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HYDROLOGICAL FACTORS INFLUENCING SEDIMENT CONCENTRATION FLUCTUATIONS IN SMALL DRAINAGE BASINS

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Abstract

Although sediment concentrations measured in two contrasting streams in East Yorkshire fluctuate in response to similar hydrological factors, the effectiveness of these factors reflects the environmental characteristics of the drainage basins. Consequently, regression relationships used to predict sediment concentrations in individual streams are not directly applicable outside the region in which they were developed. The sensitivity of sediment concentration variations to environmental conditions makes long term estimates of denudation of limited value.

INTRODUCTION

The influence of environmental factors on erosion has been studied by relating the sediment yields of rivers to catchment characteristics of climate, geology, soil and vegetation by such writers as Anderson (1954), Schumm (1954), and Copeland (1963). Work by Fournier (1960), Strakhov (1967) and Langbein and Schumm (1958) has demonstrated that world-scale variations in erosion may be explained by differences in climate. However, the denudation process is so complex that erosion may vary considerably within a given climatic region. Consequently, Douglas (1967) has stressed that before a world-wide synthesis of erosion can be refined detailed information is needed on the factors influencing erosion in individual catchments. This paper examines such factors by studying the hydrometeorological factors affecting the sediment loads of two streams draining catchments similar climatically, but different in topography and lithology, on the North Yorkshire Moors (Hodge Beck) and the Holderness region of East Yorkshire (Catchwater Drain).

The Catchwater catchment, occupying an area of 15.4km^2 is located a few kilometres south of Hornsea on the poorly drained Pleistocene deposits of Holderness. Almost from the coastline the catchment is drained inland by a network of ditches which feed the artificially straightened channel of the Catchwater Drain. Most of the catchment is underlain by boulder clay but in a few places sandy morainic ridges rise about 10m above the general level of between 12 and 15m O.D. to form local areas of free draining soil (Catt and Penny 1966). The catchment receives an average annual precipitation of between 610 and 650mm which is fairly evenly distributed throughout the year. Seasonal variations in evaporation contribute to the remarkably seasonal discharge of the Catchwater Drain (Figure 1). During the summer, between July and October, negligible amounts of flood runoff occur, even after heavy prolonged rainfall, but in the winter and spring relatively light or short periods of rain may produce considerable runoff.

The seasonality of the discharge is partly a reflection of the annual change in surface conditions on the arable farmland which occupies about 80 per cent of the catchment.

