Adapting the Lisem Model to Loess Plateau Conditions

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Abstract: Physically based erosion models have not often been applied to the Chinese Loess Plateau. To apply the physically based distributed soil erosion model Lisem to a small catchment on the Loess Plateau several changes to the model were needed. This is necessary because of characteristics particular to the Loess Plateau, such as the occurrence of steep slopes, the occurrence of very high sediment concentrations and the presence of many permanent gullies. The changes that were implemented in Lisem include: slope angle correction, use of slope dependent Manning's n, use of alternative transport equations, settling velocity correction and gully correction. The first two changes affect the simulated hydrograph, the latter three only the predicted sediment concentration. The results showed that the slope angle correction changed predicted runoff considerably, while both alternative transport equations and fall velocity correction had large influence on predicted sediment concentration. After recalibration of the model the predicted hydrograph closely resembled the hydrograph obtained with the previous version of Lisem, while the predicted concentration was also similar. Introducing theoretical improvements can give new insights into processes, but is does not necessarily increase predicting accuracy.
Keywords: soil erosion modelling, LISEM, Chinese Loess Plateau

1 Introduction

Soil erosion rates on the Chinese Loess Plateau are among the highest on earth. On-site water and soil losses reduce crop yields and so threaten the livelihoods of rural families, while off-site sedimentation poses problems to waterways and reservoirs. The Chinese government acknowledges the erosion problem and promotes comprehensive erosion control. Erosion modelling might be a useful tool to understand and predict erosion and to ultimately find ways to prevent it.

In this study the physically-based distributed Lisem model (De Roo *et al*., 1996, Jetten & De Roo, in press) was applied to the Danangou catchment in the rolling hills part of the Chinese Loess Plateau. Contrary to other well known physically based erosion models Lisem uses a grid based approach. Physically based erosion models have not been applied to the Loess Plateau often. The conditions on the Chinese Loess Plateau are very different from the conditions for which the Lisem model has been developed.

The Danangou catchment (Figure 1) is a typical small (3.5 km^2) Loess Plateau catchment in Northern China with steep slopes and a loess thickness close to 200 m. The soils are mainly silt loams. The climate is semi-arid, with occasional heavy thunderstorms in summer. Yearly rainfall is slightly over 500 mm, most of which (70%) falls in the period June-September. All heavy storms occur in this period. On average 3 to 4 storms each year are large enough to cause runoff, but the actual number varies widely from year to year. The main land uses in the catchment are: wasteland (40%), cropland (28%) and fallow (21%). Vegetation cover is generally low, also in croplands, and as the loess soils are susceptible to erosion, very high erosion rates can be reached during the summer storms. Elevation in the catchment ranges from 1,070 m to 1,370 m and the catchment is deeply dissected by gullies, which have slope angles of up to 250%. These steep slopes in the catchment also promote high erosion rates. In the catchment sediment concentrations of up to 500 g/l were measured, while concentrations of up to 1,000 g/l are reported regularly for Loess Plateau rivers (e.g. Zhaohui Wan & Zhaoyin Wang, 1994).

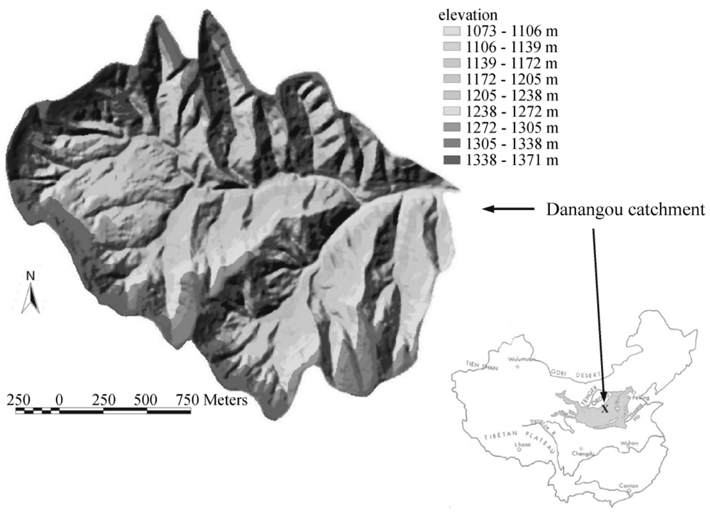

Fig. 1 Elevation map of the Danangou catchment, also showing the approximate position of the Danangou catchment (marked X) on the Loess Plateau (grey area on China map). Shading is used to bring out relief. The map of China was adapted from Pye (1987).

