Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982). IAHS Publ. no. 137.

Surface flow and erosional processes in semiarid mesoscale channels and drainage basins

RORKE B. BRYAN
Department of Geography, Scarborough College, University of Toronto, Canada
IAN A. CAMPBELL
Department of Geography, University of Alberta, Canada

ABSTRACT Detailed studies of surface flow and initiation of channels and drainage networks are facilitated in badlands where barren, rapidly eroded surfaces offer ideal sites for micro and mesoscale experiments. Studies carried out since 1968 in the Dinosaur badlands of Alberta show a considerable range of response in erosion rates and sediment and runoff yields at various scales. At the microscale, the response of desiccated shales depends on the detailed interaction of raindrop impact, particle detachment, surface sealing and sub-surface flow, while indurated sandstones and pediments yield flow and sediment almost instantly, even under low rainfall. The water and sediment flows form a complex system and different response thresholds pose considerable problems for precise monitoring in mesoscale basins.

INTRODUCTION

Spatial and temporal scales have been a focus for discussion in geomorphology, with emphasis particularly on the latter (Schumm & Lichty, 1965). Comparatively little attention has been paid to spatial aspects (Campbell & Honsaker, 1981), though both are partially bridged by concepts of magnitude and frequency of geomorphic forces (Wolman & Miller, 1960). In a spatial sense, three levels of geomorphic activity can be defined in basin studies:

(a) *Macroscale* - events and processes operating basin-wide, over tens of hundreds of square kilometres. Temporally such events are responses to major climatic factors and represent basin adjustments to prevailing regional climatic patterns.

(b) *Mesoscale* - processes affecting individual valley slopes in a major basin. Response to geomorphic forcing functions in determined by vegetation or surficial materials, producing local variations in runoff and sediment yield on a scale of tens to thousands of square metres.

(c) *Microscale* - processes which act at a scale of one to a few square metres, corresponding to experimental plot dimensions. The focus is on infiltration, runoff and detachment of individual particles. Responses to even minor rainstorms can be detected.

Although the dominant geomorphic elements identified vary with scale (Gregory & Walling, 1973), the characteristics of landforms and processes at one level represent the summation of variations at a lower level; each landscape is a series of nested landforms whose response to forcing functions varies at different spatial and temporal scales (Schumm & Lichty, 1965).

These scaling concepts while applicable to all landscapes, are ideally studied in badlands where barren surfaces reveal interrelationships and variations of landforms at different spatial scales in detail, and rapid erosion favours study of temporal scales. Since 1968 a series of microscale studies under natural and simulated rainfall in the Dinosaur badlands, Alberta (Campbell, 1970; Bryan *et al.*, 1978; Hodges, 1982; Hodges & Bryan, 1982; Bryan & Hodges, 1982) have documented the behaviour of different geomorphic and lithological units under varying rainstorm conditions. Indurated sandstones and pseudo-pediments produced almost instantaneous runoff and high sediment yields, while desiccated shales showed a delayed response, moderate sediment yields and considerable pipeflow. Attempts to integrate these data were made by Bryan & Campbell (1980). Although mesoscale water and sediment discharge patterns were explainable in terms of thresholds identified at the microscale, logistics and inadequate instrumentation precluded detailed analysis.

