Hydraulics Research
Wallingford

THE HYDRAULIC ROUGHNESS OF VEGETATED CHANNELS

PRELIMINARY REPORT

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COMMISSION

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The statements and opinions expressed in this report, however, do not necessarily reflect the view or policy of the Ministry.

The work was carried out at Hydraulics Research in the River Engineering Department headed by Dr W R White by Mr F G Charlton, assisted by Mr R W Pethick, Mr M S Knowles, Mr T O Robson (botanical surveys) and Mr R W Benson.

1 INTRODUCTION

The Commission entailed a study of the hydraulic roughness of rivers and canals containing vegetation. It was appreciated that work on this topic had already been done elsewhere; the present investigation therefore covered

(i) literature survey,

(ii) laboratory measurements,

(iii) measurements in canals and natural rivers.

Further research was commissioned because although many of Britain's rivers and canals carry substantial growths of vegetation during several months in the year, the design of drainage and flood control works has always been handicapped by insufficient information about the hydraulic roughness of vegetated channels. Engineers experienced in the behaviour of rivers in their own districts could usually compensate for this deficiency. However, with the advent of more complex numerical analyses of networks of canals undertaken by engineers with less practical experience it became even more important to improve knowledge about roughness due to flexible elements in a channel.

This report, therefore, which is the first of a series, describes the results of the literature survey and some initial laboratory and field studies.

The laboratory work was to obtain a better understanding of how the ratio of depth of flow to length of vegetation affected channel roughness, while a pilot field study similarly examined the effect of the seasonal stage of growth of vegetation.

2 LITERATURE STUDY

2.1 Preamble

Water flowing in an open channel is retarded by frictional losses against the boundaries of the channel. Early work to analyse the movement of water was concerned with channels having fixed, or rigid, boundaries, such as aqueducts or rivers and canals with inerodible beds. Later, attention turned to the more complex problems of watercourses having movable, or erodible beds which change due to the action of flowing water.

Furthermore, many channels contain growths of vegetation, which does not erode over a short time period but is flexible and changes its attitude in response to flowing water. The presence of such vegetation increases the difficulty of predicting river behaviour, although it is generally believed to increase the resistance to flow (or hydraulic roughness) and so to cause higher water levels in a given channel at a given flow rate.

As engineers began to consider the effect of vegetation on river morphology, training and flood alleviation, so an extensive literature has arisen (see Bibliography). However, the unguided study of the available papers can be confusing, even misleading, due to the complexity of the processes at work. For this reason, the following sections of the present paper first review the factors affecting roughness in vegetated channels, leading on to a classification of the phases of flow. The papers of the Bibliography are then referred to this framework.

2.2 Factors affecting roughness

To help in understanding the different methods of analysis advocated by the various authors, the principal factors which may affect flow conditions are listed below:

(a) length of vegetation

(b) cross sectional shape of stem

(c) size of stem

(d) stiffness of stem

(e) mass density of material forming plant

(f) complexity of the plant (i.e. whether a single stem or branched)

(g) spacing of the plants in the colony, whether

  (i) close, or

  (ii) open, where distance between stems is more than 6 stem diameters in a downstream direction or 3 stem diameters laterally.

The response of the plant to the flowing water may result in the stems being

(a) upright

(b) inclined and waving, or

(c) prone and probably undulating,

with the flow occurring

(a) at a depth greater than the deflected height of the vegetation, where water moves both over and through the vegetation, or

(b) at a depth less than the deflected height of the vegetation, such that water flows only through the vegetation.

2.3 Phases of flow

The hydraulic conditions within the waterway differ depending on depth of flow, stiffness of vegetation and density of cover.

In shallow water, when flow occurs through a mass of dense vegetation, resistance is primarily due to the drag forces on the elements, and the velocity distribution is nearly uniform. The resistance to flow through an open cover of vegetation (para 2.2 g) is due partly to drag forces on the elements and partly to shear on the bed between them, and the velocity profile may be logarithmic rather than uniform.

In deeper water, where the vegetation (whether upright or deflected) is totally submerged the flow in the upper layer is retarded by shear stresses at the boundary with the top of the vegetation. The velocity profile above the interface may be logarithmic while within the vegetation it may tend to a constant value.

The above conditions are shown in Table of Phases of Flow which follows and contains an example of each situation. The papers of the Bibliography are then considered under the main headings of relatively shallow and relatively deep flow.

Phases of Flow

	Attitude of Vegetation	
Upright	Inclined or waving	Prone or undulating
	Relative depth of flow — Shallow (less than deflected height)	
(a) Dense cover of long grass on flood plain & low velocity, or stiff weeds in a channel	(a) Dense cover of long grass on a flood plain or stiff weeds in a channel	
(b) Open cover of trees of bushes on flood plain. Cultivated areas of wheat, sugar cane etc.	(b) Open cover of grass or weeds on a flood plain or in a plain or in a channel	
	Relative depth of flow — Deep (greater than deflected height)	
(a) Dense cover of short grass on flood plain and low velocity	(a) Dense cover of long grass on weeds in a channel	(a) Dense cover of long grass or weeds in a channel and high velocity
	(b) Open cover of weeds	(b) Open cover of long grass or weeds in a channel and high velocity

2.4 Studies of relatively shallow flow

Most papers examined in this category describe analyses which assume that the vegetation is composed of elements sufficiently widely spaced to allow the development of the full drag force on each element, and assume that the velocity distribution is logarithmic. Papers 4, 5, 11, 16 and 18 make these assumptions.

Paper 5 is specifically intended to cover flow over flood plains past hedgerows. Equations are developed incorporating the net area of flow through a hedgerow.

Paper 11 introduces a term defining the obstruction due to vegetation, called the root mean square of bed elevation.

Paper 14 develops nomographs and tables to include resistance due to drag on vegetation, shear on bed and shear on banks.

Paper 18 develops a relation for Manning's n assuming resistance due to drag on vegetation and tractive stress on the channel boundary.

Paper 1 describes experiments on laminar flow over and through Kentucky Blue and Bermuda grasses, and records the relation of f against R for different values of S.

Paper 12 takes account of drag resistance and boundary shear for which values of Manning's n are given.

2.5 Studies of relatively deep flow

The papers in this category describe flow of depths greater than the deflected height of the vegetation.

Papers 7, 8 and 9 (all by the same author) assume a logarithmic velocity profile and relate total roughness to relative roughness and flexural rigidity. The relative roughness is also expressed in terms of total area of cross section of channel to area obstructed by vegetation.

Paper 13 relates Darcy's friction factor f to hydraulic depth R and shows that f R is a constant, a conclusion similar to that reached in Ref 1 where the depths of flow were greater. The critical value of R at which this occurs is dependent on the relative roughness which is in turn affected by the deflected height of the vegetation.

Paper 3 separates roughness into that due to shear stress on the bed and banks of the channel, and obtains a relation between n and depth of flow. It goes on to show that at large depths n becomes independent of depth.

Papers 6 and 15 are concerned with the relation between roughness and relative roughness due to rigid obstructions on the bed.

3 LABORATORY STUDY

3.1 Test conditions

It has been mentioned already that although the purpose of the investigation was to establish the effect of natural vegetation on the roughness of rivers and canals some preliminary measurements were made in the controlled conditions of a laboratory flume in order to determine the effect of vegetation on velocity distribution. The flume used for the tests was 0.90m wide and 0.30m deep (Plate 1). To represent vegetation, from among the many plastic materials available, polypropylene strip was chosen. This was initially formed 50mm wide, but was pre-folded to produce a four-ply strip about 12mm wide, and had longitudinal "roving" or tendency to split lengthwise. Portions of this strip 610mm in length were secured at mid-point by a staple (placed normal to the flow direction) driven into a wooden base-board to simulate plant elements. They were spaced on a 75mm square grid aligned with the flow direction over a length of 2.7m; at the upstream and downstream ends of this working section were smooth, non-planted sections at the same bed level, respectively 2.7m and 1.8m in length. The effect in the working section was of a colony of plants with double stems, each having a relatively stiff lower section or stalk, with free ends representing leaves (see Plates 2-5).

Discharge through the flume was measured by a V-notch weir and water levels were determined by using static tubes and manometer.

3.2 Test schedule

Measurements were made at four nominal discharges between 10 and 80 l/s. With each flow rate, the depth was adjusted to three different values. Then, for each resultant test condition three measurements of water surface level spaced regularly along the working section provided two values of water surface slope (upstream half and downstream half) and associated water depth.

Photographs were taken of the vegetation elements through the glass wall of the flume of each test condition as a means of later measuring their effective height.

A second series of observations was then made, running through the same schedule as outlined above but including the measurement of velocity profiles. A miniature current meter (rotor diameter 10mm) was used on verticals located 150mm and 187mm from the flume wall, that is either aligned with a longitudinal row of plant elements or mid-way between rows. The second test series also gave some indication of the effect of ageing on the plant elements.

3.3 Results of laboratory study

Figs 1-4 are selected plots of velocity profiles for deep and shallow flow, and low and high speeds. Each point is the mean of the velocities in line with the plant elements and between them (see 3.2). The profiles show that, for total depths in excess of the deflected height of the vegetation flow speed through the vegetation was relatively low and almost unchanged with depth, whereas above the vegetation flow speed changed with elevation. From this it appears that in a natural stream, where the plants would be more closely spaced than were the flexible elements used in the laboratory flume, vegetation would cause a profound change in the vertical velocity profile, with very little flow through the vegetation.

From the measurements made values of equivalent grain roughness k and Manning's roughness n were calculated from the respective equations

$$v = 5.75\ (gRS)^{0.5}\ \log \frac{11R}{k} \qquad (1)$$

and

$$v = \frac{1}{n}\ R^{0.67}\ S^{0.5} \qquad (2)$$

where v = mean flow velocity
= $\frac{Q}{A}$ where Q = discharge and
A = cross-sectional area of flow (see following Note)

g = acceleration due to gravity

R = hydraulic depth = d (see following Note)

S = hydraulic gradient

Note:- A assumed to be the entire wetted area, that is both the part free of "vegetation" and that containing it.

d assumed equivalent to R for flume having negligible hydraulic roughness on glass sides compared with "vegetated" bed.

Figs 5 and 6 show respectively the values of k and n obtained, plotted against a parameter log (v x d) representing specific discharge; both Figs also show results from other sources which are discussed later. From Fig 5 it may be seen that values of k ranged from about 0.90 at 0.01 m^2/s per metre width to around 0.20 at 0.1 m^2/s per metre width. Fig 6 shows a similar pattern of values of n from 0.04 to 0.2 over the same range of specific discharge.

As mentioned above, Fig 6 has superimposed curves relating Manning's n with the parameter (v x R) which were derived from work at the Stillwater Outdoor Hydraulic Laboratory for the US Dept of Agriculture and published as a handbook for the design of channels containing vegetation (Ref 17). The curves were based on field measurements for different types and heights of grasses, classified as follows:-

A Tall, over 0.76m height

B Dense, generally unmowed 0.30-0.76m height

C Dense, 0.15m-0.30m height

D Short, uncut 0.06-0.15m height

E Cutgrass and burned stubble, 0.04-0.06m height

Relating the values of Manning's n obtained from the present laboratory flume tests, using flexible elements 0.6m in height but spaced more openly than would be expected in nature, to the Stillwater curves, Fig 6 shows that the former lie generally between classes D and E (short grass). However, at low values of depth and flow velocity the flume values are less than indicated by curve E.

Further investigation of the distribution of the values of k and n obtained from the laboratory flume tests, in order to predict flow depths and velocities, has not yet produced useful results. No practical guidance could be obtained from the very complex approaches proposed by most of the authors listed in the Bibliography.

