The development of a terrain-based erosion hazard map for the Williams River catchment in eastern New South Wales

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Abstract An analysis has been carried out of topographical characteristics for 1260 km^2 of the Williams River catchment in NSW, to provide insight into the spatial distribution of land susceptible to accelerated rates of erosion. First, the land surface morphology has been represented by a range of Geographic Information System (GIS) based digital elevation models (DEMs) with regular grid structures of varying resolution. The DEMs have been developed from Land Information Centre (LIC) 1:25000 elevation contour data and stream network information. In this paper we will discuss in particular the preprocessing requirements of LIC data in regard to DEM quality. Next, the terrain analysis package TAPES-G has been used to calculate primary topographic attributes for each individual grid cell and the effect of varying grid cell size on primary attribute estimation has been investigated. Within the GIS framework the dominant terrain factors involved in erosion processes have been represented by an erosion hazard index computed from primary topographic attributes for each grid cell.

1. INTRODUCTION

The Williams River catchment is the major water supply region for over 400 000 domestic consumers and close to 10 000 commercial/industrial users in the Lower Hunter region. Water is harvested from the lower Williams River and stored in the Seaham Weir Pool and the Grahamstown Dam. The recent outbreaks of blue-green algae are symptomatic of a decline in water quality of the Williams River system, which is major concern to water supply agencies. It is generally considered that reduction in phosphorus input to the river system should contribute towards reducing the occurrence of algal blooms. An important component of nutrient input into the stream network is associated with overland movement of soil particles due to various forms of erosion. We are involved in a study aiming to identify past, current and potential sources of sediment and nutrients and rates of erosion. Our objectives are to arrive at a sediment budget for the entire catchment and to develop a sediment transport model based on physical catchment descriptors using tracer techniques, Geographical Information Systems (GIS) approaches and terrain analysis tools.

GIS techniques are increasingly used as a tool for handling spatial data for hydrological and geomorphological applications [Kienzle, 1996]. Incorporation of digital elevation data into the GIS has made it possible to represent the landsurface by Digital Elevation Models (DEMs). Analysis of DEMs by programs such as TAPES-G [Gallant and Wilson, 1996], TOPOG [O'Loughlin, 1986] and TOPMODEL [Beven and Kirkby, 1979] have enabled the spatial variability of a wide range of terrain attributes to be estimated at relatively fine resolutions [Moore et al., 1991].

By combining primary topographic parameters such as slope, aspect and upslope contributing area, steady state indices have been developed to spatially predict both, surface and subsurface erosion processes. For example, combining the rainfall-runoff factor (R), soil erodibility (K), slope length (L) and slope (S) components of the Universal Soil Loss Equation (USLE) [Wischmeier and Smith, 1978] allows for prediction of sheet and rill erosion. Arnold [1986] introduced a normalised version of this function by incorporating an allowable soil loss estimate (T) to produce an erodibility index RKLS/T. Moore and Neiber [1989] mapped this index to estimate the area of land undergoing accelerated rates of surface erosion for a 10 ha catchment in Minnesota.

From stream power theory the indices $A_s\tan\beta$ and $A_s/\tan\beta$ were developed where A_s is the upslope contributing area and β represents the slope. These indices have been quite effective in predicting the locations of ephemeral gullies in several countries including Australia (e.g. Moore et al. [1988] and Vertessy et al. [1990]) and the island of Antigua in the Caribbean [Srivastasa and Moore, 1989]. Introduction of a sediment entrainment function enabled Vertessy et al. [1990] and Mackenzie et al. [1991] to predict land at greatest risk from erosion. These two studies used a dynamic form of the erosion index by incorporating the wetness index ln $[A_s/\tan\beta]$ to identify the spatial pattern of stormflow source areas and to assess at each time increment the land contributing to stormflow for erosion hazard.

This paper addresses the sequential steps required to estimate the spatial distribution of hydrologically significant terrain parameters within the Williams River catchment, in order to define the location of land susceptible to surface erosion. Creation of grid-based digital representations of the land surface at a range of grid cell resolutions is discussed. The quality of these digital surfaces is assessed in relation to the density and location of spurious errors. The trade-off between increasing the quality of input data and the resulting improvement in DEM accuracy is considered. A comparison of the relevant primary landsurface attributes associated with surface erosion processes, estimated across the catchment for varying grid cell size, is undertaken. The impact of the attributes on calculation of an erosion hazard index for each pixel within the catchment is subsequently analysed. Specific terrain landforms likely to be affected by the long-term action of surface water movement are identified.

