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FIELD MEASUREMENTS OF SEDIMENT SUSPENSION ABOVE BEDFORMS IN A SANDY ESTUARY

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ABSTRACT

This report describes field experiments undertaken to make measurements of both mean and turbulent velocities and concentrations over a sandwave and presents the results of the initial analysis of the data collected. The measurements were made to increase the understanding of the hydrodynamics of the flow above sandwaves leading to improved numerical modelling techniques, the use of which are particularly applicable to engineering studies of sediment movement affecting dredging or navigation.

The distributions of all the main mean and turbulent hydrodynamic and sedimentary variables are plotted over the sandwave. The measurements showed that everywhere on the sandwave the hydrodynamic and sedimentary characteristics were very different to equilibrium flat bed conditions. In the trough, where intermittent separation took place, an elevated maximum occurred in the turbulent kinetic energy, the shear stress, and the sediment concentration. Regions of downward-directed diffusion of sediment occurred in the trough, as well as downstream-directed horizontal diffusion. Elsewhere the vertical diffusion was directed upwards and the horizontal diffusion was directed upstream, as is more usually observed. Sediment transport due to bedford migration was on average 19% of that due to suspended load. The streamwise variation in suspended load transport would, through sediment continuity, lead to a flattening of the sandwave profile.

Many theoretical models of sandwave dynamics assume that departures from equilibrium conditions are small. The present measurements show that this is invalid for natural fully developed sandwaves, and future models may therefore need to make more realistic assumptions if they are to provide adequate predictions for engineering application.

CONTENTS

1 INTRODUCTION

Sediment transport in estuaries and coastal areas can have a profound influence on civil engineering works. In particular sediment transport can cause rapid siltation of navigation channels, and the growth and movement of large bedforms, such as sandwaves, can seriously affect navigation depths. Very often suspended sediment and sandwaves occur together in sandy estuaries. However, there is a lack of understanding as to how the suspended sediment processes are modified by the presence of sandwaves and how in turn the sandwave dynamics are influenced by suspended sediment.

The hydrodynamics of flow over aysmmetric bedforms (ripples and sandwaves) has been studied previously in the laboratory by, for example, Raudkivi (Ref 1). However, very few field measurements have been made of the hydrodynamics, with the notable exception of Smith and McLean (Refs 2 and 3) and McLean and Smith (Ref 4). Field measurements of the suspended sediment concentrations over bedforms are even scarcer. Measurements of the mean and turbulent flow properties at the crest of a sandwave are reported by Soulsby et al (Refs 5,6 and 7). These measurements revealed a number of features which were distinctly different from classical flat bed results for both velocities and suspended sediment concentrations.

The set of field measurements reported here were taken to extend measurements to cover the complete wavelength of a sandwave and to investigate how the mean and turbulent parameters vary with position and height. The results should improve the numerical modelling of non-cohesive sediment movement especially when applied to dredging and navigation studies.

2 OBJECTIVES OF THE EXPERIMENTS

The objectives of the experiments were to measure in a sandy bedded estuary the migration rates of large scale bedforms (sandwaves) and to obtain simultaneous measurements of the suspended solids concentrations and velocities over the length of a suitable sandwave. It was decided that the experimental work would be conducted in two stages over separate financial years. During 1987/88 the first stage measurements would be conducted to determine the mean velocity and concentration fields up to 4m above the sandwave. This would be followed in 1988/89 with a second stage to record the turbulent velocity and concentration fields close to the bed. In both stages of the experiments it was planned to make daily ground surveys to determine the sandwave migration rates.

In the event the first stage measurements, carried out in July 1987, were subject to instrument and equipment failures. For these reasons it was decided to remount the exercise in October 1987. However, due to bad weather conditions this work had to be abandoned. Although some usable data was collected during these experiments, it was insufficiently complete to provide useful results. Nevertheless, these two exercises provided invaluable experience in handling the equipment and determining techniques to be employed in the 1988 experiment. To compensate, measurements of the mean velocities and concentrations were included within the programme for the 1988 experiment, which proved to be entirely successful and yielded large quantities of high quality data on both the mean and turbulent variables.

3 EXPERIMENTAL SITE

The experiments were carried out on drying sandflats at Yelland Marsh in the estuary of the River Taw in North Devon. Plate I gives an overall impression of the experimental site and its location is shown in Fig 1. The bed of the estuary comprises fine sand with a median diameter of about 200μm and during spring tide periods there are high concentrations of suspended sand having a slightly smaller median diameter of 165μm. The mean settling velocity of the grains in suspension was $0.017ms^{-1}$. There is little suspended clay or silt in the water during the flood tide and temperature and salinity are both uniform throughout the depth, due to the strong mixing, so that there is no thermohaline density gradient present.

At the experimental location it was known that unless there had been severe weather conditions in the locality causing major wave activity at the site the sandflats would be formed into sandwaves. The bar at the entrance to the Taw/Torridge estuaries in Bideford Bay protects the experimental area from much of the incoming wave activity resulting in only locally generated surface waves at the site. The sandwaves generally have a wavelength of 15-20m with a trough-to-crest height of approximately 0.8m and have sufficient width to justify the assumption that the bed and tidal flow forms a two-dimensional system. Superimposed on the sandwaves were ripples approximately 0.02m high with a wavelength of around 0.3m.

From the previous experiments conducted at this site, on the down-estuary end of the sandflat, the sandwaves were known to migrate up-estuary due to the strongly dominant flood tide. There is no evidence to suggest that during spring-tide periods, when all the measurements were made, the ebb-tide makes any major contribution to the shape of the sandwave. This flood-tide dominance was significant, since it indicated that measurements could be limited to the flood tide only. Due to its position in the estuary the tidal curve at Yelland Marsh is distinctly aysmmetric, with a shortened flood tidal period. As the actual measurement site was situated above the low water level this further foreshortened the measurement period to between 2½ and 3 hours. Table I summarises the predicted tidal data for the experimental site and measurement positions and periods for the August 1988 experiment.

A suitable sandwave was selected using the following criteria:

(i) Its position was at the down-estuary (south-western) end of the sandflat.

(ii) There were sandwaves of a similar shape and size immediately up and downstream of the selected wave.

(iii) The sandwave field was reasonably two-dimensional ie free from lateral distortions.

(iv) In the general area of the selected wave the sandwaves were propagating in alignment with the main (flood) flow direction.

(v) From practical considerations the sandwave would be uncovered reasonably early in the ebb tide.

4 EXPERIMENTAL EQUIPMENT

To ensure that all the instruments used were rigidly mounted and correctly aligned the masts supporting the instruments were mounted on frameworks erected on the exposed sandflats during low water periods. Access to the site was by means of boats, which also acted as work platforms during the measurements. Two boats were used, a 12m Rotork barge and a Zodiac inflatable, which can been seen in Plate I. The deckhouse on the Rotork barge was used to house all the instrument electronics and recording equipment.

Two frameworks were assembled on the sandflat to support the streamlined instrument masts; all other elements of the frameworks had a circular section. The instrument masts were attached to the down-estuary side of the frameworks. A 3m mast was mounted on one framework which was positioned daily on the up-estuary crest of the selected sandwave to act as a reference measurement position. On this mast there were four 0.15m diameter Braystoke impellor type current meters (ICMs) at heights of 0.2, 0.4, 0.8 and 2.5m above the bed, and pumped sample nozzles were positioned at the 0.4 and 0.8m heights. To prevent the reference mast from vibrating severely it was braced by two struts leading from the mast top to the down-flow side of the framework and by a rod, passing through the mast and approximately 1m into the sand. A bamboo cane attached at the top of the mast, surmounted by a warning flag, increased the overall height of the mast to about 5½m, which was graduated in order that water depths could be measured.

The instrument mast clamped to the second framework was 1m high and was positioned daily at the point on the sandwave at which measurements were required. This mast carried the main instrumentation for the experiments and as such it was necessary that every effort be made to prevent it from vibrating. This was achieved by a long pointed rod at the mast base which was pushed into the sand and by clamping the top of the mast to a length of thick strip metal which was driven at an angle from the mast into the sand behind the mast (see Plate II). At heights of 0.1, 0.2, 0.4 and 0.8m a 50mm diameter Electromagnetic Current Meter (ECM), ICM and pumped sample nozzle were mounted on the mast. At the top of the mast, pointing vertically downwards, was an acoustic backscatter probe (ABP) to measure concentrations of suspended sand. The ICMs and pumped sample data from the measuring mast were used to assist in obtaining field calibrations for the ECMs and ABP.

The ABP was kindly loaned to HR for these experiments by Dr P D Thorne of the Proudman Oceanographic Laboratory, Bidston, who was responsible for its design and construction. The ABP is in principle a high-frequency echo sounder. 3MHz sound is transmitted in a narrow, downward-pointing beam, and is scattered back from suspended sand. The concentration of sand is determined at as many levels as required from the intensity of a back-scattered signal, and the ranges of the levels from the transducer is determined from the time delays. In this report measurements from four heights, matching those of the ECMs, are analysed. More detailed measurements at levels were made by Dr Thorne during the first two days of the experiment, and will be reported elsewhere.

The ECMs were two component discus type orientated to measure velocities in the mean flow and vertical directions. The manner in which ECMs operate may be found elsewhere, eg Ref 8. In order to prevent interference between the magnetic fields generated by the ECM heads the frequency and switching of the magnetic fields were controlled by only one of the ECM monitors. The ABP was mounted 1m above the mast base and aligned with the vertical axes of the ECMs and displaced 0.1m laterally. The ABP beam was assumed to be close enough to the ECMs to effectively be measuring point velocities and concentrations. The positioning and instrumentation on the measuring mast is shown in Plate II. Plates III and IV are general views of the two frameworks in position on the sandwave prior to the start of measurements on Day 1.

The cables from all the instruments came to the water surface attached to a rope, with the hoses from the sampling nozzles on the measuring mast strapped to the outside of the cables to give them a degree of protection from any debris in the flow. The rope was shackled to a screw anchor in the bed and to a buoy. At the surface the instrument cables passed through watertight glands fitted to a detachable plate on the buoy in which the cables and connections were housed when detached from their respective monitors onboard the barge. The hoses from the nozzles on the reference mast were attached to a similar rope and buoy arrangement.

All 12 analogue voltage signals, representing the turbulent records of concentration and two velocities at each of the four measurement heights on the measurement mast were recorded on magnetic tape using a Racal Store 14DS FM (frequency modulated) tape recorder.

Concentrations of suspended sand were obtained using two in-line pump/filtration systems. The sand/water mixture was extracted from the main flow at the sampling points and pumped to the surface where each sample was filtered on an individual 40μm filter.

Hose sizes and pumping rate were such that the mixture maintained a sufficient velocity through the system to ensure that the sand remained in suspension.

5 EXPERIMENTAL PROCEDURE

After a suitable sandwave was selected a survey line was set up aligned with the mean flow direction. The mean flow direction was assumed to be generally normal to the lines of the crests of the sandwaves in the locality. All measurements over the sandwave were made along this survey line. An arbitary local datum for levels was established by driving a stake far enough into the sand to be unaffected by the migration of the sandwave. Daily ground surveys were conducted along this survey line with bed levels, referred to the local datum, being measured at 1m intervals, as shown in Fig 3. The reference mast was laterally displaced from the survey line by approximately 4m to avoid any wake effects from the measuring mast and framework.

Every day the reference mast was moved as the sandwave migrated up-estuary, so that its position was always initially on the crest of the sandwave. The smaller mast was moved to a different horizontal position on the sandwave day by day, so that over a period of 5 days a series of 5 positions roughly equally spaced between the trough and the crest had been sampled. The order in which the individual experiments were carried out was such that measurements on the sandwave crest and trough, the most interesting positions, coincided with the peak tides of the spring tide period when the maximum sandwave migration and suspended sediment concentrations could be expected.

The five measurement days followed the same pattern. On arrival at the site the boats were anchored and when the tide had fallen sufficiently to expose the sandwave the frameworks were dismantled and reassembled at the required positions. All the instruments were then checked and the ground survey carried out.

Recording data from the instruments began as soon as the incoming flood tide had submerged the instruments on the measuring mast and continued up to the slack water period at high water. The ICMs were monitored by hand using a multi-channel counting unit recording a count period of 4 minutes at 5 minute intervals. Pumped samples were taken in rotation from the four nozzles on the measurement mast at 5 minute intervals throughout the measurement period, ie each nozzle was sampled every 20 minutes. Pumped samples from the nozzles on the reference mast were taken at 10 minute intervals. A standard quantity of 20 l was pumped through the filter for each sample, although at times of very high concentrations this was reduced to 10 l. Bleed samples taken from the water after passing through the filter were taken to check on the levels of suspended fine material which were found to be low and uniformly distributed through the measured heights.

6 DATA ANALYSIS

The data recorded in analogue form during the field experiment was digitized at a frequency of 10Hz using an Earth Data EDR 8000 instrumentation tape recorder, digital anti-aliasing filters within the recorder had bandwidths of 4Hz. The digital data was transferred from the digital recorder onto a desk-top computer which was used to process all the data. A purpose written computer program was used to examine and remove spurious data from each digital record.

An existing computer program was modified to carry out an initial analysis of the turbulence data. Taking the data from a single height on one day the digitized signals were analysed over 5 minute periods. Calibrations were applied to the digital data to convert them into time series records of longitudinal velocity (U(t)), vertical velocity (W(t)) and suspended sand concentration (C(t)). All velocities are in ms^{-1} and concentrations in kgm^{-3}. Calibration of the ECMs and ABP was achieved by a combination of laboratory calibrations and data obtained in the field.

