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The Dynamics of a Drainage Network

A. M. Gurnell
Department of Geography, Southampton University

The dynamics of the drainage network within a small catchment, are studied in detail. Variations in the network are related both to transient characteristics of the catchment, including precipitation, soil moisture content and discharge, and to more permanent characteristics including vegetation and rock type.

Introduction

Parameters of drainage networks, notably drainage density, have been related to a wide range of catchment characteristics and hydrological variables. Drainage density has been shown to be related to transient characteristics of catchments, including high flows (Institute of Hydrology 1975, Chorley and Morgan 1962), low flows (Carlston 1963) and sediment yield (Hadley and Schumm 1961). Relationships have also been established between drainage density and more static characteristics of catchments including rock type (Gardiner 1971) and climate (Gregory and Gardiner 1975).

A large part of the research on drainage networks has been based on information abstracted from maps and this has resulted in a number of data quality problems. These problems are partly a result of variations in map scale and accuracy but the fundamental problem is that a very dynamic index is being viewed in a static manner. Studies of variations in drainage density within a catchment by Gregory and Walling (1968) and Blyth and Rodda (1973) emphasize the very large fluctuations which can occur in the extent and complexity of a drainage network in short periods of time, and Gregory and Walling (1973) have proposed a model to outline the controls on these fluctuations. It is the aim of the present paper to investigate some of the controls on the extent of the active drainage network within one small catchment and to attempt to assess the relative importance of those controls and the scales at which they operate.

The study catchment is located in the New Forest and was instrumented in 1974. It has an area of 1.28 km^2 and is underlain by Barton clay and sand with a gravel capping on extensive areas of the interfluves. The catchment is mainly covered by heathland with a few restricted areas of mixed bushes and trees. A 90° Vee-notch weir at the catchment outlet provides a basis for continuous discharge records and a rain gauge network, comprising twenty weekly storage gauges and one autographic gauge, provides information on the occurrence and distribution of rainfall. The storage gauges were emptied at approximately weekly intervals and were distributed according to a random systematic unaligned sample design to allow a fairly even spread of gauges throughout the catchment area. The autographic gauge was moved from its original site after three months of recording (Fig. 1, site A1) because of interference by the public. However, records from the new site (Fig. 1, A2) and old site were related using one of the nearby storage gauges and a regression equation was evaluated for interpolation between the two sites. Furthermore, the records from site A1 only overlap the period of study of the drainage network by one month, and so are unlikely to significantly affect the content of this paper.

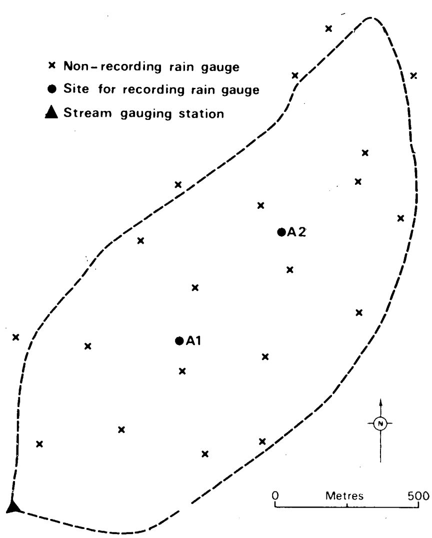


Fig. 1. The hydrometric network.

Drainage density was monitored at approximately weekly intervals from 1st March, 1975 to 28th February, 1976. A large scale base map of the catchment was constructed using aerial photographs and 1:2,500 Ordnance Survey maps. A detailed network of dry and active channels was abstracted from the photographs and this formed the basis for field mapping of the active channel network during each field visit; active channels were those in which water could be seen to be moving. Standing water was mapped but was not used in the analysis of the active drainage network.

Variations in the Complete Drainage Network

Intuitively, the extent of the active drainage network is mainly a result of current and preceding rainfall conditions. Surplus water from precipation finds its way into the active drainage network and eventually issues as stream discharge at the catchment outlet. This suggests that stream discharge is at least partly dependent upon the extent of the active drainage network at present and in the recent past, which in turn is dependent upon rainfall amount and distribution.