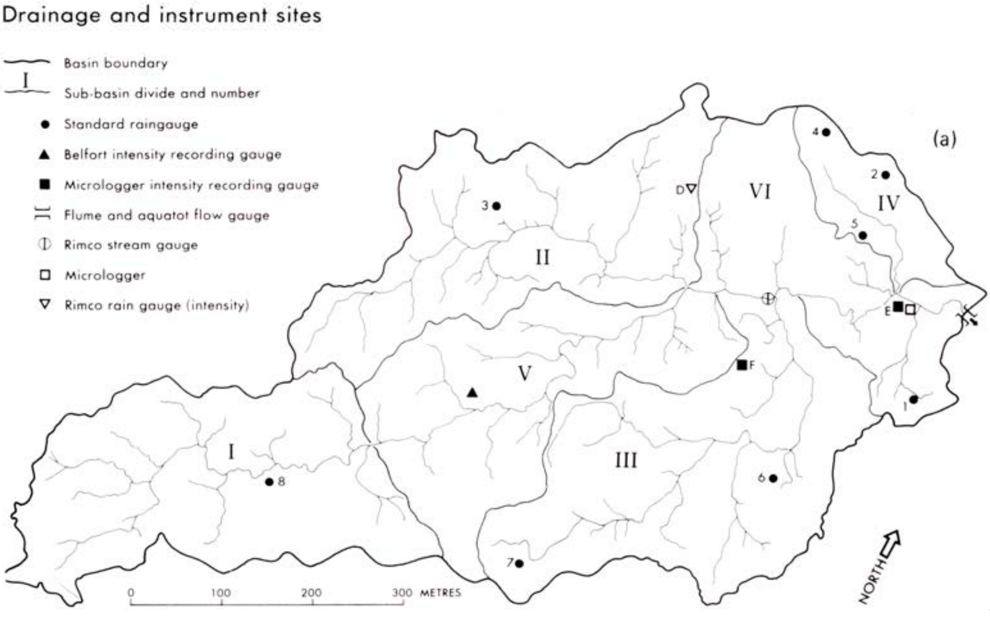
In 1981 a new study was initiated with greatly improved instrumentation and logistical support in Dinosaur Provincial Park. Badland morphology at both sites is essentially identical, having developed in similar lithologic units of the Upper Cretaceous Oldman Formation.

STUDY DESIGN

The goal is to establish the relationship between microscale processes and the hydrologic and sediment budgets for a typical mesoscale badland basin. The basin, in a restricted access zone is 0.36 km^2 in area with a longitudinal axis of 1.1 km. Typical badland morphologic features are found in the basin which is drained by an ephemeral trunk stream to the Red Deer River, approximately 1 km to the northeast. The basin drainage system is extremely complex but six sub-basins can be distinguished (Fig.1(a)).

The sub-basins vary in morphology but collectively include all major geomorphic and lithologic units. Sub-basin 1 contains flattish sandstone slopes or pediments and an extensive, flat, grassed surface (Fig.1(b)). Sub-basin 2 consists of gentle sandstone slopes and pediments with occasional shale and siderite outliers. Sub-basin 3 is dominated by flattish pediments, but has an upper rim of steep desiccated shales and rilled sandstones, honeycombed by pipes. Sub-basin 4 is a narrow, deeply-incised valley with steep desiccated slopes and abundant mass movement features. Sub-basin 5 is a composite of flat grassed surfaces, shale outliers and alluvial deposits. Sub-basin 6 is a poorly-defined area of complex morphology honeycombed by pipes and tunnel erosion.

The earlier microscale experiments documented varying surface responses to rainfall and runoff thresholds. The new basin study will determine the incidence of such conditions and the routing of runoff and sediment through the drainage system. Although this is complex in detail, the main features were clear enough to permit deployment of instruments. Sub-basins 2, 3, 4 and 5 connect



