On the assessment of flash flood impacts through the use of rainfall measurements from dual frequency microwave links and energy and water balance

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INTRODUCTION

Sheet and gully erosion are caused mainly by the action of water. Sheet erosion is a general removal of the surface soil over a large area as it slips gradually down the slopes. Gully erosion is more localised, as when a sudden rainstorm producing a concentrated run-off, rips a deep gash into the land. These forms of soil erosion are widespread in the world; even in the UK, sheet erosion may take place where a field has been ploughed up and down a slope.

In this paper we consider one specific catchment in Italy, the Rio Centonara catchment located near Bologna, on the eastern slopes of the Apennines, which contains two small rivers, the Rio Centonara itself and its tributary the Rio Ciagnano. This catchment exhibits both types of erosion, as shown in Figure 1. The upper reaches of this catchment are largely denuded of soil whereas at the lower levels erosion is not as extensive, and presently most of the land is used for arable farming.

MODELLING SOIL EROSION

Soil erosion caused by rainfall is due to raindrop impact and surface runoff. We focus in this paper on soil detachment produced by direct incidence of raindrops on the soil surface. Cerro *et al*. (1998)and others pointed out that an accurate description of raindrop mass, shape and impact velocity are required to determine the ability of raindrops to detach soil. Sharma and Gupta (1989) proposed estimating soil detachment by the effect of raindrop impacts using a linear model of mass detachment per unit area, d_T :

$$d_T = k_d (e - e_o) \qquad e \geq e_o$$

$$d_T = 0 \qquad e < e_o \qquad (1)$$

where k_d is the detachability coefficient, e is the kinetic energy of the raindrop and e_o is the threshold energy required to initiate detachment. By integrating the effect of individual drop impacts, the total detachment (D_T), may be expressed as the difference between the flux of kinetic energy of raindrops per unit time and unit soil surface (E), and the unavailable energy of the drops (E_o) both expressed in Joules m^{-2} s^{-1}, multiplied by k_d.

Fig. 1 Example of soil erosion in the Rio Centonara catchment, near Bologna, Italy.

Over the last ten years or so models of the mechanisms of water-induced soil erosion have been proposed (see for example Hairsine and Rose, 1991, Rose *et al*., 1994). Building upon these models Heilig *et al*. (2003) presented a conceptual model which clarified some of the basic mechanisms involved. Specifically, as rainfall begins and the soil surface is initially impacted with raindrops, soil particles are detached from the soil surface and entrained into the overland flow. Light particles, with low settling velocities, will move far from their original point of detachment, whereas heavy particles will settle quickly, near their original positions. Eventually, most of the light particles will be removed leaving a ‘shield’ of heavy particles that protect the underlying soil. For a simple situation of just two soil classes, one part clay which once entrained into the flow never settles, and nine parts sand which settles rapidly, Heilig *et al*. (2003) (following Sander *et al.*, 1996) specified the rate of change in the concentration of clay in the surface flow c_1 as follows:

$$Dc_1/dt = 1/D[aR^b(1\text{-}H)/I - Rc_1] \qquad (2)$$

D is the flow depth; R is the rainfall rate; I is the number of particle size classes characterising the soil in this case ten (each class represents an equal mass fraction); a is the bare soil detachability; and b is a soil parameter close to 1.0. The term Rc_1 is the mass flow rate of clay particles out of the system. The 'shielding' state is represented by the parameter H, where H = 0 corresponds to no shielding and H = 1 to complete shielding and therefore full protection from further erosion.

The conservation of mass for the sand fraction is

$$DM/dt = 9aR^b\,(1 - H)\,/I \tag{3}$$

and the shielding factor is

$$H = 1 - \exp[-9aR^b/IM_T \tag{4}$$

The power law relationship in Equations 3 and 4 was first suggested by Meyer (1981). However, since the coefficient b is almost equal to 1.0, we may replace the power law by the linear kinetic energy relationship given in Equation 1.