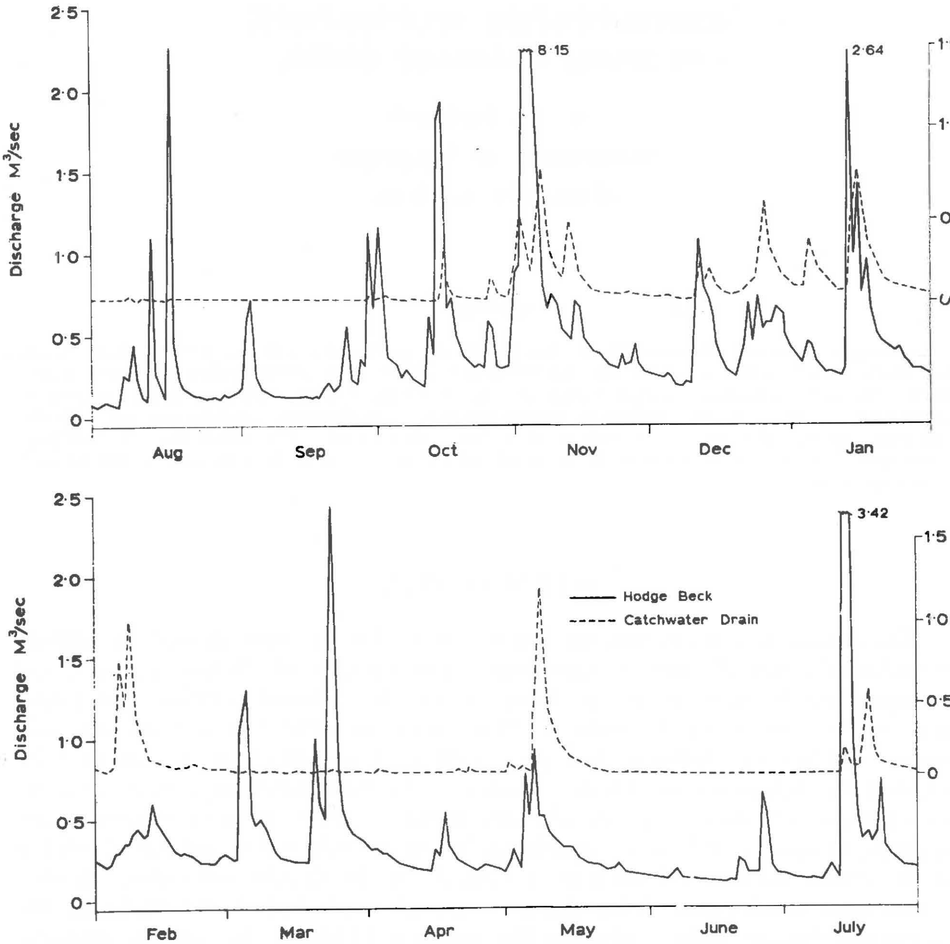

Figure 1 The location, relief (A) and land use (B) of the Hodge Beck catchment.

The Hodge Beck catchment (Figure 2) drains an area of 18.9km² on the southern limb of the Cleveland anticline on the highest region of the North Yorkshire Moors. The Hodge Beck and its tributaries have cut through the clays and sandstones of the Middle Jurassic Deltaic Series, which form the highest parts of the catchment to expose the underlying Liassic Shales in a series of concentric inliers along the valley sides and bottom (Fox-Strangways *et al.* 1892). In general the Deltaic Series rocks coincide with the relatively gently sloping (0° to 15°) area of heather-moorland beneath which the steep 20° to 50° bracken covered slopes of the Alum Shale and Jet Rock, the highest beds of the Lias, form a marked contrast. The outcrops of the Lower and Middle Lias along the lower valley sides and bottom form a relatively gently sloping area of predominantly pastoral farmland. The average annual precipitation recorded at stations within or near the catchment ranges from 970 to 1100mm according to exposure and elevation; this is between 40 and 50 per cent higher than the average annual precipitation recorded in the Catchwater catchment.

