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Influence of Digital Elevation Model Derived from Radar Remote Sensing on Prediction of Runoff, Soil Erosion and Deposition at Catchment Scale

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ABSTRACT: Distributed soil erosion models integrate spatial variability of catchment characteristics into input parameters and processes to improve its predictive outputs for each storm event. Spatial variability obtained at a grid-cell size from various resolutions and sources of satellite remotely sensed data, influences generation and routing of surface runoff and sediment in a catchment. In the study, a GIS based dynamic LISEM (Limburg Soil Erosion Model) was parameterised at 20, 40, 60, 80 and 100 m grid-cell sizes from an InSAR DEM, a reference Cartometric DEM, a 20 m land use and land cover class map and 1: 250,000 scale National Soil Database along with field observations leading to creation of ten LISEM geospatial databases of 30 parameters each which were tested for a 6-hour storm at three soil moisture levels to investigate the influence of grid-cell size and source of DEMs on surface runoff and sediment movement as well as to identify sediment source areas in a catchment. The results showed that at increasing the grid-cell size from 20 to 100 m of a DEM, the slope gradient flattened by 28% and the drainage length shortened by 79%, which had competing effect on the runoff and sediment flow routing. The prediction of surface runoff and soil loss was improved significantly for the InSAR DEM as compared to the Cartometric DEM suggesting its suitability for distributed modelling. Grid-cell size of 20 m pin-points sediment source areas for effective implementation of conservation measures.

INTRODUCTION

Soil erosion is one of the major threats to sustainable land management. It needs to be modelled spatio-temporally at catchment scale not only to quantify surface runoff and sediment production, but also to identify sediment source areas in a catchment. This will enable an effective conservation strategy of a catchment under partial area treatment plan, for an example, by encouraging stakeholders to adopt the either of best management practices and conservation measures or both in the source areas. Soil erosion models should capture the presence of physical control of terrain, soils, land use and vegetation of a catchment on surface hydrologic and erosion processes within a catchment. In such scenarios, physically-based models are preferred over empirical and conceptual models due to their wider applicability to multiple situations. Integration of such models into GIS provides a useful modelling environment for predicting surface runoff and sediment movement in space and time across a catchment and helps in identifying sediment source areas. However, these models are data intensive, which can be collected through the synergic use of remote sensing and field surveys. Remote sensing has been proved as a cost effective tool for generating high resolution and quality DEMs (Digital Elevation Models) and land use and land cover maps. These key spatial data along with soil map and field observations can further be used for model parameterisation. Since the requisite quality of terrain data for modelling is rarely available in the developing countries, satellite radar interferometry can be explored for generating the quality DEMs in this study.

Spatial variability of catchment characteristics into a model is integrated either by Hydrological Response Unit (HRU) or by grid-cell representation (Engel, 1996). HRU-based polygons use larger computational elements based on hydrologically similar characteristics that

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make the identification of source and sink areas in a catchment difficult (Kite and Pietroniro, 1996) whereas grid-cell representation uses smaller computational elements and is better to identify sediment source areas in a catchment. A grid-cell size determined by the inherent spatial variability of catchment characteristics affects the routing of surface hydrologic and soil erosion processes in a catchment. Grid-cell based spatial data can be obtained from remote sensing for model parameterization, but the original resolution/ measurement scale and grid-cell size of spatial data influence the model outputs. This study was carried out to investigate the influence of different resolutions, spatial variability representations and data sources of terrain on the performance of, GIS-based dynamic modelling of surface runoff and erosion processes for a single storm event in order to identify erosion source areas at catchment scale.

MATERIAL AND METHODS

Study Area

A small rural catchment of about 8 km^2 area located in the Eastern South Downs near east of Brighton (UK) was identified for the study as this catchment had experienced a number of floods in the past with most recent one in October' 2000. The catchment locally known as Saltdean is located in the north of Saltdean village and lies between 536,000 to 540,000 m easting and 102,000 to 108,000 m northing (Figure 1). The catchment is of low rolling chalk hills with silt loam soil and elevation ranging from 30 to 200 m above the mean sea level. The catchment is predominantly used for arable and grassland with a few patches of woodland and farmstead based built-up land. The mean annual rainfall ranges from 750 to 1000 mm with peak in autumn (Boardman, 2003).