2. WILLIAMS RIVER CATCHMENT

The study region is the 1260 km^2 area draining to the Williams River above Seaham Weir (see Figure 1). The catchment extends approximately 65 km north from the weir and is 26 km at its widest. The main river channel is over 100 km in length with another 1000 km of streams and rivers draining the catchment. About 20% of the land area is within 100 m of a stream. The 197 km^2 subcatchment draining to the Chichester Reservoir is hydrologically isolated from the rest of the catchment as the dam has essentially 100% trap efficiency [Williams River Total Catchment Management Committee, 1995]

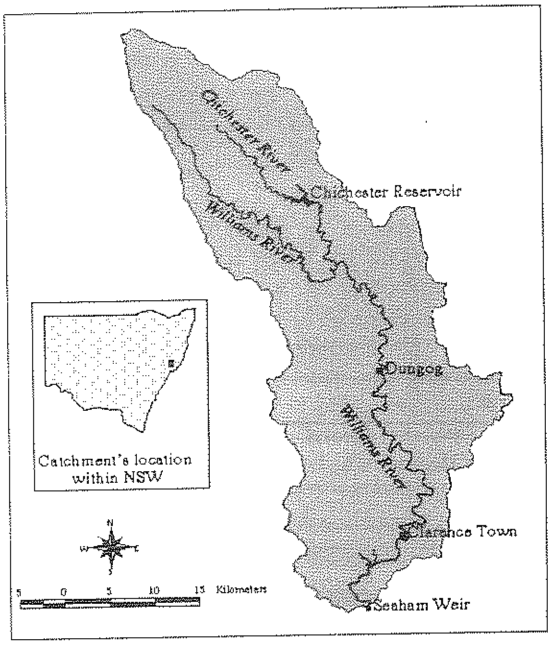

Figure 1: Locality map of the Williams River Catchment, New South Wales, Australia.

The terrestrial and aquatic ecosystems of the catchment have been significantly modified by anthropogenic activities. More than 50% of the catchment has been cleared mainly for pasture, with a relatively small area used for fodder crops. Wetlands in the lower catchment have been drained and the channel morphology is adjusting to the modified flow regime initiated by vegetation removal and the construction of channel controls. The most significant controls are Seaham Weir and Chichester Reservoir in the north-east of the catchment.

Near the Barrington Tops at the northern end of the catchment, elevation rises to 1500 m AHD and average annual rainfall is about 1600 mm. Elevation and rainfall decrease rapidly southward for about 20 km to near Barrington Guest House (at 350m AHD). Undulating hills dominate the remainder of the catchment's topography with limited flood plains stretching along either side of the main channel. The lowest annual rainfalls occur over the central part of the catchment with an average of 994 mm at Dungog. Further south, maritime influences reverse the rainfall gradient and annual rainfall increases to approximately 1100 mm at Seaham.

The catchment is located within the New England Geosyncline. The geological substratum comprises volcanic conglomerates and Carboniferous marine sediments. Quaternary alluvial flood plain sediments along the main channel derive from phosphorus rich Tertiary basalt located in the upper parts of the catchment. The soils are mostly brown podzolics with some shallow earths and skeletal variants [Story et al., 1963]. Soil erodibility increases downslope. Krasnozems and black earths on ridge crests and in the upper valleys have low erodibility. The podzolics and alluvial soils are often deep, medium to coarse grained soils, lacking cohesiveness and are therefore highly erodible [Williams River Total Catchment Management Committee, 1995].

3. TOPOGRAPHIC DATA

Digital topographic maps were obtained from the Land Information Centre (LIC) of New South Wales in ARC/INFO export format and imported into an ARC/INFO Geographic Information System database. The 1:25 000 scale data consists of one layer defining naturally occurring surface water features and another containing elevation contours at 10 m intervals representing the land surface. Thirteen map sheets were required to cover the Williams River Catchment.

