Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes (Proceedings of a symposium held at Vienna, July 1998). IAHS Publ. no. 249, 1998.

Modelling badlands erosion with SHETRAN at Draix, southeast France

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Abstract The physically-based, distributed flow and sediment transport modelling system SHETRAN was applied to the Draix basins to test its ability to represent badlands flow and erosion response, to quantify characteristic parameter values and to investigate spatial scale effects in badlands modelling. A unit gully, area 0.133 ha, was simulated using a 5-m grid resolution model and a single cell model, with comparable results. Application of the models to a badlands basin, area 86 ha, suggests that transfer of parameter sets from the gully scale to a larger scale may be feasible but, given uncertainty in parameter evaluation, a separate calibration still yields improved results. Considering the flashy basin responses, satisfactory flow simulations were achieved using physically realistic parameter values, and sediment yields were well simulated within the bounds of uncertainty. Any scale effects which may distinguish the gully and basin simulations are masked by the uncertainty in parameter evaluation.

INTRODUCTION

Available physically-based, distributed erosion models generally account for erosion by raindrop impact and overland flow and are particularly relevant to croplands. They have not been deployed to model badlands gully systems. However, at the badlands of the Draix basins, southeast France, raindrop impact and overland flow play a major role in the erosion process and existing models should therefore be applicable. There is, though, a lack of information on how model parameters might need to be adjusted for the badlands environment, compared with the more widely researched case of croplands. The physically-based, distributed flow and sediment transport modelling system SHETRAN (developed by the Water Resource Systems Research Laboratory from the Système Hydrologique Européen or SHE) (Ewen, 1995) was therefore applied to the Draix basins (which are managed scientifically by Cemagref) (Mura *et al.*, 1988) to test its ability to represent badlands flow and erosion response, to quantify characteristic parameter values and to investigate spatial scale effects in badlands modelling. So far as is known, this is the first application of a physically-based basin model to a badlands environment.

THE DRAIX BASINS

The Draix basins are located near Digne on the edge of the Alpes Maritimes. They are formed in black marne soils which erode easily into the characteristic badlands morphology of V-shaped gullies. Erosion occurs in a cycle of: soil weakening by freeze/thaw and wetting/drying action; particle detachment during rainfall events; and removal of material by channel flow. The channels themselves range from confined furrows at the base of individual gullies to conduits a few metres wide at the outlets of the larger basins. Available data include continuous precipitation and discharge, sediment yield (from trap and suspended sediment measurements), 1:2000 scale contour map, aerial photographs of vegetation distribution and a few measurements of soil-size distribution. Evapotranspiration was determined for this study from daily temperature records at a site about 8 km distant, using the Blaney-Criddle formula adjusted with data from elsewhere in southern France to avoid seasonal bias.

MODELLING APPROACH

SHETRAN was first calibrated for gully conditions through application to the Roubine sub-basin, a unit gully of area 0.133 ha, 21% covered by grass. The sub-basin was represented spatially both as a single cell (dimensions 64 m × 21 m) and by a network of 54 squares of dimensions 5 m × 5 m, to highlight any parameter scale dependency and to investigate the spatial resolution required to model a unit gully. The extent to which the calibration achieved at the scale of a unit gully is valid at a larger scale was then tested through application to the Laval badlands basin, area 86 ha, represented spatially by 344 squares of dimensions 50 m × 50 m (Fig. 1). The Laval vegetation cover is 32.2%, mostly trees with some grass.