Separate calibrations of the mean ABP signal versus the pumped sample concentration were made for each height and each day. The intensity of the backscattered signal (ie square of the logged voltage) was found to calibrate linearly with concentration, as had been found in laboratory tests. Slightly different calibration constants were found at each position on the sandwave, because the amount of attenuation of the signal between the transducer and the sample range depends on the intervening concentration profile. An example of the ABP calibrations for Day 2 is shown in Fig 2.

After calibrating the digital data the overall mean values $\bar{U}$ and $\bar{W}$ of U(t) and W(t) respectively were computed and a co-ordinate rotation applied to the U(t) and W(t) records to bring them into a frame of reference such that $\bar{W} = 0$. This co-ordinate rotation was not applied to the data obtained in the trough of the sandwave, due to uncertainties in the zero of $\bar{W}$ on that day. The 5 minute means $\bar{U}$, $\bar{W}$ and $\bar{C}$ (mean of C(t)) and linear trends due to tidal variation were removed from each of the digitized signals to leave the fluctuating quantities u, w and c. From each record of the fluctuations the standard deviations, $(\sigma_u, \sigma_w, \sigma_c)$ were calculated together with the mean values of the cross products $\overline{uw}$ (momentum flux), $\overline{uc}$ (horizontal diffusive flux) and $\overline{wc}$ (vertical diffusive flux). Further parameters were also calculated from these results; the sediment settling flux, $w_s\overline{C}$, (where w_s is the settling velocity), the mean sediment flux $\overline{UC}$ and an estimate of the turbulent kinetic energy using the expression $E = 0.751\ (\sigma_u^2 + \sigma_w^2)$. These calculations were repeated for each 5 minute period throughout the complete data set.

7 DISCUSSION OF RESULTS

The results of the ground surveys carried out during the field work to define the sandwaves (shown in Fig 3) have been combined to produce a "standard" sandwave. To do this the daily sandwave profiles have been overlaid and their relative positions adjusted, by eye, such that the crests and troughs of each profile are coincident. A mean line was then drawn through the overlaid profiles. The overlaid profiles and mean line are shown in Fig 4.

The results of the initial analysis of the data obtained from the field experiment are shown in Figs 5-16. In order to show how the measured quantities vary over the sandwave each figure contains an outline of the "standard" sandwave upon which are superimposed the vertical profiles of the quantities. The origins of the vertical profiles are positioned at the points of measurement and the vertical scale of the profiles is the same as that of the sandwave.

A form of banded averaging based on reference mast velocities at 0.4m, $U_{R0.4}$, has been employed to clarify the vertical profiles. The velocity limits (ms^{-1}) of the bands taken were:

Band 1 $0.1 \le U_{R0.4} < 0.3$
Band 2 $0.3 \le U_{R0.4} < 0.5$
Band 3 $0.5 \le U_{R0.4} < 0.7$
Band 4 $0.7 \le U_{R0.4} < 0.9$

Reference mast velocities at 0.4m for the five measurement days are shown as time series in Fig 5 along with the band limits.

During the flood tide velocities over the sandflats are distinctly asymmetric with time. Accelerating rapidly, peak velocities are usually attained within ¾h after starting the measurements. This is followed by a quasi steady state period during which velocities are slightly below their peak values, the length of this steady state period varying with height and position over the sandwave. Velocities then fall continuously until slack water. The banded averaging process used to show the results obtained so far removes any effects of these temporal changes to the flow.

The analysis of the turbulent velocity records show that at no point on the sandwave can the results of the measurements be described by flat bed boundary layer theory. The mean velocity profiles in Fig 6 demonstrate that the flow over the sandwave is complex. There is evidence of a region of intermittent separation in the trough. The banded average velocities at heights of 0.1 and 0.2m above the trough are small, but always positive. The fraction of the time for which the instantaneous velocity is directed flrtream has been calculated as a measure of the degree of flow separation. Through the first half of the tide this fraction is effectively zero at all levels, indicating no separation. However, in the latter half of the tide flow reversal occurs up to 40% of the time at 0.1 and 0.2m above the bed of the trough, and up to about 10% of the time at 0.4m. No reversal of the instantaneous velocity occurs at 0.8m above the trough, nor at any height at any of the other four positions on the sandwave. The progressive onset of separation may result from a sharpening of the crest immediately upstream as the flood tide proceeds; this may have been rounded off by the preceding ebb tide. On the flank of the sandwave, and at the crest, there is evidence of a low-level jet in the mean velocity profiles, having a maximum at a height of 0.2m, due to the topographic effect of the sandwave. At no position do the profiles conform to the flat-bed logarithmic form.

The standard deviations of the longitudinal and vertical velocity fluctuations, σ_u and σ_w (Figs 7 and 8 respectively), show that in the trough there are extremely high levels of turbulence with local turbulence intensities, $\sigma_u/\bar{U}$, as high as 50%. It is interesting to note, however, that $\sigma_w = 0.5\sigma_u$ as would be expected if dealing with classic flat bed turbulence. The estimates of turbulent kinetic energy (E), Fig 9, show that at the sandwave crest the energy is more or less constant with height, whereas in the trough there is a markedly curved distribution in which the peak values are generated above the lowest measurement height, an effect gradually diminishing along the sandwave flank. The largest values of E occur within the separated region above the trough, where the velocity shear is large (Fig 6). The large velocity fluctuations here may also be due to the intermittency of the separation process. The elevated maximum in E is also observed at the second measuring position, which is possibly close to the re-attachment point. Peak kinematic Reynolds stress values, Fig 10, also occur above the lowest measurement point in the trough and on the lower flank. The apparent increase in height of the maximum of $-\overline{uw}$ with decreasing banded average velocity in the trough may in reality be a spatial variation, since the low velocities occur predominantly in the later part of the tide (see Fig 5), when the slope has migrated nearer to the measuring mast. The largest value of $-\overline{uw}$ at 0.1m occurs in the trough, and the smallest at the crest, in marked contrast to theoretical predictions which usually indicate a maximum bed shear stress a short distance upstream of the crest. The spatially averaged shear stress was observed to increase with height in the observations of Smith and McLean (Ref 4) above natural sandwaves, in accordance with the present measurements.

Measured concentrations of suspended sand, $\bar{C}$, shown in Fig 11, indicate that the concentration is greatest in the trough. High concentrations near the bed in the trough are attributed to sand falling from suspension in the slower moving, although highly turbulent, water and possibly the effects of sand rolling down the avalanche slope of the sandwave from the upstream crest at high velocities. The effect of the flow jetting from the upstream crest, seen in the longitudinal velocities, is also apparent in the distortion to the concentration profiles on the upper flank and crest. None of the measured concentration profiles could readily be described by the usually accepted Rouse profile. The standard deviation of the concentration fluctuations, Fig 12, show that the shapes of the vertical profiles are very similar to those of the mean concentrations. In the trough both $\bar{C}$ and σ_c have peak values above the lowest measurement point, and this also occurs on the upper flank and on the crest. The ratio $\sigma_c/\bar{C} = 0.5$ in the trough but increases to a value of approximately 1 at the lower flank and maintains this value up to the crest.

The longitudinal diffusive flux, $-\overline{uc}$, Fig 13, is positive along the flank of the sandwave indicating that diffusion is occurring in the upstream direction. In the trough $-\overline{uc}$ is distinctly negative at low velocities. As velocities increase the depth of the region in which $-\overline{uc}$ is negative reduces. The mean sediment flux, $\bar{U}\bar{C}$, is shown in Fig 14. As this parameter is simply the product of $\bar{U}$ and $\bar{C}$ the vertical profiles have similar shapes to the individual $\bar{U}$ and $\bar{C}$ profiles demonstrating the same features including the distorted profiles on the upper flank and crest. Maximum values of mean sediment flux occurs within the trough. Apart from the trough, the values of $-\overline{uc}$ over the sandwave are generally less than 5% of $\bar{U}\bar{C}$, and are smallest near the bed.

The measured vertical flux results are shown in Figs 15 and 16. Fig 15 shows the vertical diffusive flux, $\overline{wc}$, which is the mechanism by which material is lifted into suspension whereas the downward settling flux, $w_s\bar{C}$, as shown in Fig 16 is a measure of material settling out of suspension. The negative values of vertical diffusive flux measured in and close to the trough implies that the diffusion is aiding settlement in the trough. At all measurement positions the vertical diffusive flux is smaller than the settling flux. Over most of the flank the ratio $\overline{wc}/w_s\bar{C}$ is typically 0.2 at a height of 0.1m, increasing with height to about 0.7 at 0.8m. This indication of a net downward settling of sediment over the entire sandwave is difficult to explain. Nevertheless, a similar result was obtained by Soulsby et al, Ref 6, using a completely different instrument for measuring sand concentrations.

Estimates of the sandwave migration rates over two complete tides have been obtained from the overlaid sandwave profiles shown in Fig 4 and are summarised in Table II. Table II also contains the calculated migration and suspended sediment transport values per metre width through each measurement position. The total suspended sediment transport was calculated from the 5 minute average measured values of mean sediment flux. The 5 minute average vertical profiles were integrated both vertically and with time to obtain the total suspended sediment transport over the flood tide. The migration sediment transport values were estimated by approximating the sandwave to a triangular profile 0.75m high with a voids ratio of 0.46 and assuming that in a single flood tide the sandwave moves half the distance measured for two tides. Table II shows that the ratio of migration transport to suspended transport is 0.188, averaged over the sandwave.

An estimate of the bed level changes which would result in one hour from the measured horizontal variations in suspended sediment transport rate has been made by applying sediment continuity (Fig 17). The transport rates for Bands 3 and 4, which are available at all 5 positions, were used. On the top graph the mass transport of suspended sand, Q, and the shear stress, $\tau_{0.1}$, at 0.1m above the bed for each measurement point has been plotted against position along the sandwave. From the mass transport rates at each position the volume deposited, or eroded, has been calculated using the conservation of mass between measurement positions. These bed level changes are plotted in the centre graph of Fig 17 whereas the lower graph shows the effect of these calculations on the sandwave profile. It would appear from these results that the effect of high sediment transport values, associated with the high local velocities in Bands 3 and 4, is to flatten the sandwave. Since the sandwave is observed to maintain its shape, this implies a large contribution from bedload transport (which could not be measured directly) in the bedform dynamics.

8 CONCLUSIONS

From the initial analysis of the data carried out the following conclusions may be drawn:

(i) The mean longitudinal velocity profiles over the sandwave are complex and differ markedly from the flat bed boundary layer logarithmic form.

(ii) The sandwave topography creates a low-level jet on the flank of the sandwave.

(iii) A zone of intermittent separation occurs at the lower levels in the sandwave trough after the longitudinal velocities have attained their maximum values.

(iv) Turbulent kinetic energy is largest within the separated region of the trough, and local turbulent intensities there are as large as 50%.

(v) Peak kinematic Reynolds stresses occur above the lowest measurement positions in the trough and on the lower flank.

(vi) The largest value of kinematic Reynolds stress at a height of 0.1m occurs in the trough and the smallest on the crest of the sandwave, contrary to theoretical predictions.

(vii) Profiles of suspended sand concentrations over the sandwave do not fit the equilibrium Rouse profile.

(viii) In the trough maximum mean concentration and standard deviation of the concentration fluctuations, occur above the bed.

(ix) The local concentration turbulent intensities, $\sigma_c/\bar{C}$, have a value of approximately 0.5 in the trough but this increases to a value of about 1 above the lower flank.

(x) The longitudinal diffusive flux is generally less than 5% of the mean sediment flux, and is directed upstream everywhere except within the separated region in the trough.

(xi) Vertical diffusive flux in smaller than the settling flux over the whole sandwave.

(xii) Sediment transport due to bedform migration is about 19% of that due to suspended load at this site.

(xiii) At the largest velocities suspension of sediment acts to flatten the sandwave. Unusually large bedload transport must occur to maintain the sandwave profile if suspension is tending to flatten it.

9 ACKNOWLEDGEMENTS

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TABLES

TABLE I Summary of tidal conditions and measurement positions for field experiments of August 1988

Date	Day	Tidal Predictions for Yelland Marsh (1)				Measurement Period		Measurement Position on Sandwave (or Activity)
		Low Water		High Water				
		Time (h BST)	Level (m ODN)	Time (h BST)	Level (m ODN)	Start (h BST)	Finish (h BST)	
26:8:88		1259	-2.36	1811	+4.34			(Commission site and check equipment)
27:8:88	1	1355	-2.76	1856	+4.84	1615	1855	1/4 Trough - Crest
28:8:88	2	1447	-2.96	1941	+5.24	1652	1930	Trough
29:8:88	3	1526	-2.96	2023	+5.34	1747	2015	Crest
30:8:88	4	1557	-2.96	2105	+5.14	1826	2045	1/2 Trough - Crest
31:8:88	5	1629	-2.76	2146	+4.64	1902	2130	3/4 Crest - Crest
1:9:88		1700	-2.36	2228	+3.94			(Decommission site)

(1) Source - Admiralty Tide Tables 1988.

