Continental Scale Sheet and Rill Erosion Modelling: Incorporating Monthly Soil Loss Distribution

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Abstract: This paper describes a spatial modelling framework for estimating sheet and rill erosion for the Australian continent. It is based on the Revised Universal Soil Loss Equation (RUSLE) using time series of remote sensing imagery and daily rainfall combining with updated spatial data for soil, land use and topography. The results are presented as a geo-referenced annual averaged soil loss map and its monthly distributions. It is found that the north part of the country has higher erosion potential than the south of the country. The prediction confirms that agricultural land use has higher erosion rate compared with most natural vegetated lands and that erosion potential differs significantly between summer and winter periods.

Keywords: Soil erosion; Rainfall erosivity; Vegetation cover; Soil erodibility; Universal Soil Loss Equation

1. INTRODUCTION

Soil erosion caused by rainfall and runoff is recognised as a major environmental problem in Australia. Suspended sediment concentrations in streams and lakes affect water use and ecosystem health. High concentrations of sediment reduce stream clarity, inhibit respiration and feeding of stream biota, diminish light needed for plant photosynthesis, and require treatment for human water use. To minimise the decline of soil productivity and water quality and to optimise the use of resources for soil conservation, spatially distributed patterns of the hazard sources and associated soil loss rate are essential to identify crucial areas appropriate for more detailed investigation. Furthermore, the basic prerequisite for understanding the consequences of changes in land use and climate on soil erosion is to know the sources and rates of erosion rate under the present land use and climate conditions.

The water-borne erosion and sediment transport project (Project 4a of Theme 5 of the National Land and Water Resources Audit) provides predictions of hillslope erosion as one of the major sources of sediment in river systems. The predictions are based on a simplified version of the Revised Universal Soil Loss Equation (RUSLE) [Renard et al., 1997] calibrated using New South Wales field data. A similar approach has been applied to the Australian continent before [Rosewell, 1997], as part of the 1996 National State of the Environment Report. This assessment provides a significant update on that assessment by inclusion of improved or new national datasets on rainfall, soils, vegetation cover, land use, and topography which were not available in 1996. Furthermore, we have been able to incorporate monthly distribution of rainfall and cover factors, which Rosewell [1997] suggested was needed for more accurate distinction of the continental pattern of soil erosion.

2. METHODOLOGY

The RUSLE calculates mean annual soil loss (Y, t ha^{-1} yr^{-1}) as a product of six factors: rainfall erosivity factor (R), soil erodibility factor (K), hillslope length factor (L), hillslope gradient factor (S), ground cover factor (C) and supporting practice factor (P):

$$Y = R\,K\,L\,S\,C\,P \qquad (1)$$

The factors included in the RUSLE vary strongly across the Australia. Using available spatial information for each factor provides a means for estimating the spatial patterns of continental scale sheet and rill erosion. Due to lack of spatial data of contour cultivation and bank systems, an assessment of the supporting practice factor (P) is excluded, and P is set to 1 everywhere.

Mean annual values for rainfall erosivity and the cover factor are often used in direct application of Equation (1) to calculate mean annual hillslope erosion. This often neglects important seasonal patterns of rainfall erosivity and cover. Problematic to the standard annual application of the RUSLE is the pronounced wet-dry precipitation regime in the Australian tropics and Mediterranean climate areas such as south Western Australia. To adequately represent the erosive potential of rainfall at different times of the year this study applies the RUSLE model on a monthly averaged basis by calculating appropriate erosivity and cover factors for each month. It can be shown that incorporation of seasonal effects reduces predicted mean annual soil loss in the tropics by a factor of 1.5. The modifications of Equation (1) discussed above yield monthly soil loss rate which can be calculated as:

$$Y_j = R_j \, K \, L \, S \, C_j \qquad (2)$$

where $C_j = \sum_{j=1}^{12} \left(SLR_j \frac{R_j}{R} \right)$, R_j and SLR_j are cover management factor, rainfall erosivity and the soil loss ratio, respectively, for month j.

Sections 2.1 – 2.3 briefly describe the calculation procedures for R. C and K factors in Equation (2). The calculation procedures for L and S factors can be found in Gallant [2001].

