CHARACTERISATION OF NON–POINT COLOUR SOURCES IN NORTH YORKSHIRE, UK

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ABSTRACT - The relationship between the distribution of naturally occurring, water discolouring material and catchment characteristics is determined for an upland catchwater system in North Yorkshire, UK. Primary non-point sources of Colour are identified as areas of Winter Hill peat with slopes ≤ 5°, particularly those with high drainage densities. Heather burning and moorland gripping are identified as land management practices likely to increase water discoloration. A stepwise regression procedure allows the development of a model to predict the spatial distribution of water discoloration. The utility of such a model is seen in hazard mapping and water resource management. The implications for predicting Aluminium, Iron and Manganese concentrations in runoff are considered.

Keywords: Colour; Aluminium; Iron; Manganese; Dissolved organic matter; peat; catchwater management.

INTRODUCTION

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In recent years discoloured water has become a matter of concern to water resource managers. Discoloured water is a major source of customer complaints for those water supply companies with upland gathering grounds[1]. In addition, discoloured water is associated with acid flushes[2], increased metal mobilisation[3] and mutagenic chlorination by products.[4,5] Discoloured water can be controlled by increasing expenditure on water treatment, and by developing land and catchwater management strategies that reduce the Colour of water arriving at water treatment works. This paper addresses the latter aspect of colour control.

Intensive sampling of all the major feeder streams in the How Stean and In Moor catchwaters, situated in the headwaters of the Nidd valley, North Yorkshire, UK, has demonstrated that consistent differences occur in true water colour between sub-catchments.[6,7,8] These apparently homogeneous sub-catchments (≤ 5 km^2), often adjacent to each other, can produce marked differences in runoff Colour. Consistently high water colour is found to originate from sub-catchments with organic rich and peat soils, especially those subject to moorland burning, ditching and with South facing slopes. Runoff Colour has a marked seasonality, with an Autumn maximum. Analysis of the long term trends in water Colour for the upper Nidd valley[9] indicate that water discolouration relates to large soil moisture deficits in the months immediately prior to the Autumn Colour maxima and to high soil moisture deficits in the previous summer. These observations suggest that high water Colour is associated with water table lowering and elevated aerobic decomposition of the upper organic layers, followed by catchment flushing.

The conclusions drawn from the Upper Nidd study have allowed recommendations (to reduce discolouration [8, 10, 11]) to be made to catchment and water resource managers. This is achieved by operating a turn-out strategy which systematically excludes highest Colour waters from water gathering so reducing the average Colour in a reservoir while minimising loss of yield. In addition a predictive, process based model is under development, which initially drew heavily on the Upper Nidd investigation.[12]

Whilst water Colour has been measured for a number of other upland sites in the U.K., there has been little attempt to explain water Colour in terms of catchment characteristics. One notable exception is the Elan valley catchment protection study[13] which supported the broad conclusions drawn from the Upper Nidd study, and additionally highlighted interfluve peats, rare in the Upper Nidd, as a source of Colour. The purpose of this paper is to characterise catchments in relation to runoff Colour. This is done for a catchwater system independent of the Upper Nidd in an attempt to justify a wider geographical application of the Colour reducing water resource strategies already developed.

METHODOLOGY

STUDY AREA

The study area (Figure 1) containing Roundhill and Leighton reservoirs (SE 16 78) is situated in the headwaters of the River Burn, a tributary of the River Ure, N.Yorkshire and covers an area of approximately 60 km². The reservoirs were built by the then Leeds Corporation Waterworks and the Claro Water Board to supply Leeds from Leighton reservoir and Harrogate from Roundhill reservoir. The source of the River Burn is located in an adjacent valley, Colsterdale, which provides a third catchwater. Water from this area is abstracted from Birk Gill, Spruce Gill Beck and the headwaters of the River Burn, where it flows under gravity to Leighton reservoir.