Information from the catchment rain gauge network shows that rainfall tended to vary systematically in space during the study period, so that it varied in a similar manner over the whole catchment with time. This was verified by the very high correlations between the weekly catches for each storage gauge and for the autographic gauge. All but one gauge had a correlation of 0.99 with the autographic gauge and ten gauges had a correlation of at least 0.996 (all correlation coefficients were significant, $P<0.001$). Total precipitation catch for each rain gauge for the study period was in the range of 615 mm to 720 mm except for two gauges in slightly sheltered positions with lower catches. Variations in the spatial structure of the rainfall pattern occurred but these fluctations were sufficiently small that they were not shown by the correlation analysis or indicated in the drainage network. The drainage network expanded and contracted, occupying channels in an almost identical order each time, regardless of the rainfall pattern. As a result, the autographic rain gauge, which provided a continuous rainfall record, was used as an index of catchment rainfall for the study period.

The relationship between precipitation and the active drainage network results from both past and present rainfall events, although this relationship is blurred by evapotranspiration losses and discharge variations. The Antecedent Precipitation Index (API) makes a fixed proportional allowance for runoff and losses and it has the advantage of combining past and present rainfall records in a continuous precipitation index and so this was used to relate rainfall to drainage density. The considerable area of clay in the study catchment allowed a rapid drainage network and discharge response to rainfall, so a coefficient of 0.8 was chosen for

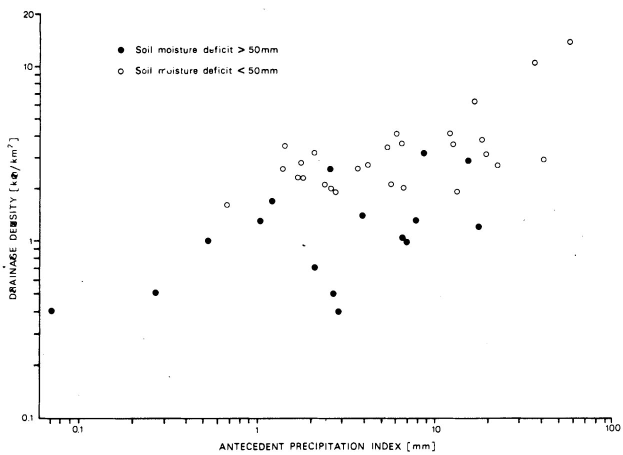
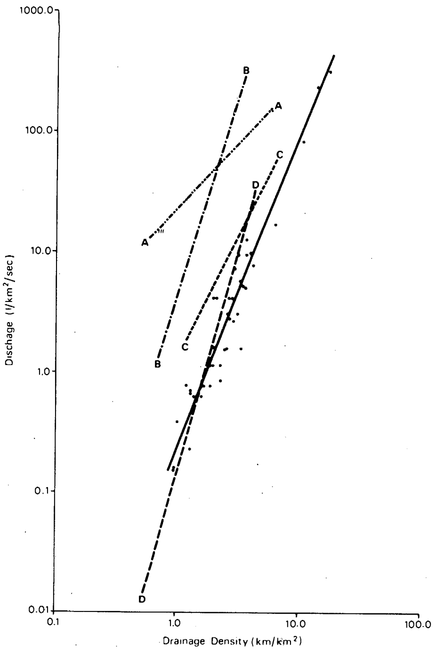


Fig. 2. The relationship between drainage density and antecedent precipitation index.

calculation of the API on a daily basis. A period of two months from 1st January 1975 was used to initiate calculations of the API before the start of the study period on 1st March 1975 and then values of drainage density and concurrent API were used to construct Fig. 2 to show the relationship between the drainage net and antecedent rainfall. Fig. 2 shows a clear positive relationship between drainage density and API but there is considerable scatter around the main trend. As spatial variability in precipitation was small, it seems likely that most of this scatter results from variable evapotranspiration losses, in particular during the hot dry summer of 1975 and the following warm dry winter. No measurements of evapotranspiration losses are available for the catchment but an index of the evapotranspiration rate has been obtained by applying Penman's (1962) formula to information from a nearby climatological station. Boscombe Down was chosen as the nearest climatological station of similar altitude to the catchment, and weekly totals of evapotranspiration loss were calculated. These data were combined with the local rainfall figures to produce the catchment water balance for the study period, using a technique described by Grindley (1967). Estimates of soil moisture deificit from the water balance procedure were then used to divide the values of API into 'summer' and 'winter' estimates using a 50 mm soil moisture deficit as a dividing line. Although the Boscombe Down observations are not strictly applicable to the study catchment, they form an effective means of splitting the data into two groups indicative of the soil moisture content and contributing area effective within the catchment at the time of observation. Clearly the water balance in general and rainfall amount in particular have some relationship with the active drainage network.

