MODELLING SOIL EROSION AND TRANSPORT IN THE BURRISHOOLE CATCHMENT, NEWPORT, CO. MAYO, IRELAND

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Introduction

The Burrishoole catchment is situated in County Mayo, on the northwest coast of the Republic of Ireland. Much of the catchment is covered by blanket peat that, in many areas, has become heavily eroded in recent years (Fig. 1). This is thought to be due, primarily, to the adverse effects of forestry and agricultural activities in the area. Such activities include ploughing, drainage, the planting and harvesting of trees, and sheep farming, all of which are potentially damaging to such a sensitive landscape if not managed carefully.

Peat bogs are formed from the partially decayed remains of living plants in areas of high rainfall and poor drainage (Ingram 1982). They are very sensitive to changes in their environment, such as variations in the seasonal pattern and chemistry of rainfall, or alterations in local land management practices (Conway & Millar 1960; Burt & Gardiner 1981). The overall impact of such changes is to de-stabilise the natural functioning of the intact mire ecosystem. This leads to rates of erosion that are significantly above 'natural' background levels (Bragg & Tallis 2001).

Peatlands cover 8 % of the land area of the British Isles (Taylor 1983) and 16 % of Ireland (Bord na Móna 2001) and are dominated by blanket peat. Most are not natural ecosystems, but are managed for a variety of purposes. These include peat extraction for burning and horticultural use, low-intensity grazing, forestry and recreation. As these activities tend to reduce the level of protective vegetation that covers the soil, they often lead to the exposure of large areas of bare peat to erosive forces (Bragg & Tallis 2001). In recent years, over-grazing by sheep has become a particularly widespread problem in this respect, with several authors showing that even when stocking densities are as low as 1.7 sheep ha^{-1} in Scotland (Birnie & Hulme 1990), 2.0 sheep ha^{-1} in Ireland (McKee & Sheehy Skeffington 1997; O'Connor & Sheehy Skeffington 1997) and 2.5 sheep ha^{-1} in England (Anderson & Radford 1994), peatland landscapes may be damaged. In their review of this problem, Bragg & Tallis (2001) concluded that stocking densities above 1 sheep ha^{-1} on this type of soil needed to be managed sensitively. Evans (1977) recommends that such management should aim at preventing the creation of areas of bare soil in the first place, rather than resolving the problem once it has started, because peat erosion from denuded areas is almost impossible to stop without completely excluding grazing animals from the damaged areas for long periods.

Although examples of elevated soil erosion rates from areas of blanket peat are common, few attempts have been made to estimate the delivery of eroded material to the drainage network. However, it is important to take this into consideration when assessing the ecological impact of this problem. This is because eroded soil degrades not only the terrestrial habitat from which it comes, but also the freshwater habitats to which it is delivered. Ecological impacts, here, include the silting up of fish spawning sites (Robinson & Blyth 1982; Olsson & Persson 1986), and the smothering of habitats that would otherwise provide an invertebrate food supply for fish.

Understanding the hydrological characteristics of blanket peat is a very important part of managing this type of ecosystem correctly. The structure and function of the bog system relies heavily on the incomplete degradation of plant remains that can only occur in soils that remain saturated for most of the year (Bragg 2002). This almost perpetual saturation is maintained through a dynamic equilibrium between net precipitation and steady, but impeded, lateral drainage (Ingram 1982). This balance may be seriously disrupted by activities that interfere with the drainage system, such as ploughing, drainage and compaction of the soil caused by heavy machinery.

Because the soils of peat bogs are usually saturated, available storage capacity within them is small. As a result, any precipitation over the catchment rapidly gives rise to runoff as the water table rises through the superficial layer (Ingram 1987; Ingram & Bragg 1984). This high level of overland flow tends to promote soil erosion processes by comparison with the hydrological processes usually seen in areas with better-drained mineral soils (Ivanov 1981). However, there is no direct relationship between runoff and sediment transport in peaty areas because the level

FIG. 1. Evidence of soil erosion in the Burrishoole catchment, Ireland.

of erosion and transport depends not only on the immediate rainfall conditions, but also on the antecedent soil moisture content and rainfall intensity (Kløve 1998). This is because, even during relatively constant rainfall and runoff, erosion and sediment transport decreases with time due to depletion of erodible material.

