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DRAINAGE DENSITY VARIABILITY AND DRAINAGE BASIN OUTPUTS

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ABSTRACT

Relationships between the drainage density of channelled flow and stream discharge, suspended sediment, and total dissolved solids were examined during rainfall events for two New England (NSW, Australia) catchments on granite and greywacke. Drainage density was found highly related to stream discharge and dissolved solid concentrations although its relationship varied with the extent of the active stream net or flow occupance along the channel. In the study catchments drainage density is a good predictor of discharge. For a representative range of flows the drainage density of channelled flow was found to increase by approximately 50 per cent for a tenfold increase in discharge. The length and cross sectional area of channelled flows are in part a function of two types of eroding channel networks on granite and greywacke catchments.

INTRODUCTION

Channel networks exhibit temporally and spatially variable perennial, intermittent and ephemeral flows. Such runoff patterns reflect both changing catchment inputs and the dynamically changing outputs of stream discharge, suspended sediment, solutes and litter. The transient nature of flow within stream channels is well documented (Ovenden and Gregory, 1980), both in terms of descriptions of flooding (Hanwell and Newson, 1970), drought (Foster and Walling, 1978), the flood hazard (Newson, 1975), adjustments of channels to changes in runoff (Newson, 1980) and fluctuations of drainage density (Day, 1978).

Drainage density of flow (the spatial extent of channelled flow) is a measure of the water balance of a catchment at an instant in time. The flow net varies with hydrometeorological, geomorphic and pedomorphic conditions. Dynamic flow nets are a surficial expression of runoff generative processes and their expansion and contraction over short periods, for example during several hours of rainfall, influences the volumes and rates of movement of water, sediment and solutes throughout the associated network system (Bello *et al*, 1978).

STATIC DRAINAGE DENSITY AND BASIN OUTPUTS

Drainage networks can be viewed as static, with 'fixed' densities, but have been related to other more dynamic hydrological factors. Drainage density estimates were introduced into many hydrological and geomorphic studies where they were thought to characterise the topography or 'the conditions of flood flow formation' (Sokolov, 1969). Static drainage density has been related to 'runoff intensity' (Melton, 1957) and to the lag time of the basin hydrograph (Hickok, Keppel and Rafferty, 1959). Both the predictions and variations of peak discharges have been investigated using drainage density as a predictive and interpretative variable. Drainage density has also been utilised to predict and explain spatial variations in base flow (Trainer, 1969). In such studies drainage density, whether of the eroded channel system, observed drainage lines or perennial flow is regarded as a fixed parameter related to the more dynamic characteristics such as discharge or percent of swamped area.

Investigations have related stream order or length to discharge for a wide range of environments (Leopold and Miller, 1956; Graf, 1975). For example, Morisawa (1967) correlated longest mean stream length with mean annual discharge for 96 basins in the eastern USA; significant relationships were also affirmed by Taylor (1967) and Thomas and Benson (1970). Rogers (1971) derived a frequency histogram for fixed first order channel lengths and related it to discharge hydrographs for individual storms.

Suspended sediment production has sometimes been found to be a function of stream channel density (Hadley and Schumm, 1961; Guy, 1964; and Douglas, 1973). Data on the statistical relationships between drainage density and sediment production are often inconclusive (Branson and Owen, 1970; McPherson, 1975).

DYNAMIC DRAINAGE DENSITY AND BASIN OUTPUTS

Drainage density of stream flow may also be considered dynamic over time and space. Investigations of drainage density dynamics have concentrated on the relationship between drainage density and discharge, for which records are more easily attainable. In their key paper on the variation of drainage density, Gregory and Walling (1968) measured flowing stream length within several catchments and related this to stream discharge for a range of hydrological events. These measurements described a dynamically changing surface runoff situation, an important advance in the field description of drainage basin processes.