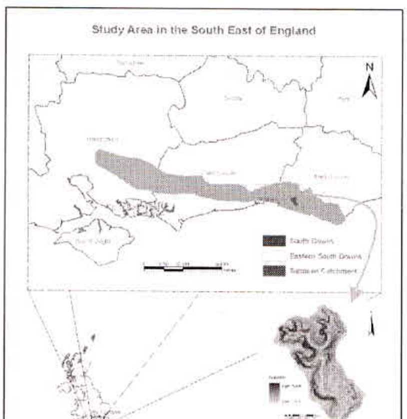


Fig. 1: Location map

Selection of a Model

A LISEM model (Limburg Soil Erosion Model) is a physically based distributed and dynamic model written in PCRaster GIS environment for simulating runoff and erosion precisely from a storm at catchment scale. The model was selected for the study because of its capability of integrating grid based spatial data for model parameterisation. The model version 2.03 was found to be suitable as it was developed for slope ranges of the Saltdean catchment. The theory of the model is described in literature (LISEM, 2004; Jetten, 2002; De Roo *et al.*, 1996a&b; Morgan *et al.*, 1998a; Wesseling *et al.*, 1996; Smith *et al.*, 1995).

Key Spatial Data

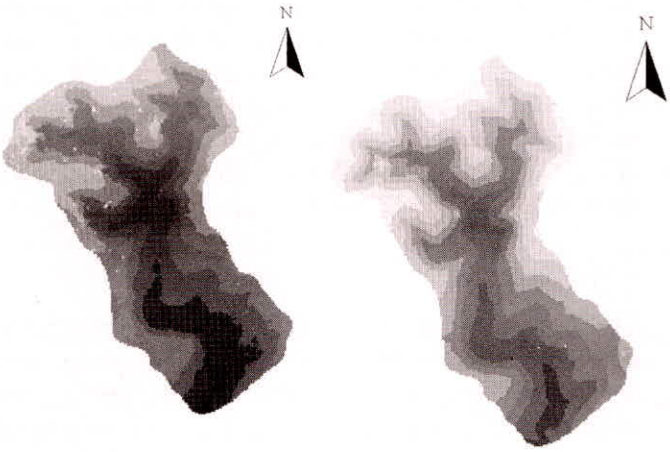
LISEM requires large amount of grid-cell based spatial data of catchment to drive model input parameters, which can be collected cost effectively through the synergic use of remote sensing and conventional methods. Optical and radar remote sensing technology was exploited for generating high quality two key spatial data of different resolutions and other sources resampled at five spatial representations for modelling (Table 1).

A 20 m Cartometric DEM of the study catchment (Figure 2a) was generated from the digitisation and interpolation of contour lines and spot heights collected from the 1:25,000 scale Topo map (Pathfinder) using Geomatica OrthoEngine (PCI Geomatics, 2004). The quality of the derived DEM checked against DGPS control points was found to be within the limit. Secondly, a quality InSAR (interferometric synthetic aperture radar) DEM of the catchment with 20 m grid-cell posting (Figure 2b) was generated from an ERS-1 and ERS-2 SAR raw tandem pair using PulSAR and

Table 1: Source of Key Spatial Data with their Five Spatial Representations

Key Spatial Data	*Data Source*	*Spatial Representations*
Test DEM	25 m InSAR DEM	20, 40, 60, 80 and 100 m
Reference DEM	Cartometric DEM from 1:25,000 scale toposheet	20, 40, 60, 80 and 100 m
Land use and land cover	20 m SPOT-1 XS data	20, 40, 60, 80 and 100 m
Soils	NATMAP Vector 1:250,000 scale	20, 40, 60, 80 and 100 m
Rain Storm	Single point raingauge data from a Meteorological Station	20, 40, 60, 80 and 100 m

InSAR toolkit software on the linux platform (Phoenix Systems, 2001 & 2002; Toutin & Gray, 2000; Gens, 1999). The quality of the derived DEM was good against the Cartometric DEM. The InSAR DEM was projected to the National Grid coordinate system to make compatible with the Cartometric DEM.