A modified form of Ewen & Parkin's (1996) validation methodology was applied, enabling the uncertainty in predicted responses to be determined as a function of the uncertainty in model parameter evaluation. Simulations are carried out for ranges of parameter values (reflecting the uncertainty in their evaluation) and

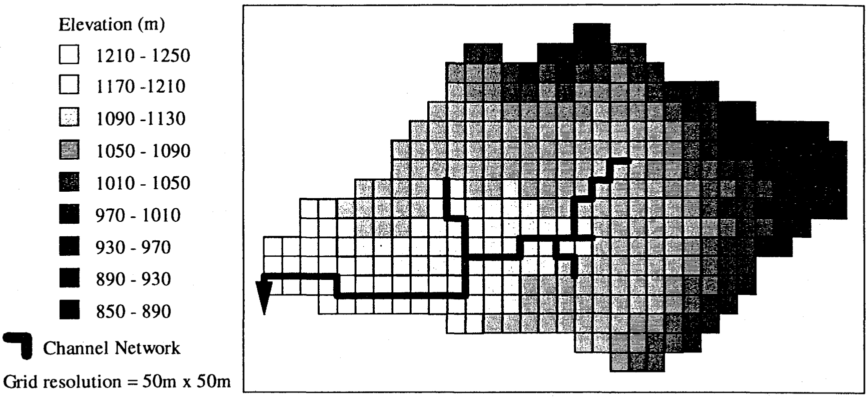

Fig. 1 SHETRAN grid network, channel system and elevation distribution for the Laval basin.

Table 1 Values for the varying model parameters and functions used in determining the Roubine and Laval flow output envelopes.

Parameter/function	Low value	Medium value	High value
Saturated horizontal hydraulic conductivity (m day^{-1})	0.5	1.5	5.0
Saturated vertical hydraulic conductivity (m day^{-1})	0.01	0.03	0.09
Strickler overland flow resistance coefficient	1.0	5.0	10.0
Soil retention curve (ψ *vs* θ/θ_{sat})	$\psi \times\sqrt{5}$ (sandier soil)	ψ for measured curve	$\psi/\sqrt{5}$ (siltier soil)

ψ = soil tension; θ = soil moisture content; θ_{sat} = saturated soil moisture content.

the results are superimposed to provide an envelope of outputs: conclusions on model performance are drawn according to the width of the envelope and the extent to which it contains the measured basin response. The validation was carried out first for the basin outlet discharges. Four model parameters (those to which the results were most sensitive) (Table 1) were allowed to vary while the others were set at fixed values. A single best-estimate flow simulation was then selected from the series making up the output envelope to drive the sediment yield simulations, bounds for which were based on sediment parameters.

Simulations were carried out for the five-year period 1987–1991. However, to avoid excessive computing time, the validation methodology was limited to 1987.

SIMULATIONS

Roubine flow simulations

The envelope of discharge outputs was obtained for 1987 from the 81 simulations representing every combination of the four sets of varying parameter values in Table 1. This contained the observed time series for 46.3% of the time in the case of the single cell model and 57.2% of the time for the 5-m grid model. These relatively poor containment percentages (80% would be considered successful) reflect the difficulty of simulating a runoff response which is very flashy, which is of the order of a few litres per second and which is generated over short periods (from a few minutes to an hour) with virtually no baseflow.

The best-estimate simulations for the two model scales for 1987 were extracted from the series of 81 and extended to the full 1987–1991 period. The values of the r^2 goodness-of-fit index obtained from the comparison with the observed time series vary between the years: the overall values are 0.44 for the single cell model and 0.55 for the 5-m grid model. In general the runoff depth is underpredicted (an observed mean annual runoff over the five years of 110 mm compared with 94 and 74 mm for the single cell and 5-m grid models respectively). However, the r^2 test is very sensitive and to some extent misleading for the difficult modelling conditions. From the point of view of the input to the sediment yield simulations, it is probably more important that the overall magnitudes and timings of the major runoff events are generally well reproduced.

Although the best-estimate parameter sets for the two model scales show some differences, they both come from the same uncertainty range of parameter values

(Table 1). It cannot therefore be claimed that the differences represent any scale effect.

Laval flow simulations

The uncertainty envelope for the Laval discharge was obtained for 1987 using the same varying parameter values as for the Roubine unit gully. This contained the observed time series for 64.1% of the time (Fig. 2).

