Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **31**, 750–761 (2006)
DOI: 10.1002/esp.1291

Model study of the relationship between sediment yield and river basin area

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Received 8 November 2004
Revised 14 July 2005
Accepted 5 September 2005

Abstract

The SHETRAN physically based, spatially distributed model is used to investigate the scaling relationship linking specific sediment yield to river basin area, for two contrasting topographies of upland and more homogeneous terrain and as a function of sediment source, land use and rainfall distribution. Modelling enables the effects of the controls to be examined on a systematic basis, while avoiding the difficulties associated with the use of field data (which include limited data, lack of measurements for nested basins and inability to isolate the effects of individual controls). Conventionally sediment yield is held to decrease as basin area increases, as the river network becomes more remote from the headwater sediment sources (an inverse relationship). However, recent studies have reported the opposite variation, depending on the river basin characteristics. The simulation results are consistent with these studies. If the sediment is supplied solely from hillslope erosion (no channel bank erosion) then, with uniform land use, sediment yield either decreases or is constant as area increases. The downstream decrease is accentuated if rainfall (and thence erosion) is higher in the headwaters than at lower elevations. Introducing a non-uniform land use (e.g. forest at higher elevations, wheat at lower elevations) can reverse the trend, so that sediment yield increases downstream. If the sediment is supplied solely from bank erosion (no hillslope erosion), the sediment yield increases downstream for all conditions. The sediment yield/basin area relationship can thus be inverse or direct, depending on basin characteristics. There still remains, therefore, considerable scope for defining a universal scaling law for sediment yield.

Keywords: erosion controls; land use impact; rainfall distribution; river basin; scale; sediment model; sediment source; sediment yield

Introduction

A principal objective of river basin sediment models is to link the on-site rates of erosion and soil loss within the basin to the outlet sediment yield. It is clear from field studies, though, that the dominant response mechanisms behind the link, along with the sediment yield itself, can change with basin scale. For example, as basin scale increases, the significance of individual local supply events decreases while the control exercised by the distance between hillslope sediment source and channel increases. Of fundamental interest, therefore, is whether there is a law which enables the dominant response mechanisms and the sediment yield to be modelled as a function of basin scale. Currently, the only working model of such a scale effect which has received much publicity is the relationship between sediment delivery ratio (or just specific sediment yield) and basin area. However, this model is inexact, empirical and (because empirical) cannot be used reliably to predict the impact of changes in basin environment, such as land use or climate. There is a need therefore to investigate the extent to which the model can be considered general, to identify the controlling response mechanisms and to define the limits of its use. As both direct and inverse forms of the relationship have been observed, an important need is to define the conditions for which the different forms are valid.

A particular difficulty in past evaluations, and the cause of the model empiricism, has been a reliance on field data, which so far have provided only a limited basis for isolating and identifying the processes controlling the sediment yield/basin area relationship. To overcome this, and to allow a systematic assessment of the relationship, this study uses a physically based, spatially distributed, basin modelling system. The spatial distribution allows the variation of sediment yield with area within the basin to be modelled while the physical basis allows both the principal erosion mechanism and the basin characteristics to be varied as desired. The simulated sediment yields are then used to investigate the robustness of the sediment yield/basin area model as a function of sediment source. It is intended that the modelling approach should both complement and provide an integrating framework for the data-based studies.

Sediment Yield as a Function of Basin Area

Attempts to relate sediment yield (or sediment delivery ratio) to basin area date back at least half a century (e.g. Brune, 1951; Dunne and Leopold, 1978, p. 680). High variability in the data is often evident and it has become clear that a relationship between sediment yield and basin area is best defined when considering regions of similar geology, land use and runoff (e.g. Dunne and Leopold, 1978, p. 681; Morris and Fan, 1997, p. 7.31). Frequently, though, and especially within these constraints, basin area has been isolated as the dominant control and over the decades several studies have suggested that specific sediment yield (as mass or volume per unit area per unit time) decreases as basin area increases. Thus Morris and Fan (1997, p. 7.31) quote Strand and Pemberton (1987) who use data from 28 reservoirs in the semi-arid USA, with basin areas of 1–100 000 km^2 to derive the relationship:

$$SY = 1098\ A^{-0\cdot 24} \tag{1}$$

where SY = specific sediment yield ($\mathrm{m}^3\ \mathrm{km}^{-2}\ \mathrm{a}^{-1}$) and A = area (km^2). Dendy and Bolton (1976) similarly give an inverse relationship (with an exponent of –0·16) based on data from 800 reservoirs throughout the USA with basin areas of 2·5 to 78 000 km^2. Avendaño Salas *et al.* (1997) use data from 60 reservoirs in Spain, with basin areas of 31 to 17 000 km^2, to show a set of inverse relationships between sediment delivery ratio and area. Explanations for the inverse nature of the relationship are that, as basin size increases, slope and channel gradients (and hence transporting energy) decrease, opportunities for deposition increase in wide valley floors and channel bars, the distance between hillslope sediment source and channel increases (reducing the sediment delivery ratio) and localized storms (which cause erosion) have proportionally less spatial effect.