The relation of $$\frac{v}{v_*} = C \log r \frac{R}{k} \qquad (3)$$

where $v_* = (gRS)^{0.5}$

C = constant (= 5.75)

r = coefficient

k = equivalent roughness, assumed equal to h, the deflected height of flexible elements ("vegetation")

to either $\frac{d}{h}$ or $\frac{A_p}{A}$

where d = total depth of flow

h = deflected height of vegetation

A = total cross-sectional area of channel

Ap = cross-sectional area of flexible elements

which has been proposed by some investigators, did not prove enlightening and so is not discussed further in the present report. However, it was found from the correlation with $\frac{d}{h}$ that the value of the coefficient r in Equation 3 lay between 1.2 and 4.4.

An alternative relation $\frac{v}{v_*} C_1 + C_2 \log d$ (4)

Ref 10

where C_1 = constant dependent on vegetation properties such as height, width and shape

C_2 = coefficient

was hoped to be more suitable, and a plot of $\frac{v}{v_*}$ against log d is given in Fig 7. By examination of the plotted points which appeared to have similar values of k, the coefficient C_2 in Equation 4 was evaluated as 5.35 over the range of values of the constant $4.5 < C_1 < 11.5$. No convincing relation between C_1 and $\frac{d}{h}$ could be discerned.

In view of the marked influence of the flexible elements on the vertical velocity profiles, which has already been discussed, the measurements obtained were re-considered taking account only of flow above the simulated vegetation. The relation between $\frac{v_u}{v_*}$ against $\log d_u$

where v_u = mean flow speed in the cross-sectional area above the flexible elements ("vegetation") i.e. $(A-A_p)$

$v_* = (g\ d_u S)^{0.5}$

d_u = depth of vegetation-free flow area i.e. (d-h), deduced from the velocity profiles

is shown in Fig 8. The scatter in this plot is greatly reduced compared with Fig 7 and there appears to be a relation between the two parameters, with $\frac{v_u}{v_*}$ tending to a steady value of 8.0 at the greatest depth used in the laboratory flume tests.

Furthermore, Manning's n_u for the upper flow area only, shown related to specific discharge $(v \times R)_u$ in Fig 9, was much reduced to values generally between 0.005 and 0.035 although with considerable scatter.

4 FIELD STUDY

4.1 Preliminary reconnaissance

The advice was first sought of the Water Authorities whose areas were most likely accessible from Wallingford regarding the choice of field sites. The requirements were:-

(a) seasonal growth of vegetation i.e. plentiful at one time of year, dying away to almost none,

(b) reasonably long, straight reach,

(c) adjacent to a permanent Water Authority gauging station

(d) free from obstructions in the channel i.e. fallen trees, and preferably not overhung by trees growing on the banks,

(e) permission from the land owner to enter and work.

Inspections were made at eleven sites in the Thames and Southern Water Authority area, from which two were selected, namely:-

(a) River Anton near Fullerton, Hants (Plate 6).

(b) River Wey (North Branch) near Farnham, Hants (Plate 7).

Each river provided a working section which was about 110m in length, albeit with minor variation within that length, was between 8m and 15m width, and lay immediately downstream of a gauging weir.

4.2 Initial preparations

At each site, the working reach was found to fall into two distinct sub-reaches of slightly different channel depth or water surface slope. Three permanent bench marks for level and location reference were set up, at the upstream and downstream extremities of the working reach and at the transition point. These marks consisted of a length of steel pipe set into a concrete pad. Further reference marks for location only were provided midway between the bench marks. The resulting chain of ten marks was then fixed in location by ground survey and levelling.

4.3 Aerial photography

From the start of the investigation it was decided that the extent, density and if possible the species population of vegetation in the chosen reaches should be monitored regularly. Particularly, it was hoped to relate hydraulic observations to seasonal changes in the vegetation.

The obvious way of obtaining overall information about the vegetation colony was by overhead photography, possibly using infra-red or false colour film for improved discrimination. Many alternative methods of supporting the overhead camera were available, such as a portable tower frame, a tethered balloon, a free-flying model airship, a model helicopter, a model aeroplane, a full-size aeroplane or a full-size helicopter. In the knowledge of successful use of model aeroplanes by regional Water Authorities, other research institutions and indeed by Hydraulics Research Ltd in another investigation, this method was tried first.

However, no useful results were obtained from the model aircraft, due partly to the difficulty of precisely locating the aircraft to produce the required large-scale negative and partly to the need to fly on pre-selected days when weather conditions were not always suitable.

Further photography was then carried out successfully using a full-size helicopter hired from an operator based near Fullerton. An example of this is shown in Plate 8.

4.4 Field surveys

Successive visits were made to carry out the following work:-

(a) hydrographic survey defining the plan shape of each reach and a series of nine cross-sections across it,

(b) hydraulic survey measuring water levels including that upstream of the gauging weir,

(c) botanical survey recording the species, distribution and deflected height of vegetation on selected cross-sections (a). This is reported under section 4.6 of the present report.

4.5 Results of field study

The values obtained from the River Anton and Wey for equivalent roughness k and Manning's n are shown in

Figs 5 and 6 respectively, superimposed on measurements from the laboratory flume.

The field values of k in Fig 5 range from about 0.6 to 1.3m for hydraulic depths 0.4-0.55m while Fig 6 shows that the values of n derived for the River Anton, where the average height of vegetation was 0.016m in the upper reach and 0.025m in the lower reach, correspond to Stillwater category C (dense grass 0.15-0.30m).

From the relation of $\frac{v}{v_*}$ against log R for data from the River Anton, it was deduced that the value of r in Equation 3 lay between 9.6 and 11.0.

The values of k and n discussed above, which assumed flow through the total wetted area of the channel, are disturbingly large. It had been planned to make field velocity measurements, similar to those in the laboratory flume tests, to compare flow in the vegetated zone with that in the unobstructed channel above. These had not been carried out at the time of writing the present report, but a further analysis was made assuming no flow in the lower vegetated zone, in line with the laboratory findings. Alternative values of k_u and n_u are shown in Table 2, assuming flow only in the upper, clear zone. Fig 8 plots $\frac{v_u}{v_*}$ against the logarithm of depth of the clear upper zone only, and shows values of $\frac{v_u}{v_*}$ only slightly larger than for the laboratory flume tests at greatest depths. This suggests a trend with increasing depth to a near-constant value of this parameter which is not greatly affected by either the nature or the distribution of the vegetation. Fig 9 plots Manning's n_u for the upper flow zone of the River Anton (listed in Table 2 as sub-values for the upstream and downstream reaches, but combined as a mean for each measurement occasion in Fig 9) against $(v \times R)_u$. The values were closely comparable to those from the flume tests under similar conditions.

In conclusion, the present work in both the laboratory and the field suggests that the assumption that flow occurs only in the upper, unvegetated zone may not be wholly true but would repay confirmation over a wider range of flow conditions and plant colonies. However, in order to design a channel containing vegetation other work would be necessary to predict the deflected height of the plants in order to obtain the effective flow depth.

4.6 Botanical survey

The first survey of the River Anton carried out on 14 November 1984, revealed four dominant species of plants: Apium, Callitriche, Ranunculus, and Oenanthe. Table 3 summarises the proportion of each cross-section occupied by the four species, but not the depth or the spacing of the plants within each colony.

A preliminary botanical survey of the River Wey was carried out on 9 December 1984, but at that time so little plant growth was present in the channel that no result is given here.

Powell, in his study of rivers in East Anglia (Ref 14) found that the most frequent species present there were Potamogeton, Elodea, Vaucheria and Euteromorpha. His work, extending over 10 years, showed values of Manning's n ranging from 0.02 to 0.05 during the winter months of November-December, rising to 0.10 during the growth season. In the River Anton, values of n during the same two winter months were considerably larger, varying from 0.06 to 0.08 (assuming flow over the total area of cross-section). This may partly be explained by a difference in river management; in the East Anglian rivers weeds are cut and the channel cleared during the autumn i.e. immediately preceding Powell's observations, but in the Anton the clearance period is April-May so that measurements were made after almost six months further growth.

5 CONCLUSIONS

Many papers have been written on the subject of flow in vegetated waterways. Reference to them can be confusing and misleading unless care is taken to ensure that conditions in any proposed application are similar to those from which the conclusions presented were drawn.

The preliminary results from both the flume, in which the simulated vegetation was of simple form and sparsely distributed, and the field (complex forms of vegetation, closely spaced) suggest that the flow area is generally confined to above the level of the deflected vegetation. At present, however, there is no method of calculating in advance the deflected height of the vegetation.

The small proportion of the flow which passes through the roughness elements is nearly uniform while the majority, above the vegetation, has a logarithmic velocity profile.

The flume tests show a value of Manning's n varying between about 0.04 to 0.2 when the full channel section was assumed to carry the flow, and between about 0.005 to 0.035 when flow above the elements only was considered. The measurements made in the River Anton showed ranges of about 0.06 to 0.09 for the full section and about 0.02 to 0.03 for flow above the vegetation only.

The values of n deduced for the River Anton in November and December are greater than those obtained by Powell (Ref 14) for rivers in East Anglia. The difference may be due in part to the cutting of vegetation in East Anglia in autumn; there was no cutting on the Anton at this time.

The results of both flume and field tests agreed fairly well with the predictions made using the proposals contained in the report by the Stillwater Laboratory (Ref 17) and it is suggested that until other recommendations are available, the methods suggested in that report be used for design purposes.

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(iv) Mr T Marsh (model aircraft photography).

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T A B L E S

TABLE 1 - SUMMARY OF RESULTS OF LABORATORY FLUME TESTS.

FIRST SERIES

Test No	Discharge (ℓ/s)	Depth (mm)	Slope ($\times 10^{-3}$)	n	k (m)
1 a	11.0	238.0	0.806	0.215	1.648
1 b	11.0	235.8	0.554	0.176	1.472
2 a	11.0	169.1	0.967	0.134	0.917
2 b	11.0	166.7	0.831	0.121	0.840
3 a	11.0	122.3	1.619	0.101	0.553
3 b	11.0	119.1	1.312	0.087	0.468
4 a	19.6	225.6	1.216	0.136	1.197
4 b	19.6	223.1	0.656	0.098	0.892
5 a	19.5	178.9	1.179	0.091	0.691
5 b	19.5	175.9	1.385	0.095	0.711
6 a	19.5	122.5	2.425	0.070	0.371
6 b	19.5	117.6	2.690	0.069	0.352
7 a	40.0	217.8	1.597	0.072	0.607
7 b	40.0	214.7	1.050	0.057	0.418
8 a	40.0	178.2	2.220	0.061	0.406
8 b	40.0	174.3	1.501	0.048	0.235
9 a	40.0	118.5	5.656	0.049	0.211
9 b	40.0	109.1	4.563	0.038	0.121
10 a	78.5	225.7	2.806	0.051	0.359
10 b	78.5	220.6	2.369	0.046	0.275
11 a	79.1	177.4	5.399	0.048	0.262
11 b	79.1	168.2	4.315	0.039	0.161
12 a	78.5	160.5	6.608	0.045	0.216
12 b	78.5	147.7	6.465	0.039	0.147

