Soil erosion and associated sediment supply to rivers
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Citation for published version (APA):
van Dijk, P. M. (2001). Soil erosion and associated sediment supply to rivers Amsterdam: UvA IBED FG
4 EVALUATION AND RESEARCH NEEDS
4.1 INTRODUCTION

The studies presented in this thesis show that the occurrence and the severity of soil erosion is very variable in time and space. Large scale patterns are determined by the global conditions of soil, climate, relief and elevation. Within these global patterns, soil erosion varies strongly depending on finer-scale features like land use type, hillslope and catchment morphology, subsurface soil conditions, and on very fine-scale features such as soil surface conditions, micro-relief, tillage direction and crop cover. Understanding of soil erosion processes is growing and as a result insights into reducing erosion and related problems is growing too. However, with respect to sediment delivery to streams, it should be recognised that much less is known about the fate of eroded sediment during transport towards streams than is commonly supposed.

On the basis of the studies presented in the chapters 2 and 3, this chapter is concerned with some issues related to erosion on hillslopes and the subsequent transport and delivery to streams channels. The aims are to identify a) those parts of the sediment supply system that need special attention in further research and b) difficulties that are specific to large scales (like the scale of the large river basin or the global scale). It is clear that the modelling of erosion and associated sediment supply in the Rhine basin (Chapter 3) is rather 'preliminary' as it is constrained by the 28 months of available time and based on the experience derived from a restricted number of field studies. The field studies provided an indispensable basis for the modelling work. Without the field investigations, the interpretation of process-description and model output would have become entirely disconnected from reality. This risk is especially great when working at the scale of the large river basin. Although the modelling study is explorative and surrounded by many uncertainties, it demonstrates, more or less, what is today possible at the scale of the large river basin. Not less important, it shows gaps in our knowledge and indicates what kind of information is missing and needed to construct better, large scale erosion/sediment supply models.

The experience from the field together with the findings of the modelling study at the scale of the Rhine basin have led to the identification of some issues that might be considered 'bottlenecks' in the estimation of soil erosion and associated sediment supply at the scale of the large river basin. Some of the major problems that are encountered by the researchers are discussed below. They can be divided into two categories:

- Problems due to insufficient process knowledge and (or because of) insufficient field data. In this chapter, the uncertainty about connectivity between disjunctive source areas and stream channels, and the role of gullies is being stressed (section 4.2).
Sediment delivery and connectivity

- Constraints of the type "large areas and data availability" (section 4.3). This includes scale issues of which the following two are highlighted: a) quantification of overland flow occurrence on the regional or global scale, and b) validation of large scale erosion models. Computation limitations are not dealt with here, but their importance is far from negligible in global scale computer models. The duration of a simulation run must be acceptable and determines for a large part what kind of model with what kind of process equations can be applied.

4.2 SEDIMENT DELIVERY AND CONNECTIVITY

4.2.1 Concentrated flow erosion in winter time

In this thesis, general seasonal patterns of soil erosion and sediment supply to streams were identified that apply to the temperate climate zone of western Europe. The modelling study reveals that the temporal patterns of these two processes, erosion and supply, are not in phase: diffuse soil erosion depending strongly on the character of the rainfall in combination with the agricultural calendar, sediment supply depending on the amount of rainfall in combination with basin moisture conditions. The model predicts high erosion rates for the spring time and early summer, because of low vegetation cover and higher intensity rainfall. This is confirmed by many soil erosion studies including the field study presented in Chapter 2.1. According to the model, the best conditions for sediment supply occur in winter time, from November until April, for which relatively low erosion rates are predicted. The field study presented in Chapter 2.1, however, indicates that strong erosion in the form of concentrated flow erosion can occur in winter time due to saturated soil conditions. This type of winter erosion mainly takes place in temporal transport routes in the landscape, such as valley bottoms, which connect relatively well to stream channels. More evidence of the importance of saturation overland flow and associated winter erosion is, among others, provided by Auzet et al. (1995). On the contrary, summer erosion induced by high intensity rainfall mobilises sediment in a more diffusive manner, the locations depending on land use characteristics rather than on hillslope morphology. This sediment has to travel some way before reaching the central valley axis. The sediment supply model RECDES does not explicitly account for concentrated flow erosion which is common in winter time. Therefore, the model may underestimate sediment supply in the winter because of an underestimation of sediment production in this period.

