Title of Monitoring and Modelling Runoff in Semi-arid Areas from the Hillslope to the Watershed Scale

Richard Brazier, John Wainwright, Tony Parsons, D. Mark Powell, Roger Simanton, Howard Larsen

Abstract

Response of the landscape to intense rainfall events is a complex and poorly understood problem. An understanding of the spatial variability of runoff generated by such storms at the hillslope scale is a necessary goal if patterns of runoff and soil erosion are to be understood at the field and catchment scale also. In recent years, it has been recognised that linking these scales of runoff may provide an approach by which accurate predictions may be made at all scales from the small hillslope to the large catchment (Wainwright et al. 2001). Furthermore, by studying the way in which patterns of runoff vary with spatial scale a better understanding of sediment delivery problems and the dynamic connectivity of systems at a variety of scales can also be made.

To address the issue of scaling within runoff, a series of nested experiments was carried out to monitor the flux of runoff after intense, natural rainfall events at a range of scales at the Walnut Gulch Experimental Watershed in the semi-arid south western US. Data from these experiments were used to evaluate a distributed, dynamic, process-based model, previously shown to perform well at the plot scale on semi-arid shrubland (Parsons et al. 1996). To extend previous work, the model was applied to sites ranging in size from 2 m^2 up to 0.5 km^2 to investigate model response to changes in scale and to provide a means of linking predictions made at the hillslope scale with those made at the catchment scale. Results indicate that given high quality input data accurate predictions can be made at a range of hillslope lengths. Limitations focus upon high data requirements, though remote sensing techniques are being developed to reduce time spent on data capture of surface condition parameters. Scaling of erosion and sediment transport is being investigated also using a unified approach that uses characteristics of transport distances to provide an inherent scaling factor. Initial results of the runoff modelling are presented as a basis for future development of the erosion model.

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Keywords: semi-arid, runoff, erosion, scaling

Introduction

Understanding the response of hillslopes to extreme rainfall events is a complex problem. To date, numerous monitoring and modeling strategies have been employed in an effort to not only characterize hillslope runoff and erosion as a response to rainfall, but also to extend lessons learnt at the hillslope scale to the wider environment at the sub-watershed or watershed scale. Examples in the United States date back to the work of Cook (1936) who identified the chief controlling variables of soil erosion by water, through to Wischmeier and Smith (1965) who developed the Universal Soil Loss Equation (USLE) and more recently Lane and Nearing (1989) who present a more process-based understanding of rainfall-runoff and soil erosion in the framework of the Water Erosion Prediction Project (WEPP). Such work has been instrumental in furthering the understanding of runoff and erosion processes and crucially has led to the development of tools which can guide policymakers and farm managers alike as to the effects of cultivation or grazing upon the natural response of the environment to rainfall events.

To further understanding in this field, it is suggested herein that the problem of up-scaling assessments of runoff and erosion from the hillslope to the watershed scale is addressed. Many of the existing predictive models rely upon empirical observations made at the hillslope or plot scale (from the USLE plots for instance). These data sets, though undoubtedly a unique resource and clearly very useful in their time, tend to rely upon uniform plot dimensions - typically 22 x 4 m in the case of the USLE plots (Wischmeier 1976), which do not describe hillslope responses over a range of scales. Therefore, the following paper presents results from a nested monitoring and modeling scheme which seeks to overcome this spatial limitation of existing data sets (and models) by explicitly considering runoff (and in due course soil erosion) as a function of hillslope length on a range of sites from 2 m^2 to 1200 m^2 in size.

A spatially designed monitoring experiment, to complement the existing monitoring infrastructure at the USDA-ARS Walnut Gulch Experimental Watershed, Arizona, was developed and maintained for three monsoon seasons. The approach taken coupled field observations directly with model development in order to ensure that full evaluation of the model was possible, as called for by Brazier, (in press). The following paper describes preliminary results of the hydrological model performance against observed data from a range of scales.

Nested Monitoring Scheme

In order to observe water and sediment fluxes at the hillslope scale, four pairs of erosion plots were constructed within watershed 223, downstream of the Lucky Hills watersheds. Each of four large plots (Wise, Abbott, Laurel and Dud) were constructed alongside four small plots (Morecambe, Costello, Hardy and Pete) of equal size (2 m in length) on interrill areas. The large plots ranged in length from 4 m to 28 m and were installed to sample:

- Rainfall
- Event hydrograph
- Total flow
- Suspended sediment flux (1 minute intervals)
- Total soil loss
- Nutrient fluxes

In this manner, it was anticipated that detailed description of hillslope response to natural events could be made and comparisons drawn between plots and on both an inter- and intra-event basis. An example of observed results for a single event is included in Figure 1.