Thus, in this study, Lisem was applied to an area with very steep slopes, very high sediment concentrations in runoff and with large, permanent, gullies. These characteristics require a number of adaptations to the Lisem model. The purpose of this paper is to identify which changes are needed, to implement these changes and to evaluate the effect of these changes on the predictions of the Lisem model.

2 Method

The Loess Plateau has steep slopes, high concentrations and permanent gullies. These characteristics are specific to the Chinese Loess Plateau and make the following changes to Lisem necessary:

- Correction for overland flow distance. So far, Lisem used the distance between pixel centres as flow distance. The grid is, however, essentially a horizontal grid. For steep slopes the overland flow distance is not equal to the distance between pixel centres. For example, if the slope is 45 degrees and the distance according to the grid is 10 metres the actual distance over the surface is 14.4 m. To correct for this a map showing the overland flow distance is calculated from the slope map. Another slope-related difference between the original version of Lisem and the new version is that in the new version the Manning equation uses sine instead of tangent. This is theoretically better since the slope in the Manning equation is the energy slope. The sine of the slope angle gives the actual distance over which friction is exerted on the flow.
- Use of a slope dependent Manning’s n. Hessel *et al.* (in press) found that for the steep erodible slopes of the Danangou catchment flow velocity was independent of slope angle. The Manning equation, however, predicts an increase of velocity with slope angle. The most pragmatical solution to this problem is to allow the Manning’s n to vary as a function of slope instead of taking a value that is constant for each particular land use.
- Introduction of a concentration dependent fall velocity. At high sediment concentrations settling velocity is significantly lower than settling velocity in clear water. This is due to the effect of hindered settling (Zhaohui Wan & Zhaoyin Wang, 1994). Here, the Chien & Wan (1983) equation was implemented because it was developed for Chinese conditions.
- Use of alternative transport equations. So far, the Lisem model has only used the stream power based equation developed by Govers (1990) to predict transport capacity. A number of other equations was tested for the Danangou catchment.
- Introduction of a map with loose material derived from gullies. Observations in the Danangou catchment showed that loose material accumulates on gully floors in between runoff events due

to soil falls. A daily-based gully model was developed by Hessel & Van Asch (in press) to model the amount of loose material available on gully floors. The output of this model is a map that can be used by Lisem. During the Lisem run the only factor determining whether or not the material is removed is the availability of transport capacity. The remaining available material will be recalculated during each timestep and erosion will stop when there is no material remaining.

- Use of sine instead of tangent. The effect of using sine instead of tangent has already been discussed above for the simulation of discharge. It will, however, also influence sediment transport. Equations for shear stress and stream power incorporate the sine of the slope angle. For gentle slopes the tangent is almost equal to the sine. Most studies have so far used tangent. The Lisem model is no exception. For steep slopes, however, the tangent is much larger than the sine. Therefore, shear stress and stream power will be larger for steep slopes when tangent is used instead of sine.

To evaluate the effect of these changes to Lisem a calibrated dataset for an event that occurred on July 20th, 1999 will be used. During this event 15.8 mm of rain fell. Maximum intensities recorded were 130 mm/h for a 1minute interval. The resulting peak discharge from the Danangou catchment was 3,700 l/s.

All the proposed changes are in theory an improvement of Lisem. For some changes it is, however, difficult to assess whether or not a change is also an improvement in simulation. If one starts with a calibrated model and then implements a theoretical improvement it can be expected that the adapted model gives less good predictions. To evaluate if the implemented change is an improvement in terms of simulation accuracy one has to recalibrate the model. If this results in either a better fit with observations or the use of more realistic calibrated parameter values the change can be considered to be an improvement. This method most easily applies to changing Manning's n and to slope correction because these changes affect the hydrograph. Therefore, the hydrographs can be compared to the predicted hydrographs of the original version. The other changes affect only sediment transport and are more difficult to test since the measurements of sediment concentration are less frequent and probably less reliable, so that there is also uncertainty about the accurateness of the measurements.