Cerro *et al*. (1998) discussed the estimation of the effective kinetic energy, $(e - e_o)$, using an exponential drop size relationship, and Bech *et al*. (1999) considered the estimation of $(e - e_o)$ from weather radar data. However, from this work it is clear that the effective kinetic energy is very dependent upon the drop size relationship that is used. Also estimation of the rainfall rate using radar is dependent upon the drop size distribution. Only if the drop size relationship is known reliably can the soil erosion be specified using equations similar to Equations 2–4. The use of rainfall estimates made using the signal attenuation caused by rainfall along microwave communication links offers a procedure for warning of the likelihood of severe soil erosion which is independent of the drop size distribution.

DUAL FREQUENCY MICROWAVE LINK MEASUREMENTS OF RAINFALL

It has been shown by Hardaker *et al*. (1997) and Holt *et al.* (2000) that good estimates of path-averaged rainfall may be obtained from the difference in signal attenuation caused by rainfall at two frequencies along a microwave link. The specific attenuation K (dB km^{-1}) is a function of the rainfall rate R (mm $hr–^{-1}$) along the link according to,

$$K = cR^d \tag{5}$$

This relationship depends critically upon the signal frequency, and the parameters c and d are unknown, but sensitive to temperature, rain drop shape and drop size distribution. However, Goddard *et al*. (1998) demonstrated that, if a dual-frequency microwave link is to be used, two frequencies and polarisation states could be selected for which the specific attenuation difference is relatively insensitive to these unknown parameters. After the raw attenuation measurements have been adjusted for gaseous absorption, there is a linear relationship between this parameter and rainfall rate. Hence, use of rainfall measurements so-derived for soil erosion estimation from Equations such as 2 to 6 could be more reliable than using weather radar estimates of rainfall. Certainly there is a close correspondence between line integrated rainfall measurements made using raingauges and microwave link attenuation, as shown in Figure 2. However,

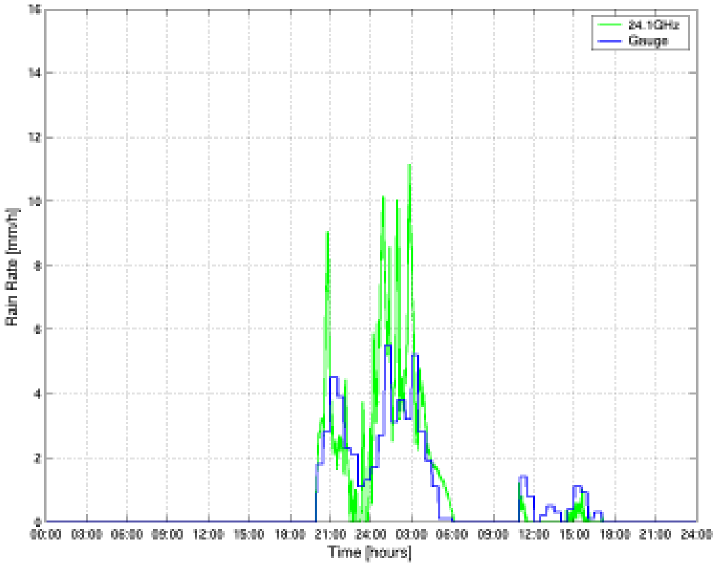

Fig. 2 Microwave link attenuation at 24.1 GHz and raingauge (RG) estimates of line integrated rainfall for the Rio Centonara catchment near Bologna, Italy on 11–12 April 2003

the microwave link measurements are averages over the length of the link, and therefore only areal estimates of soil erosion are possible. In the case of the Rio Centonara catchment, the links are only 3 km long, extending over most of the catchment. Therefore the use of the links is likely to be more reliable than the use of weather radar (the area is covered by a C-band radar to the north of Bologna), unless the radar is extremely well calibrated all the time.

For larger catchments, in which the line-integrated measurements cannot represent the catchment rainfall properly, it is likely that the microwave link data could be better used to effect such a radar calibration rather than be used on their own. Nevertheless, if the microwave links extend along a river valley covering most of the drainage basin, then the use of the link estimates of rainfall are likely to be more reliable than either raingauge or radar data in providing a catchment-wide warning of conditions likely to lead to severe soil erosion.