Sediment yield and hydrology of the Burrishoole catchment

Measuring sediment yield at the subcatchment scale

In the present study, sediment yield from the Burrishoole catchment was investigated through intensive, close interval monitoring of sediment concentrations and discharge rates at the outflow of the Glenamong subcatchment (Fig. 2). This subcatchment, 1791 hectares in area, accounts for 23 % of the entire Burrishoole catchment and ranges in elevation from 12 m.a.o.d to 710 m.a.o.d. Soils within the subcatchment comprise peat (62 %), peaty-iron podzols (36 %) and alluvium (2 %), and land cover consists of unexploited peat bog (75 %), coniferous forest (23 %) and scrub (2 %).

Flow and sediment concentrations were measured at 8-hourly intervals from 5 February 2001 to 8 November 2001 with an automatic sampler and separate flow gauge, and hourly averages were recorded between 4 July 2002 and 6 September 2002 using an automatic river monitoring

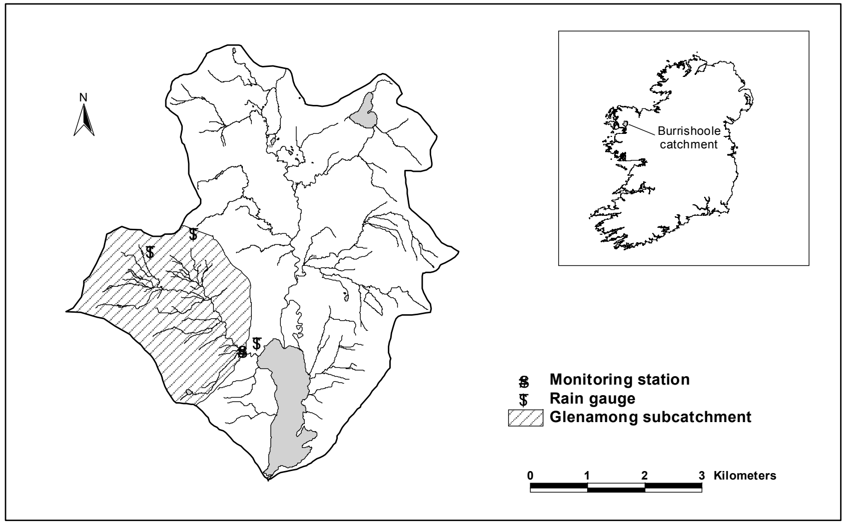

FIG. 2. Sediment, flow and rainfall monitoring sites within and close to the Glenamong subcatchment of the Burrishoole catchment; inset shows the location of the catchment within Ireland.

system [ARMS] (Rouen et al 2005., this volume). In addition, daily rainfall was monitored at three locations within, or just outside, the subcatchment boundary (Fig. 2) from 5 February 2001 to 29 May 2002.

Analyses of the 8-hourly data (February to November 2000) showed that the average sediment yield from the Glenamong subcatchment was about 790 kg d^{-1}, with individual values lying between 79 kg d^{-1} and 7890 kg d^{-1}. This wide variation in values reflects a similarly wide range of average daily rates of flow (11 l s^{-1} to 5648 l s^{-1}) recorded over the same period. In contrast, in-stream sediment concentrations were much less variable, ranging between 3 mg l^{-1} and 37 mg l^{-1}, with a mean of 9.8 mg l^{-1}. The organic content of these sediments, estimated by loss on ignition in a muffle furnace, was about 34 %.

In general, the data show a very close relationship between average daily rainfall over the catchment and mean daily flow in the Glenamong River over the study period (Fig. 3). Little evidence was found of any delay between rain falling over the catchment and a corresponding increase in flow being recorded in the drainage channel. This, and the fact that total flow accounted for more than 90 % of the volume of precipitation falling over the subcatchment, suggested that the hydrology of this catchment is dominated by runoff rather than subsurface flow. To test this hypothesis, a hydrologic simulation model (HYSIM) was used to simulate the flow