For inland catchments, surface water features such as lakes and dams, minor tributaries and major rivers are delineated. In addition dam walls and levee banks are also included. In the digitised data, a single line feature represents those drainage channels on the 1:25 000 aerial photographs for which a measurable width of water surface cannot be observed. Wider major streams and rivers are subsequently digitised with opposing riverbanks, forming a polygon feature. In response to natural narrowing and expansion of rivers along their length, it is not uncommon for a single drainage length to be alternatively represented by line and polygon features. In regions such as valley floors where the terrain is flat, the location of water features may not be clearly defined. To avoid incorrect placement of such drainage lines, sections are not digitised therefore isolating subcatchments with respect to drainage connectivity.

4. METHODS

Grid-based digital representations of the land surface need to be created which define the spatial distribution of hydrologically significant terrain parameters within the Williams River Catchment, in order to define the location of land susceptible to the processes of surface erosion. The quality of these digital surfaces produced using square pixels is assessed in relation to the density and location of spurious errors. The trade-off between increasing the quality of LIC input data and the resulting improvement in DEM accuracy is considered.

A comparison of the relevant primary landsurface attributes associated with surface erosion processes, estimated across the catchment for varying grid cell size, is undertaken. For each pixel within the catchment, the impact the attributes have on the computation of an erosion hazard is subsequently assessed. Specific terrain landforms likely to be affected by the long-term action of surface water movement are identified. The digital elevation model (ANUDEM) and terrain analysis programs (TAPES-G; EROS) as described in sections 4.1 and 4.2, are used sequentially to produce the spatially distributed erosion hazard index from original data sources.

4.1 Digital Elevation Model

ANUDEM [Hutchinson and Dowling, 1991] uses irregularly spaced elevation points, contour lines of elevation and stream line location data to produce a DEM fitted to a regular grid structure. The program interpolates between input elevation data points and lines and uses stream network location data when available. The resolution of the pixel size is user defined and for this study square cells of 25, 50, 75 and 100 m sides have been selected. Tolerances control the process of removing sinks or depressions from the DEM and for this study the recommended values for 10 m contour data were used. This enabled the program to remove elevation data points which block drainage by less than 5 m. It was not expected that all sink points would be removed by this tolerance level, thus allowing comparison of the sink errors obtained for the range of grid resolutions.

The better the quality of input data describing elevation and breaks in the surface landform the more accurate the DEMs representation of the actual surface. Streamlines input to ANUDEM also aid in the removal of spurious depressions and must be fully connected to the catchment outlet. Breaks in the connectivity of the LIC stream network ensures a significant portion of the catchment's DEM be constructed without this input data source. To assess this impact on DEM quality, each DEM was rebuilt with a streamline input file containing hand digitised connections. Direct comparison is made between DEMs of the same resolution created with the different input source data. The quality of output DEMs is therefore used as an indicator to assess the merits of preprocessing the original LIC digital contour and streamline maps.

4.2 Terrain Analysis Programs

TAPES-G [Wilson and Gallant, 1996b] is the grid-based terrain analysis component of the TAPES (Terrain Analysis Programs for the Environmental Sciences) suite of programs. This program calculates slope, aspect, principal drainage direction, specific catchment area, profile and plan curvatures and flow path length at each node in a DEM grid. These attributes may be used in characterizing a wide range of hydrological, erosional and geomorphological processes occurring in complex landscapes.

Output DEMs still containing depressions are read from ANUDEM to the TAPES-G program. In TAPES-G the option to smooth out the depressions of the DEMs was invoked. The elevation residual between the input and depressionless output DEM is evaluated for each grid cell to determine if gross errors exist. Using the FREQ module of TAPES, fitted frequency distributions for relevant terrain parameters can be compared for surfaces based upon varying grid resolution or between surfaces of the same resolution created with drainage networks of increasing detail. Drainage direction calculations and catchment area computations were based on the D8 flow algorithm in which flow is orientated in the direction of steepest slope towards one of the eight nearest neighbouring pixels. The limitations of this simplistic approach in directing flow are discussed by Wilson and Gallant [1996b].

EROS [Wilson and Gallant, 1996a] characterises the sediment transport capacity of overland flow using a stream-power approach. It is grid based and estimates the spatial distribution of soil loss potential for each pixel within a catchment using a three-dimensional adaptation of the length-slope factor of the Revised Universal Soil Loss Equation [Renard et al., 1991].

$$T_c = \left(\frac{A_s}{22.13}\right)^m \left(\frac{\sin\beta}{0.0896}\right)^n \qquad (1)$$

Equation (1) combines the effects of local slope (β) (in degrees) and specific catchment area or drainage area per unit width orthogonal to a flowline (A_S) (m^2m^{-1}) to determine areas with high sediment transport capacity (T_c) and therefore high susceptibility to erosion caused by the action of flowing water [Moore and Wilson, 1992]. Both m and n are constants equal to 0.6 and 1.3, respectively. In this study, uniform rainfall excess is assumed to be the mechanism through which surface water flow is initiated. The effect of varying DEM pixel resolution will be determined by comparing fitted frequency distributions of the erosion index across the catchment.