TABLE II Sandwave migration, migration and suspended sediment transport values

Date	Day	Position	Sandwave Migration (m)	Migration Transport (kg/m)	Suspended Transport (kg/m)	Migration Transport / Suspended Transport
26-27:8:88			0.7	188		
27-28:8:88	1	1/4 Trough-Crest	1.5	402	1379	0.292
28-29:8:88	2	Trough	0.7	188	2551	0.074
29-30:8:88	3	Crest	0.9	241	1502	0.160
30-31:8:88	4	1/2 Trough-Crest	0.5	134	1086	0.123
31:8:88-1:9:88	5	3/4 Crest-Crest	1.0	268	1028	0.261
TOTAL			5.3	1421	7546	0.188

FIGURES

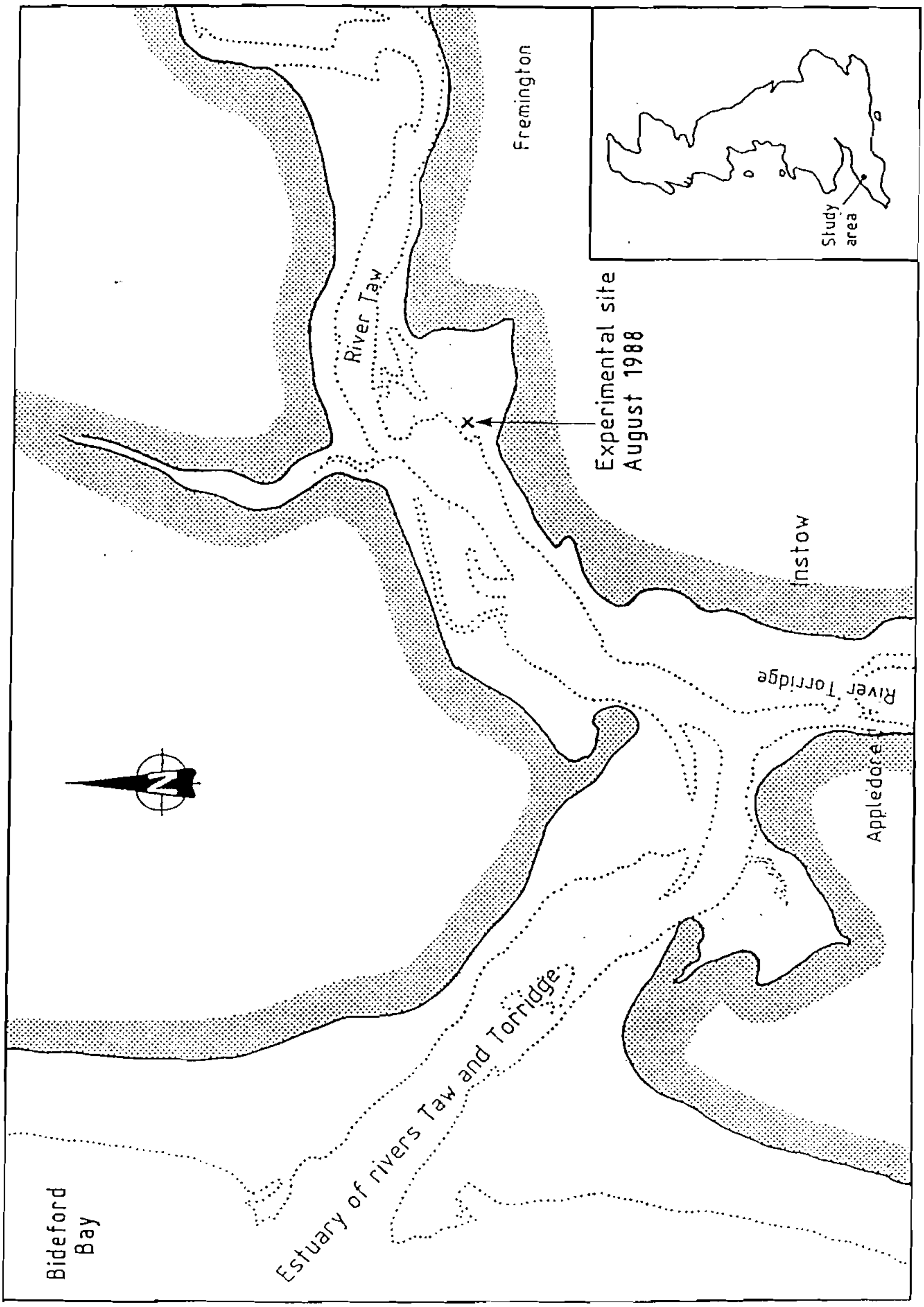

Fig 1   Location map

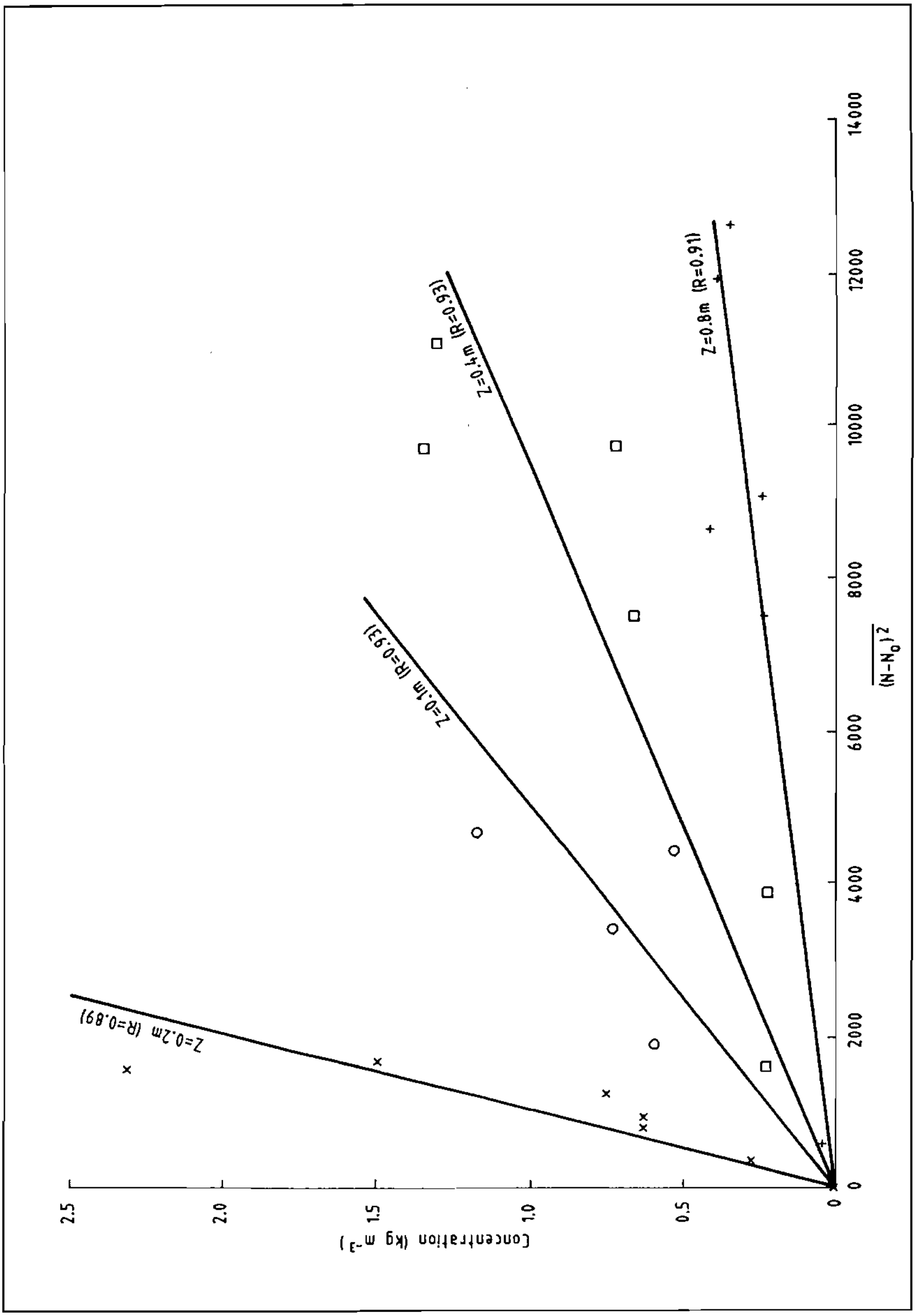

