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# Assessment of erosion and some implications for model validation

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**Abstract** Methods used in Denmark to evaluate or monitor erosion at different scales are described. The accuracy of the methods is discussed from both a practical and a theoretical point of view. It is clearly demonstrated that only primitive methods exist in many cases and that using such methods for validation of more sophisticated erosion models is not possible. As models often have a better time resolution than it is possible to apply in monitoring under field conditions, it is often not possible to validate more than a few events. This paper discusses different approaches to model validation based on the Danish experiences.

## INTRODUCTION

Since the early attempts to model soil erosion, e.g. Wischmeier & Smith (1978), a rapid development of new and more sophisticated models has taken place, e.g. Morgan (1995), Nielsen & Styczen (1986). The development is due to the rapid development in EDP and the development of GIS which makes it possible to incorporate the spatial distribution of parameters and land-use classes.

A similar development has not taken place in the technique of monitoring of erosion. Still many field observations have to be carried out using manpower on the spot. In particular dynamic observations of mass transport caused by erosion have to be mainly based on manual sampling. Significant advances have taken place by the development of data loggers capable of operating under harsh weather conditions, and now with a rather low-power consumption.

Also the development of spaceborne platforms has made it possible to follow large-scale features of erosion; furthermore images can be used as input for computation of spatial distributions of erosion parameters and for creating DTMs. GIS systems, e.g. ARCINFO facilitates automatic computation of streamlines and drainage area per m contour line, features that make it much easier to pinpoint erosion risk areas.

The aim of this work is to give a presentation of recent methods used for monitoring of erosion at different scales in Denmark. The shortcomings of the methods are described and the potential for validation of erosion model output is also evaluated. The thoughts, assumptions and principles behind monitoring of erosion/deposition along the pathways of the sediment are discussed with special emphasis on model validation. The discussion relies mainly on my own experiences obtained while carrying out fieldwork for individual projects or participating in joint programmes such as the NPo-programme (Nitrogen, Phosphorus and organic matter), the Danish Strategic Environmental Monitoring programme (STM) or the development of the EUROSEM model.

## EXPERIENCES WITH EROSION MONITORING

Erosion monitoring at different scales is described with reference to technical problems, accuracy and potential for validation of modelling.

Splash erosion is responsible for the detachment of particles and breakdown of aggregates. The influence of wind speed on splash erosion has been studied by use of splash cups; results are found in Pedersen & Hasholt (1995). It was found that the aspect of splash cups and the erosion slope in relation to wind direction during an erosive rainfall is important for an interpretation of the volumes collected. When this was taken into account it was shown that high wind speeds during rainfall, which thereby increased energy input, could explain outliers in a relationship between rainfall energy and sediment released by splash erosion. It was also demonstrated that short-time rainfall with high intensity had a significant impact on erosion.

This could be explained by the fact that short bursts of intense rainfall may exceed the local infiltration capacity and thereby create Hortonian overland flow under circumstances where the intensity based on computations of time intervals of 5 –10 min would indicate that this type of overland flow would not occur.

Acknowledging the importance of overland flow led to the question of how to monitor it. The author constructed a small sampler for collecting water and sediment (Figs 1 and 2). The small size is necessary because of the possible need to place the