Positions of the flowing stream network in drought, 'normal' and flood conditions were found useful predictors of discharge in Somerset, UK (Hanwell and Newson, 1970). In the same region a close relationship between throughflow discharge and flow length was also determined within the headwater zone of the East Twin catchment (Weyman, 1970, 1971). Similar significant associations between the two variables were shown for four basins in Oregon, USA (Roberts and Klingeman, 1972), for a clay basin in SE England (Blyth and Rodda, 1973) where the data indicated separate relationships for the seasons, and for the New Forest, UK (Gurnell, 1978).

In small catchments within the New England Tablelands near Armidale, NSW, Australia, seasonal differences in the relationship of discharge to flow length were masked by highly variable antecedent rainfall and soil moisture conditions (Day, 1980a). Relationships among the variables differed for individual storms, a function of the influence of lithology on channel capacity and the specific type of channel in which flow occurred, whether this was an eroded or grassed drainage line.

There has been speculation on the timing of peak discharge and peak drainage density within a catchment (Calver, Kirkby and Weyman, 1972). It was suggested that the network fluctuates linearly with stream discharge (Roberts and Klingeman, 1972). Recent findings (Day, 1980, a, b) indicate that, for storms in small catchments, maximum drainage densities precede peak discharges by an approximately fixed interval of time, varying between catchments. Cognisance of this lag relationship seems important in further understanding the rate of water transfer along the stream channel and the reasons for a changing sediment and solute yield.

RESEARCH PROBLEM AND DESIGN

Abundant documentation exists on the association between rainfall, stream discharge, suspended sediment and stream solute levels, but little is known of how these outputs vary with expansion and contraction of the drainage network within a catchment for the range of runoff, antecedent conditions and season.

This paper summarises drainage density and output relationships for two temperate mid-latitude catchments. Comparisons were made firstly, over 16 months between one catchment on igneous and another on sedimentary rocks and secondly, between one individual storm in each catchment.

FIELD AREAS

The two study catchments (B, 0.202 km^2; D, 0.086 km^2) are located near Armidale (Fig. 1) on the New England Tablelands NSW, at about 1100 m above sea level. Mean annual rainfall is approximately 795 mm with average monthly evaporation varying considerably from 40 mm in July to 165 mm in January. A fall of 50 mm of rain in one hour is likely to be equalled or exceeded only once in 50 years on average.

Catchment B, in the upper Sandy Creek basin (Fig. 1) is formed on adamellite with grey brown podsolic soils. The basin is drained by two perennial tributaries and has a relatively stable base flow with a drainage density of flow of 0.81 km/km^2. Five ephemeral tributaries develop during intense storms to give a maximum extended network density of 7.80 km/km^2. The channel system is 164 m in length; channels are uniformly wide and shallow with width and depth at the catchment outlet of 3.4 m and 0.4 m respectively. Discharges range from 0.8 l/s during base flow to around 160 l/s during peak flows.

The second catchment, D, is an eastern tributary of Pipeclay Creek (Fig. 1) and is formed on feldspathic lithic wacke. This exhibits an ephemeral stream system developed within yellow solodic soils and bedrock channel segments. Flow is absent between storms. Streamflow discharges have risen to approximately 250 l/s during heavy rainfall when