In order to improve large-scale modelling of erosion and associated sediment supply to streams, it is thus necessary to better and more explicitly address the
different overland flow mechanisms, namely Hortonian and saturation overland flow and overland flow resulting from snowmelt (see also 4.3.2).

4.2.2 Field evidence for sediment supply from hillslope sources

It is often assumed that a large proportion of the suspended sediment load of streams is derived from soil erosion on hillslopes (e.g. Van der Drift and Kwaad, 1995; Richards, 1982). However, this assumption can be wrong or at least depend strongly on local or regional conditions (Asselman, 1999; Walling, 1990). Often, the origin of the suspended sediment in rivers is in fact only assumed. Especially, the contribution of sediment mobilised by surface runoff from distant fields is difficult to assess. Figure 4.1 shows the river Geul in Dutch South Limburg after heavy rainfall, clearly carrying a large amount of suspended sediment. It also shows the occurrence of bank erosion, which constitutes an instream source for suspended sediment. What is the relative importance of the different sediment sources and supply processes?

![Figure 4.1. The sediment-laden water of the river Geul in Dutch South Limburg after heavy rainfall.](image)

Using rating curves techniques, the prediction of the suspended sediment yield is possible, but the sediment source areas remain unclear. The characterisation of the delivery conditions is a major source of uncertainty in modelling sediment supply to streams (Walling, 1990; Burt, 1998). The Rhine basin study (Chapter 3) utilises the sediment delivery concept to estimate the contribution of soil erosion
on hillslopes to the suspended sediment yield of rivers. Sediment delivery ratios, which are affected by many factors, including climate, land use, local physiography, and soil texture, are extremely variable and often quite site-specific (Moldenhauer and Foster, 1981; Asselman, 1997). Though very few studies provide quantitative evidence (Walling, 1990), values of 0.4 to 0.6 are often assumed for the sediment delivery ratio. The delivery ratio module of GAMES yields similar values, ranging from about 0.3 to 0.6 for the main subbasins within the Rhine basin, and 0.5 as the basin average (see Table 3.11, section 3.5).

These values might be too high for Europe, particularly for sediment produced on arable land in the early growing season, which is known as an important erosion period. But in this period, the connectivity in the overland flow system is poor compared to that under winter conditions. Hortonian overland flow, which often occurs during the growing season, is basically a point process which occurs at locations scattered in the landscape. These locations do not necessarily connect to give larger quantities of overland flow which reach the permanent stream channels. The overland flow connectivity in the growing season is reduced by the high spatial heterogeneity of soil and land use features, which results in relatively low runoff volumes (see also section 2.1.5). Saturation overland flow is, in general, not a point process but requires a minimum upslope catchment area. It is a result of connectivity in the hydrological system and characterised by much higher runoff volumes. Erosion in summertime, therefore, often has the character of soil relocation within the catchment, while sediment eroded in wintertime will generally be transported out of the catchment.

The measurement results of Chapter 2.1 support these statements. In the growing season, just after tillage and crop germination, erosion is characterised by little amounts of overland flow with high sediment concentrations. Under these conditions, deposition of sediment can be induced by the slightest change in the hydraulic conditions, caused by sometimes rather subtle features in the landscape. As a consequence, large proportions of eroded sediment are deposited as colluvium long before reaching a stream channel (Figure 4.2). There are numerous places in the landscape where overland flow might loose its sediment load. Figure 4.3 shows a wire-fence between an arable field and pasture. During an erosion event, dead plant material was trapped in the fence and as a consequence a thick layer of sediment was deposited behind it. But sediment can also be deposited in furrows (Figure 4.4), at field boundaries, at gradient changes due to roads or paths (Figure 4.5), in concave parts of the hillslope, etc. Mutchler and Murphree (1981) showed that depositional opportunities are especially numerous in low relief areas with slopes less than 4%. It is evidently dangerous to base erosion rates in catchments on sediment yield data of rivers. These kind of data have little meaning in terms of soil
erosion and disregard soil relocation within the catchment (e.g. Blandford, 1981).