5. RESULTS AND DISCUSSION

5.1 Pre-processing requirements of LIC data

Prior to DEM creation, essential modifications to the 'raw' streamline network data were required, as ANUDEM is incapable of using a network containing closed flow loops or polygons. Features of this type in the data arise due to various reasons. The most common example from the Williams River data is double sided main channels totaling over 100km in length. An approximate, digitised, single centreline replaced the streambanks and all connecting tributaries were subsequently extended to meet this line. Further polygons are formed in areas of low sloping terrain where meandering streams form anabranches. Reference to paper versions of the 1:25 000 topographic maps revealed that the digital scanning of drainage lines had introduced a small number of additional errors in locations where streamlines are in close proximity. Contour data was also modified in certain locations near cliff features as it was found that in certain instances adjacent contour elevation lines merged. It was noted in the creation of preliminary DEMs that contours omitted over locations of quarries invariably caused sinks in the DEM. To avoid this and subsequent complications with upslope contributing area calculations, approximate contours were digitised over quarries.

Optional modifications to the stream data were performed to enhance the quality of the DEM. This involved developing a set of criteria by which drainage lines would be connected to the remainder of the network. Separated lines were joined to the "connected" drainage network if the area they drained was greater than 0.5 km^2 and/or the downstream termination point was within approximately 250 m of an already connected drainage line.

5.2 Quality of DEM

Naturally occurring depressions in the landscape are rare features [Band, 1986] and their presence in a DEM most likely indicates an interpolation error due to a lack of sufficient elevation data. Therefore a measure of the quality of input data and resulting DEM, is the number of sink points remaining in the surface. Table 1 gives a summary of the number of depressions. Data point sinks have been formed even though elevation data was available at the individual locations, whereas the more frequent non-data point sinks are pixels located where no elevation data was available. There is a clear trend of decreasing sink points as pixel size is increased. The locations of all sink points were found to be within the relatively flat terrain adjacent to the Williams River and Chichester River main channels. The ability of ANUDEM to resolve drainage through this region of sparse contour data is restricted. No attempt was made to add additional point elevation data to supplement the contour information. For all eight DEMs, a reduction in the number of depressions in the surface resulted from using the "connected" drainage network.

Table 1: Summation of errors in Digital Elevation Models created from pixels of varying size. Shaded columns indicate use of "connected" streamline data.

Pixel Size (m)	Data Point Sinks		Non Data Point Sinks	
25	39	31	743	639
50	26	21	369	282
75	17	15	257	199
100	16	13	163	141

If the depths of sinks in the DEM surface are large, revision of input data and DEM creation parameters may be required. TAPES-G reports these depths as elevation residuals between the original DEM and a depressionless version it creates. The maximum residual value ranged between 8 to 12 m for the eight DEMs constructed, with no apparent trend relating the depth of maximum depressions to the resolution of pixels. National Mapping Council guidelines [Manning, 1983] indicate no more than 10% of elevation data points be in error by half the contour interval. Therefore, two adjacent contour lines could be in error a maximum of 10 m. It was decided to revise DEMs having depressions greater than this value.

Ideally, DEMs built for the same catchment should have identical distributions of terrain parameters. A consequence of increasing the pixel size however is an increasing generalisation of the flow network and a smoothing of the surface.

