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Modelling the impacts of climate variability on sediment transport

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Abstract The detection and prediction of changes in long-term sediment yield under changing land-use practices in a watershed are very difficult due to the sources of variability in sediment transport. An approach is described to examine variability in sediment transport introduced by spatial and temporal variation in rainfall. This includes the use of a rainfall–runoff and erosion model and a space–time rainfall database. A key finding is that there is increased variability in the relationship between sediment discharge and flow when variability in rainfall is incorporated into the simulation. Scaling effects are exhibited by increasing variance in the sediment rating curves generated from increasing drainage areas. Antecedent sediment supply, conditions of overbank flow, and the temporal and spatial structure of rainfall are important factors that influence the variance seen in sediment yield data.

Key words KINEROS; rainfall–runoff model; sediment transport; spatial variability

INTRODUCTION

Soil erosion from managed lands is a major contributor to nonpoint source pollution. Although considerable effort has been expended over the past several decades to control erosion from these lands, it has been difficult to document the effectiveness of land-use practices at the watershed scale. This is true even in areas where there is nearly 100% participation in land-use management programmes (Walker *et al.*, 1995). This is largely due to the enormous variability in suspended sediment data and the difficulty in explaining the sources of variance.

Many authors (e.g. Parker & Troutman, 1989; Walling, 1994) have noted the potential for enormous variance in estimates of sediment loads. Historically, sediment erosion and transport models have been most successful at predicting small-scale processes such as erosion from a hillslope or scour around bridge piers. There are numerous examples of sediment erosion and transport models that have been successfully applied to a selected field, hillslope or channel reach (van Rijn, 1984; Nearing *et al.*, 1989; Lane *et al.*, 1994). At the larger scale, such as in a channel network or over an entire watershed, successful modelling of sediment transport remains a challenge. Understanding the variability of suspended sediment transport in time and space is necessary to optimize sampling strategies, estimate long-term sediment yields and to predict and detect change in the sediment transport regime of a watershed.

METHODOLOGY

To focus on the issue of spatial variability in sediment transport we selected a rainfall–runoff and erosion model (KINEROS2) and a space–time rainfall database developed from a dense raingauge network in Illinois, USA. KINEROS2 (Smith *et al*., 1995) is an event, physically-based, distributed rainfall–runoff and erosion model. The model simulates the processes of interception, infiltration, overland runoff, channel flow, surface erosion and sediment transport from small agricultural and urban watersheds. The kinematic wave approximation is used to model overland and channel flow and the Engelund & Hansen (1967) sediment transport equation is embedded in the erosion algorithm. The model accommodates spatial and temporal variability of rainfall and spatial variation in infiltration, runoff and erosion parameters. Applications of KINEROS2 have been demonstrated by Goodrich (1990) and Renard *et al.* (1993) with a focus on the hydrological component of the modelling.

KINEROS2 was modified to track the sediment as it moves through the watershed during individual events. Modifications were made to track sediment deposited in channels for flows of bankfull or less and partitioned between the flood plain and in-channel for overbank flows.

Basin design

A hypothetical basin was designed based on the Kickapoo River in southwestern Wisconsin. The Kickapoo River basin is the largest watershed (1869 km^2) contained solely within the Driftless Area in southwestern Wisconsin. The Driftless Area has higher relief and sediment yields than any other area in the Upper Mississippi River basin and is a major contributor to sediment in the Mississippi River. The first watershed project undertaken by the US Soil Conservation Service was in the Coon Creek watershed in the Driftless Area (Trimble, 1981). Thus there are existing field data on hydraulic geometries and historical sediment transport rates in this area that contribute to model calibration processes. The drainage pattern is dendritic and based on the Strahler system for ordering networks; the trunk stream in this basin is a seventh-order stream. The design of this hypothetical basin utilized functional hydraulic geometry relationships developed for the Kickapoo River Basin (Knox 1977). Knox's (1977) hydraulic geometry equations were used to calculate channel lengths, widths, depths, slopes, and Manning's *n*. A 130-km^2 portion of the basin network was then translated to a symmetric third-order basin shown in Fig. 1. The symmetric geometry allows for a clearer analysis of spatial and temporal variability in rainfall. The parameters for soils, vegetation and land uses were selected to represent a small basin (130 km^2) in the Driftless Area.