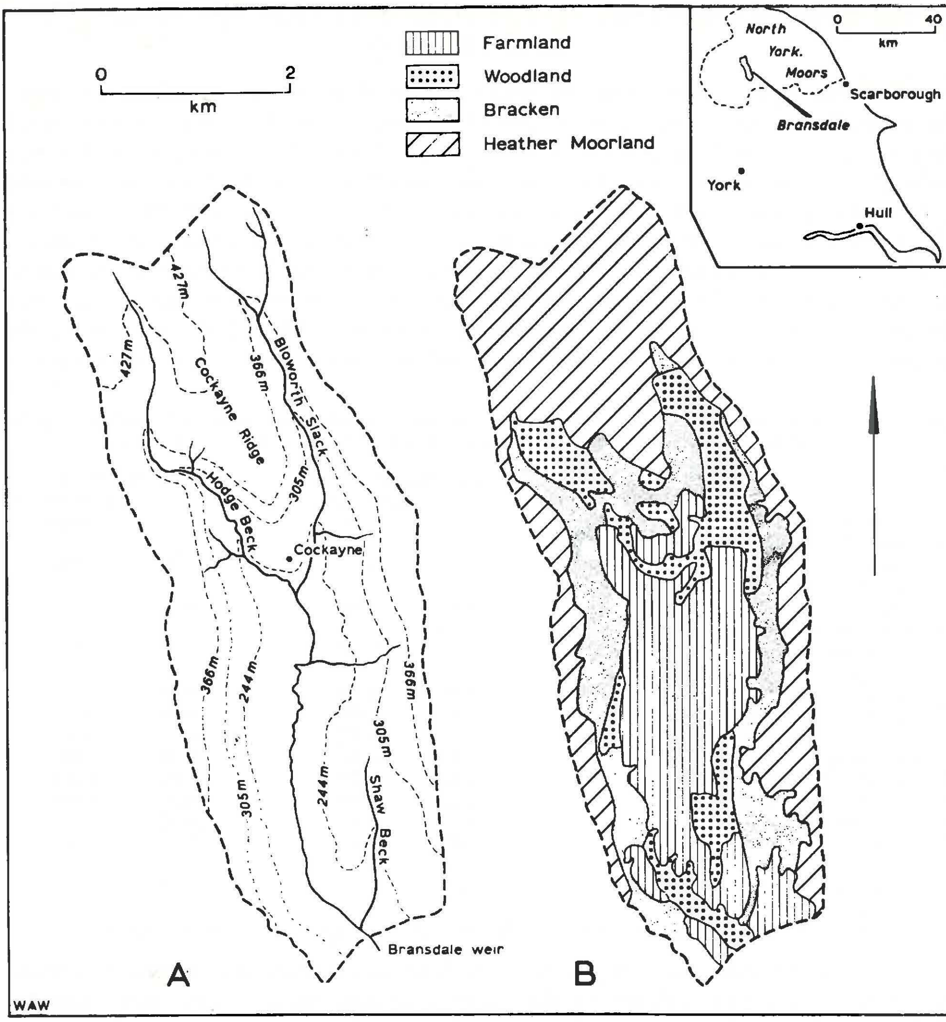

Figure 2 The discharge of the Hodge Beck and Catchwater Drain from August 1967 to July 1968.

Sediment and Hydrometeorological Measurements

The suspended sediment measurements discussed below were made between January 1967 and July 1968 from depth-integrated samples collected in a U.S.DH 48 hand sampler or from single stage samples (U.S. Inter-Agency Committee on Water Resources 1953, 1961). The concentrations were measured using the Millipore procedure as outlined by the Society of Automotive Engineers (1963). Rainfall measurements were obtained from recording rain gauges located within or near the catchment areas while discharge measurements were calculated from continuous water-level recordings at weir or flume sites.

In the following discussion the distinction is made between the measured sediment concentration and the calculated sediment load. As the latter is derived by multiplying the sediment concentration by the water discharge, the sediment load and water discharge are closely related. To avoid obscuring the relationships of the sediment yield to other variables, the sediment concentration rather than the sediment discharge is considered below.

HYDROMETEOROLOGICAL FACTORS INFLUENCING SEDIMENT CONCENTRATIONS

One reason for considering the sediment concentration in a single river draining a small catchment over a short period of time is that it enables factors which vary areally or over long periods of time to be considered as constant; in this way sediment concentration variations may be regarded as a function of changing hydrometeorological and land use conditions. Guy (1964) and Bobrovitskaya (1967) found that short term variations in the sediment concentrations of individual streams were related to various discharge, rainfall and flood intensity variables. In the Catchwater Drain and Hodge Beck, the hydrometeorological variables shown in table 1 are capable of explaining respectively 94 and 80 per cent of the variance in sediment concentration measurements made over a two year period.

Table 1 Correlation coefficients (r) between sediment concentrations and hydrometeorological variables for the Catchwater Drain and Hodge Beck during wet weather.

	Catchwater Drain		Hodge Beck	
Variable	r	significance level	r	significance level
1. Amount of rain 0–24 hours before sampling	0.103	n.s.	0.46	0.002
2. Amount of rain 0–48 hours before sampling	0.51	0.005	0.2	n.s.
3. Amount of rain 0–72 hours before sampling	0.51	0.005	0.25	n.s.
4. Amount of rain 24–48 hours before sampling	0.58	0.001	0.21	n.s.
5. Rainfall intensity index	0.4	0.02	0.08	n.s.
6. Rainfall intensity — duration index	0.52	0.005	0.2	n.s.
7. Discharge	0.81	0.001	0.86	0.001
8. Flood intensity index	0.62	0.001	0.84	0.001
9. Flood peakedness index	0.72	0.001	0.83	0.001
10. Air temperature	–0.22	n.s.	0.05	n.s.
11. Water temperature	–0.45	0.01	0.01	n.s.
Number of observations	32		39	

n.s. denotes that the correlation coefficients are not significant at the 0.1 level.