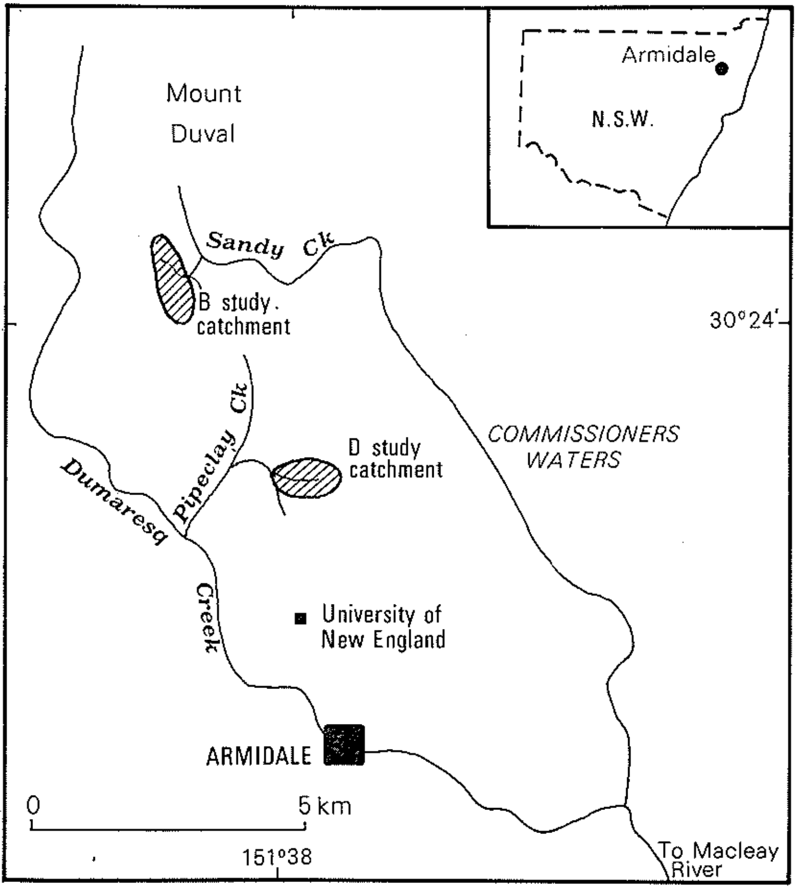

FIG. 1—Catchment location, Armidale, N.S.W., Australia.

antecedent soil moisture levels are high. Flow along the 500 metre eroded first order channel is segmented during the early phases of storms. Further rainfall can result in continuous flow. In the upper catchment, overland flow generated above and within the channel frequently moves downslope as a small flood wave. The fully integrated flow net at its maximum extent results in a drainage density of 9.22 km/km^2. This channel is more sinuous than those of Basin B and is V shaped with a width of 1.65 m and depth of 0.62 m at the catchment outlet. Channel forms include incised bedrock sections and segments where channels are wide and grassed with no incision.

Remnants of dry schlerophyll woodland, in association with improved pasture grasses, occur within both catchments. Light sheep and cattle grazing occurs at each location.

MEASUREMENT OF FLOW DYNAMICS

Length of detectable channel flow was measured along all channels and valley networks during all rainfall events and every four days in the two catchments. Total flow length for both perennial and ephemeral streams was measured by a rapid inspection of the entire channel system as discrete flow segments formed and moved along the channels. Segments were often discontinuous in early phases of large storms or during stages of flow recession. During the middle phase of a substantial rainfall period, when the flow net was fully extended, fluctuations of streamflow length could be readily observed at the upstream ends of concentrated channel flow. These points were often found to be highlv unstable, and. depending on site and rainfall variability could remain stationary for several hours or rapidly move up or down channel for many metres.

Changes in the flow networks of catchments B and D were measured during individual storms over a 16 month period when rainfall was slightly above average. All measurements were carefully timed during rainfall and for each flow length estimate there was a simultaneous estimation of stream discharge and rainfall with closely timed water sampling of streamflow. Total dissolved solid concentrations were estimated by measurement of specific conductance of the water samples in the laboratory.

Stage was automatically recorded at V notch weirs at the basin outlets. Volumetric determinations of total discharge were also often made. Water samples (500 ml) were collected above the weirs when flow length estimates were made during and after rainfall. The frequency of observations depended on observer mobility and length of channel inspected, and ranged from 5 to 30 minutes.

RESULTS FROM ALL STORMS

All storm data for drainage density, discharge, and concentrations of suspended sediment and total dissolved solids were pooled for each catchment and plotted to obtain an overall view of the apparent relationships between drainage density and catchment outputs (Figs. 2, 3 and 4).

TABLE 1—Correlation coefficients for drainage density and variables describing drainage basin outputs in basins B and D.