Note:- a = upstream half of working length

b = downstream half of working length

TABLE 1 - SUMMARY OF RESULTS OF LABORATORY FLUME TESTS. SECOND SERIES

Test No	Discharge (ℓ/s)	Depth (mm)	Height of elements (mm)	Slope ($x10^{-3}$)	n	k (m)	υ (mm/s)	n_u*	k_u* (m)
13 a	79.0	154.7	47.5	6.051	0.042	0.181	707	0.0227	0.0241
13 b	79.0	143.4	44.0	4.905	0.033	0.096			0.0085
14 a	79.0	232.8	60.5	1.963	0.044	0.263	398	0.0267	0.0530
14 b	79.0	229.0	59.5	1.501	0.038	0.188			0.0315
15 a	79.0	174.3	47.2	4.264	0.041	0.188	578	0.0243	0.0335
15 b	79.0	166.7	45.2	3.418	0.034	0.115			0.0155
16 a	40.3	104.6	52.2	6.227	0.042	0.140	529	0.0131	0.0015
16 b	40.3	91.9	45.9	6.582	0.034	0.084			0.0005
17 a	40.3	165.2	59.6	1.780	0.048	0.249	288	0.0226	0.0237
17 b	40.3	161.6	58.3	1.443	0.041	0.183			0.0131
18 a	40.4	229.3	66.0	0.842	0.056	0.431	212	0.0321	0.0942
18 b	40.4	227.1	65.4	0.620	0.048	0.309			0.0546
19 a	20.0	231.4	77.0	0.293	0.068	0.589	95	0.0348	0.1148
19 b	20.0	229.7	76.5	0.306	0.069	0.595			0.1177
20 a	20.0	171.7	69.0	0.293	0.059	0.375	140	0.0249	0.0339
20 b	20.0	169.7	68.2	0.306	0.054	0.320			0.0244
21 a	20.0	114.1	53.7	1.626	0.049	0.208	217	0.0171	0.0062
21 b	20.0	110.8	52.2	1.210	0.041	0.139			0.0023
22 a	20.0	73.7	49.6	5.575	0.044	0.125	355	0.0069	0.0000
22 b	20.0	60.0	40.4	8.812	0.040	0.341			0.0000
23 a	20.0	56.2	42.8	4.601	0.051	0.132	205	0.0047	0.0000
23 b	20.0	42.8	32.6	10.510	0.046	0.101			0.0000
24 a	10.0	115.0	78.2	0.593	0.061	0.296	96	0.0092	0.0001
24 b	10.0	113.0	76.8	0.583	0.059	0.276			0.0001
25 a	9.8	170.1	100.0	0.220	0.072	0.504	707	0.0165	0.0053
25 b	9.8	168.5	99.1	0.284	0.081	0.576			0.0090
26 a	9.8	222.3	98.5	0.168	0.099	0.896	47	0.0372	0.1206
26 b	9.8	220.8	97.8	0.241	0.117	1.043			0.1753

Note:- a = upstream half of working length
b = downstream half of working length
* = for flow above plant elements only

TABLE 2 - SUMMARY OF RESULTS OF FIELD MEASUREMENTS

River	Date	Discharge (m^3/s)	Reach+	Section	Wetted perimeter (m)	Area (m^3)	Hydraulic depth (m)	n_u*	k_u*	Water surface slope ($\times 10^{-6}$)
Anton	14.11.83	1.318	1-5	T	12.48	5.46	0.438	0.075	1.06	954
				U	12.30	3.34	0.272	0.031	0.13	954
			5-9	T	10.73	5.98	0.557	0.083	1.30	708
				U	10.52	3.03	0.288	0.030	0.06	708
	28.11.83	1.358	1-5	T	12.35	5.10	0.413	0.064	0.79	919
				U	12.17	2.99	0.246	0.024	0.06	919
			5-9	T	10.60	5.62	0.530	0.074	1.18	708
				U	10.41	2.75	0.264	0.026	0.03	708
	8.12.83	1.358	1-5	T	12.23	4.77	0.390	0.058	0.64	936
				U	11.85	2.76	0.233	0.022	0.04	936
			5-9	T	10.50	5.37	0.511	0.069	1.03	708
				U	9.79	2.72	0.278	0.027	0.03	708
	10.12.83	1.358	1-5	T	12.25	4.83	0.394	0.063	0.74	1042
				U	11.87	2.81	0.237	0.024	0.05	1042
			5-9	T	10.51	5.40	0.514	0.068	1.00	668
				U	10.08	2.74	0.272	0.026	0.03	668
Wey	9.12.83	0.93	1-5	T	7.72	2.15	0.297	0.035	1.12	1509
			5-9	T	7.14	1.72	0.241	0.035	1.09	2194

Note:- + = 1-5 upstream portion of working length, 5-9 downstream portion

T = total cross-sectional area of channel

U = cross-sectional area of channel above deflected vegetation

* = for flow above vegetation only.

TABLE 3 - SPECIES OF PLANTS IN RIVER ANTON - 14 NOVEMBER 1984

Section	% Coverage across width			
	Apium	Callitriche	Ranunculus	Oenanthe
1 - 2	9.0	16.3	8.3	4.4
3 - 4	30.6	14.9	8.9	8.2
5 - 6	25.7	0.0	39.1	0.0
7 - 8	11.2	14.3	8.7	8.8
9 - 10	12.0	7.2	24.2	4.0