These catchments are approximately 100 m lower than those of the upper Nidd valley, and are largely covered by rocks of the Millstone Grit series. There are also areas of sandstone, shale, mudstone, limestone and in the upper reaches of Colsterdale, thin seams of coal. The land use of this area is mixed, with areas of grouse moor grazed by sheep, reclaimed grassland, some lowland arable land and mixed woodland managed by the Swinton estate.

WATER QUALITY VARIABLES

Throughout 1989 waters from 45 of the most significant sub-catchments, in terms of discharge, were sampled. In all, 14 'snapshots' were taken, with more frequent sampling during the wetter Autumn and Winter periods. True Colour was measured after 0.45µ filtration on a Pye-Unicam UV/Vis spectrophotometer at $400nm^{-1}$. Several other water quality parameters thought to be associated with Colour were also determined. Conductivity and pH were measured within 8 hours of collection, pH with a low conductivity probe. Aluminium, Manganese, Iron, Calcium and Magnesium were measured by atomic absorbtion spectrophotometry. (Al < 7%). The residual standard deviation is a measure of the departure of a range of standards from the spectrophotometer calibration curve. Total Hardness was determined by calculation.[14]

Fluctuations in water quality during the c.8hr sampling period were assessed by sampling sub-catchment one first and last. Maximum deviations (Table I) were found during October and February when rainfall was greatest, but were generally within the band of experimental error. Two tailed t-tests demonstrate that, with the exception of Total Hardness, no significant differences exist between the two sets of samples. Thus each sample group can be considered a true snapshot.

CATCHMENT MORPHOMETRIC CHARACTERISTICS

For each subcatchment sampled in the Upper Burn catchwaters, 32 morphometric variables were calculated. These variables are detailed in table II. All values were determined from 1:25000 scale maps using a digitising tablet where appropriate.

CATCHMENT SOIL CHARACTERISTICS

The soils in the study area are diverse, including 12 soil associations. These include the Revidge (311a), Rivington (541g), Belmont (651a), Maw (652), Dunkeswick (711p), Hallsworth (712d), Brickfield (713g), Ticknall (713h), Kielder (721a), Roddlesworth (721b), Wilcocks (721c), and Winter hill (1011b) associations (sub group shown in parenthesis)[23]. These soils range from loam and clay soils to blanket peat. The best published soils data for this area is at a scale of 1:250000, which is of limited value for this study. Therefore a soils map at 1:25000 scale was prepared by the Soil Survey and Land Use Centre (SSLUC). This map represents the most detailed soil information available for this area. However, errors may exist as it was compiled from air photo interpretation with less ground testing than is usual for published maps.

DISCUSSION

SEASONAL PATTERN OF COLOUR

The annual pattern of Colour flow in the three main catchwaters and rainfall for the whole catchwater is presented in Figure 2. High Colour flows were experienced during February, March and October. These were the wettest periods in a drier than average year, with only 91.9 per cent of the long term average rainfall. Periods of high Colour come in months where the average monthly rainfall is high following a previous dry month (Jan-Feb 31.5-117.5 mm, Sep-Oct 17.4-101.9 mm). The timing of these high Colour flows is consistent with that observed in many other catchments, including the Upper Nidd and Elan valleys, where high Colour flows follow high rainfall, the rapid replenishment of soil moisture deficit and 'flushing' of dissolved organic matter. The seasonal pattern of Colour flow in these catchments can thus be considered typical.

SPATIAL PATTERN OF COLOUR

The spatial variation in Colour is presented in Fig. 3. There are consistent differences in Colour between sub-catchments throughout the catchwater system. The Colour of runoff from some sub-catchments, particularly from those in Colsterdale, is significantly and consistently higher than from others. This is an important observation as it supports the previous conclusions drawn from the Upper Nidd and Elan valley studies. This implies that a turn-out strategy similar to that designed for the upper Nidd is likely to be effective when applied on a wider geographical scale.

COLOUR AND CATCHMENT CHARACTERISTICS

Of the 44 variables used to describe the catchments sampled in the catchwater system, only two were significantly correlated with runoff Colour. These were the proportion of catchment covered by the Winter Hill (%1011b) soil association ($r=0.4363$ $P<0.001$, $n=48$) and the proportion of total channel length found in areas of catchment with slopes ≤5° degrees, $\%TCLA_{5°}$ ($r=0.3833$ $P<0.01$, $N=48$).