2.1. Rainfall Erosivity (*R*)

Rainfall erosivity (R) is defined as the mean annual sum of individual storm erosion index values, EI_{30}, where E is the total storm kinetic energy and I_{30} is the maximum rainfall intensity in 30 minutes. To compute storm EI_{30}, continuous rainfall intensity data are needed. Wischmeier and Smith [1978] recommended that at least 20 years of pluviograph data be used to accommodate natural climatic variations. However, the spatial and temporal coverage of pluviograph data is often very limited.

Yu [1998] proposed a rainfall erosivity model in which storm EI_{30} for the month j is related to daily rainfall amount, R_d, in the form:

$$EI_{30}(j)=\alpha[1+\eta\cos(2\pi f\, j-\omega)] \sum_{d=1}^{N} R_d^{\beta} \qquad R_d > R_0 \qquad (3)$$

where R_d is the daily rainfall amount, R_0 is the threshold rainfall amount to generate runoff [set to 12.7 mm; Wischmeier and Smith, 1978], and N is the number of days with rainfall amount in excess of R_0 in the month. The first part of the equation is a sinusoidal function with a period of twelve months (f = 1/12). It is used to describe the seasonal variation of rainfall erosivity for a given amount of daily rainfall. The parameter ω is set at $\pi/6$, implying that, for a given amount of daily rainfall, rainfall intensity is highest in January, when the temperature is the highest for most part of the continent. Regional relationships were derived using 79 stations located in NSW, SA, and the tropics for parameters α, β, η:

$$\alpha = 0.395\ [1 + 0.098 \exp(3.26\ \Psi/M)]$$
$$\beta = 1.49$$
$$\eta = 0.29$$

where M is the mean annual rainfall and Ψ is the mean summer rainfall (November to April).

The model was applied to the Australian continent using 0.05° resolution daily rainfall data interpolated by Queensland Department of Natural Resources [Jeffrey et al., 2001]. In this study, 20 years of gridded daily rainfall from 1st of January, 1980 to 31st of December, 1999 are used. The ratio Ψ/M was calculated using the same daily rainfall data. The resulting rainfall erosivities calculated are the mean annual R factor (averaged annual EI_{30}), and mean monthly R factors for the 20 year period.

The estimated spatial pattern of the R factor and the monthly distributions for selected locations across the continent are shown in Figure 1. For the northern part of the continent, the monthly distributions of R factor estimated using Equation (3) generally show peaks in summer period, from December to February. Approximately 80% of the annual rainfall erosivity occur between December and March. A negligible fraction occurs in the months from April to October in northern Australia. This is consistent with the common rainfall pattern in the Australia's tropics of intense storms during summer and little rainfall during winter. For the south-eastern part of the continent, predicted monthly R factor distributions change gradually from summer dominance to uniform when moving from north to south, which is comparable with continent rainfall intensity distribution. Winter dominant monthly R factor distributions are obtained for the coast area of southwestern part of Western Australia. The pattern then changes to a summer dominance inland within one hundred kilometres from the coast. This is also comparable with the distributions of the R factor estimated using pluviograph data for the region [Lu et al., 2001a].

2.2. Cover and Management Factor (*C*)

The cover and crop management factor (C) measures the combined effect of all the interrelated cover and crop management variables. It is defined as the ratio of soil loss from land