As is to be expected (Guy, 1964), in both catchments the sediment concentration is more closely related to the water discharge than to any other variable (Table 1). Although one reason for this is the increase in competence with increase in discharge, more important on streams such as the Hodge Beck and Catchment Drain, which respond rapidly to rainfall as surface runoff or interflow enter the stream, is the expression of the general state of catchment wetness and the volume and intensity of rainfall by the discharge variable. For this reason most of the discharge and rainfall variables shown in Table 1 are related, and similar variables correlate with the sediment concentration in both streams. These variables largely express different aspects of a hydrological system in which the output of water and sediment reflect the varying input of rainfall.

Principal components analysis has been shown to be helpful in sorting out complex interrelationships (Cooley and Lohnes, 1962). Such an analysis on hydrometeorological data for the Catchwater Drain and Hodge Beck showed that most of the variance in the sediment concentration could be accounted for by the first two components which describe independent directions of variance in the hydrometeorological conditions.

In the Catchwater Drain analysis, most of the variance in the sediment concentration (51 per cent) is positively linked with component one whose significant positive loadings on all of the rainfall and most of the runoff variables, indicate that it provides a generalised measurement of what might be termed catchment wetness. Departures from the linear relationship shown in Figure 3 (1), where the component scores are plotted against sediment concentrations, refer to samples collected during unusual hydrometeorological circumstances not accounted for by this variation. For example, some of the sediment concentrations measured during the summer are lower than component one would suggest because they were collected after heavy rainfall which, because of the seasonal runoff characteristics (Figure 1), failed to produce an immediate increase in discharge. Seasonal variations in the hydrometeorological variables associated with such departures appear to be measured by component two which links positive component loadings on the temperature variables with negative loadings on the sediment concentration, discharge, river stage and flood peakedness variables, describing what appears to be a seasonal variation. Consequently, when the sediment concentration measurements plotted in Figure 3 (2) are ranked according to their component scores, they are separated into summer observations with high scores and winter observations with low scores.

The two components described above measure the two dominant trends in the hydrometeorological situation which influence the sediment concentration of the Catchwater Drain. Although the relationships that they express, namely an increase in sediment concentration with 'catchment wetness' and a seasonal winter increase in sediment concentration associated with a changing rainfall-runoff relationship, are possibly obvious, they provide a realistic measurement of the dominant factors influencing sediment concentrations in the Catchwater Drain.

A similar analysis computed for the Hodge Beck provides an interesting comparison. Again, most of the sediment concentration variance (57 percent) is associated with a component that can be interpreted as measuring the state of 'catchment wetness'. This component is slightly more important in terms of the sediment concentration, than the similar Catchwater Drain component probably because a similar rainfall-runoff relationship persists throughout the year (Figure 1) in a catchment where steep slopes and rapid erosion ensure a plentiful supply of sediment. The second component, containing 26 percent of the sediment concentration variance is more difficult to interpret but it differs considerably from the Catchwater Drain component two. Rather than seasonality, it appears to measure a variation in the hydrometeorological variables associated with the amount and intensity of runoff. Flood intensity is likely to be an important factor influencing sediment concentrations in the Hodge Beck because the amount of sediment in the river increases dramatically during periods of high discharge. Whereas peak concentrations in the Catchwater Drain may reach 12,000mg/litre, in the Hodge Beck they occasionally exceed 20,000mg/litre. Although sediment concentrations vary seasonally in the Hodge Beck, with high winter and low summer concentrations, this variation occurs in sympathy with changes in the catchment wetness factor. As component one, therefore, takes seasonal variations into account, an independent direction of variance associated with seasonality is not necessary to explain sediment concentration variations in the Hodge Beck.