Fig 2 Example calibrations for ABP, Day 2

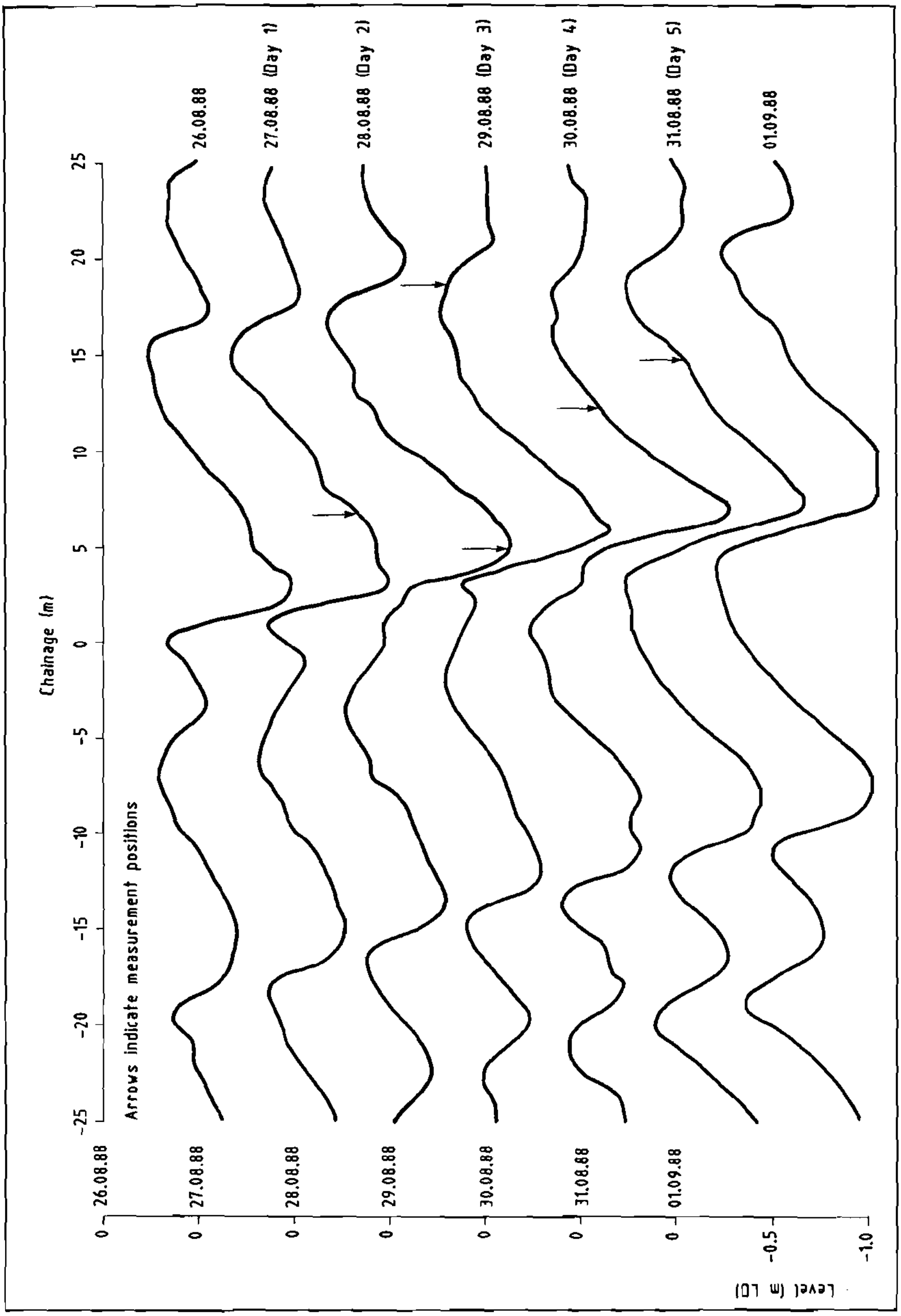

Fig 3 Ground surveys of sandwaves during the experiments

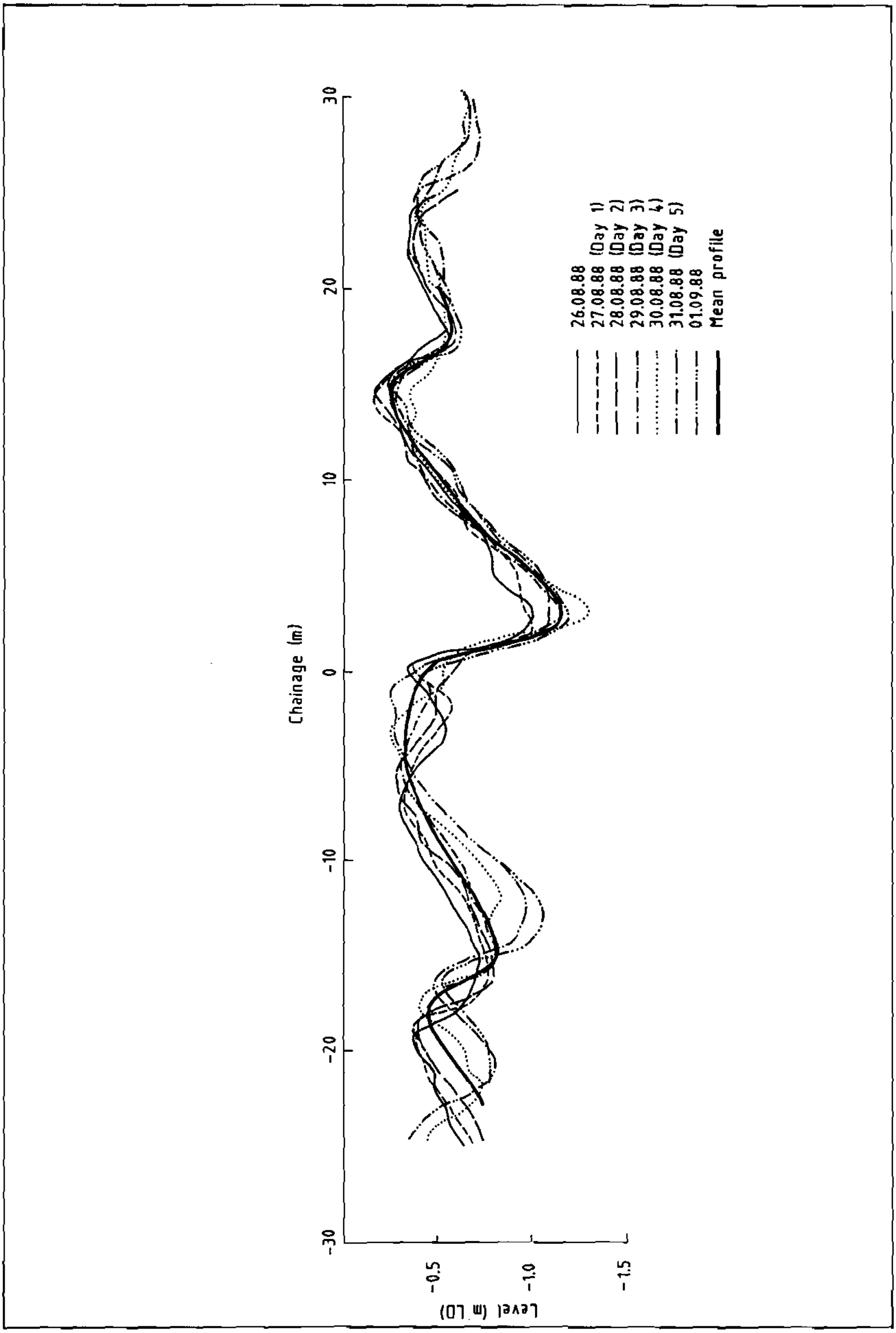

Fig 4 Overlaid sandwaves and "standard" sandwave

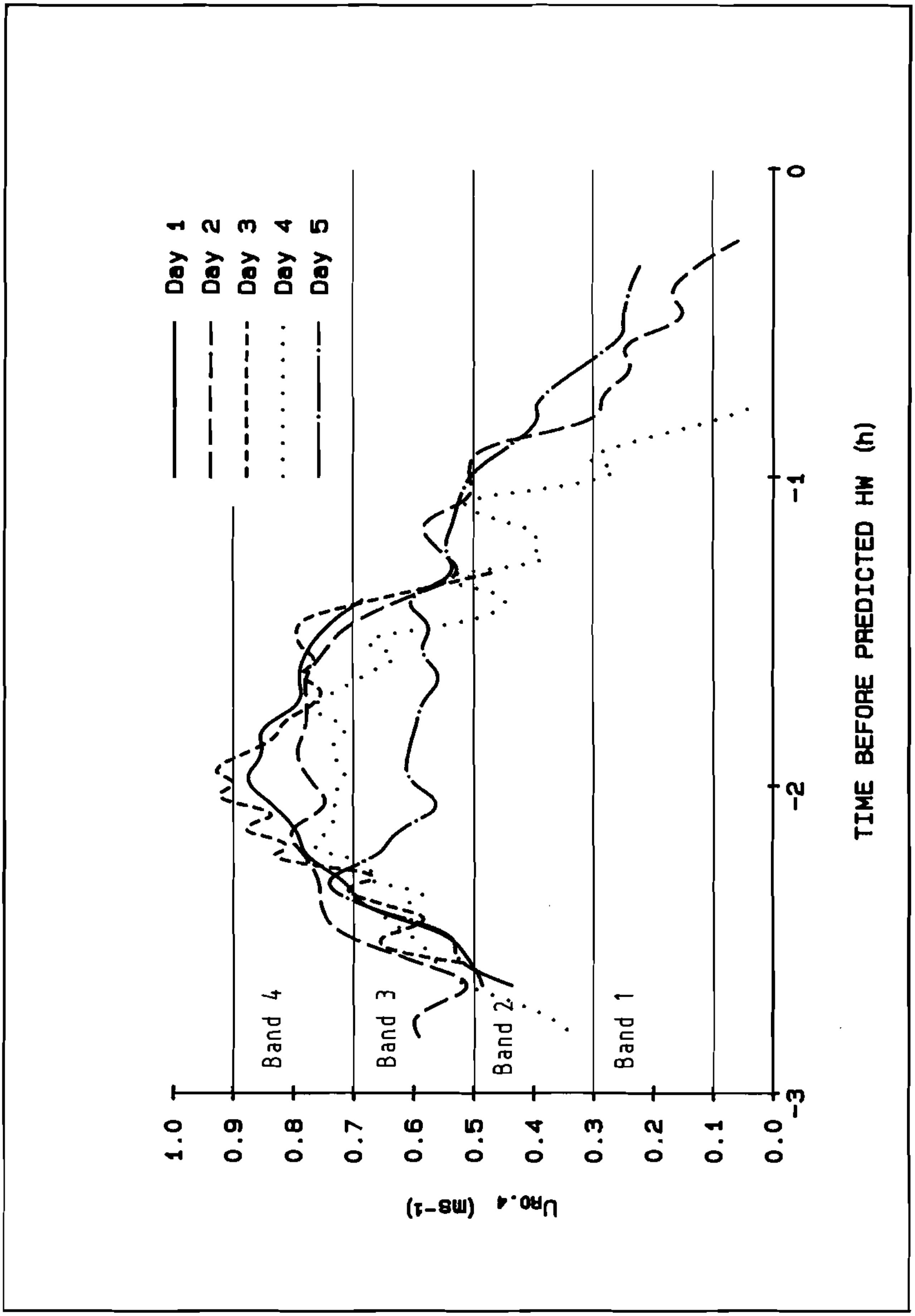

Fig 5 Reference mast velocities at 0.4m for Day 1 to Day 5

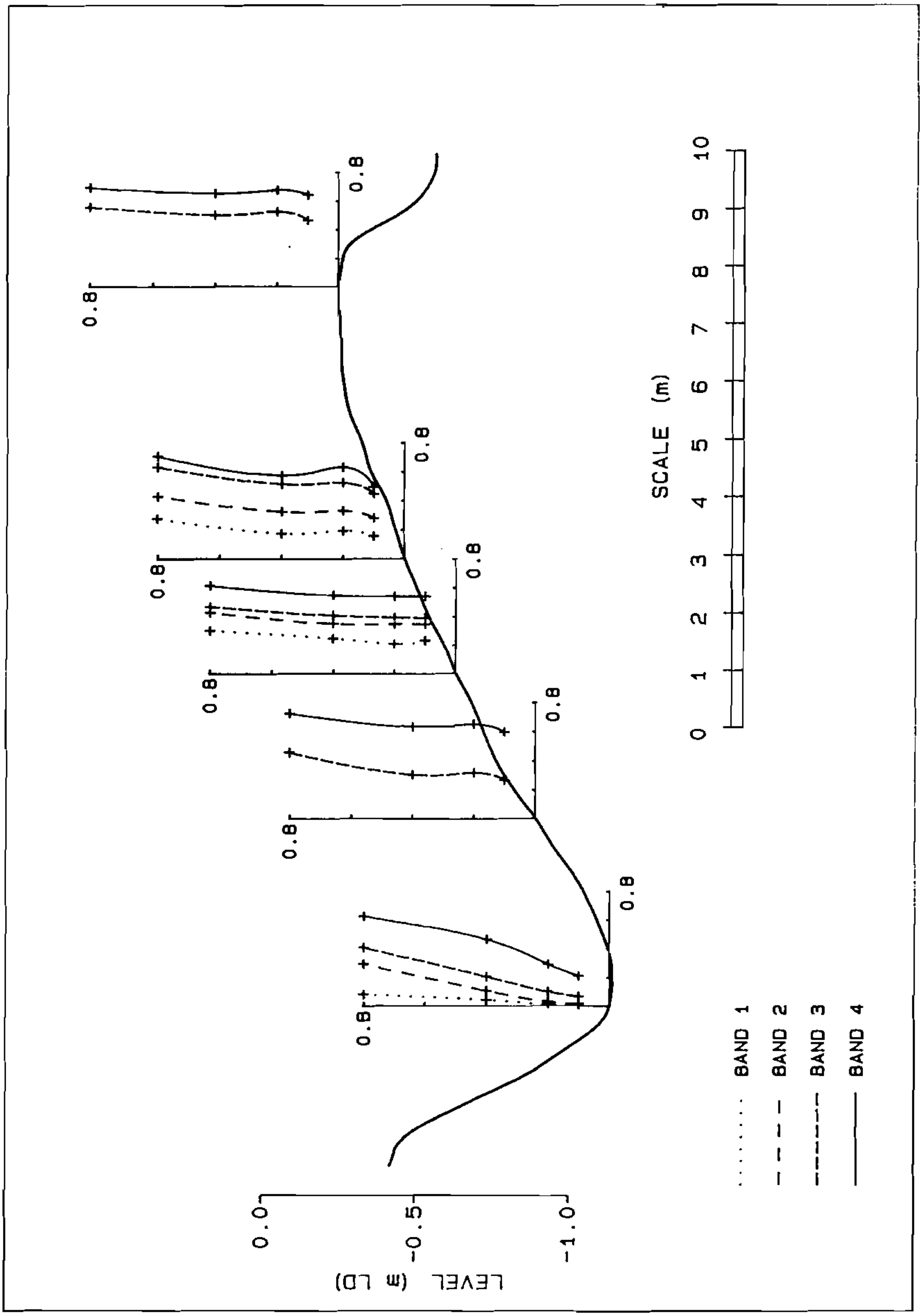

Fig 6 Variation over sandwave of mean longitudinal velocity (U, ms^{-1})

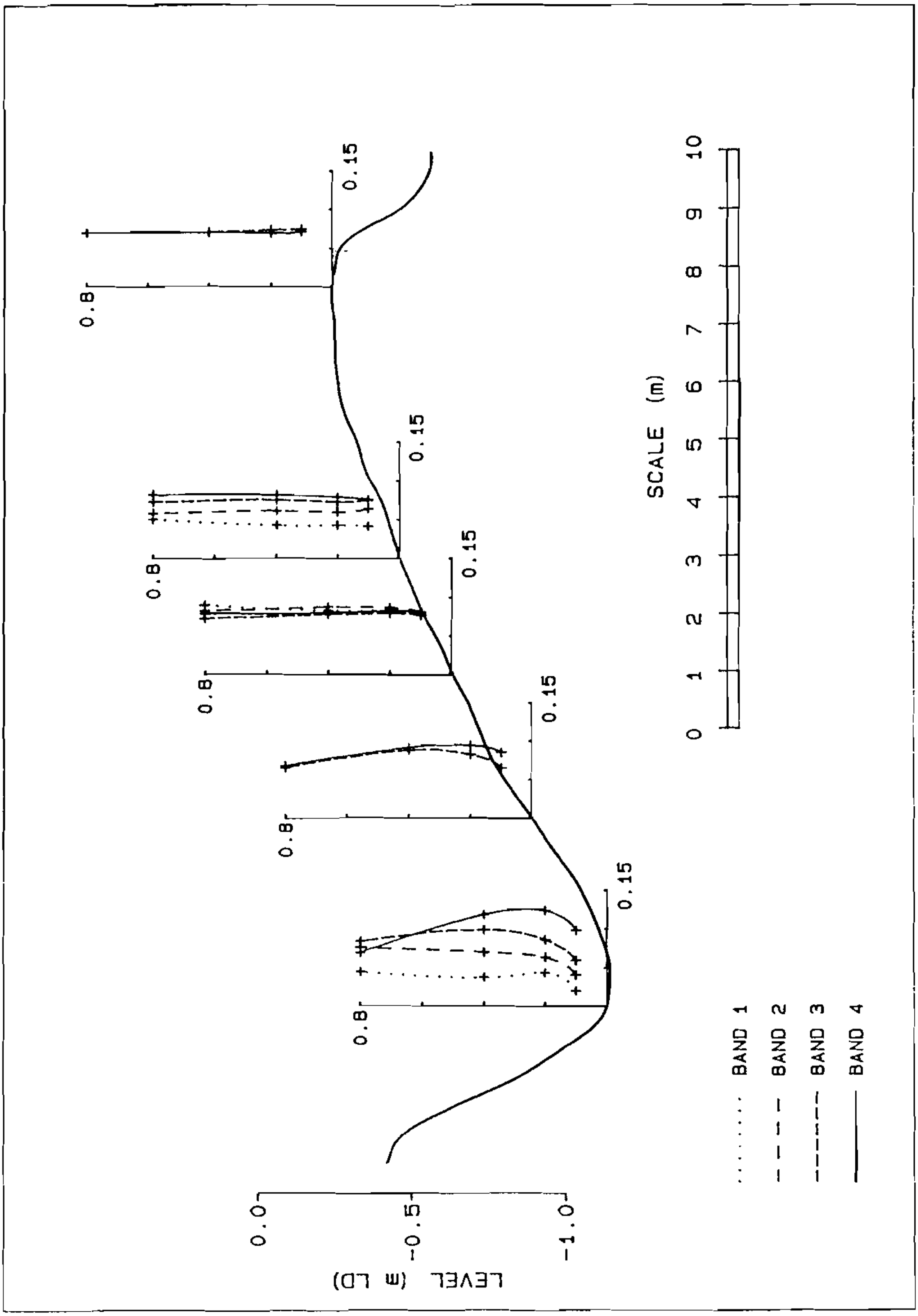

Fig 7 Variation over sandwave of standard deviation of longitudinal velocity fluctuations (σ_u, ms^{-1})