3 Results

3.1 Flow distance

The combined effect of the slope correction and the use of sine in the Manning equation is shown in Figure 4. Figure 4 shows that the difference is large; peak discharge has decreased by about 50%. A decrease in discharge was to be expected since:

- On steep slopes the pixel areas have increased. The amount of rainfall per pixel is unaffected because it is assumed that the rain is falling vertically. The same amount of water is therefore spread out over a larger area, so that the water layer will be thinner. The hydraulic radius will also be smaller, so that flow will be slower according to the Manning equation.
- The flow distance between pixels is larger.
- Since on steep slopes the pixel area is larger infiltration will be larger as well.
- For large slope angles sine is significantly smaller than tangent, hence the flow velocity as calculated by the Manning equation will be smaller too.

Factors that affect flow distance or flow velocity will also affect discharge because longer flow distance and lower flow velocity allow more time for infiltration.

3.2 Manning's n

Using a slope dependent Manning's n retarded the peak discharge slightly. The effect was much smaller than of using a slope correction.

3.3 Transport equations

Figure 2 shows simulated concentrations at the catchment outlet for different transport equations. As can be seen from the figure the differences are large. In the simulations the maximum concentration was restricted to 1,060 g/l because higher concentrations were assumed physically unrealistic. This restriction affected most results considerably (e.g. the Yang equation), but the effect of the restriction on the results obtained with the Govers equation was small. Thus, the equation that is at present being used by Lisem, was found to perform best.

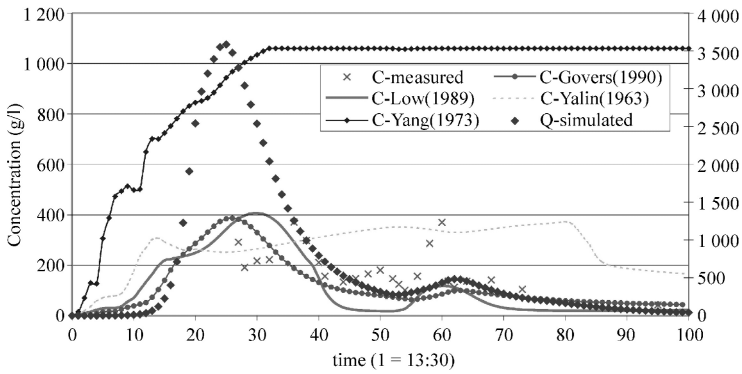

Fig. 2 Measured and predicted sediment concentrations using different transport equations

3.4 Fall velocity

Figure 3 shows that by using the settling velocity correction the predicted sediment concentrations increase during the runoff peaks, but remain equal otherwise. The result is slightly unexpected since the settling correction could be expected to slow down settling after the sediment peak. This would result in higher concentrations after the sediment peak. Instead, concentrations rise faster and decline faster. This might be caused by the fact that the chart shows the integrated result for the entire catchment. The overall predicted effect of the settling correction seems reasonable.

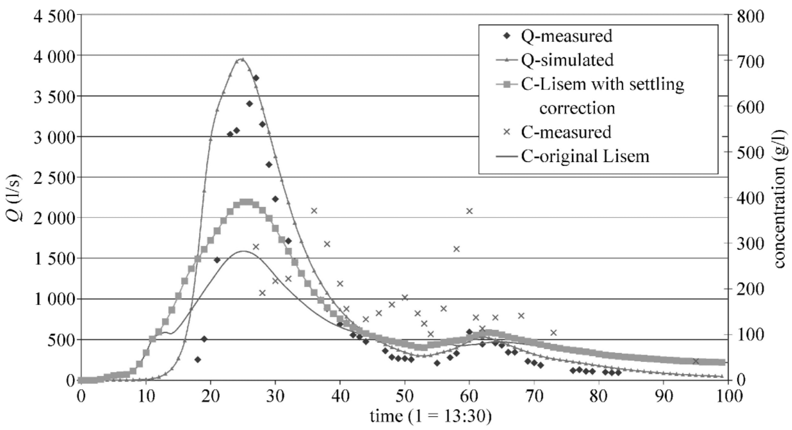

Fig. 3 Comparison of sediment concentration predicted with the original version of Lisem (1.63) and with settling correction added. Event of 990720. Approximate calibration only

3.5 Loose material map

The results using the model that incorporated a loose material map showed that in some places a considerable amount of material was removed. For the entire catchment the amount of loose material declined from 372 t to 265 t, so that 107 t of loose sediment was taken up by the flow. Nevertheless, the total amount of sediment leaving the catchment only increased by 1 t — 2 t. Apparently the extra eroded sediment is deposited before reaching the catchment outlet. The deposition map produced by Lisem confirms that this happens. Most pixels with loose sediment showed only a small decline in loose material. This can be explained by the fact that many of these pixels did not experience much runoff because they had fairly small upstream areas. The results indicate that including a loose material map is likely to have more effect when the loose material is present close to the outlet of the catchment.