The Winter hill association is very acid blanket peat to a minimum depth of 40 cm. It is the deepest organic soil in the Soil Survey classification and has the greatest volume of organic material in the catchwater. Water is coloured by dissolved organic matter, such as humic and fulvic acid, which are most abundant in peat soils. The Winter hill association, the deepest peat in the study area, thus represents the main source of water discolouring material in the catchwater.

Colour was positively correlated with $\%TCLA_{5°}$. Plateau areas have low hydraulic conductivities, giving water the maximum potential to dissolve decomposition products and become coloured. When combined with a high drainage density water discoloration is promoted in two further ways. Firstly, a well drained catchment will have a lower water table, producing a greater zone of aerobic decomposition and a larger pool of organic, water discolouring material. Secondly, a high drainage density allows more rapid movement of drainage water, a faster export of organic solutes and therefore a more intense Colour flush.

REGRESSION MODEL

The data collected from the survey of the Upper Burn can be used to estimate the discolouration of water from catchments where no water sampling has taken place. This can be done by producing a predictive equation in a similar manner to that done for flood prediction from ungauged catchments.[24]

Water Colour was related to catchment morphometric and soils data using a stepwise multiple regression technique. The dependent variable, Colour, approximated to the normal distribution curve after a log transformation (Kurtosis = 0.21, Skewness = 0.64).

The resulting equation is:-

$$\mathrm{Log}_{10}\mathrm{Colour} = 0.00512(\%\mathrm{TCLA}_{5^\circ})-0.609(\mathrm{MSS})+0.00368(\%1011b)+0.21435$$

When all catchments and are entered into the equation 60.1% of the variance can be explained by the independent variables ($P<0.001$, $N=45$). A third component, Main stream slope is significant when entered in the regression model, although not significantly correlated with colour. Variables were added to the equation by demanding a significance level of 95% and selecting that variable which gave the maximum addition to the explained radiance in combination with the variable already entered into the equation. The negative direction of the relationship is a further indication that shallow slopes promote water discoloration. The final, highly significant, predictive model demonstrates the rôle highly dissected peat plateaus play in determining the spatial distribution of discoloured runoff within the catchment.

The predictive power of the equation is further improved to 81.6% ($P<0.001$, $N=42$) by dropping three catchments from the analysis whose standardised residual exceeds +1.5. Two of these catchments were extensively burnt for grouse moor management, while the third has an intense artificial ditch network that is not represented on the OS 1:25000 map. These observations thus confirm the particularly strong influences of ditching and burning, first identified for the Upper Nidd, in increasing water discoloration.

IMPLICATIONS FOR IRON, ALUMINIUM AND MANGANESE

The seasonal variation in dissolved Aluminium, Iron and Manganese follows a broadly similar pattern to Colour, with peak output in March and October following high rainfall. Consistent differences in the concentration of these metals were also found between sub-catchments.

The correlation matrix (Table III) of all water quality variables in the study shows highly significant relationships between Colour and Aluminium, and Colour and Iron ($P<0.001$, $N=658$). Regression models were able to account for 67.6, 76.0 and 54.8 per cent of the variance in Aluminium, Iron and Manganese respectively. The variable $\%TCLA_{5^\circ}$ was common to all regression models, and was accompanied by independent variables describing catchment slope and extent of organic soil. In common with the development of the colour model it is possible to identify those catchments (observations) which cause inefficiency in the model. These can be excluded from the model. In no case was more than five observations forced out. Three excluded catchments were common to all models and these must form a basis for further investigation. Only six catchments from forty-eight were excluded in all four model structures. This suggests that burning and ditching practices are also significant in terms of Iron, Aluminium and Manganese in runoff.