regime in the subcatchment from the corresponding rainfall monitoring data. This model represents the hydrologic process as a linked set of storage compartments. The maximum transfer rates between, and the capacity of, these storage compartments are represented by a set of parameters that are used, in conjunction with precipitation, flow and potential evapotranspiration (PET) data, to predict the runoff from the catchment. The calibration process allows the analyst to provide initial values for the parameters, usually obtained from the literature, and then an optimisation routine is run that modifies a limited subset of the parameters in order to fit the model output to the measured runoff. In the present study, the model was calibrated over the longest period for which continuous flow records were available, i.e. 5 February 2001 to 30 September 2001. The simulated data fitted closely to the observed data (Fig. 4), and the parameters used to achieve such a close fit provided a useful insight into the likely hydrologic processes occurring within the catchment. They indicated that the soil had a very low storage capacity, the permeability of the soil was significantly impeded and the lateral movement within the soil horizon was limited. This lead to the conclusion that most of the runoff was being generated as overland flow. It also suggested that little of the incident rainfall was being stored in the soil, so any rainfall event would result in a fairly instant overland flow response.

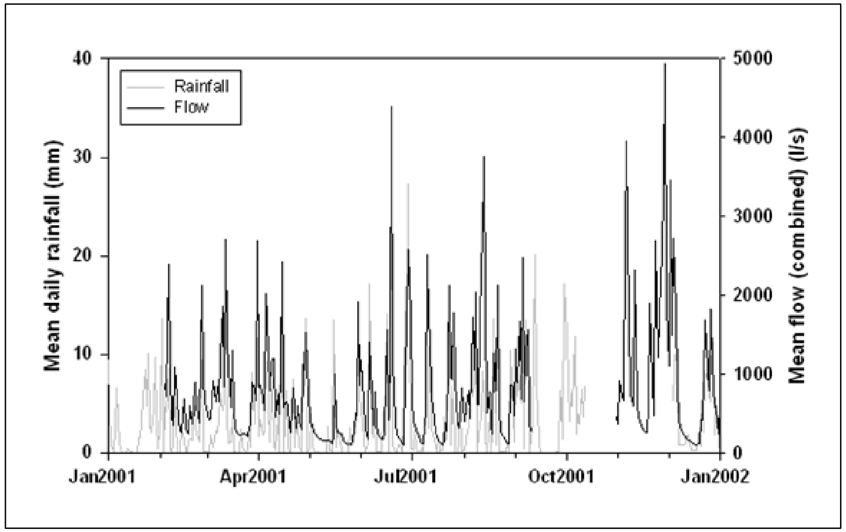

FIG. 3. Average daily rainfall and mean daily rates of flow in the Glenamong River and its catchment during 2001.

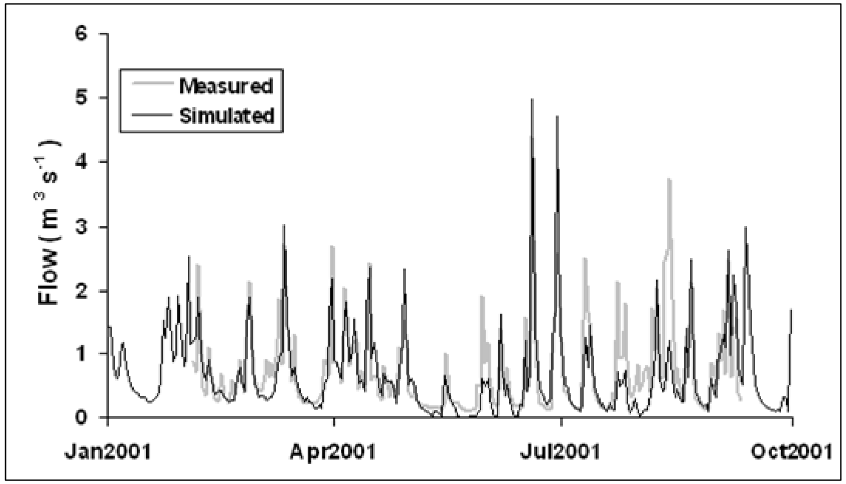

FIG. 4. Measured and simulated rates of flow in the Glenamong River.

The parameterisation of the model suggested a very short time lag of about 2 hours in the runoff response to rainfall. These conclusions support published accounts of the hydrology of peat bogs (Ingram 1987; Ingram & Bragg 1984) and confirm our initial judgement on the hydrology of the Glenamong subcatchment made from the simplified volume analysis described above.