Precipitation network

The precipitation data used in this study are from a dense raingauge network established by the Illinois State Water Survey (East Central Illinois Network). The record contains 13 years of continuous hourly rainfall from 1955 to 1968. The raingauge sequence

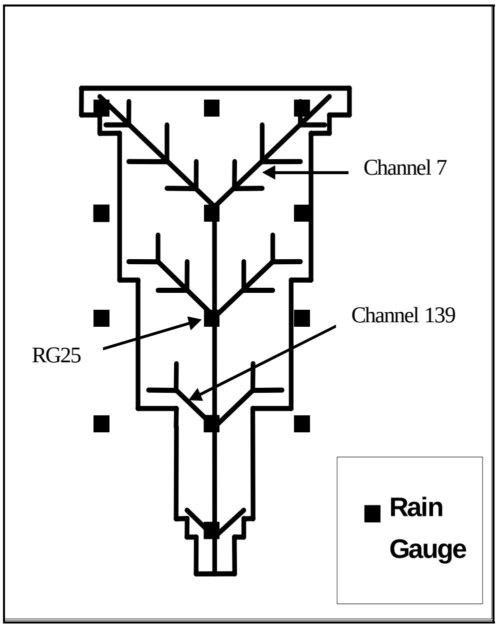

Fig. 1 Basin schematic as seen by the KINEROS2 model.

has been used in a number of other studies including Huff (1967), Beven (1988), Bradley & Potter (1991) and Changnon & Huff (1991). This network provides unique information on the spatial and temporal structure of rainfall. This study utilizes 13 gauges from the centre of the network, the location of which is illustrated in Fig. 1. The KINEROS2 model was "calibrated" based on a bankfull event. Two critical assumptions underlie the calibration: (a) geomorphic features of alluvial channels are controlled by bankfull stage (Wolman & Miller, 1960), and (b) the runoff from a storm with a return period of 1.58 years produced bankfull flow (Dury, 1973). The model is calibrated for an event for which the hydrological response of the system results in bankfull flow and the sediment delivery response of the system results in no net erosion or deposition.

Experimental design

Using the calibrated model, rainfall–runoff and erosion simulations were performed using three different raingauge combinations. The spatially varied case includes all 13 raingauges. Two other raingauge configurations are used: a spatially uniform mean storm over the 13 gauges, and a spatially uniform storm that occurred at a single gauge (RG25) from the centre of the watershed. For each simulation, values for peak flow (m^3 s^{-1}), storm volume (mm), peak sediment discharge (kg s^{-1}), and storm sediment yield (t) are analysed for each of the first-, second- and third-order channels. Sediment rating curves were developed for each simulation and a time-averaged, sediment delivery ratio (SDR) was calculated using the equation below:

$$SDR = \frac{\text{Sediment load at basin outlet (kg)}}{\text{Sediment transported off fields to a channel (kg)}}$$

High (CV = 0.96) Rainfall depth (mm)			Gauge number			Low (CV = 0.08) Rainfall depth (mm)		
0.00	0.00	1.78	10	11	12	54.1	53.3	59.9
0.76	3.05	4.32	17	18	19	64.0	51.5	54.9
1.02	4.83	10.92	24	25	26	47.8	53.3	53.3
1.52	7.11	10.92	31	32	33	45.7	54.4	53.6
	18.03			39			54.9	

Fig. 2 Total rainfall depth at each of 13 raingauges for two representative storms.

Simulations were performed over a five-year period from 1961 through to 1965. This particular five-year period was chosen because it contained a sequence of years minimally influenced by missing data and contained the largest storm on record, a 140 mm 24-hour event. The coefficient of variation of the total storm depth was calculated from these data by dividing the standard deviation by the mean total rainfall depth. This number ranged from 0.08 to 1.10 with a mean value of 0.34. Figure 2 shows the raingauge network configuration and illustrates the spatial variability in total rainfall depth for two separate storms.