Through time the inverse relationship has acquired the status of accepted convention. Warnings have been issued about its empirical nature (which effectively represents a wide range of erosion and transport processes), about the potentially over-riding influence of local site conditions and about regional variations (e.g. Walling, 1983; Morris and Fan, 1997, p. 7.32; Verstraeten *et al.*, 2003). Nevertheless, in the right circumstances, it provides an attractive scaling model. In the last decade or so, though, a number of studies have indicated that the relationship can be direct as well as inverse. Suggested causes include remobilization of channel sediments, perhaps laid down thousands of years ago in more erosive times (Church and Slaymaker, 1989; Ashmore, 1992), riparian erosion (Rondeau *et al.*, 2000), downstream increase in cultivated area (and hence soil erodibility) (Krishnaswamy *et al.*, 2001) and spatial distribution of rainfall erosivity (Krishnaswamy *et al.*, 2001). From an analysis of 1872 mountain rivers around the world, Dedkov and Moszherin (1992) conclude that, where hillslope erosion (i.e. sheet and gully erosion) is the main source of sediments, sediment yield decreases as basin area increases, whereas where channel (e.g. bank) erosion is dominant, erosion rates and sediment yield increase as basin area increases. On the basis that hillslope erosion tends to be dominant in areas disturbed by human activity (e.g. agriculture) and that the early sediment yield studies were often dominated by data from the USA (where the land is heavily affected by human activity) the possibility has been raised that the inverse relationship is in fact a reflection of human impact on the fluvial system rather than a basic principle (Walling and Webb, 1996). Evidence that this may indeed be the case has been provided recently by Dedkov (2004) who, analysing 352 Eurasian basins, found that the inverse relationship is characteristic only of intensively cultivated basins (where hillslope erosion may be presumed to be significant). A direct relationship between sediment yield and basin area was observed for uncultivated basins or basins with limited cultivation (where bank erosion may be presumed to be the principal source of sediment). Further complexity has been added by Jiongxin and Yunxia (2005) and de Vente and Poesen (2005) who present examples in which sediment yield first increases and then decreases as area increases, as a function of surface material distribution, basin adjustments at large time and space scales, basin-scale variation in energy expenditure and the relevant erosion and sediment transport processes.

The recent studies show that a single-natured relationship between specific sediment yield and basin area is oversimplistic. However, their interpretation of the overall trends in the sediment yield/basin area relationship is based on analysis of the distinguishing features, such as land use, of the test basins. They do not consider the controlling erosion and transport processes directly or in isolation from each other and are therefore limited in the extent to which they can provide a consistent overview of how the relevant controls determine whether the relationship varies in one sense or the other. A principal aim of this study is to investigate systematically, using mathematical modelling, the conditions under which the sediment yield/basin area relationship is inverse or direct. In particular it follows up the findings of Dedkov and Moszherin (1992), Krishnaswamy *et al*. (2001) and Dedkov (2004) on the importance of sediment source and the spatial distribution in land use and rainfall erosivity. In so doing it also tests the ability of our current models to reproduce the overall observed patterns. The authors are not aware that the topic has previously been addressed on a modelling basis.

Justification for Use of Physically Based Model

The ideal basis for investigating the sediment yield/basin area relationship would be data sets collected on a nested basis in basins with spatially homogeneous geology, soil type, vegetation and rainfall. Comparison of the relationships so derived between basins with different characteristics would indicate both the generality of the basin area dependency and the effect of the variations in characteristics. However, it is not easy to delineate test areas of a sufficient size which have a homogeneous geology, land use and runoff. Further, available data sets tend to refer, not to nested basins, but to collections of neighbouring basins. In practice, therefore, the opportunity for systematic investigation of the sediment yield/basin area relationship for a range of controlling influences is limited using field data.

By contrast, using a physically based, spatially distributed, basin model it is possible to generate data sets to support systematic investigation. The spatially distributed nature of the model allows sediment yield to be determined on a nested basis within the model basin. The physical basis allows basins with a range of geological, land use and runoff characteristics to be created. Also, the erosion and sediment transport processes are represented individually (not as a lumped whole) so that, for example, the separate influences of hillslope and river bank sediment supply can be identified.

However, when using physically based, spatially distributed models to investigate scale dependency, it should be remembered that these models are subject to their own scaling constraints (e.g. Beven, 2001, pp. 19–23). Their effects should not be confused with those of the physical delivery system being investigated. In their favour, the models represent the erosion and transport processes in a manner quite independent of the sediment yield/basin area relationship under investigation, so are not predisposed to provide any particular form of the relationship. That is, the models derive sediment yield by simulating on-site soil erosion, transporting the eroded material in overland flow to the river system and then transporting it along the river to the outlet: they do not use any area-based function. On the other hand, the model results may vary with the size of the grid square, or other discretization unit, used in representing spatial distribution (e.g. Beven, 2001, pp. 19–23; Vázquez *et al*., 2002). Uncertainty in model parameterization may also arise when adapting the typically point measurements of, for example, soil properties for use with a grid resolution which may be as large as 2 km. However, these effects tend to have a greater impact on output magnitudes, rather than the overall trends and directions of change which are of interest in this study. Comparison of results for different representations of a basin remain valid as long as those representations are self-consistent.

SHETRAN

The modelling system used in this study is SHETRAN, a physically based, spatially distributed, hydrological and sediment yield modelling system applicable at the river-basin scale (Ewen *et al*., 2000). Spatial distribution of basin properties, rainfall input and hydrological response (including soil erosion and sediment transport) is represented in the horizontal direction through an orthogonal grid network and in the vertical direction by a column of horizontal layers at each grid square.

The hydrological component provides an integrated surface and subsurface representation of water movement through a river basin. The version of SHETRAN used here (v3.4) represents the subsurface as a one-dimensional (vertical flow) unsaturated zone overlying a two-dimensional (lateral flow) saturated zone. This allows overland flow to be generated both by an excess of rainfall over infiltration and by upward saturation of the soil column.

The sediment transport component models soil erosion by raindrop impact, leaf drip impact and overland flow, modified according to the protection afforded by vegetation cover (Wicks and Bathurst, 1996). Eroded material is carried to the stream network by overland flow. Within the channel, bank erosion may add to the supply of material, as a function of excess flow shear stress above a threshold value. For the fine (silt- and clay-size) particles, channel flow is assumed to be able to transport all the supplied material and the resulting component of sediment load therefore increases in the downstream direction in an absolute sense (as a mass or volume). For the coarser (non-cohesive) particles, the flow has a limited transport capacity (defined by a transport equation): a balance between transport, deposition or erosion is then achieved as a function of the transport capacity and the availability of material (Wicks and Bathurst, 1996). The sediment yield is determined from the accumulated total sediment discharge (coarse and fine material) modelled at the basin outlet.