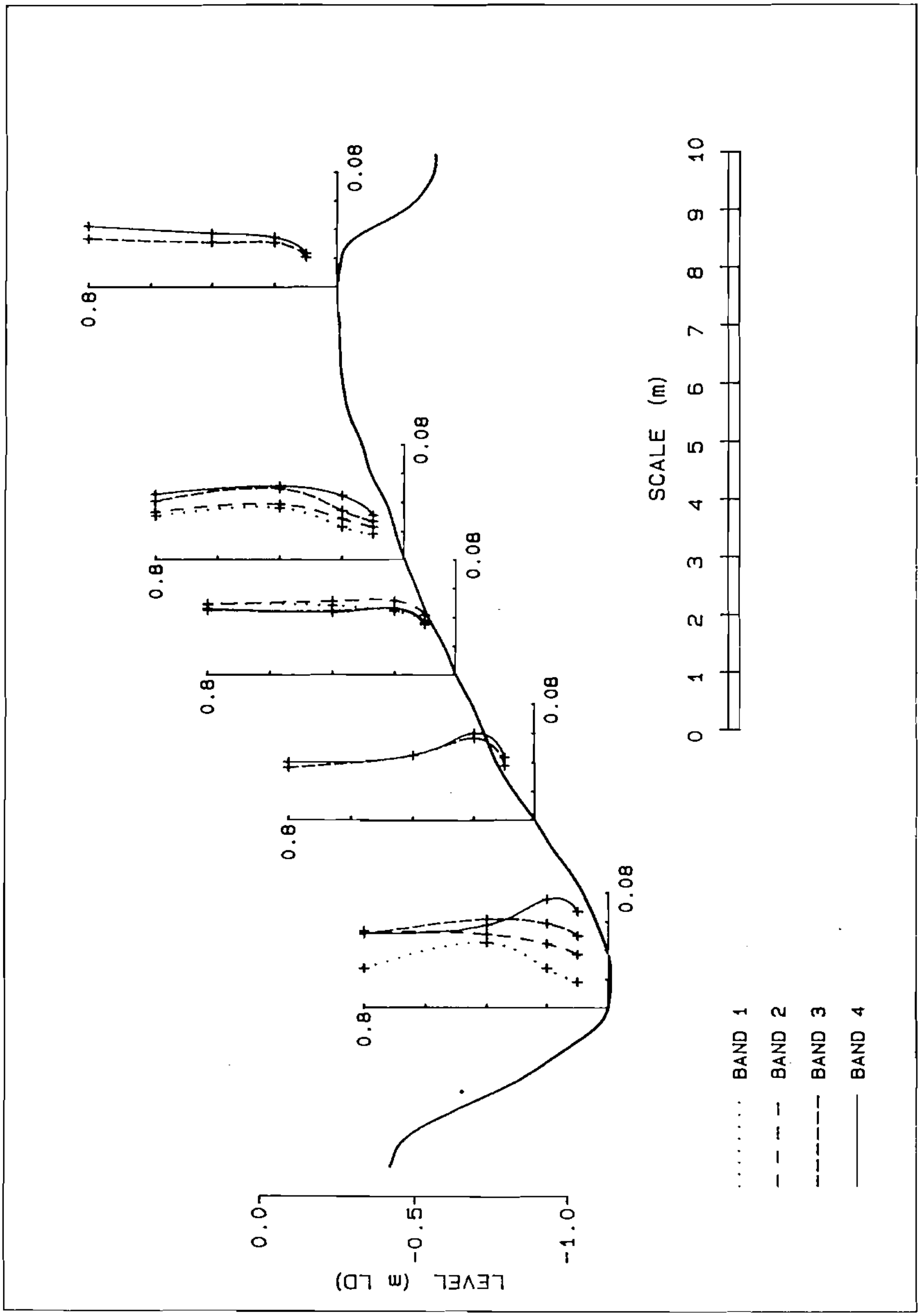

Fig 8 Variation over sandwave of standard deviation of vertical velocity fluctuations (σ_w, ms^{-1})

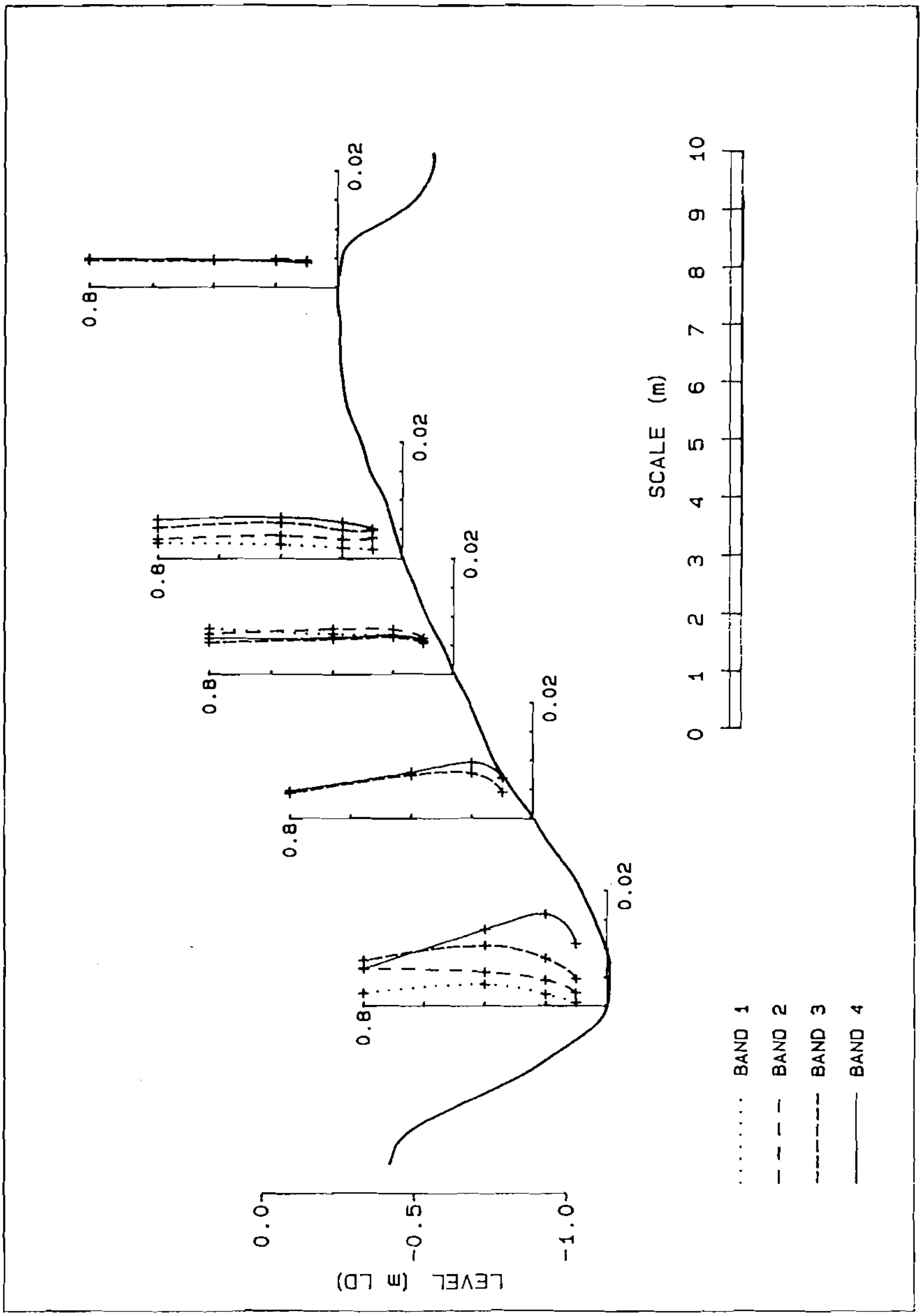

Fig 9 Variation over sandwave of turbulent kinetic energy (E, m^2s^{-2})

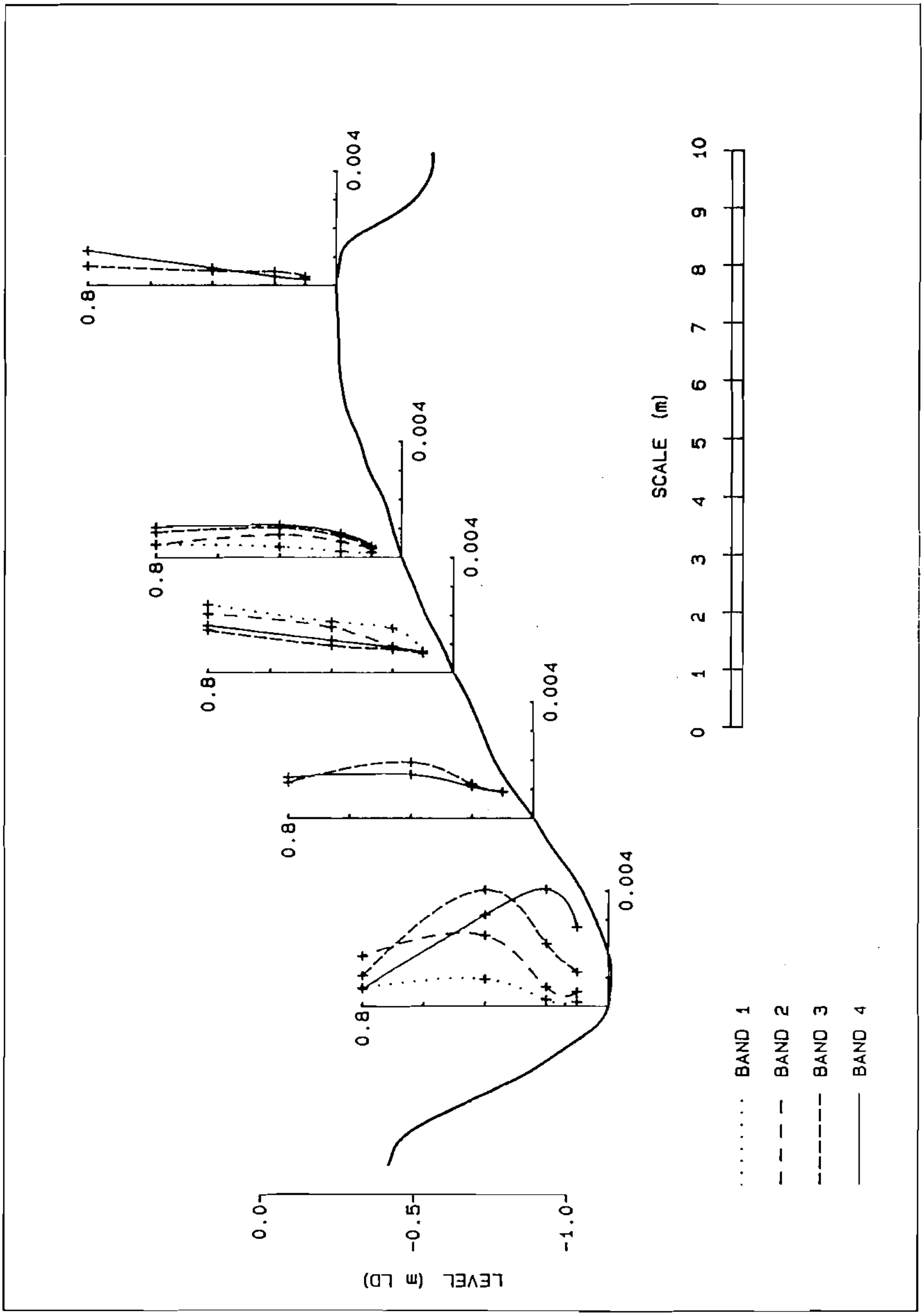

Fig 10 Variation over sandwave of kinematic Reynolds stress ($-\overline{uw}$, $m^2 s^{-2}$)

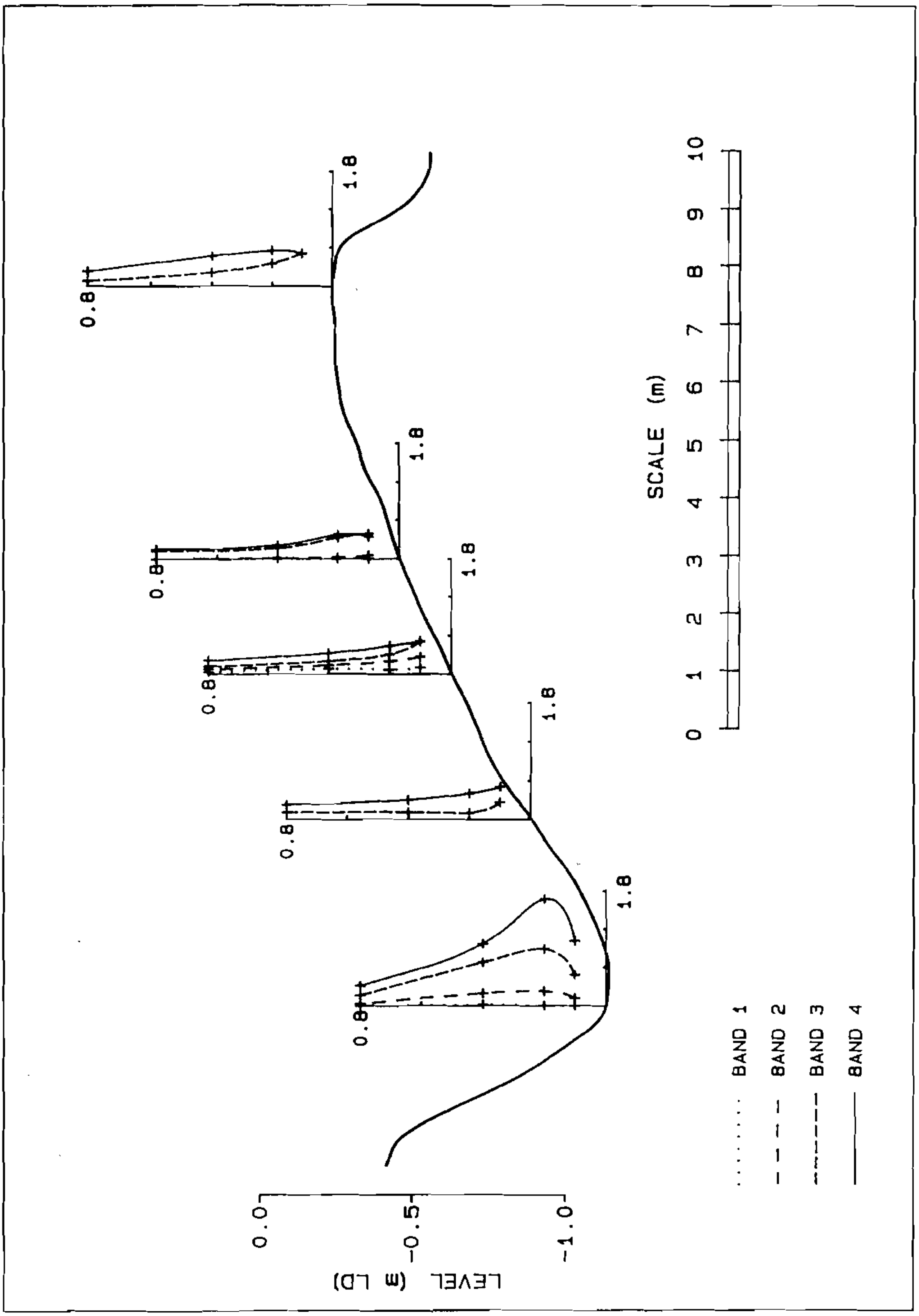

Fig 11 Variation over sandwave of mean concentration ($\bar{C}$, kg m^{-3})