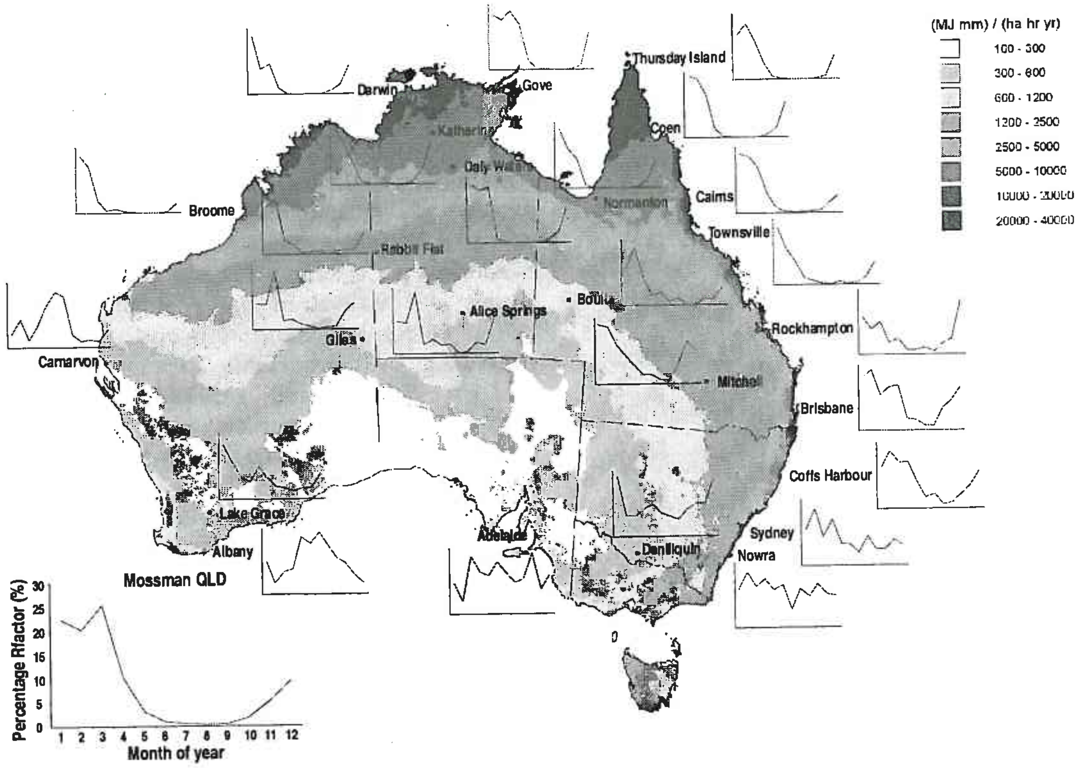

Figure 1. Rainfall erosivity (R factor) and its monthly distributions for selected locations.

maintained under specified conditions to the corresponding loss from continuous tilled bare fallow. It is an estimate of the combined effects of prior land use, crop canopy cover, surface cover, surface roughness, and organic material below the soil surface. Although tree canopy cover can be estimated on an annual averaged basis, there are strong seasonal patterns to ground cover in the Australian continent reflecting seasonal patterns in rainfall. Mean monthly values of C were calculated to reflect seasonal variations in cover, based on time series analysis of remote sensed imagery from AVHRR [Lovell and Graetz, 2000].

For each grid cell, the calculation of C factor involves the following distinct steps:

1. Separating the NDVI signals into three components, perennial NDVI, seasonal NDVI and random NDVI using time series decomposition;

2. Estimating vegetation covers by regression equations between long-term annual averaged perennial NDVI and woody cover, and between monthly averaged seasonal NDVI and ground cover using site measurements;

3. Calculating monthly soil loss ratio (*SLR*) using a simplified version of SOILOSS [Rosewell, 1993]; and

4. Calculating annual C factor values by weighting SLR with the fraction of rainfall erosivity (R) associated with the corresponding month.

Annual averaged woody canopy cover and monthly averaged ground vegetation cover were estimated from NDVI by separating the NDVI signals into two components: perennially green vegetation that is linked to the slowly varying base of the NDVI time series, and seasonally green vegetation that is linked to the seasonal cycle in the NDVI data. Our analysis was carried out by applying a time series decomposition scheme in the form

$$NDVI_i = T_i + S_i + R_i \qquad (4)$$

where i = 1 to N, with N is the total number of images in the time series, T_i is the trend component, S_i is the seasonal component, and R_i is the irregular component. Frequency components of variation are obtained through a sequence of locally weighted regression smoothing LOESS [LOcal rEgreSSion; Cleveland et al., 1990].

The component NDVI values for perennial (woody) cover and seasonal (ground) cover were converted to cover fractions using empirical relationships based on Lu et al. [2001b] and McVicar et al. [1996].

For woody cover

$$F_c = -22.5 + 150 * NDVI \quad (5)$$

For ground cover:

$$LAI = a + b\left(\frac{1 + NDVI}{1 - NDVI}\right) \quad (6)$$

$$F_c = 100 * (1.0 - e^{(-LAI/2)}) \quad (7)$$

with *a* and *b* parameters for different cover types obtained from McVicar et al., [1996].