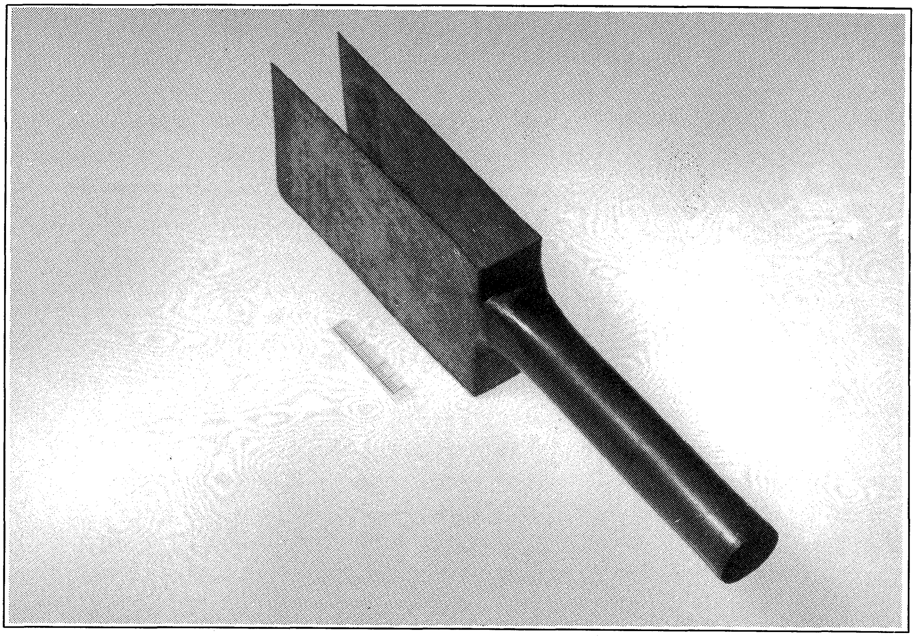

**Fig. 1** Mouthpiece of overland-flow sampler. Water and sediment enter top left are led to a collecting bottle via a tube connected to the tube section of the mouthpiece. The length of the scale bar below is 3 cm.

sampler in small depressions in the terrain and the fact that it should be easy to install and not influence crops and management of the fields. The flanges in the intake section secure the intake against undercutting by running water and furthermore define the width of the intake area. Knowledge of the intake area is important for making quantitative measurements of erosion, it is nevertheless very difficult to determine this area at some distance from the sampler. In principle the collecting bottle could be equipped with a pressure transducer and spot values of overland flow could be recorded. However, because of its small size until now the sampler has been used mainly to prove whether overland flow has taken place on a particular area within a certain time. It is not possible with a few samplers to cover a whole slope, however, by choosing "worst case" spots as locations for the samplers it is believed that it is possible to determine whether or not overland flow has occurred. "Worst case" spots are concave parts of slopes with small depressions, protorills or tracks of previous running water.

Overland flow and erosion on slopes have been monitored by use of Gerlach troughs. Although some information was obtained using Gerlach troughs in Denmark, many problems have occurred. Due to the size the collection bottle must be larger and therefore more difficult to place. The lip of the sampler has proved difficult to insert without disturbing the soil and several cases of undercutting have been observed. Because of frost the lip and the whole trough can be displaced. Also the cavity for the collecting bottle has been disturbed by frost action and the bottle "drowned" because meltwater could not drain away.

Due to its relatively small size and the difficulty of defining the contributing area, this sampler has been used mainly as an indicator of occurrence and of concentration levels.

Studies of erosion on slopes by use of plots were initiated during a NPo- project, (Hasholt *et al.*, 1990). In two research catchments two plots were installed on what would be characterized at "worst case" locations, on steep slopes close to water courses. These plot installations consisted of a large collecting gutter at the foot of the slope. Water and sediment from the local watershed on the top of the slope was collected from a slope width corresponding to the length of the gutter. Slope lengths of approximately 100 m and widths of 30–50 m were used. From the centre of the gently sloping gutter, water and sediment were led into a tank in a cellar, overflow from the tank took place through a Thomson weir. Discharge was recorded by measuring the stage in the tank. Water from the weir fell into a tipping bucket sampler from where subsamples were collected as a cumulating sample each time the bucket tipped to the left-hand side. The whole installation had to be installed in a fairly deep (2–3 m) cellar that was drained and above the groundwater surface. There were several reservations about the feasibility of this installation. First of all a separation of particle sizes took place—sand, gravel and larger aggregates were trapped in the gutter and only silt and clay went through to the tank, where sedimentation took place before it reached the tipping bucket sampler. This meant that although a time distribution of runoff could be recorded, the simultaneous transport of sediment could not be recorded adequately. After a major erosion event, the gutter had to be cleaned and the sediment collected there should be weighed in order to compute the amount of sediment from the slope. Therefore in spite of the time resolution of the runoff, the installation could only record erosion after an event and not during the event. Therefore these plots are not suitable for detailed studies of erosion and for time distributed models.

