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An erosion model for evaluating regional land-use scenarios

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ABSTRACT

The conversion to pasture of indigenous forest on New Zealand hill country has led to increased mass-movement erosion and consequently increased sedimentation of waterways. Effective soil conservation requires a model that can evaluate erosion and sedimentation for different land-use scenarios. In this paper, we develop a model of mean sediment discharge related to mean erosion rates through a sediment delivery ratio. Mean erosion rate in a particular terrain ("erosion terrain") is the product of (i) the square of mean annual rainfall with (ii) a cover factor and (iii) an erosion coefficient that depends on erosion terrain. Measurements of mean sediment discharge are used to estimate erosion coefficients for each erosion terrain. The model can be used to predict mean sediment discharge in response to land-cover/land-use scenarios. It is easy to execute and uses input data readily available in GIS layers in New Zealand. This makes it suitable for widespread management application, in contrast to physically based models which are presently only suitable for research catchments. We demonstrate the utility of the model for three different applications: evaluating land-use scenarios in the Motueka catchment; setting priorities for soil conservation in the Manawatu catchment; and determining national trends in agricultural erosion over a 30-year period. The general methodology is applicable to countries dominated by mountains and steep hills with high erosion rates.

1. Introduction

Over the last 150 years following European settlement, much of the original indigenous forest in New Zealand has been converted to pastoral agriculture. In hill country, where trees are important for stabilising slopes, deforestation has led to increased soil erosion and consequently increased sedimentation in waterways (extremely so for some catchments when considered in the global context: Jansson (1988)). This can have detrimental effects on aquatic ecosystems by smothering fish habitat and significantly reducing the penetration of photosynthetically active light. In major catchments where stop banks have been constructed to reduce the risk of flooding, deposition of sediment in floodways reduces flood capacity. Increased storminess associated with climate change can only exacerbate these negative environmental effects. To mitigate sedimentation in waterways, catchment-wide approaches to reducing soil erosion are required (Newham et al., 2004). For large rivers, this is tantamount to regional approaches to soil conservation. Because the implementation of farm plans and retirement of steep hill country over large areas is expensive, it must be guided by predictive models that explicitly link erosion and sedimentation with land use. Then soil conservation work can be targeted to produce the greatest reduction in sedimentation.

Erosion in New Zealand is dominated by mass-movement processes, as in other mountainous and hilly countries. Common processes include landslides, large gullies (better described as fluvio-mass-movement gully complexes: Fuller and Marden, 2008), and earthflows (Eyles, 1983; Glade, 1998; Krausse et al., 2001; Hovius et al., 1997). Modelling of these processes in New Zealand has been confined to a limited number of geographic areas (Dymond et al., 1999; Mueller, 1998; Claessens et al., 2006; Claessens et al., 2007; Ekanayake and Phillips, 1999; Hovius et al., 1997; Crozier, 1996). For national and region-wide modelling, Griffiths and Glasby (1985) used an empirical approach to relate measurements of mean sediment discharge at 80 river sites around New Zealand to mean annual rainfall. They found that mean sediment discharge was proportional to mean annual rainfall raised to the power of 2.3. In a more comprehensive study, Hicks et al. (1996) used 203 sites to determine that mean sediment discharge was a function of rock type and mean annual rainfall raised to the power of 1.7. The difficulty with using either the Griffiths and Glasby (1985) or the Hicks et al. (1996) model is that neither involves land cover as a factor and yet we know from other studies that at the hillslope scale erosion rate depends significantly on land cover

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(Crozier, 1996; De Rose, 1996; Dymond et al., 2006, 1999; Fransen, 1996; Hicks, 1991; Marden and Rowan, 1993; Pain, 1969; Pain and Stephens, 1990; Page and Trustrum, 1997).

There are many erosion models reported in the international literature (Merritt et al., 2003; Aksoy and Kavvas, 2005).The focus is mainly on predicting surficial erosion in flat and rolling landscapes (Cogle et al., 2003; Heatwole et al., 1988; Jakeman et al., 1999; Jordan et al., 2005; Morgan et al., 1998; Mitasova et al., 1996; Moore and Wilson, 1992; Renard et al., 1991; Wischmeier and Smith, 1978). Models of mass-movement erosion do exist, but similarly to New Zealand, they are confined to limited geographic areas because of the need to obtain many input parameters (Borga et al., 1998; Doten et al., 2006; Hungr, 1995; Montgomery and Dietrich, 1994; Terlien, 1998; Wu and Sidle, 1995). Some empirically-based models of mass-movement erosion have been applied more broadly but tend to be GIS-based models of erosion risk rather than erosion rate (Aniya, 1985; Gokceoglu and Aksoy, 1996; Gritzner et al., 2001; Guzzetti et al., 1999; Huabin et al., 2005; Jibson et al., 2000; Luzi et al., 2000; Larsen and Torres-Sanchez, 1998; Lee et al., 2003; Turrini and Visintainer, 1998).