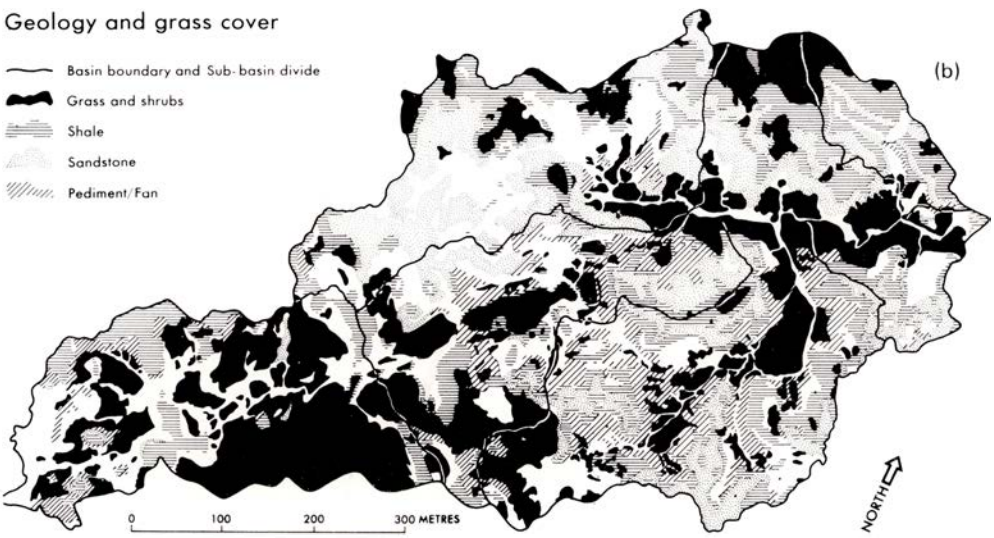


FIG.1(a) Basin and sub-basins, gauging stations and instrument sites. (b) Characteristics of surface cover and lithology.

directly to the main channel. Sub-basin 1 enters the system in a sinuous, braided channel through sub-basin 5, and the major flow from sub-basin 6 drains largely through a diffuse pipe network.

In 1981 two gauging stations were installed. Station A (Fig.1(a)) is on a terrace at the basin outlet where the channel is incised 1 m. A Parshall flume with 0.46 m throat was constructed. Discharge will eventually be automatically monitored with an Aquatot sonic flow instrument, but technical problems prevented this in 1981, so manual gauging was done. At Station B above the confluence of sub-basins 3 and 4, (Fig.1(a) and (b)) is a pressure-operated water level recorder linked to a Rimco-Sumner III chart recorder. This provided an automatic stage record, but some manual gauging was also carried out. During storms bed load samples were collected with a manual Helley-Smith bed load sampler and samples were collected for suspended sediment and solute determinations. Automatic sampling will be carried out in 1982 at Station A with an ISCO 1680 sampler.

Precipitation is measured with four recording and eight non-recording gauges (Fig.1(a)). Gauge C is a Belfort weighing gauge with a weekly clock and gauge D is a tipping bucket gauge with 0.25 mm closures linked to the Rimco recorder which gives one chart mark every 6 min. Tipping bucket gauges E and F have 1 mm closures providing a 1 min pulse output to a Campbell C-21 microdata logger (Fig.1(a)), signals being stored on magnetic tape. The analogue channels will be linked to a specific ion analyser in 1982.

STORM CHARACTERISTICS

During the three-month field season 16 significant rainstorms were observed; another 10 storms provided traces of precipitation. The typical storm pattern is one of sporadic localized low intensity precipitation and very occasional high intensity storms and conforms to those studied earlier (Bryan & Campbell, 1980). Ignoring minor showers, the average storm interval was 4.1 days compared with 4.7 (1968) and 3.9 (1976). The highest intensities occurred on 1 July when 27.5 mm fell at gauge D in 14.5 h. During the first 40 min, intensity averaged 24.3 mm h^{-1}, reaching 84 mm h^{-1} for one 6 min period. Data from the nearest meteorological station (Brooks, 30 km to the south) show a return period of 2-5 years for the 24.3 mm h^{-1}, and of 10 years for the peak intensity.

Stream observations were made during all significant rainstorms, but because of technical problems and the necessity for manual gauging the data record is incomplete. Three storms, for which data are relatively complete, have been selected for review (Table 1).

Storm of 13 June

This storm is typical of the area, where a rather extensive, relatively slow-moving system covered the basin. Rain started essentially simultaneously at all gauges and persisted for over 17 h with occasional short breaks. Total precipitation ranged from 17 to 24.2 mm with an average intensity of 1.4 mm h^{-1}. No marked variation between gauges sites was noted (Table 1); the difference between recording gauges at D and F may reflect topographic shielding of the latter for storms from the southwest, the usual direction of approach.