The relationship between the drainage network and discharge has been quite widely documented. Gregory and Walling (1968), Calver, Kirkby and Weyman



Results for the study catchment can be compared with relationships established by other studies:-

A)A. Calver,M.J. Kirkby and D.R. Weyman,1975 (East Twin Brook)
B)K.J. Gregory and D.E. Walling, 1968 (Catchment A, Devon)
C)K.J. Gregory and D.E. Walling, 1968 (Catchment B, Devon)
D)K. Blyth and J.C. Rodda, 1973 (River Ray Catchment)

Fig. 3. The relationship between discharge and drainage density.

(1972) and Blyth and Rodda (1973) have shown strong positive relationships between drainage density and discharge within individual catchments and Walling (1971) has demonstrated the effect of the drainage network and contributing area on the form of flood peaks. Fig. 3 indicates that the study catchment showed strong relationships between discharge and drainage density. The relationship is similar to those produced for other catchments but variations, possibly resulting from varying catchment characteristics, are apparent. As drainage density changes so also does the structure and efficiency of the drainage network. The network tended to expand and contract along the same routes so that for a given discharge a particular network structure could be assumed (Fig. 4). The graphs represent the frequency of occurrence of 100 m segments of active drainage network at given distances along the stream network from the catchment outlet under varying discharge conditions. Assuming equal channel capacity a centre of gravity can be calculated for the network. Since channel capacity decreases upstream, the centre of gravity has an exaggerated upstream position but the upstream trend in its location with an expanding channel network indicates the increasing efficiency of the channel network in draining the catchment. The more complex the network the shorter the average distance that surplus water has to travel before it can be evacuated rapidly from the catchment along the active channel network and thus the greater the peak flow (Kirkby 1975).

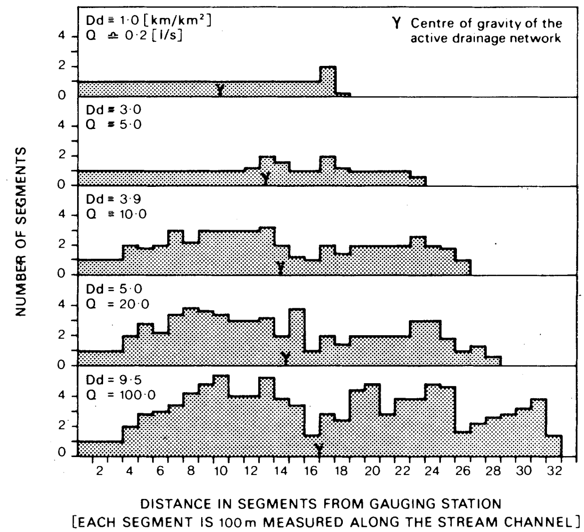


Fig. 4. The variation of the active network structure with discharge at the catchment outlet.

Network structure as well as drainage density indicate the condition of the catchment and the area contributing to flow. Contributing area and the active channel network available to evacuate water have an important impact on the catchment response to rainfall. This can be demonstrated by comparing streamflow reponse to similar storms with varying preceding conditions. An inspection of rainfall and discharge records yielded six storms of similar duration and, after correction for evapotranspiration loss using Boscombe Down data, similar effective rainfall amount. Stormflow peaks were constructed for each storm, using the baseflow recession curve as a means of hydrograph separation. The peaks were found to be very different in form (Fig. 5). The preceding baseflow used in conjunction with Fig. 3 allowed interpolation of preceding drainage density and its effect on each stormflow peak (Fig. 6). The hydrographs show that as the drainage network contracted a smaller volume of water was evacuated from the catchment in a longer period of time and with a more delayed and less peaked hydrograph, even though the effective rainfall input did not vary. A similar effect has been suggested by Kirkby (1975) and demonstrated by Walling (1971).