In summary, the availability of quantitative field data concerning the sediment delivery system (i.e. production and losses during transport) is very poor compared to that of local plot and field erosion rates on hillslopes (see also section 3.6.4). The fact that the delivery of sediment from its source on the hillslope to streams has been underinvestigated was apparent at the recently organised COST 623\(^1\) workshop 'Linkage of Hillslope Erosion to Sediment Transport and Storage in River and Floodplain Systems' in Almeria (Spain), organised by Working Group 1 ('Linking processes across temporal and spatial scales') of COST Action 623 (http://www.cost623.leeds.ac.uk/cost623).

![Figure 4.2. Erosion on a hillslope and sedimentation at the foot of the slope.](image)

Concerning the conveyance and production of sediment, there is an important role for the zones in the landscape where overland flow concentrates and where concentrated flow erosion occurs. Recent research has led to a much better appreciation of the importance of rill and gully erosion and of the role of gullies in transferring sediment from upland areas to permanent stream channels (e.g. Poesen et al., 1998; Govers, 1991; Vandaele and Poesen, 1995). The increased awareness of the importance of gullies has recently resulted in an 'International

\(^1\)COST Action 623: a European platform for the co-operation in the field of scientific and technical research concerning soil erosion and global change.
Symposium on Gully Erosion under Global Change in Leuven (Belgium), also in the framework of COST Action 623.

4.2.3 Relevance of sediment source assessment for surface water quality

The suspended sediment load of a river can derive from several sediment supply processes, like mass wasting, earth flows, land slides, river bank erosion, and soil erosion from upslope fields. These processes can have very different source areas. It is important to be able to estimate whether the suspended sediment in the river derives from instream sources or from disjunctive source areas. Many gravity related processes provide sediment from nearby sources in the direct proximity of the stream channel. Sediment deriving from soil erosion and transported by overland flow can have distant sources which are often located in agricultural areas. These areas are important nutrient sources. Werner et al. (1991) and Werner and Wodsak (1994) estimated the input from diffuse sources to the surface water for Germany. They concluded that 76% of the diffuse N sources and 72% of the diffuse P sources in Germany are of agricultural origin. P is much more strongly held by soil particles than N, consequently only a small fraction of soil P leaches to the groundwater. As soil P content increases, the potential for P transport in overland flow through soil erosion increases. For P this is the major pathway from soil to surface water (De Wit, 1999). Thus the sediment delivered to streams that derives from soil erosion might constitute a significant source for nutrients in surface water. Furthermore, the sediment may
carry pollutants like mercury (Probst et al., 1999) and other heavy metals. And finally, the suspended sediment itself affects surface water quality and the surface water ecosystems. In short, overland flow and related fluxes of sediment and pollutants/nutrients should be considered in studies concerning surface water quality.

![Figure 4.4. Sedimentation in tillage furrows (South Limburg).](image)

**4.3 LARGE SCALE ASSESSMENTS**

**4.3.1 Introduction**

Soil erosion and sediment transport are processes of great importance for environmental management. They relate to the quality and quantity of global soil resources, and they play an important role in the transfer of nutrients and contaminants from terrestrial to aquatic systems. It is not surprising that these subjects have become important issues in environmental research during the last decades. Recently, interest in more global assessments of soil erosion, environmental pollution and the effects of climate change has strongly increased. There is a clear need for improved quantitative estimations of water, sediment and nutrient fluxes at the global scale. Researchers are being increasingly asked to quantify and map these fluxes, in order to meet policy demands. It has to be recognised, however, that there is a lack of knowledge as how to assess soil erosion and sediment transport on a global scale. This hampers studies related to nutrient fluxes as well.
As the photos above illustrate, many details in the landscape determine the amount of sediment that eventually reaches a stream channel, but these kinds of detail can never be implemented as such into a global scale model. Even a 'simple' parameter like field slope angle poses problems at the large river basin scale. Almost all soil erosion models, including the USLE, require this variable as input. However, for large study areas like the Rhine basin, this kind of information is normally lacking. Application of physically-based models with input variables derived from coarse data sources can lead to large errors in the model output. In spite of this, there are many examples of studies that, sometimes without comment, use the USLE with slope angles derived from coarse-resolution DEM's. This is due to the fact that in regional or larger scale studies, the information to derive at least an approximation of the USLE-factors is often available from soil and land use maps and a DEM. The application of other models is often not possible because of (much) higher input data requirements. Nevertheless it is important to emphasise that basically the USLE is a field-scale model.