The installation of the ARMS in July 2002 provided an opportunity for the importance of storm events to be assessed in relation to sediment transport within the Glenamong subcatchment. These data, collected hourly over a 3-month period (1535 values), show a very close relationship between flow and sediment concentration in the runoff from this area. This relationship followed a well-defined pattern during and immediately following storm events (Fig. 5). At the beginning of each storm event, the sediment concentration increased rapidly as flow increased (Phase I). This was followed by a period when the flow continued to rise, but the sediment concentrations began to fall sharply (Phase II). A little later, the rate of flow began to fall as the storm event came to a conclusion (Phase III). This phenomenon has been demonstrated in other peatland catchments (e.g. Crisp & Robson 1979; Labadz et al. 1991) and is thought to be due to a decrease in the availability of erodible sediment as the storm continues. The mean sediment concentration in the Glenamong River varied greatly over these three phases of storm development, rising to 32 mg l^{-1} during Phase I, declining to 8 mg l^{-1} during Phase II and then falling to 4 mg l^{-1} during Phase III.

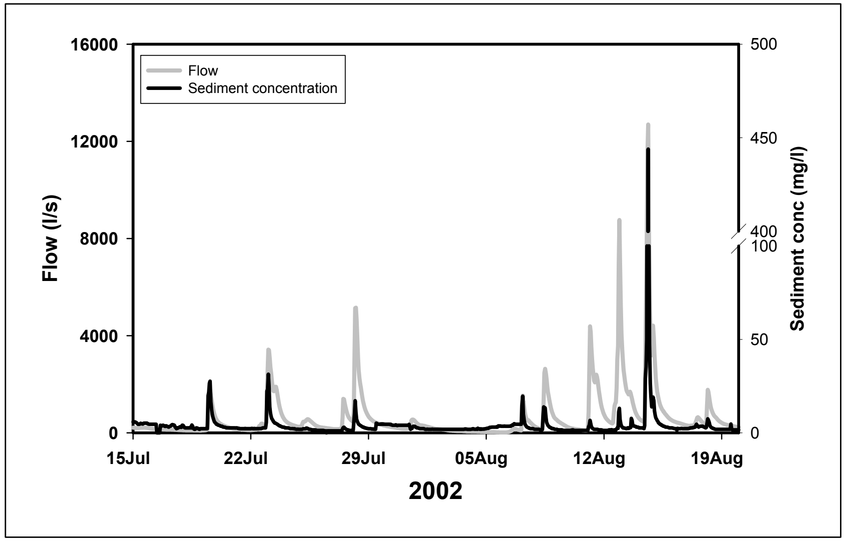

FIG. 5. Flow and sediment concentrations in the Glenamong River (hourly records).

The overwhelming importance of storm events in the transport of sediments through the Glenamong subcatchment is clearly shown by the monitoring data. Summarising the hourly ARMS data in terms of the contribution of individual samples to the total estimated sediment yield between July and September 2002 indicated that 90 % of the total sediment load was accounted for by only 12 % of the sampling occasions. In addition, when the hourly data were 'subsampled' to represent 8-hourly, daily and weekly sampling regimes, the estimated sediment yield from the catchment over this period varied enormously (Table 1), decreasing as the sampling interval became longer and storm events were missed. This illustrates the importance of using close interval or continuous sampling regimes when estimating sediment transport in such areas.

The annual yield of eroded material from the Glenamong subcatchment was estimated from the 8-hourly data by calculating an average daily load for the period of observation and multiplying that value by 365. This suggested that the sediment loss from this subcatchment was about 290 t y^{-1} in total, or 0.16 t ha^{-1} y^{-1}. This value is much smaller than those estimated for parts of the Glenamong catchment by May (1994), who found sediment loss rates of 62.5 t ha^{-1} y^{-1} from an area with high levels of erosion and 1.25 t ha^{-1} y^{-1} from a 'control' site with little evidence of erosion. However, this author concentrated on estimating sediment delivery rates

Table 1. Comparison of estimated sediment yield from the Glenamong catchment over the 3-month period July to September 2002 determined from 8-hourly, daily and weekly subsampling of the hourly data from the ARMS.

