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SOIL EROSION ON LAND CULTIVATED AND DRAINED FOR AFFORESTATION

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Abstract

Soil erosion from forest furrows on certain susceptible soils may represent a loss of a valuable resource and, at the same time, soil entering streams may result in environmental problems. Erosion can be controlled by careful site preparation including a consideration of the effective spacing of cross-drains which prevent furrow run-off building up to excessive levels. This report considers the erosion process and the question of identifying preferred cross-drain spacings on a rigorous scientific basis.

Soil erosion in plough furrows has been monitored at three different locations in Scotland for some 18 months. The degree of erosion at given intervals down furrows has been considered as a function of the distance from the furrow head (a surrogate for water discharge) and the local gradient of the slope. Critical thresholds for erosion also have been examined in a laboratory flume.

The various data have been analysed using (a) multiple regression techniques, and (b) through the application of the streampower concept. Formulae are presented which can be used to estimate the critical spacing for cross-drains which would preclude significant erosion on a variety of slopes. However further data are needed to refine these relationships to provide robust estimation procedures. To this end, further fundamental field and laboratory work is identified.

Introduction

The aim of the research reported here is to establish a basis from which quantitative guidelines can be developed which determine the prefered spacing of cross-drains on newly ploughed forestry land. The spacing should be such as to minimize potential erosion within the furrows commensurate with practical limitations and due economy.

The approach has been to establish relationships between the quantity of erosion (measured as an increase in cross-sectional area of the eroded furrow) and furrow length and gradient. The basic tenet being that erosion will increase down slope as run-off is concentrated in the furrow. If the relationship for a particular soil type in a furrow of constant gradient is, say, of the form

$$E = k(X-X_c)^m$$

where X_c is the critical length of furrow above which the degree of erosion (E) is acceptable, and k is a constant which depends on furrow gradient and soil type under a specified rainfall history, then total erosion could be minimized by placing cross-drains at a spacing of X_c. This of course is a gross simplification but it serves to demonstrate the fundamental principle.

In order to address the problem rigorously, erosion has been monitored in furrows of varying length and gradient on three lithologies. In addition, limited laboratory investigations have been conducted to ascertain values of discharge and slope that in combination would preclude serious erosion on each soil type.

Collection and Initial Data Reduction

A large number of potential research sites were visited in 1988. None of these sites could be described as ideal, in that of preference, the research furrows should be on a range of uniform slopes. No site visited (where the ploughing time-table fitted into the time-framework of the project) exhibited a range of long uniform slopes. Eventually three sites, which were close to requirements, were selected for detailed monitoring. These are at Carron in Kintyre (NR. 936997), Lambdoughty in Galloway (NX. 488970) and at Scotston (NN. 917437) near Aberfeldy in Perthshire.

A summary description of the soils, vegetation and geology can be found in Appendix 1. Briefly, the soils at Carron and Scotston are surface or peaty gleys (sometimes associated with an iron pan) developed on Dalradian rocks whilst at Lambdoughty surface water gleys predominate on Ordovician greywacke and granite.

Within two weeks of the initial ploughing of each slope, the sites were visited and monumented stations established down a number of furrows. Station spacings reflected the length of furrows at each site. At Lambdoughty, furrows were very short, so that two furrows were monitored with three stations 10m apart in each furrow. Each station consisted of three replicate cross-sections spaced 0.5m apart. At Scotston and Carron the situation was much better. Long plough runs on fairly uniform slopes up to 250m allowed the establishment of 4 to 5 stations every 30 or 50m apart on up to three furrows at each site representing a range of slopes (Table 1). Once again each station consisted of three replicates.

The cross-sectional profile at each cross-section was recorded using a profile frame, consisting of 50 steel rods 2cm apart inserted into a horizontal reference bar. The latter was positioned on reference pegs driven into the ground on either side of the furrow to provide arbitrary datum points. Rods were allowed to drop onto the bed and then locked into position to record the variation in the bed level across the furrow. The length of each rod was recorded in the field and these data transferred to a computer data-base which eventually consisted of over 35000 data points. To accommodate local spatial variability, data for each set of replicates were averaged to yield a cross-sectional area representative of individual stations at a given time. By repeating the surveys every three months, deposition or erosion along the length of the furrows was recorded as a loss or gain in the total cross-sectional area at each station (Table 1,Figs. 2-8). Finally, data were summarized to indicate the degree of erosion (+ values) or deposition (- values) which had occurred at each station at the end of the twenty-month period (Table 2). The nature of the data collected can conveniently be shown as a block diagram (Fig. 1). The data shown in Fig. 1 are an example of a furrow at Carron.

The long profile of each furrow was surveyed to obtain the over-all gradient (Figs. 9-15). These slope values were used to identify each furrow (as in Tables 1 & 2) and, in addition, detailed surveys immediately up-slope and through each station provided information on the local slope. These data are listed in Table 2, whilst a comparison of the two sets of slope data are given in Table 3.

Undisturbed soil samples were obtained from furrows at each location using a box-corer and these were retained for laboratory studies of erosion under a water current. These data were required to rank each soil in terms of its erodibility. Each box-corer consisted of a steel channel (100mm deep, 300mm long by 150mm wide) open at the top and at the ends. When inverted this could be readily hammered into the surface of the sediment, carefully dug out and trimmed. By machining the sections to fit the width of an hydraulic test flume, the samples could be placed end to end on the bed of the flume without disturbing the sediment.

Soil erosion can be locally severe following catastrophic rainfall, but within the constraints of present technology the worst effects can be mitigated using appropriate conservation techniques. Above all, it is important that erosion is prevented as far as possible under the more usual annual rainfall regime. Thompson (1979) , considering the design of forestry cross-drains, selected a design rainfall intensity of 25mm h^{-1} as critical. He argued that under this regime, 75mm h^{-1} would commonly occur for ten minute periods, and that properly designed drains should not erode given these conditions. With this in mind an autographic rain gauge was installed at Scotston so that a record of the prevailing rainfall regime might be obtained at this site.

General Observations On Field Data

A number of general observations can be made from an initial inspection of the field data. A range of slopes are represented by the data, ranging from 4° to 16°. Despite the angle of the slope over-all, local variation in slope is very important in influencing erosion or deposition. For example, at Lambdoughty there was very little erosion and considerable deposition, whilst at Scotston, deposition and erosion alternated through time (Figs. 6-8) and also down slope so that local slope had more influence on the erosion process than the distance down the furrow. In addition, periods of erosion could be followed by periods of infilling. In most cases it appeared that a condition of stability was approached towards the end of the study period, when it was noted that vegetation had begun to establish itself in the furrow. From the above observations it would be untrue therefore to argue that furrows universally erode. Instead they can act as local stores for sediment moving down the furrow; thereby reducing the quantity of sediment delivered to the downslope end of the furrow and spreading this delivery over a considerable time period. At Scotston, the deepening of the furrows is most evident where the local slope exceeds 11°.

At Carron, slopes are uniform and all sections eroded. A downstream increase in erosion was evident in the steepest furrow (Fig. 3) and deepening of the furrows occurred throughout the period represented in Figs. 2 & 3. The process rate however declines with time, becoming negligible after about a year. In the absence of renewed incision, the decline in the erosion rate may follow an exponential function, even being followed by a period of deposition as the furrow stabilizes. For example, this is well demonstrated at the 60m station in the low gradient furrow (local gradient =0.2495). The data (Fig. 2 & Table 1)) fit the function

$$E_t = (C-B)e^{zT} + B$$

where E_t is the cross-sectional area of the furrow at time T, the cumulative number of days since the furrows were cut. Setting the initial cross-sectional area (3404.1 cm^2; Table 1) equal to unity then E_t and C can be expressed as fractions relative to B. For example, C is the asymptopic value of E_t when erosion ceases (C/B= 1.1443). Using the least squares procedure, regression analysis gives $\lambda = 0.0125$ when (C-B) = 0.1443 with a coefficiant of determination of 0.61.

Despite the erosion, it should be noted that only c. 0.03 m^3 of soil was removed from each 1m run length of furrow on this susceptible soil. However, over the length of a typical 200m furrow this represents a loss of some 6 m^3 of material equivalent to c 12 tonnes of soil in each furrow. At Carron this material does not seem to have reached streams owing to effective conservation techniques, ie. carefully aligned cross-drains and the provision of grassy buffer strips adjacent to water-courses. Nevertheless when multiplied by the number of furrows in any given area, a considerable soil loss is indicated.

A final observation may be made. It was apparent that erosion was nearly always initiated in the tine slot (some 10cm wide). This is because run-off is concentrated in this location. Water depths and hence shear stresses over the bed are maximized as the flow cannot spread out over a bed width greater than 10cm. Erosion progressed not only downwards but also laterally, eating into the steep side-walls of the slot. Side walls were under-cut, over-steepened and consequently, erosion of the furrow bed either side of the slot accelerated.

Background to Mathematical Analysis

An understanding of the processes of shallow rill flow and sediment entrainment is central to the development of models of furrow erosion and practical soil-loss control. Approaches can range from the purely empirical to physically based deterministic approaches. The latter require extensive parameter evaluation and currently are not suitable for practical application. A model for applied use should be simple, yet versatile and therefore of preference it needs be based on fundamental principles, from which more refined solutions can be developed as data and requirements permit. A deterministic model might include such factors as infiltration losses down the furrows, progressive armouring and the effects of progressive vegetation establishment. However, here it is assumed that the catchment is wet, infiltration losses are negligible and the furrows do not intercept any water courses. Run-off is generated by rainfall falling on a linear catchment strip the boundaries of which lie equidistant between furrows.

A simple model can be expressed in the general form:

$$E = k_1 X^m S^n \qquad (1a)$$

where E is the eroded cross-sectional area at a given section down slope, X is the distance down the furrow and S is the tangent of the angle of the local slope. In this formulation X acts as a surrogate for discharge (Q) as discharge per unit width is proportional to the area drained per unit width (effectively, X) with an exponent of 0.6 to 1.0 (Kirkby, 1971). Thompson (1979) argued that in forestry furrows subject to a rainfall intensity of 25mm h^{-1}, Q increases downslope approximately as

$$Q = \alpha X^{1.0} \qquad (2)$$

where α is a constant equal to $2.5 \cdot 10^{-5}$. For example, equation (2) yields 0.005 $m^3\ s^{-1}$ (0.5 litre s^{-1}) when X is 200m.

If Q is substituted into equation 1a in place of X using eq. 2, and the erosion considered as a loss of sediment mass (Q_s) rather than area, 1a becomes,

$$Q_s = k_2 Q^m S^n \qquad (1b)$$

which may be derived from a number of physically-based bedload transport equations. The above formulation is useful for applied work, being simple and a reasonable description of the sediment erosion process down slope (Kirkby, 1971). At the same time its validity can be determined by comparison to related physically-based relationships.

For highly erodible soils on convex slopes, the constants m and n commonly have the values 2 and 1.66 respectively (Thornes, 1988). Values of 1.3-1.7 and 1.0 respectively appear typical of less erodible slopes subject to rain splash and soil wash (Kirkby, 1971) although $n < 1$ can pertain on concave slopes developed on resistant materials (Band, 1985).

Considering the erosion data (E), in the first instance as a function of X, no clear relationship could be shown between the length of furrow and erosion for the sites at Scotston. This was not the case for the data representing Carron and Lambdoughty (Fig. 16). Deposition clearly characterizes the short furrows at Lambdoughty whilst erosion occurs further down furrows at Carron. Using a least squares regression technique,

$$E = 0.49\,X^{1.39} \qquad r^2 = 0.67 \qquad (3)$$

where E is expressed in cm^2 (to avoid the presentation of small fractions of m^2) and X is expressed in meters. This equation is plotted in Fig. 16. It should be noted that such a power function gives $E = 0$ when $X = 0$, when more realistically, a minimal distance down the drain is required to concentrate flow to cause erosion.

Local slope is the other variable in equation 1a. A relationship between E and S although scattered could be shown for all sites except the steep furrow at Scotston. These data are shown in Fig. 17. We can estimate the slope below which erosion is negligible and deposition predominates using the function

$$E' = aS^{b} - z$$

where a and b are constants and z is a constant (= 300) that converts the values of deposition from negative values to positive values. Empirically,

$$E' = 1424.79S^{0.74} - 300 \qquad r^2 = 0.31 \qquad (4)$$

When $E' = 300$ (ie. erosion = 0) then $S = 0.12$ (c. 7°). An expression for values of erosion alone, appropriate to equation 1a is,

$$E = 847.23\ S^{1.04} \qquad r^2 = 0.24 \qquad (5)$$

An exponent close to unity implies that erosion rates do not increase more rapidly on steeper slopes. The values of the exponents in equations 3 and 5 are typical of soil wash on bare hill-slopes (Kirkby, 1971). Consequently, despite the data scatter, the results indicate that a formulation in terms of equation 1a might be appropriate. Equation 1a may be expressed as

$$\log E = \log k_1 + m \log X + n \log S \qquad (6)$$

Because of the lack of dependence of the Scotston erosion data to the distance down slope, equation 6 was fitted to the Carron and Lambdoughty data by least squares yielding $k_1 = 4.99$, $m = 1.095$, $n = 0.721$ with $r^2 = 0.71$. The values of the exponents are somewhat different to those obtained in equations 3 and 5 owing to the mutual adjustment of exponents in a multiple regression analysis. The small values of the exponents would indicate that the soils are not unduly sensitive to slope variations. However, a n-value less than 1 might imply that the erosion process is size selective, preferentially removing the finer fractions and leaving the coarser materials concentrated on the surface of steeper slopes as an armour layer. Although this aspect was not addressed directly a coarsening of the bed-material on steeper slopes was noted whilst only finer materials collected at the base of the slope. The progressive effects of armouring (or an increase in vegetation cover) could account for the decline in the erosion rate noted at Carron.

Although not attempted here, this could easily be modelled as a function of the surface protection provided by increasing concentration of coarse particles with time, ie.

$$E_1 = (1- \exp(-k_aC) \qquad (7)$$

where E_1 is the fraction of the bare soil erosion rate removed under differing conditions of armour development, k_a is a constant of armouring and C is a particle concentration factor.