The hydrographs (Fig.2) show typical responses to a moderate rainstorm, with a lag of about 1.25 h between onset of precipitation and generation of runoff, and an earlier crest at the upstream gauge. Based on earlier data (Bryan *et al.*, 1978; Hodges & Bryan, 1982) it appears that the initial flow to Station B comes from the sandstones

TABLE 1 Precipitation totals for gauge sites (mm)

Date	Standard gauges: 1	2	3	4	5	6	7	8	Recording gauge: D	E	F	$\bar{X}$	δ
13 June	19.0	22.6	20.0	23.5	20.0	17.0	18.0	21.8	24.2	22.0	17.0	20.6	2.3
1 July	31.0	32.0	24.7	31.0	34.5	29.5	30.0	25.9	27.5	32.0	27.0	30.4	3.4
13 July	8.5	7.6	9.3	7.6	7.9	6.0	6.0	7.8	7.0	8.0	8.0	8.2	2.4

TABLE 2 Stage, discharge and sediment load characteristics at Stations A and B

13 June					1 July					13 July				
t (h)	h (cm)	q ($m^3 s^{-1}$)	s ($g\ l^{-1}$)	b ($g\ min^{-1}$)	t (h)	h (cm)	q ($m^3 s^{-1}$)	s ($g\ l^{-1}$)	b ($g\ min^{-1}$)	t (h)	h (cm)	q ($m^3 s^{-1}$)	s ($g\ l^{-1}$)	b ($g\ min^{-1}$)
STATION A														
0800	21.0	0.111	21.74	155.2	1211	54-60	0.476		900.7	1954	54.0	0.476	34.31	
0803	24.0	0.137			1214	54	0.476	42.53		2000	30.0	0.201	33.86	
0807	25.0	0.145	24.72		1742	15	0.064	22.12		2012	23.0	0.119		925.2
0817	29.0	0.186	27.12		1753	14.5	0.059		82.0	2019	23.5	0.119		820.3
0819	31.0	0.208		185.0	1757	14.5	0.059	20.63		2042	8.5	0.029	15.74	35.1
1018	10.0	0.037		21.3						2051	6.0	0.021	13.12	
1025	9.5	0.035	14.79											
1036	9.0	0.033	16.19											
1220	6.0	0.021	13.68											
1224	6.0	0.021		2.7										
1233	6.0	0.021	11.03											
1316	4.0	0.016	14.66											
1530	7.5	0.026	35.74											
STATION B														
0834	8.0	0.04		34.9	1205	22.5	0.238^e	35.67		2006	15.0	0.126^e	30.96	
0853	14.0	0.11	20.59		1219	22.5	0.238^e		138.9	2033	8.0	0.04		5.4
0857	14.0	0.11	20.25		1815	3.5	0.014			2037	8.0	0.04	15.98	
0947	8.0	0.04		6.2										
0950	6.0	0.03	13.29											
1301	2.0	0.01	10.08											

t = time; h = stage; q = discharge; s = suspended sediment concentration; b = bed load; e = estimated.