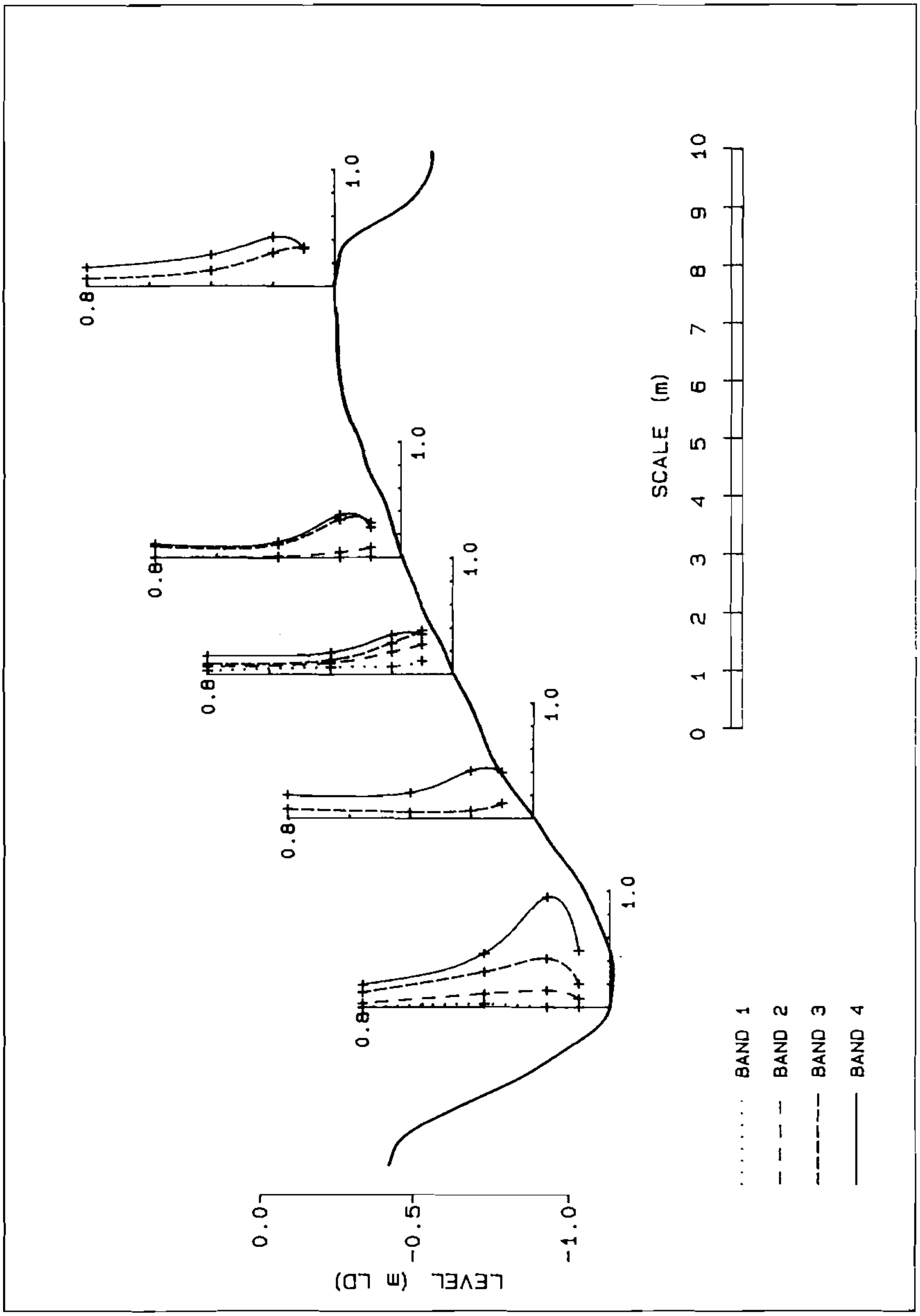

Fig 12 Variation over sandwave of standard deviation of concentration fluctuations (σ_c, kg m^{-3})

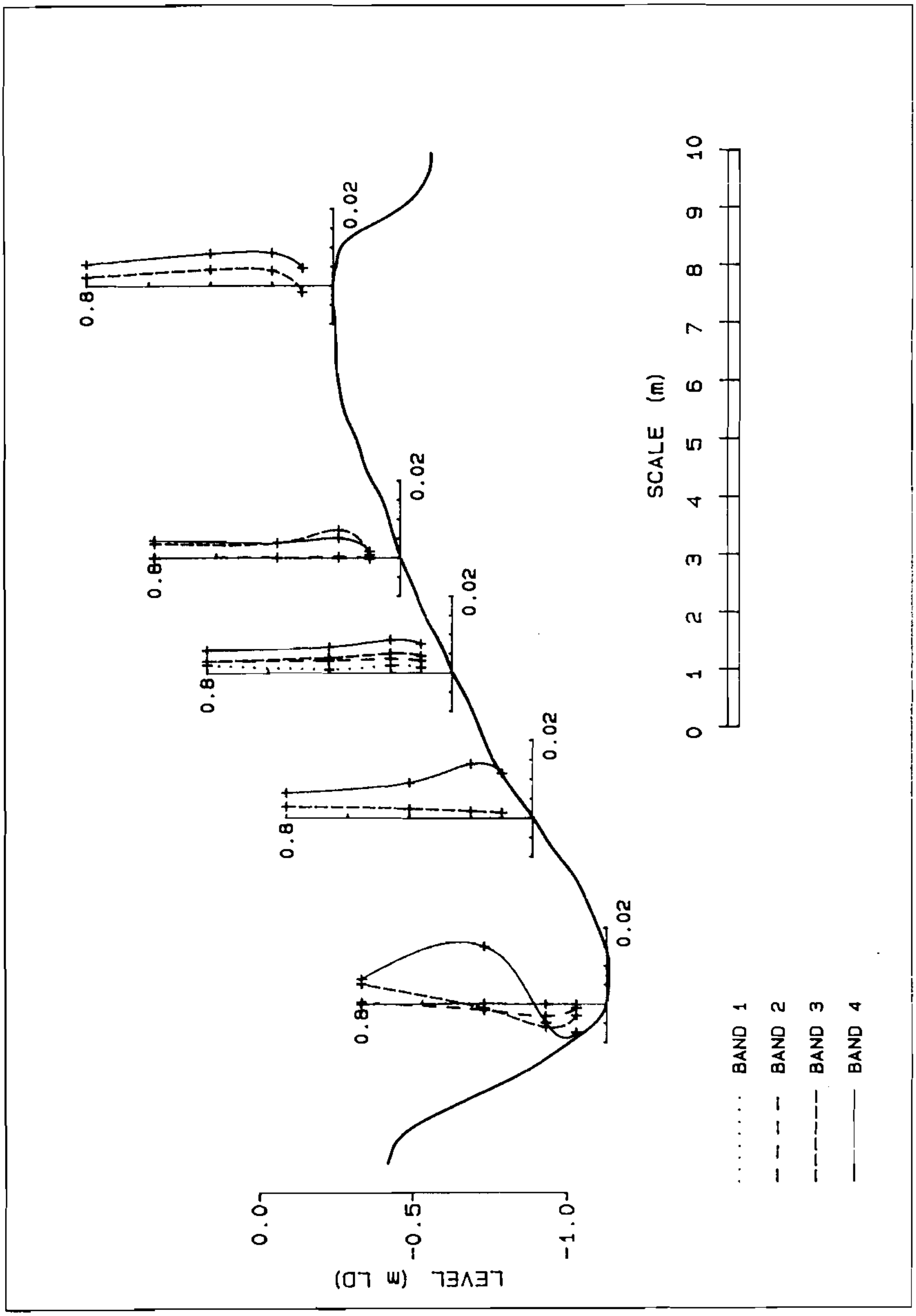

Fig 13 Variation over sandwave of longitudinal diffusive flux ($-\overline{uc}$, kg m^{-2} s^{-1})

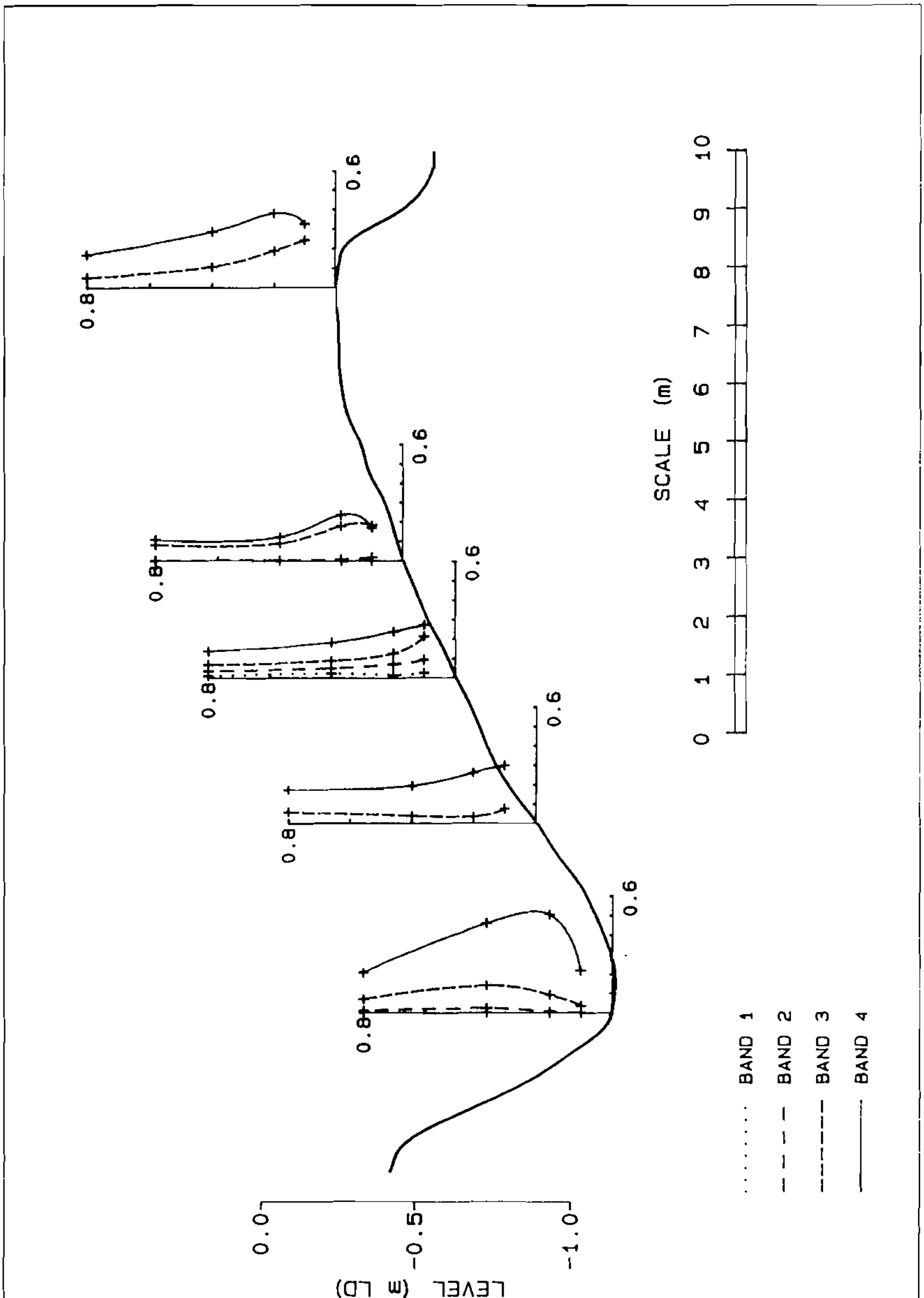

Fig 14 Variation over sandwave of mean sediment flux ($\overline{UC}$, kg m^{-2} s^{-1})