Sub-sampling interval	Estimated sediment load July to September 2002 (tonnes)	Difference compared to hourly sampling (%)
Hourly	103	0
8-hourly	83	-19
Daily	33	-68
Weekly	25	-76

from small areas rather than the whole subcatchment, so the results are not directly comparable with the present study.

Table 2 summarises some of the results from this and other studies that have estimated sediment delivery rates to surface waters from upland, peat-covered, catchments in the British Isles and Ireland. These studies have used a variety of techniques, such as in-lake sediment accumulation rates and in-stream sediment transport rates, to determine these values. The results show that the value determined for the Glenamong subcatchment by the present study is lower than the range of values determined elsewhere. However, when any of these values are compared with the rate at which new peat accumulates, as estimated for blanket peat in Derbyshire by Tallis

Table 2. Estimates of sediment yield/delivery to standing waters from peat covered catchments in Britain.

Location	Sediment yield ($t\ ha^{-1}\ y^{-1}$ DW)	Organic content (%)	Source	Comment on method
Ireland	0.16	34	This study	In stream sediment and flow monitoring
Derbyshire	1.28	24.5	Hutchinson (1995)	Sediment accumulation rate in reservoir
Wales	0.66	46	Francis (1990)	In stream sediment load
Pennines	1.12		Crisp (1966)	In stream sediment load
Pennines	2.04	19	Labadz et al. (1991)	Sediment accumulation rate in reservoir
Pennines	0.51 – 2.89		Butcher et al. (1993)	
Scotland	0.68 – 2.05		Duck & McManus (1990)	

(1985) (i.e. 0.06 – 0.96 $t\ ha^{-1}\ y^{-1}$), it can be concluded that such high rates of erosion will lead to a net loss of peat from many catchments if allowed to continue.

Modelling sediment yield at the catchment scale

The development of the GIS-based model of soil erosion and transport that was applied to the Burrishoole catchment during this study is described in detail by May & Place (2005, this volume). In outline, the approach combines the Universal Soil Loss Equation (USLE), which predicts soil losses from the catchment, with a delivery ratio that determines the amount of eroded soil that enters the drainage network. By implementing this model within a GIS framework, it has been possible to take spatial variation in slope, elevation, land use and soil type into account in predicting soil loss and transport across the catchment.

The delivery ratio is calculated as a function of the erosive forces carrying the sediment across the catchment, and the travel distance to the receiving waterbody. In this study, erosive force was determined as a

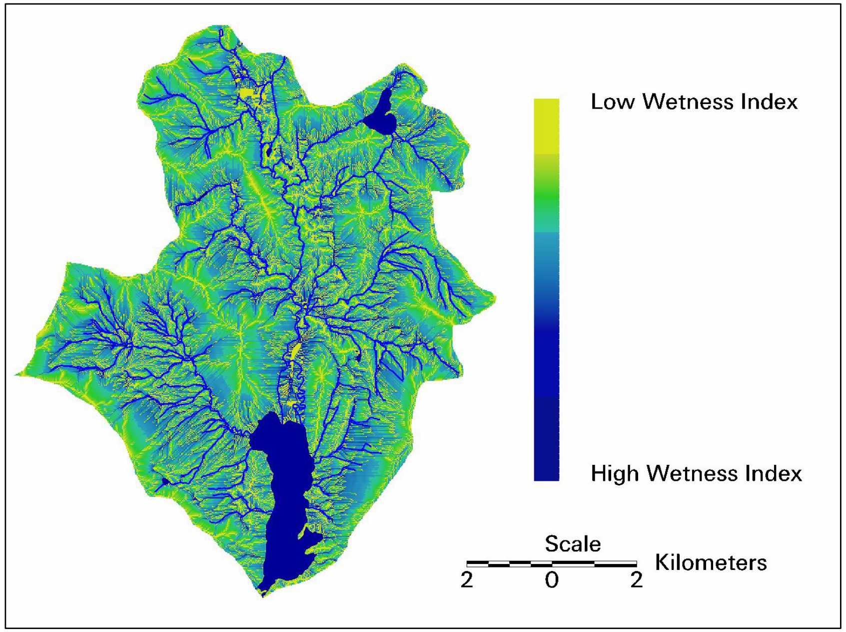

FIG. 6. Degree of saturation of areas of the catchment, as indicated by their Wetness Index value.