Although the preceding drainage network and contributing area are very important in controlling the streamflow response to rainfall, they are not static during a storm. Weyman (1973) has shown that contributing area can adjust rapidly to rainfall. In the study area the drainage network also adjusted rapidly as was shown by observation of a storm on 28th November 1975 (Fig. 7). The storm was of quite an even intensity, yielding 19 mm precipitation over six hours. This meant that it was possible to map the drainage network reasonably accurately,

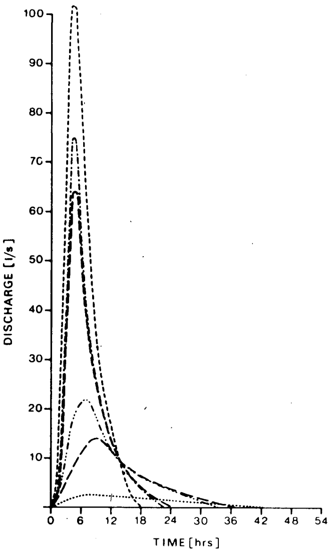


Fig. 5. Storm hydrographs in response to 5 mm nett rainfall (precipitation less evapotranspiration losses) in 4 hours with varying antecedent conditions.

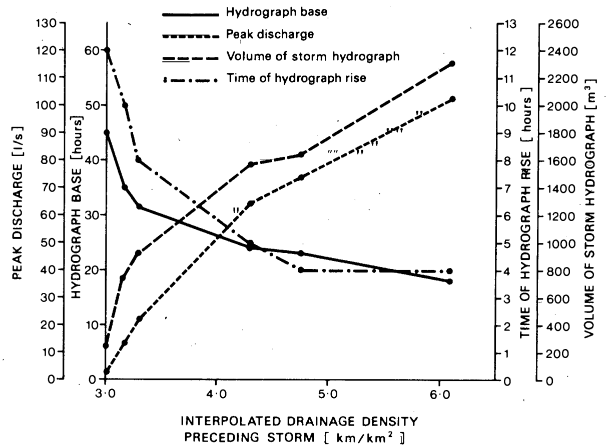


Fig. 6. The effect of preceding drainage density on some parameters of the storm hydrograph.

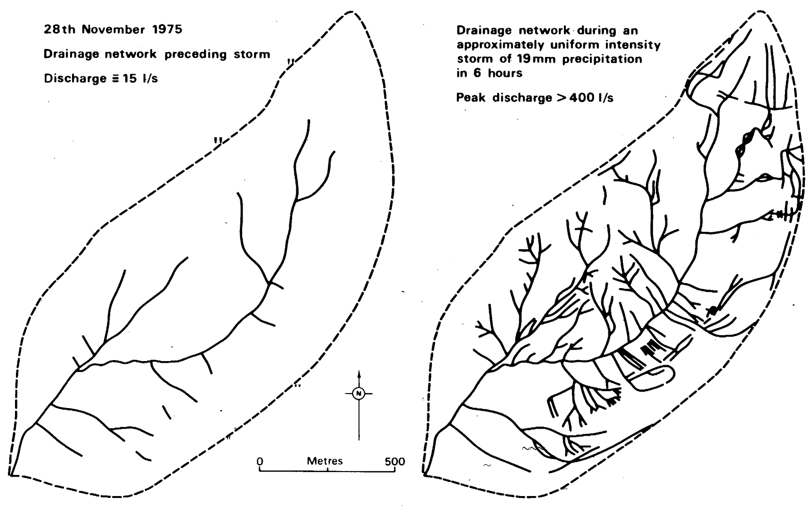


Fig. 7. The adjustment of the drainage network during a storm.

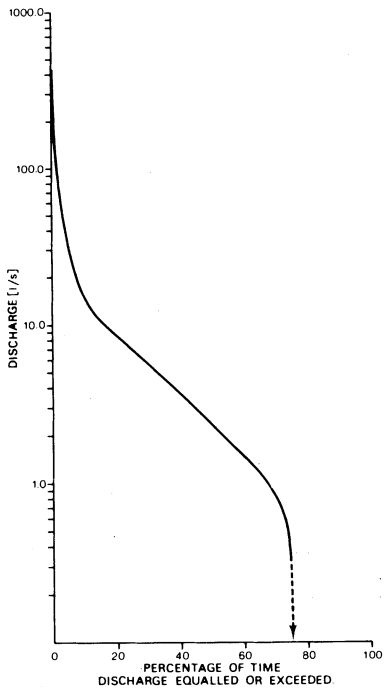


Fig. 8. The catchment flow duration curve for hourly flows during the study period.