Variables correlated with drainage density (no transformation)	Correlation Coefficients Basin B df = 106	 Basin D df = 118
Streamflow discharge (Log_{10})	.949	.856
Suspended sediment concentration	.289	−.247
Specific conductance	−.842	.603
all coefficients significant at .01 level		

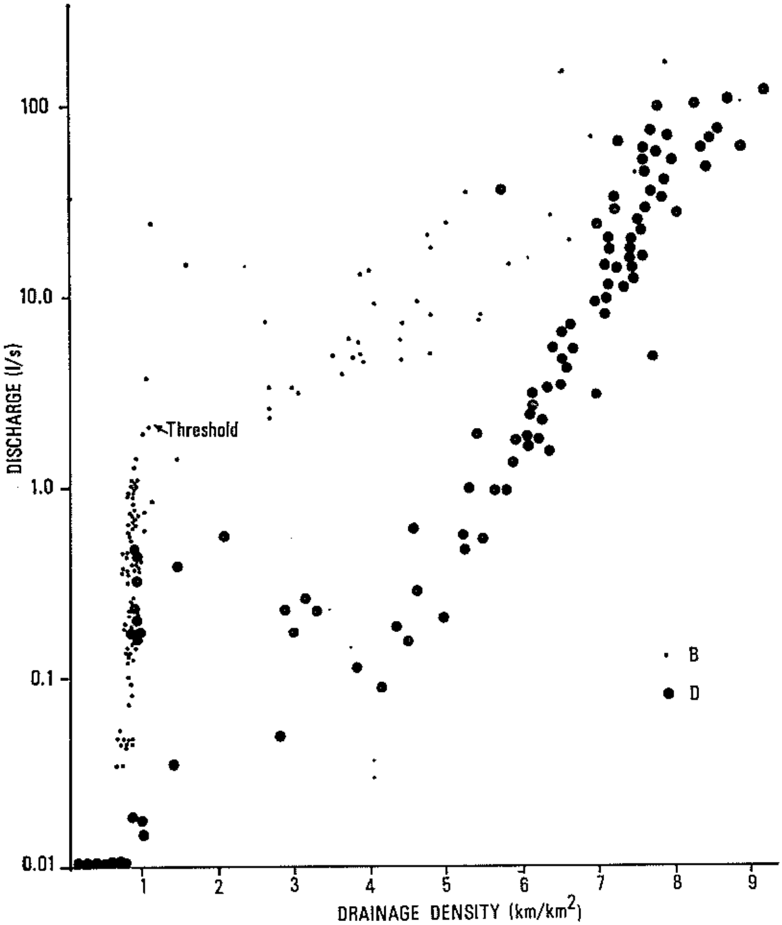

FIG. 2—Plotted data for drainage density and discharge—all storms, Basins B and D.

DRAINAGE DENSITY AND DISCHARGE

Drainage density and stream discharge were highly related during rapid expansion and contraction of the two flowing networks (Fig. 2, Table 1). In catchment B there is a threshold above and below which separate relationships occur (Fig. 2). Here, numerous flows at a drainage density of approximately 0.8 km/km^2 extended only to the highest eroding nick points on the two main tributaries. For this density a range of discharges was recorded due to changing flow widths and depths within the eroded channel. Flows extended above and outside the eroded channel network when a bankfull discharge of just over 1 l/s was exceeded. For this net-

TABLE 2—Changing flow dimensions and discharge with a fixed stream length in B.

Time (hours)	Flow Length (m)	Depth of water at crest stage gauge (cm)	Width of flowing channel at crest stage gauge (cm)	Discharge at weir (l/s)
1000	170.0	25.0	333.0	185.0
1400	170.0	14.0	80.0	47.0

work the relationship between drainage density and discharge for flows within the eroded channel and for those extending outside into the valley net differ radically. Above the nick point, rapid drainage density increases and decreases follow the rainfall pattern. The scatter of data has a logarithmic form indicating that, at near maximum drainage densities, a greater range of discharges occur due to the more variable contributions of base flow and adjustments in the cross sectional area of flow along channel systems. An example of such a relationship can be seen in one of the main tributaries in B during a short summer storm (Table 2). Here, the length of flow remained the same for 4 hours after rainfall had ceased, but during that time the depth and width of channel flow just above the tributary junction had decreased along with discharge at the weir. Drainage density had thus remained the same although the dimensions of flow in the cross section were reduced prior to the contraction of the flow network, some hours later.