The principal components analyses described above indicate that in both the Hodge Beck and Catchwater Drain, sediment concentration variations reflect, more than anything else, similar catchment wetness factors. However, in spite of their similarity, the effectiveness of these factors, in terms of the amount of sediment eroded and transported, is very different because this is also a function of environmental conditions of geology, relief, soil and vegetation. To some extent environmental conditions also explain why different hydrometeorological factors, as expressed by the second components in the principal components analysis, influence sediment concentrations in the two rivers.

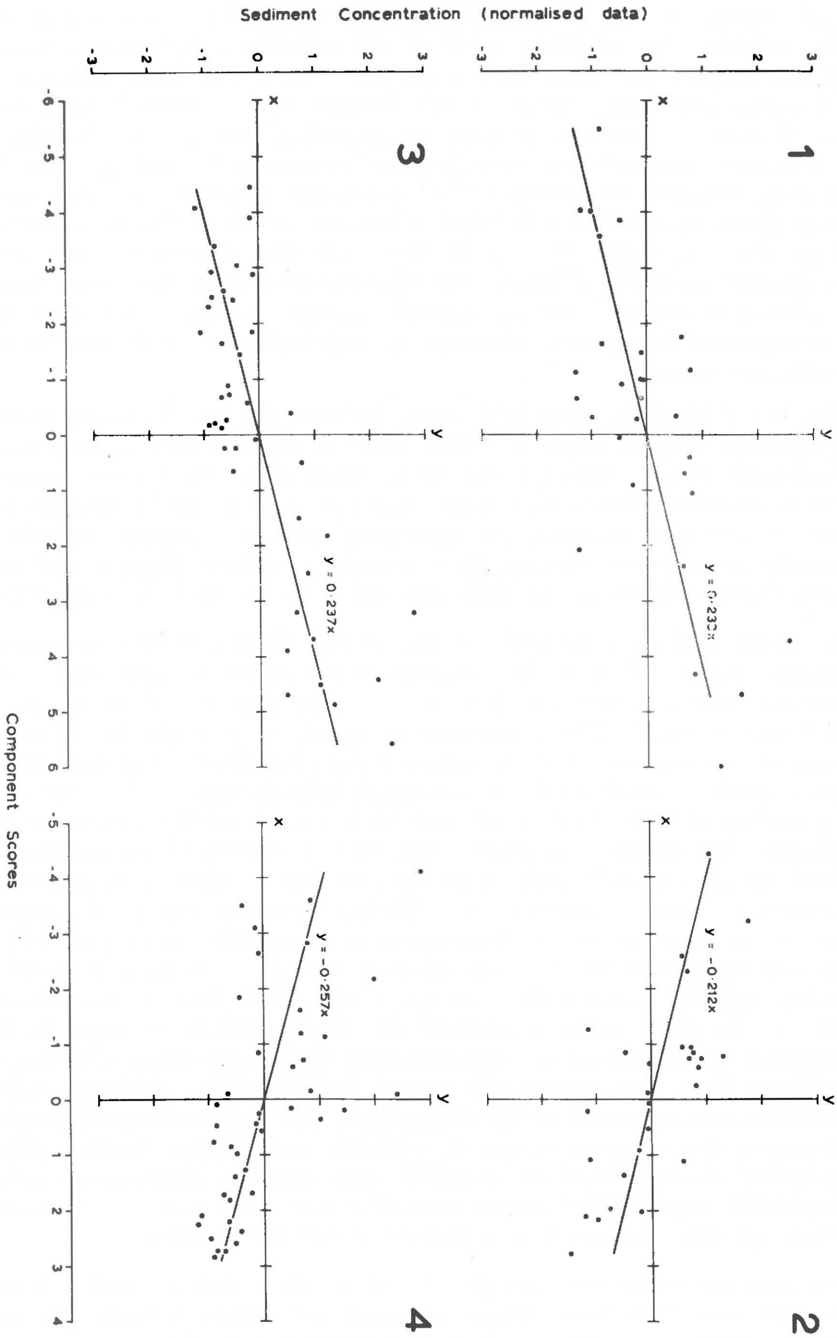

Figure 3 Relationships between sediment concentrations and component scores for the Hodge Beck and Catchwater Drain.