F I G U R E S

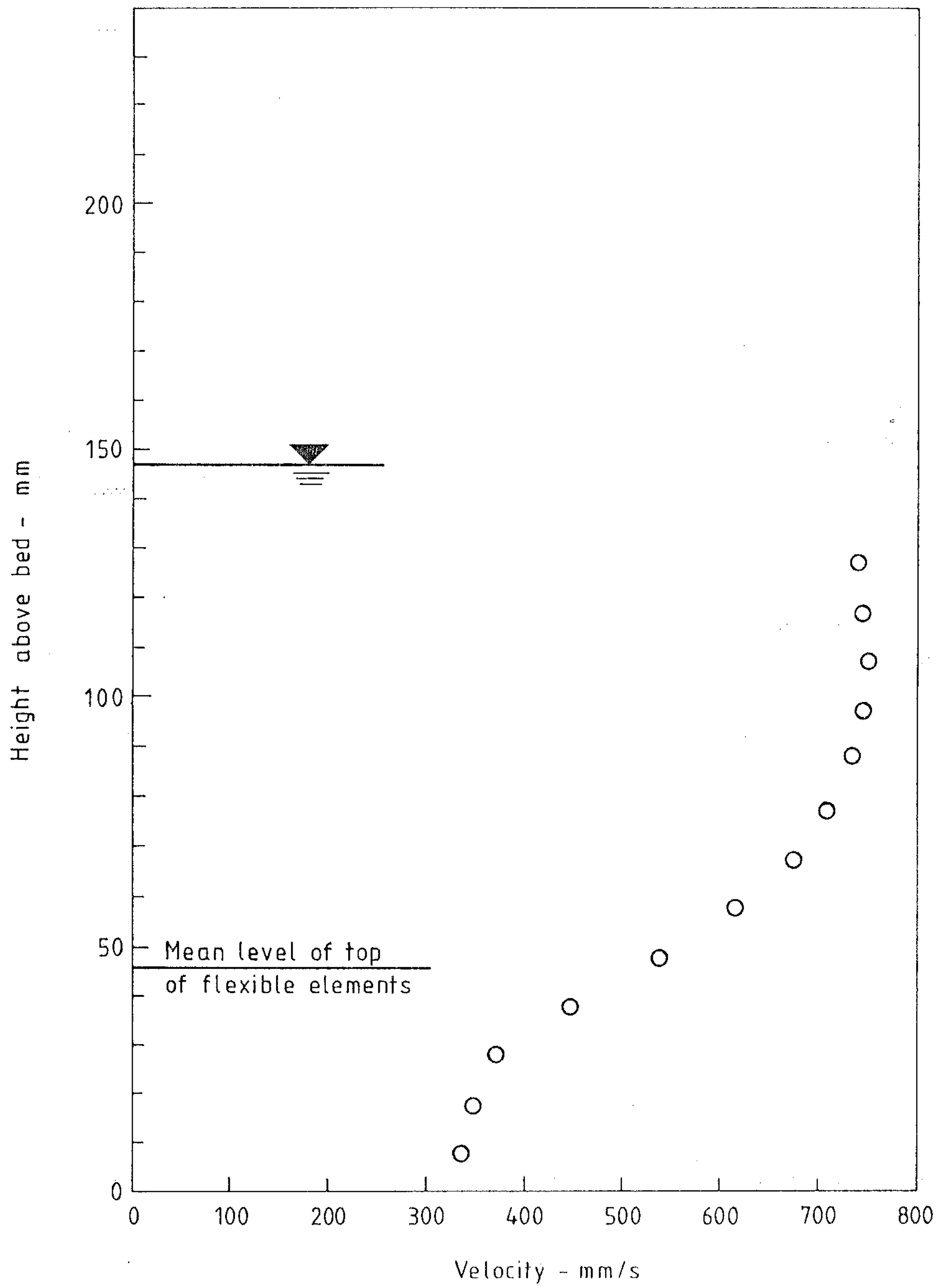

Fig. 1 Vertical velocity profile. Flume test No. 13

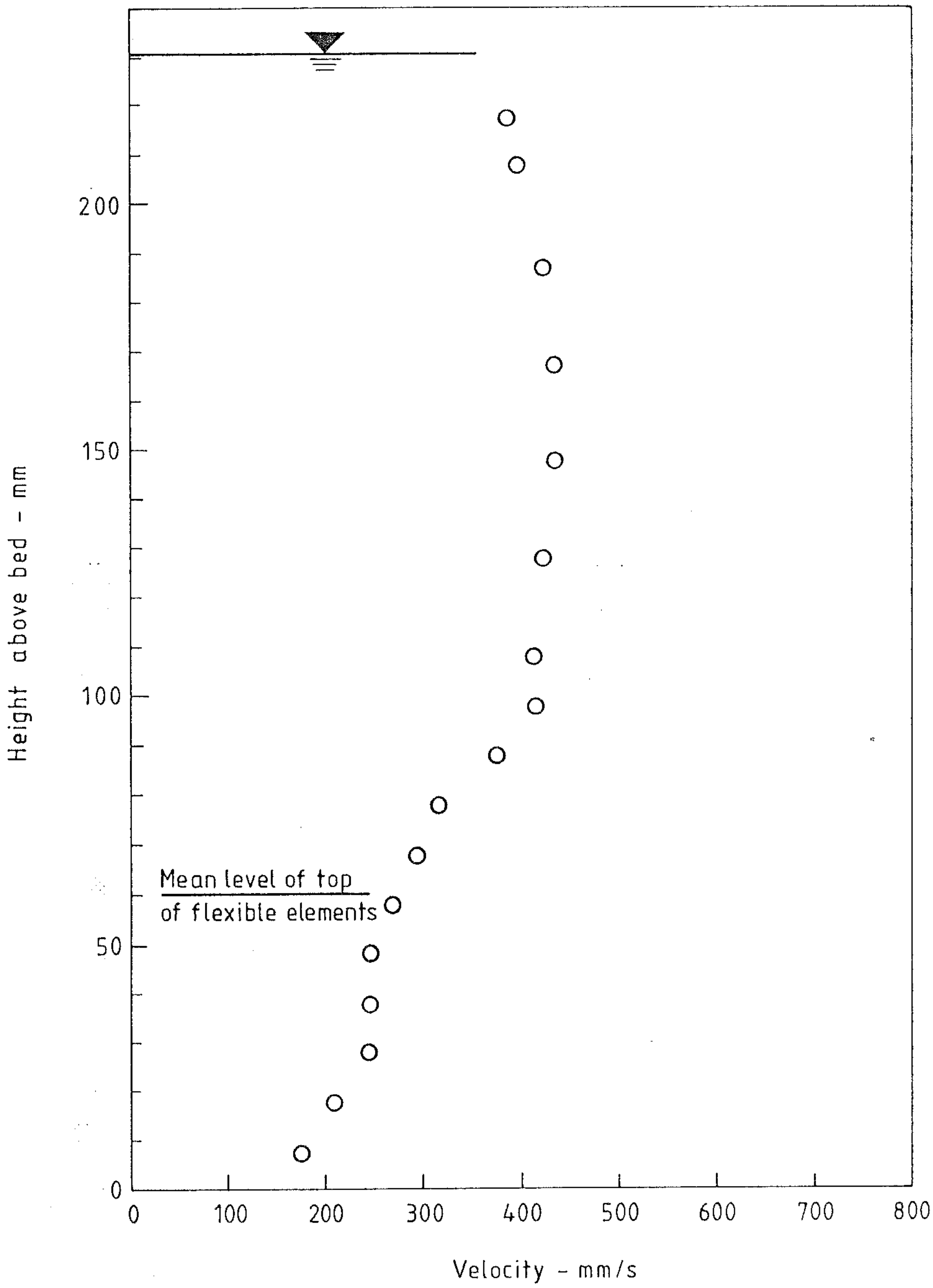

Fig. 2 Vertical velocity profile Flume test No. 14

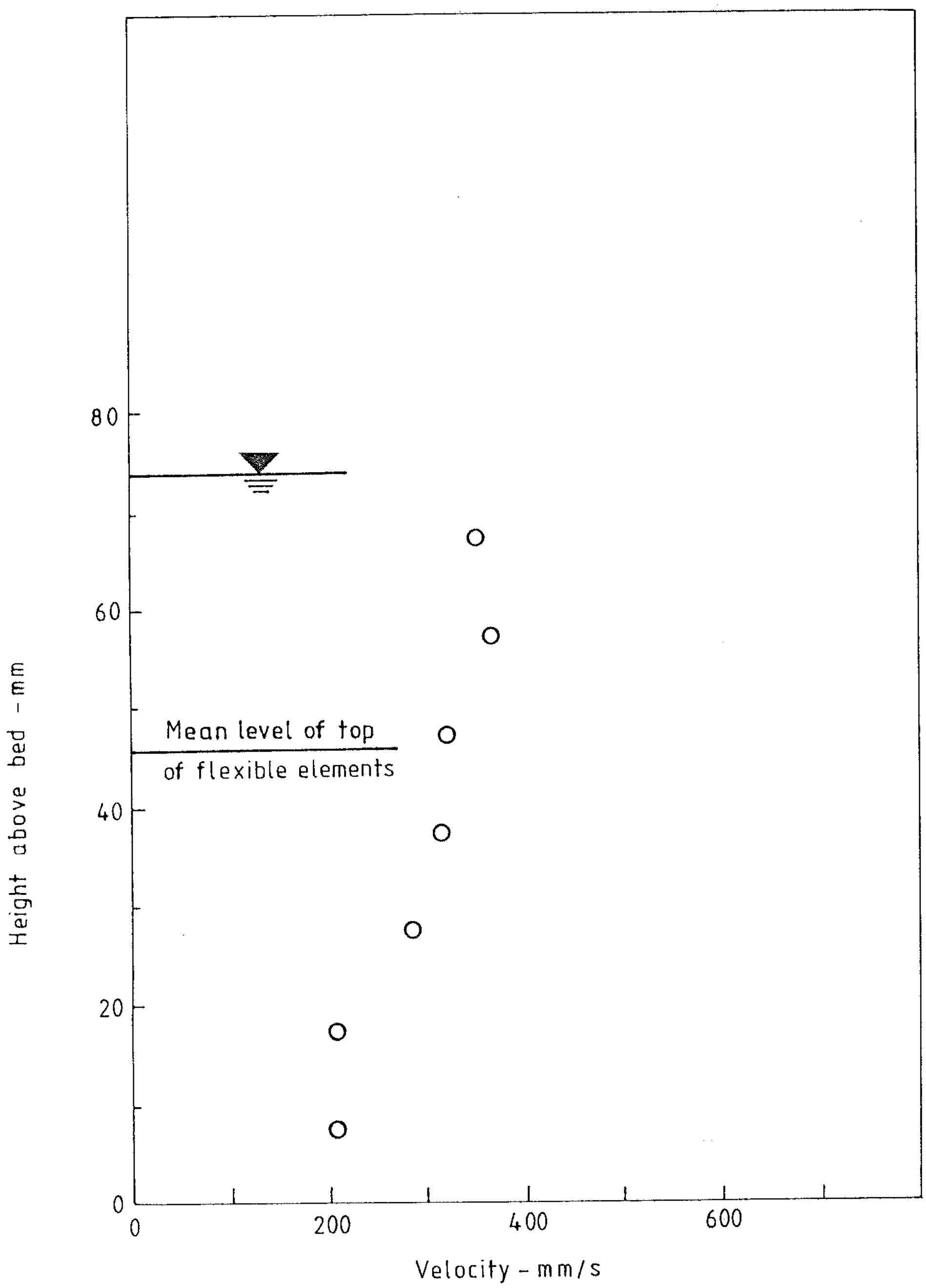

Fig. 3 Vertical velocity profile. Flume test No. 22

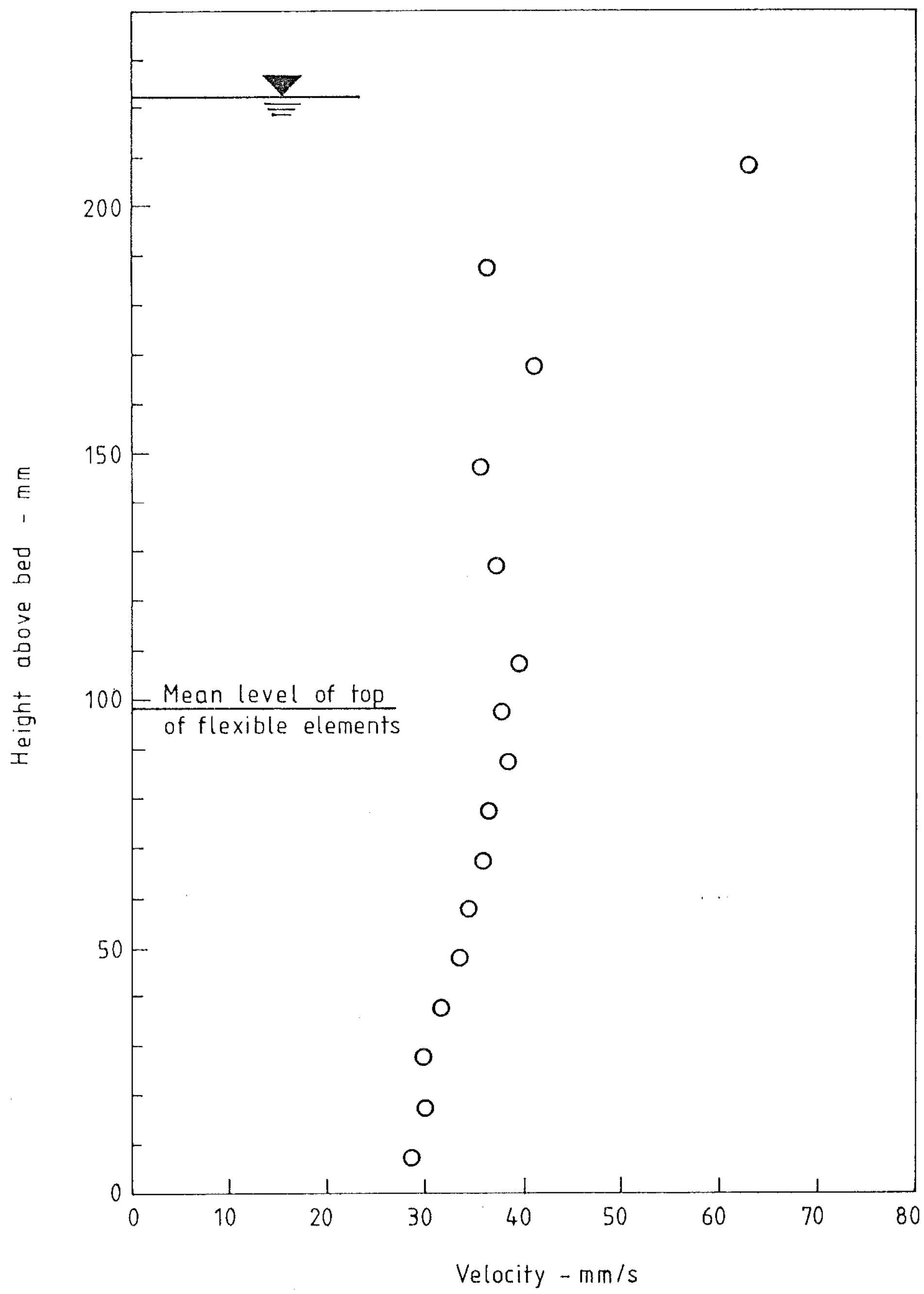