For catchment D (Fig. 2) the relationship of drainage density to discharge at low flows is poor as channel flows were initially generated upstream (similarly to arid streams) with the lower catchment channel having no surface flow. A positive linear relationship for discharges above one litre per second, when drainage densities exceed 5 km/km^2, indicates that once flow segments have coalesced during the initial phase of network extension, flow length increases linearly with discharge (Table 1). At a fixed discharge, for example 1 l/s, drainage densities are over six times greater on the sedimentary catchment (D) which is less than half the area of the granite basin. This is partly a reflection of different channel capacities between the two lithologies; the sedimentary catchment displays more channelled flow over bedrock and grassed channel segments.

DRAINAGE DENSITY AND SOLUTE CONCENTRATIONS

During rainfall, solute concentrations decreased with increasing flow length (Fig. 3). In the granite basin, B, a strong negative relationship exists (Table 1) for flows which extend above the eroded channel network. Increases in drainage density are here linearly associated with decreases of total dissolved solid concentrations due to the dilution of dissolved material by greater flow volumes along the channel system. A clustering of values at approximately 0.8 km/km^2 indicates that flows from the two nick points are associated with a wide range of dissolved material con-

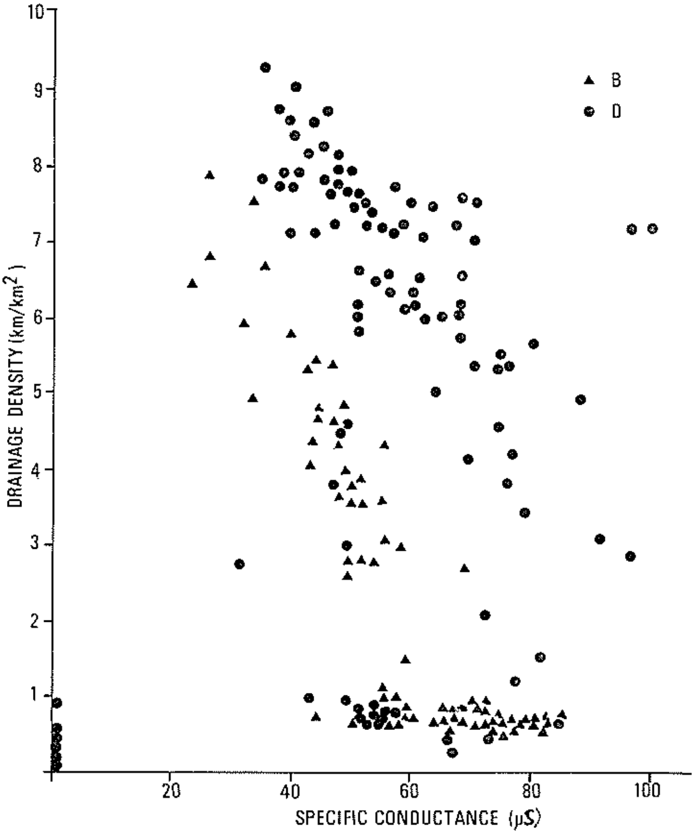

FIG. 3—Plotted data for drainage density and dissolved solid concentrations—all storms, Basins B and D.

centrations over time. Several relationships between drainage density (and hence discharge) and dissolved solids were found, depending on the location of flow within the net, runoff volumes and the variability of surface and sub-surface sources of solutes.

Correlation coefficients indicate a positive relationship for the two variables in the sedimentary catchment (Table 1). However, for drainage densities of flow greater than the eroded channel density (6.0 km/km^2) there is a negative trend in the data plot. This trend is associated with flows above the eroded channel head where larger proportions of runoff originate as saturated overland flow or quickflow around the channel. Here, rapidly-rising shallow water-tables remain close to the surface causing intercepted rainfall to build up quickly in depression stores and to move downslope contributing to significantly larger flow volumes.