The data expressed in terms of equation 1a are shown in Fig.18. It is clear that because emphasis in the data collection was placed on steep slopes and long furrow runs there is a deficiency in data for values of $X^{1.1}$ $S^{0.72}$ less than 10, whilst a number of points represent erosion greater than 200cm^2. For illustrative purposes, this latter value can be selected as a threshold, above which values of erosion would be unacceptable and below which other conservation techniques would adequately control soil loss from the site. It is a simple procedure then to specify the erosion threshold (200cm^2) and a range of slopes to calculate (using equation 6) the acceptable run-length of furrow (X_c) before a cross-drain needs be installed. Some examples are tabulated below,

$E = 200cm^2$	tan S	X_c (m)
	0.0875	145
	0.1763	91
	0.2679	69
	0.3640	57
	0.4663	48
	0.5774	42

It should be borne in mind that this simple model implicitly incorporates progressive stabilization of the slope by such factors as the concentration of coarser particles on the surface as fines are winnowed from the bed, compaction, and by the growth of vegetation in the furrow. Such processes will reduce the erosion risk with time but are not of significance when cross-drains are usually cut; immediately after ploughing. The model is consequently conservative, as the degree of protection afforded by selecting the above spacings would increase with time. It is interesting to compare the above data with the current recommendations for steep slopes (Pyatt & Low ,1986) ; cross-drains being usually spaced at 40m intervals. However, more data are required for gentle slopes (c 0.0875 - 0.2679) to confirm the above results.

An alternative approach, other than multiple regression, is to consider the erodibility of the soil in terms of the power (ω) exerted by the flow per unit bed-length down the furrow. This approach, as well as being theoretically sound, is advantageous in that total streampower (J m^{-1}) effectively is defined as the product of slope and discharge; the latter a function of the furrow length;

$$\omega = \rho g S Q = \rho g S \alpha X \qquad (8)$$

where ρ the density of water = 1000 kg m^{-3} and g is the acceleration due to gravity, 9.81 m s^{-2}.

The increase in the cross-sectional area per unit length of furrow owing to erosion can readily be converted to a mass by considering the mass density of the soil at field moisture capacity(2076g m^{-3}). These data are shown in Fig. 19 and can be represented by the function,

$$I_b = 29.7043 \, (\omega - \omega_o)^{0.43} \qquad r^2 = 0.92 \qquad (9)$$

where ω_o = 0.2121 J m^{-1} is the critical power exerted on the bed to promote minimal erosion of the finest sediments. This value was estimated by identifying the zero erosion intercept of a log-linear regression line on the abscissa in Fig. 19. It may be seen that it is equivalent to the lowest power value recorded in the field (Table 4). When equations of the form of equation

9 are applied to data from loose uncompacted river-bed materials the exponent is commonly 1.5. The small value for the exponent recorded for the present data refects the fact that the soils are not highly erodible. The identification of a zero erosion threshold indicates that a certain run-length of furrow must be exceeded before entrainment can occur. This critical length varies with slope, but is equal to

$$X_o = \omega_o / \alpha \rho g S \qquad (10)$$

When the slope equals 0.0875, $X_o \simeq 10$m and when the slope equals 0.2679, then $X_o \simeq 3$m. These are clearly unrealistic distances at which to space cross-drains so some limited sediment entrainment will inevitably occur between cross-drains. In order to isolate thresholds for significant erosion, recourse is made conveniently to laboratory data.

Laboratory Tests of Soil Erodibility

Undisturbed soil samples (150mm wide by 300mm long) were placed end to end along the bed of the test flume. The slight gaps between samples were carefully filled with sediment so that a uniform surface, representative of a newly cut tine-slot in a furrow, was achieved. The sediment was wetted and a low discharge passed down the flume to remove any loose sediment disturbed during preparations.

Unlike investigations of uniform loose sands, it is not possible to define an absolute threshold of erosion for heterogeneous consolidated sediments. Such a threshold must be represented by the initial motion of the finest grain within the test section, which not only is difficult to observe but is also of limited practical utility. Instead, the following procedure was adopted.

The flume was set to a zero slope and the discharge increased until fine sand was observed in transport and was caught in a sediment trap at the downstream end of the flume. The discharge was then reduced until no motion was observed. (The water-surface slope associated with this no motion condition equalled 0.003). This procedure was repeated across a range of bed-slopes. A similar procedure was then adopted examining the initial transport conditions of coarse sand, granules, and pebbles. Under the latter conditions peds of soil were ripped from the bed and erosion could be regarded as 'irreversible' whilst for finer grain-sizes, the bed tended to stabilize with time as a degree of armouring occurred. Although the threshold of motion of each size fraction was only approximately defined, sufficient data were collected to demonstrate that the threshold discharge for each size-fraction decreased as the bed-slope increased (Fig. 20).

Two discriminant curves are represented in Fig. 20. The upper curve represents a condition of constant threshold stream power ($\omega_o = \rho gQS$) equal to 1.18 J m^{-1} and discriminates between serious erosion (pebbles and soil peds) and the flushing of finer sediments, whilst the lower curve represents the threshold of minimal erosion of finer sediment as defined from the field data, ie; $\omega = 0.21$ J m^{-1}. There is good agreement between the field data and the laboratory results in that the lower curve well represents the threshold of movement of fine sand across a range of steep slopes. The curve deviates however from the laboratory data at low slopes and careful inspection shows that for low slopes, data fall below the curve whilst for high slopes data fall above. This is most noticeable for the upper curve. The trend of the data would suggest that the test sediments were more erosion resistant at high slopes. The most obvious explanation is that the most easily eroded peds had been removed during the initial runs at low slopes and low discharges. For logistic reasons it had proved impossible to replace all the sediment sections after every test run representing a single slope/discharge combination. In subsequent tests on the other two soils this problem was minimized, (but not eliminated) by testing a series of slopes at random, rather than sequentially raising the bed-slope, and by changing the sediment as often as practical.

The laboratory data and the constant streampower curves, representing thresholds for serious erosion, are show in Fig. 21. The Scotston soils are the most susceptible to erosion, as $\omega_o = 0.8407$ J m^{-1}, whilst the Lambdoughty soils are the least erodible, $\omega_o = 3.9181$ J m^{-1}. This latter observation concurs with the field data, in that the Lambdoughty sections tended to show only slight erosion (Table 2) and incidently rapidly revegetated.

In practice in the field it was not possible to absolutely differentiate the relative degree of erosion on the three soil types other than to note the relative resistance of the Lambdoughty soil. It is possible to use the laboratory data in a more precise fashion and to estimate cross-drain spacings for each soil type. This can be done with reference to equation 10 (derived from eq. 8)

$$X_o = \omega_o / \alpha \rho g S \qquad (10)$$

and examples are tabulated below for slopes of 0.0875 and 0.2679.

Calculated Cross-Drain Spacings

	ω_o	S	X_o
	($J\ m^{-1}$)	(-)	(m)
Scotston	0.8407	0.0875	39
"	"	0.2679	13
Lambdoughty	3.9181	0.0875	183
"	"	0.2679	60

The Lambdoughty results obtained using this physically-based approach compare well with the results obtained using the multiple regression model and an arbitrary threshold of acceptable erosion (ie. X_o = 145m and 69m respectively) for 0.0875 and 0.2679 slopes.

Concluding Discussion

The variability of the field data was more pronounced than expected. However, such data will always be required to scale and assess any predictive model based solely on laboratory data. It is clear that the approach is valid in that simple predictive relationships can be developed which relate basic factors of slope and furrow length to the degree of erosion.

Using the data from the field it was not possible to detect clearly a difference in the degree of erosion on each soil type. Nevertheless the soils are not equally susceptible to erosion. This fact was demonstrated using the simple hydraulic laboratory tests and the streampower concept. The latter approach potentially is very useful, in that the method can be applied to a number of soil types. These soils might then be ranked in terms of susceptibility to hydraulic erosion. Simple field tests could then be devised so that soils 'at risk' could be identified readily in the field.

The streampower analysis showed that some slight sediment entrainment will occur close to the top of furrows and this cannot be prevented using cross-drains. A small degree of erosion is inevitable and must be accepted. However, the approach adopted here is valuable in that a degree of flexibility can be incorporated in any guidelines. The degree of 'acceptable erosion' can be specified before an estimate of preferred cross-drain spacings is made. Clearly in environmentally sensitive areas, the specification can be strict, but the forester retains the option of employing a degree of judgement; balancing environmental considerations against cost constraints, for example, or other limiting factors. The latter will include the suitability of complimentary soil conservation practices to specific sites.

A major limitation of the current model is the lack of a precise relationship between rainfall intensity and runoff. An investigation is required which considers how runoff builds-up down the furrow length for known rainfall intensities. In the present analysis it is assumed that Thompson's function (equation 2) is universally appropriate, but it is unclear how the function was devised and what confidence can be placed in it's general utilization. Such an investigation is most appropriately conducted on a range of fairly gentle uniform slopes where additional field data concerning erosion on low gradient slopes can be collected. These data can be used to refine the multiple regression or streampower models for general use.

Finally, it was noted that run-off was concentrated in the central tine slot, which resulted in accelerated erosion. Alternative site preparation techniques should be explored, including the use of tine-less plough shares.

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Table 1 . Summary Listing Of Basic Data For Stations At Various Distances Down Slope

DDS = Distance Down Slope (m). Summary values are cross-sectional area of furrow (cm^2) at the time of survey.

Location CARRON

Furrow Gradient: 0.1900

Date	081287	200388	200588	230888	171188	020389	170589
DDS							
30	3552.6	3582.0	3743.1	3731.0	3775.0	3822.7	3808.9
60	3404.1	3684.3	3828.2	3827.0	3895.4	3797.7	3731.7
90	3295.5	3420.1	3535.7	3579.8	3555.7	3639.9	3616.4
120	3037.8	3123.3	3258.4	3213.0	3251.9	3336.5	3288.4
150	3202.7	3393.9	3412.8	3472.0	3456.9	3419.1	3508.2

Location CARRON

Furrow Gradient: 0.2777

DDS							
40	4115.1	4110.3	4173.6	4218.5	4256.3	4261.5	4303.5
80	3244.1	3178.7	3338.2	3327.8	3310.3	3306.4	3343.7
120	2877.2	3070.5	3286.1	3109.9	3190.1	3262.7	3300.7
160	2948.1	3182.3	3133.0	3371.0	3255.1	3281.8	3328.9

Location LAMBDOUGHTY

Furrow Gradient: 0.1035

Date	201187	010388	190588	161188	010389	160589
DDS						
10	3200.4	3203.7	3198.7	3132.9	3232.3	3202.9
20	3627.1	3492.8	3526.5	3563.3	3511.1	3552.4
30	3147.3	3172.3	3239.5	3098.6	3159.6	3199.1

Location LAMBDOUGHTY

Furrow Gradient: 0.1044

DDS						
20	4439.9	3231.6	4264.2	4246.1	4007.1	4260.9
40	3769.0	3470.2	3574.4	3498.2	3572.0	3493.1
60	4148.1	4130.1	4131.5	4122.1	4064.9	4132.5

Table 1 cont. Summary Listing Of Basic Data For Stations At Various Distances Down Slope.

Location SCOTSTON

Furrow Gradient: 0.0750

Date	200488	200788	181088	180189	120489
DDS					
30	4905.9	4791.9	4681.3	4729.5	4749.1
60	3972.8	4014.5	3934.3	3989.5	4100.2
90	4331.4	4368.6	4368.5	4171.4	4379.7
120	3828.3	3946.9	3873.3	3901.9	3928.6
150	4164.6	4165.3	4287.9	4286.1	4339.1

Location SCOTSTON

Furrow Gradient: 0.1250

DDS					
50	3369.1	3474.7	3467.2	3298.7	3416.4
100	3323.9	3719.5	3708.6	3646.9	3686.5
150	3969.8	3770.5	3781.8	3836.1	3885.4
200	2943.9	2927.4	2823.6	2759.9	2747.1
250	4732.1	4789.6	4778.0	4679.0	4751.1

Location SCOTSTON

Furrow Gradient: 0.2933

DDS					
20	4342.8	4234.0	4227.1	4022.7	4090.1
40	4009.4	3961.4	3915.1	4205.3	4400.6
60	4088.8	4142.3	4254.5	4314.9	4382.6
80	4060.9	4088.2	4101.0	3963.8	3896.4

Table 2 . Total Erosion Or Accretion At End Of Project

	DDS (m)	E/A (cm^2)	tan S (-)
CARRON: 0.1900	30	256.3	0.1790
	60	327.6	0.2545
	90	320.9	0.3886
	120	250.6	0.2718
	150	305.5	0.1537
CARRON: 0.2777	40	188.4	0.2707
	80	99.6	0.3815
	120	423.5	0.2811
	160	380.8	0.2690
LAMBDOUGHTY: 0.1035	10	2.9	0.0863
	20	- 74.7	0.1700
	30	51.8	0.0855
LAMBDOUGHTY: 0.1044	20	-179.0	0.1063
	40	-275.9	0.0659
	60	- 15.6	0.1097
SCOTSTON: 0.0750	30	-156.8	0.0990
	60	127.4	0.0479
	90	48.3	0.1214
	120	100.3	0.0544
	150	174.5	0.0922
SCOTSTON: 0.1250	50	47.3	0.1250
	100	362.6	0.2195
	150	- 84.4	0.0829
	200	-196.8	0.0821
	250	19.0	0.1800
SCOTSTON: 0.2933	20	-252.7	0.2640
	40	391.2	0.2813
	60	293.8	0.4889
	80	-164.5	0.2837

NB: DDS= Distance down slope (m). E/A= Erosion or Accretion. Negative values are accretion. Data represent increase/decrease in cross-sectional area (cm^2) at end of survey. tan S= local slope at station.

Table 3 . Summary Of Slope Data.

	Mean Gradient (Based On Long Profile)	Mean Gradient (Based On Av. Of Local Station Gradients)
CARRON	0.1900	0.2495
CARRON	0.2777	0.3006
LAMBDOUGHTY	0.1035	0.1139
LAMBDOUGHTY	0.1044	0.0937
SCOTSTON	0.0750	0.0829
SCOTSTON	0.1250	0.1592
SCOTSTON	0.2933	0.3295

Table 4 . Erosion And Streampower Data

Soil Mass, I_b ($kg\ m^{-1}$)	Total Power, ω ($J\ m^{-1}$)
53.20	1.32
68.00	3.75
66.61	8.58
52.02	8.00
63.41	5.65
39.11	2.66
87.91	8.27
79.04	10.56
0.60	0.21
10.75	0.63
75.27	5.38
26.44	0.71
20.82	1.60
36.22	3.39
81.20	2.76
60.99	7.19

NB: See Figure 19.

Figure Captions

Fig. 1 Block diagram showing change in furrow section between two survey dates.

Fig. 2- 8 Temporal changes in furrow cross-section

Fig. 9-15 Profile of furrow slope.

Fig. 16 Relationship between erosion (+) or deposition (-) and the distance down the furrow. ● Erosion at Carron; ▲ Deposition at Lambdoughty.

Fig. 17 Relationship between erosion (+) or deposition (-) and the local slope of the furrow. ● Erosion at Carron and Scotston; ▲ Deposition at Lambdoughty.

Fig. 18 Plot of data obtained using equation 6.

Fig. 19 Mass erosion as a function of streampower.