Table III shows that highly significant relationships ($P<0.001$, $N=658$) exist between pH and all five metal ions determined. These correlations are positive between pH and Calcium and Magnesium, and negative between pH and Aluminium, Iron and Manganese. Water pH and conductivity were positively correlated ($P<0.01$, $N=658$). It is known that Colour is flushed from soils during periods of high rainfall. Therefore these results suggest that during periods of high flow the relatively hard Calcium and Magnesium rich baseflow is diluted by soft throughflow and overland flow of low pH. These waters are acidic due to a high load of dissolved organic matter, such as Humic and Fulvic acids, which discolour water and readily bring Aluminium, Manganese and Iron into solution.

These observations strongly suggests that the release of Manganese and particularly Iron and Aluminium into water arises from the same or similar process that result in discoloured runoff. Therefore any remedial action suitable for reducing discolouration, such as a turn-out strategy, is likely to have the added advantage of systematically excluding high levels of Aluminium, Iron and Manganese.

CONCLUSION

The seasonal pattern of Colour in the Upper Burn valley is typical of upland catchments. Peak Colour responds to periods of high rainfall, and relatively dry antecedent conditions, suggesting that a Colour flushing mechanism is operating in this catchwater. Significantly, there are differences in the spatial distribution of Colour, with some catchments consistently contributing high Colour levels to the reservoirs. This supports the conclusions drawn from the upper Nidd study, and justifies a wider geographical application of Colour reducing water resource strategies.

High colours were found to originate from the Winter Hill soil association, deep peat, which represents the greatest volume of organic matter in the catchwater. Some of the organic matter decomposition products are soluble in water, causing discoloration. In plateau areas ($\leq 5°$) hydraulic conductivities are generally low due to minimum gravity drainage, allowing maximum solute pick-up. When such areas have an intense drainage network the zone of aerobic decomposition is greater, producing a larger store of water colouring decomposition products. During periods of rainfall the intense drainage network allows a rapid movement of water, faster export of organic solutes and a more intense Colour flush.

Particularly high Colour was found to originate from areas of moorland burning and artificial ditching. This is consistent with observations on water Colour in the Upper Nidd where it is suggested that both these practices increase the zone of aerobic decomposition, producing a larger Colour store. South facing slopes, associated with discoloration in the Upper Nidd were not found to be important in the Upper Burn. This is probably due to the largely North to North-Easterly aspect of the peat catchments.

A regression model accounts for 81.6 per cent of the spatial variance in Colour. Further regression models are able to account for 67.6, 76.0 and 54.8 per cent of the spatial variance in Aluminium, Iron and Manganese concentrations. All regression models used variables that describe the extent of peat in the catchment, its gradient and the degree to which plateau areas are dissected. Aluminium and Iron were highly correlated with Colour. These observations suggest that high concentrations of Aluminium, Iron and Manganese in runoff arise from processes the same as, or similar to those that produce high Colour. Therefore the operation of a strategy to systematically exclude highly coloured water while minimising loss of yield is likely to have the additional benefit of excluding high levels of Iron, Aluminium and Manganese.

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Table I. Deviation in chemical concentrations of sub-catchment one during sampling period.

	Difference Mean	Difference Std.Devn	t	2 tailed prob	Maximum difference	Max. diff occurred
Colour	0.298	0.2154	1.22	0.256	0.585	29 Oct
pH	0.167	0.3624	0.77	0.463	1.130	15 Oct
Conductivity	8.800	15.2707	0.08	0.937	49.000	4 Feb
Aluminium	0.025	0.0288	-1.57	0.156	0.090	29 Oct
Manganese	0.014	0.0181	-1.39	0.203	0.047	29 Oct
Iron	0.039	0.0420	-2.28	0.052	0.138	29 Oct
Calcium	0.650	0.6970	1.78	0.113	1.960	15 Oct
Magnesium	0.234	0.1965	1.25	0.246	0.600	29 Oct
T.Hardness	2.214	2.4900	2.44	0.041	6.701	15 Oct

(Units: Al, Mn, Fe, Ca, Mg (mg/l), Colour (au/m) at 400 nm^{-1}. Total Hardness (mg/l $CaC0^{3}$) equivalent,

* Sig level <0.05, but Total hardness determined by calculation.

