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Remote Sensing and Geographic Information System in Water Erosion Assessment

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ABSTRACT

The aim of this review paper is to provide a comprehensive overview of geographical information system and remote sensing–based water erosion assessment. With multispectral and multi-temporal low cost data at various resolutions, remote sensing plays an important role for mapping the distribution and severity of water erosion and for modeling the risk and/or potential of soil loss. The ability of geographic information system to integrate spatial data of different types and sources makes its role unavoidable in water erosion assessment. The role of satellite data in identification of eroded lands and in providing inputs for erosion modeling has been discussed. The role of GIS in mapping eroded lands based on experts' opinion, in generating spatial data inputs from sources other than remote sensing and in integrating the inputs to model the potential soil loss has been discussed.

Key words: AHP, CORINE, Erosion risk, Multi criteria decision analysis, RUSLE.

Controlling water erosion, the most wide spread process of land degradation in the world (Lal, 2001; Oldeman *et al*., 1990), would be a crucial challenge for achieving land degradation neutrality – a sustainable development goal. It accounts for 55% (1094 M ha) of total degraded lands in the world (1965 M ha) causing up to a 17% reduction in crop productivity (Oldeman *et al*., 1990). In India, the recent estimate by Maji *et al*. (2010) shows proportion of water erosion to 68.4% of the total degraded lands (120.72 M ha) of the country. Sharda *et al*. (2010) have documented a productivity loss of 13.4 m tons of food grain due to water erosion only in rainfed areas of the country.

Formulation of effective mitigation strategies and implementation of conservation measures to control water erosion needs spatial information on water erosion. The spatial information on soil water erosion may be generated in the form of a map showing: distribution and severity of erosion (Singh and Dwivedi, 1983; Oldeman, 1990; Sujatha *et al*., 2000), or potential erosion risk (Chowdary *et al*., 2013; CORINE, 1992), or actual soil loss potential based on distributed process models (Cohen *et al*., 2005; Grimm *et al*., 2003). This necessitates a data source of spatial nature and a tool to quickly integrate these to assess the erosion. The geographic nature of the factors affecting soil erosion makes it possible, to analyze them using geographical information system (GIS). The satellite data, with sub-meter to kilometer spatial resolutions and hourly to monthly temporal resolutions, can be used as a significant information source for mapping and monitoring erosion, as well as for estimating indicators describing topography, surface cover and rainfall. GIS allows integration of spatial data from various sources (Sahu *et al*., 2015; Kumar *et al*., 2018). It also allows interpolation of data collected or estimated from field observations to get a spatially distributed layer (Isaaks and Srivastava, 1989, Kumar, 2013; Kumar and Sinha, 2018). Furthermore, the periodic availability of remote sensing data helps the conservationist to periodically monitor the status of the erosion in the watershed.

In this review we discuss the use of remote sensing (RS) and GIS in mapping of: (i) eroded areas and erosion severity, (ii) erosion risk assessment and (iii) actual soil loss estimation.

Remote Sensing and GIS in mapping of eroded area and severity

RS data and GIS have been effectively used for identification and mapping of eroded lands and their severity. The GLASOD - Global Assessment of Soil Degradation approach (Oldeman *et al*., 1991) and other assessments based on it (Kessler and Stroosnijder, 2006; Maji *et al*., 2010) have used GIS to map the eroded lands and the severity of erosion. Visual interpretation of aerial photographs has been used for identifying and mapping eroded areas (Kamphorst and

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Iyer *et al*., 1972; Frazier *et al*., 1983). The satellite data have been analyzed visually (Dwivedi *et al*., 1997; Abdelrahman *et al*., 2016) and digitally (Bocco and Valenzuela, 1988; Floras and Sgouras, 1999) to identify and map eroded lands. The digital analysis reduces the time, the costs and the degree of subjectivity in mapping the eroded lands. Multi-temporal images allow monitoring of eroded area by assessing the increase or decrease of the spread of eroded lands (Sujatha *et al*., 2000; Curzio and Magluilo, 2010).