MODEL RESULTS

A model simulation consists of 55 events in sequence from 1961 through to 1965. Sediment transported within the basin is tracked between storms and summed over the period of record. Results are summarized in Table 1. The average annual sediment yield ranges from 2.26 to 3.30 t ha^{-1} year^{-1}. These values fall within the range of sediment yields reported for small watersheds in the Kickapoo Basin where estimates range from 1.82 to 3.32 t ha^{-1} year^{-1} (Knox *et al.*, 1974). The spatially varied simulation results in lower sediment yields at the basin outlet than the single-gauge simulation. However, the spatially varied simulation has more efficient transport of the sediment that is eroded from the fields as indicated by a *SDR* of 0.85 for the spatially varied case compared to 0.78 for the single central gauge.

Table 1 Basin-scale results from five-year period.

	Spatially varied (13 gauges)	Single central gauge (# 25)	Mean storm (over 13 gauges)
Sediment delivery ratio *SDR*	0.85	0.78	0.71
Sediment leaving system (t ha^{-1} year^{-1})	2.91	3.30	2.26
Sediment deposited in system (t ha^{-1} year^{-1})	0.52	0.92	0.54

The higher *SDR* for the spatially varied simulation is because this simulation results in a greater number of storms that produce stormflow at the basin outlet. Of the 55 events that produce runoff somewhere in the basin, only 23 produce a significant amount of stormflow at the outlet for the mean storm, 30 for the single-gauge case, and 38 for the spatially varied case. Runoff at the outlet allows for more sediment to be moved downstream through the watershed.

Output variable distributions

The means and variances of the output variables are heavily influenced by the large storms in the simulation. When the largest storm is included in the simulation, the single-gauge simulation results have the highest mean values and variances for peak flow, peak sediment discharge, flow volume and sediment mass transport. If the largest storm is removed, the spatially varied case has higher variance in flows and sediment delivery. A few large storms deliver a great percentage of the total sediment delivered over a period of time, which is consistent with observations made in the literature. In the spatially varied simulation, 81% of the total annual sediment load was transported during two storms (21% of total annual storm duration) and 99% of the load was delivered during 35.8% of the total annual storm duration.

Removal of the single largest storm (Julian day 127, 1961) causes the average annual sediment yield to drop by 50% for all simulations and the spatially varied case now yields the highest sediment load on an average annual basis (Table 2). The spatially varied case also has the highest means and variances for peak values of flow and sediment discharges. Storm flow volumes and sediment loads have higher or very similar mean values when compared to the single-gauge simulation, but the variance is lower for the spatially varied case. The mean storm consistently produces the lowest values for means and variances for all output variables.

Table 2 Summary results from five-year period less largest storm.

	Spatially varied (13 gauges)	Central gauge (# 25)	Mean storm (over 13 gauges)
Sediment delivery ratio *SDR*	1.00	0.84	0.92
Sediment leaving system (t ha^{-1} $year^{-1}$)	1.68	1.59	1.10
Sediment deposited (t ha^{-1} $year^{-1}$)	0.004	0.27	0.09

Further investigation of the largest storm reveals that this storm is the largest event over all gauge configurations over the entire record with an estimated return period of 100 years (Bradley, 1992). The factors, which are causing the single central gauge to result in a much higher peak flow than the spatially varied case are that the effective mean rainfall at gauge 25 is high at 131 mm and that there is a spatial structure to this storm such that the heaviest part of the storm is over the central gauges. In summary, the central gauge in this storm recorded the second highest total rainfall and the highest intensity of rainfall over the longest duration.

Because this event is so influential, the simulations were re-run for the single-gauge case using two different gauges. Gauge 26 was chosen because it recorded a total rainfall depth (113 mm) approximately equal to the averaged rainfall for the spatial case. Gauge 12, which reported the lowest total depth (82 mm), was also chosen. The five-year average sediment yield value is highly dependent on the gauge used during this single largest storm, as illustrated by Table 3. A single uniform storm can result in a long-term average annual sediment yield that is higher, lower or equal to the average annual sediment yield that results from the spatially varied case. However, the *SDR* is always lower for a single-gauge simulation.