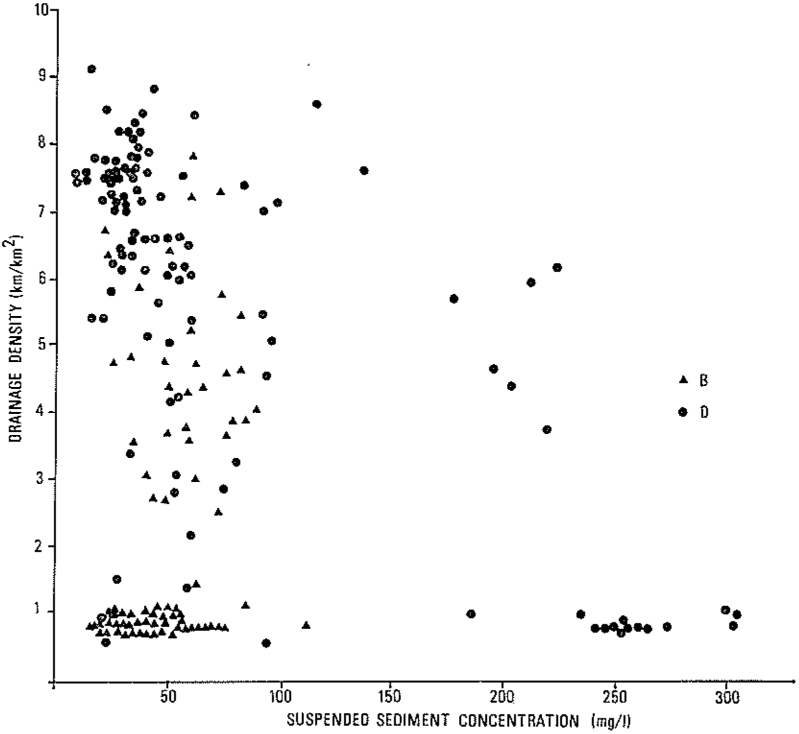

FIG. 4—Plotted data for drainage density and suspended sediment concentrations—all storms, Basins B and D.

DRAINAGE DENSITY AND SUSPENDED SEDIMENT CONCENTRATIONS

Concentrations of suspended sediment varied significantly during rainfall in both basins. The correlation coefficients (Table 1) indicate general increases in concentrations with length in B and decreases in D. The scatterplot for the pooled data (Fig. 4) shows no discernible relationship between the two variables. The granite catchment (B) shows lower overall concentrations, up to 100 mg/l, with a range of low concentrations at all flow lengths. Higher concentrations, up to 300 mg/l, were recorded in the sedimentary basin (D) with no real pattern in the data. Such pooled data masks individual sediment and solute transport responses to rainfall and hence the following data for two individual storms is given to indicate more definite relationships for specific channels.