Expert opinion

GIS plays an important role in mapping the eroded lands and its severity by expert opinion approach. Local erosion experts assess erosion risk from the current state of erosion in a specific area. An example of an expert-based approach is GLASOD which maps the status of soil degradation within loosely defined physiographic units. The GLASOD project prepared a global map, at a scale of 1:10 million indicating type, extent, degree, rate and main causes of degradation (Bridges and Oldeman, 1999). Out of a total of 1965 M ha land of the world 1094 M ha was found to be degraded with water erosion thus affecting the majority of the land. Although the original GLASOD map was compiled "manually" and only digitized afterwards, its sequel, the Assessment of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD) maps was generated by a computerized database, linked to a GIS (Oldemanand Lynden, 1996). The linking of the data into GIS enables flexible output generations according to need of the users.

Indian Council of Agricultural Research (ICAR)-National Bureau of Soil Survey and Land Use Planning (NBSS and LUP) used GLASOD approach to identify degraded lands and the processes of degradation in India based on soil resource map of 1:250K in GIS (NBSSandLUP, 2004). Another example of an expert approach is the soil erosion risk map of Western Europe (De Ploey, 1989). Kessler and Stroosnijder (2006) utilized historical data and farmers' knowledge to identify eroded lands and severity of erosion in the Bolivian mountain valleys based on indicators of soil, productivity and vegetation cover loss. However, the approaches based on experts and users' opinion are subjective and qualitative (Thomas, 1993; Bai *et al*., 2008) and have proven inconsistent and hardly reproducible (Sonneveld and Dent, 2009).

Visual interpretation

This approach involves identification and delineation of eroded lands on satellite data (panchromatic or multispectral) or on aerial photographs manifested by their conspicuous colour, size, shape, tone, texture, pattern, association etc. On a standard false colour composite (FCC) of medium resolution sensors such as Landsat Multispectral Scanner (MSS) or The Thematic Mapper (TM), areas affected by sheet erosion are identified as contiguous patches of irregular shapes with smooth texture and colour slightly brighter than surrounding land on sloping lands with poor vegetation (Krishna *et al*., 2009; Rajankar *et al*., 2012). Moderately eroded lands are gently undulating and are characterized by the presence of rills and relatively sparse vegetation cover that could be detected in the standard FCC print (Sujatha *et al*., 2000). The gullied and ravined lands are identified as discrete to contiguous patches of irregular shapes with slightly coarse texture and colour brighter than surrounding lands or grey in colour depending on soil colour and are invariably associated with nullah (natural drains) and streams (Sujatha *et al*., 2000; Krishna *et al*., 2009).

Aerial photo interpretation and photogrammetric technique have been used mostly in assessment of gullies and ravines (Kamphorst and Iyer *et al*., 1972; Casasnovas 2003). Servenay and Prat, (2003) applied segmentation techniques on the aerial photographs of 1975, 1995 and 2000 in order to obtain the extension of eroded areas. Aerial photos provide high geometric quality, fine spatial resolution, stereo/photogrammetric capability, with records often going back for many decades. However, these can only be visually interpreted and the major limitations of working with aerial photos are that they are generally collected for smaller regions of interest, are not frequently acquired and have no multi spectral information.

Different multispectral satellite data in the optical region of the electromagnetic spectrum have been extensively interpreted visually, supported by other relevant information such as, topographical data, digital elevation model (DEM) etc., for mapping eroded lands and severity classes (Jabbar, 1979; Singh and Dwivedi, 1983; Abdelrahman *et al*., 2016) and ravenous lands (Karale *et al*. 1988; Dwivedi *et al*., 1997; NRSC, 2005; Ajai *et al*., 2009). Singh *et al*., (1998) used multi temporal IRS 1C panchromatic (PAN) data for monitoring gullied and ravines in northern India. The fusion of high resolution PAN data and low resolution multispectral data provide enhanced interpretability of the eroded features. Padmini and Mohapatra (2001), found IRS-1C Linear Imaging Self-scanning System (LISS)-III + PAN merged data to be better than simple FCC in discriminating shallow, moderately deep and deep ravines. Krishna *et al*. (2009), visually interpreted IRS LISS-III + PAN merged data of a mountainous area to identify different severity classes of degradation, from slight erosion to deep gullies. Karale *et al*. (1988) performed a bi-temporal comparison using aerial photos and Landsat TM imagery. Although a clear increase of eroded lands was found, aerial pictures allowed for a better differentiation of ravine types than satellite imagery.