ESTIMATION OF THE LIKELY OCCURRENCE OF SOIL SHIELDING

The shielding state is represented by the parameter H in Equations 4 and 7. The rainfall rate or kinetic energy of the raindrops can be estimated from microwave link or weather radar data. However, to evaluate H the total mass of deposited sand (M_T) (for the model considered earlier), the bare soil detachability (k_d) and the number of particle size classes (I) used, need to be known. The values of these parameters are usually derived from laboratory or careful field experiments (see for example Proffitt *et al*., 1991, Herlig *et al*., 2001). However, the likelihood of shielding is related to the ability of the soil to absorb radiation which is related to the soil porosity and soil moisture content (SMC). Consider the energy balance equation,

$$H_s = R_n - G - lET \tag{6}$$

where H_s is the sensible heat flux; ET is the evapotranspiration; lET is the latent heat of evaporation of water; R_n is the net radiation; and G is the energy stored in the soil-canopy system. The evapotranspiration can be deduced from the simple water balance:

$$ET = R - P - (SMC_t - SMC_{t-1}) \tag{7}$$

where R is the rainfall over the period t-1 to t and P is the percolation of water into the soil. If the time period t-1 to t is short then, as a first approximation P may be taken as zero, although this is not always the case.

It is proposed that G may be considered as a proxy measure of the soil porosity, and hence the shielding potential. Therefore Equation 6 can be used to derive G from automatic weather station (R_n, lET) and acoustic anemometer (H_s) data.

If we normalise G with the total energy received at the Earth's surface, R_n, then we consider the resulting ratio as the parameter (1-H). For example, little energy will penetrate the soil if there is either considerable vegetation or the soil surface comprises large heavy particles, i.e. the underlying soil is shielded. Conversely, if a high proportion of the incident energy penetrates the soil we may assume that the surface soil particles are small and there is little shielding.

From Table 1 we see that the potential for shielding in the Rio Centonara catchment is high on 14 April 2003 (a), and hence soil erosion, should heavy rainfall occur is unlikely. However, on the 22 May 2003 (b) the potential for shielding is lower than on 14 April 2003, and therefore erosion is somewhat more likely. Between the two cases, crops have grown, acting to cause moisture to percolate downwards via the root systems. The magnitude of this percolation has been estimated from the observed increase in flow of the Rio Ciagnano. Before the end of April, even when rain occurred, there was very little variation in the flow of this river.

On the 22 May the river level rose by about 5 cm over 4 hours, returning to the base flow level some 18 hours later. The volume of water removed from the catchment over this period, divided by the catchment area, gives the mean percolation downwards and eventually into the river. No overland flow was observed except in the river channel. Evaporation continued during this period, and it is estimated that the total loss of water from the catchment on this day is about 12 mm.

Table 1. The variation of R_n, ET, H_s, P and G for (a) 14 April 2003 and (b) 22 May 2003 at the Villa Poggiolina, Rio Centonara catchment near Bologna, Italy

Date	*R_n(w m^{-2})*	*H_s(w m^{-2})*	*ET(mm)*	*P(mm)*	*G(w m^{-2})*	*H*
14 April 2003	249	71	3.2	0	10.7	0.96
22 May 2003	379	124	6.6	5.8	254	0.83

OVERLAND FLOW

The likelihood of rapid run-off in heavy rainfall situations will be substantially increased if shielding occurs. Hence, continuous evaluation of G is necessary in assessing flash flood potential. Whilst surface based instrumentation, as used in the present study, provides the necessary data to do this, it is clear that conditions will vary substantially throughout a catchment. It may therefore be necessary to employ satellite-based remote sensing techniques to estimate G, such as described by Fox *et al.* (2000) using the Normalised Difference Vegetation Index (NDVI) approach described by Choudhury and Idso (1987).

CONCLUDING REMARKS

The use of estimates of rainfall derived from microwave link attenuation and weather radar data in providing warnings of the likely occurrence of soil erosion has been discussed. Microwave link data have the advantage of not being dependent upon knowledge of raindrop size spectra when deriving the kinetic energy of raindrops. Nevertheless, single dual frequency links may be of limited applicability in large catchments.

The impact of soil surface layer shielding is important in assessing the impacts of heavy rainfall and subsequent timing of flash floods and erosion. A simple method of assessing the existence or otherwise of shielding, based upon the absorption by the soil of incident solar energy, has been proposed and partially tested. Further field studies are necessary to validate this approach.

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