Fig. 20 Relationship between critical discharge and slope for soil at Carron. Symbols represent: ● no motion, ○ fine sand, ■ coarse sand, △ granules, ◆ pebbles and soil peds. See text for details.

Fig. 21 Relationship between critical discharge and slope for serious erosion at Carron, Scotston and Lambdoughty. ○ = Scotston; △ = Carron; ▲ limited erosion at Lambdoughty; ● Lambdoughty. See text for details.

Fig. 1

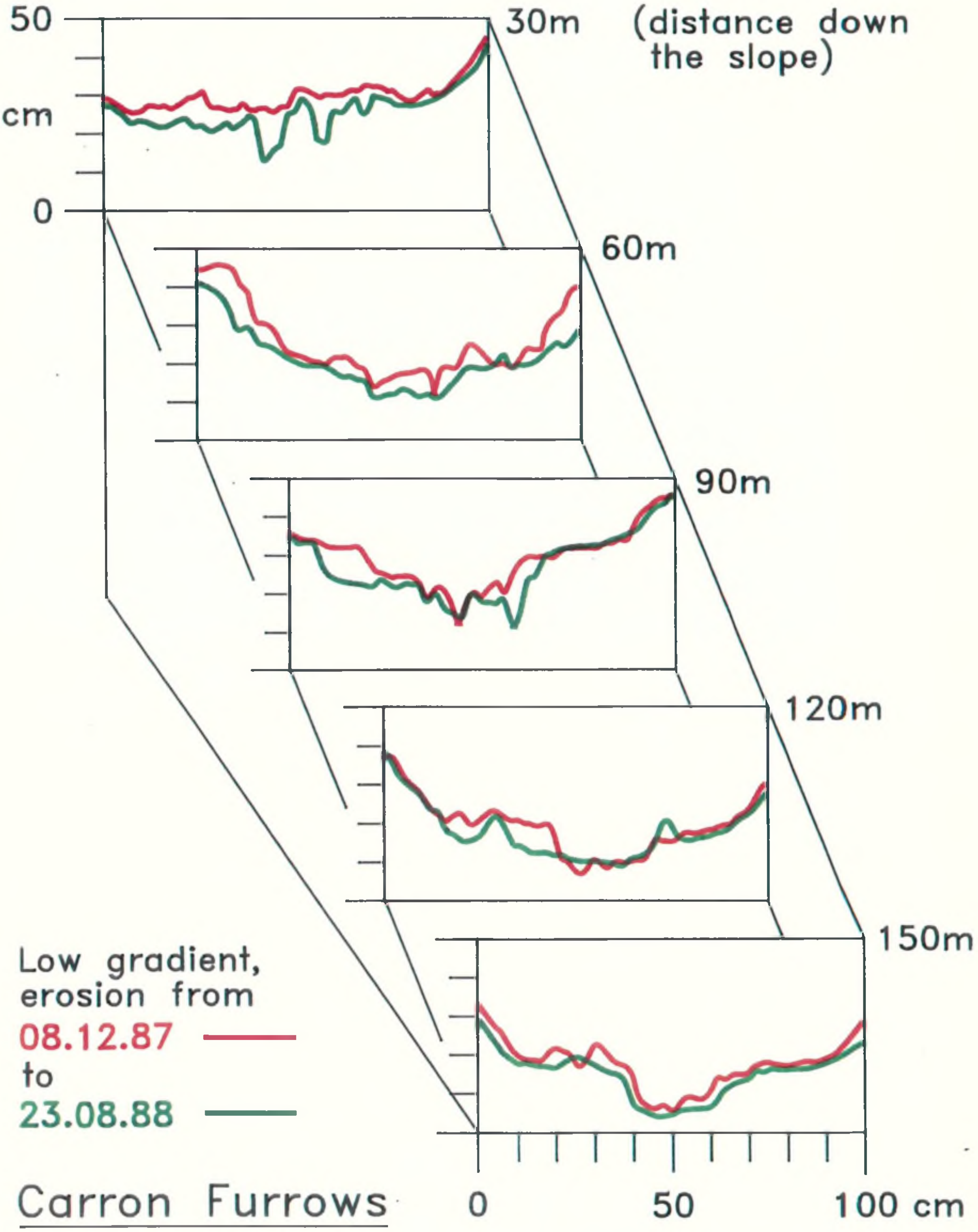

50
cm
0
30m (distance down the slope)
60m
90m
120m
150m
Low gradient, erosion from
08.12.87
to
23.08.88
Carron Furrows
0
50
100 cm