With the availability of high resolution optical satellites, in particular IKONOS, QuickBird, Cartosat, GeoEye 1 and WorldView, as well as higher resolution radar sensors, options for detecting and monitoring individual small scale features have increased, though their potential for erosion mapping has been scarcely explored. Vrieling *et al*., (2007) digitized gullies from QuickBird image for validating gully classification results from Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) scenes. James *et al*., (2007) generated accurate gully maps and showed the ability of topographic data, derived from airborne

laser scanning to identify gullies and their morphologic information.

Classification techniques

An alternative for visual interpretation techniques is the automatic extraction of eroded lands from satellite imagery based on their spectral response. The spectral response of eroded lands has been found to be consistently higher in all spectral bands than that of top bare soils. Both, unsupervised and supervised classification techniques have been applied for identifying eroded lands and severity classes. Servenay and Prat (2003) applied k- means, an unsupervised classification algorithm to various band combinations of multispectral SPOT (Satellite Pour l'Observation de la Terre) High Resolution Visible (HRV) data to distinguish four different degree of erosion. However, unsupervised classifications, based only on statistical distances are less effective in precise inventory of soil cover (Gomer and Vogt, 2000).

Under supervised classification, mostly maximum likelihood classifier (MLC) has been used for identification of eroded lands and severity classes. Bocco and Valenzuela (1988) applied the MLC on multispectral Landsat TM and SPOT HRV images to discern erosion classes and found the higher resolution SPOT data more effective in classifying eroded areas. Dwivedi *et al*. (1997) also found that SPOT Multispectral Linear Ar-ray (MLA) data was better in classifying eroded lands than Landsat MSS/TM data and multi-sensor combinations thereof such as, a combination of MSS band 1, MLA band 2 and TM band -4, or a combination of MSS band 1 and 2 and SPOT MLA band 3. Floras and Sgouras (1999) used the MLC on a composite of principal components of Landsat TM imagery to separate erosion classes. Tahir *et al*. (2010) used MLC on ASTER ortho-images from dry and wet seasons to identify erosion gullies. Better accuracies were observed from dry season image because visible-near infrared (VNIR) and short wave infrared (SWIR) channels are more capable of discriminating erosion gullies in the dry season due to higher spectral reflectance. They also applied the same technique on moderate resolution imaging spectroradiometer (MODIS) data of same date to discriminate gullies from other features. The overall accuracy of MODIS was less than that of ASTER due to insufficient spectral and spatial resolution of the MODIS data. Vrieling *et al*., (2007) employed a MLC on ASTER imagery to classify only two classes, gullies and non gullies. Depending on the feature characteristics, supervised classifications can provide satisfactory results for quantitative analyses on eroded areas. However, the selection of adequate training pixels requires an in depth knowledge of the study area and careful analyses of the separability of spectral signatures, which is the key element for performing successful classifications.

Remote sensing and GIS in erosion risk assessment

The erosion risk assessment allows the planners to prioritize the catchment or part of the catchment based on the state indicators representing the factors affecting soil erosion. The topographic indicators include slope degree and length, curvature, aspect, drainage morphometry and topographic indices such as wetness index (WI), stream power index (SPI) etc. Climatic indicators may be based on the frequency of high intensity precipitation and on the extent of aridity or rainfall seasonality. Soil indicators affecting soil erodibility may include aggregate stability, crusting tendency, texture, depth, organic matter and stoniness. These indicators either individually or in combination, provide a measure to indicate, evaluate and classify areas at risk for erosion. Multiple indicators may be combined into a single scale by multiplications, simple addition or weighted summation approaches.