SHETRAN is a hydrological rather than a hydraulic model and therefore does not allow for feedback from erosion and deposition to hillslope and channel morphology. Thus, for example, channel bank erosion supplies sediment but does not alter the channel geometry. Further, bank erosion at one reach is not necessarily balanced in the long term by deposition at another. For the typical time scales and spatial resolutions at which SHETRAN is applied, this omission has an insignificant impact on the results. Within the context of a study into sediment yield dependencies, though, it suggests that SHETRAN's results are most relevant at relatively short time scales, up to a decade or two.

Methodology

Two basins for which SHETRAN has already been validated were selected to provide the test topographies and river networks for this study: the 1532-km^2 Agri basin in southern Italy and the 701-km^2 Cobres catchment in southern Portugal. These are large enough to provide a significant extent of basin nesting. They also provide contrasting topographies: the Agri basin is largely upland, rising to 1976 m, while the Cobres basin has a moderate, homogeneous topography (115–376 m). The original applications to the basins are described in Bathurst *et al*. (2002) for the Agri basin and in Bathurst *et al*. (1996) for the Cobres basin. The advantage of using basins for which SHETRAN had already been validated was that the models were available for immediate use, the model parameters had been evaluated and the model results could be viewed with confidence. It should be recognized, though, that the simulations reported here are not representations of the existing real-world basins. They simply use the basin topographies and river networks as a framework within which to investigate systematically the relationship between sediment yield and basin area for a number of specified conditions.

The simulations carried out for each basin are summarized in Table I. They were designed to indicate the effect of sediment source (hillslope or channel bank), spatial distribution of rainfall and spatial distribution of land use on the sediment yield/basin area relationship, considering each effect separately and in combination with the others. The simulations were run for 5 years 5 months for the Agri basin and 6 years for the Cobres basin, these periods representing the available rainfall and potential evapotranspiration time series for the basins already in the SHETRAN-specific format. For each basin, the accumulated sediment yield over the total length of the simulation was determined at several points along the river network, so as to show the variation with upstream basin area. The contributing areas so selected were defined by the basin channel network and ranged in area from 172 to 1532 km^2 for the Agri basin and 32 to 704 km^2 for the Cobres basin (Table II). (The areas are as defined by the model: hence the modelled Cobres area is 704 km^2 while the surveyed area is 701 km^2.)

Table I. Summary of the simulations, showing the specified conditions

Run	Catchment	Land-use*	Rainfall	Sediment source
1	Cobres/Agri	Wheat	Uniform	Hillslope
2	Cobres/Agri	Wheat	Uniform	Bank
3	Agri	Wheat	Non-uniform	Hillslope
4	Agri	Wheat	Non-uniform	Bank
5	Cobres/Agri	Pine	Uniform	Hillslope
6	Cobres/Agri	Upland pine, lowland wheat	Uniform	Hillslope
7	Cobres/Agri	Upland wheat, lowland pine	Uniform	Hillslope
8	Cobres/Agri	Pine	Uniform	Bank
9	Cobres/Agri	Upland pine, lowland wheat	Uniform	Bank
10	Cobres/Agri	Upland wheat, lowland pine	Uniform	Bank
11	Agri	Pine	Non-uniform	Hillslope
12	Agri	Upland pine, lowland wheat	Non-uniform	Hillslope
13	Agri	Upland wheat, lowland pine	Non-uniform	Hillslope
14	Agri	Pine	Non-uniform	Bank
15	Agri	Upland pine, lowland wheat	Non-uniform	Bank
16	Agri	Upland wheat, lowland pine	Non-uniform	Bank

* 'Upland pine, lowland wheat' means pine on the higher ground, wheat on the lower ground

Table II. The Cobres and Agri subcatchments

	Cobres		Agri	
Subcatchment number	**Subcatchment area (km^2)**	**Upstream area (km^2)**	**Subcatchment area (km^2)**	**Upstream area (km^2)**
1	32	32	172	172
2	44	76	136	308
3	36	112	120	428
4	180	292	108	536
5	56	348	80	616
6	76	424	60	676
7	280	704	128	804
8			48	852
9			144	996
10			536	1532

Model Set-up

Cobres basin

A full description of the data sources and model parameterization for the original SHETRAN application is given in Bathurst *et al.* (1996). The basin was represented by 176 grid squares of dimensions 2 km × 2 km (Figure 1a) and a total soil column thickness of 2·3 m. Hourly precipitation records were available for five gauges. However, annual precipitation varies relatively little across the basin (472–580 mm) and a spatially uniform precipitation was therefore applied in the simulations, using the gauge with mean annual precipitation closest to the basin mean annual precipitation. Potential evapotranspiration was supplied at the daily scale and actual evapotranspiration was calculated as a function of the potential value, soil moisture and vegetation type. A sequence of seven nested sub-basins was defined, as shown in Figure 1a and Table II.

