A GIS-BASED MODEL OF SOIL EROSION AND TRANSPORT

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Introduction

Soil erosion is a natural process that occurs when the force of wind, raindrops or running water on the soil surface exceeds the cohesive forces that bind the soil together. In general, vegetation cover protects the soil from the effects of these erosive forces. However, land management activities such as ploughing, burning or heavy grazing may disturb this protective layer, exposing the underlying soil. The erodibility of the underlying soil depends on its type, location and degree of exposure to erosive influences. Only those erosion processes that are related to water are considered here. These are summarised in Fig. 1.

The process of soil erosion and transport involves not only the detachment of soil particles from a particular site, but also their transfer and deposition elsewhere in the catchment (Meyer & Wischmeier 1969). Only a relatively small proportion of the eroded material carried across the catchment by flowing water ultimately enters the drainage system. The remainder is re-deposited in areas where a decrease in catchment slope reduces the velocity and transport capacity of the overland flow (Haan et al. 1994). This is especially true of larger particles. However, relatively small amounts of sediment lost from the catchment may constitute a significant and ecologically damaging sediment gain to the receiving waters. The proportion of eroded material that reaches the watercourse is known as the delivery ratio. This tends to decrease with the size of the catchment drainage area (Vanoni 1975). The amount of material that leaves the terrestrial catchment and enters the watercourse is known as the sediment yield.

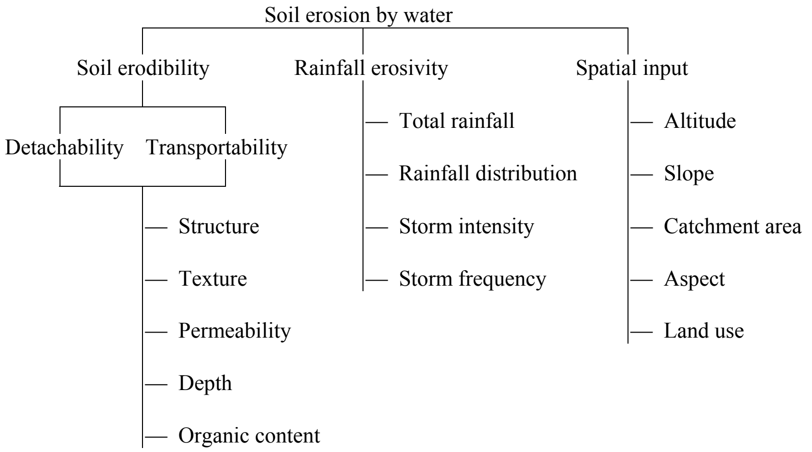

FIG. 1. The main processes affecting soil erosion by water (after Sanders 1986).

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Rural catchments must be managed sensitively if serious soil erosion problems (e.g. Fig. 2) are to be avoided. This requires informed decision-making by the managers and users of the land, i.e. farmers, foresters, conservationists and regulatory authorities. In the United States, this decision making process is often supported by the predictive modelling of soil erosion and sediment transport processes within the catchment, using established techniques such as the Universal Soil Loss Equation [USLE] (Musgrave 1947; Wischmeier & Smith 1978) and the Agricultural Nonpoint Source pollution model [AGNPS] (Young et al. 1986). In this article, we examine the range of erosion models currently available and describe the application of one of these to the Burrishoole catchment on the north-west coast of Ireland, which has suffered heavy erosion of blanket

FIG. 2. Serious soil erosion problems in the Burrishoole catchment, Ireland.

peat in recent years. The output from the Burrishoole model is described in May et al. (2005, this volume).

Modelling soil erosion and transport within a catchment

A variety of statistical, process-based, physically-based and spatially distributed models can be used to simulate soil erosion and transport within lake catchments. These include those published by Yamamoto & Anderson (1967), Beasley (1977), Foster et al. (1977), Foster (1982), Singer & Walker (1983), Beven et al. (1984), Moore & Burch (1986), O'Loughlin (1986), Sharma & Correia (1987), Oslin et al. (1988), Vertessy et al. (1990), Govindaraju & Kavvas (1991), Hairsine & Rose (1992a,b), Carling et al. (1993), Moore et al. (1993), Moussa & Bocquillon (1994), Nearing et al. (1994), Rose (1994) and Quinn et al. (1995). Existing models range from mathematically and conceptually simple approaches to complex models that try to include the complexities of the real world. Many of these are reviewed below in relation to their suitability for use at the catchment scale.