Kumar *et al*., (2008) generated WI, SPI and Sediment Transport Index (STI) from Cartosat-1 DEM to characterize topographic potential of soil erosion. These indices are based on unit stream power theory (Moore and Wilson, 1992) that takes into account influence of terrain shape and its geometry and suited to assess erosion risk in complex topographic terrain at watershed / catchment scale (Kumar *et al*., 2008, Kumar and Gupta, 2016). A higher WI value corresponds to the area with lower slope and high soil moisture content and *vice versa* (Qin *et al.* 2006; Ma *et al*. 2010). WI has been extensively used to identify zones of saturation and zones of runoff generation (Beven and Kirkby 1979; Kumar *et al*., 2008). Kumar and Gupta, (2016) observed good correlation between soil erodibility factors computed using equation of Wischmeier and Smith (1978) and WI followed by slope. They developed a multiple linear regression model to derive soil erodibility using these two parameters. The area with high SPI indicates the area of high susceptibility to the erosive power of runoff and soil erosion (De Roo, 1993). The higher STI denotes the area with more sediment transport than those with lower STI values. Thus, severity of soil erosion can be predicted with STI (Desmetand Govers, 1995; Mitasova *et al*., 1996). Kumar *et al*., (2008) categorized a watershed into zones under very low to very high erosion risk based on STI.

Approaches using multiple criteria for assessing erosion risk include experts' decision rules, the Co-ordination of Information on the Environment (CORINE) model and Multiple Criteria Decision Analysis (MCDA).

Decision rule based mapping of soil erosion risk

Wang *et al*., (2013) developed standard decision rules for classification and gradation of soil erosion risk using three factors: vegetation cover factor derived from Normalized Difference Vegetation Index (NDVI) values, slope gradient and land use. The assessed erosion risk was compared with erosion risk of field samples with overall accuracy of 93%. Wawer and Nowocien (2007) developed digital map of water erosion risk in Poland based on decision rules including spatial layers representing: soil type (texture), slope, average annual rainfall and land use type.

CORINE model for mapping of soil erosion risk

CORINE model is a simplification of Universal soil loss

equation (USLE) (CORINE 1992; Briggs and Giordano 1995) to determine the Soil Erosion Risk (SER). In CORINE model, the actual SER is calculated by overlaying vegetation cover layer on potential SER layer, which is calculated as a function of soil erodibility, erosivity and topography. The indicators used for soil erodibility include soil texture, soil depth and soil stoniness (CORINE 1992). Fournier index and Bagnouls-Gaussen Aridity Index are used as indicators for rainfall erosivity. Slope gradient is included, but without a slope length correction and vegetation and crop management are collapsed into two categories of protected and not fully protected (Yuksel *et al*., 2008; Tayebi *et al*., 2017). These factors are combined to estimate three categories of potential and actual soil erosion risk based on a multiplicative approach. The CORINE model has a great advantage of simple structure and it is also easy to apply with GIS. The CORINE model correctly identified the areas of the Mediterranean, which have the highest risk of erosion (Gobin *et al*. 2003). The CORINE model is mostly used by the European and Mediterranean countries (Dengiz and Akgul, 2005; Aydın and Tecimen 2010; Barakat *et al*., 2015; Reis *et al*., 2016) for SER assessment.

The identification of factors and the factor weights is the main steps for the SER assessment of a region. Besides, the combined effects of factors and interrelationship of the factors should also be considered while assessing SER. The indicators and their weights in CORINE model are fixed and are derived for Mediterranean and European region. This makes its use limited to other regions of the world. However, it has also been used in other parts of the world (Sepehr and Honarmandnejad, 2012; Zhu, 2012; Gupta and Uniyal, 2012; Ekpenyong, 2013; Tayebi *et al*., 2017). However, experts may feel to have different indicators depending on the regional conditions of the area and availability of data. Also, the CORINE model does not consider the combined effect of factors and interrelationship of the factors.