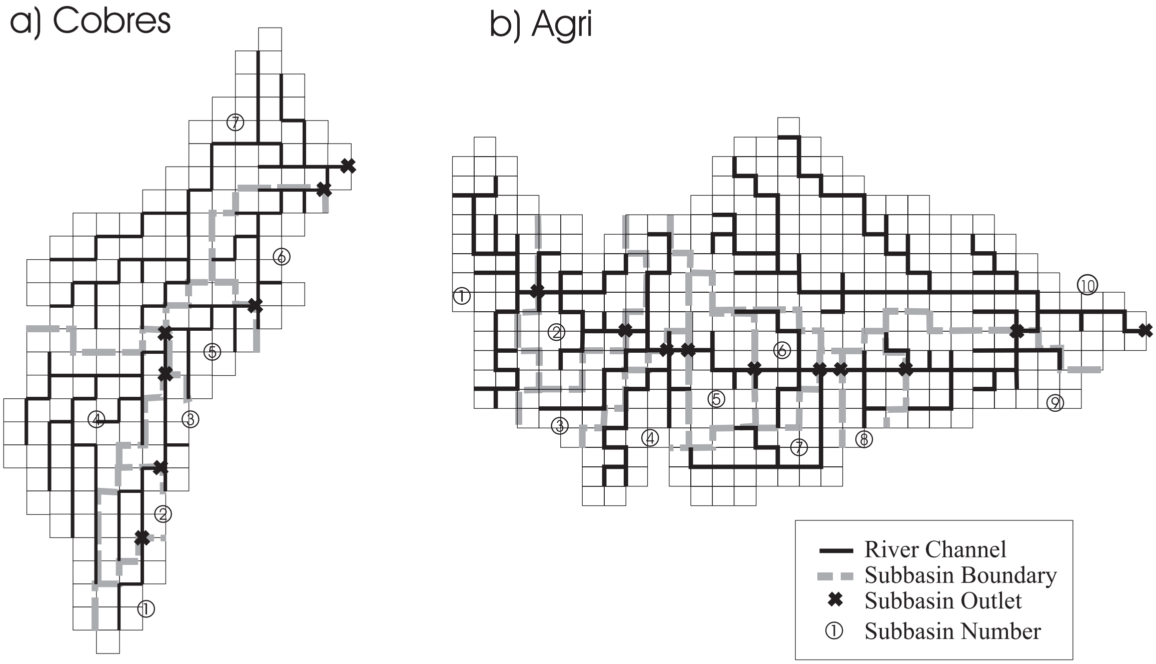

Figure 1. SHETRAN grid, channel and sub-basin network for the test basins. The grid resolution is 2 km in both cases.

Agri basin

A full description of the data sources and model parameterization for the original SHETRAN application is given in Bathurst *et al.* (2002). The basin was represented by 383 grid squares of dimension 2 km × 2 km (Figure 1b) and a total soil column thickness of 10 m. Hourly precipitation records were available for 15 gauges. Annual precipitation ranges from 530 mm at the coast to 1100 mm in the mountains. For those runs requiring a spatially uniform precipitation, the gauge with mean annual precipitation closest to the basin mean annual precipitation for the simulation period (878 mm) was used. Potential and actual evapotranspiration were applied as for the Cobres basin. A sequence of ten nested sub-basins was defined, as shown in Figure1b and Table II.

Simulation Results

Figures 2 and 3 compare runs 1 and 2 (Table I) for the Cobres and Agri basins respectively. In run 1, the model bank erodibility parameter is set to zero while the raindrop impact and overload flow erodibility parameters have non-zero values, so that hillslope erosion is the only source of sediment. In run 2, the raindrop impact and overland flow erodibility parameters are set to zero while the bank erodibility parameter has a non-zero value, so that bank erosion is the only source of sediment. Rainfall is uniformly distributed and there is a uniform land use of wheat cultivation. (The associated variation in vegetation cover follows an annual cycle in the Agri basin and a two-yearly cycle, alternating with fallow land, in the Cobres basin.) In both basins, limiting the sediment supply to hillslope erosion

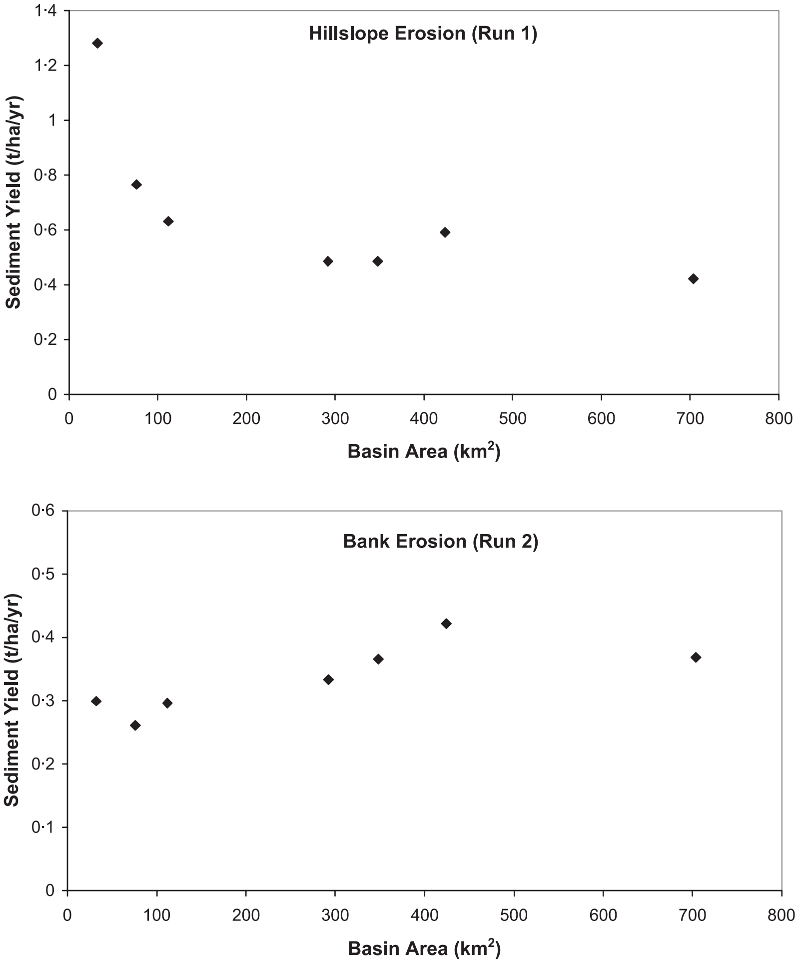

Figure 2. Simulated sediment yield in the Cobres basin with a uniform wheat land cover and uniform precipitation.