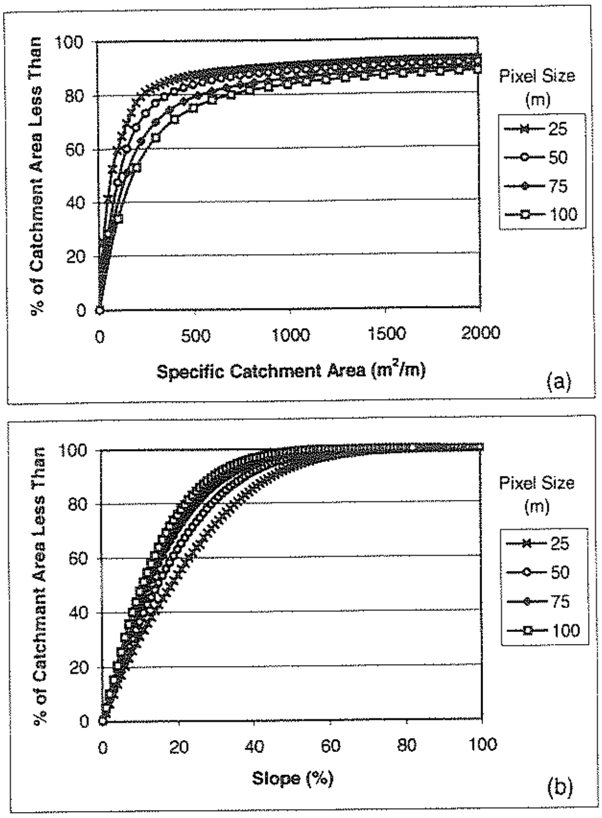

Figure 2: Cumulative frequency curves of a) specific catchment area and b) slope for the Williams River catchment, derived from DEMs with 25, 50, 75 and 100m pixel resolutions. Curves relate a parameter value to the proportion of catchment area less than the value.

Before using (1) to calculate the erosion index for all pixels, it is important to understand the magnitude of variation that exists for the landsurface related parameters specific catchment area (As) and slope (β). Cumulative frequency distributions of the four DEM resolutions are shown in Figure 2a for A_S and Figure 2b for β. Distributions for the DEMs created from the modified drainage network were omitted from Figure 2 as they showed insignificant variations to the curves presented. For any A_S value, the higher the resolution of DEM the larger the proportion of catchment area less than the value. The effect of this is an average decrease in T_c values for DEMs with relatively smaller sized pixels. The β curves also show a pronounced difference between DEM resolutions, most likely as a direct consequence of the surface smoothing. For example, the 25 m pixel DEM estimates only 53% of the area within the catchment has a β value less than 20%, whereas for the 100 m DEM this rises to 76%. This indicates average T_c values would be higher for DEMs with smaller sized pixels. Therefore, over the range of DEM resolutions, the respective effect of A_S and β estimation on the magnitude of T_c values is inverse.

5.3 Comparison of erosion hazard maps at different resolutions

The cumulative frequency distributions of the erosion hazard index for the four DEM resolutions are presented in Figure 3. Curves relate an erosion hazard index value to the proportion of catchment area less than the indicated value.

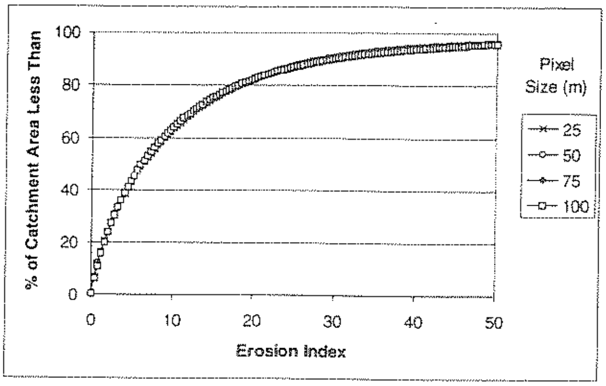

Figure 3: Cumulative frequency curves of erosion hazard index (T_c) for the Williams River catchment, derived from DEMs with 25, 50, 75 and 100 m pixel resolutions. Minimal variation between all four curves is apparent.

There are only minor variations of no greater than 1% between the curves shown on Figure 3. For calculations of T_c using (1), this indicates DEM pixel size does not have a significant influence on the average areal distribution of the index. The tendency of T_c values to be decreased by A_S estimation but increased by β estimation at higher DEM resolutions (and vice-versa for lower DEM resolutions), appears to be responsible for maintaining similarity between the curves. This may have implications for selection of a DEM pixel size for erosion index studies, as there may be computational and data storage concerns favoured by lower resolution pixel sizing.