FIG. 2

CARRON. Furrow Gradient: 0.1900

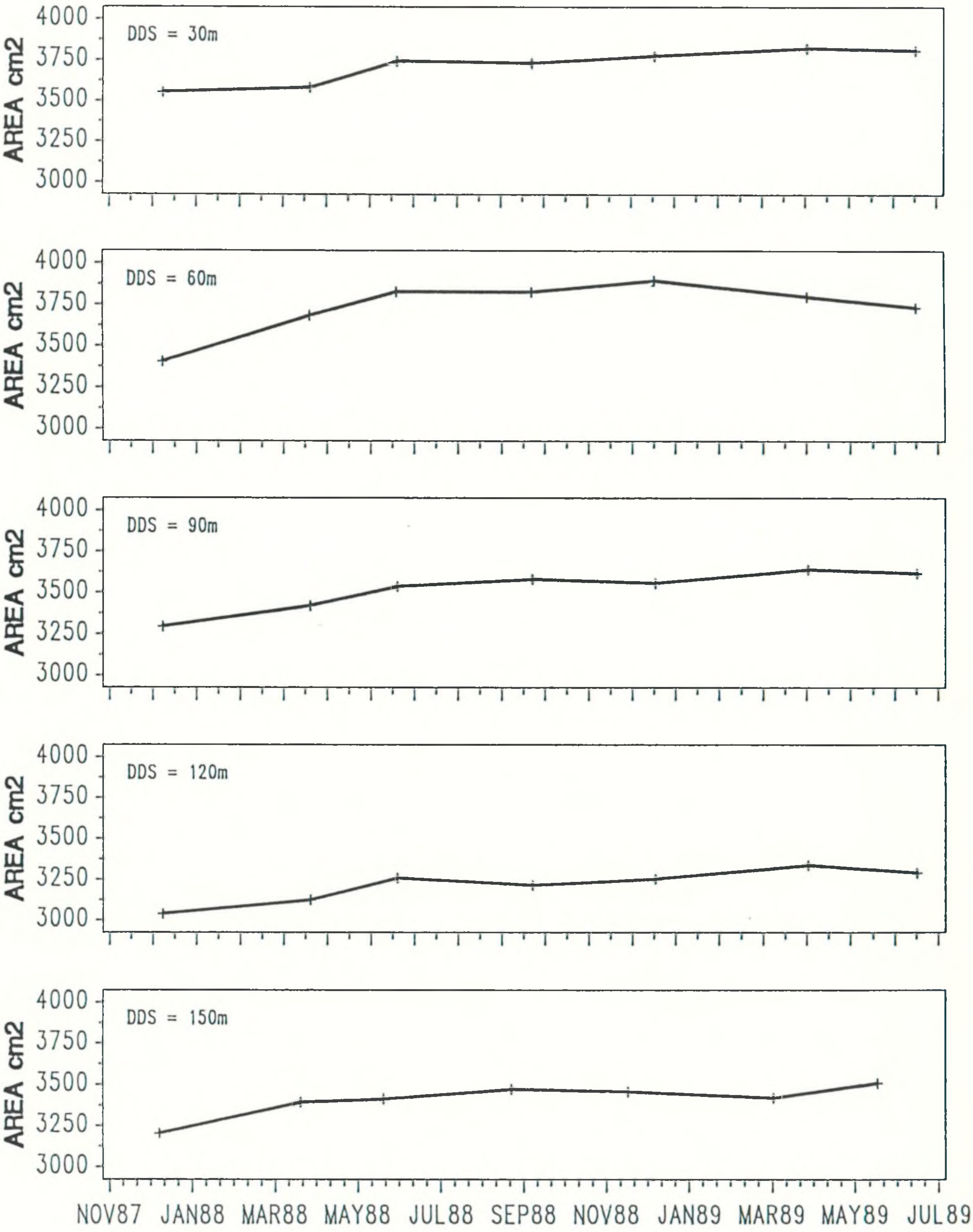


FIG. 3

CARRON. Furrow Gradient: 0.2777

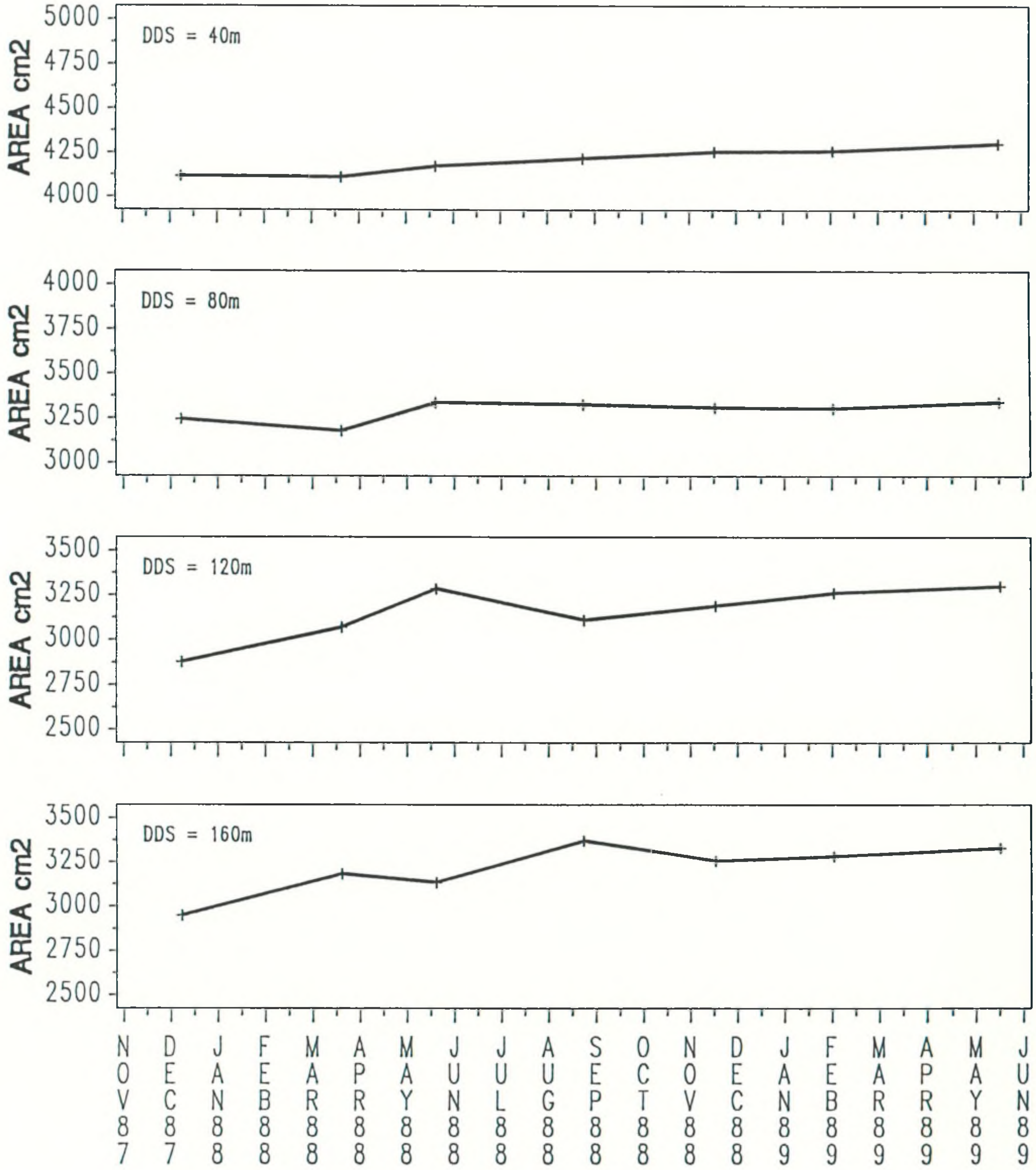


FIG. 4

LAMBDOUGHTY. Furrow Gradient: 0.1035

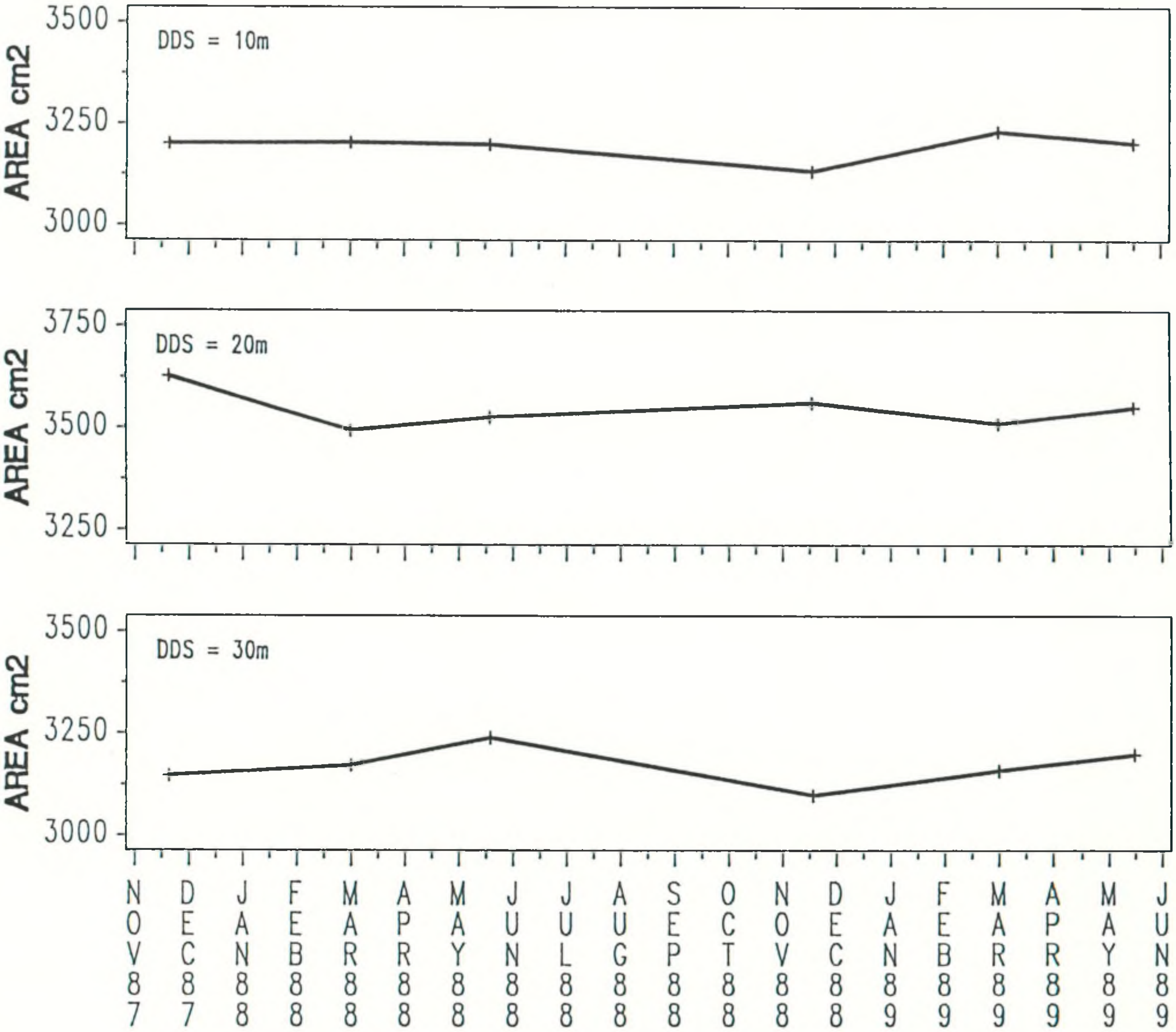


FIG. 5