The results from the plot studies showed very low levels of surface runoff, only 0.1–1.5% of the precipitation, furthermore, the erosion from these slopes was very low, less than 2 t km$^{-2}$ year$^{-1}$, which is well below the annual load in nearby water courses. A possible explanation for these low values could be that in spite of slope steepness from 4 to 12%, the demand for a deep cellar at the end of the slope caused a selection of slopes with a large depth to the groundwater at the foot of the slope. This would hinder the development of saturated overland flow, which is often believed to be an important mechanism causing surface runoff.

In 1989 plot studies were initiated on two soil types, a typic hapludult and a typic agrudalf, at the Foulum and Ødum reseach stations respectively (Schjønning *et al.*, 1995). These plots were close to standard Wischmeier plots and they were tilled and

**Fig. 2** Overland-flow sampler in measuring position, seen from above. The tube leading to the collecting bottle is shown.

sown with typical crops in order to test the effect of tillage and crops on the amount of erosion. The author participated in a special investigation on the formation of rills. In these plots a gutter was placed at the end of the slope, at right angles to the flow; water and sediment were collected in a plastic tank situated further down the slope and connected to the gutter by a tube. The tank and the gutter had to be emptied after a major event, or sometimes even during an event, to prevent overflow.

The system served its purpose well apart from the same reservations as above with respect to particle separation. In order to produce a better time resolution it was attempted to take water samples during an event, and to place transmissometers in the flow. The triggering of the sampling was obtained in some cases by the rise of stage in the tank, in others samples were taken at a certain flow rate. These experiments showed that any obstruction of the water and sediment flow cause sedimentation. It was also shown that the large sediment concentrations caused clogging of the sampling tubes of ordinary samplers. Because of the particle separation and the bad time resolution, these plots could only be used for validation of the summed result of a model and not for validation of concentration levels within an event.

These findings were taken into account when new investigations were initiated in 1993. One aim of the new investigations was to get a better insight in the initiation of rills under Danish conditions, another aim was to design a system for automatic recording of the erosion.

Probably the best way to carry out investigations of erosion processes is to use manned research plots or laboratory installations. When the installations are manned it is quite easy to collect instream manual samples without causing separation of particle sizes because of constrictions. However, when the installation is placed at a remote location and when the occurrence of erosion is determined by natural weather conditions, maintaining readiness for sampling over longer periods is not possible, therefore automation is needed.

The following requirements were set up for the plot installation:

(a) The system (automated plot) should be compatible with the other plots so that manual samples of accumulated sediment could be carried out after an erosion event. A collecting tank is therefore placed in the measuring cellar.

(b) The inlet from the plot to the cellar should be sedimentation free. This means that all particle sizes and aggregates should pass through to the collecting tank, without any delay caused by sedimentation.

(c) In order to have as natural formation of runoff as possible, the groundwater level around the measuring cellar should be allowed to fluctuate naturally, without any artificial drainage.

(d) The volume of water and sediment in the collecting tank should be recorded continuously.

(e) The weight of water and sediment in the collecting tank should be recorded continuously.

(f) Flow-proportional samples of water and sediment should be collected.

(g) During an erosion event, types of erosion should be registered by use of a video-recorder.

Some results of the first version of the system are described in Hasholt & Hansen (1995). Many problems were encountered and solved. The cellar has now stayed in place for 5 years without leaking, in spite of boyancies up to 9 t caused by fluctuating groundwater stage. The intake, built of smooth stainless steel with slopes steeper than slopes on the plot, did not trap much sediment. An exception was seen when falling leaves were blown into it and blocked the inlet of the tube to the cellar. The weighing of the collecting tank proved reliable and accurate ±0.2 kg, which is acceptable for validating the transport during an erosion event. The recording of volume was based on the very stable construction of the collecting tank, it kept an area of one square metre without bulging during fill-up. It was, however, not possible to monitor the stage with an accuracy better than ±1.5 mm, equivalent to ±1.5 kg. This is not good enough for detailed validation of a model during an event.