Multi-criteria decision analysis for mapping of soil erosion risk

Other method for integrating multiple erosion factors into a single scale is MCDA approach, of which, the Analytical Hierarchic Process (AHP) (Saaty, 1980) is the most used method in SER assessment (Rahman *et al*., 2009; Nasiri, 2013; Chakraborty *et al*., 2016). The MCDA method allows choosing indicators and their weights based on the regional conditions and their severity (Kumar *et al*., 2014, 2018). The AHP, introduced by Saaty (1980), has emerged as a popular decision making technique for solving multi-criteria problems which is based on the additive weighting model (Basnet *et al*., 2001; Kumar, *et al*., 2017, 2018). The AHP generates weights according to the experts' pair-wise comparisons. In addition, the AHP checks the bias in the decision making process. It also normalizes the bias of any factor in the evaluation process by considering combined effect of factors on erosion (Kumar *et al*., 2017; 2018; 2019). Rahman *et al*. (2009), assessed the SER of north-western part of Hubei province of China by applying AHP on selected nine factors including soil erodibility, slope, soil depth, rainfall, elevation, vegetation, fallow land, population density and presence of existing soil erosion. Kachoury *et al*., (2015) identified six indicators namely, slope gradient, annual precipitation, lithofacies, NDVI, drainage density and land use for SER assessment in central Tunisia using AHP. Nekhay *et al*., (2009) identified proximity to rivers and streams as an important factor for SER assessment along with vegetation cover, rainfall-runoff potential, slope length and steepness and soil erodibility and used an improved generalisation of AHP called Analytic Network Process (ANP). Alexakis *et al*., (2013) generated erosion risk map of a catchment by applying AHP on factors including proximity to streams along with the other six factors of RUSLE model. The results were compared with the erosion risk map generated by classifying the erosional loss estimates using revised universal soil loss equation (RUSLE) method. They observed that, 80% of the study area belongs to the same erosion risk severity class in both methodologies and concluded that the two methodologies can be implemented complimentary to each other.

Remote sensing and GIS in soil loss estimation

For assessment of actual soil loss, generally two types of models are used, i.e. empirical models and physically based models (Morgan and Quinton, 2001). Physically based models such as, Aerial Non Point Source Watershed Environment Response Simulation (ANSWERS) (Beasley *et al*., 1989), Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1995), the Water Erosion Prediction Project (WEPP) (Nearing *et al*., 1989) and more recently the European Distributed Basin Flow and Transport Modelling System (SHETRAN) (Bathurst *et al*., 1995) and the Soil and Water Assessment Tool (SWAT) (Arnold and Fohrer, 2005) etc. use mathematical relations to describe processes, consequently being more uniformly applicable. Their applicability is, however, limited by their large data request, resulting in mostly small-scale, relatively complex, time consuming and sometimes user-unfriendly models (Drake and Vafeidis, 2004; Mulligan, 2004; Gobin *et al*., 2006). Empirical models are based on statistically significant relationships between desired model output and input. The most well-known and widely applied empirical model to predict soil losses by water erosion is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its derivate (RUSLE) (McCool *et al*., 1995; Renard *et al*., 1997). It predicts soil loss through sheet and rill erosion, disregarding other types of erosion (Blackley *et al*., 2015). This empirical equation adapts a multiplicative approach to integrate the factors including rainfall erosivity, soil erodibility, slope length, slope steepness, vegetative cover and protection measures.

Availability of spatial databases, satellite imagery and digital elevation models (DEMs) allow these models to predict erosion potential on a cell by cell basis in a raster based GIS.

CONCLUSION

This review shows that the remote sensing satellite data can be used effectively in water erosion assessment in many ways. The review also discusses the use of GIS in remote sensing of water erosion. Satellite data can be interpreted visually or digitally to identify and map the distribution and severity of erosion and can be used as inputs to derive the factors affecting soil erosion to model the erosion risk and/ or potential soil loss. Satellite data in optical regions of electromagnetic spectrum are mostly used for identification and mapping of water eroded areas. Many satellite data in optical region are available with spatial resolution from sub-meter to 1 km and spectral resolution from panchromatic to hyper-spectral.

The digital elevation models are the most useful satellite products for erosion models, providing the topographic and hydrologic data. Limited uses of remote sensing data have been found in generating factors of rainfall erosivity, soil erodibility and conservation practices. To map the conservation practices, high resolution satellite datasets should be utilized. The factors for calculating the soil erodibility may also be generated from hyper-spectral images. The limitations related to rainfall erosivity and soil erodibility may be overcome by use of GIS. GIS helps to generate raster datasets from soil maps and point data. GIS also offers the advantage of integrating data of diverse nature in terms of scale, resolution, time, source and structure.

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