LAMBDOUGHTY. Furrow Gradient: 0.1044

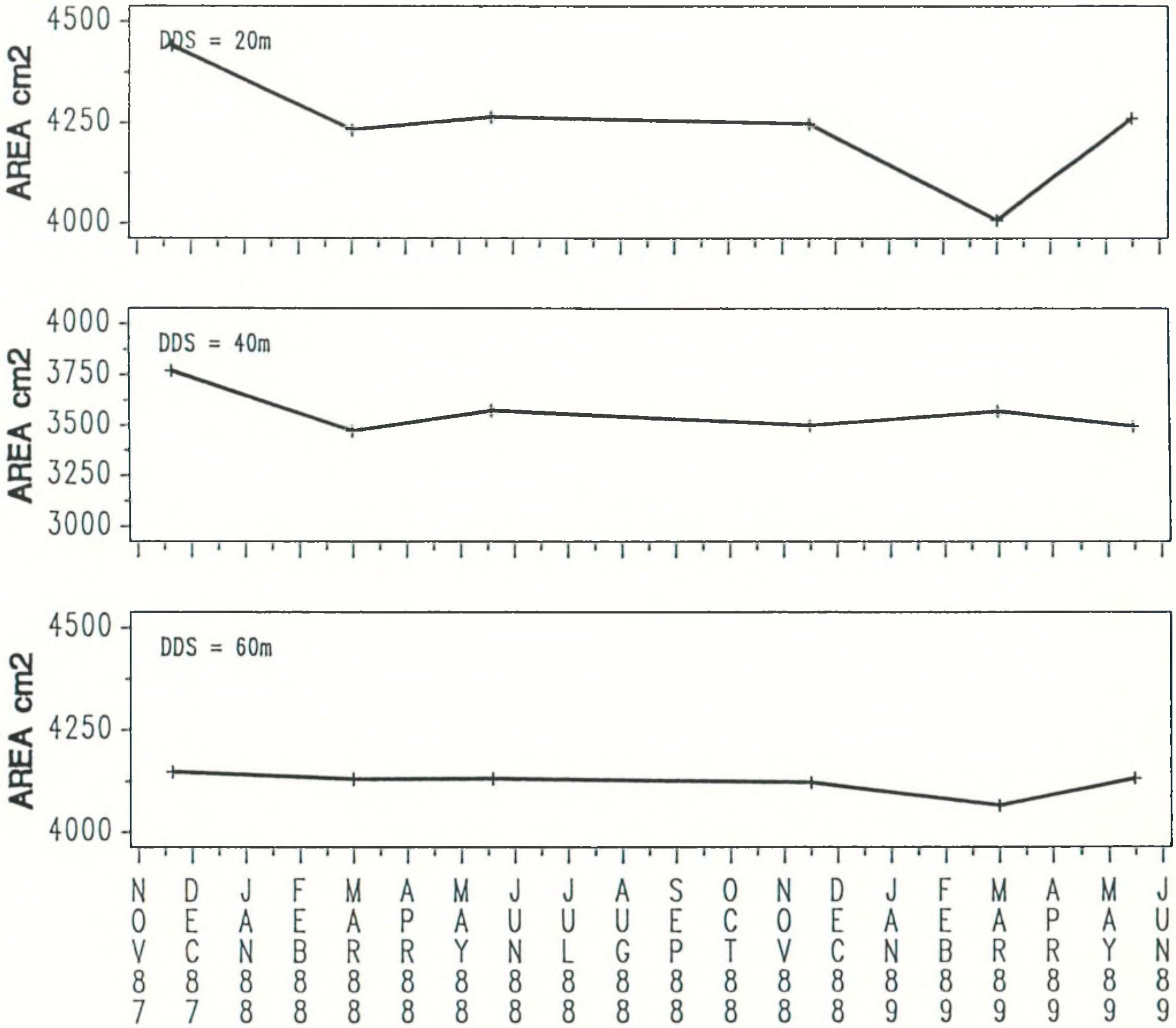


FIG. 6

SCOTSTON. Furrow Gradient: 0.0750

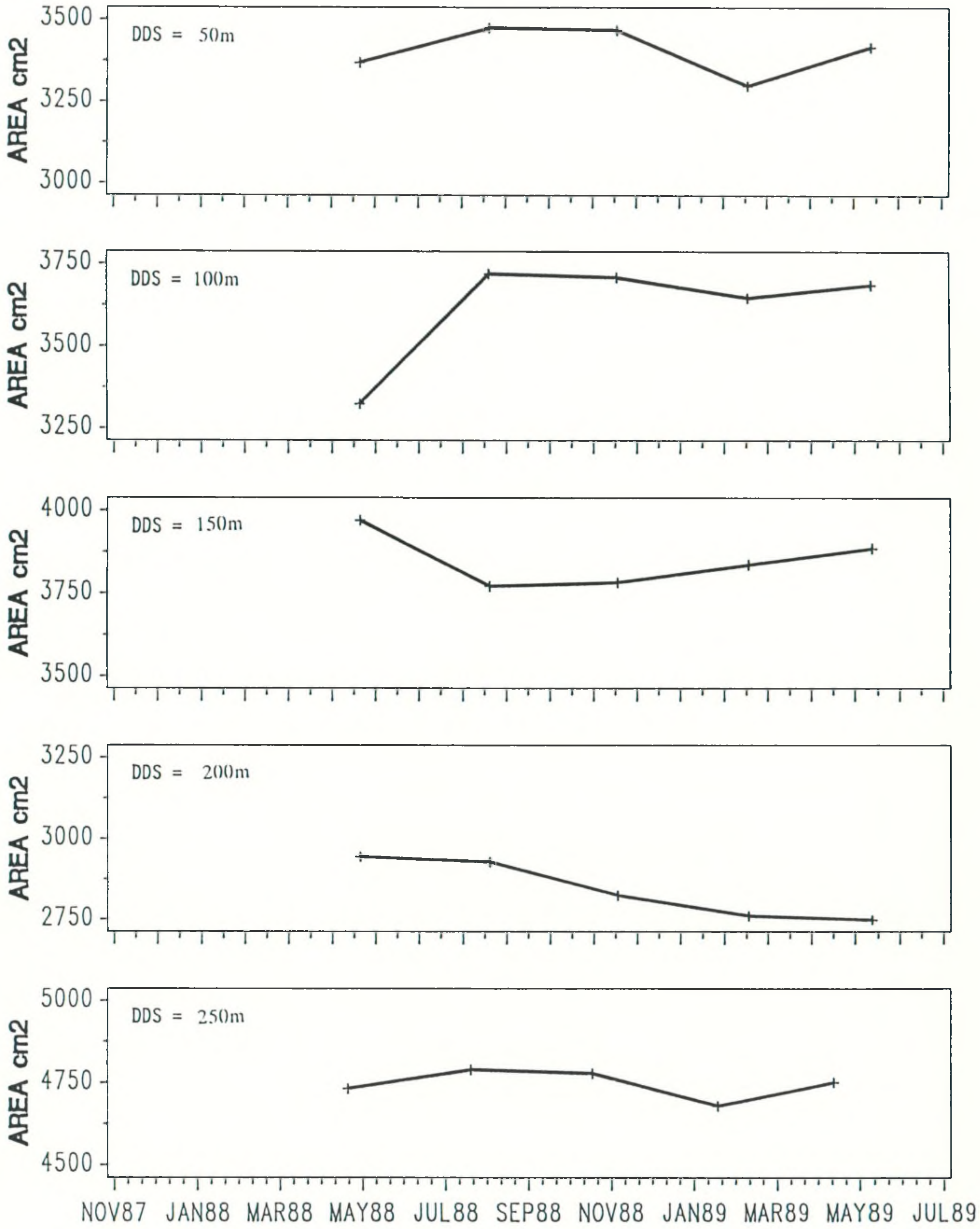


FIG. 7

SCOTSTON. Furrow Gradient: 0.1250

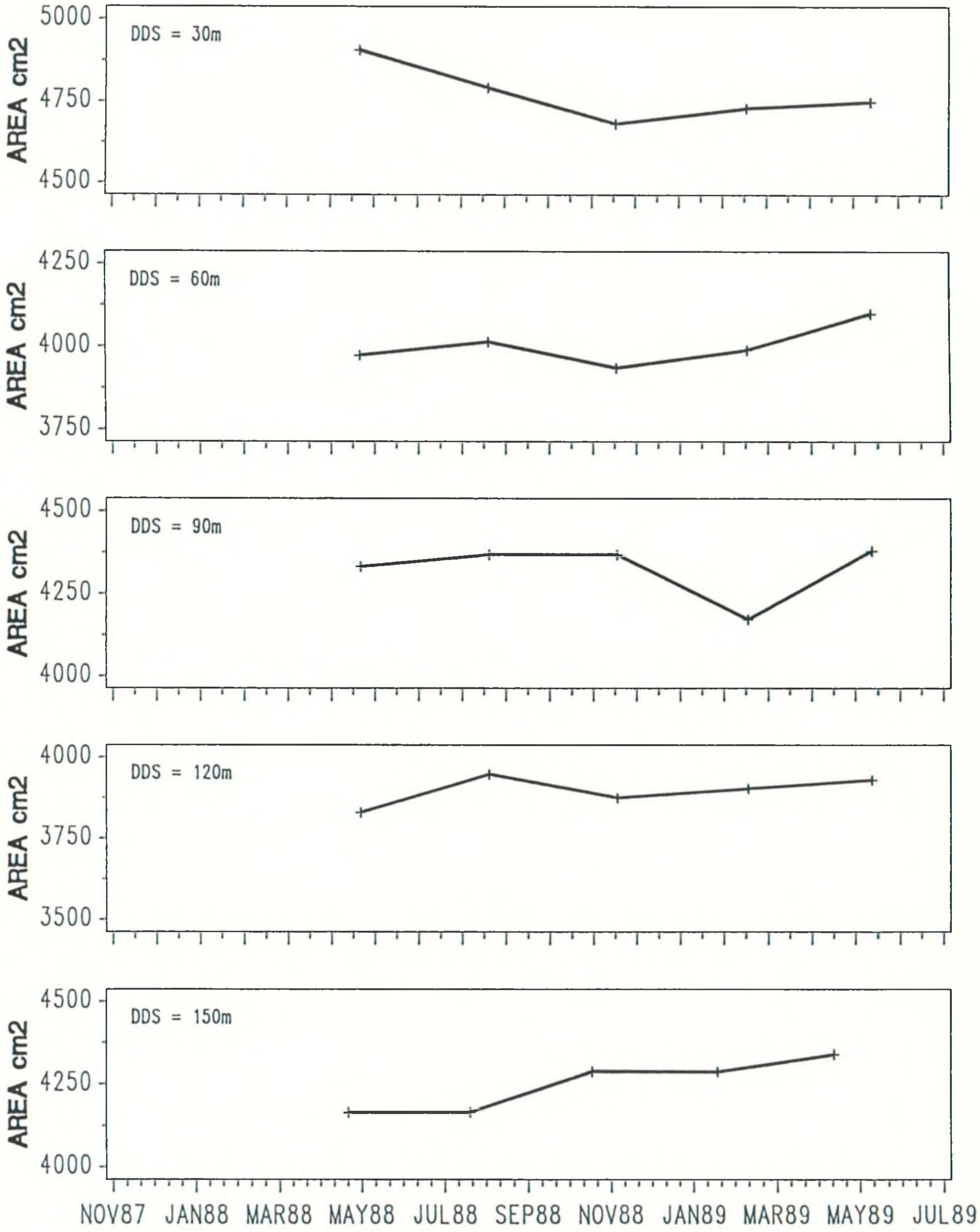
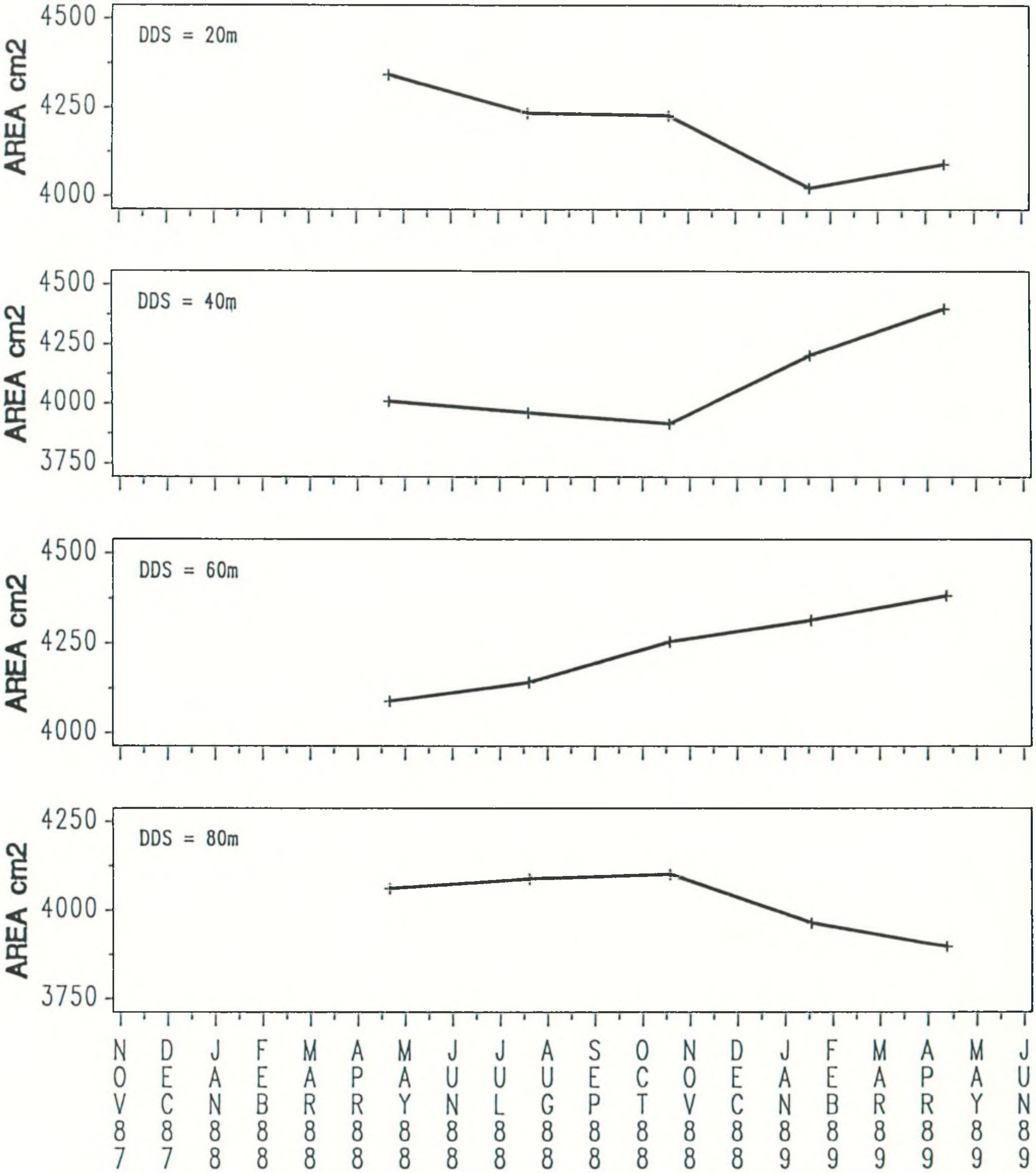