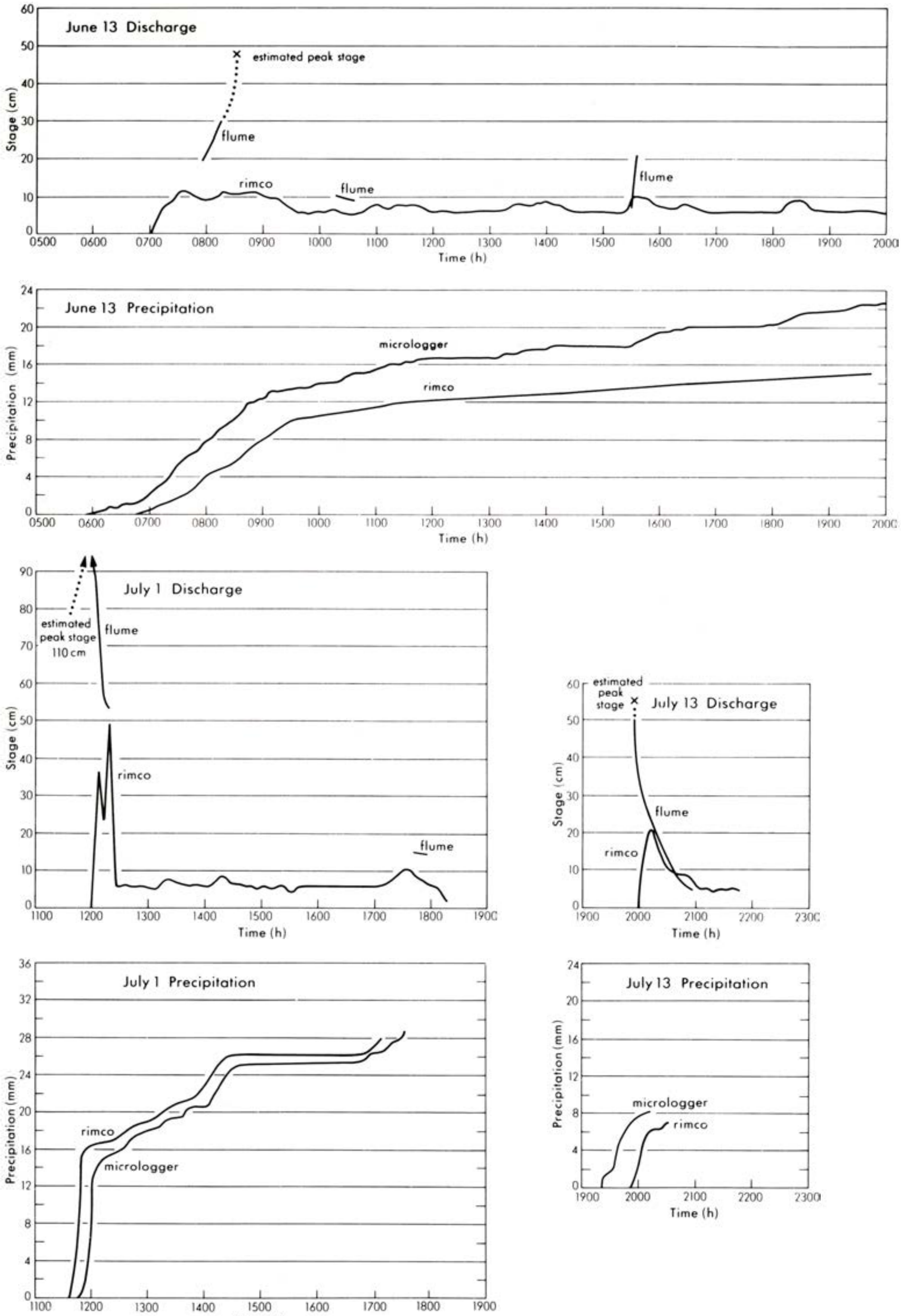


FIG.2 Storm hydrographs and precipitation for three rainstorms at two gauging stations.

and pediments of sub-basin 2, and at Station A from sub-basin 3. Shale areas yield no runoff initially, but once a threshold of 5-10 mm precipitation has fallen desiccation cracks seal and runoff starts. In this storm, flow from shale surfaces may be expected after about 2 h of rainfall. The major shale areas are in sub-basins 4 and 6, and contribute little runoff at Station B. This explains the low, broad crest of the hydrograph while the crest at Station A is higher and more peaked. The secondary crest at both stations around 1530 h may be a delayed contribution from pipeflow.