(a) (b)

Fig. 2: An InSAR DEM (a) and a reference Cartometric DEM (b) of the study catchment

A land use and land cover map with nine classes of the catchment was generated from the digital classification of SPOT-1 XS data acquired on 26th October 2000 using Bayesian classifier. The confusion matrix showed that the overall classification accuracy of the classified image was 90%. The higher accuracy was achieved in the bare soil class and least accuracy in built-up area class. The area weighted classified image with nine classes was filtered to smooth the thematic image. The smoothed classified image was used to extract the land use and land cover map of the catchment at 20 m grid-cell size and was further resampled using a nearest neighbour method to extract at 40, 60, 80 and 100 m grid-cell size maps to derive land use dependent model parameters. The land use and land cover classes of the catchment consisted of 14.1% bare soil, 18.5% harvested field and 2.7% set-aside; 26.2% hill grassland, 24.5% semi improved and 8.0% improved grassland; 4.9% open and 0.3% dense wood and scrubland; and 0.8% built-up land.

Soil data of the study area from 1:250,000 scale NATMAP National Soil Database (Jarvis *et al.*, 1984) was obtained and rasterised into five grid-cell sizes on the basis of dominant soil series. The soil map of the catchment at each grid-cell size was then extracted. The soil data is of soil association level which contains many soil series with a dominant series. All other soil series occupy very small area and were merged into the dominant soil series in an association. Andover and Marlow dominant soil series were finally used in the soil map of the catchment, which were used to assign the infiltration parameter values to obtain parameter maps at five grid-cell sizes.

Spatial distribution of a storm in the catchment can be computed from rainfall data from multiple raingauge stations using either the Thiessen polygon or geomorphological analysis technique. A single raingauge station data was available for the catchment from the University of Sussex, Brighton which is about 2.5 km from the northwest of catchment top boundary. Since, the distribution of rainfall intensity over the catchment was uniform for frontal storms, the assumption remained valid for simulation. An extreme storm of 30th October 2000 with the maximum intensity of 11.4 mm h^{-1} lasted for 6 hours, was selected. A rain zone map along with breakpoint rainfall intensity data file in a defined format was created to drive the model.

Parameterisation of a PCRaster Based Distributed Model

The slope gradient, local drainage direction, catchment area and outlet of the catchment were derived from both DEMs in PCRaster. The slope gradient used is the sine of the slope in the direction of local drainage and its value lies between zero and one. The Random Roughness (RR) for the storm was estimated for the possible field conditions of each land use and land cover class at nearly same time period according to the guidelines suggested in the LISEM and EUROSEM Manuals (LISEM, 2004; Jetten, 2002; Morgan *et al.*, 1998) and relevant random roughness data obtained from similar catchments at Limburg, Waremme and Ganspoel. The characteristics of the Saltdean catchment are quite similar to that of the Catsop catchment located in the South Limburg for which the model was originally developed, and Ganspoel catchment where the model was applied (Boardman, 2003; Hessel *et al.*, 2003).

The local drainage direction and slope gradient of the main channel were derived from the DEM. The channel width and its cross section shape were measured during the field survey. The soil cover (PER), Crop Height (CH) and Leaf Area Index (LAI), soil aggregate stability (AGSTAB), soil cohesion (COH), additional cohesion by plant roots (COHADD), soil median texture (D50), Manning's roughness (n) for overland and channel flow, and cohesion of the channel were determined for each land use and land cover class and soil conditions in the catchment (Table 2). The soil surface cover such as

Table 2: Crop, Soil and Erosion Parameters for Various Land Use and Land Cover Classes

Parameter	*Land Use and Land Cover Classes/ID*								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
PER	0	0.15	0.5	0.95	0.95	0.95	0.95	0.95	0
CH	0.03	0.15	0.05	0.1	0.1	0.1	5	5	0
LAI	0	0.39	0.45	1.86	1.86	1.86	1.86	1.86	0
RR	0.97	0.97	0.97	0.7	0.7	0.7	1.36	1.36	0.5
N	0.12	0.14	0.14	0.227	0.227	0.227	0.3	0.3	0.01
AGSTAB	–1	10	10	–1	–1	–1	–1	–1	200
COH	3	3	3	3	3	3	3	3	9999
COHADD	0.1	0.6	0.6	3.32	3.32	3.32	2.8	2.8	9999
D50	30	30	30	30	30	30	30	30	30
RWID	0	0	0	0	0	0	0	0	0
GWID	0	0	0	0	0	0	0	0	0
CRUST	0	0	0	0	0	0	0	0	0
COMP	0	0	0	0	0	0	0	0	0
STONE	0	0	0	0	0	0	0	0	0

(*Note:* ID as 1: Bare field, 2: Harvested field, 3: Set-aside, 4: Hill grassland, 5: Semi-improved grassland, 6: Improved grassland, 7: Open woodland and scrub, 8: Dense woodland and scrub, and 9: Built-up land)

crust cover (CRUST), grass strips (GWID), stone cover (STONE) and road cover (RWID) were not possible to estimate from the land use and land cover map and moreover, none of them existed in the catchment. Hence, all cover parameters were set to zero and the maps of zero parameter values were created for running the model.