FIG. 8

SCOTSTON. Furrow Gradient: 0.2933



SLOPE PROFILE AND GRADIENT for CARRON **0.1900**

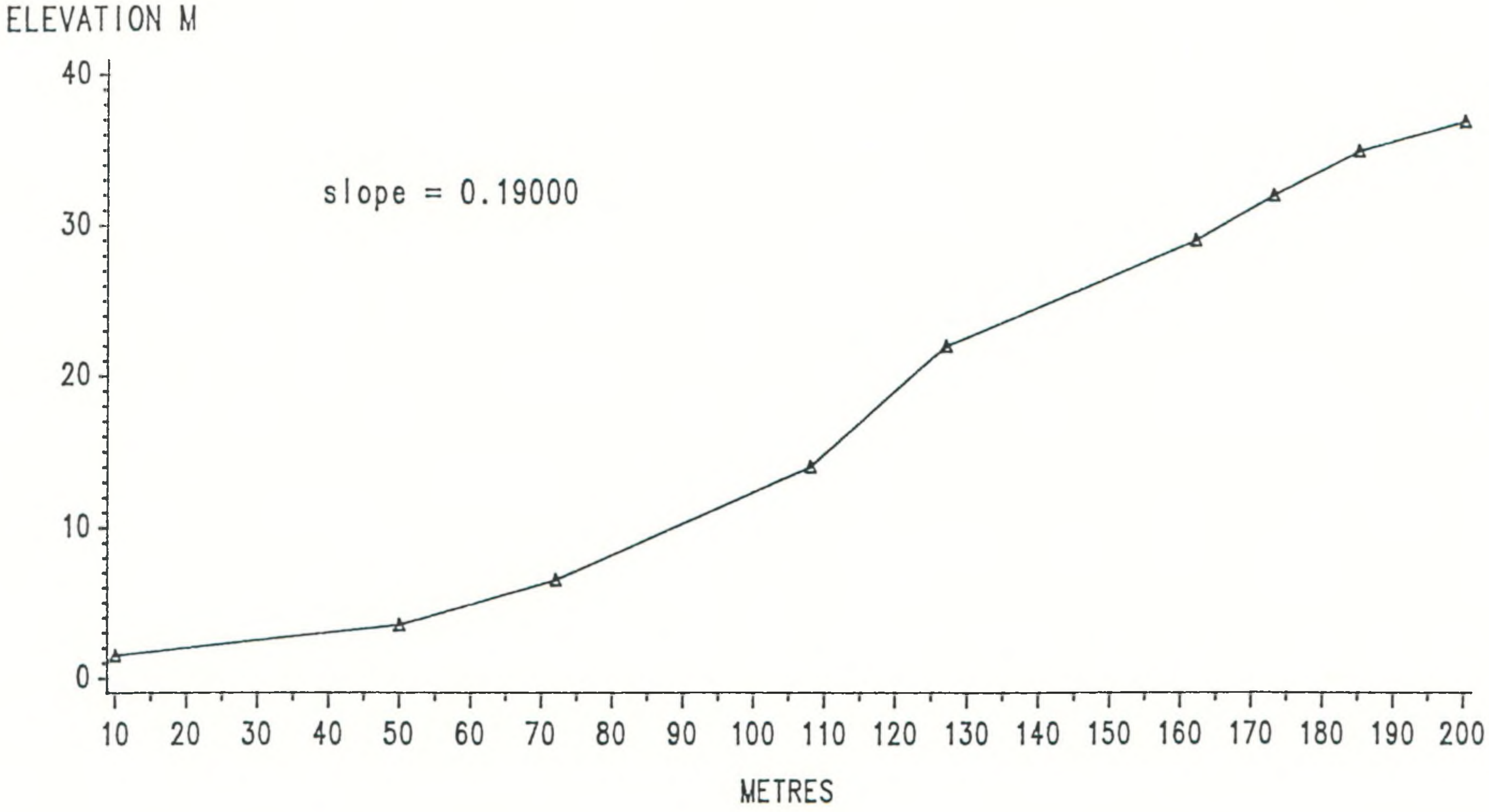


FIG. 9

SLOPE PROFILE AND GRADIENT for CARRON **0.2777**

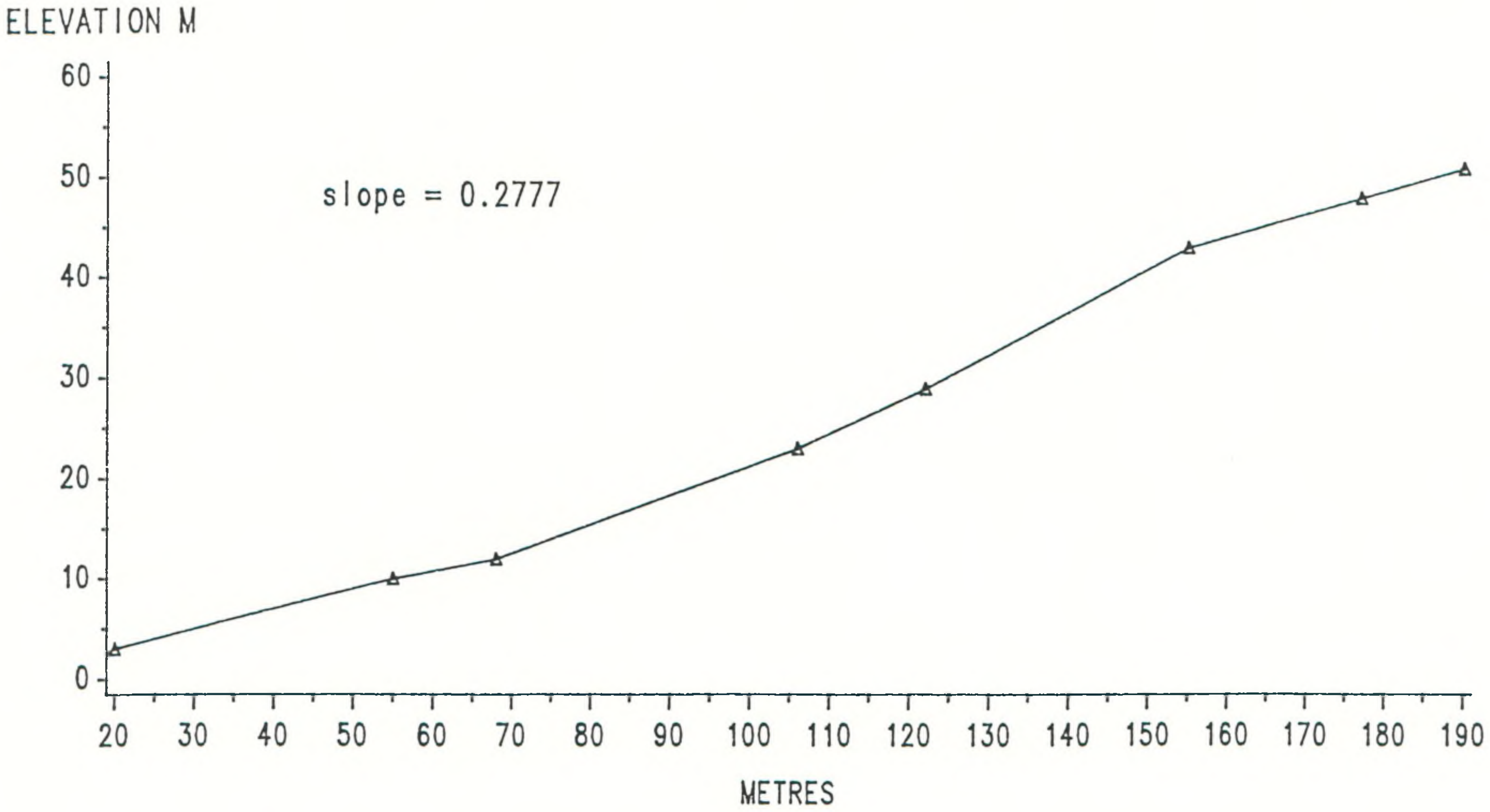


FIG. 10

SLOPE PROFILE AND GRADIENT for LAMBDOUGHTY **0.1035**

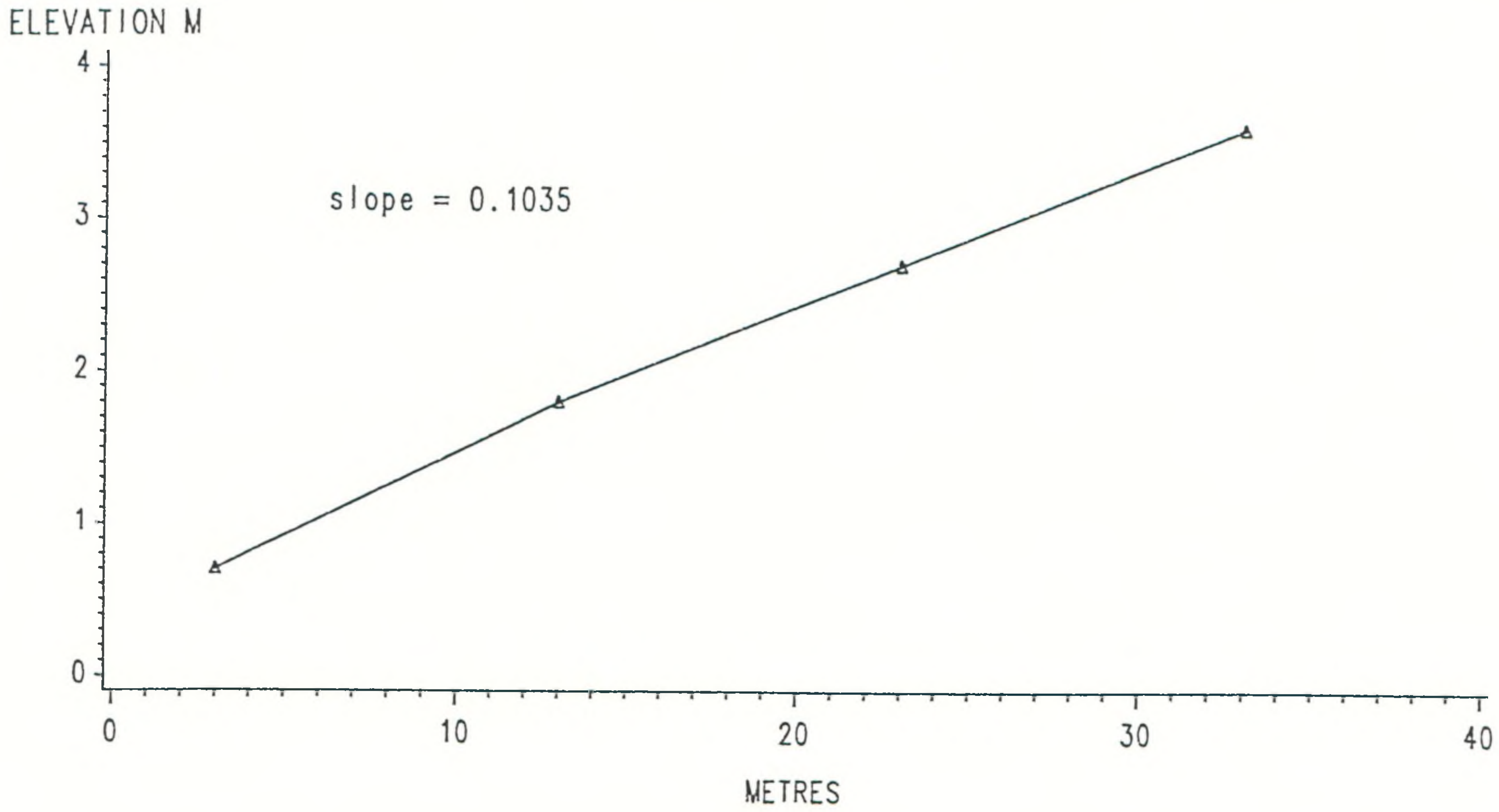


FIG. 11

SLOPE PROFILE AND GRADIENT for LAMBDOUGHTY **0.1044**

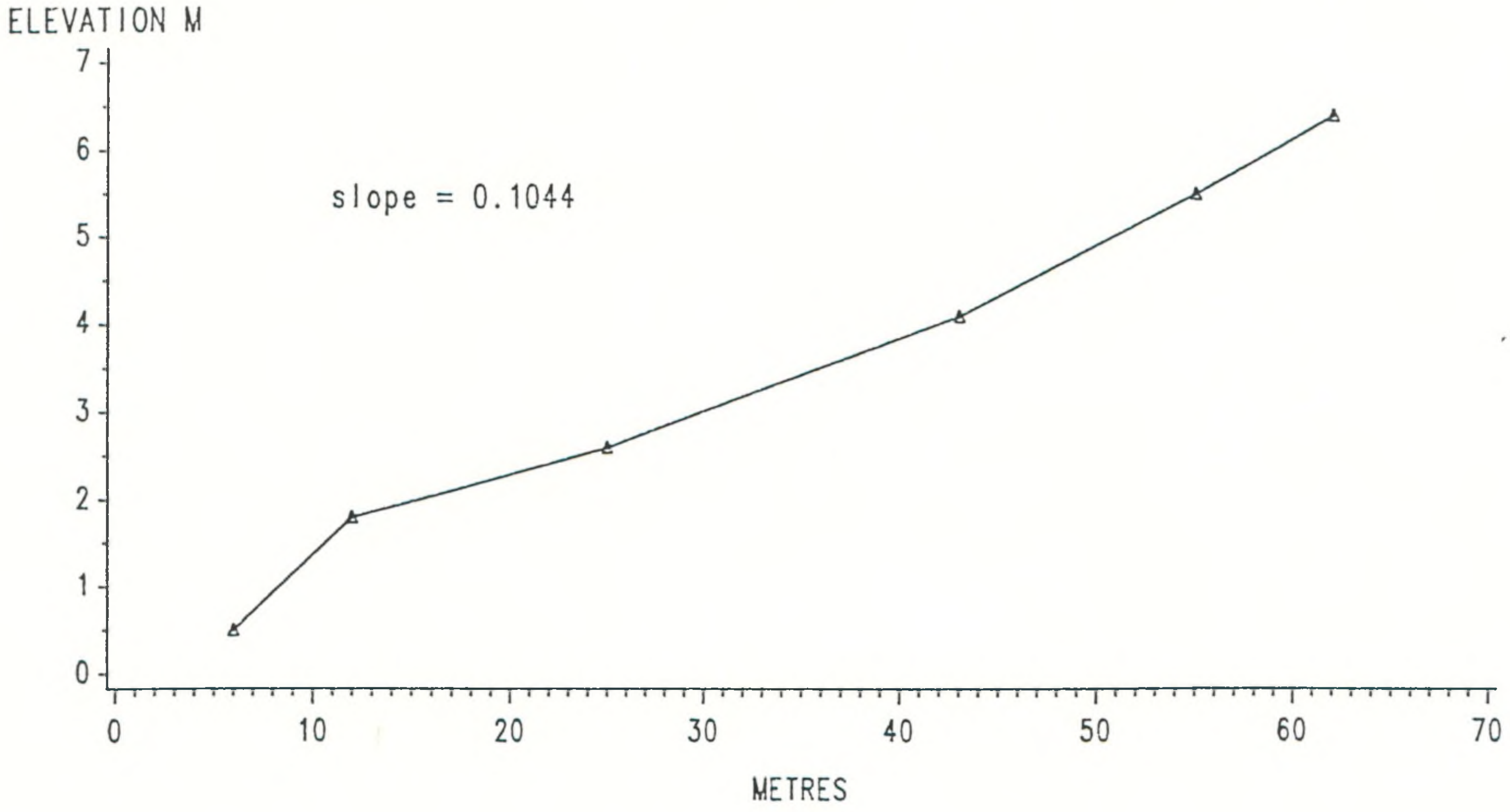


FIG. 12

SLOPE PROFILE AND GRADIENT for **SCOTSTON 0.0750**

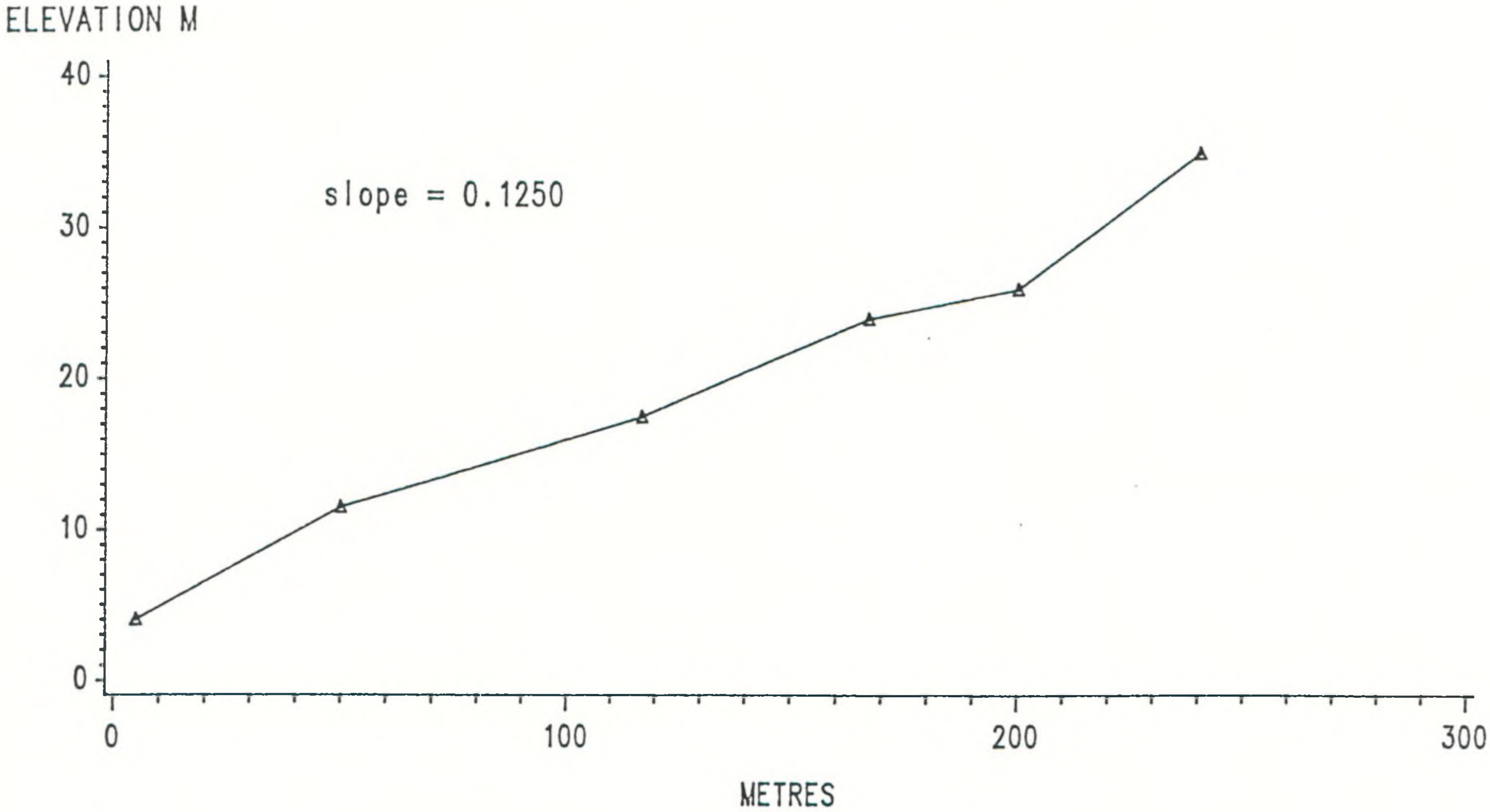


FIG. 13