Table II. Description of Morphometric variables.

Area	Basin area (Km^2).
Per	Basin perimeter (Km).
$Elev_{max}$	Highest point on the basin (m).
$Elev_{min}$	Lowest point on the basin (m).
$A_{5°}$	Area (Km^2) with a slope of ≤5 degrees.
$\%A_{5°}$	($A_{5°}$/area) x 100.
$A_{3°}$	Area (Km^2) with a slope of ≤3 degrees.
$\%A_{3°}$	($A_{3°}$/area) x 100.
BR	Basin relief. ($Elev_{max}-Elev_{min}$) (m).
BL	Basin length. Distance of line from basin mouth to point on perimeter equidistant from basin mouth in either direction (m).
MSS	Main stream slope[15]. Slope between 10 & 85 percentiles of main stream length.
Elgn	Elongation[16]. (2x $Area^{0.5}$)/(BL x *1*).
Cren	Crenulation[17]. Relative perimeter crenulation. (per^2/Area)/(4*1*).
RR	Relief ratio[16]. BR/BL.
RRf	Relative relief[18]. Area/Per.
DD	Drainage density[19]. TCL/area.
GeoN	Geometry number[20]. Area/DD.
TCL	Total channel length on OS 1:25 000 map (km).
MCL	Main channel length. Length of the highest order stream in basin (Km).
NO1st	The number of first order streams[21]
NO2nd	The number of second order streams.
NO3rd	The number of 3rd order streams.
Rugg	Ruggedness[20]. Area/DD
SF	Stream frequency[19]. (2xNO1st-1)/Area
DI	Drainage intensity[22]. SF/DD
BRt	Bifurcation ratio[19] NO1st/NO2nd
Asp	Aspect. Degrees deviation from North.
Spr	Number of springs depicted on OS 1:25 000 map.
$CLA_{5°}$	Channel length in area of slope ≤5°.
$\%TCLA_{5°}$	Percent of TCL in ≤5°.
$CLA_{3°}$	Channel length in area slope ≤3.
$\%TCLA_{3°}$	Percent of TCL in ≤3°.

Table III. Water quality variables correlation matrix.

	Colour	pH	Cond.	Al	Fe	Mn
pH	**-0.5130**					
Conductivity	0.1346	0.3763				
Aluminium	**0.6132**	**-0.7507**	0.1301			
Iron	**0.8146**	**-0.5925**	-0.0391	**0.5660**		
Manganese	0.1234	**-0.6157**	-0.2459	**0.4908**	0.3263	
Calcium	-0.2203	**0.6836**	**0.8240**	-0.2204	-0.2878	-0.3399
Magnesium	-0.2502	**0.6781**	**0.7985**	-0.2911	-0.2902	-0.3826
T.Hardness	-0.1869	**0.6498**	**0.8479**	-0.1803	-0.2448	-0.3331