While this is an encouraging result, spatially averaged erosion index values must also be considered in relation to their distribution throughout the catchment. Erosion hazard index values for part of the Williams River catchment are shown on Figure 4. It is evident smaller pixel sizing results in higher spatial definition of erosion hazard susceptibility. The DEM in Figure 4a is based on 25 m pixel resolution and clearly indicates low erosion hazard along ridge tops and adjacent to the river's main channel. Hillslopes and drainage paths are shown to be the areas most likely to be affected by sheet and minor rill erosion. For progressively coarser resolutions, the terrain features become increasingly generalised and this is directly reflected in the spatial distribution of the erosion index values.

6. CONCLUSIONS AND FURTHER WORK

The main conclusions drawn from the work discussed in this paper are as follows:

(1) Terrain analysis of DEMs provides a framework for obtaining spatial estimates of land susceptible to the effects of sheet and minor-rill erosion. The development of a catchment wide sediment budget, in which areal values of subcatchment scale erosion data are of interest, can be achieved from a single elevation data set. It is proposed to model stormflow routing together with sediment entrainment and deposition processes to enhance the predictive capabilities of the methodology.

(2) The process of modifying the drainage network to form the "connected" streamlines is a time consuming and laborious task. Based on the moderate improvement of depression removal and the lack of effect on depression depths, the trade-off between time spent preprocessing

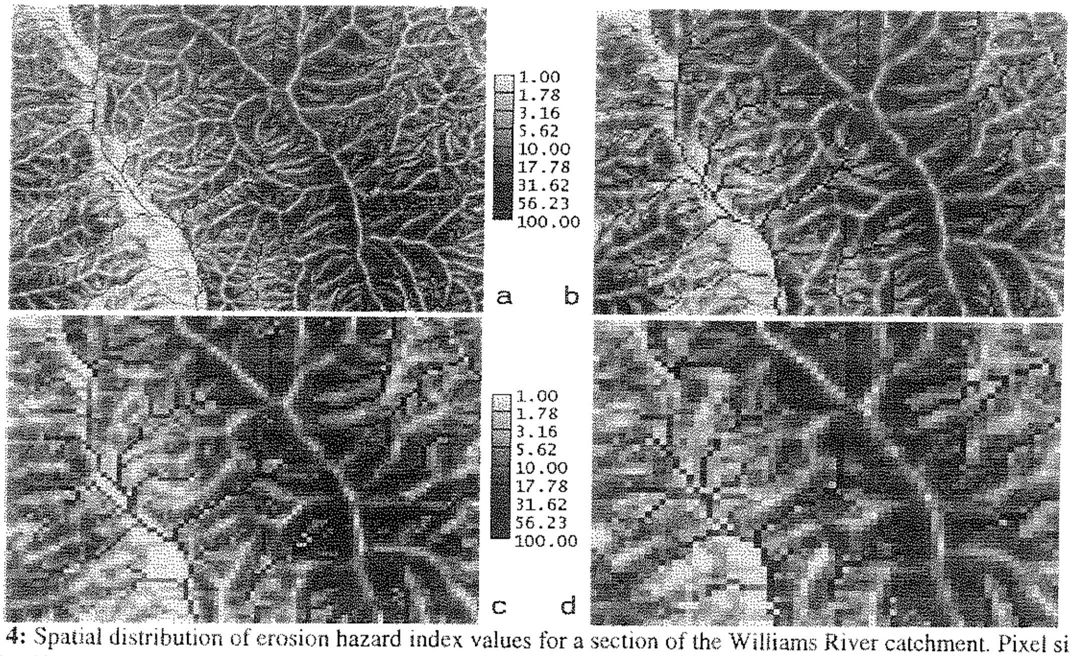

Figure 4: Spatial distribution of erosion hazard index values for a section of the Williams River catchment. Pixel sizes are a) 25 m, b) 50 m, c) 75 m and d) 100 m. The darker the pixel colour the more susceptible that location is to surface erosion by water movement. The wide, lighter coloured band most clearly defined on the left-hand side of a) is the gently sloping region adjacent to the Williams River main channel.

drainage lines and the resulting improvement in DEM quality is unjustified for this study.

Soil and vegetation data has recently become available for the Williams River catchment from the Department of Land and Water Conservation. Incorporation of this information will enable alternative over land flow initiation mechanisms to be modeled. This is considered to be a more realistic approach. The department has also produced an erosion risk map combining a USLE based approach and a ground truthing regime to estimate actual sheet erosion rates. It is planned to compare this erosion risk map with long-term erosion rates from hillslopes derived from tracer techniques, and also against erosion hazard maps derived from other erosion indices.

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