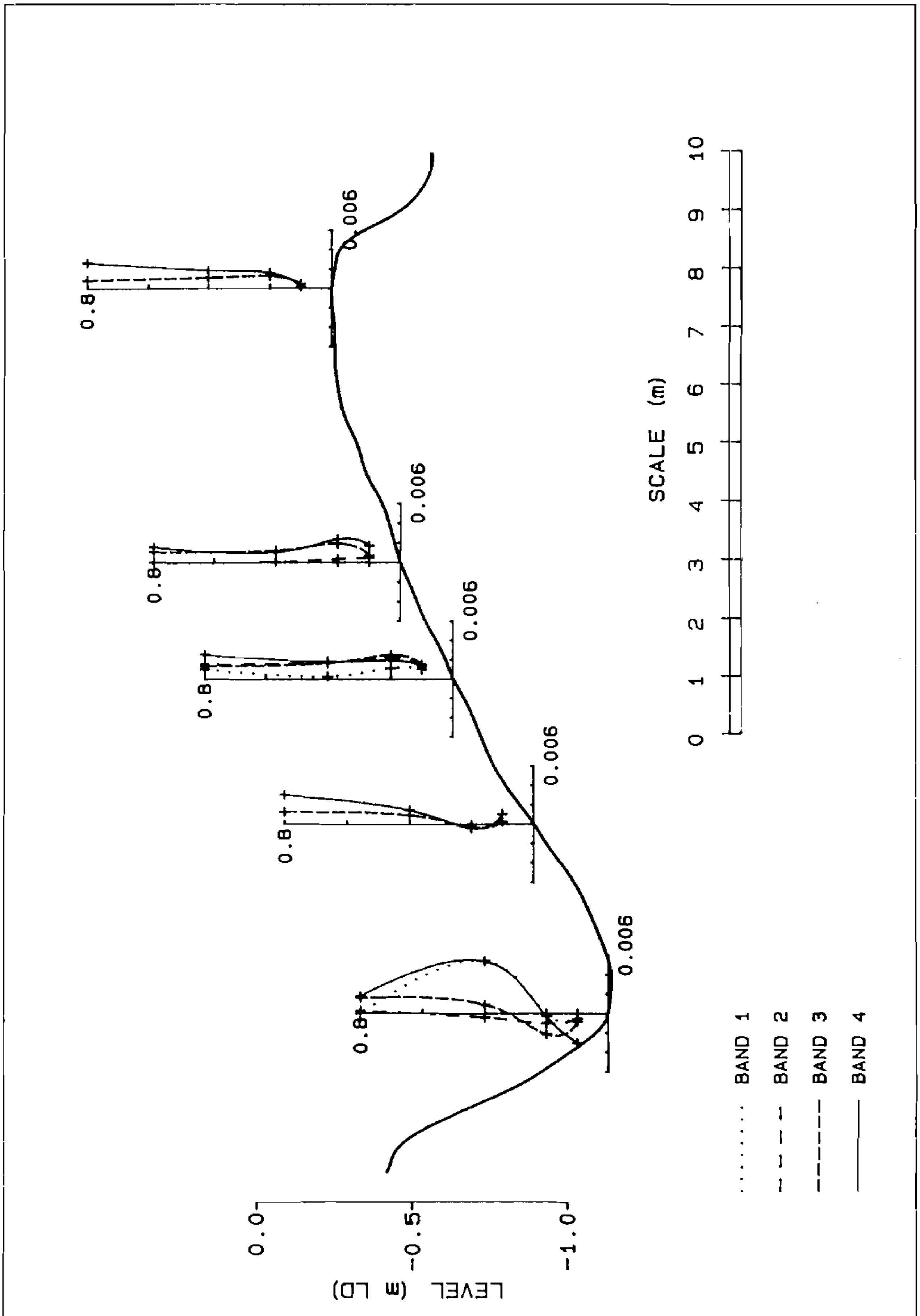

Fig 15 Variation over sandwave of vertical diffusive flux ($\overline{wc}$, kg $m^{-2}s^{-1}$)

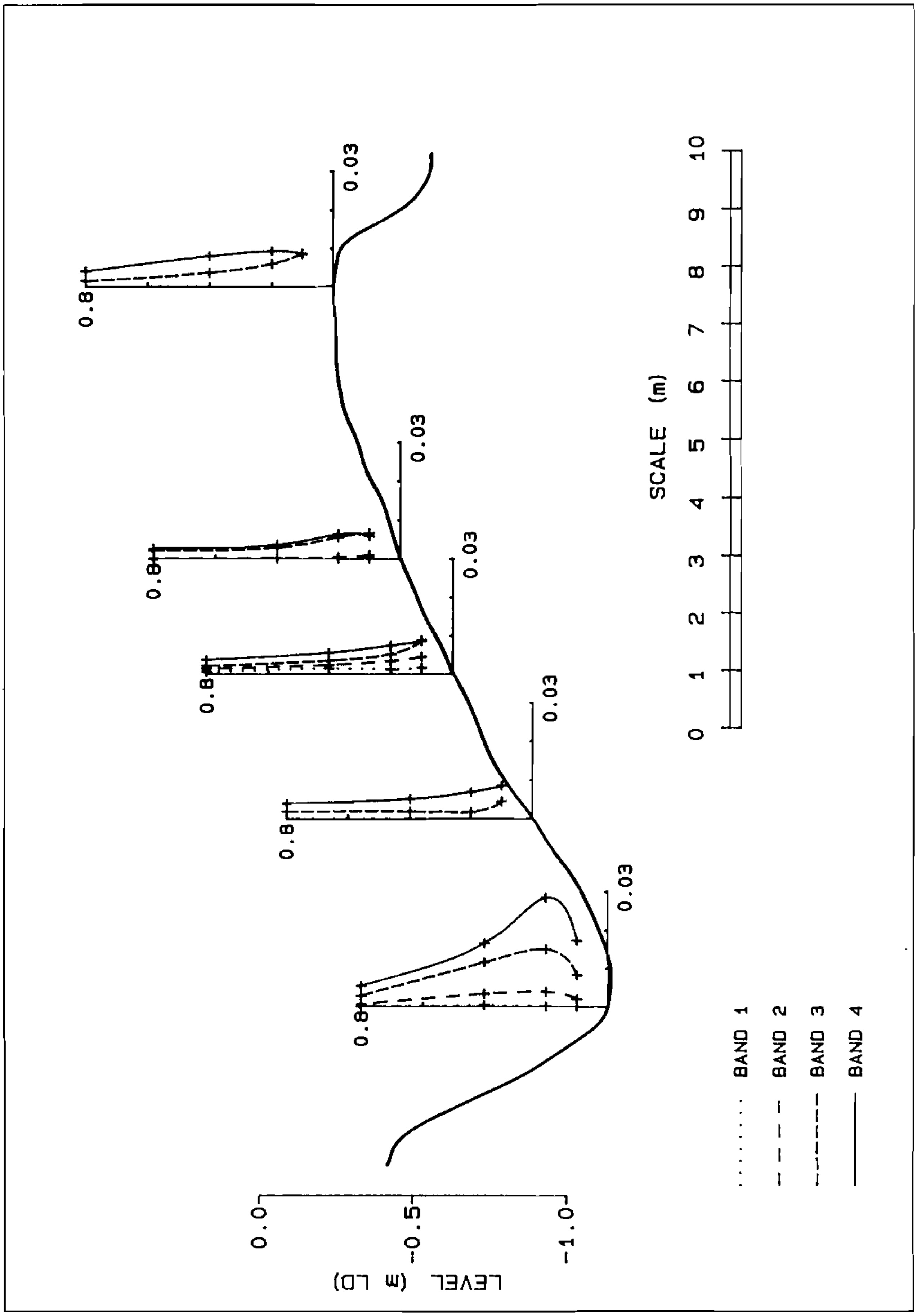

Fig 16 Variation over sandwave of settling flux ($w_s \bar{C}$, kg m^{-2} s^{-1})