RESULTS FROM INDIVIDUAL STORMS

The runoff, sedimentological and dissolved output responses to two

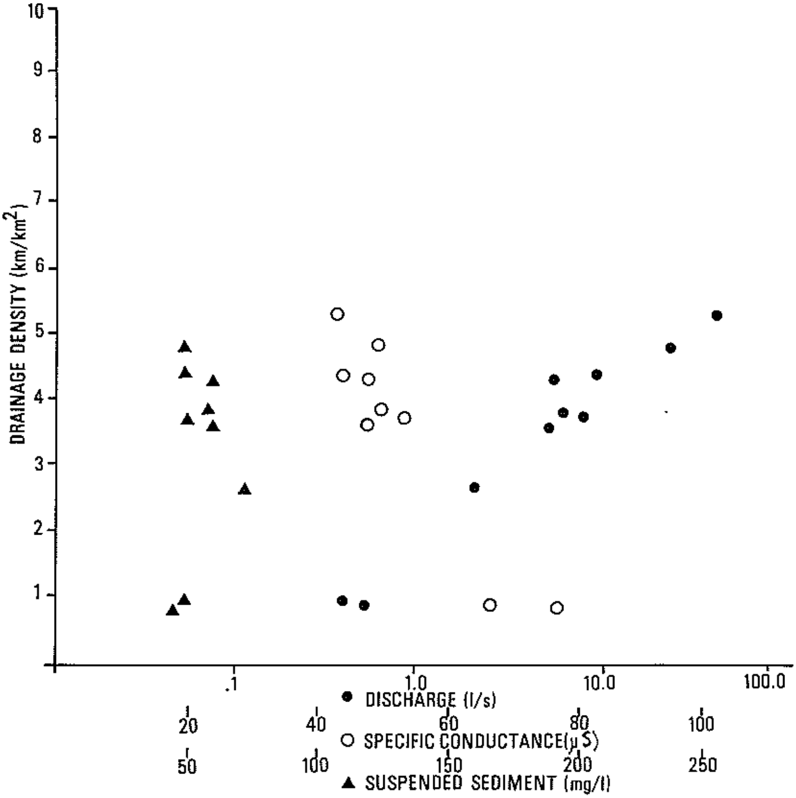

FIG. 5—Variations in drainage basin outputs with drainage density for a storm in B.

separate storms are indicated by scatterplots for the granite catchment B and for the sedimentary basin D (Figs. 5 and 6). In B, 7 mm of rain falling over several hours resulted in extension of the catchment network density from 2.5 km/km^2 to 5.3 km/km^2. In D, over 140 mm of rain falling over 5 days increased the drainage density from 3.1 km/km^2 to 8.3 km/km^2. For each storm, values of drainage density, discharge, suspended sediment concentration and dissolved solid concentration were correlated (Table 3).

DRAINAGE DENSITY AND DISCHARGE

Drainage density and stream discharge were highly correlated for the two storms (Table 3, Figs. 5 and 6). Values are more closely related on the falling stage of the hydrograph (Table 4) where there is a slow return to base flow conditions with more inherent network stability. For the same

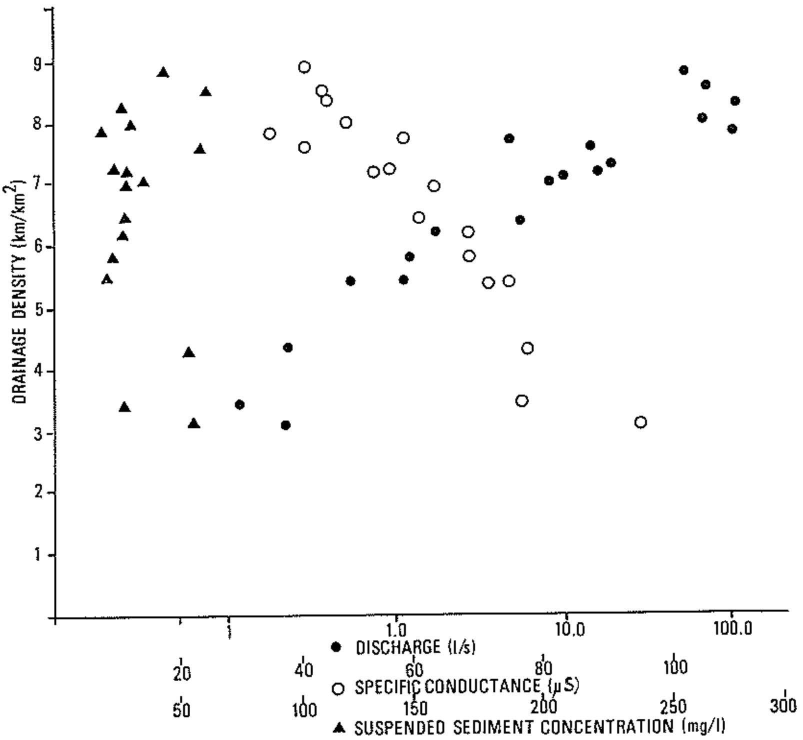

FIG. 6—Variations in drainage basin outputs with drainage density for a storm in D.

discharge, drainage densities were higher within the sedimentary catchment (Figs. 5 and 6) where the density of stream channels is higher and their cross sectional areas lower.