1. Catchwater Drain component one.
2. Catchwater Drain component two.
3. Hodge Beck Component one.
4. Hodge Beck component two.

THE PREDICTION OF SEDIMENT CONCENTRATIONS IN TERMS OF HYDROMETEOROLOGICAL CONDITIONS

The extent to which fluctuations in the sediment concentrations in the Hodge Beck and Catchwater Drain are a function of changing hydrometeorological conditions is illustrated by the multiple regression equations shown in Table 2. These equations, calculated by a stepwise procedure, enable concentrations to be predicted quite accurately in both rivers to the extent that calculated and observed concentrations seldom differ by more than 20 per cent.

Table 2 Multiple regression equations for predicting sediment concentrations (Sc.) at the 5 per cent significance level in the Hodge Beck and Catchwater Drain during wet periods.

Hodge Beck	Catchwater Drain
log (Sc) = 1.024 log (discharge)	log (Sc) = 0.413 log (discharge)
+0.365 log (flood intensity index)	+0.236 (rain 24–48 hours before sampling)
+1.2118	+1.154
Multiple correlation = 0.89	Multiple correlation = 0.96

Except in rivers draining similar catchments nearby, it is doubtful if the regression equations could be used to predict sediment concentrations accurately elsewhere. This is largely because the independent variables refer to hydrometeorological conditions that influence sediment concentration fluctuations rather than sediment concentration amounts. As well as hydrometeorological conditions, the amount of sediment carried in suspension by a river is also a function of environmental conditions of geology, relief, soil and vegetation, none of which are considered in the regression relationships. However, the relationship of such environmental factors to sediment loads is known for certain areas (for example, Anderson, 1954; Schumm, 1954). Using such relationships to estimate the amount of sediment likely to be carried by particular rivers, it might be possible to extend relationships describing temporal variations in sediment concentrations, such as the equations described above, over wider areas. These equations would in a sense form a temporal extension of the equations developed to predict spatial variations in sediment discharge. The possibility of extending the above equations to other areas, providing the effect of different environmental characteristics is known, is suggested by the similarity of the 'catchment wetness' factors described by the principal components analyses, in the Catchwater and Hodge Beck catchments.

GENERAL RATES OF DENUDATION

Although the catchments considered here lie within the same general climatic region, environmental conditions are so important in influencing the effectiveness of essentially similar hydrometeorological factors that erosion rates vary dramatically from 8.91 tonnes/yr/km^2 of suspended material in the Catchwater Drain, to 480 tonnes/yr/km^2 in the Hodge Beck. This suggests that although the interpretation of the amount of material being discharged by a river as an overall rate of denudation may be of value in small homogeneous catchments, in a large or heterogeneous catchment it might be misleading. For example, the load carried by a hypothetical river draining the North Yorkshire Moors and Holderness would reveal little about the nature and rates of erosion in the individual regions. Even within a small catchment it is difficult to locate the source areas of sediment transported by the catchment river.

The sensitivity of sediment concentration fluctuations to environmental conditions makes it difficult to extrapolate the erosion rates of today backwards through time to estimate long term rates of denudation (Douglas, 1962; Meade, 1969). Much of the sediment carried by the Hodge Beck comes from small areas of land exposed to erosion by burning or cultivation so that the present rate of denudation bears an unknown relationship to past rates of denudation. This further complicates the influence of climatic change and variations in the intensity and seasonality of hydrometeorological processes. Because the sediment discharge is more dependent on the water discharge than the sediment concentration, small climatic or land use changes influencing the hydrology of the catchment would produce large changes in the rate of denudation.

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