

Invited Commentary, Hydrological Processes Today

Sediment Delivery Ratios: A misaligned approach to determining sediment delivery from hillslopes

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Considerable interest exists in the impact of land management on water quality throughout the world. A large number of non-point source (NPS) pollution or water quality models exist. In many cases, these models use the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) or the revised version of the USLE (RUSLE, Renard et al., 1997) to model erosion on hillslopes in conjunction with sediment delivery ratios to determine the sediment delivered from the hillslope to water bodies. The sediment delivery ratio (SDR) can be defined as the ratio of the erosion upslope of a point in the landscape to the sediment delivered from that point.

Erosion involves detachment, transport and deposition processes that operate all the time. The net loss or gain of soil material depends on the balance between the rates of particle uplift and deposition. In the context of modelling sediment delivery on hillslopes with respect to water quality, erosion refers to the situation where there is a net loss of soil material from the soil surface, and deposition to the situation where there is a net gain. The use of SDRs owes its origin to the observation that using erosion predicted by the USLE overestimates the amount of sediment delivered from hillslopes because sediment deposition often occurs on hillslopes whereas the USLE does not account for deposition. The USLE was developed on planar surfaces and was not designed to apply to situations where there is a net gain of soil material on the area being considered. However, SDRs are essentially “performance” factors which simply relate observed or modelled amounts at the plot scale to observed amounts at a larger scale. Using them to predict sediment delivery from hillslopes can produce erroneous results.

One of the features of the USLE/RUSLE – SDR approach is that the predicted amount of sediment delivered from the hillslopes varies directly with the predicted erosion for any given hillslope profile. Halve the erosion and that results in a halving of the amount of sediment delivered from the hillslope. However, the deposition effect results from sediment in

or entering the flow exceeding the transport capacity of that flow at a point on the hillslope. As a result, sediment delivery is directly related to erosion if the transport capacity of the flow is not exceeded (i.e. $SDR = 1.0$) but is limited by the transport capacity if erosion exceeds the capacity of the flow to transport the eroded material (i.e. $SDR < 1.0$). This concept is encapsulated in Fig. 1 and in so called process based erosion models like WEPP (Laflen et al., 1997). In reality, when the SDR is less than 1.0, reducing the erosion rate will not necessarily result in a reduction in the amount of sediment delivered from the hillslope. It may simply increase the value of the SDR. This is illustrated by the following example.

Consider a 1 ha segment at the bottom of a hillslope. Consider, for example, that, because of existing hydrologic and hydraulic conditions, the element can, over some given period of time, transport 5 t of sediment crossing the upslope boundary across the segment and over the downslope boundary. Consider also that the element has the potential to erode at 2 t/ha. Now consider that the upslope area delivers 15 t to the element. This results in 10 t being deposited in the element; the element does not erode, and the $SDR = 5/15 = 0.3$. If the upslope area delivers 10 t, 5 t is deposited and the $SDR = 5/10 = 0.5$. However, if the upslope area delivers 3 t, there is no deposition in the element and the element erodes to add 2 t to the output. In this case, the $SDR = 5/5 = 1.0$. The SDR will be 1.0 whenever the upslope area delivers 5 t or less (Fig. 2)

Given that SDRs are essentially “performance” factors which simply relate observed or modelled amounts at the plot scale to observed amounts at a larger scale, NPS or water quality models should be based on an alternative approach. Williams (1975) contended that the delivery ratio is not necessary if the rainfall energy factor in the USLE is replaced by a runoff rate factor because watershed characteristics such as drainage area, slope, and watershed shape influence runoff rates and delivery ratios in a similar manner. The resulting equation has become known as the Modified USLE (MUSLE). SWAT (Soil and Water Assessment Tool, Arnold et al., 1998) uses the MUSLE despite the MUSLE lacking mathematical integrity (Kinnell, 2004). The MUSLE uses the USLE factors for soil erodibility (K), the crop and crop management factor (C), the soil conservation protection factor (P) and the topographic factors (L,S) while using an event erosivity index based on runoff parameters rather than the EI_{30} index (where E is event kinetic energy and I_{30} is the maximum rainfall intensity in 30 minutes) used in the USLE and the RUSLE. However, the K factor has units of soil loss per unit of the erosivity index. Consequently the USLE K factor

cannot be applied unless the erosivity index is EI_{30} . Also, if the MUSLE event erosivity factor is based on runoff from anything but bare fallow with cultivation up and down the slope, the C and P factor values will also need to be different from those used in the USLE or else the effect of runoff will be considered twice. Thus, even if Williams' contention that the delivery ratio is not necessary if the rainfall energy factor in the USLE is replaced by a runoff rate factor is correct, and that is open to question, the MUSLE disobeys fundamental mathematical rules. Two currently popular approaches in NPS and water quality modelling (the USLE with SDRs and the MUSLE) lack scientific or mathematical robustness.