Statistical models

The USLE is probably the most widely used model of overland flow erosion in the world. It is based on a series of empirical relationships that describe the effect of a range of factors on soil erosion. These include rainfall intensity, soil erodibility, length and steepness of slope, land cover and land management practices. When combined with a sediment delivery ratio (Dickson et al. 1986), the potential sediment loading to the catchment drainage system can be estimated (Hession & Shanholtz 1988).

The approach has a number of limitations, the most important of which are that (1) gullying or mass movement are not considered; (2) deposition of sediment cannot occur within the area under consideration; and (3) the slope length and steepness factors must be determined only on the area that is contributing to runoff (Zhang et al. 1996). Also, it has been found to be less effective in applications outside the range of conditions for which it was developed (Foster 1982; Millington 1986; Nearing et al. 1994).

Despite its problems, Zhang et al. (1996) concluded that the USLE model could be used to evaluate erosion at any point within a catchment. Several agricultural transport models, such as CREAMS [Chemicals Runoff and Erosion from Agricultural Management Systems] (Knisel 1980), GLEAMS [Groundwater Loading Effects of Agricultural Management Systems] (Leonard et al. 1987) and Erosion-Productivity Impact Calculator (EPIC; Williams et al. 1984), use the USLE equation, or modifications of it, to estimate soil erosion and to quantify the sediment yield from catchments (Ferro & Minacapilli 1995; Ferro 1997; Kothyari & Jain 1997; Ferro et al. 1998; Di Stefano et al. 1999). When the USLE (or one of its variants) is combined with gridded data from a geographical information system (GIS), the predictive power of this approach is increased (Spanner 1983; Jain & Kothyari 2000) – see below.

Process-based models

Process-based models take into account the three forms or stages of soil erosion caused by water travelling across a catchment. These are sheet erosion (removal of soil over the entire surface), rill (small channel) erosion and gully (large channel) erosion. A range of these models is reviewed by Zhang et al. (1996) who conclude that these models cannot be applied with any confidence to conditions not reflected in the calibration dataset of the original model. This is because the range of processes included is oversimplified and many complex feedback processes have been ignored. These models also ignore a number of important spatial interactions that occur within a catchment.

Physically-based models

Physically-based models, such as the Water Erosion Prediction Project [WEPP] model (Laflen et al. 1991; Flannagan & Nearing 1995), are intended to represent the essential mechanisms that control erosion, such as interrill and rill erosion (Sharma et al. 1995). They also take into account other parameters such as plant growth and climate. Examples of these models are reviewed by Zhang et al. (1996), who conclude that these models are very powerful because they can represent a synthesis of the individual components that affect erosion, including the complex interactions between various factors and their temporal variability. However, it is generally very difficult to obtain the unique set of optimal parameters needed to drive physically-based models using parameter estimation methods. It is also very difficult to apply such a model that has been developed for a small area to a much larger area, such as a catchment.

Spatially distributed models

Spatially distributed models, such as TOPMODEL, TOPOG, AGNPS and Erosion Hazard Index models require a spatial representation of the topography of an area using 3-dimensional coordinates as input (Zhang et al. 1996). Such a dataset is known as a Digital Elevation Model (DEM) (Miller & Laflamme 1958). These data provide detailed information on attributes that affect erosion and sediment transport rates, such as elevation, slope, aspect, drainage, flow direction, flow accumulation and contributing catchment area. In addition to the above, spatial information on soil type, land cover, rainfall and other catchment characteristics may be added as separate data layers, where these are required to calculate erosion rates.

The data provided by the GIS-based DEM can be loosely linked to a soil erosion model, as in the case of the Areal Non-Point Source Watershed Environment Response Simulation model (ANSWERS) (Beasley 1977), or fully integrated with a soil erosion model, as in the Limburg Soil Erosion Model (LISEM) (De Roo et al. 1996). However, it is important to take into account that the underlying erosion models may not have been developed for application at the wider (catchment) scale. The USLE, for example, was developed for use at the plot scale and is not applicable to large areas (such as entire catchments) unless it has been extended to include a sediment delivery term (Ferro & Minacapilli 1995). This is because the original equation does not simulate sediment deposition. CREAMS also applies only to field sized areas (Donigian & Huber 1991).