The first version of the sediment sampler is also described in Hasholt & Hansen (1995). The sampling was collected by the tipping part of the flume leading to the collecting tank backwards, so that the water in the flume was passed into a funnel, leading to a 250 ml collecting bottle placed on a conveyor belt. Flow proportional sampling was obtained by triggering the sampler every time the weight has increased e.g. 1 kg or every time the stage has increased 1 cm. The rate of flow was computed by the data logger from the time it took from one passage of a step of either stage or weight until the next passage. Based on this flow rate, the time for filling the sampling bottle was computed. The funnel was kept open so that the sampling bottle was three-quarters full. From the recorded time and volume in the bottle a flow rate could be computed. Comparing results of sediment transport computed by use of the discrete water samples and transport found by drying and weighing the sediment in

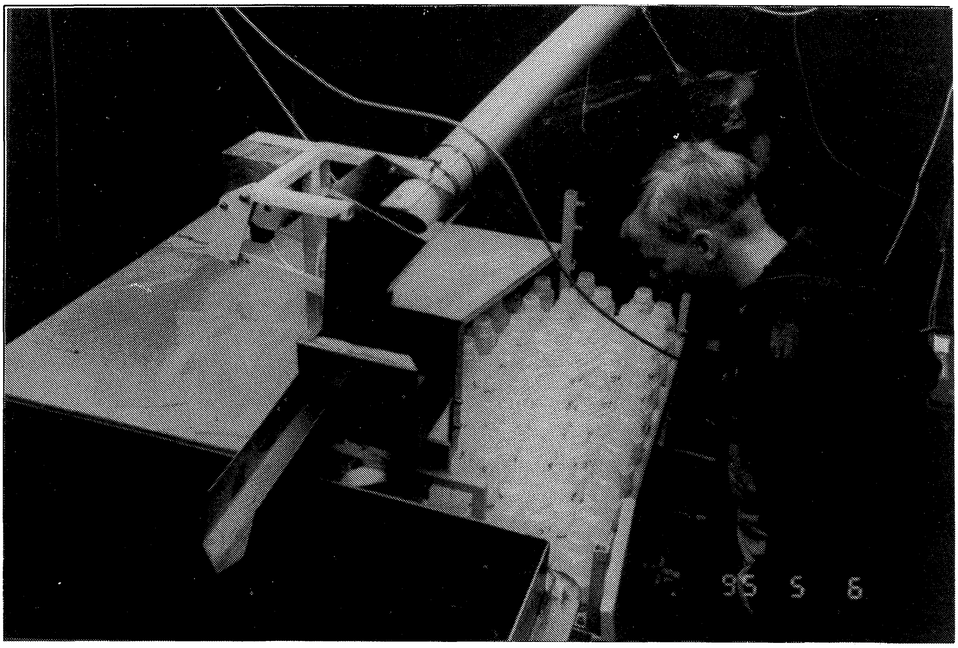

**Fig. 3** Sediment sampler. Inlet tube from plot enters moving funnel from the top of picture. Below left is seen the flume leading to the collecting tank and the upper corner of the tank. In the centre is seen the fixed funnel leading to the sampling bottles placed on the conveyor belt.

the collecting tank, it was found that the load based on the sediment samples was up to 10 times lower than the true load. This was quite puzzling until the sampling was observed during a storm. It was observed that when the funnel tipped backwards to allow sampling, the flow was reversed and the coarser grains were difficult to accelerate in the opposite direction. Therefore a serious particle separation took place.

The sampler had to be changed, but still the sample should be collected "in stream" without causing sedimentation or particle separation. Several procedures were inaugurated, but the one that needed the least change of the sampler was to change to a "tipping funnel". In the no sampling position, water and sediment pass from the plot to a moveable funnel, kept over a flume leading to the collecting tank by a spring. When sampling is triggered, a solenoid causes the moving funnel to swing into position above a fixed funnel leading to the sample bottle on the conveyor belt (Hasholt *et al.*, 1996). The installation is shown in Figs 3 and 4. After this modification the sampler has found its final form and the concentrations of sediment are no longer too low.