Given the relative ease by which erosion at the plot scale can be predicted by empirical models like the USLE, or valid variants of it like the USLE-M (Kinnell and Risse, 1998), one approach is to use a sediment transport model to control the movement of sediment when deposition conditions exist. The approach is consistent with that illustrated in Fig.1. The erosion model acts as source of the sediment which is yielded for transport, and deposition occurs if that amount exceeds the transport capacity determined by the sediment transport model. There are many sediment transport models and the issue in this approach then becomes centred on the choice of sediment transport model and its performance. Many sediment transport models owe their origin to modelling sediment movement in channels, rivers or streams. Sediment transport capacities associated with these models usually depend on parameters related to flow velocity that vary in both space and time. While erosion may be predicted on an event basis using the USLE or better still, a variant of it like the USLE-M, the sediment transport model may need to operate on a within event basis. This often means that assumptions about temporal variations in rainfall are necessary to generate flow conditions that enable sediment transport capacities to be calculated. While incorrect assumptions will lead to errors, this approach is more scientifically defensible than using SDRs.

There are those who will consider that the use of empirical models with either SDRs or sediment transport models should be replaced by models that account for erosion and deposition processes more explicitly. Examples of more process based models that fall into this category are WEPP (Laflen et al, 1997) and EUROSEM (Morgan et al., 1998). A small watershed version of WEPP exists and LISEM (De Roo et al., 1996) uses a EUROSEM based approach in grid cells using dedicated software within a GIS (PCRaster). EUROSEM is an event based model. WEPP is a continuous simulation model. Both require more data to run than empirical models like the USLE/RUSLE. The data requirements may be prohibitive in

many cases so that the empirical erosion model approach may be the only practical one. The USLE/RUSLE plus SDR approach is relatively simple but it can lead to errors which may be avoided by using the USLE/RUSLE, or a valid variant, with a sediment transport model.

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Figure Captions

Figure 1. Approach used by Meyer and Wischmeier (1969) to simulate the processes of soil erosion by water.

Figure 2. Variation in sediment delivery ratio for hillslope in relation to the sediment input to the bottom segment whose transport capacity is 5 t.