The best-estimate parameter sets for both Roubine models were applied to the Laval basin for the years 1987–1991 to see which provided the best means of evaluating parameter values at the gully scale for use at the basin scale. However, neither model showed a good agreement with the observed discharge time series, with r^2 values either low or negative. The Laval best-estimate simulation was then extracted from the series of 81 simulations used to create the uncertainty envelope. Extended to the full 1987–1991 period, the r^2 values for each year are more consistent than for the Roubine, mostly fluctuating around the overall value of 0.32. The simulated mean annual runoff is 197 mm compared with the observed figure of 165 mm. (The results apply only to periods for which the Laval discharge record is intact and do not include periods when there are gaps in the record: both observed and simulated runoffs are therefore underestimates of the true runoff.)

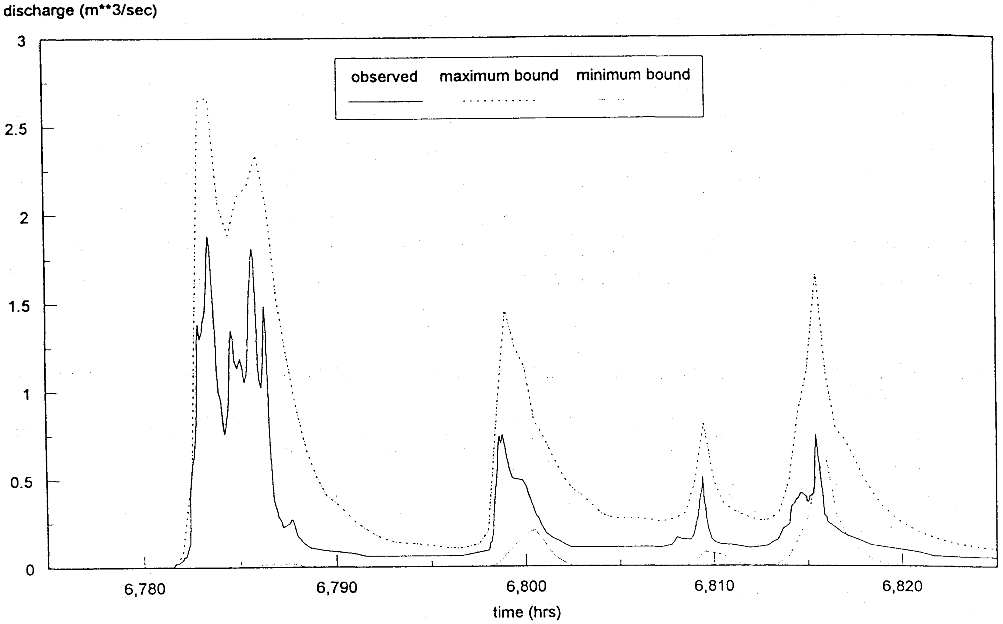

Fig. 2 Comparison of the observed discharge hydrograph with the bounds of the simulated output envelope for the Laval containment test. Results are shown for a short sequence of runoff events during 1987.

Sediment yield simulations

Bulk measured sediment yields for comparison with the simulated values were obtained by combining the trapped and sampled (suspended sediment) volumes. To produce consistent sets of yields, the sample measurements (which refer to periods of hours and are available for only a number of events) were extended to cover the same periods as the trap measurements, using sediment rating curves generated from the suspended sediment and flow discharge measurements and then applied to the recorded discharge time series. Although inaccurate for determining individual event sediment yields, it was expected that the curves would provide reasonably accurate bulk yields when applied to the periods of weeks between trap measurements. The combined sediment volumes are referred to as the generated yields. For the Roubine, 46 such yields were derived to provide a continuous record for the period 1987–1991. For the Laval, 21 totals were derived, with intervals between them corresponding to gaps in the water discharge and sediment trap records.