To calculate the soil loss ratio factor, land use data is required in addition to percentage vegetation cover. The recently produced National Land and Water Resources Audit (NLWRA) land use mapping of Australia (with spatial resolution of 1 km^2) was used to assign land use to one of 19 groups aggregated from the original data.

The land use and mean percentage cover for each month were used to calculate monthly *SLR* and *C* factor following the procedure described in SOILOSS [Rosewell, 1993]. Small *SLR* values (0.00001 and 0.0001, respectively) were assumed for built-up areas and waterbodies irrespective of cover. The calculations of *SLR* for forests, woodland and native pasture land follow the tables D4 and D5 in SOILOSS for estimated canopy cover and ground cover from the NDVI data. The monthly *SLR*s for cropping lands and improved pasture were calculated using the land use sub-factor approach of splitting the crop cycle into growth phases. It was assumed that the sowing date for crops is four months prior to the month with maximum greenness and the harvest date occurs two months after the month with maximum greenness. Although our program can be run with different tillage system options, without sensible spatial data, it was assumed that conventional tillage system is used everywhere, which is the worst scenario and gives the highest erosion rate due to tillage. Other parameters, such as maximum canopy height, canopy height after harvest, residue coefficient, rate of decay of surface and incorporated residue, temperature factors for residue decay rates, etc are assigned to the same values as the closest cropping type given in SOILOSS [Rosewell, 1993]. Finally, annual cover and management factor values were calculated by weighting SLRs with the fraction of rainfall erosivity (*R*) associated with the corresponding month.

2.3. Soil Erodibility (K)

Soil erodibility (*K*) is a measure of the susceptibility of the soil to erosion. In the RUSLE, it is a quantitative value determined experimentally. For a particular soil, it is the rate of soil loss per erosion index unit as measured on a unit plot maintained under continuous bare fallow. Direct measurements is costly and time-consuming, so considerable attention has been paid to estimate soil erodibility from soil attributes such as particle size distribution, organic matter content and density of eroded soil [*e.g.* Wischmeier et al., 1971; Loch and Rosewell, 1992]. Even these data, however, are not readily available at regional or continental scales.

In this study, a modified nomograph equation [Wishmeier et al., 1971] was used to estimate *K* factor for Australian soils. The soil erodibility surface has been generated using the equation [Loch and Rosewell, 1992]:

$$K = 2.77\,(100\,P_{125})^{1.14}\,(10^{-7})\,(12 - 2\,O_c) + 3.29\,(10^{-3})\,(Pr - 3) \quad (8)$$

where P_{125} is the percentage of particles with diameter less than 0.125 mm, O_c is organic carbon in percentage, and *Pr* is the soil permeability rating. These soil attributes were obtained using data including polygon-based soil information from various state agencies, the digital Atlas of Australian Soils [Northcote et al., 1960-1968], and a digital polygon coverage of the Soil-Landforms of the Murray-Darling Basin. An organic carbon surface is obtained by statistical modelling using point observations, climatic data, elevation data and LANDSAT MSS satellite data. Using a look-up table linking unique soil type described as Principle Profile Form (PPF) with interpreted soil attributes [McKenzie et al., 2000], a weighted mean approach was taken to average soil attribute values in each polygon. Based on the area occupied by each PPF, the final soil attribute value for a polygon was calculated by the addition of the area weighted soil attribute value for each PPF. Rosewell's [1993] classes for soil permeability were used to categorise the saturated hydraulic conductivity of the A-horizon derived by the Australia Soil Resource Information System (ASRIS) project of NLWRA. The *K* factor surface is a product of ASRIS project.

It is found, nationally, that heavy clay soils (Vertosols) are highly erodible as they are structurally unstable. Relatively large *K* values are estimated for chemically dispersible sodic soils (Sodosols). Kandosols and Calcarosols with sandy topsoil are slightly less erodible. Rocky soils (Rudosols) and weakly developed soils (Tenosols) are least erodible. Soils with high organic matter content are less erodible than those with low organic matter content. There is an obvious state boundary between SA and Victoria, partly due to land management differences and to original map sources of soil data.