3.6 Sine versus tangent

The effect of using sine instead of tangent is small for simulations for the entire catchment. Simulated total soil loss from the catchment decreased from about 1,050 t to 1,000 t. Because the slopes near the catchment outlet are fairly gentle transport capacity close to the outlet will not have changed much by using sine instead of tangent. It seems likely that the effect would be larger when only steep areas are simulated.

3.7 Recalibration

After the changes to Lisem were implemented the model was recalibrated. Figure 4 shows the results obtained with the original calibration as well as with the new calibration. It shows that the adapted version of Lisem better predicts the measured rise of discharge, but it also shows that the falling limb of the hydrograph is predicted slightly less well. Overall, the quality of fit is comparable. Concentrations predicted with the adapted Lisem were, after recalibration, also similar to those previously obtained.

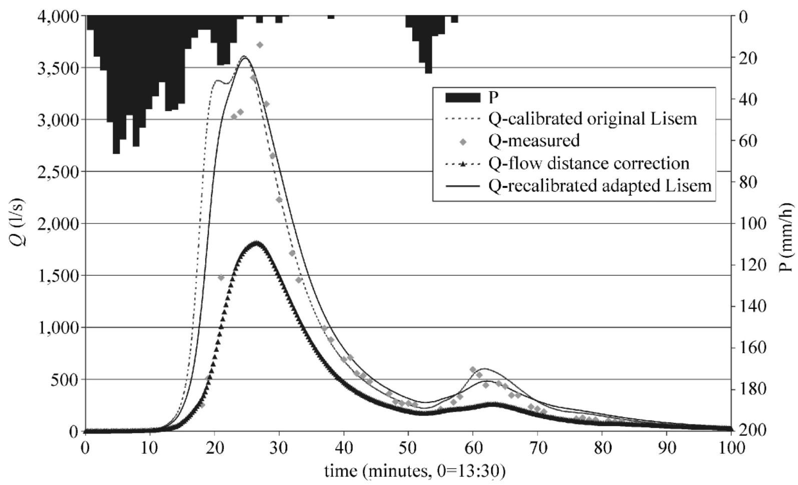

Fig. 4 Lisem simulation results with the calibrated old version of the model, with a flow distance correction and with the calibrated adapted version of the model

4 Discussion

The results presented in this paper show that the changes made to Lisem, though all theoretically improvements, do not all influence the simulation result much. The prediction of discharge was most influenced by the slope correction, while the prediction of concentration was most influenced by choice of transport equation and by use of a settling velocity correction. It was found also that calibration of the adapted version of Lisem does not give significantly better results than calibrating the original version. This shows that improving the structure of physically based erosion models does not guarantee that predictions will be improved too. The cause is likely to be that such models are so complicated that fairly good predictions can always be obtained by calibrating, especially for areas that are also topographically complex.

5 Conclusions

Several model changes were needed to apply the physically based distributed soil erosion model Lisem to a small catchment on the Loess Plateau. This was necessary because of characteristics particular to the Loess Plateau, such as the occurrence of steep slopes, the occurrence of very high sediment concentrations and the presence of many permanent gullies. The implemented changes to Lisem included: slope angle correction, use of slope dependent Manning's n, use of alternative transport equations, settling velocity correction and gully correction. The first two changes affect the simulated hydrograph, the latter three only the predicted sediment concentration. The results showed that the slope angle correction changed predicted runoff considerably, while both alternative transport equations and fall velocity correction had large influence on predicted sediment concentration. After recalibration of the model the predicted hydrograph closely resembled the hydrograph obtained with the previous version of Lisem, while the predicted concentration was also similar. Introducing theoretical improvements can give new insights into processes, but is does not necessarily increase predicting accuracy.

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