This kind of equipment is well suited both to validate modelled concentrations and to obtain samples for determination of aggregate and grain sizes.

The results from a replicate plot situated only 10 m from the instrumented plot could differ by as much as 50% from the instrumented one. In order to explain such differences video recording has proven useful. During one winter the videotapes showed that a large snowdrift was formed at the intake end of the instrumented plot. During snowmelt, where high concentrations and high transport rates usually occur,

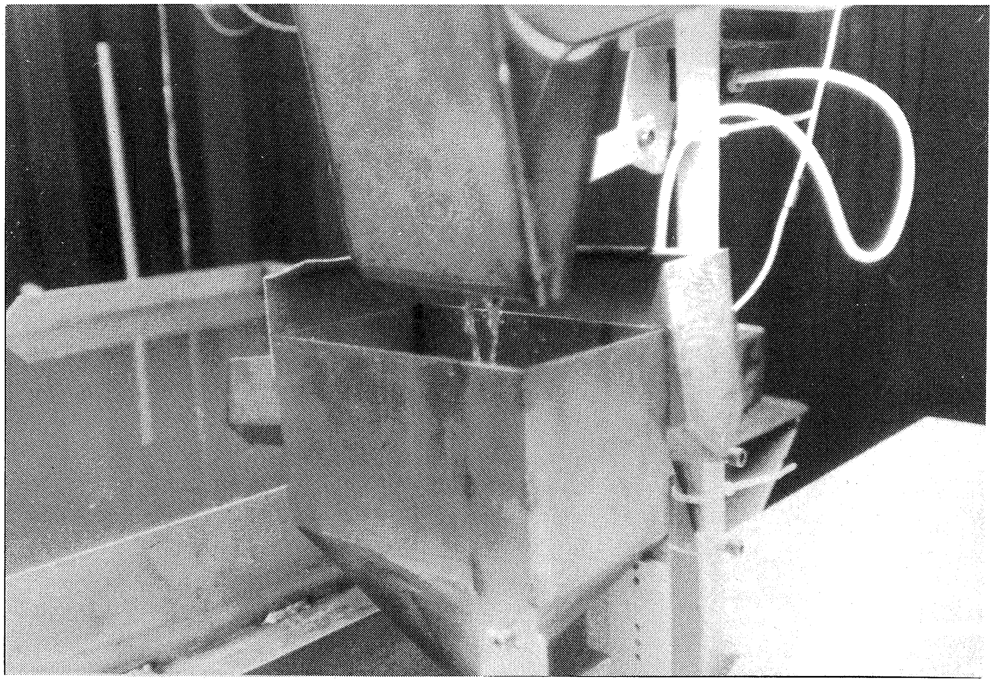

**Fig. 4** The moving funnel and the fixed funnel seen during sampling. Behind is seen the flume leading to the collecting tank, which is now full.

only low concentrations were found. This was because much of the water that should have run down the slope, now melted close to the intake, without being able to pick up sediment. Besides, water from the upper end of the slope was trapped in the snowdrift and depleted of its sediment. Such conditions are quite unusual, and if it had not been for the video recording, the low erosion during this snowmelt period would have been very difficult to explain.

When rills are formed, the sediment yield from a field increases significantly, e.g. Bryan (1987) and Hasholt (1995). This knowledge is based on *in situ* measurements of rill volume and number of rills in a certain area. To monitor rill erosion is very time consuming, when this erosion form is strongly developed on a slope, therefore a way to reduce the amount of surveying has to be found. The computation of the volume eroded by a rill is based on cross-sections measured with a certain spacing along the rill and of measuring the rill length. The effect of different spacing on the result was tested against the "correct" result, based on a spacing of 0.5 m. It was shown, Madsen (1992), that a spacing of 5 m between the cross-sections gave results that deviated less than 20% from the "correct" value. The total amount of sediment eroded by rill erosion on a slope is found by actual measurements of representative rills multiplied by the number of rills counted. The amount of rill erosion determined in this way on fields in Denmark could be as high as 2000 t $km^{-2}$ for field sizes up to 0.03 $km^2$ (Hasholt, 1995). This figure is probably correct within ±50%. It is therefore, not possible to validate results of modelling of rill erosion on a whole hillslope more rigorously. The net contribution of eroded sediment, to a water course situated at the foot of the slope, is found by measuring the amount of sediment accumulated in an alluvial cone at the lower end of the rill, and subtracting this volume from the volume of the rill. The determination of the accumulated volume is more difficult than that of the rill volume, because the margins are often more diffuse. The resulting net transport is therefore less accurate. Results from Denmark indicate that although sedimentation is often found at the foot of a slope, sediment released by rill erosion might nearly all end up in the water course. Concerning the limited accuracy of the field measurements, it is difficult to test the ability of a model to route the sediment correctly.