3. RESULTS

Figure 2 shows the monthly distributions of continental hillslope erosion. It is found that over 90% of the erosion occurs in the summer period (from November to April). This summer dominant erosion pattern is more distinct for tropical Australia, which is mainly caused by intense summer monsoon rainfall. It is predicted that the northern part of the country has considerably more erosion than the southern part of the country. This predicted trend is consistent with measurements [Freebairn, 1982; Edwards, 1993].

It was found that about 4.8×10^9 tonnes of soil is moved annually on hillslopes over the continent, which is 3-4 times smaller than previously estimated [Wasson et al., 1996]. Compared with a global estimate of soil movement [75×10^9 t yr^{-1}, Pimentel et al., 1995], it is predicted that Australia contributes 6.4% of global soil erosion from 5% of the world land area. The average soil erosion is 6.3 t ha^{-1} yr^{-1}. If we classify a pixel with soil loss rate below 0.5 t ha^{-1} yr^{-1} as low erosion, larger than 10 t ha^{-1} yr^{-1} as high erosion, and in between as medium, it is estimated that about 23% of the continent experiences low erosion, 16% faces high erosion and 61% of the continent experiences medium hillslope erosion. Overall, 25% of the area is eroded at a rate greater than the continental average rate, showing the potential to target erosion control to problem areas. Under any given rainfall regime, the map shows that the reduction of protective ground cover increases the risk of high soil losses.

Table 1 divides hillslope erosion into land use classes. In general, agricultural lands have higher erosion rates than forests, but not necessarily more than native pasture lands. The predicted average erosion rates for cereals are relatively low because they are often located in floodplains where the slope is low. However, the rates are higher compared with surrounding non-cropping area with similar climatic, soil and topographic conditions. This confirms that land use and management practices have a major impact on soil erosion. However, as our prediction is more or less based on the worst scenario assumption for cropping land, the actual rate for those lands could be rather less than the predicted rate. The maps also identify areas of high soil erosion potential within some of the National Parks in the tropics, but these are the natural conditions in steep lands experiencing high intensity rainfall, and do not represent elevated soil erosion rates.

Total soil loss is dominated by the pastoral industries, including grazed woodlands, because of the vast areas that these land uses occupy. Thus the sediment loads of large regional catchments such as the Burdekin and Fitzroy catchments of Queensland will be dominated by sediment derived from pastoral land. Cropping land of high erosion hazard is more restricted in extent but can cause local problems as indicated by the high soil loss rates, and will be significant in relatively small catchments dominated by intensive land use. The relatively high average erosion rates predicted for national parks is primarily due to most national parks being located on north part of the country, where the rainfall intensity is high, or in the arid inland, where the cover is low.

The acceleration of erosion is the ratio of current hillslope erosion rates to erosion rates under natural cover before European settlement as described in Lu et al. [2001a]. The results show that although the current erosion rates of cropping lands are not high compared with some landuse

Table 1: Soil Loss from land use categories.

Landuse Description	Approx. Total area (km^2)	Total Erosion (t yr^{-1})	Average Erosion Rate (t ha^{-1} yr^{-1}).	Acceleration factor Since European Settlement
Closed Forest	25,116	2,772,706	1.10	1.1
Open Forest	285,796	9,896,968	0.35	1.0
Woodland (unmanaged lands)	2,179,326	1,102,649,750	5.06	1.2
Commercial native forest production	157,460	5,864,068	0.37	1.1
National Parks	183,303	188,824,306	10.30	1.1
Cereals excluding rice	182,936	39,517,812	2.16	10.3
Legumes	22,568	795,556	0.35	3.2
Oilseeds	6,242	2,390,087	3.83	9.5
Rice	1,573	115,250	0.73	5.9
Cotton	4,053	2,784,581	6.87	11.3
Sugar Cane	4,736	18,694,681	39.47	56.8
Other agricultural landuse	2,138	2,402,811	11.24	33.6
Improved Pastures	200,295	46,307,300	2.31	5.1
Residual/Native Pastures	4,257,824	3,388,486,244	7.96	1.9

groups, acceleration of erosion is high when it was put in context of erosion under natural vegetation cover for the same location. It provides essential information for the assessment of landuse impact in terms of possible environmental degradation and pollution of both land and water resources.