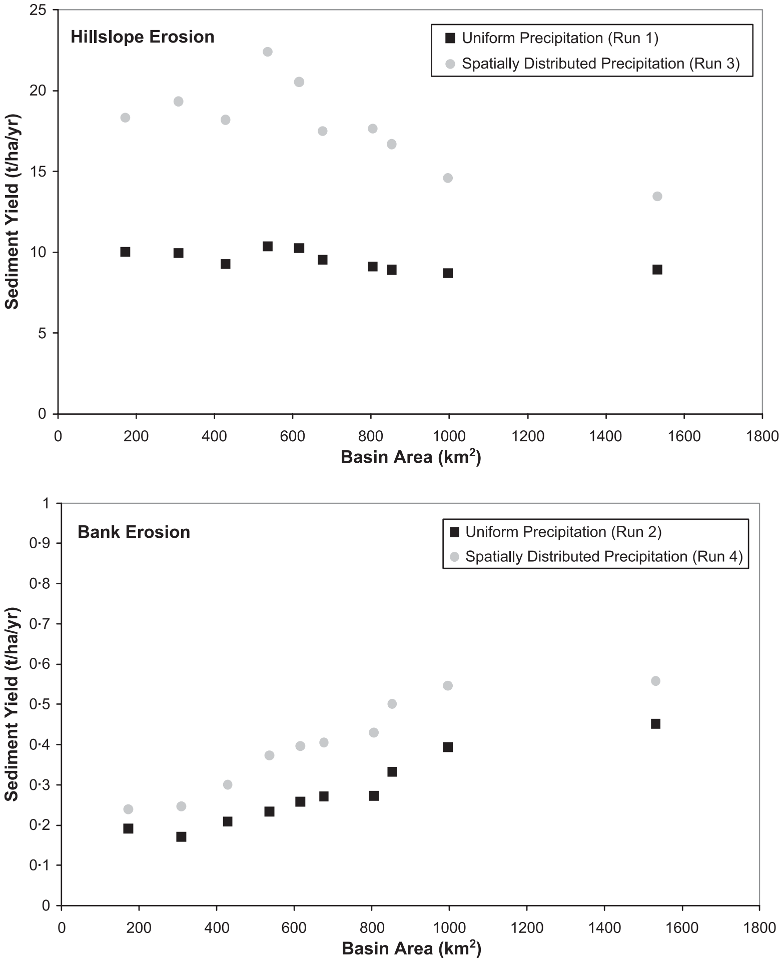

Figure 3. Simulated sediment yield in the Agri basin with a uniform wheat land cover.

results in a slight decrease, or very little change, in sediment yield as basin area increases. A possible reason for the relative insensitivity may be that neither basin is large enough to exhibit the effect of increasing distance between sediment source and channel which could support a downstream decrease in sediment yield. Also, in the case of the Agri, the topography is generally steep throughout, thereby limiting the opportunities for sediment deposition. In the case of the Cobres basin, the headwater areas are steeper than the rest of the basin, so supporting higher sediment yields there. The greater steepness of the Agri basin relative to the Cobres is evident in the higher yields simulated for the former (around 10 t/ha/yr) compared with the latter (mostly less than 1 t/ha/yr).

Limiting the sediment supply to bank erosion produces a downstream increase in sediment yield in both basins. Within the model, bank material is mostly fine-grained and, once mobilized, remains in transport. The sediment load therefore increases in the downstream direction, at a rate dependent on, among other factors, the water discharge (for transport capacity), the upstream drainage density (for amount of contributing channel bank) and the rate at which bank surface area per unit length of channel increases (since the amount of erosion depends on the contact area between flow and bank). In the simulated cases, sediment load (in t/yr) increases at a greater rate than basin area. However, the yields from bank erosion are smaller than those from hillslope erosion.

Figure 3 (runs 3 and 4) also shows that distributing the rainfall spatially (increasing with ground elevation) generally reinforces the above trends for the Agri basin. The average basin rainfall remains the same as for the uniform distribution but is higher in the upstream areas and lower in the downstream areas. Heavier rainfall implies increased hillslope erosion and the distributed rainfall therefore accentuates sediment delivery from the upstream areas relative to the downstream areas for run 3. The increase in yield from the upstream hillslopes more than compensates for the decrease from the downstream hillslopes so that, overall, sediment yield is higher than for the uniform rainfall case.