The choice of soil erosion model to link to a GIS-based, spatially distributed model of soil erosion and sediment transport can have a big impact on the accuracy of the output. Although there is a general assumption that complex, physically-based models should provide better results than the simpler soil erosion models, De Roo (1998) shows that this is not so. The author compared the output from a range of distributed models of varying complexity with detailed field measurements of soil erosion. The study showed that predictions from spatial models based on relatively simple erosion models, such as the USLE, compare favourably with those based on more complex, physically-based, soil erosion models at the local scale. When scaled up to the catchment level, the simpler models tended to give better results than the more complex models. This is because the latter require a large number of input variables (e.g. infiltration capacity, soil texture, soil moisture content) to be estimated or measured at the catchment scale, introducing many sources of uncertainty and error into the simulations (Jetten et al. 1999). De Roo (1998) recommends that simple models that encompass only the dominant processes operating in a catchment should be further developed in this context.

Modelling soil erosion and transport within the Burrishoole catchment

As the USLE was found to be the most widely used soil erosion model, and the most easily implemented at the catchment scale, this was used to develop a soil erosion and transport model for the Burrishoole catchment. The model was loosely linked to a GIS-based spatial database describing the topography, soil type and land cover characteristics of the area and calibrated against estimates of sediment transport within the Glenamong subcatchment. These were derived from field measurements of flow and sediment concentration collected as part of the automatic water quality monitoring programme implemented within the catchment (Rouen et al. 2005, this volume). In addition to the above, output from the model was also used to create a map of soil erosion risk for the catchment. This compared favourably with visual signs of erosion observed on a digital aerial photograph of the area (May et al. 2005, this volume).

Implementation of the USLE in the Burrishoole catchment

The USLE (Wischmeier & Smith 1978), as modified for western Europe by Bollinne (1985) was used to estimate soil erosion rates within the Burrishoole catchment. The basic form of the equation is as follows:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where A is the *average annual soil loss per unit area* (t ha^{-1}), R is the *rainfall intensity factor* (MJ mm ha^{-1} h^{-1}), K is the *soil erodibility factor* (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the *length and steepness of slope factor* (dimensionless), C is the *vegetation cover management factor* (dimensionless) and P reflects the *management practice* (dimensionless). The model was parameterised using close interval flow and sediment monitoring data collected from the Glenamong subcatchment (Rouen et al. 2005, this volume) prior to application to the entire catchment.

The *rainfall intensity factor* (R) quantifies the impact of raindrops falling onto the catchment in terms of their kinetic energy. Ideally, rainfall data should be collected at very short time intervals for the determination of R (Weischmeier & Smith 1978). However, as this was not possible in the present study, daily values of R (MJ mm ha^{-1} h^{-1}) were calculated from daily cumulative rainfall values for periods when the measured rainfall was greater than 1 mm d^{-1}, as follows:

$$KE = 8.74 \times log\left(I\right) + 11.89 \tag{2}$$

and

$$R = 0.19 \times KE \times I + 0.64 \tag{3}$$

where I is the rainfall intensity (mm h^{-1}) and KE is the *kinetic energy* of that rainfall (MJ ha^{-1}). The value of R was set to 0 for rainfall levels of less than 1 mm d^{-1}, as suggested by Bolline (1985).

The *Soil erodibility factor* (K) was calculated using five characteristics for each soil type. These were obtained from the literature by equating each soil type in the study catchment to a similar soil type elsewhere in the British Isles (Jarvis et al. 1984; Avery 1990). The characteristics determined for each soil type included soil particle size distribution, soil structure, organic matter content and wetness (i.e. duration and degree of waterlogging). The values obtained were combined, using the soil nomograph given by Wischmeier & Smith (1978), to give a *K* factor for each soil type (Table 1). These *K* factors were then converted to a European equivalent value using the method described by Bollinne (1985). When organic matter content was greater than 4 %, i.e. the maximum value shown by Wischmeier & Smith (1978), a value slightly greater than 4 was used as an approximation in most cases (Penning-Rowsell 1996). However, in the case of peat soils, which have a very high organic content, the nomograph does not apply. As these soils are considered to be very vulnerable to erosion (Jarvis et al. 1984), they were assigned a relatively high value of 0.7 in this study.

The *length and steepness of slope factor* (*LS*) was derived from digital elevation data (20 m × 20 m grid) supplied by the Marine Institute, Ireland, under licence from the Ordnance Survey, Ireland. Values were determined for each grid square using the equation of Hessian and Shanholtz (1988):

$$LS = \left(\frac{\lambda}{22}\right)^{m}\left(\frac{0.43 + 0.3S + 0.043S^{2}}{6.574}\right) \tag{4}$$

where λ is the length of the slope (m), S is the gradient of the slope (%) and m is given values according to the value of S such that $m = 0.2$ if $S < 1.0$, $m = 0.3$ if $1.0 < S \leq 3.5$, $m = 0.4$ if $3.5 < S \leq 4.5$, and $m = 0.5$ if $S > 4.5$.