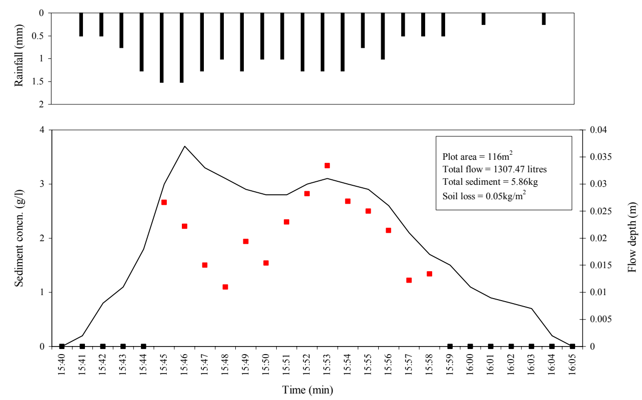

Figure 1. Rainfall, flow depth and suspended sediment concentration from the Abbott hillslope plot - 30/07/00.

Varying rates of sediment flux from all of the hillslope plots is shown in Figure 2. A clear relationship between soil erosion and plot length can be seen, with shortest plots (ca. 2 m) yielding highest fluxes per unit area and longest plots yielding lowest concentrations of sediment.

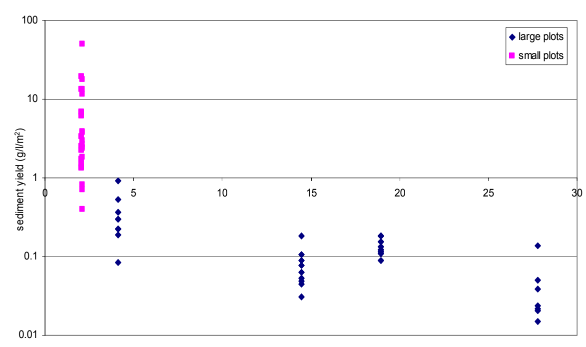

Figure 2. Observed interrill sediment flux as a function of hillslope length.

To supplement the hillslope monitoring and bridge the gap to the larger watershed scale monitoring conducted by the USDA-ARS at Walnut Gulch, a number of small watersheds, again nested within watershed 223 were also instrumented. These were the Cleese and Alan Bennett watersheds, both watersheds covering areas of approximately 1220 m^2 and five watersheds draining through the main channel of watershed 223 known as; 103, John, Paul, George and Ringo with areas of 35,065 m^2, 57,102 m^2, 285,692 m^2, 377,787 m^2 and 468,691 m^2 respectively. For the purpose of this paper, results from the Cleese watershed are presented alongside the hillslope observations, results from the larger watersheds are detailed in Brazier et al. (2003). Within this watershed, similar parameters to the hillslope monitoring schemes were observed with the notable addition of a bedload monitoring trap to provide information on the real time fluxes of coarser, bed material. Surface cover maps of the four large hillslope plots and the Cleese watershed are shown below (Figures 3 and 4.) to illustrate variation in pavement cover as surveyed during the pre-monsoon period.

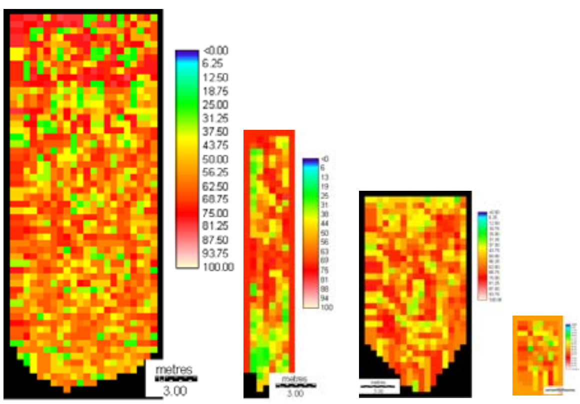

Figure 3. Desert pavement cover for hillslope plots; ranges from 100% (dark red) to 0% (blue).