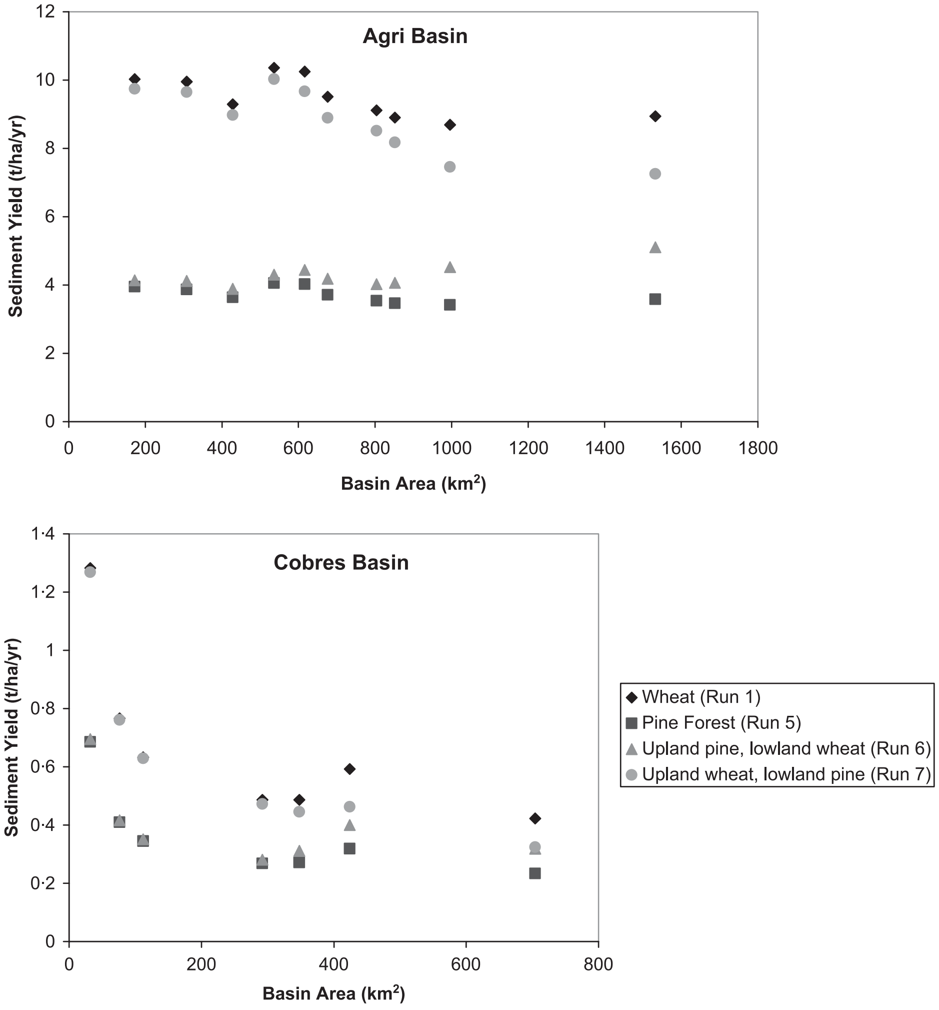

Figure 4. Simulated hillslope erosion sediment yield for different land uses with uniform precipitation.

For run 4 (bank erosion as the sediment source), the heavier upstream rainfall means higher flows in the upstream channels and thus greater bank erosion compared with the uniform rainfall case. There is no significant loss of water from the river so the net downstream flows (and hence bank erosion) are similar to the case with uniform rainfall. Thus overall there is again an increased sediment yield compared with the uniform rainfall case.

For run 3 it is noticeable that sediment yield in the headwater sub-basins first increases with upstream area (as far as sub-basin 4) before then decreasing as area increases. This is due, at least in part, to sub-basin 4 containing the highest part of the Agri basin and thus suffering the highest rainfall and hillslope erosion.

Figure 4 shows the effect of a distributed land use, with uniformly distributed rainfall, on sediment yield derived from hillslope erosion. For each basin, simulations were carried out with the whole basin covered by wheat (run 1), with the whole basin covered by pine forest (run 5), with pine on the higher half of the basin and wheat on the lower half (run 6) and with wheat on the higher half and pine on the lower half (run 7). Pine forest provides a time-invariant cover and was simulated by reducing the soil erodibility parameters, increasing the proportional ground cover and increasing interception and transpiration losses relative to wheat. (This is in line with the generally accepted effects of forest relative to grass cover; e.g. Bosch and Hewlett, 1982.) In other words the presence of pine forest reduces both runoff and soil erosion compared with wheat. The result is that the forested basins produce lower sediment yields than do the wheat-covered basins, although the pattern of the variation in sediment yield with basin area remains much the same. Correspondingly the mixture of pine cover on the higher ground and wheat on the lower ground tends to

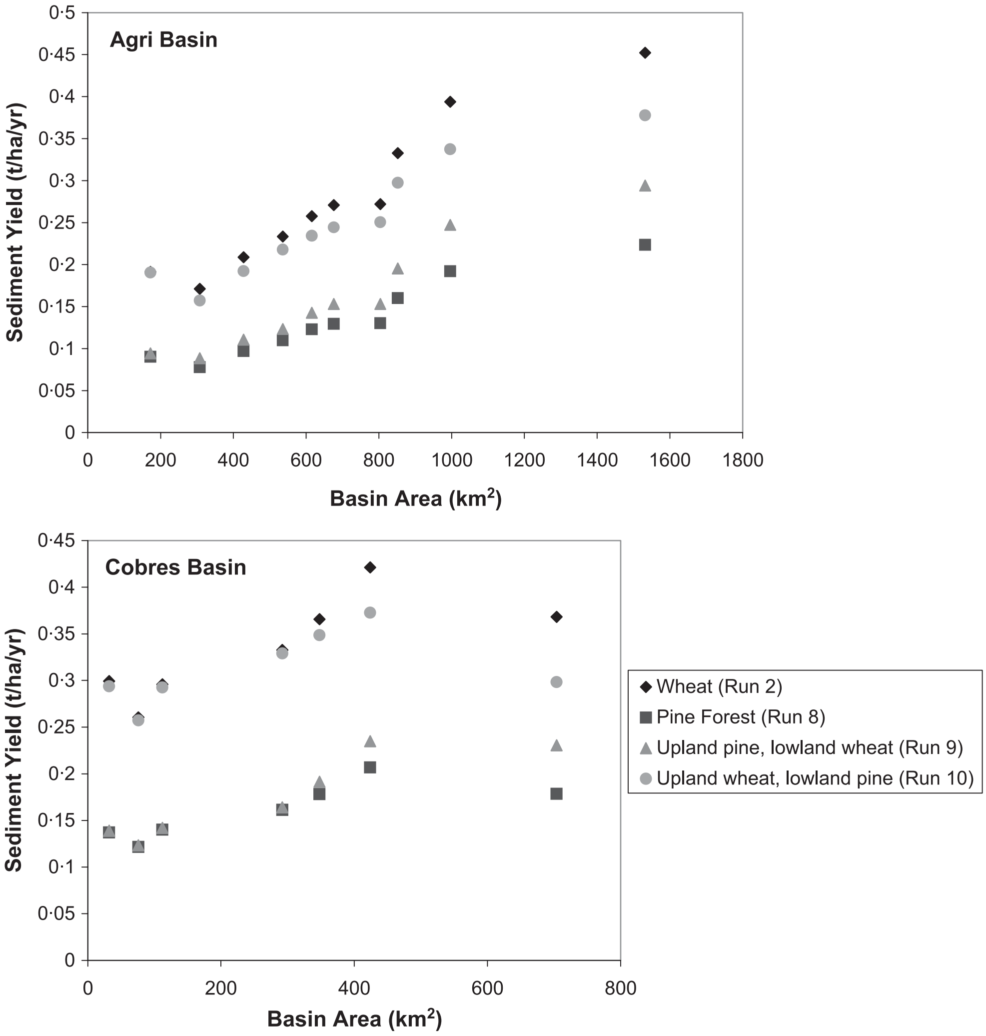

Figure 5. Simulated bank erosion sediment yield for different land uses with uniform precipitation.