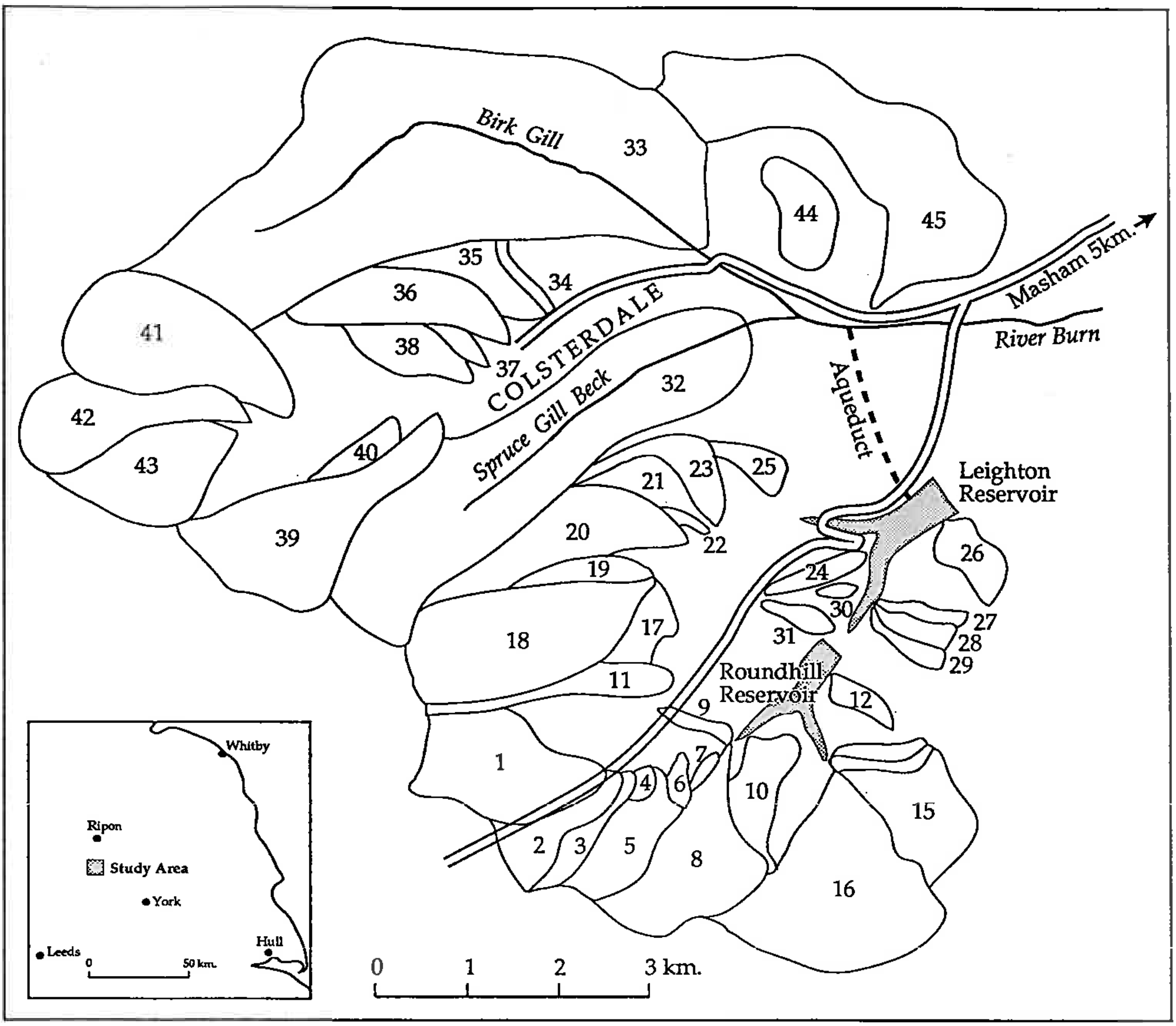
N=658 sig at 0.01 **sig at 0.001**

Figure 1. The study area including Colsterdale and Roundhill and Leighton reservoirs. Numbers denote sub-catchment labels.

Figure 2. Seasonal variation in mean catchwater group colour.