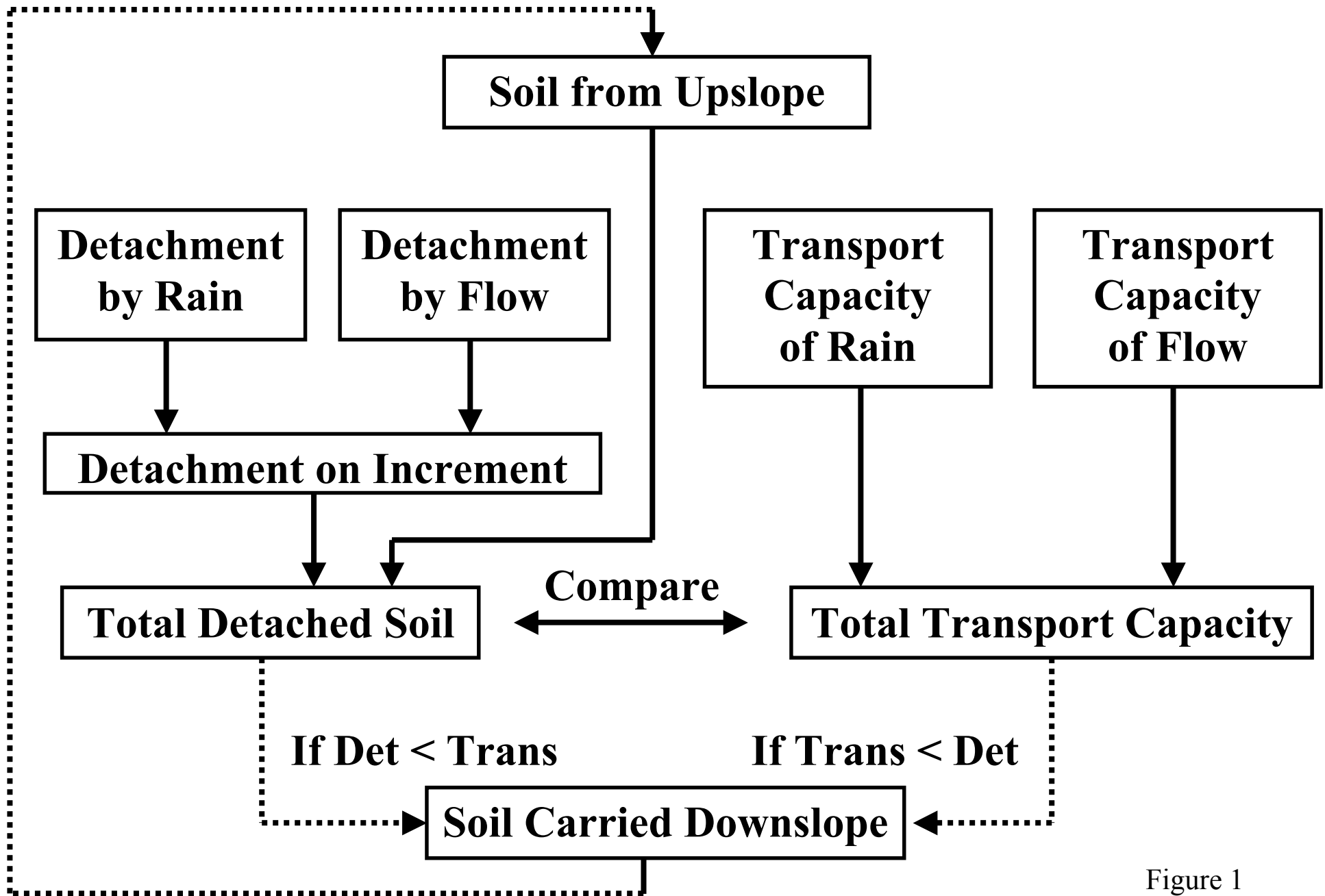


Figure 1

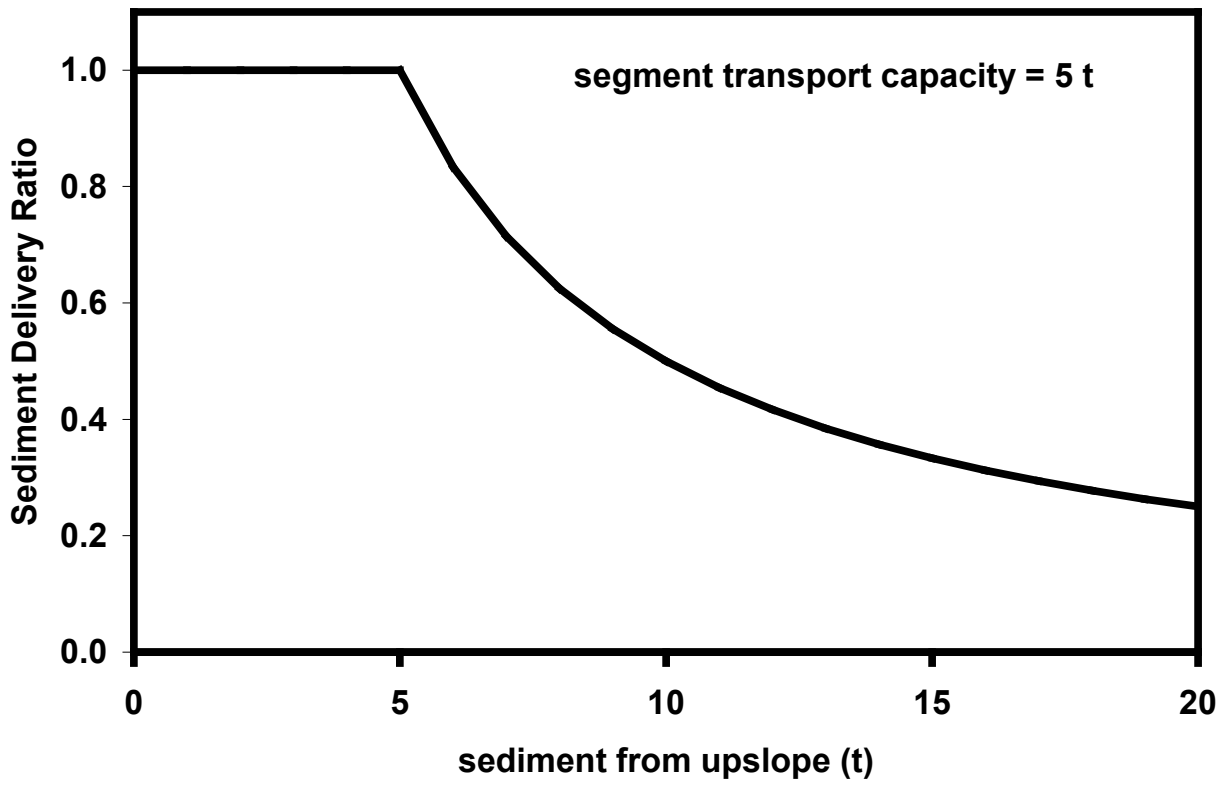


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