counteract the trends shown for hillslope erosion in Figures 2 and 3. Erosion, and hence sediment yield, is potentially greater in the downstream part of the basin than in the upstream part. The sediment yield in the Agri basin, in particular, now increases as basin area increases. By contrast, wheat cover on the higher ground and pine cover on the lower ground reinforces the downstream decrease in sediment yield suggested by run 1.

Figure 5 shows that the land use changes do not alter the basic trends of Figures 2 and 3 for sediment yield derived from bank erosion. The same patterns of land use were simulated as for Figure 4, with uniform rainfall (giving runs 2, 8, 9 and 10). However, the bank erodibility parameters are not affected by the land use and the simulated differences in sediment yield relative to run 2 are due to the effect of the land use change on channel discharge. Pine forest is parameterized to use more water through evaporation and transpiration than does wheat, so discharge is reduced by afforestation. Lower discharge means lower bank erosion and hence reduced sediment yields. The mixture of pine cover on the higher ground and wheat on the lower thus steepens the rate of increase of sediment yield with basin area, while the reverse land use pattern has the opposite effect.

Figure 6 shows the patterns for runs 11–16, which repeat runs 5–10 for the Agri basin but with distributed rainfall. Combining distributed rainfall with upland pine and lowland wheat restores the downstream decrease in sediment yield derived from hillslope erosion (run 12) and accentuates the same trend for all the other land uses. The trends for sediment yield derived from bank erosion remain largely unaffected.

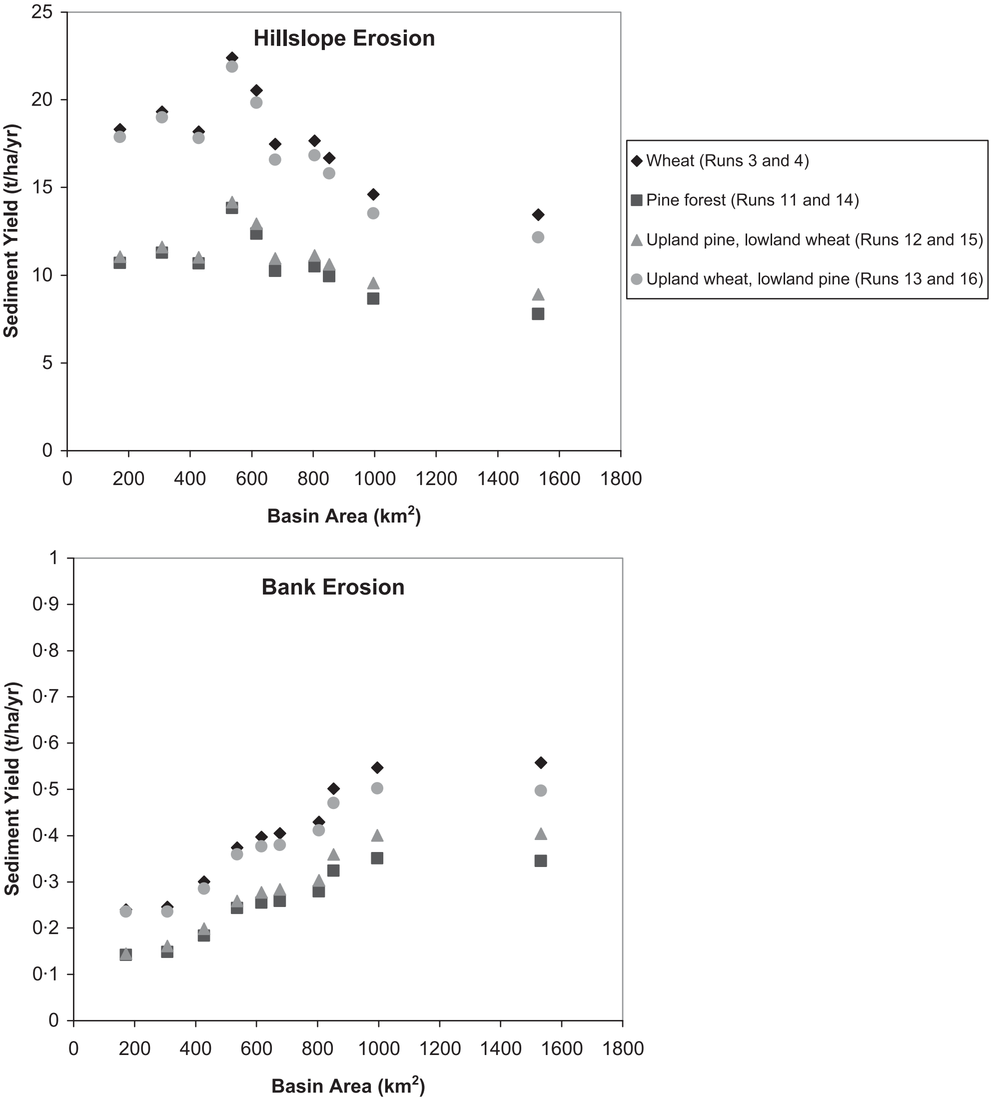

Figure 6. Simulated sediment yield in the Agri basin for different land uses with non-uniform precipitation.