Fig. 4   Vertical velocity profile. Flume test No. 26

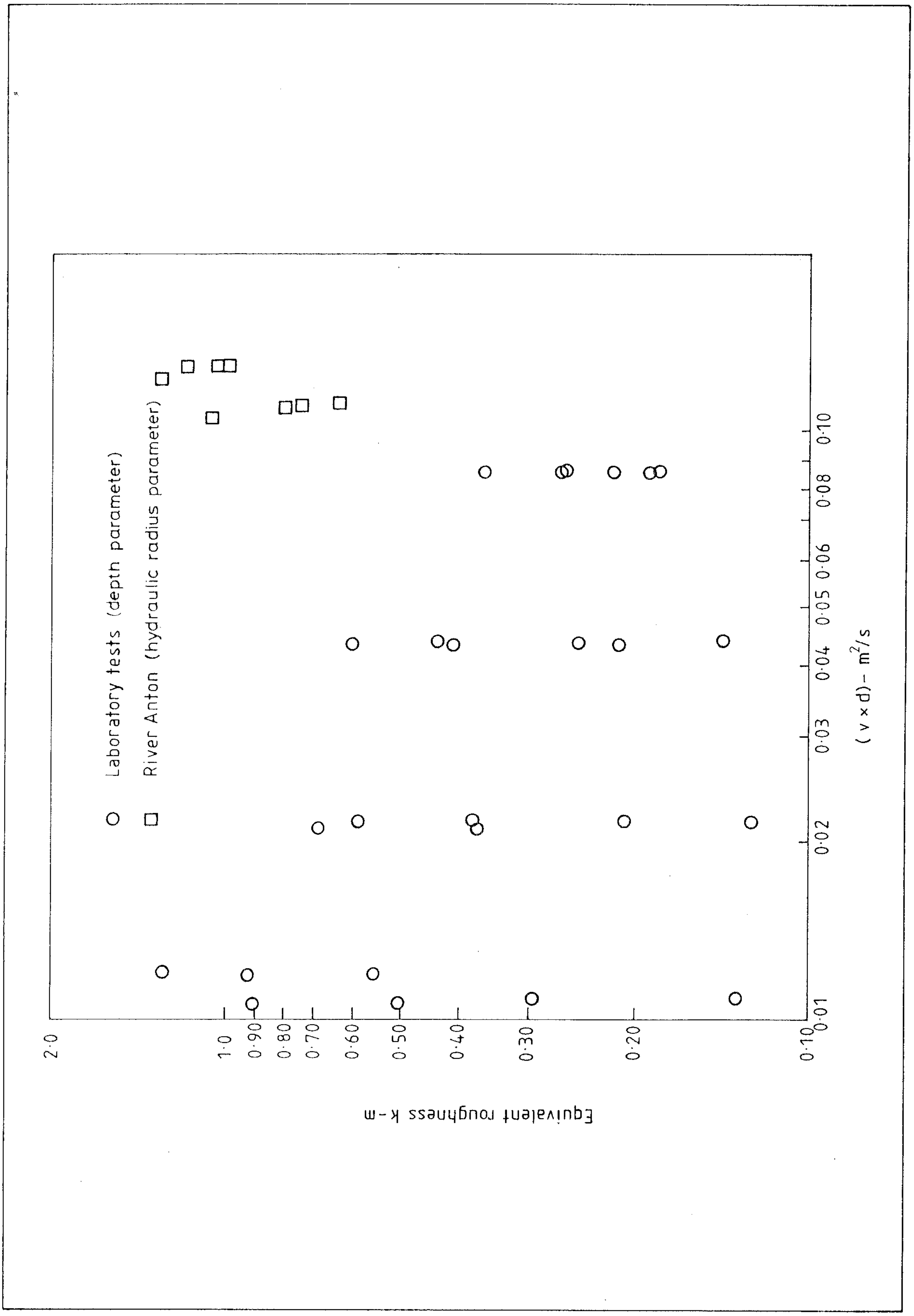

Fig 5 Relation of equivalent roughness k to product of velocity and depth

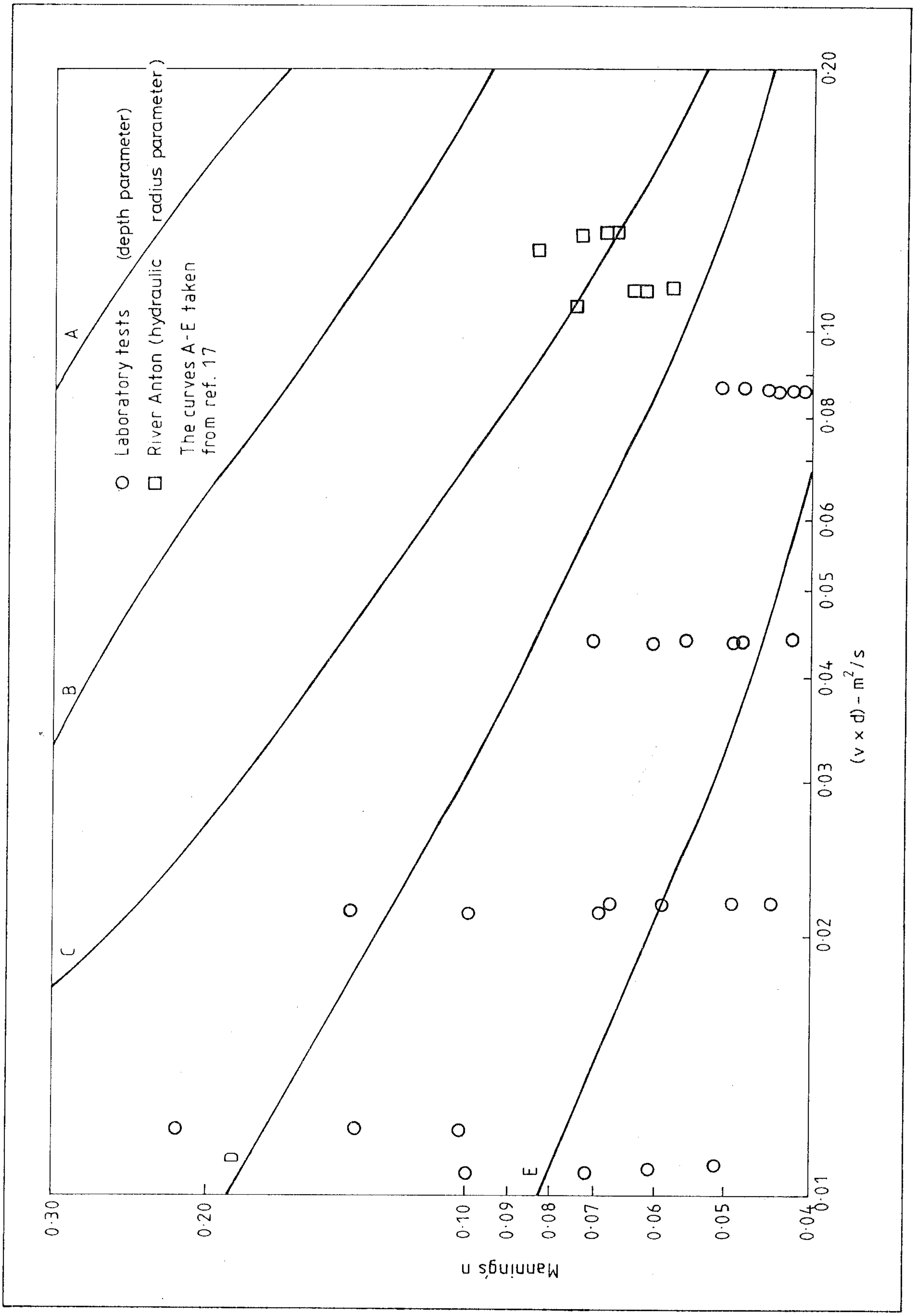

Fig 6 Relation of Manning's n to product of velocity and depth

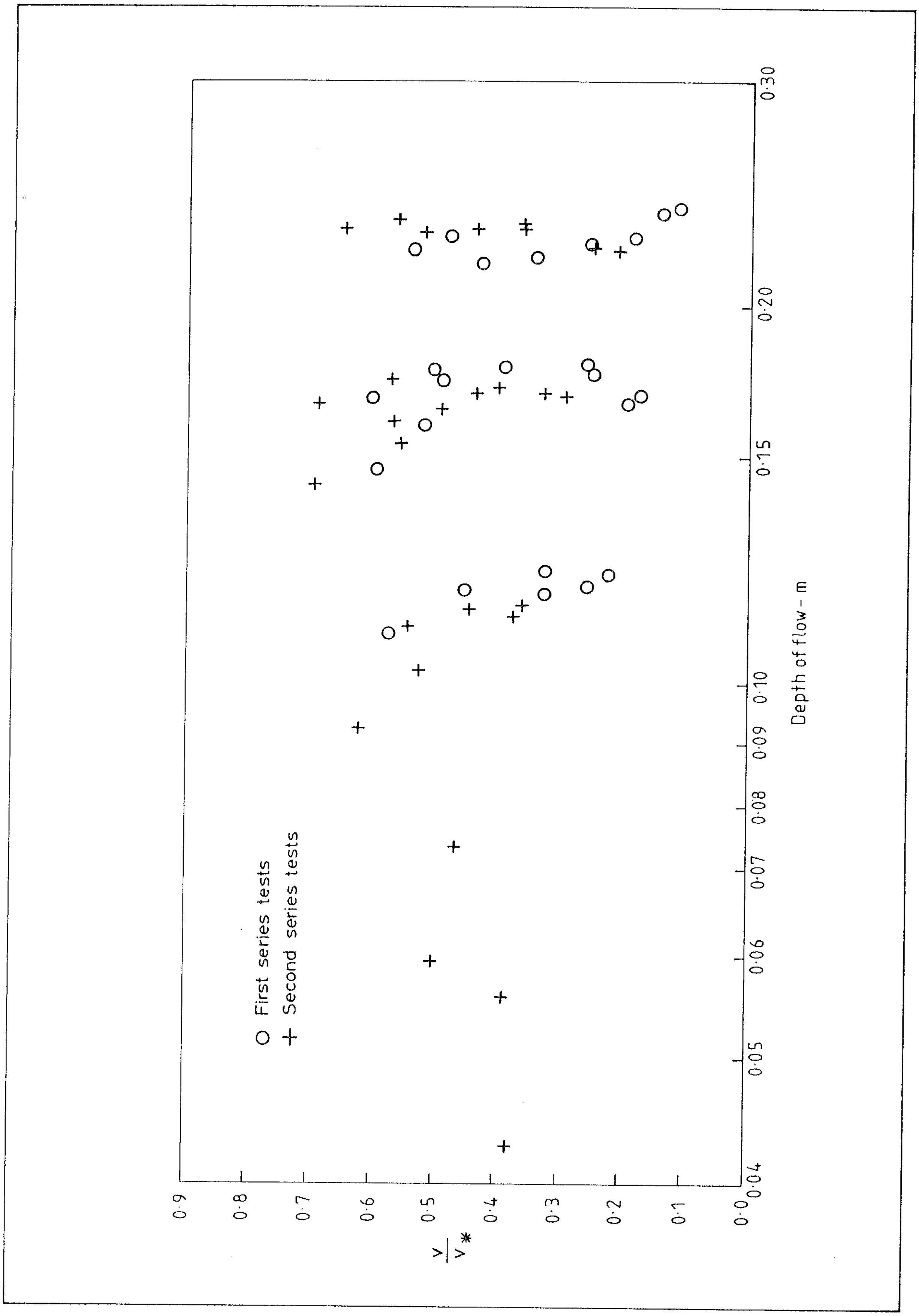