The inclusion of rill erosion is different from one model to another, e.g. in EUROSEM the occurrence of rills has to be specified in advance, in the model by Nielsen & Styczen (1986) an indicator for the formation of rills is built in. Concerning the importance of rill erosion, it is essential to model validation to check if rills are actually present if predicted by the model. Data from the NPo-project was used to check model predictions of rill occurrence (Hasholt & Styczen, 1993). Although there was reasonable agreement between predicted and recorded occurrence of rills, a better way to validate the model would have been first to run the model, and then afterwards carry out field checks at the spots where the model predicts rills to occur.

Monitoring of erosion from catchments is described in Hasholt (1988, 1992) and Sibbesen *et al.* (1996). First of all the sampling or monitoring frequency at the station at the basin outlet has to be high enough to ensure that no peak events are left unrecorded. In Denmark it was found that one to two daily samples collected by use of an automatic sampler is sufficient to give yearly load estimates correct within

±5%. This was tested by use of transmissometers that measured every 2 min. However, for describing the transport during a single event, daily samples are not enough and indirect determination of the concentration by use of calibrated transmissometers is necessary. Alternatively the automatic sampler could be programmed to pool more frequent samples into a single bottle, to exploit the fixed number of sample bottles. Another possibility is to collect flow or load proportional samples. The amount of sheet erosion in a catchment is determined by recording measurable erosion contributions e.g. bed and bank erosion and rill erosion and subtract these contributions from the total load from the basin (Hasholt, 1991). This approach is very labour intensive and relies on the precondition that material released in the catchment will pass the monitoring station at the outlet within the recording period. The separation of erosion into different components is therefore only possible in smaller catchments, e.g. with an area of about 10 km$^2$. A validation of the sediment routing by measuring the transport and its components is therefore difficult. Use of tracers might be a better solution in this case, but because of rigorous restrictions on the use of tracers this has not been tried in Denmark.

## DISCUSSION

A broad spectrum of methods for monitoring erosion and deposition along the sediment pathway has been described above. Despite the shortcomings many of the methods have described the ongoing processes satisfactorily, both qualitatively and quantitatively. A main constraint on extended use is that the methods are often tedious, and require large amounts of manpower and time. The more sophisticated methods are also rather expensive because of the high costs of instrumentation. Together economic constraints make it impossible to fully monitor an area. Compared with the time scale of the processes, e.g. duration of a single storm, the time consumption for monitoring is critical, for the time resolution, that can be obtained. Another critical time aspect is that the time of arrival of a storm at a certain spot is difficult to predict—this means that a lot of resources must be spent on readiness to carry out monitoring or alternatively on automatic monitoring. Another time-dependant factor that is critical is when farmers actually till or otherwise treat their fields. Within even a small area in Denmark, there can be large individual differences in the time of ploughing. As a result, erosion features occurring late autumn or late winter might have disappeared before monitoring has been possible. This again stresses the importance of costly readiness. Altogether it is demonstrated that it is not possible to fulfil the ideal demands of a complete monitoring programme for erosion. Therefore there is a need for ways to determine the "optimal" use of monitoring. Some thoughts on the problem are dealt with above, but the following discussion will try to demonstrate how and where a combination of the "true point value", obtained by monitoring could be combined with the "area-covering" capabilities of modelling in a fruitful way.