A *cover and management factor* (*C*) was determined for each land cover type (Table 2) from values for similar land cover types given by Wischmeier & Smith (1978).

Table 1. Summary of soil types within the Burrishoole catchment and their associated soil erodibility (*K*) values, as used in the present study.

Soil type	Area of catchment covered (%)	Soil erodibilty factor (*K*)
Alluvium	2.87	0.45
Complexes	2.99	0.5
Dry podzol	1.04	0.35
Peat	61.77	0.7
Peaty iron-pan podzols	21.67	0.33
Wet podzol	3.56	0.55
Peaty podzol	0.06	0.57

Table 2. Summary of land cover types within the Burrishoole catchment and the associated factors used in the present study. Land cover factor (*C)* determined from Appendix 3 of Wishmeier & Smith (1978) and Manning's coefficient of roughness (*n*) as given by Newson (1994) and Shaw (1994).

Land cover type	Land cover factor (*C*)	Manning's coefficient of roughness (*n*)
Coniferous forest	0.36	0.1
Natural grassland	0.043	0.03
Pasture (low productivity)	0.043	0.035
Peat bogs (unexploited)	0.025	0.03
Agricultural land	0.5	0.04
Transitional woodland/scrub	0.13	0.15

The *management support practice factor* (*P*) is a measure of the effectiveness of land management practices aimed at reducing soil loss within the catchment. Such practices include contour ploughing, strip-cropping, terracing, etc. For the purposes of the current implementation of the USLE, this value was set to 1 as no relevant and sufficiently detailed information on current management practices within the catchment was available.

The USLE estimates the total amount of soil eroded from the catchment, but does not predict the amount of that eroded material that will reach the drainage network. Much of the eroded soil is re-deposited as the sediment moves across the catchment in the surface runoff. The proportion that enters the drainage network is estimated by applying a *sediment delivery ratio* (*DR*) to the initial soil loss value. The delivery ratio concept employed in this study is based on the work of Dickinson et al. (1986) and is expressed as a function of the velocity of overland flow, as follows:

$$DR = a\left(\frac{V}{L}\right)^{b} \tag{5}$$

where $a =$ is a constant (see below), $V =$ velocity of overland flow (m s^{-1}) and L is the distance to the stream channel (m). Velocity of overland flow is a function of surface roughness, the slope gradient and the amount of overland flow. These can be combined in the following equation:

$$V = n^{-1}S^{0.5}D^{0.67} \tag{6}$$

Table 3. Summary of data used to develop and test the soil erosion and transport model for the Burrishoole catchment.

Data description	Data type	Data supplied by:
Elevation	Spatial (20m resolution)	Marine Institute/Ordnance Survey of Ireland
Land cover	Spatial (CORINE level 4)	Marine Institute
Soils	Spatial	Marine Institute
Rainfall	Time series (daily)	Marine Institute; this project
Stream flow	Time series (8-hourly)	Marine Institute; this project
In-stream sediment concentration	Time series (8-hourly)	Marine Institute; this project
Aerial photography	Spatial (9m resolution)	Compass Infomatics, Dublin

where n = Manning's surface roughness coefficient, S = the slope gradient (%), and D = depth of overland flow (m). In order to use this equation in a variable time frame, it is necessary to replace depth of overland flow with a relative term that can identify areas more likely to generate surface runoff. One such term is a drainage area-slope term, or wetness index. Patton & Schumm (1975) and, later, Montgomery & Dietrich (1994) identified this term as an important indicator in the determination of gully erosion, as it identifies the spatial extent of saturated overland flow. Such a Wetness Index (W_I), was described by Moore et al. (1988) in the following terms:

$$W_I = \ln\left(\frac{A_u}{S}\right) \tag{7}$$

where A_u = upstream contributing area (m^2) and S is the slope gradient (%).

Substituting this Wetness Index into equation 6 gives:

$$DR = a\left(\frac{W_I S^{0.5} n^{-1}}{L}\right)^b \tag{8}$$

where a and b are constants that are determined for a test area by calibration to measured sediment loads. In this study, the test area was the Glenamong sub-catchment for which there were detailed sediment concentration and flow data, from which sediment load could be calculated. The values determined for this area were $a = 0.1$, $b = 0.5$.

The model outlined above was developed and calibrated for the Burrishoole catchment using the data summarised in Table 3. Output from the model is described and evaluated by May et al. (2005, this volume).

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