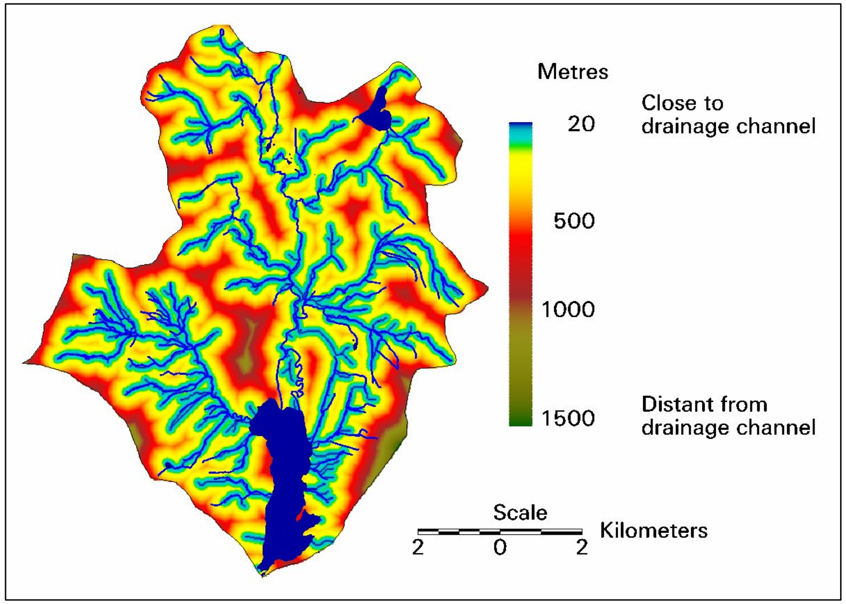

FIG. 7. Map showing the distance of each grid square within the catchment from the drainage channel into which it drains.

function of the Wetness Index (WI), slope characteristics and surface roughness of the drainage area. The Wetness Index identifies points in the catchment where saturation is likely to occur and was determined for every point in the catchment. The higher the value of WI, the wetter the area and the more likely it is that any rainfall will cause overland flow that will erode the surface of the soil. Particularly 'wet' areas of the catchment, as indicated by their high WI value, are shown in Fig. 6.

The method used to determine WI can also be used to identify the prevailing drainage network within the elevation dataset. It is important to identify this drainage network so that it is possible to determine its distance from any point within the catchment (a value needed for the delivery ratio calculation). A Euclidean cost distance function was applied to the drainage network data in order to determine the distance from any cell within the catchment grid to the appropriate 'downstream' drainage channel (Fig. 7).

These derived datasets were combined with the appropriate slope characteristics and roughness coefficients (based on land cover type), as described by May & Place (2005, this volume) to produce a model that would predict sediment delivery to the Glenamong River from its

catchment. Constants *a* and *b* within the delivery ratio were parameterised by calibrating the product of the total soil loss (as predicted by the USLE) and associated delivery ratio to the total annual sediment load (estimated from that measured in the river). These parameters could then be used to create a delivery ratio-derived dataset for the whole of the Burrishoole catchment (Fig. 8). These data highlight areas close to the drainage network and those on steep slopes as being the areas of the catchment that contribute the greatest proportion of their eroded material to the drainage network. This is an important modifier to the USLE approach as it moderates the total load on the basis of proximity to the drainage network and facilitates the production of a catchment map that shows the amount of sediment that each area contributes to the drainage network (Fig. 9). From this, it is possible to produce an estimate of the total annual sediment load for the Burrishoole catchment. This value is 1920 tonnes per annum. Although this result can also be used to identify the areas that are contributing most to the sediment transport within the drainage system, it cannot provide a detailed spatial analysis or prediction of the areas where catastrophic erosion, or gullying, is likely to occur.