SLOPE PROFILE AND GRADIENT for **SCOTSTON 0.1250**

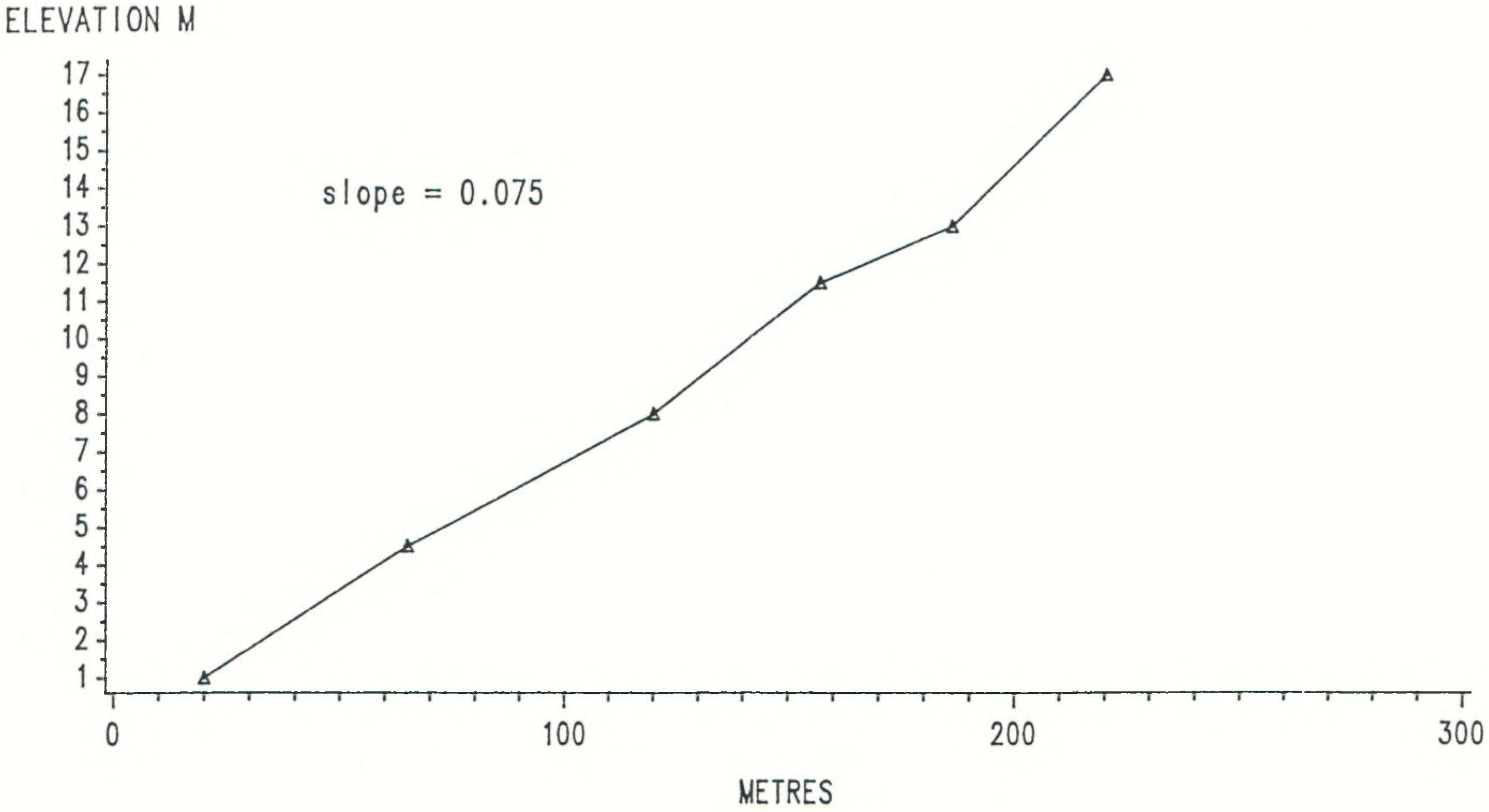


FIG. 14

SLOPE PROFILE AND GRADIENT for **SCOTSTON 0.2933**

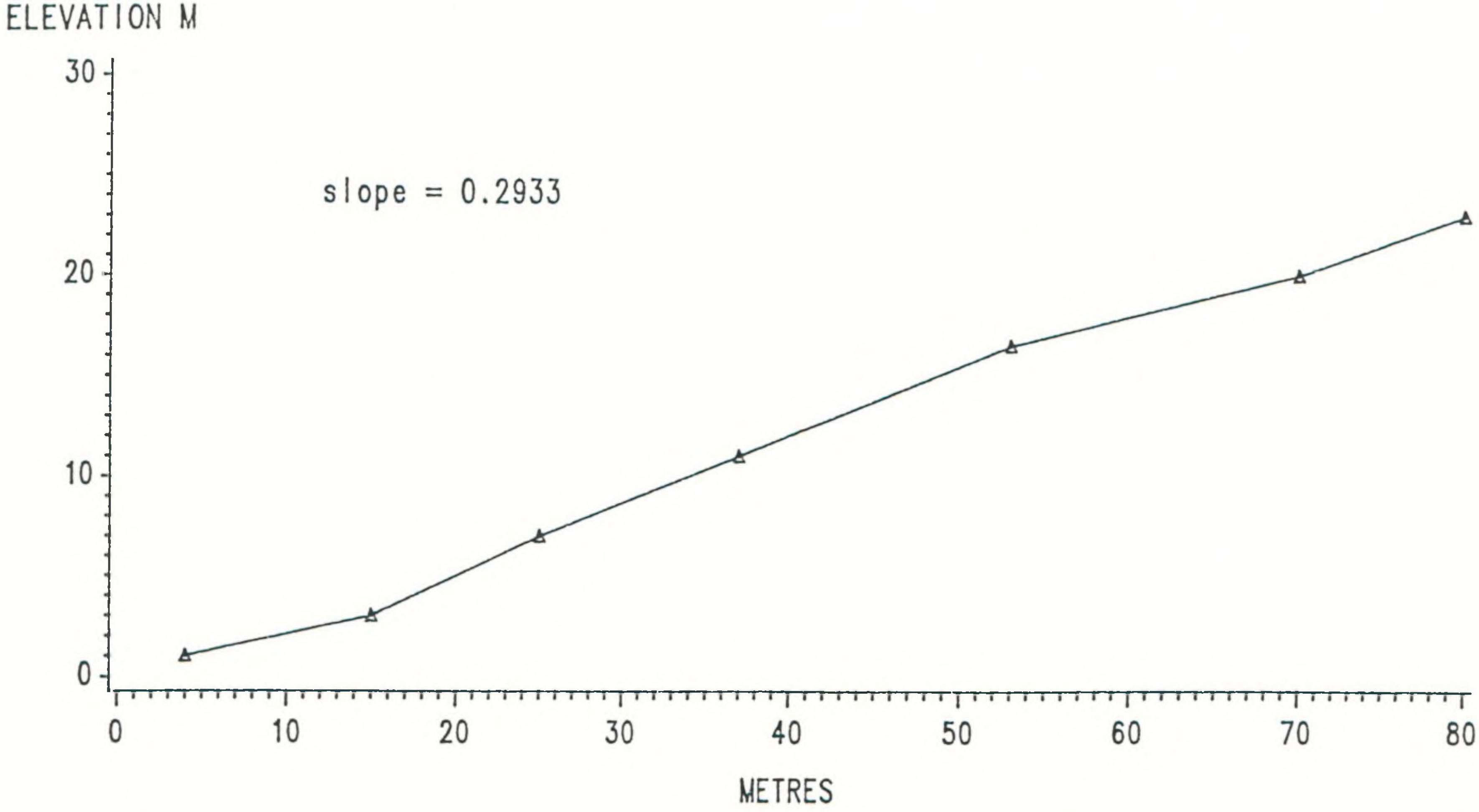


FIG. 15

FIG. 16

DDS V ACCRETION/EROSION

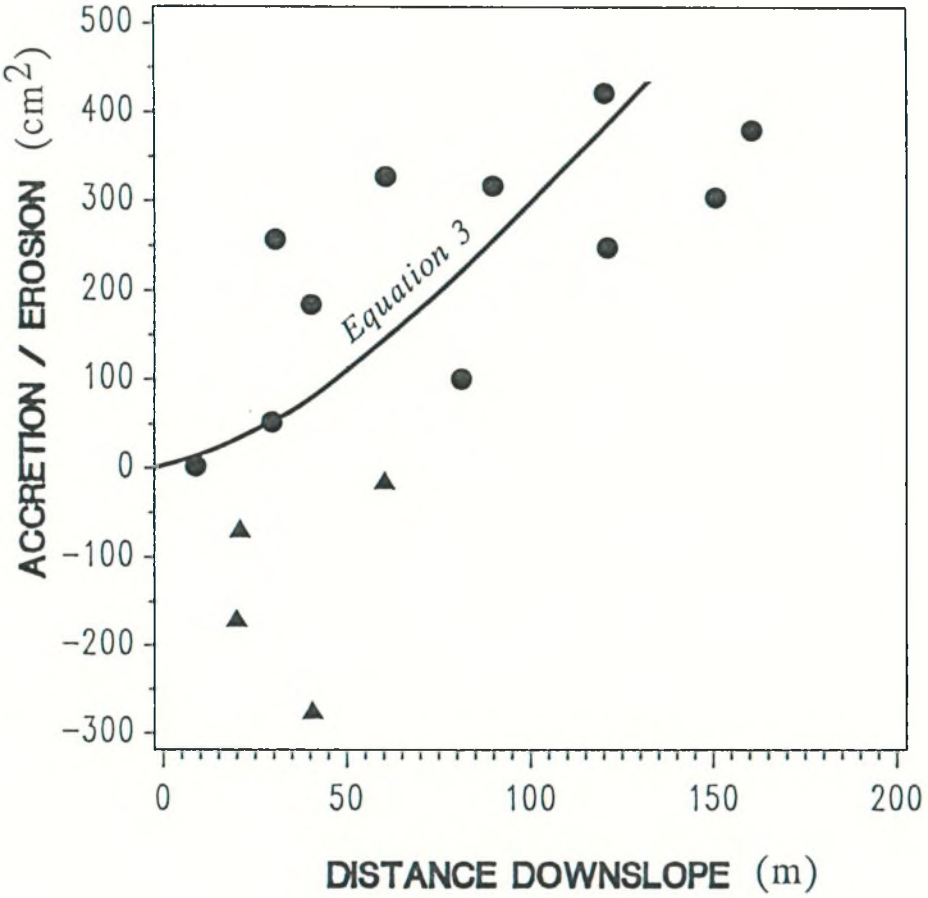


FIG. 17

LOCAL SLOPE GRADIENT V ACCRETION/EROSION

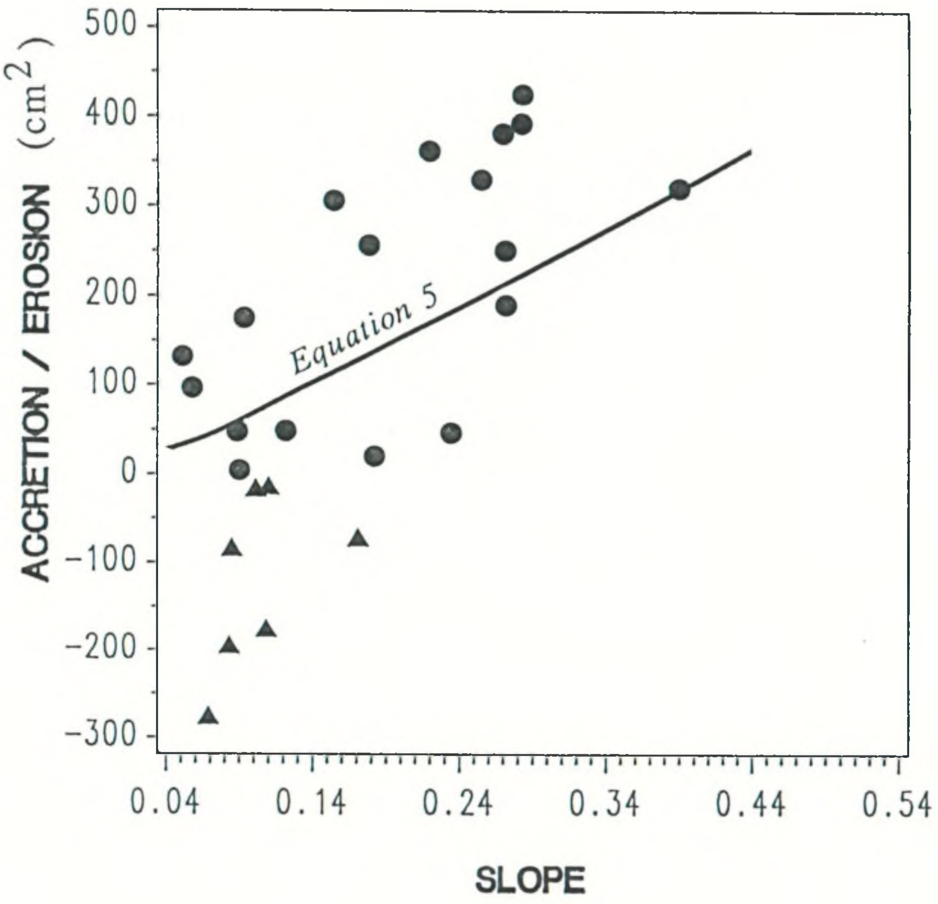


FIG. 18

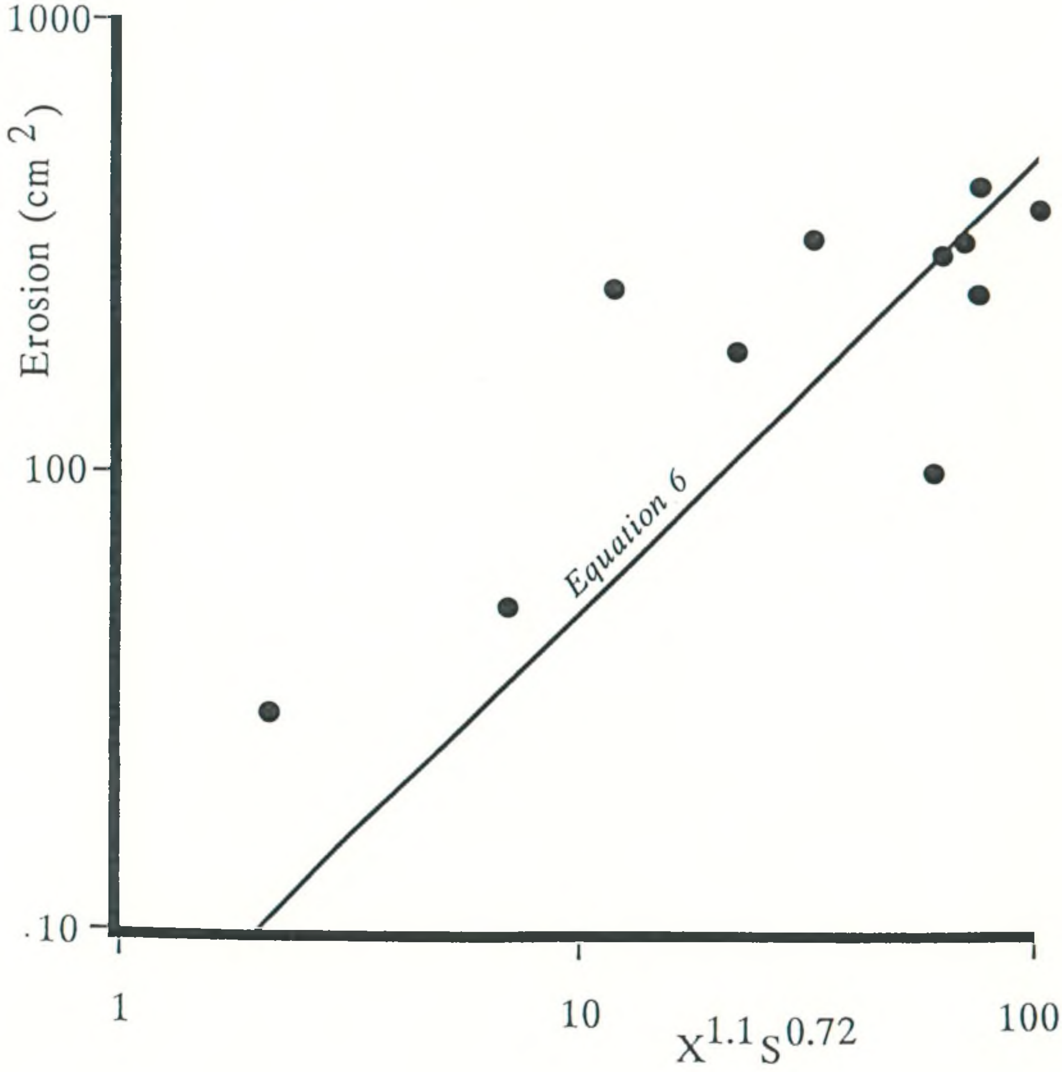
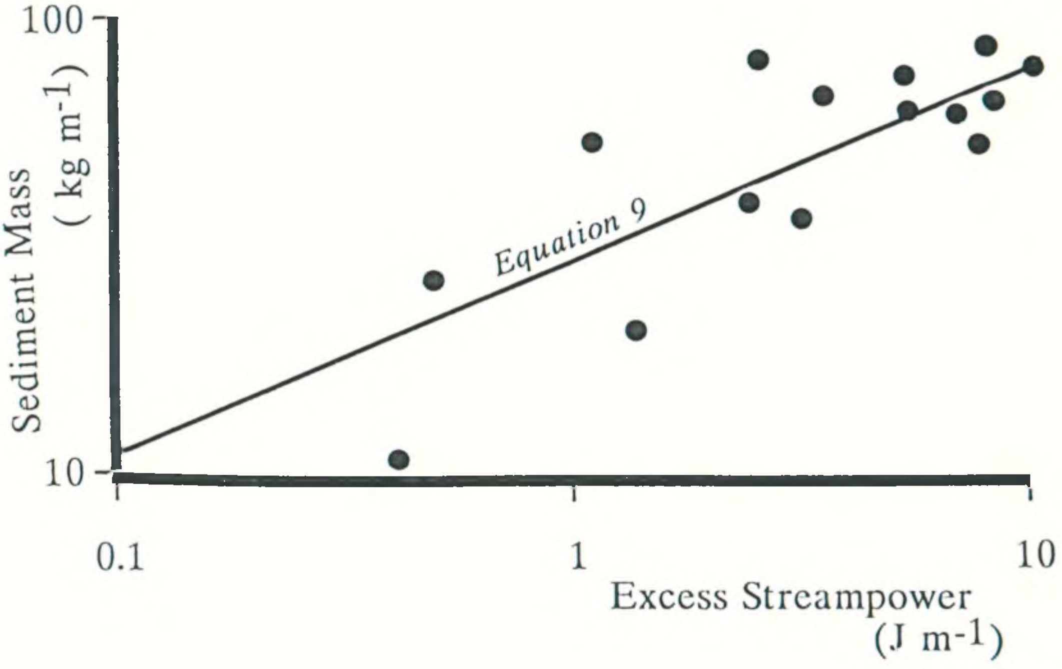
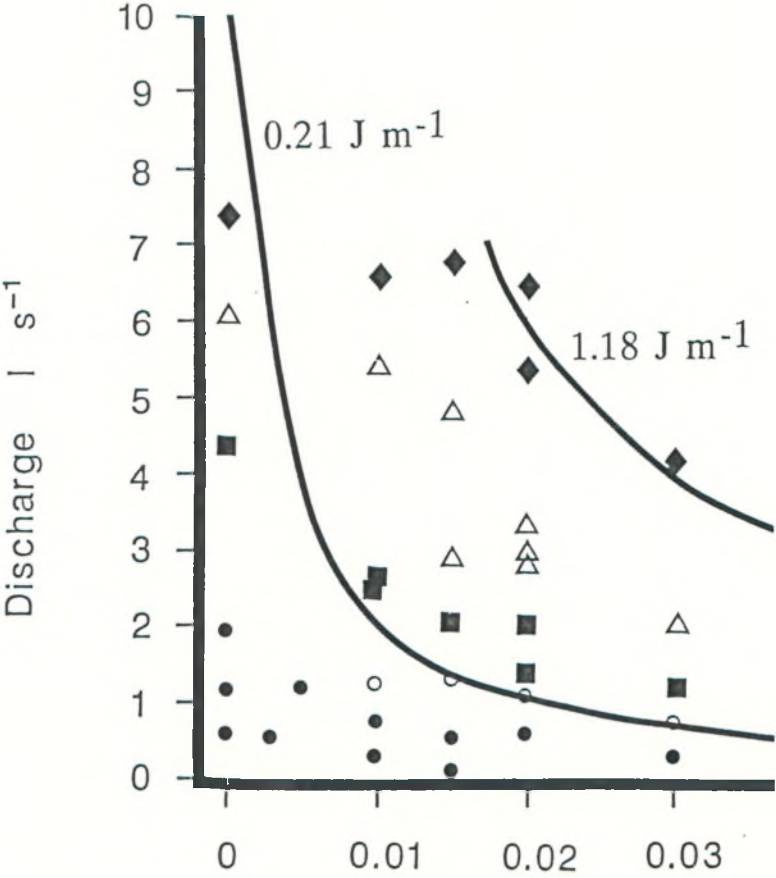


FIG. 19


100
10
Sediment Mass
(kg m-1)
Equation 9
0.1
1
10
Excess Streampower
(J m-1)