Storm of 1 July

The storm of 1 July was much more severe, producing an average of 30.4 mm in about 14.5 h (Table 1). The conspicuous difference is not the total amount but the period of very high initial intensity. This exceeded the threshold for all surfaces; runoff started swiftly throughout the basin, with a lag of only 10 min at Station B. Observers missed the rising stage at Station A, and probably the crest, which overtopped the 90 cm high Parshall flume. If the hydrograph conforms to Station B, which is likely, and the limbs are projected, the crest was probably about 110 cm. At this stage, however, the record becomes unreliable as the flume constriction backed up the flow and flooded the terrace. The hydrograph at Station B shows a pronounced double crest; probably reflecting the separation between the storm-crest from the high runoff-yielding area of sub-basin 2 and that from the head of the basin in sub-basin 1. The same feature may have occurred at Station A, but it was probably smoothed out by contributions from the high-yield area of sub-basin 3 and the shale areas of sub-basins 4 and 6.

Apart from the storm's severity, the most marked feature is that unlike the 13 June storm, the crest at Station A preceded that upstream at Station B. The raingauge records indicate that although the pattern of the storm and the total amount of precipitation did not vary greatly over the basin, the timing of rainfall did. The storm entered the basin from the northeast not the more usual southwest, reaching gauges E and F before that at D (Fig.1(a)), and flow then occurred at Station A before any precipitation was recorded.

The hydrograph during the low intensity later stages of the storm resembles that for the 13 June storm with minor crests reflecting short bursts of shower activity and possibly some pipeflow inputs.

The extremely high peak intensities recorded early in the storm revealed a serious flaw with the micrologger. The combination of a 1 mm tip and a pulse output limits the maximum recordable intensity to 60 mm h^{-1}. Measurement of higher intensities requires more frequent scanning, drastically reducing the unattended monitoring capacity. Although the micrologger is an attractive monitoring technique in a remote area, this is a serious limitation. The Rimco equipment with a 0.25 mm tip seems more suited to measure these critical high intensity storms.

Storm of 13 July

The storm of 13 July is more typical of the area, providing a brief localized rainstorm of moderate intensity and an average of 8.2 mm over 42 min (Table 1). The variation between gauges in this storm was over 30% reflecting varied topographic shielding and the considerable local turbulence associated with badland rainstorms. Again the storm entered the basin from the northeast producing a storm crest at Station A before Station B. While the rising stage at Station A was missed it seems that the maximum stage shown in Fig.2 was very close to the crest. The hydrograph at Station B shows a simple single crest with rather rapid recession. This probably represents flow from sub-basin 2 as the high-yielding area of sub-basin 1 is too far from the gauge to contribute a second crest during the storm.

STAGE, DISCHARGE AND SEDIMENT TRANSPORT RELATIONSHIPS

Because of instrument problems and the limitations of manual gauging in an area where storms are unpredictable, localized and often of short duration, only limited data are available and attempts to develop relationships must be tentative. The Parshall flume at Station A is rated by specification, so good discharge data are available from manual stage measurements. At Station B where a continuous stage record is available, velocity measurements were manual, and because most attention was given to Station A, most measurements come from the recession. Discharges at this site are only available for stages up to 14 cm.

The most interesting point to emerge from comparison of discharge data (Table 2) and the peak and estimated peak discharge (Fig.2) from the two stations is the change in the ratio with storm intensity. The low intensity, prolonged storm of 13 June produced a peak discharge of 0.06 m^3s^{-1} at Station B and an estimated 0.22 m^3s^{-1} at Station A, and thus a ratio of 3.8. The intense, prolonged storm of 1 July gave a peak of approximately 0.82 m^3s^{-1} at Station B and an estimated 1.11 m^3s^{-1} at Station A, and a ratio of 1.4, while the short intense storm of 13 July produced peaks of 0.22 and 0.48 m^3s^{-1} respectively, with a ratio of 2.2. On a yield per unit area basis these data show that in low intensity storms the yield for the upper part of the basin is less than 50% of that of the entire basin. In short intense storms it is almost the same, and for prolonged intense storms it becomes the dominant runoff producing sector.