The parameters of a single layer Green and Ampt infiltration model such as hydraulic conductivity (Ksat), average suction head at wetting front (ψ), effective porosity (θs), antecedent moisture content (θi) and soil depth (dep) were estimated from soil property dataset of the NATMAP Soil data using Pedotransfer Function (PTF). The three Antecedent Soil Moisture Conditions (AMC) were considered as low, medium and high with 0.07 and 0.08; 0.22 and 0.24; and 0.44 and 0.46 for the Marlow and the Andover series, respectively. Therefore, the parameter values were calibrated in the model on the basis of runoff and soil loss in the catchment and were finally set to 2.41 mm h^{-1} and 4.27 cm and 2.42 mm h^{-1} and 3.92 cm for the Andover series and Marlow series, respectively, except for the built-up land where the parameter value was set to zero. These assumptions simplified both the spatial and temporal variations. Nevertheless, this approach was considered to be acceptable for a high intensity storm event.

The three key spatial data were first resampled into five grid-cell sizes using an appropriate sampling scheme and were then converted into the ArcInfo Grid ASCII format in ArcGIS for importing into PCRaster. In addition to these spatial data in the PCRaster, crop and vegetation, soil surface and erosion parameter values for each land use and land cover class, and infiltration parameters for the dominant soil series were required to create by reclassifying the land use and land cover map, and soil map of the catchment. After having imported the key spatial data at five grid-cell sizes into PCRaster, a LISEM database of 30 input parameters was created from the key spatial data and parameter values (Table 2) by reclassification. A total of ten LISEM databases of 30 parameters each in map format were created, which include 300 maps for model testing at three antecedent moisture conditions.

RESULTS AND DISCUSSION

Effect of Grid-cell Size of Slope and Drainage Length

The mean slope gradient from the InSAR DEM was 17% and was higher by 2.3% than that from the Cartometric DEM. The higher slope gradient from the InSAR DEM was due to minimal smoothing applied during its generation whereas the lower slope gradient from the Cartometric DEM was due to different level of smoothing and generalisation applied during their cartographic production process. As the grid-cell size was increased, the mean slope gradient from the InSAR DEM flattened by 28% (Figure 3a). Vieux (2000) reported the same trend of slope flattening with increasing grid-cell size. It was caused by cutting of hills and filling of valleys at lower grid-cell sizes by resampling. Similarly, same slope flattening trend was also observed for the Cartometric DEM.

Total length of drainage is the sum of overland and channel flows. The total length of drainage from the InSAR DEM dataset was 480 km approximately at 20 m grid-cell size. It decreased by 78.9% as the grid-cell size was increased from 20 to 100 m (Figure 3b). The coarser grid-cell sizes short circuited the drainage streams by cutting of hills and filling of valleys, thereby causing an overall shortening of the drainage network.

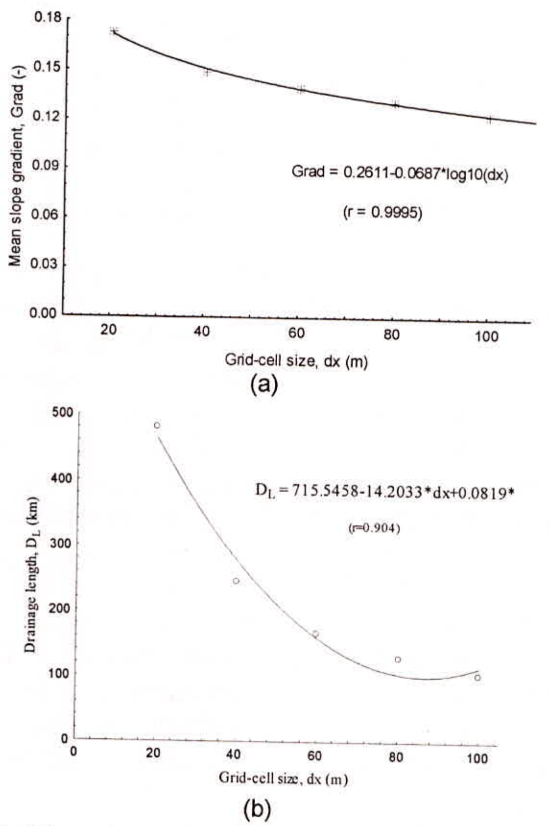


Fig. 3: Effect of grid-cell size of InSAR DEM on (a) slope gradient and (b) drainage length