So far, most erosion modelling has focussed on fine-scale processes in highly detailed, physically-based models, with the event as the basic temporal unit and often the catchment as the basic spatial unit. Even these models are not always successful in accounting for the details, like those mentioned above. More or less
as a consequence of the emphasis on physically-based models, regional and global scale modelling has remained underdeveloped. However, the interest in larger scale models related to soil erosion and sediment delivery is growing. Large efforts are necessary to overcome their special problems.

Most existing methods for quantifying soil erosion and sediment supply to streams are not compatible to regional or global scale objectives. They relate to the hillslopes scale at which the processes modelled operate. According to Lee (1998), there are three approaches to resolve this cross-scale issue:

a) Scale the input, so that input variables are spatially and temporally averaged and used as input for a high resolution model. But to what extent can fine-scale detail be neglected? Some detail can be considered as noise. However, problems arise in cases of spatial heterogeneity combined with non-linearities in the relevant processes. In these situations, averaging of input data is not allowed. Therefore, this approach is seldom appropriate;

b) Scale the model, so that the model formulations describe those factors that dominate at the scale of the analysis. The input data and the predictions are consistent with this scale;

c) Scale the output. In this approach, a high resolution model is used with high resolution data for selected sites. The model output is then scaled to a region by extrapolation techniques.

The second approach, (b), is most appropriate for several reasons (Kirkby, 1998; De Wit, 1999). In general it can be stated that the larger the area that has to be studied, the less detailed is the resolution, both spatial and temporal, of the available data. Detailed process-based soil erosion models are not suitable for the large scale, because the quality of the available input data will disharmonise with the model complexity. Application of such models with global input data will lead to unacceptably high levels of uncertainty in the modelling results. De Wit (1999): "There is no point in using a model for which the appropriate data are not available". Moreover, these detailed models produce information that is irrelevant for regional studies, because the research aims change with increasing scale of the analysis. In the case of regional or global studies, the objective is not to precisely know what is happening during an erosion event on each specific hillslope, but rather to understand longer term regional patterns. Thus, for these scales a completely different type of model is needed. The maker of a large scale sediment delivery model has to think in a global fashion, while knowing about the detail processes that cause erosion in the field. This is very difficult, but necessary. The CSEP model (Kirkby, 1994; Kirkby and Cox, 1995; Kirkby, 1998) is a valuable attempt towards more general formulations fitting to the coarse regional and global scale. It combines rationally rainfall statistics and a significant soil hydraulic parameter to give a measure of the climatic component in soil
erosion transport. As the model gives an index for potential erosion, it can not be applied for estimations of erosion rates and sediment supply for specific situations. Nevertheless, the approach utilised in CSEP offers a considerable potential for large scale modelling and deserves further exploration.

4.3.2 Modelling of overland flow on the large scale

Overland flow transports sediment and nutrients, and links agricultural fields to streams. Its assessment is of vital importance in understanding and tackling problems related to soil erosion, sediment transport and colluviation, but also for surface water quality (sediment and nutrients) and river ecology.

Research on overland flow, most frequently carried out in the context of soil erosion projects, has so far mainly focused on the spatial scale of the hillslope and the small agricultural catchment and on the temporal scale of the event. Several models have been developed and tested, and are available for the assessment of overland flow at these spatial scales. However, most of these models are not suitable to estimate the seasonal patterns in the delivery of sediment to stream channels, and especially unsuitable for the regional or global scale.

Processes of overland flow generation

For the generation of overland flow, two basic mechanisms can be distinguished which are referred to as infiltration-excess overland flow (occurs when the rainfall intensity exceeds the infiltration capacity of the soil) and saturation-excess overland flow (occurs when the soil water storage capacity is exceeded). The factors that determine its generation are fairly different for both types of overland flow. Soils of low infiltration capacity are likely to produce only infiltration-excess overland flow. Key variables for this type of overland flow are rainfall intensity, state of the soil surface, sorptivity and the saturated hydraulic conductivity. On the other hand, soils with a high hydraulic conductivity are likely to produce only saturation-excess overland flow. Soil saturation is encouraged at the foot of any slope where the upslope drainage area is at a maximum, and in talweg-like topographies where convergence of flow lines favours the accumulation of soil water (Burt, 1998). These areas are typically the locations where saturation-excess overland flow may occur. Saturation-excess overland flow can be generated in places and in times where infiltration-excess overland flow does not occur. Key variables for the generation of saturation-excess overland flow are the presence of an impeding layer or a shallow ground water table in the soil, the moisture storage capacity of the soil above this impeding layer or ground water table, and the volume of rain.