In the simulations, soil was eroded by raindrop impact, leaf drip impact and overland flow. Transport of the eroded material was simulated using the Engelund–Hansen total load equation for overland flow and the Ackers–White total load formula for channel flow. No additional material was supplied from the channel bed or banks. The simulations were driven by data from the respective best-estimate flow simulations for the Roubine and Laval basins. Uncertainty bounds on the simulated sediment yield were determined by varying the coefficients which represent the ease with which soil can be eroded. (Raindrop impact erodibility coefficient = 0.1–10 J^{-1}; overland flow erodibility coefficient = 1–20 mg m^2 s^{-1}. Details of the sediment model are in Wicks & Bathurst (1996).) Two soil size distributions were applied: one relatively fine from a soil sample, the other coarser from the Roubine sediment trap.

For the Roubine, the sediment trap size distribution provides the better result. For 17 of the 46 measurement periods, the generated sediment yields lie within the simulation bounds, as does the 5-year total (Table 2). In the case of the Laval, the soil sample size distribution provides the better result: for 15 of the 21 measurement periods, and for the overall period, the generated yields lie within the simulation bounds (Fig. 3, Table 2). (Because of gaps in the discharge record the Laval totals are not 5-year totals.) In Fig. 3 the vertical lines represent the ranges between the upper and lower simulated yields for each period; the horizontal lines indicate the generated yields. As the measurement periods vary in length, the range of yields per

Table 2 Comparison of simulated (upper and lower bounds) and measured (i.e. generated) sediment yields for the Roubine and Laval basins.

Simulated sediment yield bounds (*t*) based on soil size distribution from:				Generated sediment yield (*t*)
Soil sample:		Roubine trap:		
Upper	Lower	Upper	Lower	
Roubine (1/1/87–19/11/91)				
551	301	345	66	78
Laval (21 periods during 1987–1991)				
58 120	17 070	18 935	5815	32 225

The Laval results apply only to periods for which the Laval discharge record is intact and are not full 5-year totals.

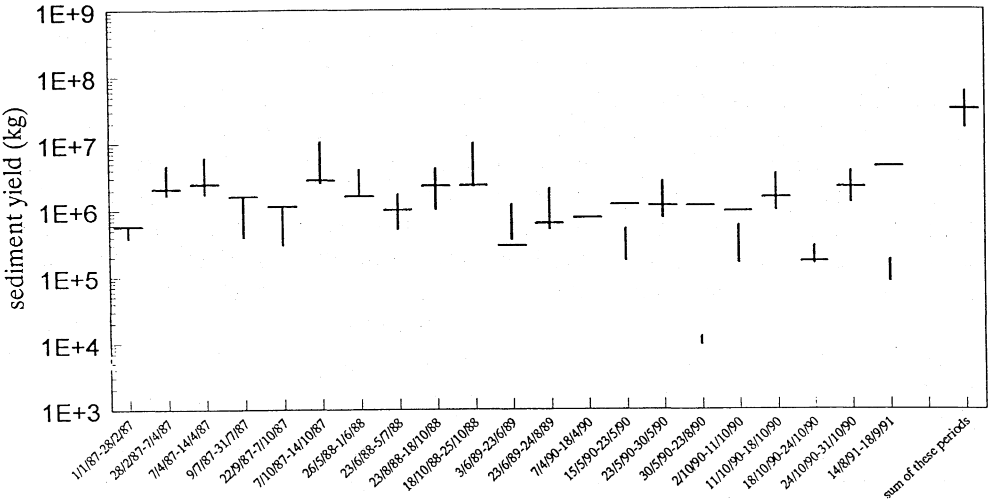

Fig. 3 Comparison of the Laval simulated sediment yield envelopes (vertical lines) and measured (i.e. generated) yields (horizontal lines) for the 21 measurement periods and for the combined periods during 1987–1991.

unit time is rather wider than may first be apparent from the figure.