What is required is a spatial model of mean erosion rate that (i) makes use of both land cover and land management factors in addition to geology and mean annual rainfall, and (ii) is widely applicable geographically. Proposed land-use scenarios could then be evaluated in advance to ensure region-wide plans for soil conservation were effective in achieving objectives for reducing erosion and sediment yield. In this paper, we extend the structure of the Hicks et al. (1996) empirical model to incorporate land cover. We formalise the relationship between mean erosion rate and mean sediment discharge through the use of a sediment delivery ratio. This permits the application of *a priori* knowledge of the influence of land cover on hillslope erosion into an erosion model for use at region-wide (and national) scales. The model requires stratification of the landscape into erosion terrains within which erosion processes are similar. We demonstrate the utility of the model for three different applications: estimating sediment discharge into Tasman Bay for different land-use scenarios of the Motueka catchment; determining national trends in erosion associated with agriculture over a 30-year period; and setting priorities for soil conservation in the Manawatu catchment. The general methodology is applicable to countries dominated by mountains and steep hills with high erosion rates.

2. Erosion terrains

Erosion processes vary throughout New Zealand, depending on rock type, landform (especially slope angle), and rainfall. We partitioned New Zealand on the basis of these factors at the scale of 1:50,000 to produce areas with similar erosion processes, called erosion terrains, by amalgamating land-use capability units from the New Zealand Land Resource Inventory (Eyles, 1983). While differences in land use or management and vegetation cover are important, these were omitted from the definition in order to represent intrinsic erosion susceptibility independently from factors that can change with time. A three-level hierarchical classification was used for both the North and South Islands (Appendices 1 and 2). For the North Island, we differentiated nine groups at the top level on the basis of landform and slope. At the second level, 26 groups were differentiated on rock type. At the third level we differentiated fifty-two groups on the basis of erosion processes and further detail of rock type. For the South Island, we differentiated nine groups at the top level, based on landform and slope. At the second level 18 groups were differentiated on rock type, induration, and presence of loess, and at the third level 37 groups were differentiated on erosion processes and further detail of rock type.

3. Model equations

The model describes long-term mean erosion rates at the source and the resulting long-term mean sediment discharge in rivers. The erosion rate at a geographic point (*x*,*y*) is defined as the rate of soil mass loss per unit area (kg m^{-2} s^{-1}). Erosion rates vary in space and time, so may be denoted by $e(x,y,t)$. The long-term mean erosion rate is denoted by $\bar{e}(x,y)$, and defined by

$$\bar{e}(x,y) = \frac{\int_{t_0}^{t_0+T} e(x,y,t)dt}{T} \tag{1}$$

where *T* is of the order of decades.

Similarly the sediment discharge at a point (*x*,*y*) in a river is defined as the rate at which sediment mass passes a point (kg s^{-1}). Sediment discharge varies in space and time, so may be denoted by $s(x,y,t)$. The long-term mean sediment discharge is denoted by $\bar{s}(x,y)$, and defined by

$$\bar{s}(x,y) = \frac{\int_{t_0}^{t_0+T} s(x,y,t)dt}{T} \tag{2}$$

The relationship between long-term mean sediment discharge and long-term mean erosion rate is simple if all sediment mobilised by erosion reaches a stream where fluvial forces transport the sediment through the river network. In this case, sediment discharge is the integral of erosion rate over the watershed above the discharge point. However, landscapes are sometimes disconnected from streams, or erosion processes deliver only a proportion of eroded sediment to streams, and so a sediment delivery ratio needs to be considered. The sediment delivery ratio at a point, denoted by $D(x,y)$, is defined as the ratio of mass of sediment delivered to a point in the stream network (x_0 , y_0) from (*x*,*y*) over the mass of eroded soil at (*x*,*y*):

$$D(x,y) = \frac{\Delta\bar{s}(x_0,y_0)T}{\bar{e}(x,y)\Delta x\Delta yT} \tag{3}$$

where Δ represents a small change in the mean sediment discharge due to erosion at (*x*,*y*). (Floodplain deposition and bank erosion are not regarded as source erosion but as temporary storage in sediment delivery). The relationship between long-term mean sediment discharge at a point (x_0,y_0) and long-term mean erosion rate may then be written as

$$\bar{s}(x_0,y_0) = \iint\limits_{\substack{\text{catchment}\\ \text{above}(x_0,y_0)}} D(x,y)\bar{e}(x,y)dxdy \tag{4}$$

Hicks et al. (1996) and Griffiths and Glasby (1985) showed that for medium to large New Zealand catchments, geology and annual rainfall were important factors in explaining long-term mean sediment discharge. Although these studies found land cover was not an explanatory factor, other studies (see Introduction) show it is important; moreover, there were insufficient data in the Hicks et al. (1996) and the Griffiths and Glasby (1985) studies to investigate the full interaction of geology, rainfall, and land cover, as there are few instances of paired catchments with the same geology and with homogeneous but differing land cover. Therefore, we postulate that