Besides the two mechanisms mentioned above, there is a third process which can be of great importance for the production of overland flow: snowmelt. In
areas with regular snowmelt, meltwater can be a major cause of erosion. Several studies have shown the significance of snowmelt in the occurrence of rill erosion (e.g. Botterweg, 1998; Zachar, 1982; Bernsdorf et al., 1995; Hayhoe et al., 1995). Freezing and thawing reduces soil shear strength and infiltration rates can be very low because of ice layers (Botterweg, 1998). Thawing soil over a frozen layer may be oversaturated and susceptible to erosion. Snowmelt can produce large amounts of overland flow over very large surfaces. It can create dense networks of water flows which connect well to the permanent stream channels. The role of snowmelt in transferring sediment and nutrients to streams must therefore be considered. Snowmelt can be responsible for supplying sediment to streams during periods when rainfall is not very erosive and at locations where rainfall does not have an impact on the soil surface because of the presence of a snow cover. Therefore, snowmelt erosion may significantly affect the amount and the temporal pattern of sediment supply in areas where snowfall is a common type of precipitation.

Each of the overland flow generating processes has its own set of controlling factors. As a consequence, each overland flow process occurs at different times and locations in the basin. The Rhine basin study (Chapter 3) showed that in most of the German and French subbasins, monthly variations in erosion and sediment supply are related to the dynamics of the agricultural system, to variations in rainfall erosivity and to the soil moisture state in the basin. Sediment supply resulting from erosion by snowmelt runoff plays a role in the middle mountains like the Vosges and the Black Forest. The latter process tends to increase the amplitude of both the highs and the lows of the erosion and sediment supply curves during the year. The overland flow and erosion measurements in South Limburg (Chapter 2.1) showed that saturation overland flow occurred mainly in winter, while Hortonian overland flow occurs mainly in the summer when high rainfall intensities are more common.

Thus, there are strong seasonal variations in the occurrence of these overland flow generating processes and consequently in the occurrence of erosion and sediment delivery to streams. Moreover, agricultural practices have a profound effect on the soil surface and subsurface conditions through tillage and crop growth. These practices strongly affect the occurrence and routing of overland flow.

Modelling implications
In order to properly model sediment production, transport and delivery to streams on the large scale, these three processes of overland flow generation must be addressed as well as their seasonal variations. An overland flow model suitable for large scale studies is not yet available.
Many of the physically-based models are event-based models, which do not account for lateral water displacement in the subsoil, because on this time scale lateral components are of minor importance. For instance, Ritsema et al (1996) found that vertical flow dominated during rain events, and that average lateral water transport varied between 1 and 5% of the total water displacement. Therefore they decided to incorporate a one-dimensional water flow module in the soil erosion model LISEM (De Roo et al., 1996). As a consequence, before the simulation of an event, the user has to specify the initial soil water state in the catchment as an input variable.

In environmental studies at the regional scale, the scale of the hydrological event is often not at the time scale of interest. At longer time scales, lateral components of soil water movement are of great importance in explaining spatial soil moisture patterns. These patterns are determined mainly by topography and soil features, and they control the generation of saturation-excess overland flow. The areas prone to saturation-excess overland flow are generally located close to the stream channels and are therefore a well-connected source for sediment and pollutants. So in the light of studies concerning sediment supply to stream channels, the incorporation of the saturation overland flow process into the model is indispensable. A model which accounts for this type of overland flow is TOPMODEL, which predicts the relative amount and spatial distribution of subsurface, infiltration-excess, and saturation-excess overland flow based on surface topography and soil properties (Beven and Kirkby, 1979). However, studies have shown that the cell size of the grids used by TOPMODEL should not exceed approximately 30 m, while for simulation on the large regional scale, cell sizes generally range between 100 m and 1 km.