For observations made at four day intervals, correlation coefficients for discharge and drainage density were lower (B, $r = +0.839$, significant at 0.01; D, $r = +0.644$, significant at 0.01) than for those obtained during storms, where the flow net was highly variable (Table 1). Nevertheless, the drainage density-discharge relationship at four day intervals (which represents a range of flow head positions) can be shown as

Basin B $Dd = 1.12\,Q^{.37}$
Basin D $Dd = 3.58\,Q^{.19}$
where Dd = drainage density of flow
Q = streamflow discharge

This indicates that the drainage density of channel flow increases by approximately 50 per cent for a ten fold increase in discharge.

TABLE 3—Individual storms: correlation coefficients for drainage density and variables describing drainage basin outputs in basins B and D.

	Discharge (Log)	Suspended sediment concentration at weir	Total dissolved solid concentration at weir
Drainage density	(n=10) B +.954	B +.074	B −.834
	(n=19) D +.898	D +.022	D −.869
Discharge (Log)		B +.048	B +.773
		D .000	D +.835
Suspended sediment concentration at weir			B .000
			D +.003

——— significant at 1 % level

TABLE 4—Correlation coefficients for discharge and drainage density on the rising and falling stages of the hydrograph, for basins B and D.

	Correlation coefficients	
Rising stage	B .942	D .819
Falling stage	B .973	D .972

DRAINAGE DENSITY AND DISSOLVED SOLID CONCENTRATIONS

Flow length and dissolved solid concentrations were significantly correlated (Table 3) in each catchment. For similar drainage densities, concentrations were lower in B although the range of concentrations was similar for both catchments. As drainage density increased during rainfall, dissolved solid concentrations progressively decreased through dilution. It is apparent (Table 3) that variations in dissolved solid concentration are more closely related to oscillations of the flow net than to changing stream discharge. Further variations in dissolved solid concentrations relate to mixing of channel precipitation, throughflow, surface runoff, base flow and quickflow components of runoff.

DRAINAGE DENSITY AND SUSPENDED SEDIMENT CONCENTRATIONS

Fluctuations in flowing stream length over the two storms were not significantly correlated with the low suspended sediment concentrations (Table 3). The low concentrations (<75 mg/l) result from high antecedent rainfall and runoff conditions prior to the observations. Sediment sources are not uniformly distributed along the channel systems and commonly are restricted to particular sites, for xample, along several metres of a discontinuous gully segment. Thus the position of the flow net along the channel as well as the erosive power of the flow is critical in the entrainment and transport of sediment downstream. Discontinuous flows along valley floors may not result in significant associations between sediment concentrations and discharge of that flow segment above the weir.

CONCLUSIONS

Expansions and contractions of stream networks at the two sites studied result from a dynamic balance between rainfall inputs and drainage basin outflows moderated by diverse catchment attributes, such as infiltration capacity, slope and soil depth. Changing streamflow positions along eroded channels and drainage lines exert significant controls on the timing and volumes of discharge, sediment and solutes at the basin outlet (Day, 1980a). As flow nets demonstrate instability and change, so do outputs from the drainage unit.

In this study the surface runoff dynamics of two small catchments have, for the first time, been measured in a series of highly frequent and detailed observations. In these New England catchments the drainage density of flow was measured as it fluctuated over rainfall events in a 16 month period. Additionally such network changes were related to variability in stream discharge and dissolved solid concentrations for all storms, with higher correlations between these hydrologic variables for individual storms. For the catchments, drainage density can be used as a predictor of discharge.

Data pooled for each catchment reveal that there are major differences in the runoff response (Fig. 2) and this can be partially attributed to distinctive morphological differences between the catchments, specifically by contrasting densities of channel networks due to basic lithological and pedological differences.

Rapid expansion and contraction of the flowing stream network exerts a dominant control on drainage basin outputs. These investigations lead to the necessity for intensive field observations and measurements of runoff formation (Dunne, 1980) in order to understand the factors which govern short term changes in the frequency and volume of drainage basin outputs

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