CONCLUSIONS

Modelling badlands

Considering the flashy nature of the runoff regime, the simulated flows may be considered satisfactory. In general the simulations vary in the same manner as the observations, at the level of individual events and on an annual basis. However, the relatively poor containment percentages suggest that insufficient allowance was made for uncertainty and that the parameter ranges for the flow simulations should have been set wider.

The sediment yields are well simulated within the bounds of uncertainty, with the observed variability between the measurement periods well reproduced. Application of the separate Roubine and Laval sediment models (with uncertainty bounds) to the full 1987–1991 period gives sediment yields of 100–520 and 90–300 t ha^{-1} year^{-1} respectively, which enclose the values of 157 and 127 t ha^{-1} year^{-1} measured by Borges (1993, p. 142). The uncertainty bounds on the erodibility coefficients are therefore considered appropriate.

Representation of the surface and subsurface lateral water transfer processes in the highly dissected terrain of the badlands required some adjustment of SHETRAN parameter values from typical values obtained in model applications to less dissected hillslopes. The best-estimate Strickler overland flow resistance coefficient (equal to 10 for the Roubine unit cell model and for the Laval model) is larger than the typical values of 1 for vegetated areas and 5–7 for agricultural areas with bare soil but is smaller than the value of 50 which has been obtained for bare soil plots. The value of 10 may therefore be an "effective" grid scale value, representing a bare soil with a subgrid gully system and locally steep slopes. The best-estimate saturated zone hydraulic conductivity (5 m day^{-1} for the above two models) is likewise relatively high (although within physically realistic limits). Its value may reflect a relatively rapid transfer of water in thin soils at the typically steep slopes. The bound values of the soil erodibility coefficients are similar to those derived in previous applications and are the same for the Roubine and the Laval basins. As the simulations accounted for erosion by raindrop impact and overland flow only, this may suggest that other processes such as local mass movement are relatively unimportant in the Draix badlands. However, it is also possible either that the coefficient values may empirically include some compensation for errors in the flow simulations or that the real erosion rate is indeed increased by additional processes but that their effect is balanced by sediment storage at the scale of the model grid. It is similarly not clear if the dependency of the sediment yield simulations on the soil size distribution represents a real physical effect or is a model compensation.

Overall, it may be concluded that SHETRAN can be applied satisfactorily to a badlands basin using physically realistic parameter values, albeit with some calibration. Results are likely to be more accurate at the annual scale than the event scale.

Spatial scale effects

Calibration of a model at a small scale is usually cheaper, simpler and involves less uncertainty than calibration at the scale of a full basin. It was of interest, therefore, to see whether SHETRAN could be calibrated for the Roubine and then applied to the Laval, or whether scale effects would require a separate calibration for the Laval.

For the Roubine simulations, within the uncertainty attached to parameter evaluation, it cannot be claimed that either the 5-m grid or the single cell model is more representative or that differences in their results represent any scale effect. However, the single cell model, as the easier to implement, is preferable on practical grounds.

For the Laval basin, the Roubine flow models performed poorly and a better reproduction of the observed runoff was obtained with a separate Laval best-estimate model. However, because the Roubine and Laval models are based on the same uncertainty range of varying parameter values (Table 1), the improved result cannot be claimed to indicate any scale effect in parameter evaluation. Calibration at the scale of a unit gully and transfer of the resulting parameter set to the scale of a badlands basin may therefore be feasible. However, given the uncertainty in parameter evaluation, improved results may still be gained through separate calibration of the full basin.

Overall, any scale effects which may distinguish the Laval and Roubine flow and sediment yield simulations are masked by the uncertainty in parameter evaluation. Use of a single cell model in calibrating the soil erodibility coefficients at the gully scale is likely to minimize any scale effects in the application of the calibrated values for a full badlands basin.

Acknowledgements Thanks are due to the Cemagref staff who collected the field data. The study was part of the EC DM2E project, contract number EV5V-CT91-0039.

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