Effect of Grid-cell Size and Source of DEM on Runoff and Soil Erosion

The Hortonian surface runoff decreased with a decrease in antecedent soil moisture for both DEMs at 20 m grid-cell size and with an increase in grid-cell size (Figure 4). The runoff coefficient was higher for the InSAR DEM dataset with 9.33, 2.97 and 0.24% variability at high, medium and low moistures as the grid-cell size was increased. Similarly, the runoff coefficient was lower for the Cartometric DEM dataset with 7.19, 2.51 and 0.13% variability at high, medium and low moisture conditions. A large variation in runoff coefficient was observed at smaller grid-cell sizes at high AMC and got narrowed down at larger grid-cell sizes. Similarly, the runoff coefficient has lower variations at medium and low moistures, which further narrowed down in both cases. The higher runoff with higher variability was observed for the InSAR DEM dataset at all moisture conditions as compared to the Cartometric DEM. It was due to higher slope gradients and hence, more runoff.

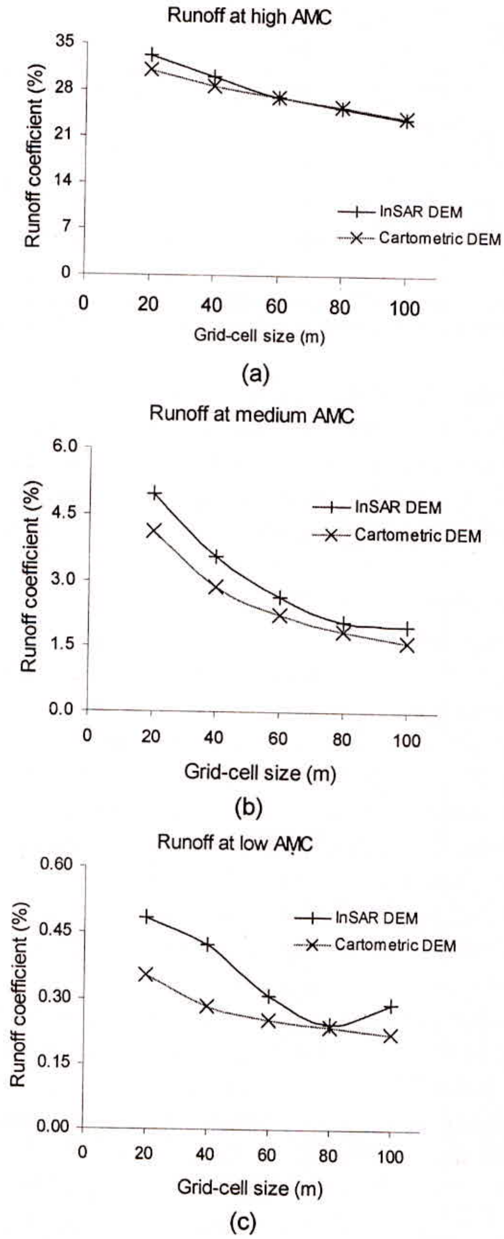


Fig. 4: Effect of grid-cell size on surface runoff at three AMCs

The average soil loss from the catchment decreased as the grid-cell size was increased for the both DEMs at three moisture conditions (Figure 5). The InSAR DEM dataset produced higher average soil loss at smaller grid-cell sizes at all moisture conditions as compared to the Cartometric DEM. The results showed that the total and average soil loss decreased at coarser grid-cell sizes and lower soil moisture levels. The total and average soil loss for the InSAR DEM was higher at 20 m grid-cell size and was almost same at 60 m (except at high AMC) and 100 m grid-cell sizes as compared to the Cartometric DEM at all moisture conditions.