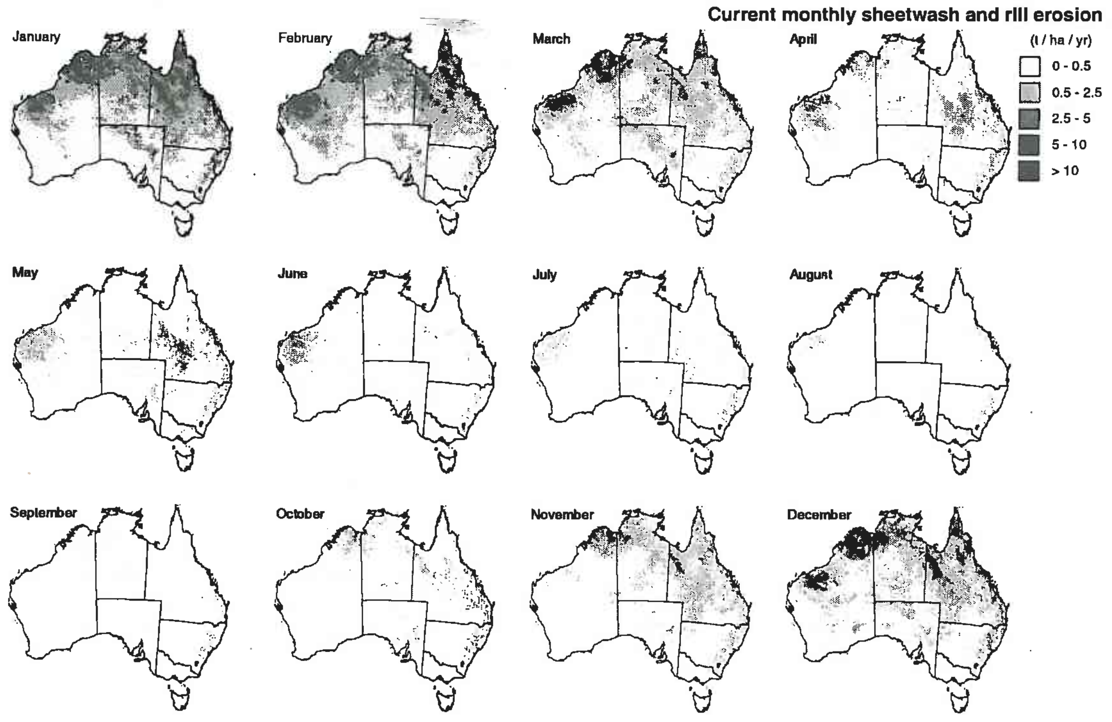

Figure 2. Predicted monthly soil erosion rate patterns for the Australian continent.

The amount of gross erosion needs to be adjusted to account for rock cover. The full erosion potential may not realised for some of the areas predicted as highly erodible (such as upper Queensland and Northern Australia) because of the high percentage of rock cover and shallow soil depth.

4. CONCLUSIONS

Based on recently available topographic, rainfall, soil, landuse and time series analysis of remotely sensed data, a nationwide prediction of hillslope erosion has been developed. This study applied the USLE model on a monthly averaged basis, calculating appropriate erosivity and cover factors for each month, to represent the erosive potential of rainfall and runoff for each temporally distinct period.

The broad predicted hillslope erosion patterns are consistent with a qualitative analysis of plot data gathered from literature [Edwards, 1993]. It is predicted that hillslope erosion increases from south to north, which is mainly determined by continental scale rainfall intensity pattern. Seasonally, the erosion rate is higher in summer for most of the continent, especially for the tropics, which also follows the large scale climatic trend. Erosion rate is high for the area with steep gradients. Regions such as Tasmania and SW Western Australia are predicted to have low soil erosion rates, largely a result of low rainfall intensity at times of low cover. Most of the predicted patterns are supported by the available field data [Edwards, 1993].

Better prediction could be achieved by bringing in more information. For example, prediction for cropping land can be improved by specifying tillage types, crop rotation, contour cultivation and bank management. For pasture lands, the erosion rate can be better predicted by giving grazing pressure for the location. For forests, providing density of roads and logging frequency can improve the prediction. However, more input data do not always guarantee better prediction. Low quality inputs may introduce more errors and make the overall prediction worse off. Therefore, it is important to check the input data quality and its suitability before using them.

5. ACKNOWLEDGEMENTS

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