Fig 7 Relation of $\frac{v}{v_*}$ to depth of flow. Flume tests

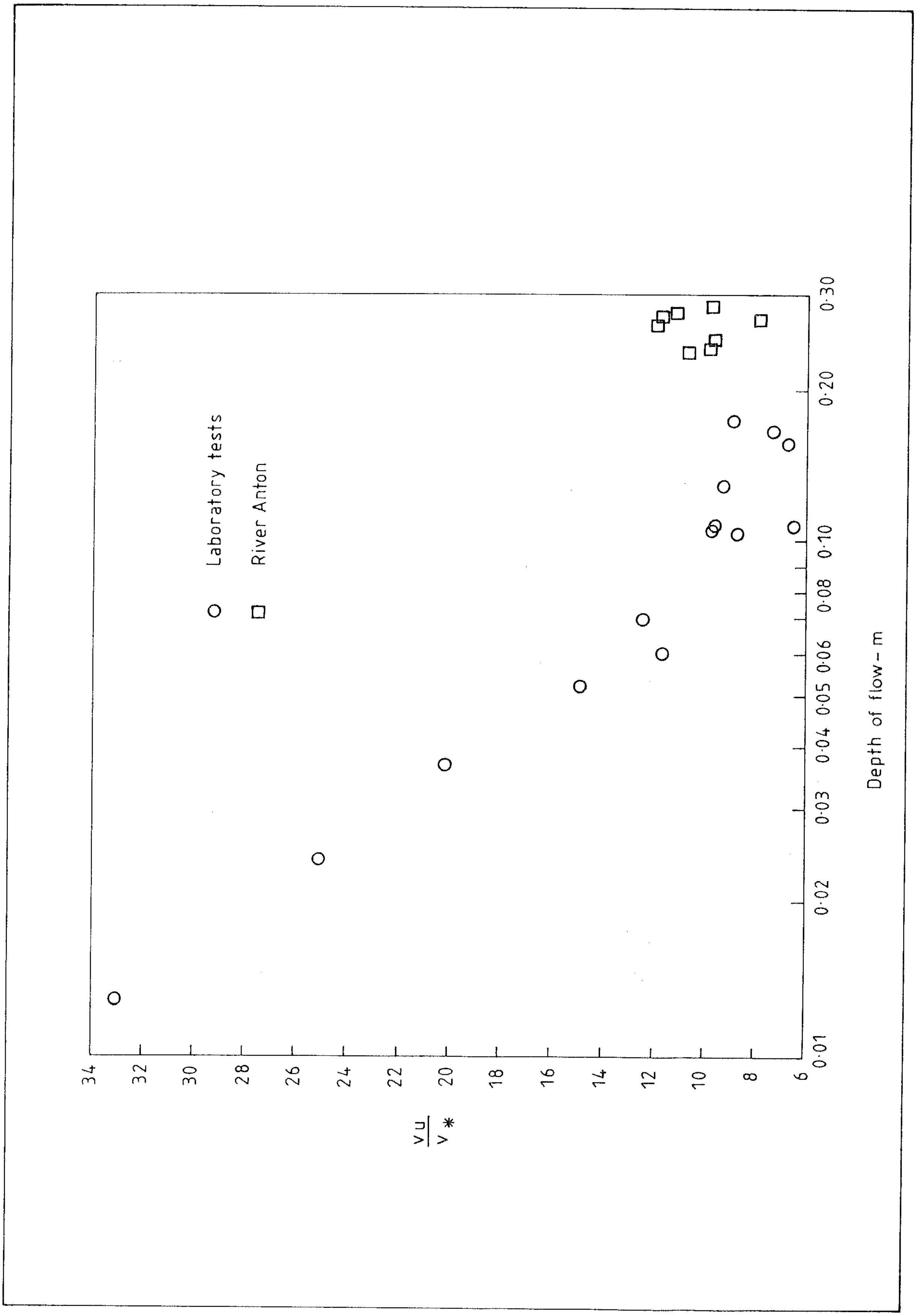

Fig 8 Relation of v_u / v_* to depth of flow above vegetation

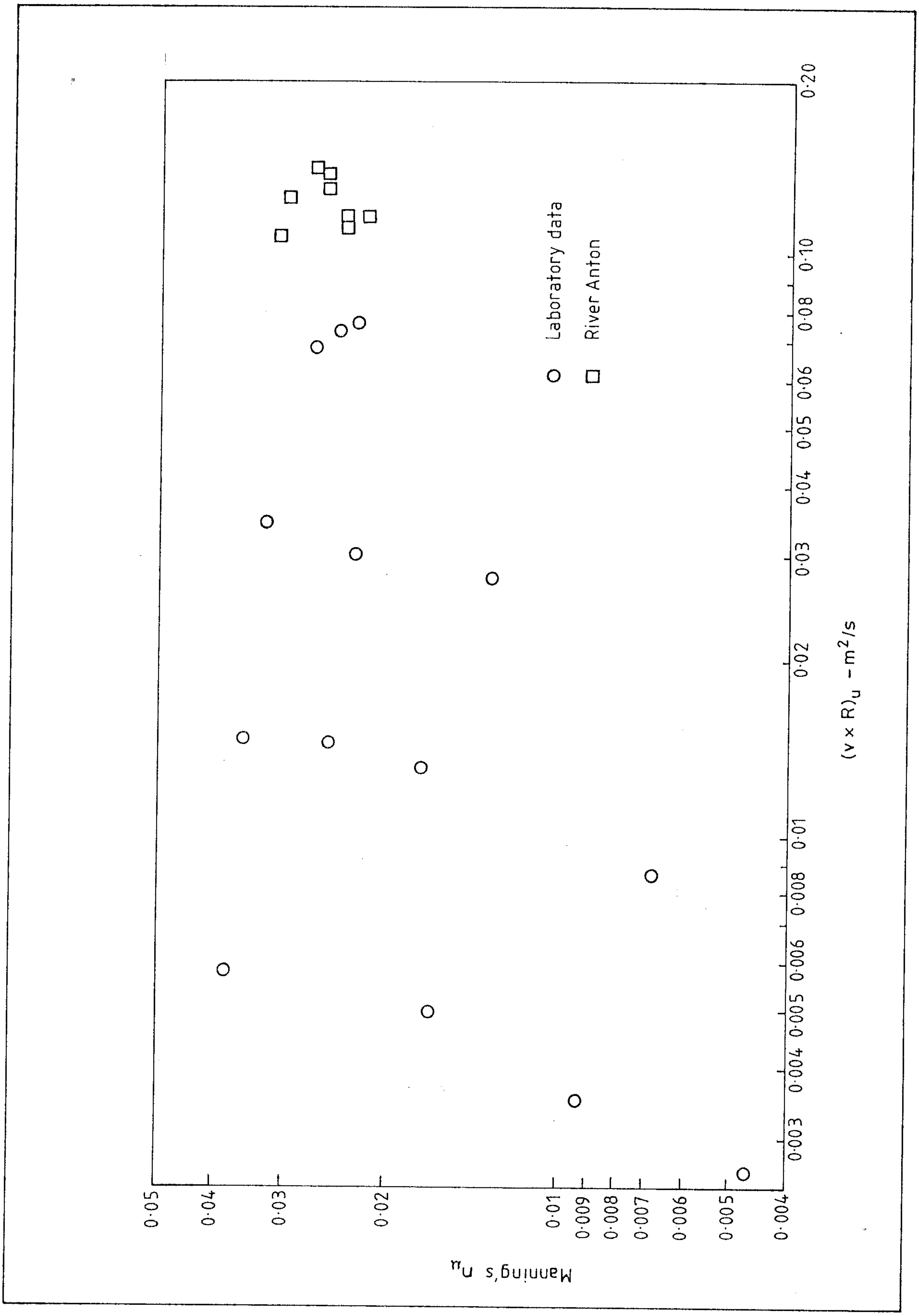

Fig 9 Relation of Manning's n to product of velocity and hydraulic depth, for flow above vegetation