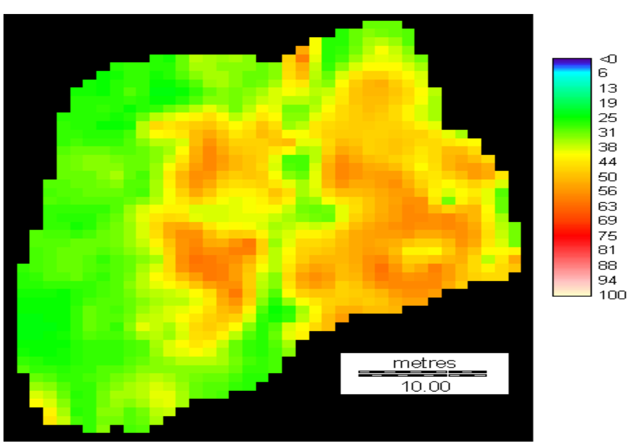

Figure 4. Desert pavement cover for Cleese watershed; ranges from 100% (dark red) to 0% (blue).

Modeling rainfall and runoff response

As detailed above, the nested monitoring scheme was specifically designed to educate model development; this made it possible to conduct a direct evaluation of model performance for sites with adequate observed data to provide confidence in model results. The model developed the work of Scoging (1992) who used a distributed approach to predict the spatial pattern of overland flow hydraulics (Parsons et al., 1997). Overland flow is first generated using a modified Green-Ampt equation:

$$f_t = a + bt^{-1} \tag{1}$$

where f_t is the infiltration rate (mm min^{-1}), a is the final infiltration rate, b is the rate of decline of infiltration rate to its final value and t is time (min). The following continuity equation (2) is then used in combination with rating equation (3) to distribute the flow as a 1-D kinematic wave:

$$\frac{\partial q}{\partial x} + \frac{\partial d}{\partial t} = e_x \tag{2}$$

$$q = \alpha d^m \tag{3}$$

where q is overland flow discharge per unit width ($cm^2\ s^{-1}$) , x is distance (cm), d is depth of flow (cm), e_x is rainfall excess (cm s^{-1}), with α and m being the empirical terms of rating equation (3). The Darcy-Weisbach friction factor f is used to compute flow velocity (v) which, combined with flow depth gives q:

$$v = \sqrt{\frac{8gds}{f}} \tag{4}$$

where g is acceleration due to gravity (cm s^{-2}) and s is the surface slope (m m^{-1}). Water will then move from cell to cell along one of the four cardinal directions within a finite difference grid controlled by the greatest difference in height between cells.

In order to build spatial representation of infiltration rates into the model the driving parameters of equation (1), (a and b) were related to pavement cover (%P) in each cell by the following empirical equations (after Abrahams and Parsons, 1991a):

$$a = 1.628 - 0.014\%P \quad (5)$$

$$b = 0.785 + 0.021\%P \quad (6)$$

Also, the friction factor (f) was related to the depth parameter (d) (Abrahams and Parsons, 1991b) by the following equation:

$$f = 14.46 - 17.35d \quad (7)$$

The model was then applied without calibration, to the four large hillslopes hillslope plots. The initial results of which are described below.

Results

Hillslope plot scale

As an initial test of model performance, flow routing at the hillslope scale was output to verify that flow direction corresponded well with expected flow patterns from the high resolution (0.5 m) DEM. Figure 5. illustrates flowpaths for the event dated 30/07/2000 on the Abbott plot which coincides with the observed data illustrated in Figure 1 and the hydrograph predictions made in Figure 6.

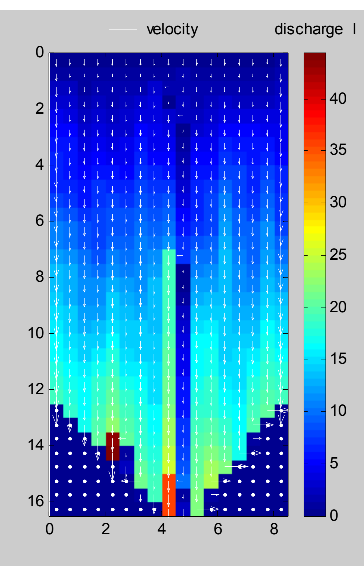

Figure 4. Predicted flowpaths from the Abbott hillslope plot for the 30/07/2000 event.

Results from 2 single events for the Abbott hillslope plots are shown below in Figures 5 and 6. Observed hydrographs at the outlet and total flow data are represented incorporating associated RMS error (see Table 1).