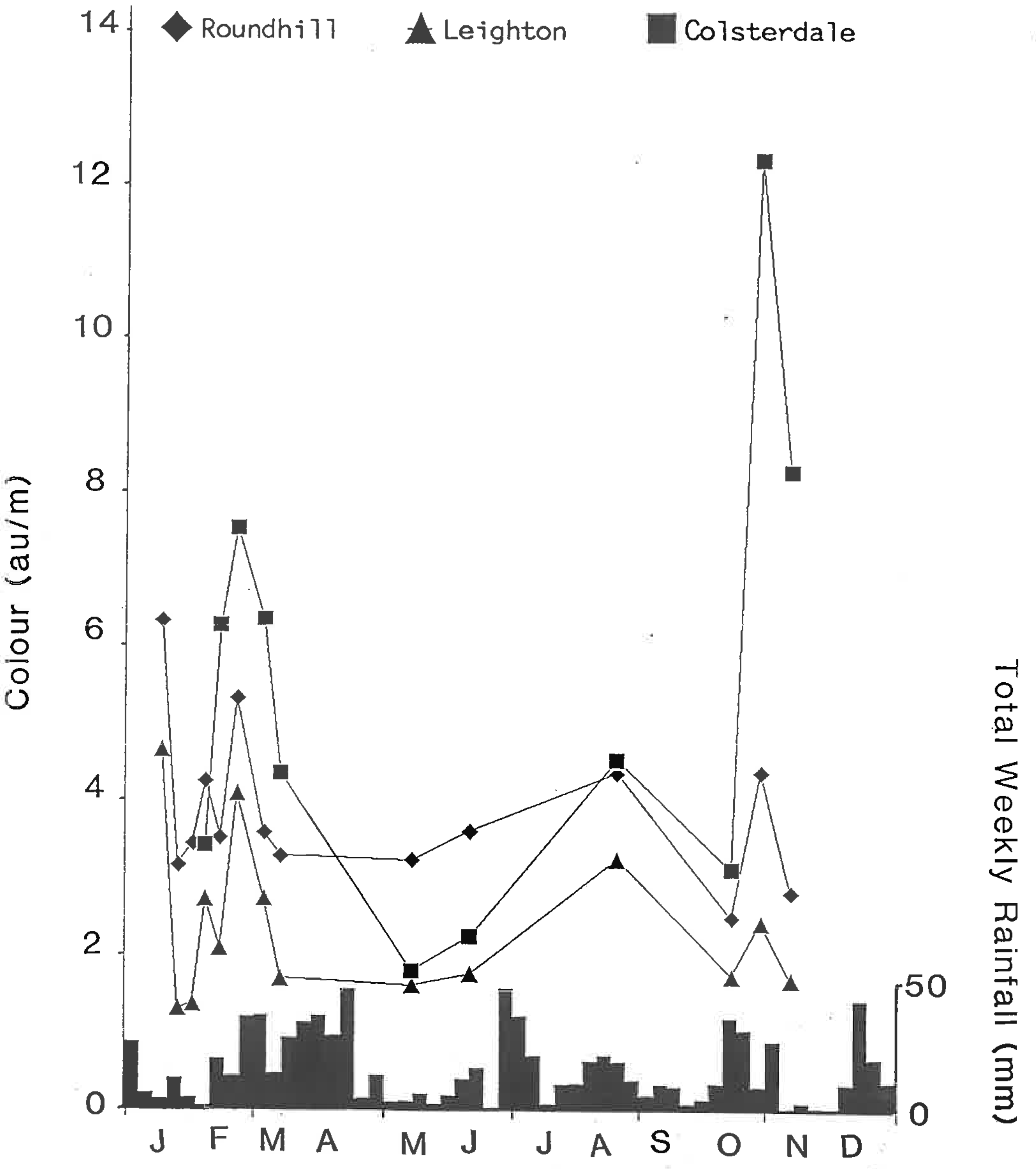
Figure 3. Spatial variation in annual mean sub-catchment colour.