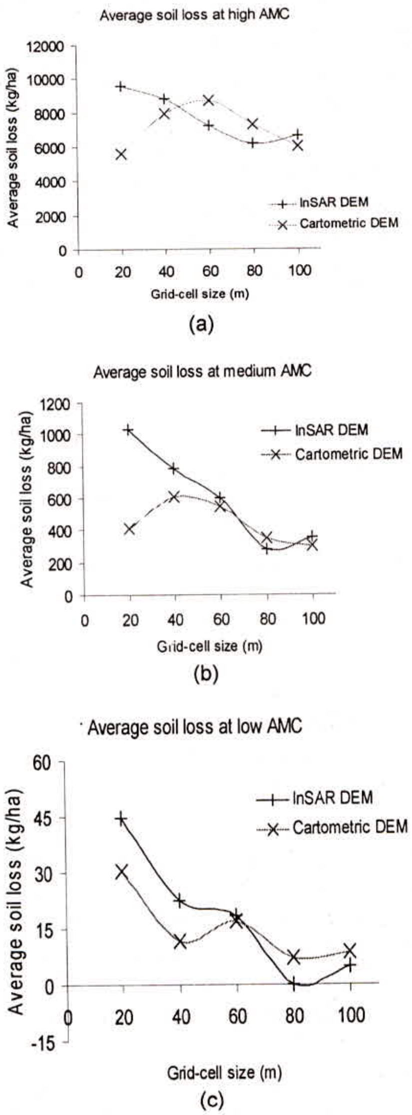


Fig. 5: Effect of grid-cell size on average soil loss at three AMCs

In the developing countries, observed data on runoff and soil loss from a catchment are seldom available. In such cases, a relative evaluation across DEM sources was carried out. At high AMC, the prediction of runoff and soil loss improved considerably at 20 and 40 m grid-cell sizes and remained more or less unaffected at other grid-cell sizes for the InSAR DEM as compared to the Cartometric DEM. At medium and low AMCs, the runoff and soil loss predicted more or less same as compared to the Cartometric DEM. The InSAR DEM improved predictions due to better slope gradients mapped by remote sensing as compared to the Cartometric DEM. This suggests that the InSAR DEM is suitable for distributed erosion modelling and should be used at the original resolution as far as possible.

Effect on Grid-cell Size on Spatial Distribution of Soil Erosion and Deposition

The distribution of soil erosion within the catchment at 20 m grid-cell size of the InSAR DEM was more spatially detailed to identify the erosion source areas. The areas with erosion rate of 10 Mg ha^{-1} was identified as the erosion source areas in the catchment for treatment (Figure 6). The lesser details were

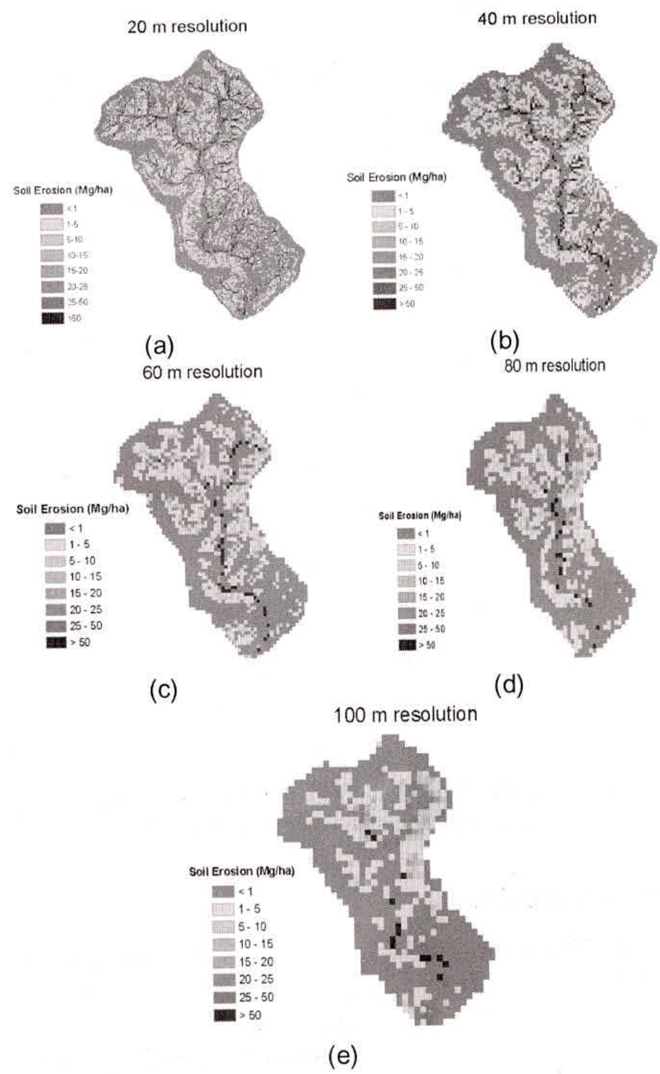


Fig. 6: Effect of grid-cell size on the spatial distribution of soil erosion in the catchment

extracted from spatial maps at larger grid-cell sizes such as 60, 80 and 100 m, which made locating source areas rather difficult. Similarly, the soil deposition maps were more spatially detailed at smaller grid-cell sizes (Figure 7) and can be used to prevent soil deposition on high value lands such as village properties, farmstead and, approach road, etc. in the catchment.