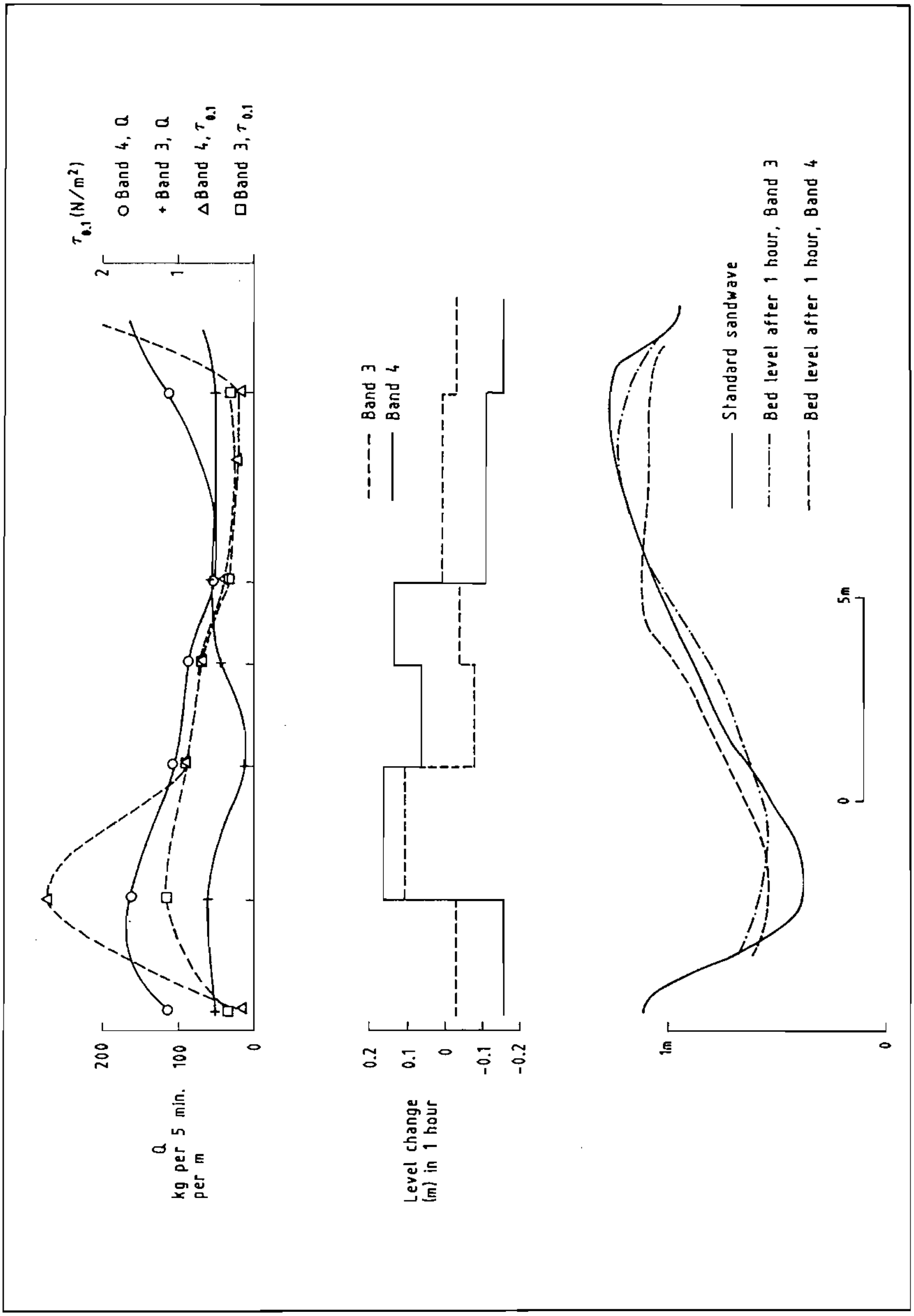

Fig 17 Bed level changes due to suspended sediment transport

PLATES

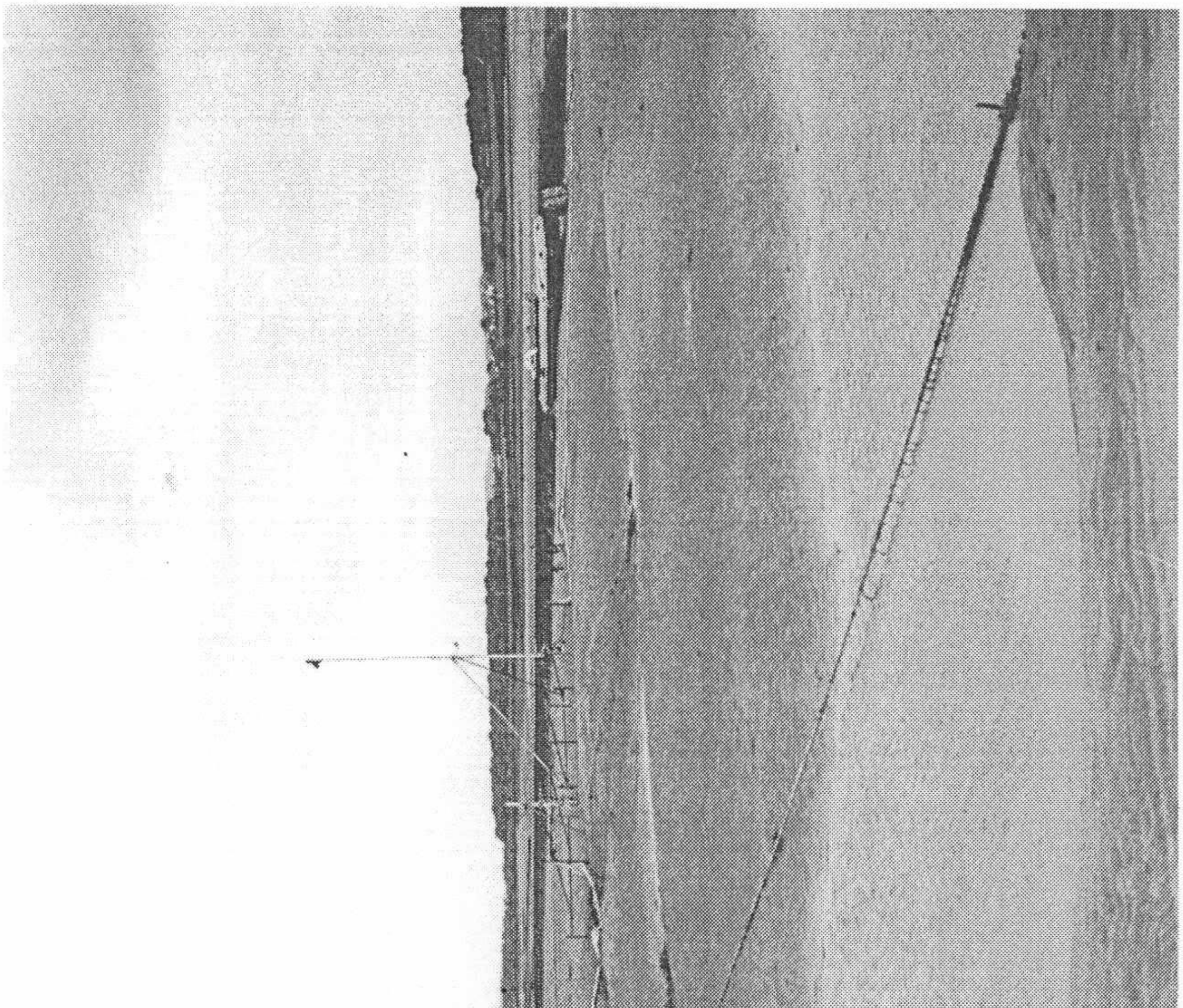

PLATE 1 General view of experimental site

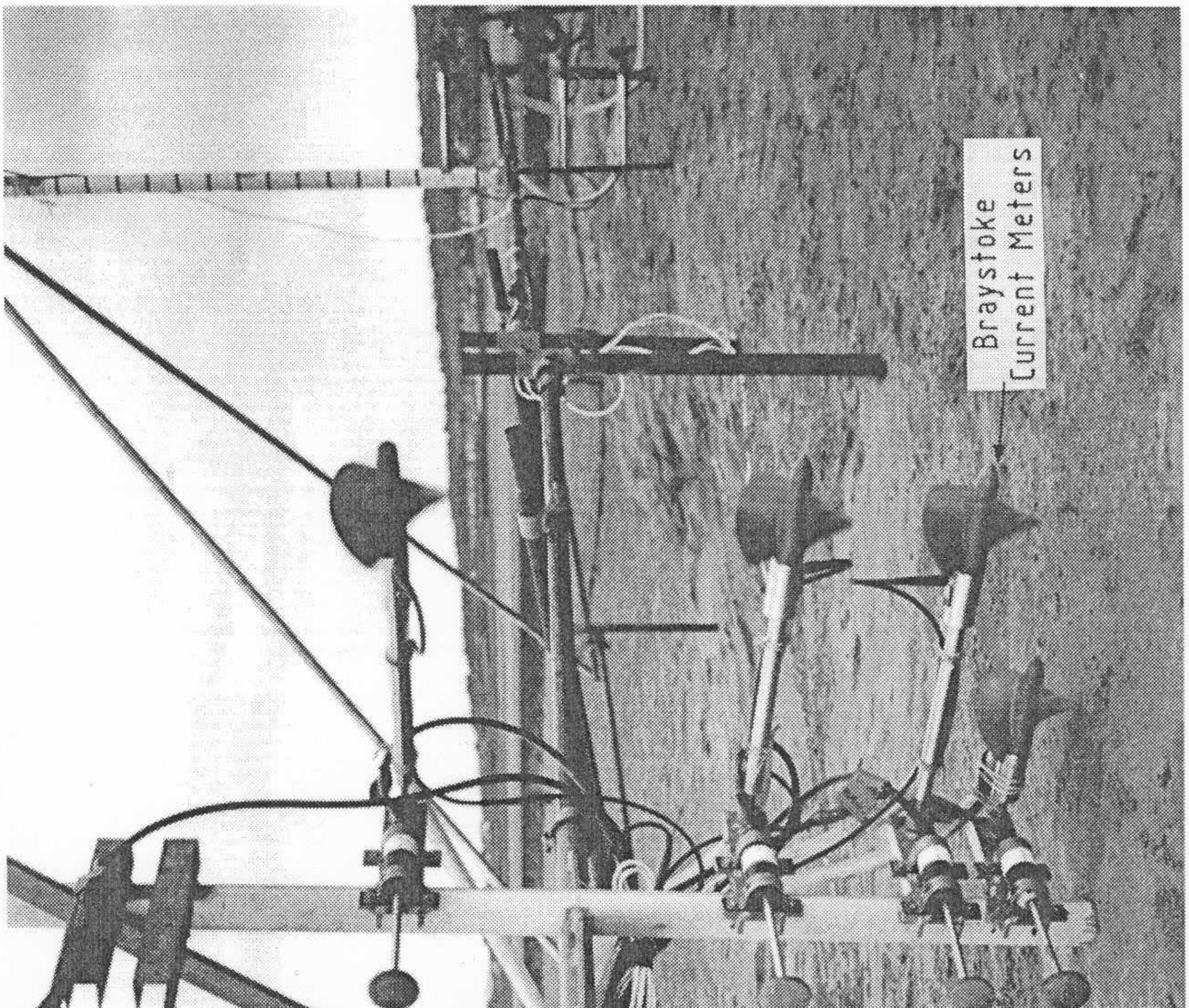

PLATE 2 Arrangement of instrumentation on measuring mast

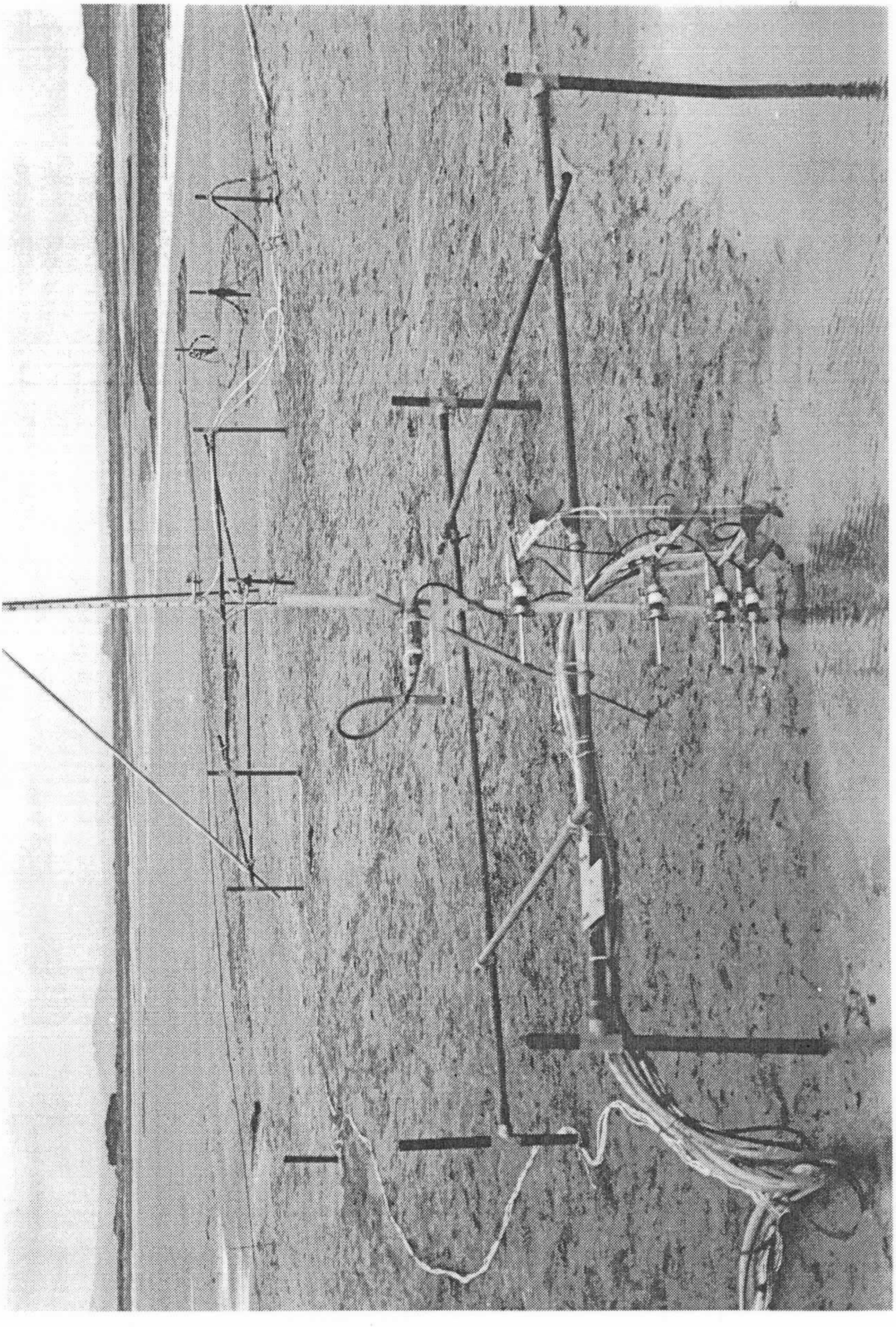

PLATE 3 General view of experimental equipment

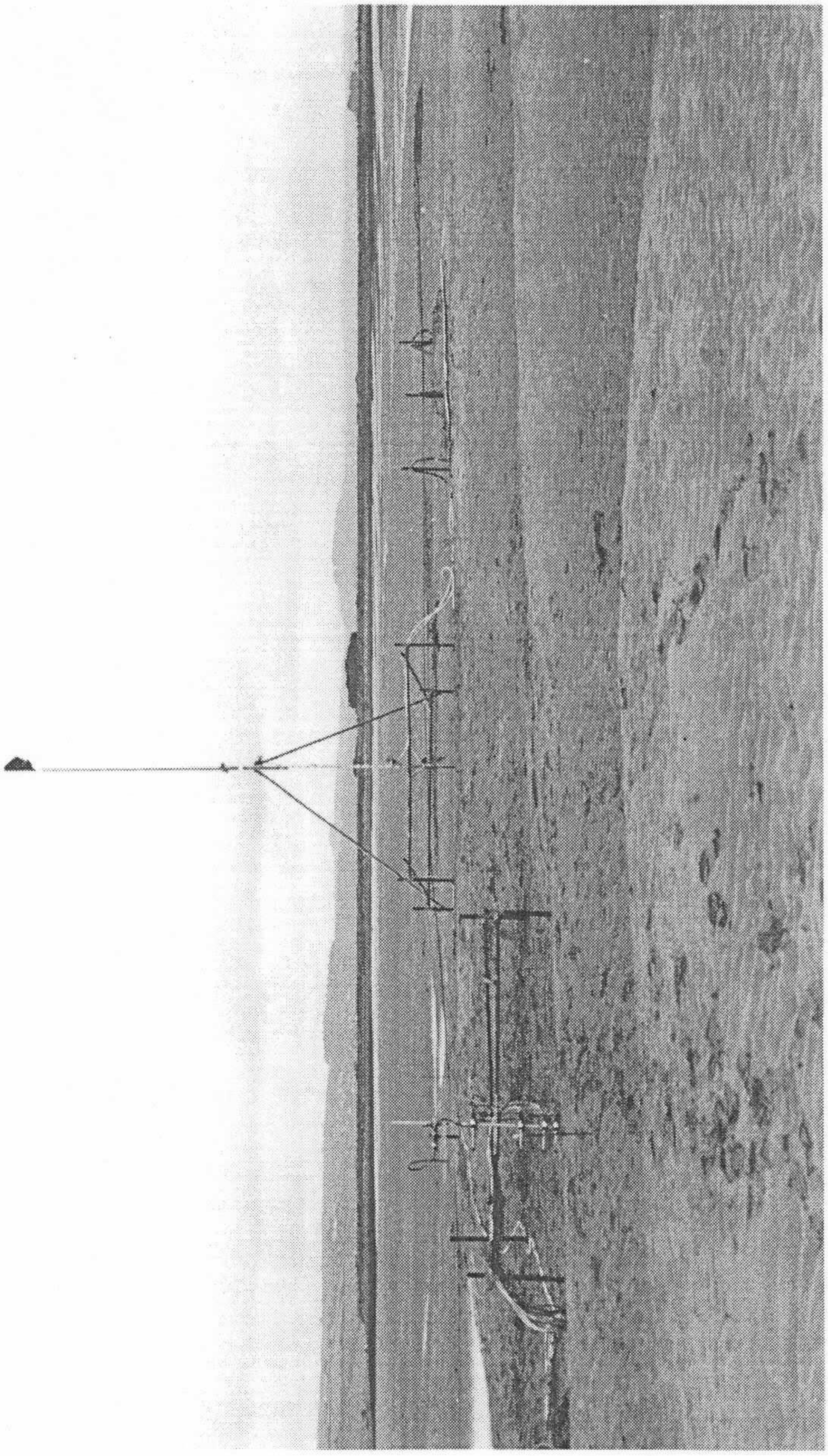

PLATE 4 General view of experimental installation