P L A T E S

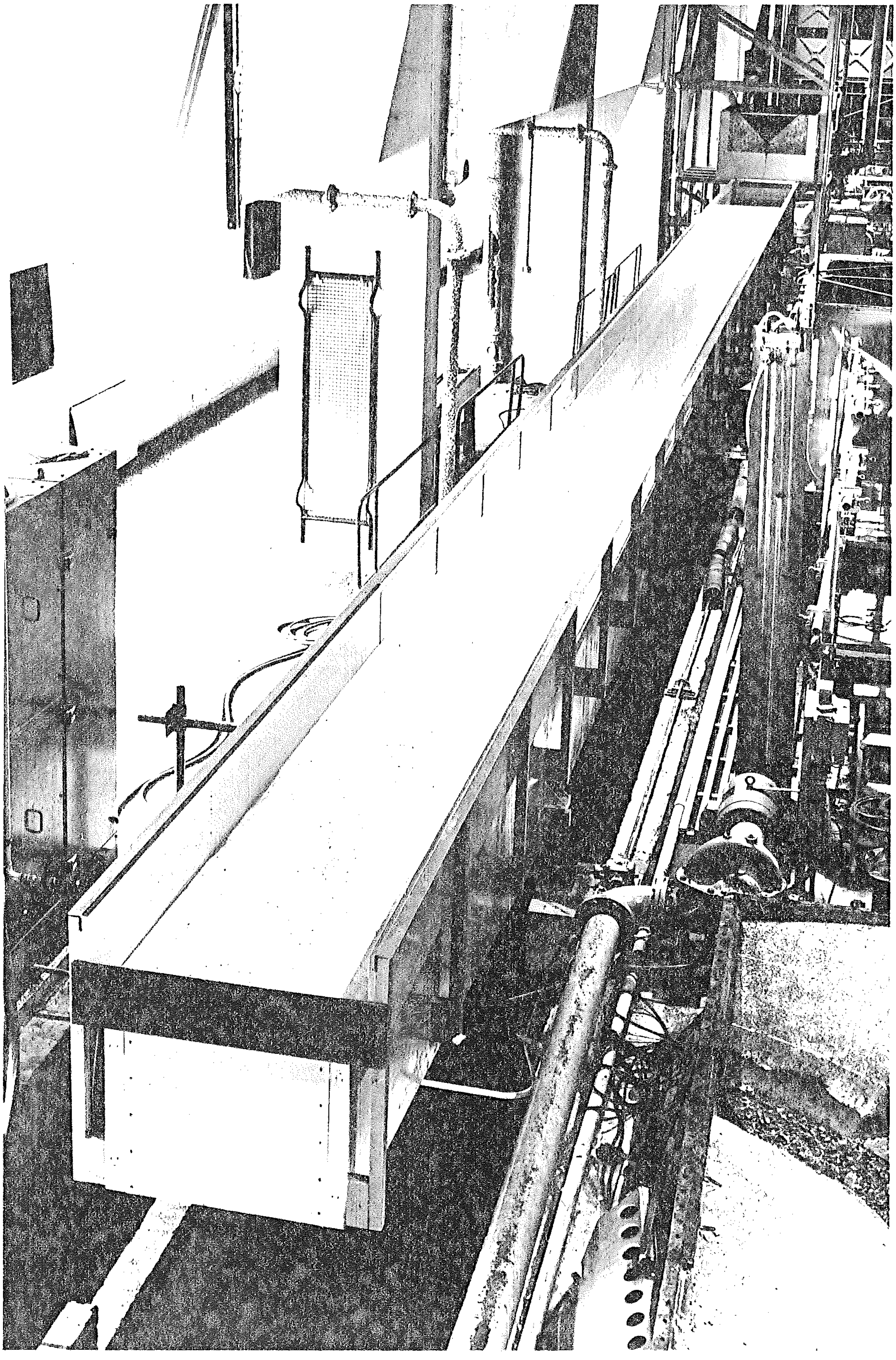

Plate 1   Laboratory flume

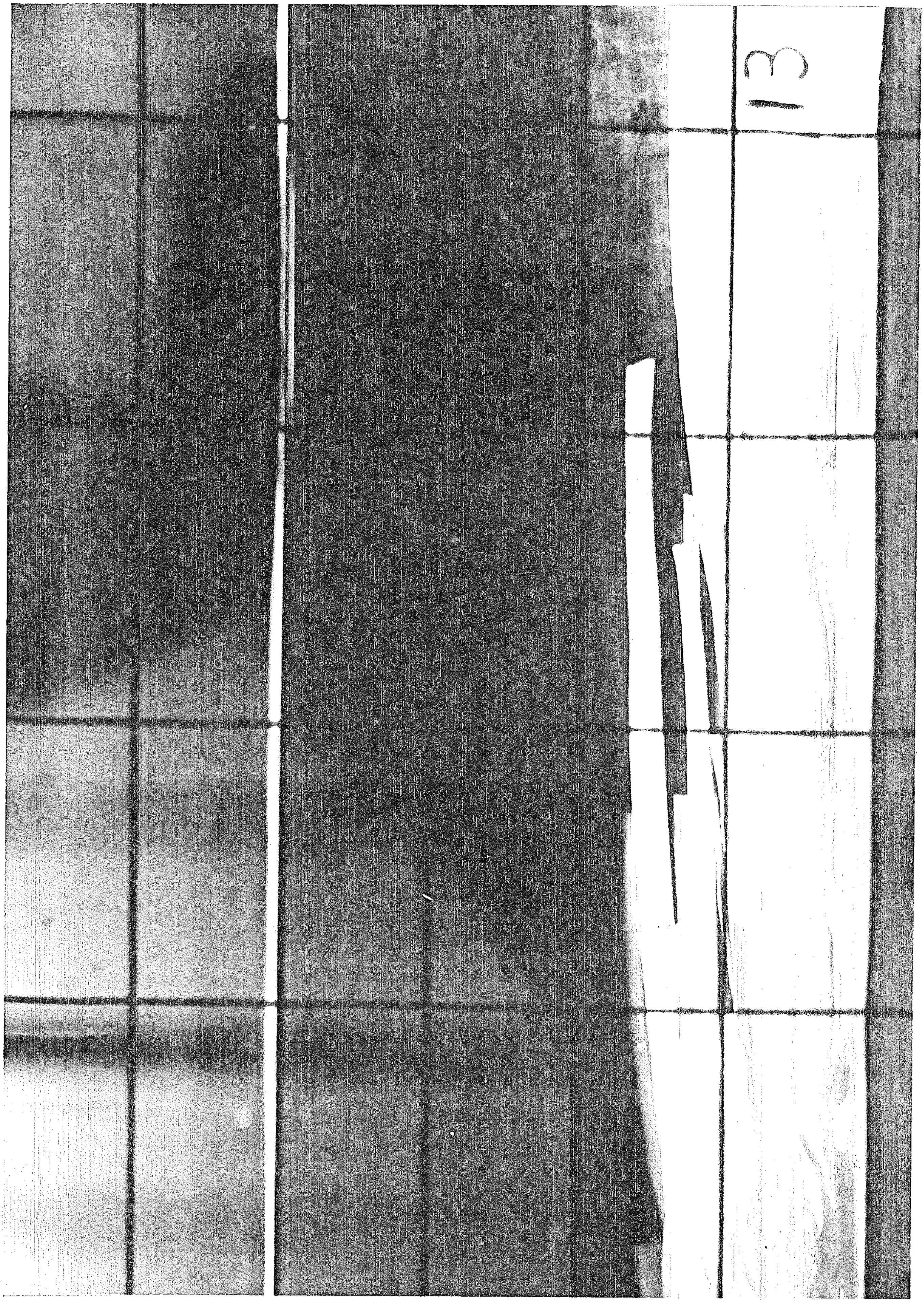

Plate 2 Deflection of elements in test 13. Grid size 75mm x 37mm

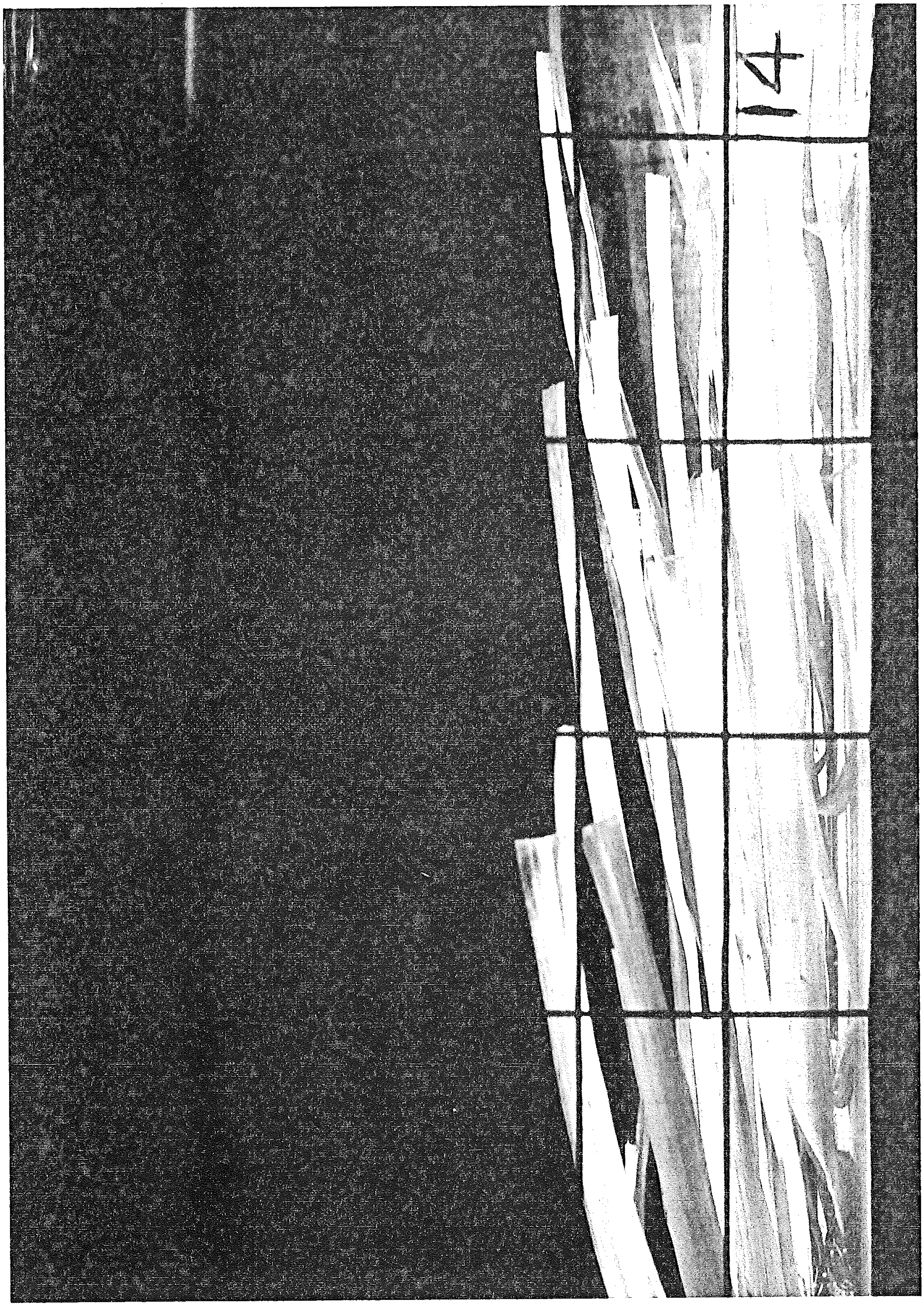

Plate 3 Deflection of elements in test 14. Grid size 75mm x 37mm

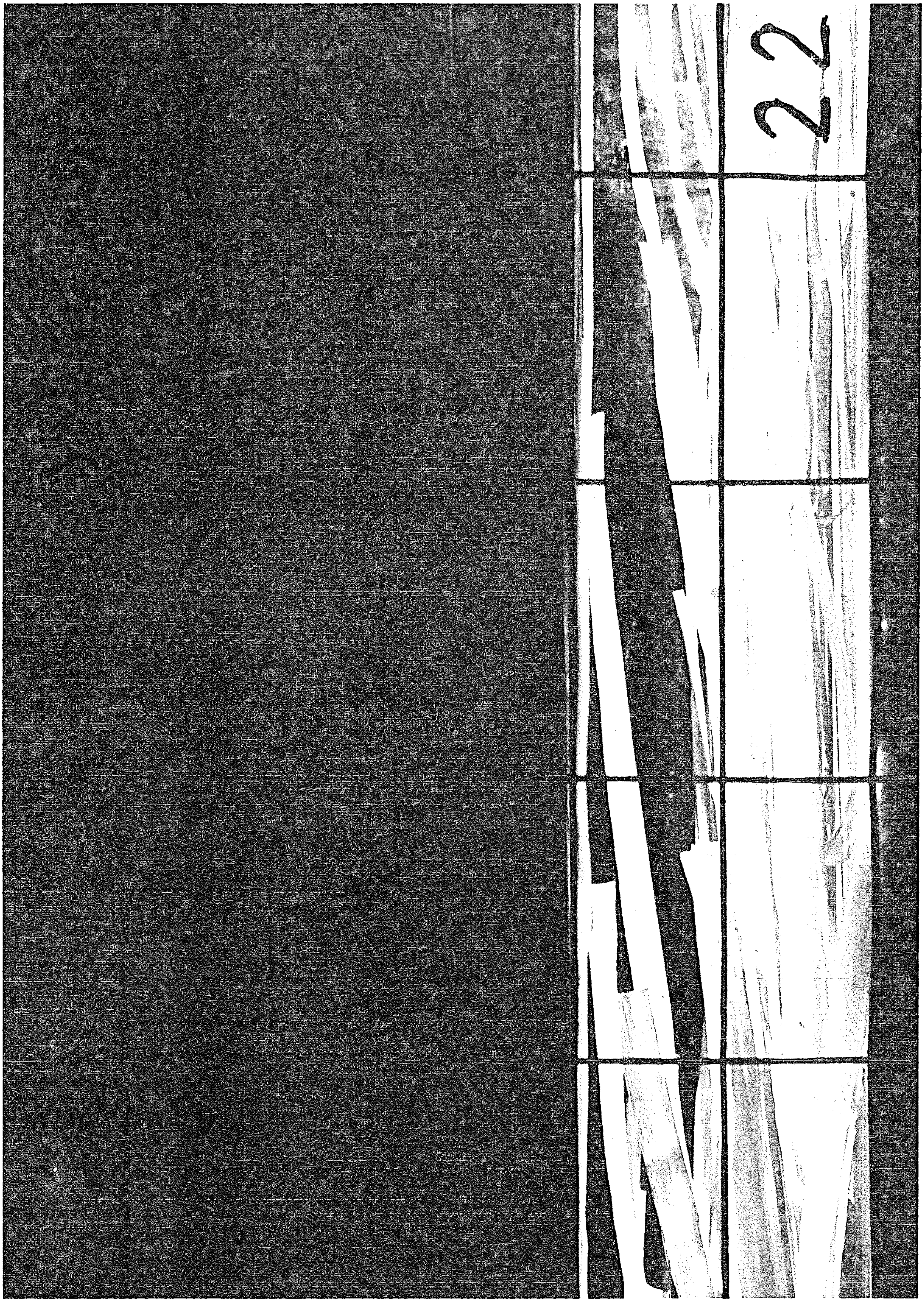

Plate 4 Deflection of elements in test 22. Grid size 75mm x 37mm