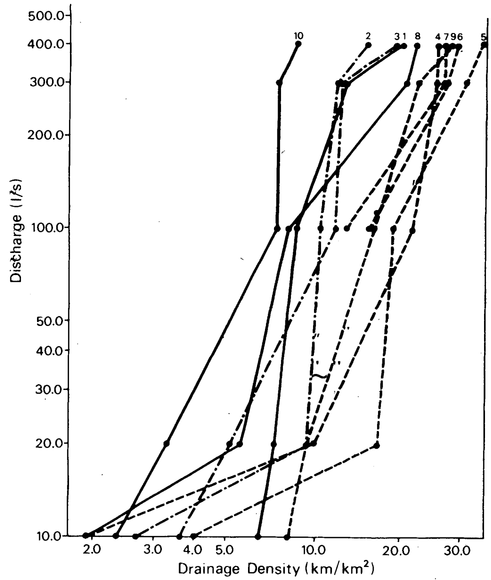
because after an initial expansion the network adjusted to rainfall intensity and became fairly stable. The preceding flow of 15l/s indicates that there was a low soil moisture deficit and, in addition, the water balance for the period suggests that the soil was at field capacity. A low soil moisture deficit is conducive to rapid adjustment of the drainage network to a stable condition. Fig. 7 should, therefore, provide an accurate idea of the form of the drainage network before and during the rainfall event.

Further information on the relationship between drainage density and discharge can be gained by inspection of the flow duration curve for hourly flow values for the study period. The form of this curve (Fig. 8) is interesting because of the two distinct changes of slope it exhibits. The very dry nature of the study period and the large area of underlying clay meant that the gauging station was dry for 24.5% of the time although there was continuous flow in a short section of channel upstream of the gauging station. The change of slope at about 0.9l/s may be indicative of 'normal' perennial flow in the catchment. More interesting is the change of slope at about 12 to 15l/s since this forms a division between a more stable network of intermittently occupied streams producing baseflow conditions and the extension to rapidly adjusting ephemeral streams, which were active for only short periods of time mainly during and immediately after storm peaks. The intermittently occupied channels were clearly defined on the ground but many of the ephemeral channels formed only slight identations on the ground surface. These ephemerally occupied indentations are particularly interesting because they can provide information on the impact of drainage basin characteristics on drainage density. Many of these channels form true first order and second order streams and so they reflect the impact of local rather than distant upstream characteristics. It is for this reason that more detailed analysis was carried out on the channel network generated in association with flows of more than 10 l/s at the gauging station.

Variations in the Ephemerally Occupied Channel Network

The network of channels occupied during flows of more than 10 l/s were active for a maximum of only 15% of the time and, therefore, only a limited number of observations were obtained for these streams and conclusions must necessarily be tentative. However, these small channels are very sensitive to local conditions because they are low order streams generated entirely by adjacent slope drainage and so they provide interesting indications of the effects of local factors on the stream network.

The catchment has a variable rock type and so an attempt was made to assess the impact of this factor on the ephemeral network. Although much of the area is underlain by impermeable clay, there are quite large areas of more permeable gravels and sands. It was possible to isolate ten subcatchments of varying size (see Fig. 9, characteristic C), average slope (characteristic D) and rock type (characteristic B). The catchments were grouped in classes according to whether they were immediately underlain by less than a 10% gravel and sand cover (group 1). more than a 90% gravel and sand cover (group 3), or between a 10% and 90% gravel and sand cover (group 2). The rock type of the subcatchments was investigated using a hand auger to modify and enhance information from the Ordnance Survey geological map of the area. The catchments were investigated at maximum intermittent flow (10 l/s at the gauging station) and at four levels of ephemeral flow related to discharges of approximately 20, 100, 300 and 400 l/s at the gauging station. The catchments varied greatly in character and size and could have received systematically different rainfall amounts. Allowances were made, therefore, for a range of other factors before the impact of rock type could be revealed. Sophisticated multivariate analysis is not a feasible means of achieving this since data from only ten subcatchments are available, and so simpler, less direct methods have been used to try to eliminate the effects of factors other than rock type. The drainage density was calculated from the active drainage network for each catchment for the range of discharges chosen. Calculation of drainage density automatically makes allowance for variations in catchment area. Indices of average slope were then evaluated using relative relief and maximum catch-