Two factors are involved in producing these results. Much of the upper basin is flat grassland (Fig.1(b)) which yields runoff only during intense rainfall. Being remote from the main channel, flow from the grassland affects the discharge pattern only in prolonged storms. The second factor is the influence of piping, which greatly affects discharge patterns. Sub-basin 6 is largely drained by pipes and in low intensity or short-lived storms most water passing into pipes will be lost to the drainage system. In prolonged intense storms, however, the delayed pipeflow response has time to develop fully.

As no automated sediment sampling was possible in 1981, relatively few sediment load data are available, and these come primarily from Station A during flood recessions (Table 2). The curvilinear relationship between discharge and sediment concentration shown in

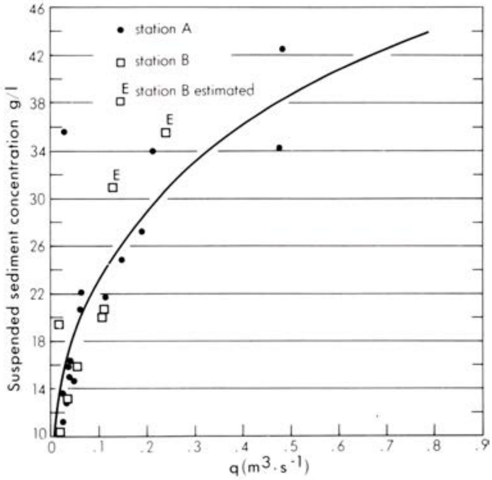


FIG.3 Relationship between discharge and suspended sediment concentration.

Fig.3 is very tentative, especially for Station B. The suspended sediment concentrations are analogous to those recorded previously (Bryan & Campbell, 1980) with peak concentrations falling in the range of high and extreme concentrations (Beverage & Culbertson, 1964). They are comparable to those recorded in other ephemeral arid and semiarid basins, plotting amongst those for the Nahal Yael (Schick, 1977) and Sde Boker (Yair *et al.*, 1980) drainage basins in Israel, though below those from the highly erodible basins of Mt Sdom (Gerson, 1977). Peak concentrations are considerably lower than those recorded on experimental microcatchments at Dinosaur (Bryan *et al.*, 1978; Bryan & Hodges, 1982), but these were under simulated rainfall of higher intensity. The lack of information from rising stages is unfortunate as *a priori* reasoning suggests that as early flow comes primarily from sandstones and pediments, which yield very high concentrations in experiments, the peak sediment concentrations would probably occur during rising stages. Conversely, much of the sandstone sediment is probably transported as bed load, while material from the shale surfaces, which yield later, is typically 80-90% fines, and moves mostly in suspension. Bed load data, though scant, show that it is a highly significant mode of sediment movement in high flows. Data are not yet available on particle size distributions of sediment load fractions, but observations indicate the bed load is primarily coarse sand and siderite fragments. As information on rising stages is lacking, peak bed load transport rates have probably not been observed.

CONCLUSION

The 1981 field season data show that water and sediment flows are complex and varied, responding to differences in storm intensity, duration and tracking pattern. Attempts to develop a detailed sediment budget would be premature but the basin seems comparatively efficient geomorphically and water and sediment pass through rather rapidly with limited long-term storage or loss. Although shale surfaces generate runoff less frequently, most of the fines probably pass through the complete drainage system in one storm, while coarser materials from sandstone or pediment surfaces remains considerably longer in temporary storage as bed load. Precise delineation of these trends requires the more continuous data which will be available when sediment sampling is more fully automated. The additional instrumentation will include automatic stage recording and suspended sediment sampling at Station A, and, a continuous recording of flow velocity at Station B. Sub-gauging stations will be located at the outlets of sub-basins 1 and 2, and dye tracing experiments will be done to establish flow frequency and timing from sub-basin 1.

ACKNOWLEDGEMENTS Field work in Dinosaur Provincial Park was made possible by permission from Alberta Recreation and Parks, and cooperation from Mr J.Stomp, Park Ranger, and other staff. Field observations were carried out by Ross Sutherland, Lawrence Harvey and Jim Proudfoot. The work was supported by research grants to each author from the Natural Sciences and Engineering Research Council of Canada.

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