Table 3 Summary results from five-year period with varying single-gauge storms.

	Spatially varied	Central gauge (# 25)	Central gauge (# 26)	Central gauge (# 12)
Sediment delivery ratio *SDR*	0.85	0.78	0.78	0.83
Sediment leaving system (t ha^{-1} year^{-1})	2.91	3.30	2.96	1.79
Sediment deposited in system (t ha^{-1} year^{-1})	0.52	0.92	0.83	0.38

These results highlight two areas for further investigation. The first issue is the importance of the largest events in this record. The largest events transport a high percentage of the total sediment load over the time period and significantly influence the mean values. The second issue is the importance of the mid-sized storms. The mid-sized storms are the source of greatest variance in peak flows and sediment discharges of the spatially varied simulation.

Changes in channel geometries

The output from model simulations includes the change in channel bottom profile for each channel element in the basin. The most striking difference between the spatially varied case and the single-gauge case is that the channel bottom elevations change more in the spatially varied case. Figure 3 illustrates the changes in the average depth of the channel bottom for a second-order channel reach. By the end of the simulations the average channel depth change is nearly equal, yet the spatially varied case has varied more over deposition and erosion.

This pattern is consistent for every second-order stream in the basin and for the upper portions of the third-order channel. The average absolute value of change in channel bottom profile for an individual event in the spatially varied case is 2.4 mm with a standard deviation of 1.6 mm. The average absolute value of change in channel bottom profile for an individual event in the single-gauge case is 1.4 mm with a standard deviation of 0.9 mm. This observation is consistent with the fact that the spatially varied simulation results in a higher *SDR*. The effect of summing the erosion

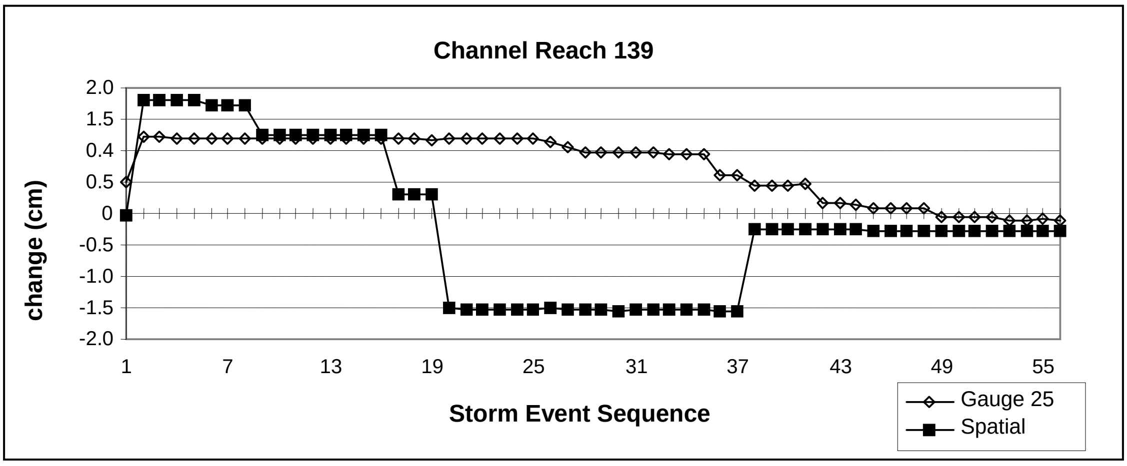

Fig. 3 Average change in channel depth over the storm sequence.

and deposition is that less sediment remains in the channels at the end of the five-year period than for the single-gauge case.

Relationship between flow and sediment discharge

A common way to calculate a sediment rating curve is to plot the storm sediment load against characteristic output variables of the storm. This curve is presented in Fig. 4 for peak flow. The sediment rating curves, generated from the spatially varied simulation, exhibit greater variance than the sediment rating curves generated by a single-gauge simulation. This result is true even though the variance in the individual output variables is lower for the spatially varied simulation. The increased variability seen in these relationships must be a result of including the spatial and temporal variability in the rainfall. All other controls (transport capacity, antecedent soil moisture conditions) are equal between the two cases.