The ideal requirement of a model is that it is able to reproduce fully, within a certain scale, the modelled part of the physical environment and the processes taking place. It is required that the reproduction is in accordance with the physical laws and able to produce results that are quantitatively correct. The closest approximation to these ideal requirements is found in physically-based fully distributed models ("white box models").

At the end of the day the requirements depend on a compromise between specified demands to a model and the available funding. Therefore simple models, e.g. regression based ("black box models") in many cases are found satisfactory, especially for technical purposes.

The present discussion focuses mainly upon the more sophisticated modelling, partly because, from a scientific point of view, this is the most interesting, and partly because it is believed that the need for a more complete understanding of our physical environment will grow in the future.

The process of evaluating a model in relation to the demands or requirements is often termed: model validation. There is no acknowledged standard procedure for such a validation, an example of aspects of validation can be found in Refsgaard & Knudsen (1996) and in Quinton (1994), referring mainly to the EUROSEM model, but also with general comments. According to Quinton it is very important to relate the validation to the actual purpose for which the model is designed. This is both true and fair, but in the present case an " idealistic" approach is aimed at.

Considering an "ideal" physically distributed model the demands to the model can be seen as stepwise growing—the more rigorous tests the model is able to pass, the better the model:

1. Incorporation of relevant physical processes.
2. Relevant physical processes included in correct proportion.
3. Interaction between processes, including feed back loops, described correctly.
4. Quantitative correct representation of relevant physical processes.
5. Quantitative results referring to 3 above.

What are the criteria for fulfilment of the demands stated above? Generally the fulfilment of 1–3 can be judged by experts trained within the field of global geomorphology. It is obvious that models operating at higher latitudes and in high mountains should incorporate processes in frozen soils in order to be complete. In unknown areas a certain time must be spent on skilled observation, before it can be stated that criteria 1–3 are fulfilled. This process could be termed "visual validation". My own experiences show that this can partly be obtained by use of automated digital cameras or video recorders or on a larger scale by use of remote sensing, if it is not possible to be "on the right spot at the right time". A way to optimize the use of "visual validation" and of monitoring equipment, is to look for critical thresholds and key areas, for instance "worst case" areas, or indicator areas. An example of this could be to check the factual occurrence of surface runoff at a given spot on at a given time. As surface runoff is a prerequisite for major erosion, this could be considered a critical test. Another example is the formation of rills. It is well established that the amount of released and transported material increases several orders of magnitude when erosion changes from sheet- to rill erosion. Therefore inclusion of rill erosion in a model is important, but the model ability to predict where and when rills will develop is even more important. This is again a crucial test of model performance. Equipment should in the first phase be located at such key locations where they can test critical behaviour of a system and quantify the maximum values of erosion. In some cases this information is enough, especially when the maximum values found are below accepted limits for soil loss. However, if this is not enough, the next question is—how representative are the results for larger areas or even whole catchments? If the model passes these first tests satisfactorily, it could be assumed with some confidence that it works in other areas too.

The model could then be used to point at locations for further testing, and an interactive process between model creation, testing and monitoring will take place. This calls for not too often found cooperation between the modeller and the monitoring field worker.

In order to limit the amount of work and demands for data, a number of models are event based. Many of these models are very sensitive to the starting conditions or the initialization of the model. This was the case for EUROSEM (van der Keur & Hasholt, 1996). A way to overcome this is to run erosion models "on top" of hydrological models, e.g. the SHE model, so that erosion might be computed, so to say "on line". A validation of the model could then be carried out by field checks of measured *vs* predicted erosion after an erosion event. This will take more computer time but the costly need for readiness can be avoided.

A topic for further research is the routing of sediment through a catchment, definitely grid-based models have some shortcomings in producing correct slope angles, depending on grid size and also in routing across grid borders and in water courses. On the monitoring side it has been shown that very frequent sampling is needed to give a satisfactory description of the sedigraph through time. Although transmissometers might overcome some of the problems, they are very sensitive to changes in grain size, and need frequent calibration—there is certainly a need for new instrumentation for measuring sediment load. Also here for instance cooperation between modeller and field worker might be able to identify where the needs are most important.

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