript in a row differ significantly ($p<0.05$).

In general, the values of area percentage in sheet erosion and deposition of MERIT and ALOS are very homogeny proved in the diagram of Figure 3.

		Rill Erosion-MERIT %						Rill Erosion-ALOS %					
		Erosion			Deposition			Erosion			Deposition		
Basin	Area Sq/Km	High	Moderate	Low	Low	Moderate	High	High	Moderate	Low	Low	Moderate	High
Zahrani	102	-	-	-	0.084	-	-	-	-	0.045	0.561	0.023	-
Sainiq	109	-	-	0.165	0.474	0.013	-	-	-	0.053	0.544	0.029	-
Beirut	237	0.012	0.063	0.280	0.613	0.069	0.015	-	0.001	0.095	0.810	0.050	0.001
Damour	308	-	0.005	0.237	0.576	0.019	-	-	-	0.023	0.543	0.008	-
El Bared	263	0.005	0.102	0.817	1.320	0.161	0.005	0.004	0.027	0.252	1.022	0.172	0.032
El Djoz	194	-	0.051	0.252	0.574	0.066	-	-	-	0.087	0.785	0.050	-
El Awali	297	-	0.041	0.233	0.529	0.038	-	-	-	0.047	0.645	0.023	-
El Kalb	254	-	0.006	0.160	0.565	0.008	-	0.001	0.007	0.113	0.715	0.065	0.008
Oustouene	164	-	-	0.034	0.112	-	-	-	-	0.014	0.377	0.005	-
Arka	133	-	-	0.064	0.223	-	-	-	0.004	0.049	0.581	0.020	0.004
Litani	2110	-	0.011	0.083	0.209	0.013	-	-	0.001	0.039	0.419	0.020	0.001
Abou Ali	472	0.037	0.219	0.537	1.025	0.249	0.042	0.002	0.012	0.168	0.830	0.107	0.014
Ibrahim	332	-	0.011	0.227	0.516	0.017	-	0.001	0.003	0.067	0.521	0.038	0.004

Figure 6. Percentage of Rill Erosion and Deposition Areas of ALOS and MERIT

According to independent-samples t-test, values in low level of MERIT rill erosion was significantly higher ($P<0.05$) than those obtained from ALOS datasets Figure 7. These results are very similar to the results of MERIT sheet erosion with difference at low levels. Otherwise there is no significant difference between MERIT and ALOS datasets for rill deposition in all levels and especially for the lower one. The fact of having no significant results in rill deposition is related to small deposition areas. For Both datasets and at all levels, deposition and erosion have a significant way of ($p<0.05$), this is due to the strict separation between levels obtained through classification formulas.

		Rill Erosion/Deposition	
	Level	MERIT	ALOS
Erosion	High	0.00415 ± 0.010463a	0.00062 ± 0.001193 a
	Moderate	0.03915 ± 0.062576 a	0.00423 ± 0.007726 a
	Low	0.23762 ± 0.221871 b	0.08092 ± 0.065916a
Deposition	High	0.00477± 0.011966a	0.00492 ± 0.009142a
	Moderate	0.05023± 0.074573 a	0.04692 ± 0.046428 a
	Low	0.52462± 0.348231 a	0.64254 ± 0.182125 a

Figure 7. Statistical Analysis for Results Obtained with MERIT and ALOS Datasets for Rill Erosion and Deposition

[a,b] Values with different superscript in a row differ significantly ($p<0.05$).

This study has found that rill erosion and deposition have an influence on high spatial resolution DEMs, due to the good terrain representation especially the concave forms of deposition.

This result shows the increased rill erosivity of channel flow in the downstream, and sediment deposition in concave areas.

STI values influenced on the calculation of ED and reflect the accumulation of the sediment because it demonstrates the sediment flow convergence and divergence.

High DEM spatial resolution has been documented by Mitasova et al. (1996) to be the most reliable elevation data for erosion and deposition modeling.

4. Conclusion

In this study, we tested the DEM spatial resolution impact on hillslope sheet and rill erosion and deposition modeling of Lebanese watersheds, the model framework included STI applied to the USPED used to estimate soil erosion and deposition.

The model was evaluated for different DEM spatial resolutions ALOS 30-m, and MERIT 90-m and topographic exponents n=m=1.0 for sheet erosion and n=1.3, m=1.6 for rill erosion.

This study demonstrated the importance of the spatial resolution and the topographic exponents to estimate and map soil redistribution with the spatial identification where erosion and deposition occurring at high rates in Lebanese watershed basins influenced by only hydrological and topographic factors. Additional work is needed to improve the current results for these basins by better characterizing the rainfall erosivity and land cover management factors and by considering the effect of changes in topography over time caused by erosion and deposition. Future work also would include applying the model frame work over larger agricultural areas, improving predictions about soil erosion and deposition in agricultural landscapes.

Depending on the scale of the project, we suggest the use of high spatial resolution DEM for modelling erosion and deposition at local scales, hence for global scales the use of low spatial resolution datasets.

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