A close look at the sediment rating curve indicates that the greatest amount of variation in the spatially varied case is generated by storms that occur in the mid-range of flows (14–42 $m^3 s^{-1}$). Flow goes overbank in the main channel in the range of 34–42 $m^3 s^{-1}$. The transition between bankfull flow and overbank flow has the potential for large variation in the way the system transports sediment over a small range of flows. When the channel is just below bankfull, it is most efficient at transporting sediment. If, however, the flow goes overbank, then sediment is deposited quickly on the flood plain. The result is a flat-peaked hydrograph, due to the limits of overbank and a decreasing sediment supply due to deposition in the flood plain. This results in a large variation in the sediment transport that occurs around the overbank flow range.

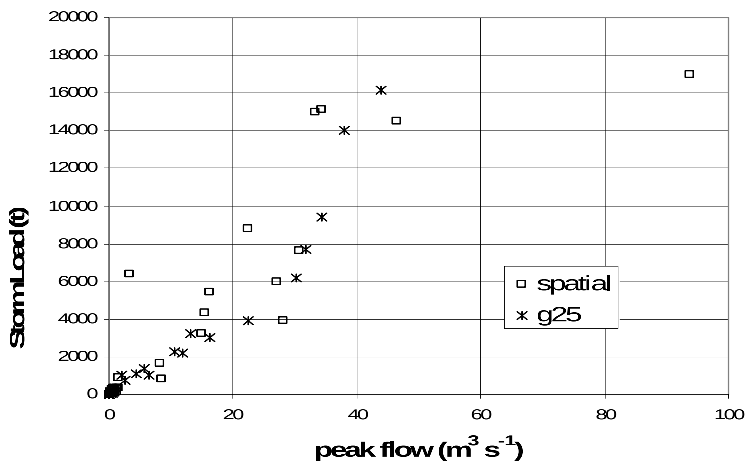

Fig. 4 Peak storm flow *vs* storm sediment load over the simulation period.

First- and second-order channels

In first-order channels, the spatially varied case has a lower mean value and a lower variance for peak flow, peak sediment discharge, stormflow volume and sediment yield when compared to the single-gauge case. The variance for suspended sediment peak discharge is higher for the spatially varied case in second-order streams. The fact that the variability in the suspended sediment peak discharge and loads begin to exhibit themselves in the second- and third-order streams suggests that the interactions of supply and temporal and spatial variability are indeed influencing the variability. The first-order streams very rarely see any depositional material in the channel, they do not erode, and they are not affected by the spatial and temporal variability due to time lags and travel through the basin. The first-order channel exhibits less scatter in the relationship between peak flow and sediment load than the second-order channel.

CONCLUSIONS

Including more detail on the spatial and temporal distribution of rainfall leads to increased variability in the relationship between modelled flows and sediment discharges. Other significant results include the increased efficiency in sediment delivery for the spatially varied case. The *SDR* is always highest when spatial variation in rainfall is simulated. This is accompanied by an increase in the variability in channel bottom elevations.

The statistical summary of the results from the model simulations suggest a number of potential sources of variance in the sediment rating curve. These include: antecedent sediment supply, the apparent nonlinear fluctuations in transport capacity between bankfull and overbank flow, and the spatial and temporal distribution of intensity of precipitation. These clues lead one to a more detailed analysis of individual storms. The full benefits of using a physically-based model are realized at this point because there is a way to identify the physical processes that might be contributing to the spatial and temporal variability in sediment transport.

The key finding is that there is increased variability in the relationship between sediment discharge and flow when the spatial and temporal variability in rainfall is incorporated into the simulation. There is some evidence of scaling effects suggested by increasing variance in the sediment rating curves with increasing drainage area.

REFERENCES

Beven, K. J., Wood E. & Sivapalan, M. (1988) On hydrological heterogeneity—catchment morphology and catchment response. *J. Hydrol.* **100**, 353–375.