FIG 1



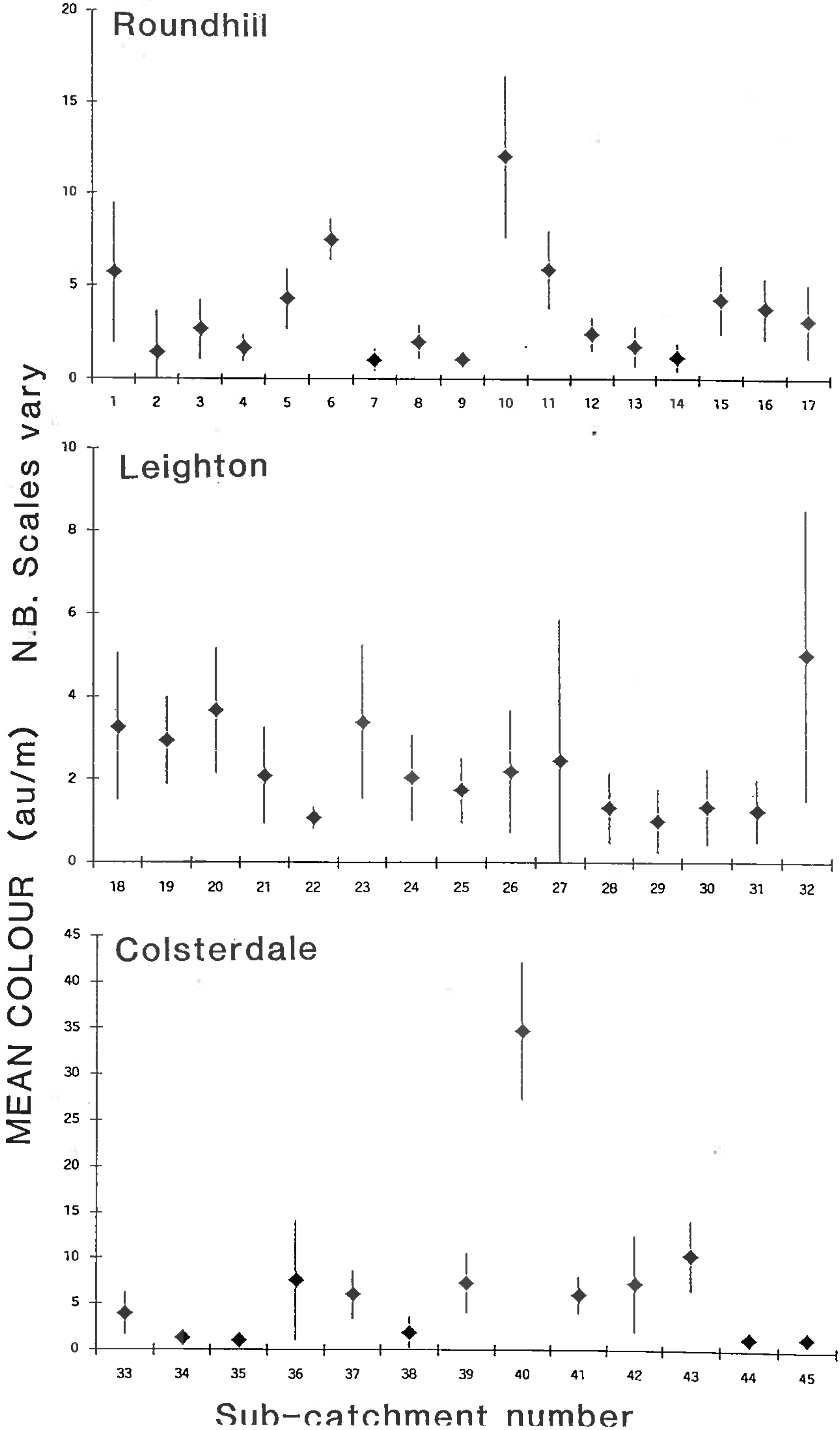
Birk Gill
33
44
45
Masham 5km.
35
34
36
COLSTERDALE
River Burn
41
38
37
Spruce Gill Beck
32
Aqueduct
42
43
40
25
23
21
Leighton
Reservoir
39
20
22
26
19
24
30
27
28
29
18
17
31
11
Roundhill
Reservoir
12
9
1
7
4
6
10
15
2
3
5
8
16
Whitby
Ripon
Study Area
York
Leeds
Hull
0
50 km.
0
1
2
3 km.

Fig 2.



Roundhill
Leighton
Colsterdale
14
12
10
8
6
4
2
0
Colour (au/m)
50
0
Total Weekly Rainfall (mm)
J F M A M J J A S O N D

Figure 3.


Roundhill
Leighton
Colsterdale
MEAN COLOUR (au/m) N.B. Scales vary
Sub-catchment number
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
10
8
6
4
2
0
18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
45
40
35
30
25
20
15
10
5
0
33 34 35 36 37 38 39 40 41 42 43 44 45