Catchment characteristics

A	B	C	D
1	1	35900	4° 19'
2	2	52000	3°25'
3	2	53000	3°01'
4	3	80300	1°38'
5	3	55000	1°46'
6	3	42600	1°40'
7	3	37100	3°01'
8	1	61500	4°26'
9	3	52600	3°42'
10	1	34000	2°54'

Fig. 9. The relationship between catchment discharge and drainage density within subcatchments of varying rock type.

ment length. The results demonstrate that most of the subcatchments had similar indices of slope angle, falling in the range of 3 to 4½ degrees, although three of the high gravel and sand catchments sloped more gently. Each group contained a sufficient range of slope angles to allow comparison between groups. The final major control on the active drainage network is rainfall. It was possible that some catchments of a particular rock type would consistently receive rainfall of a higher or lower amount than the other groups. This problem was investigated by plotting subcatchment drainage density against rainfall in the preceding week for each set of network observations. The most recent rainfall is likely to have the greatest effect on the ephemeral drainage network but Fig. 10 shows that rainfall in the preceding week had no perceptible effect on the drainage density of any rock type at the observed levels of discharge. Having eliminated the effects of catchment area, slope and rainfall, Fig. 9 shows that there still seems to be some modification of drainage density according to local rock type. Since subcatchment discharge is unknown, it is untenable to discuss the relative positions of the subcatchment data with respect to drainage density but the general trends or 'slopes' of the information can be compared. Such a comparison shows that subcatchments with a low gravel-sand and high clay area maintained an active drainage network through the whole range of catchment discharges above 10l/s but the rate of expansion of the active network was relatively slow. In comparison, the high gravel-sand catchments had very limited or non-existent active

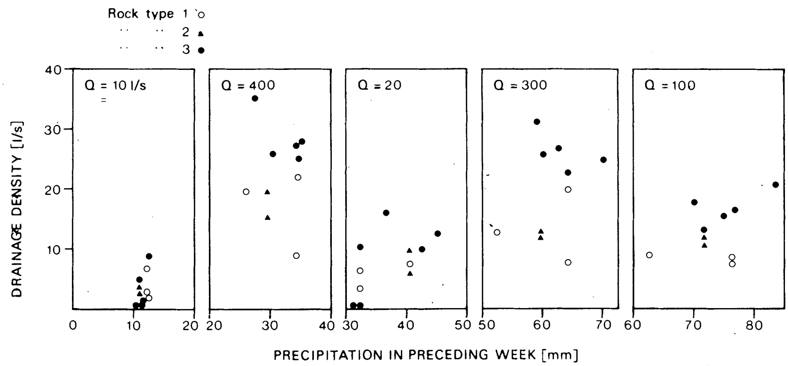


Fig. 10. The effect of precipitation in the preceding week on drainage densities on different rock types.

networks during the lower range of flows but a network appeared and expanded rapidly as discharge increased. This was not just an effect of low angle of catchment slope (see for example subcatchment 9) but was presumably related to the position of the water table within the more permeable rock.

Another pair of factors which may influence the ephemeral drainage network are the combination of vegetation and soil characteristics. Arnett (1976) has demonstrated the impact of vegetation and soils on interflow volumes and so one might expect a complimentary effect on surface drainage, given an impermeable underlying rock. This phenomenon could be investigated in the present study area. A large section of the North West facing side of the catchment was underlain by clay below the gravel capping. The lower slope had a constant angle of six degrees and four main plots of apparently different vegetation composition were identified along the slope at different sites below the almost continuous cover of *Calluna vulgaris* on the gravel. Estimates of mean percentage cover of species were obtained using a systematic point quadrat method over each of the four plots, and a summary of the results for the commonly occurring species are shown in Table 1. The results indicate that the plots range from humid to wet heaths with *Calluna* and *Erica tetralix* as classified by Gimmingham (1972) and that it is possible to differentiate between the plots on the basis of composition of the vegetation communities and their association with the water balance of the habitat. Many of the species are tolerant over quite a wide range of soil moisture conditions but in general *Calluna vulgaris* tends to occur in less moist sites than *Erica tetralix,* and *Sphagnum* and *Juncus* species and *Narthecium ossifragum* are indicative of even wetter conditions (Gimmingham, 1972). On the basis of the vegetation composition it is possible to suggest that plot A generally has the highest soil moisture content, and plot C the lowest. It is difficult to differentiate between the intermediate plots, B and D. although the vegetation on plot D may indicate slightly moister conditions than plot B.