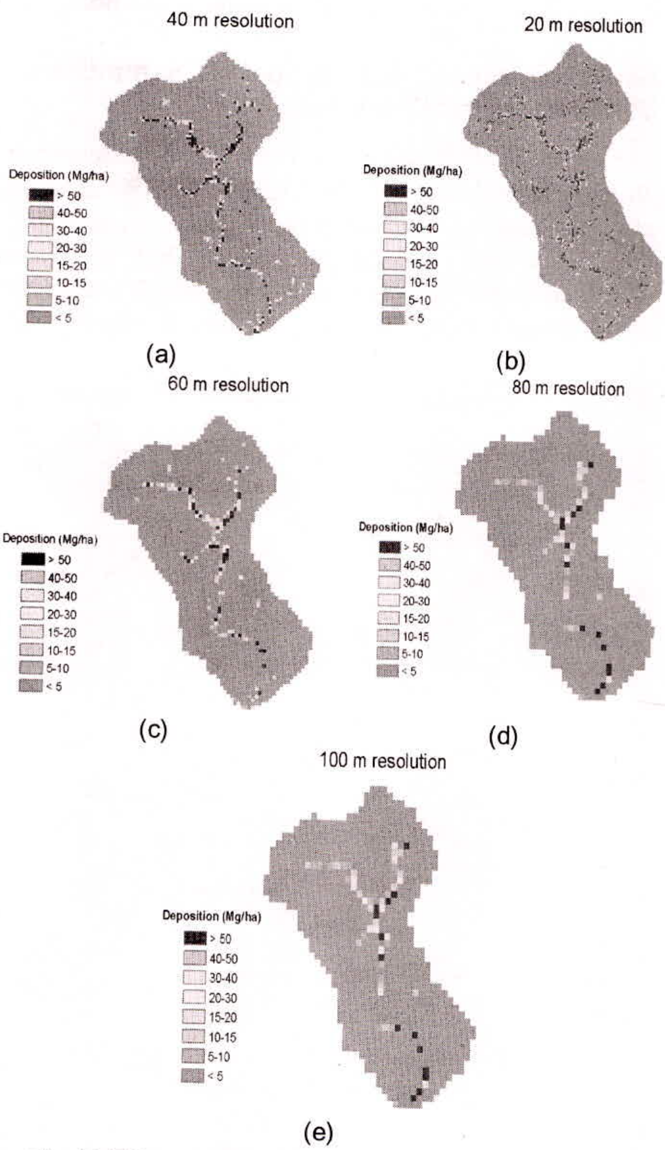


Fig. 7: Effect of grid-cell size on the distribution of sediment deposition in the catchment

CONCLUSIONS

The PCRaster based LISEM model is a useful tool for predicting the effects of grid-cell size and source of DEMs on surface runoff and erosion dynamics for a storm. As the grid-cell size increases from 20 to 100 m for a DEM, the slope gradient flattens, and the drainage length shortens and both have a competing effect on runoff and sediment routing in a catchment. The runoff coefficient decreases with an increase in grid-cell size and with a decrease in soil moisture. High variability in runoff occurs at 20 m grid-cell size of both DEMs and gets narrowed down at coarser grid-cell sizes as well. The average soil loss decreases at coarser grid-cell sizes and at lower soil moisture levels. A high grid-cell size DEM can be used for modelling at the original grid-cell size as far as possible. The InSAR DEM dataset is found to be most suitable for improving the prediction of both runoff and soil erosion as compared to the Cartometric DEM. This highlights the role of remotely sensed derived DEMs for improving model predictions. This demonstrates the potential of this approach in the developing countries. Smaller grid-cell size datasets are the most suitable for identifying the exact location of sediment source areas thereby facilitating the adoption of effective conservation measures in a catchment.

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