On the other hand, the hydrological models which focus on the larger scales often adopt very crude methods of dealing with overland flow. At the global scale, overland flow as such, is in most cases considered to be 'non-determinable'. At these scales, most existing hydrological models are runoff models, which are not able to separate interflow from overland flow and groundwater recharge. No methods exist that explicitly addresses overland flow. Solutions to this problem have been mainly pragmatic, so far, depending on the data availability: (1) in some cases, a simple ratio between overland flow and rainfall is used, (2) sometimes overland flow is assumed to relate to or to be equal to direct runoff (which is not correct, as direct runoff consists of the sum of overland flow and interflow in the upper soil layer), or (3) sometimes indices are used which are derived from soil water storage calculations. Thus, overland flow on the large regional scale is often quantified using crude estimators, which is inherent to the regional scale. The existing methods (a) do not properly address the three processes of overland flow generation, and (b) are largely based on assumptions: there is no certainty at all about their validity.
In the framework of soil erosion projects, in order to avoid the problem of quantifying overland flow, the researcher is often forced (or tempted) to use USLE-like approaches to assess soil erosion on regional scales. The value of such studies for other research areas, like those concerned with nutrient fluxes and river ecology, is limited. This is due to the nature of the USLE which only addresses net soil loss in agricultural fields with rill and interrill flow. Transport of sediment to streams, sedimentation, gully erosion and basin sediment budgets cannot be quantified using the USLE. In short, the absence of appropriate methods of characterising overland flow on the large regional scale restricts the universal value of regional erosion studies.

The last years, more and more research projects have been dealing with soil erosion and water quality focusing on the large regional scale, often in the framework of environmental quality assessment and large scale impact studies of climate and land use change. The need for global modelling of the variable overland flow is evident. The approaches used so far on the regional scale are sufficient for tentative studies, but as long as their validity is unknown they are not satisfactorily for studies that are supposed to direct environmental policy.

4.3.3 Validation of large scale erosion models

Unless a model can be validated, its value is marginal. For this reason, it is important to anticipate this explicitly when starting a modelling study.

However, validation of erosion models is difficult because of several reasons. First, collecting erosion data is laborious and expensive. Secondly, erosion data relate to a certain area and time span (hereafter this spatio-temporal scale is referred to as ‘support’). For example, measured soil losses can refer to plots, slopes, or catchments, and can be determined for a single events, months, years, etc. or sometimes for unknown periods. The measured soil losses are related to the corresponding support. The existing data as reported in literature vary widely in their support, though most data apply to the plot and hillslope scale. These data can relatively simply be used for the validation of hillslope or small catchment erosion models.

Validation of global scale erosion models is even much more difficult. The existing erosion data always apply to small spatial units, which cannot be identified with sufficient accuracy in the database of the coarser regional scale model. Thus, validation of modelled erosion using point data is not possible. However, as stated before, in global scale studies it is important to know whether the general levels of the calculated erosion and sediment supply rates are accurate at a regional scale. Therefore, instead of validation on the basis of point data, the author suggests a ‘categorical validation method’ for large scale erosion models, following the methodology described in section 3.6.4. This method is based on
grouping published erosion rates according to the corresponding land use, soil and measuring scale. The resulting average erosion rates are then compared with the modelled erosion rates for each group. This method is a rather general approach, which traces the existence of systematic errors in the level of the calculated erosion rates.

The validation is most accurate for the categories of land use and soil texture which have received most attention in field erosion studies (i.e. arable land/loess soils). For obvious reasons, there is little quantitative knowledge about erosion rates for less erosive soil or land use conditions. For instance, forests occupy almost 40% of the surface of the Rhine basin, but the validation data consist of very few records. More information is needed about erosion rates and transport conditions in forested areas, in order to improve validation of the sediment supply model for the Rhine basin. The fact that sediment fluxes may be lower in forested areas does not make forests less interesting or less important when considering the whole of the basin.

A further extension of the validation database presented in this thesis is of great importance to increase the insight into the validity of regional scale erosion models. In this respect, Working Group 3 ('Datasets for erosion studies') of COST Action 623 can provide the essential access to existing erosion data in Europe. Lots of erosion data exist in Europe and elsewhere. But a large part is not accessible. An inventory of erosion data resources and its documentation, with reference to location, scale, measuring method, measuring period etc. is worth gold. Because measuring erosion is difficult and every number represents a major effort.