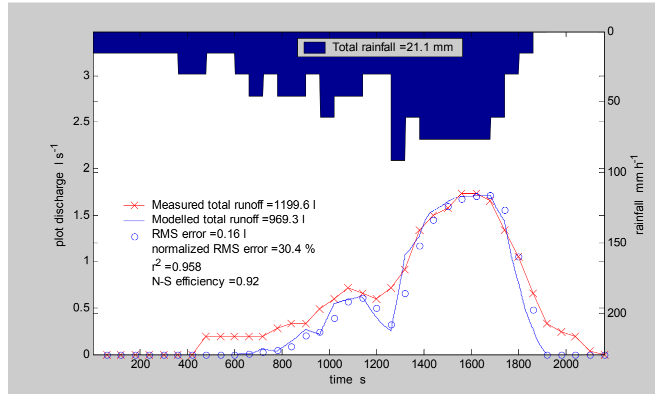

Figure 6. Observed and predicted hydrographs from the Abbott hillslope plot 30/07/2000.

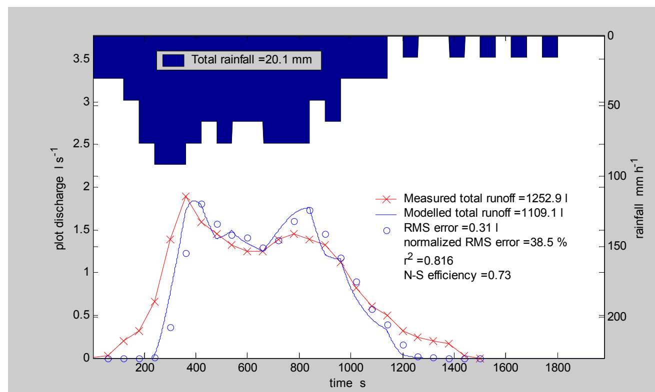

Figure 7. Observed and predicted hydrographs from the Abbott hillslope plot 10/08/2000.

In general results from these two events are encouraging with high r^2 values indicating a good level of agreement between observed and predicted hydrograph form and timing. However, these events are very similar in nature, both being in the region of 20 mm rainfall total with rainfall intensities only reaching 100 mm hr^{-1}, thus it might be expected that the model would perform equally well for each event. Clearly, further model simulations need to be performed on the range of hillslopes for a full range of storm characteristics before definite conclusions about model performance at different scales can be drawn.

Table 1. Model performance statistics for simulations on the Abbott Hillslope plot: 30/07/2000 and 10/08/2000.

	Abbot plot Event 30/07/00	Abbott plot Event 10/08/00
Observed total runoff (l)	1199.6	1252.9
Predicted total runoff (l)	969.3	1109.1
RMS error	0.16	0.31
Normalized RMS error	30.4%	38.5%
r^2 value	0.958	0.816
N-S Efficiency	0.92	0.73

Nonetheless, it is encouraging to note that the bi-modal characteristics of both the observed hydrographs are simulated reasonably well and the timing of runoff peaks is also simulated well, despite the disparity between the magnitudes which are particularly noticeable for the 10/08/2000 event. Also noteworthy are the levels of error associated with predictions for the two events. In both cases the normalized RMS values are in excess of 30% indicating that significant error is associated with model predictions. Furthermore, here consideration of error in observations has not been made nor has it been incorporated in goodness of fit tests. Thus, these results must be interpreted as preliminary and will undoubtedly become more meaningful with further effort to quantify both error associated with the observations and uncertainty surrounding model predictions.

Conclusions

Variation in observed results from the range of hillslope lengths indicates that hillslope length plays an important role in controlling flow and sediment flux from the hillslope as a whole. Recourse to data sets based on single length plots can therefore not be made if the scientific goal is to learn about the influence that hillslope length (to the channel for instance) plays in semi-arid environments. For future studies, it is suggested that plot length is incorporated into the list of variables that are varied between monitoring sites in order to more fully describe the change in both water and sediment fluxes as upscaling from the (small) hillslope to the watershed scale is made. Furthermore, it is shown that nesting monitoring sites within pre-existing frameworks (as at Walnut Gulch) provides a straightforward means of bridging the gap between scales of observation which can educate model development.

Model results indicate that the model performs reasonably well in predicting the event hydrographs of 30/07/2000 and 10/08/2000 on the Abbott hillslope plot. However, errors associated with observed data are not inconsiderable and must be taken into account when considering the validity of model results. It is noted that no observed data will be error free, (though hydrographs in particular are often treated as such), thus it is advisable to fit predictions to data sets which explicitly demonstrate this error, to provide a more meaningful assessment of model performance.

Future work will build upon both the data collection and modeling work presented here to construct a soil erosion component to the model that also considers the effect of slope length upon transport distance of individual particles.

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