Bradley, A. A. (1992) Flood frequency analysis of simulated flows. Dissertation, Department of Civil and Environmental Engineering, University of Wisconsin at Madison, USA.

Bradley, A. A. & Potter, K. W. (1991) Flood frequency analysis for evaluating watershed conditions with rainfall–runoff models. *Water Resour. Bull.* **27**, 83–91.

Changnon, S. A. & Huff, F. A. (1991) Potential effects of changed climates in heavy rainfall frequencies in the Midwest. *Water Resour. Bull*. **27**, 753–759.

Dury, G. H. (1973) Magnitude-frequency analysis and channel morphology. In: *Fluvial Geomorphology* (ed. by M. Morisawa), 91–121. Publications in Geomorphology, State University of New York, New York, USA.

Engelund, F. & Hansen, E. (1967) A *Monograph on Sediment Transport in Alluvial Streams,* Teknisk Vorlage, Copenhagen, Denmark.

Goodrich, D. C. (1990) Geometric simplification of a distributed rainfall–runoff model over a range of basin scales. PhD Dissertation, University of Arizona, USA.

Huff, F. A. (1967) Time distribution of rainfall in heavy storms. *Water Resour. Res*. **3**, 1007–1019.

Knox, J. C., Bartlein, P. J. & Johnson, W. C. (1974) Environmental assessment of sediment sources and sedimentation distributions for the Lake LaFarge watershed and impoundment. In: *Environmental Analysis of the Kickapoo River.* IES Report 28, Institute of Environmental Studies, University of Wisconsin at Madison, USA.

Knox, J. C. (1977) Human impacts on Wisconsin stream channels. *Annals Assoc. Amer. Geogr.* **67**, 323–342.

Lane, L. J., Nichols, M. H., Hernandez, M., Manetsch, C. & Osterkamp, W. R. (1994) Variability in discharge, stream power, and particle size distributions in ephemeral stream channel systems. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby), 335–342. IAHS Publ. 224. IAHS Press, Wallingford, UK.

Nearing, M. A., Lane L. J. & Lopes, V. L. (1994) Modeling soil erosion. In: *Soil Erosion Research Methods* (ed. by R. Lal), 127–156. St Lucie Press, Delray Beach, Florida, USA.

Parker, R. S. & Troutman, B. M. (1989) Frequency distribution for suspended sediment loads. *Water Resour. Res.* **25**, 1567–1574.

Renard, K. G., Lane, L. J., Simanton, J. R., Emmerich, W. E., Stone, J. J., Weltz, M. A., Goodrich, D. C. & Yakowitz, D. S. (1993) Agricultural impacts in an arid environment: Walnut Gulch studies. *Hydrological Science and Technology* **9**, 145–190. American Institute of Hydrology.

Smith, R. E., Goodrich, D. C., Woolhiser, D. A. & Unkrich, C. L. (1995) Chapter 20. KINEROS – A KINematic runoff and EROSion model. In: *Computer Models of Watershed Hydrology* (ed. by V. P. Singh). Water Resources Publications, Colorado, USA.

Trimble, S. W. (1981) Changes in sediment storage in the Coon Creek Basin, Driftless Area, Wisconsin, 1853 to 1975. *Science* **214**, 181–183.

van Rijn, L. (1984) Sediment transport, Part II: Suspended load transport. *J. Hydraul. Engng* ASCE **110**, 1637–1641.

Walker, J. F., Graczyk, D. J., Corsi, S. R., Owens, D. W. & Wierl, J. A. (1995) Evaluation of nonpoint-source contamination, Wisconsin: land-use and best-management practices inventory, water year 1994. *US Geol. Survey Open-File Report 95-320*.

Walling, D. E. (1994) Measuring sediment yield from river basins. In: *Soil Erosion Research Methods* (ed. by R. Lal), 39–80. St. Lucie Press, Delray Beach, Florida, USA.

Wolman, M. G. & Miller, J. P. (1960) Magnitude and frequency of forces in geomorphic processes. *J. Geology* **68**, 54–74.

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