Analysis of Results

The simulation results indicate the following.

(1) For uniform land use and rainfall distribution, hillslope erosion supports an inverse or near-constant relationship between specific sediment yield and basin area. Bank erosion supports a direct relationship. This agrees with the analyses of Dedkov and Moszherin (1992) and Dedkov (2004). In the model, mean hillslope gradient decreases as basin size increases, so reducing the potential for basin-scale erosion. Sediment discharge derived from hillslope erosion increases in the downstream direction but at a lesser rate than does basin area. In the channel, material derived from bank erosion is generally fine and is maintained in suspension with no deposition: the load derived from bank erosion therefore grows in the downstream direction, at a rate greater than the increase in basin area.

(2) Distributing the rainfall spatially while maintaining uniform land use produces heavier rainfall, and therefore greater erosion, on the higher ground relative to the lower. For sediment yield derived from hillslope erosion, the result is to enhance the inverse relationship, in agreement with Krishnaswamy *et al*. (2001).

(3) Distributing the land use while maintaining uniform rainfall has a significant impact on the sediment yield derived from hillslope erosion. If erosion is reduced in the higher ground relative to the lower (pine cover on the higher land, wheat on the lower), the inverse relationship can be reversed. The downstream increase in soil erodibility allows specific sediment yield to increase as basin area increases. If, on the other hand, the land use pattern is reversed, the greater erosion on the higher ground relative to the lower enhances the inverse relationship. This suggests that cultivation patterns can potentially alter the variation of sediment yield with basin area, in agreement with Krishnaswamy *et al*. (2001).
(4) Combining a distributed rainfall with a land use of upland pine and lowland wheat restores the inverse relationship. In this case the effect of the rainfall in causing greater erosion and transporting capacity in the smaller (headwater) basins more than counteracts the protective effect of the pine trees. It is not clear, though, if this is a general result. Rainfall and vegetation cover have counteractive and interactive effects on soil erosion, resulting in a complex pattern of response (e.g. Calder, 1999, pp. 14–19).
(5) In all the simulations, sediment yield derived from bank erosion consistently varies directly with basin area. The rainfall and land use changes affect only the relationship for hillslope erosion. Sediment yield derived from bank erosion is affected only to the extent that river discharge (and thence erosive power and transporting capacity) is affected. For the given conditions the impact on river discharge is not enough to alter the sense of the sediment yield/basin area relationship.

The results generated for this study do not of course automatically apply to all basin conditions. Different combinations of rainfall and land use distributions (and the introduction of processes not included in SHETRAN) could create a different balance between the variations in sediment yield and basin area. The results are therefore an illustration of the variety of forms which the sediment yield/basin area relationship may adopt, not a general description for all basins.

Conclusions

The inverse relationship between sediment delivery ratio, or specific sediment yield, and basin area is currently the only working model of a scale effect in the response mechanisms linking erosion to outlet sediment yield. Recently, though, the inverse relationship model has been challenged by studies which show a direct relationship. This study has therefore carried out a systematic set of model simulations to investigate the robustness of the sediment yield/basin area model. A particular aim was to follow up the work of Dedkov and Moszherin (1992), Krishnaswamy *et al*. (2001) and Dedkov (2004).

The model results are consistent with the recent studies. They show both inverse and direct relationships depending on the principal source of sediment in transport, on rainfall spatial distribution and on land use distribution. If the sediment is supplied solely from hillslope erosion (no channel bank erosion) then, with uniform land use, sediment yield either decreases or is nearly constant as area increases. The downstream decrease is accentuated if rainfall (and thence erosion) is higher in the headwaters than at lower elevations. Introducing a non-uniform land use (e.g. forest at higher elevations, wheat at lower elevations) can reverse the trend, so that sediment yield increases downstream. If the sediment is supplied solely from bank erosion (no hillslope erosion), the sediment yield increases downstream for all conditions.

The consistency between the model results and the recent study observations gives some confidence in the model structure and in our ability to simulate at least the correct sense of the sediment yield/basin area relationship for a given set of circumstances. Nevertheless, this consistency does not necessarily mean that the model reproduces all the responsible mechanisms. Clearly the model represents only some of the processes which have been suggested to affect the relationship. Further, by not allowing channel bar deposition to compensate for bank erosion, the model is not able to represent the long-term development of the relationship correctly. The important point, though, is that the model shows that the relationship can vary, and can be inverse or direct, as a function of basin characteristics. From this it may be concluded, as already suggested by the recent studies, that the inverse relationship does not form a universal scaling law. However, regionally and for the appropriate basin characteristics it may provide a general relationship.

The results suggest a potential for defining the conditions or criteria which determine whether the relationship is inverse or direct. This in turn may provide a basis for predicting the impacts of land use change on the relationship, at least for short-term periods.

The study also shows the usefulness of physically based, spatially distributed modelling in illustrating the effects of different controls on sediment yield, in exploring the topic in a systematic manner and in avoiding the data limitations of field-based studies. By identifying important controls it allows field studies to be efficiently targeted and to be designed with minimum data needs.

A final conclusion is that there is still considerable scope for defining a scaling law for sediment yield. The sediment yield/basin area relationship is operationally simple and, in its form, is a clearly defined scaling law, but it is inexact and does not form a reliable basis for predicting the impacts of changes in basin environment. Physically based models provide a means of distinguishing between basins with different controls on sediment yield and can be used predictively, but they do not of themselves form a simple scaling law. The need is for an intermediate law which combines simplicity with generality and predictive capability.

Acknowledgements

The work described here was funded by the European Commission through the MEDACTION project (contract number EVK2-CT-2000-00085) and this support is gratefully acknowledged. Two anonymous reviewers are thanked for comments which allowed a significant strengthening of the paper.

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