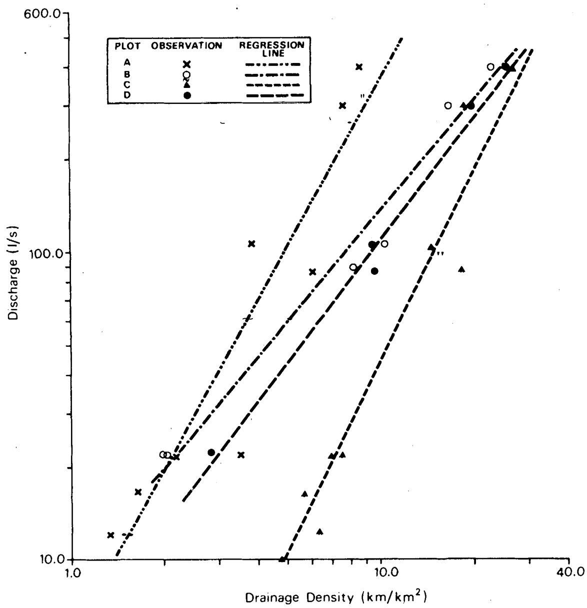
Table 1 – Percentage cover of commonly occurring species on plots A to D

Plot	A	B	C	D
Species:				
Calluna vulgaris	1	34	50	16
Erica tetralix	33	34	23	38
Myrica gale	5	3	3	11
Pteridium aquilinum			6	1
Molina caerulea	66	69	69	66
Agrostis spp.			8	3
Trichophorum cespitosum	4	1	1	2
Narthecium ossifragum	13		1	12
Juncus spp.	18	5	3	11
Sphagnum spp.	22	14		10

Mean percentage cover for each species obtained by a systematic point quadrat method over each plot. Figures are rounded to the nearest whole percentage.

The presence of active drainage networks were investigated on the four plots. The slope only had surface drainage under ephemeral flow conditions during the period of study. The consistent slope angle and aspect and only slightly varying altitude indicated that the whole of the area should receive the same amount of rainfall and total study period catches of 696.5 mm. 661.6 mm and 655.4 mm in the three gauges along the slope verified this. Drainage density of the active network was calculated for each of the plots for a range of ephemeral flow discharges at the gauging station and relationships were established using linear regression analysis (Fig. 11). It is again difficult to justify direct comparisons of drainage densities for the different plots as differences in plot discharge were unknown, although similar rainfall input and plot size made comparison more feasible than in the case of the data for rock type. Nevertheless the slopes of the regression lines for each plot could be compared and an attempt made to explain the relationships.

Plot A had a generally low drainage density in relation to catchment discharge. This may be explained by the moist nature of the soil, allowing the development of throughflow, probably mainly concentrated throughflow, in preference to overland flow on the slope. The steep slope of the regression line for plot A indicates that even during very moist conditions there was little surface drainage on this plot although some surface drainage was maintained through the whole range of ephemeral flow conditions. In contrast, plot C experienced relatively high drainage densities, possibly reflecting the lower infiltration capacity of the compacted, drier soil. The rapid rate of change of drainage density with discharge on plots B and D is possibly indicative of the mixed nature of their vegetation. Throughflow may have occurred in some zones of these plots but in wet conditions overland flow developed leading to high active drainage densities.



The fitted relaionships are:

Plot A $Q \equiv 5.475D^{1.832}$
Plot B $Q \equiv 8.586D^{1.194}$
Plot C $Q \equiv 0.315D^{2.157}$
Plot D $Q \equiv 5.202D^{1.335}$

Fig. 11. The relationship between catchment discharge and drainage density within plots covered by vegetation of varying composition.

Conclusions

Observations of the dynamic drainage network in a small catchment have verified the results of previous workers. However, more detailed investigation has shown that during high flow and low soil moisture deficit conditions an ephemeral network of small streams develops which is not only sensitive to the general water balance of the catchment but also reflects local characteristics including rock type and vegetation.

The results presented are partly based upon data collected for the restricted periods of ephemeral flow during one year but field observations are continuing to reveal further details of the temporal and spatial variations of drainage density.

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Address: Department of Geography,
The University of Southampton,
Southampton S09 5NH,
England.