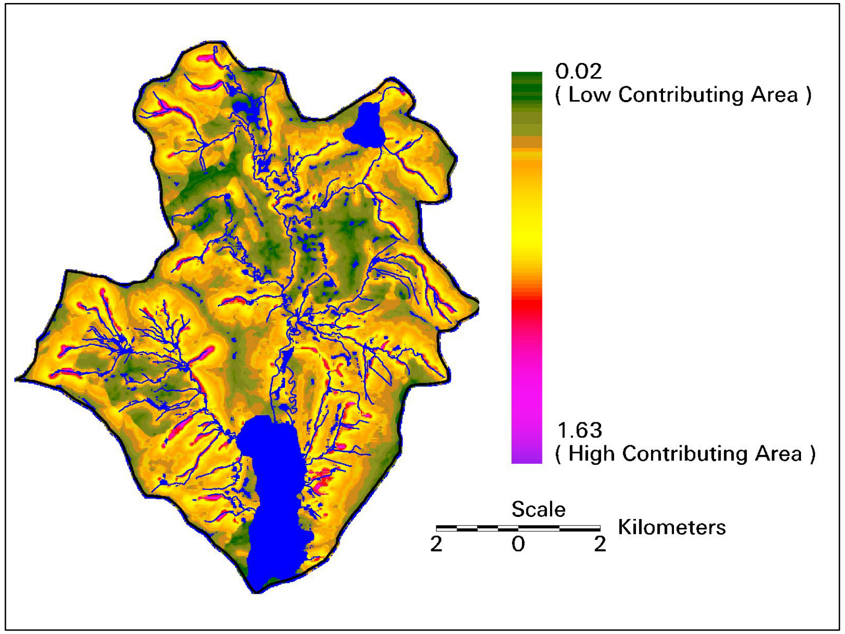

FIG. 8. Spatial variation in estimated delivery ratios across the Burrishoole catchment.

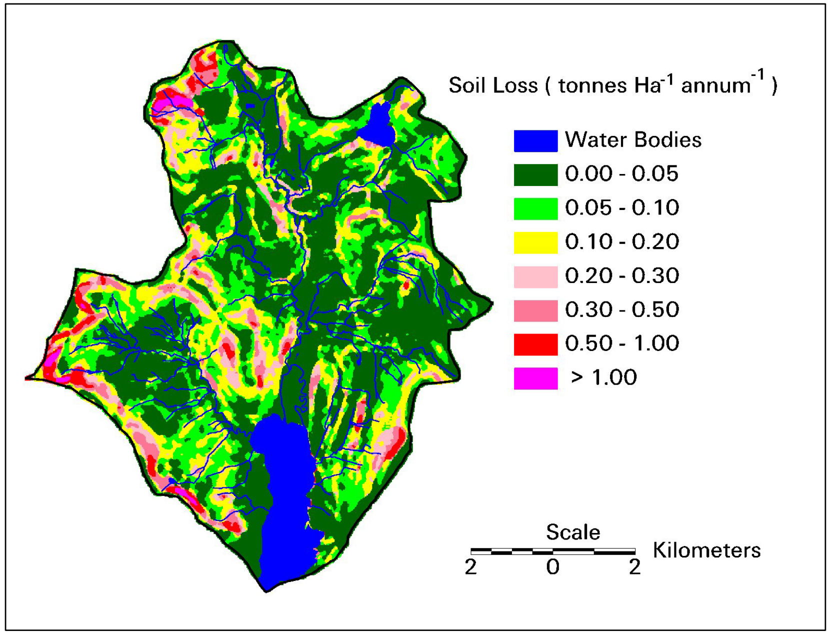

FIG. 9. Variation in the amount of sediment delivered to the drainage network by different areas within the Burrishoole catchment.

The results of these analyses were compared, in a qualitative manner, with the aerial photography available for the Burrishoole catchment to see whether areas that were predicted to contribute large proportions of eroded material to the drainage network corresponded with areas where peat erosion could be identified through photo-interpretation. Fig. 10 shows there is reasonable correspondence between the areas of exposed rock (which appear pale in the lower image) and the areas highlighted in the prediction as contributing most eroded material to the drainage network. This suggests that, in times gone by, these areas have lost most of their erodible material. Some sections, which have now become part of the drainage network (as seen in the aerial photography), are also being highlighted as high contributing areas. Again, this suggests that, under certain topographic conditions, high contributing areas become eroded to such an extent that they eventually become part of the drainage network. It was not possible to do a quantitative assessment of this comparison, as this would require more detailed land cover and management information than was available to the study.