Discharge l s-1
10
9
8
7
6
5
4
3
2
1
0
0.21 J m-1
1.18 J m-1
0
0.01
0.02
0.03

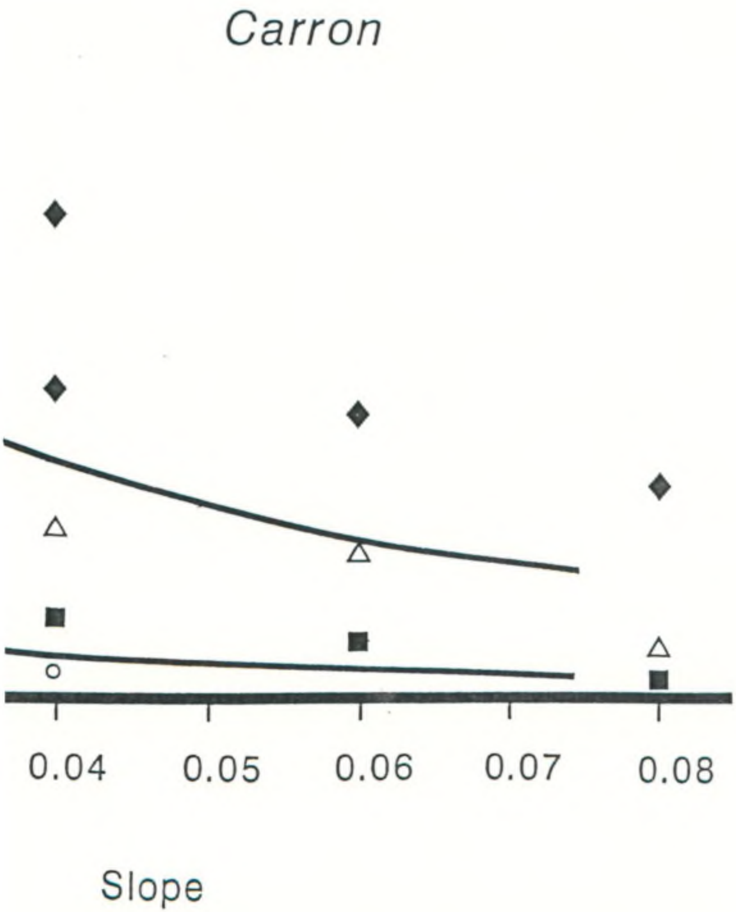
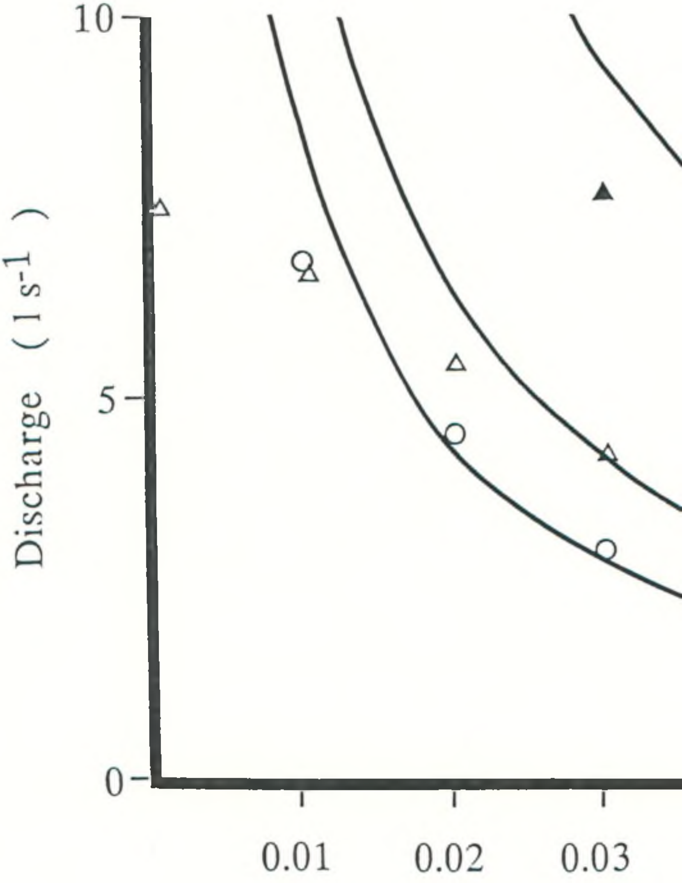


FIG. 20


10
5
0
Discharge (l s-1)
0.01
0.02
0.03

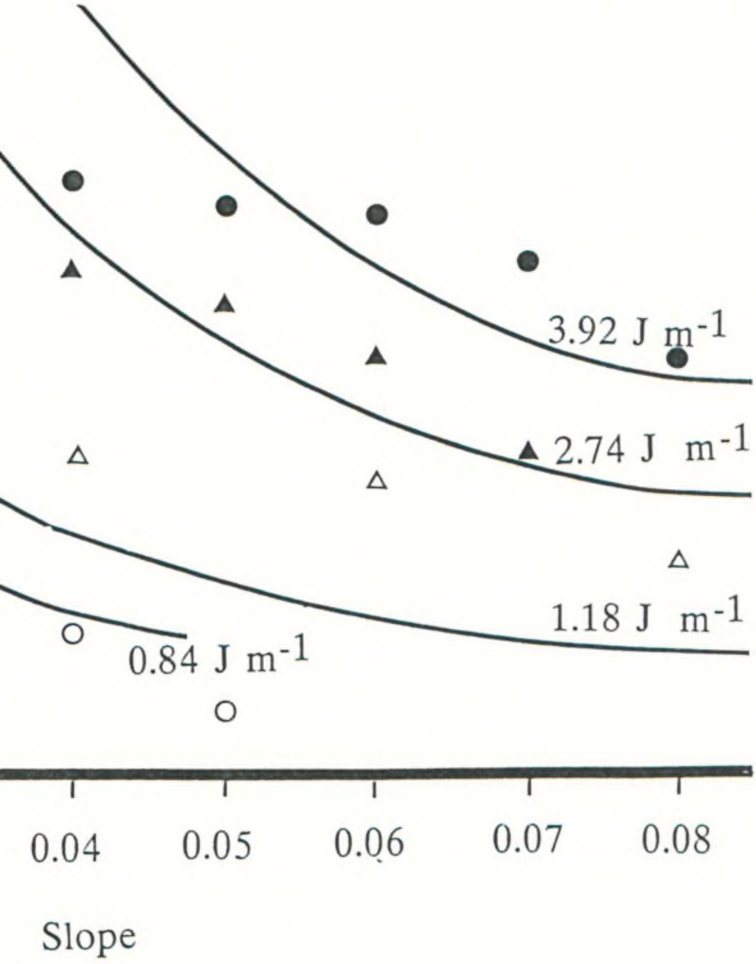


FIG. 21

Appendix 1

Soil Descriptions.

Prepared by Dr. D.G. Pyatt

Carron Furrow gradient : 0.1900

Soil type: Peaty ironpan soil, 4pg.

Geology: Dalradian quartzite, phyllite and porphyry.

Vegetation:

Vegetation:	Molinia	d
	Other grasses	f
	Potentilla	o

Oh 0-15cm Black amorphous peat; granular structure; matted with roots.

Eg 15-22cm 10YR 3/1 very dark grey; moderately stony including ochreous rotting stones; humose loam; structureless; friable to firm.

Bf 2mm thick Trace of ironpan. (Pan frequently exposed on plough ridges.)

Bs(g) 22-52cm 10YR 5/6 and 5/4 yellowish brown with yellowish red and rusty patches; very stony; loam to clay loam; weakly blocky structure; friable; frequent roots.

Cxg 52+ 2.5Y 6/4 light yellowish brown with pale grey and ochreous patches; extremely stony, stones are subangular to angular; clay loam with distinctly silty feel; silty cappings on stones; very firm.

Furrow depth 20-25cm i.e. about depth of ironpan. Tine channel in Bs(g).

<u>Carron</u> Furrow gradient : 0.2777

Soil type: Surface-water gley, loamy texture; 71.

Geology: As Carron gentle furrow.

Vegetation:

Molinia and other grasses	d
Ranunculus	f
Juncus acutiflorus	a

Ag 0-15cm 10YR 3/1 very dark grey; humose loam; slightly stony; weak blocky structure; friable; abundant roots.

Eg 15-25cm 10YR 6/1 grey with abundant ochreous patches associated with well rotted stones; moderately stony, stones mostly soft; sandy loam; structureless; friable.

Bg 25-55cm 10YR 6/4 light yellowish brown with 50% mottling of 10YR 5/6 yellowish brown; moderately stony; clay loam to loam; weak blocky structure; friable; many dead roots.

Cg 55-cm 5GY 6/1 greenish grey; very stony, stones are angular and subangular quartzites and porphyries, mainly <10cm but some up to 20cm; loam to clay loam with a silty feel; structureless; firm; frequent dead roots.

Lambdoughty Furrow gradient: 0.1035

Soil type: Surface-water gley, loamy texture; 71.

Geology: Parent drift is mixture of Ordovician greywacke and granite.

Vegetation:	Molinia and various finer grasses	d
	Calluna	o
	Erica tetralix	o
	Potentilla	o

Horizon Depth Description

Ag 0-17cm 10YR 5/1 grey (when dry); slightly stony, sub-rounded and subangular greywackes and granites, many of which are crumbling; gritty sandy loam; fine subangular blocky structure; friable consistence; well rooted.

B1 17-29cm 10YR 5/2 greyish brown; very gritty sandy loam; structure indeterminate; friable; well rooted.

Bg 29-44cm 2.5Y 5/2 greyish brown with occ. ochreous mottles; very stony, hard greywackes and crumbly granites up to 25cm long; gritty sandy loam; structureless; firm; fewer roots than above.

C(x)g 44-60cm+ 2.5Y 5/3 slightly olive brown with frequent dark ochreous to dark brown mottles and pale grey patches; very stony as above; gritty sandy loam; weakly platy structure; very firm consistence; few roots.

Furrow depth about 30cm, exposing B1 or Bg horizons. Furrow bottom 10% covered in stones. Tine slot (of D45/T60 ploughing) mostly infilled.

Lambdoughty Furrow gradient: 0.1044

Surface-water gley, loamy texture; 71

Geology: Parent material as Loch Doon steep furrow.

Vegetation: As Loch Doon steep furow.

Ahg 0-17cm 10YR 4/1 dark grey; very humose sandy loam; few stones; fine subangular blocky structure; friable; matted with roots.

Bg 17-40cm 10YR 7/3 very pale brown and 5/3 brown; gritty sandy loam; mainly friable but with some firm patches (indurated material); well rooted.

Cxg 40-50cm+ 2.5Y 6/2 light brownish grey with many dark brown and ochreous mottles; gritty sandy loam; very stony, mainly greywackes; silty cappings on stones; weakly platy structure; extremely firm consistence.

Scotston Furrow gradient: 0.0750

Description for downslope part of furrow.

Soil type:	Surface-water gley/Ironpan soil intergrade; 71/4g.
Geology:	Dalradian mica-schist including garnet mica-schist.
Vegetation:	Calluna d Vaccinium myrtillus f Deschampsia flexuosa f

Ah 0-5cm Black very humose sandy loam.

Eg1 5-8cm 10YR 5/2 and 4/2 dark greyish brown; sandy loam; moderately stony, subangular schists up to 15cm long; structureless; friable to firm.

Eg2 8-11cm 2.5Y 6/4 light yellowish brown with ochreous mottles; stones as above; sandy loam; structure and consistence as above, few roots.

Bg 11-26cm 10YR 7/6 yellow with abundant mottles of 7.5YR 5/8 yellowish brown; moderately stony; sandy loam; weakly blocky; friable; few roots.

Cxg 26-36cm+ 2.5Y 6/4 light yellowish brown with abundant dark brown mottles; very stony; sandy loam; moderately platy structure; very firm.

Scotston Furrow gradient: 0.0750

Description for upslope part of furrow.

Soil type: Peaty ironpan soil; 4pg.

Geology and Vegetation as before in this furrow.

Oh 0-15cm Black amorphous peat with distinct vertical cracking.

A/Eg 15-27cm Very irregular patches of 10YR 7/2 light grey and 10YR 5/6 yellowish brown with abundant ochreous mottles, patches and streaks of black humose material; very stony; sandy loam; occasional vertical cracks; friable to firm; frequent roots.

Bf Traces of ironpan.

Bs(g) 27-42cm 2.5Y 6/4 light yellowish brown with frequent ochreous mottles; slightly stony; loam; weak blocky structure; friable.

Cx 42-52cm 2.5Y 6/4 light yellowish brown and 10YR 6/6 brownish yellow; very stony; sandy loam; platy structure; very firm; silty cappings on stones.

Scotston Furrow gradient: 0.1250

Description for downslope part of furrow.

Soil type: Intergrade ironpan soil; 4b.

Geology: As Scotston 1.

Vegetation:	Deschampsia flexuosa	a
	Galium saxatile	f

Oh 0-1cm Black amorphous peat.

Eg/Bf 1-7cm 10YR 6/1 grey and 10YR 3/4 dark yellowish brown with distinct but discontinuous thin ironpan within peds and along lower boundary; moderately stony; sandy loam; weakly blocky structure; friable.

Bs1 7-14cm 7.5YR 4/4 dark brown; very stony; sandy loam; fine blocky structure; friable.

Bs2 14-34cm 2.5Y 5/6 strong brown; moderately stony; loam; crumb structure; friable, well rooted.

Cx 34-44cm+ 2.5Y 5/3 light olive brown; very stony; sandy loam; platy structure; very firm; silty cappings on stones.

This soil occurs between the lower two measure sites within the furrow.

Scotston Furrow gradient: 0.1250

Description for upslope part of furrow.

Soil type: Peaty gley, loamy texture; 61.

Geology: As Aberfeldy 1.

Vegetation:	Calluna	a
	Deschampsia caespitosa	o
	Other grasses	o

Oh 0-5cm Black amorphous peat.

Ag 5-12cm 10YR 4/2 dark greyish brown; slightly stony; sandy loam; weakly blocky; friable.

Eg 12-22cm 10YR 6/2 light brownish grey with much dark brown dead root material; sandy loam; weakly blocky structure; friable.

Bg 22-32cm 10YR 6/3 pale brown with abundant black or dark brown Fe/Mn concretions mainly <1cm; sandy loam; very firm. This horizon when exposed on the top of the plough ridge and dried becomes white and powdery with very hard brown concretions.

Cx 32-42cm+ 2.5Y 6/2 light brownish grey; very stony; sandy loam; platy structure; very firm; silty cappings on stones.

Scotston Furrow gradient: 0.2933

Soil type: Intergrade ironpan soil; 4b.

A/Eg/Bf 0-5cm 10YR 6/2 light brownish grey and 7.5YR 4/4 dark brown with incipient ironpan at bottom of horizon; sandy loam; friable to firm.

Bs1 5-20cm 10YR 5/3 brown; moderately stony; sandy loam; crumb structure; very friable.

Bs2 20-35cm 10YR 5/8 yellowish brown; moderately stony; sandy loam; crumb structure; very friable.

Bs3 35-65cm 10YR 6/8 brownish yellow; moderately stony; loam; weakly blocky structure; friable.

Cx 65cm+ 2.5Y 6/4 light yellowish brown; very firm.

This soil is the deepest and best drained of those described, and occurs throughout the furrow.