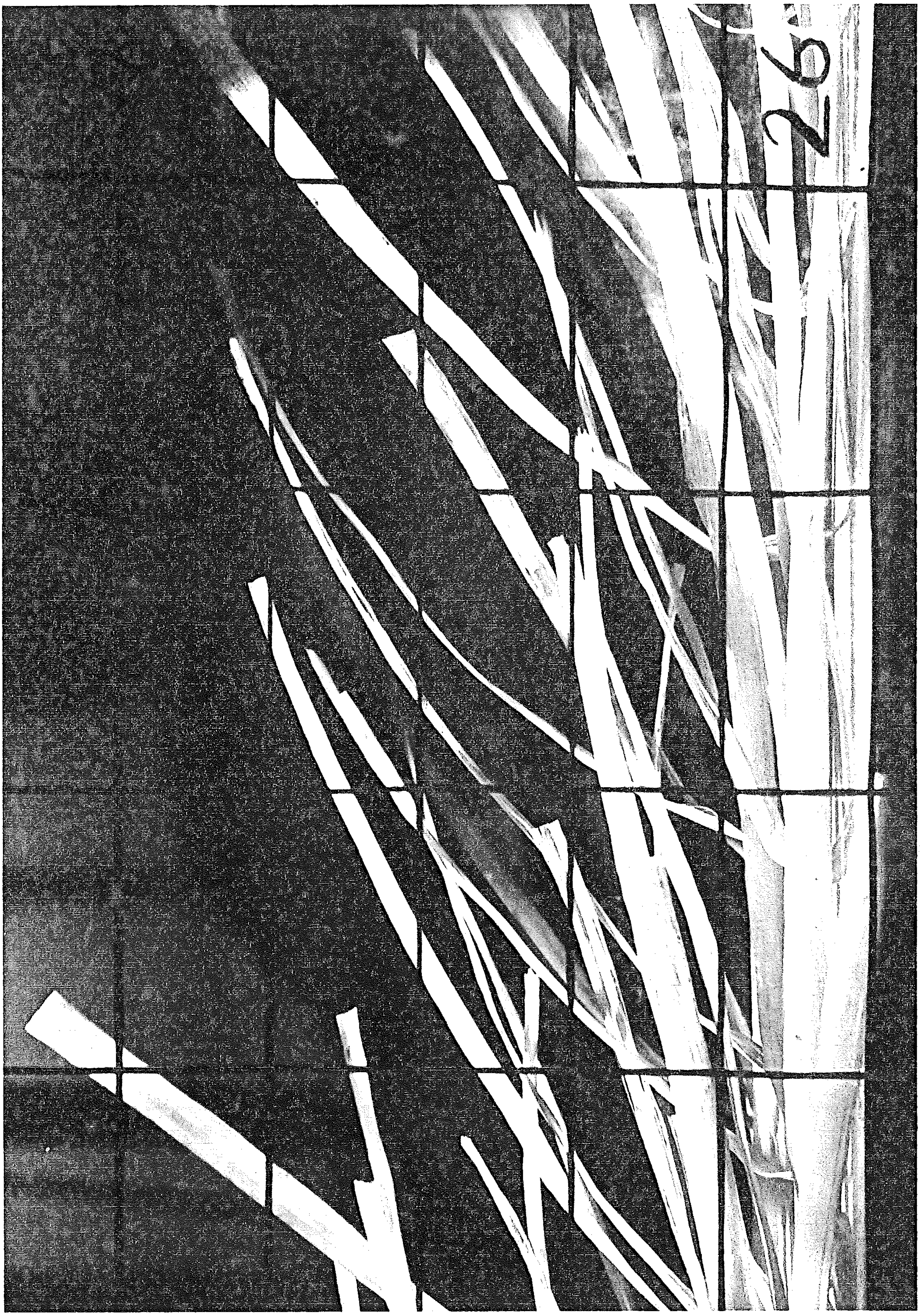

Plate 5   Deflection of elements in test 26. Grid size 75mm x 37mm

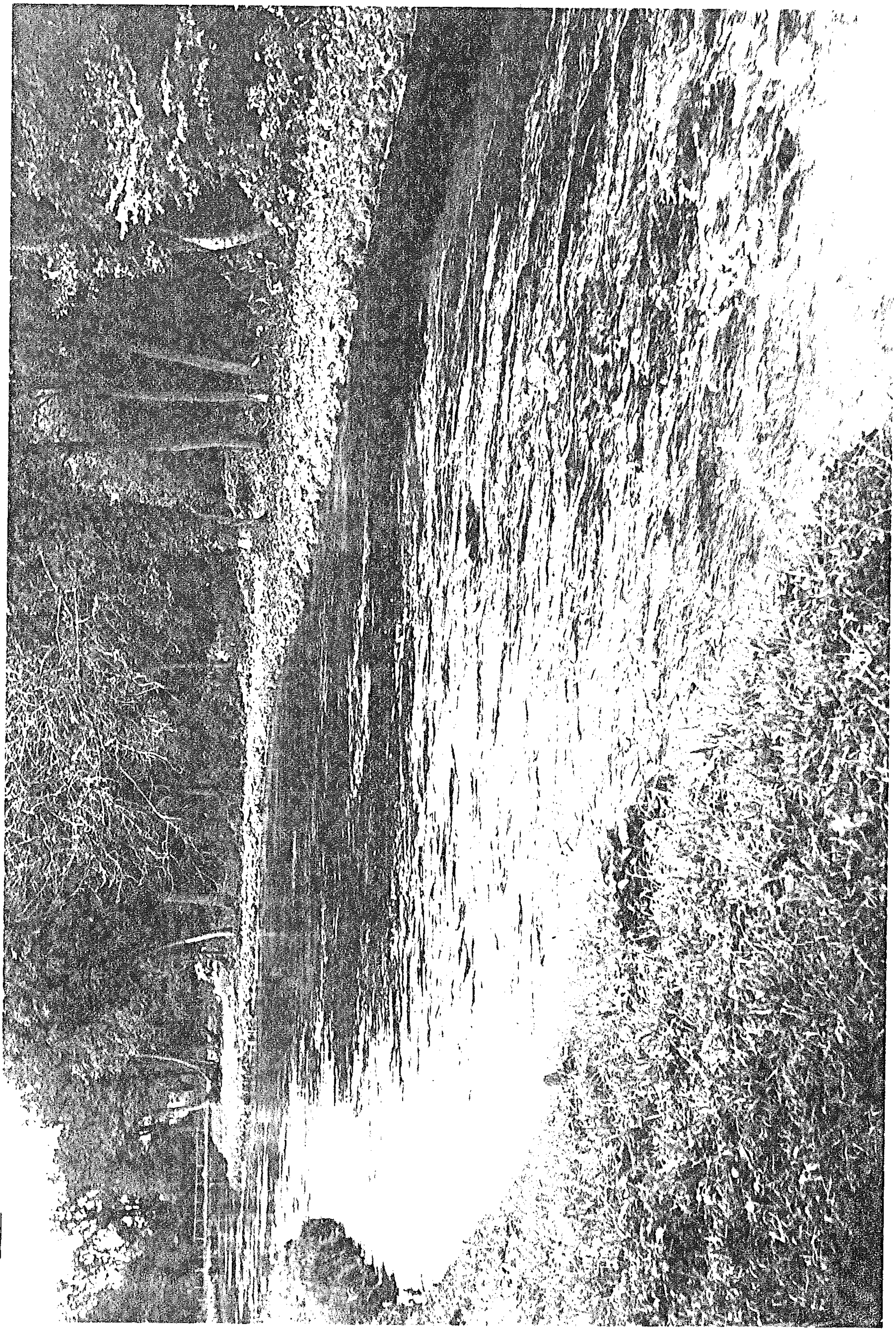

Plate 6 River Anton near Fullerton, looking downstream 26 October 1982

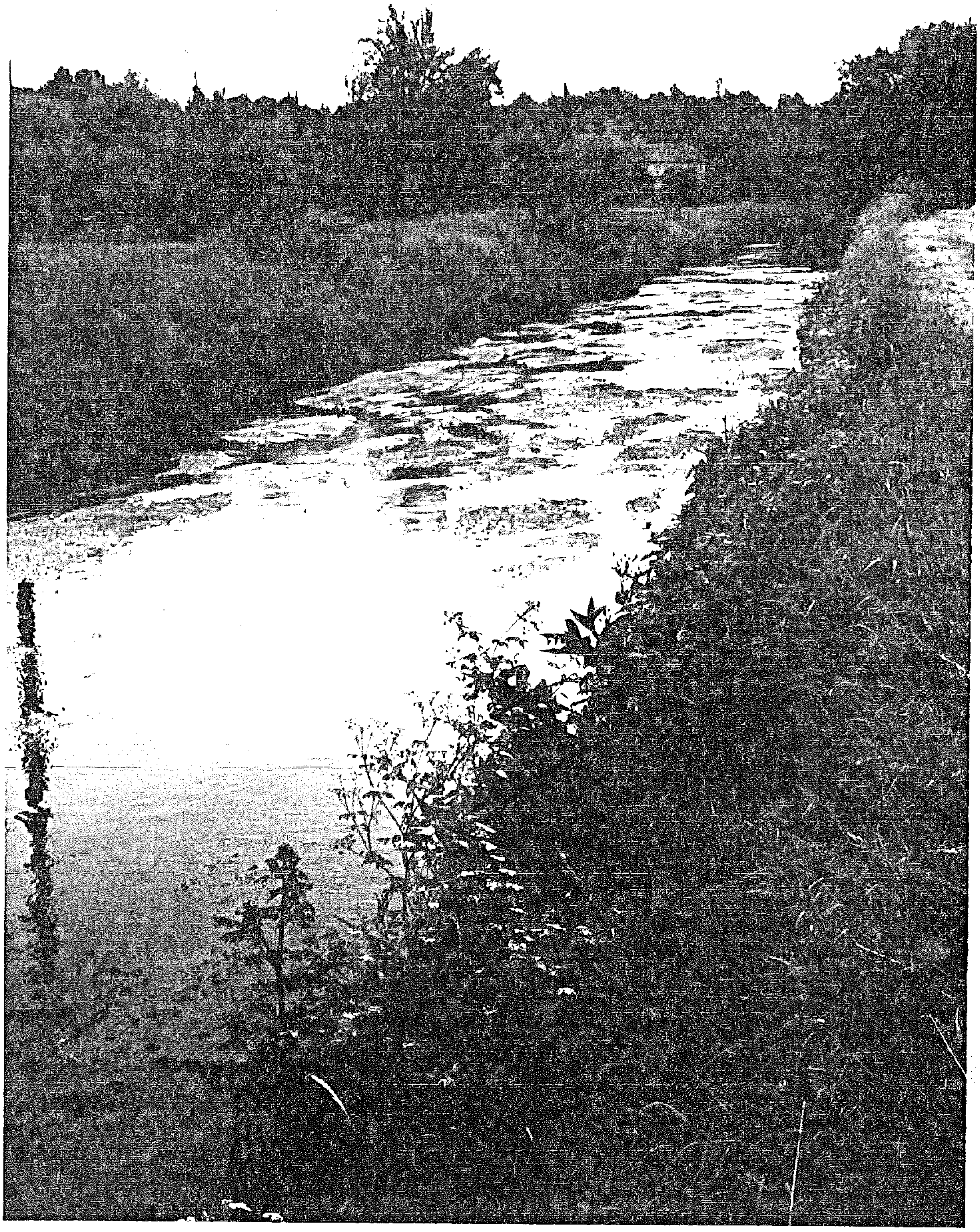

Plate 7 River Wey near Farnham, looking upstream 13 July 1981

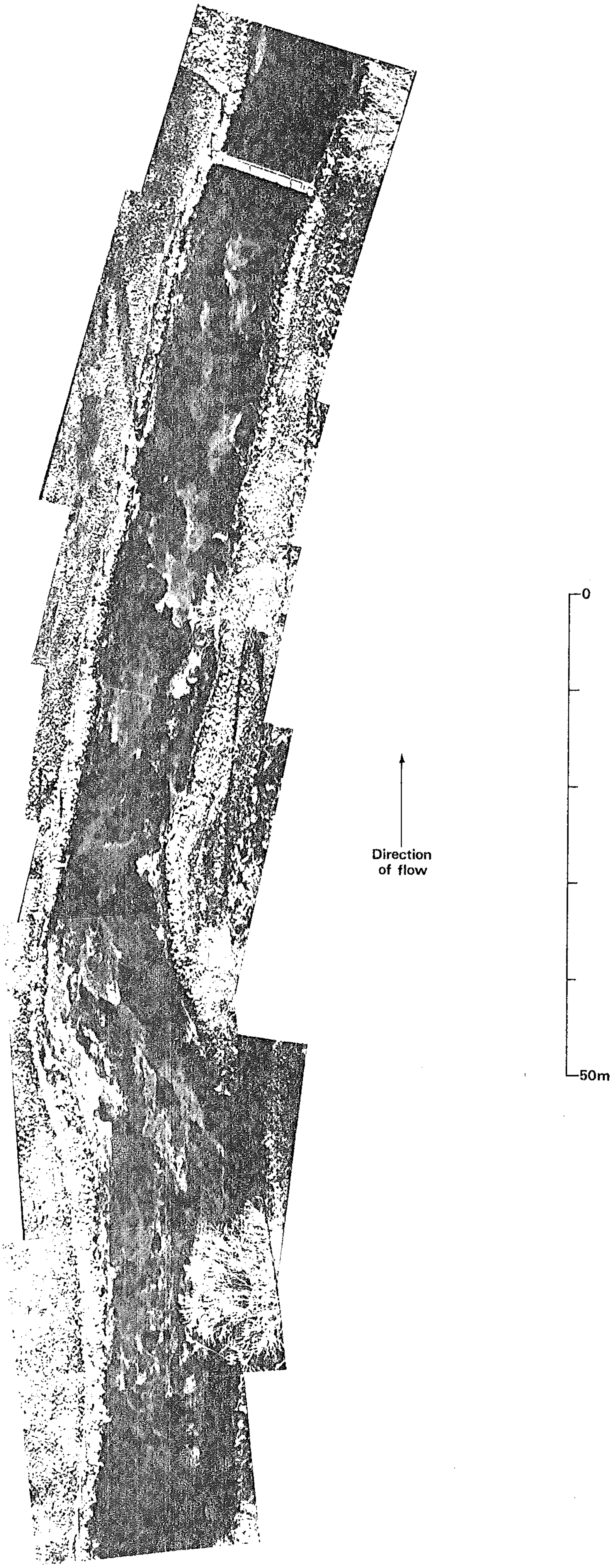

Plate 8 Aerial photograph of River Anton 10 December 1983