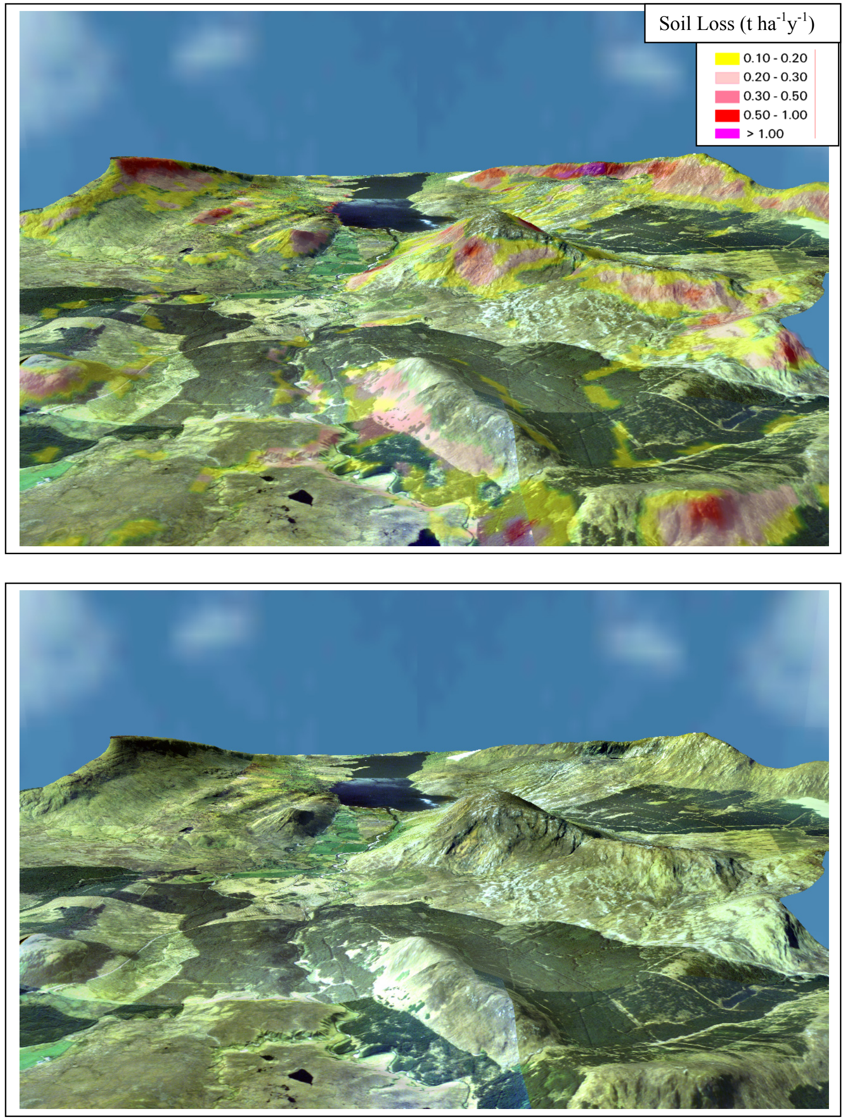

FIG. 10. 3-D view of the Burrishoole catchment (facing south), with *(above)* and without *(below)* predicted erosion rates superimposed.

One possible avenue for further investigation would be the use of the Wetness Index approach together with another derived measure, the Compound Topographic Index, to identify areas susceptible to gullying. This approach was used successfully by Montgomery & Dietrich (1994) under Australian conditions, but the threshold levels used by these authors would need to be re-determined to reflect local conditions for use in a peat dominated catchment on the west coast of Ireland. This process would need a detailed field survey to be undertaken to determine precisely where the areas of catastrophic erosion were occurring. As erosion in these conditions is being accelerated by anthropogenic effects, it is likely that any threshold approach would also need a detailed analysis of the effects of current management practice, a detailed survey of the variation in management practice across the catchment and, last but not least, an analysis of the behaviour of livestock within the catchment.

Acknowledgements

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