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SILT REGIMES: A study of Long Reach in the Thames Estuary

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ABSTRACT

The suspended solids concentrations in the Thames Estuary have been monitored extensively in the past by a number of researchers. Inglis and Allen (1957), Hydraulics Research (1971) and Thorn and Burt (1978) have all conducted studies of the silt regime of the Thames Estuary. In the work by Thorn and Burt, the results of the analysis of long term monitoring of suspended solids concentrations were combined with the tidal excursion derived from comprehensive field measurements to deduce the probable locations of silt sources and sinks.

However, it was considered appropriate to ascertain whether, within a reasonably short stretch of the estuary, it is possible to identify and quantify the processes of cohesive sediment transport by detailed field measurement of the suspended solids concentrations and tidal velocities. Hence, measurement throughout the water column during an entire tidal cycle would enable the sediment flux to be calculated. By monitoring simultaneously the suspended solids concentration and velocity at a number of positions along a streamline in the Thames Estuary it would be possible to identify the location of any silt sources and sinks which may exist between the monitoring stations as well as quantify to some extent the sediment transport processes. Furthermore, such a monitoring exercise should also be helpful in verifying the location of the principal sources and sinks of cohesive material identified by Thorn and Burt (1978).

Field measurements were made within Long Reach in the Thames Estuary at three positions simultaneously for three complete and one half tidal cycles between 28.9.85 and 1.10.85. Two of the survey positions were fixed at jetties and the third position was an anchored survey boat which was moved further away upstream from the jetties on each day of the survey. Suspended solids concentration readings were recorded throughout the water column at each of the three locations with velocity measurements also being made from the survey boat.

The suspended solids concentrations were consistent over the four day period at the two fixed survey positions and all the data was regarded to be of good quality.

Seven peaks in the suspended solids concentration against time graphs of a complete tidal cycle for the survey positions were identified. These peaks occurred repeatedly during each flood and ebb tide and were termed events. The passage of these events through the reach was analysed and their likely sources and sinks identified.

With respect to the findings relating to the areas of sources and sinks of the earlier work on the Thames (Thorn and Burt, 1978) the results of the present work do not disagree.

At any given point, transient events tended to result in an increase in suspended solids concentrations throughout the water column; local events were normally evident only in the lower waters.

A simple computational model of the movement of sediment within the survey part of Long Reach was developed. The processes of advection, deposition

and erosion were incorporated into the model. This research has confirmed that the physical processes as represented in the simple computational model lead to sensible predictions of the interaction between bed and suspended silt under the influence of tidal currents. These processes can therefore be more confidently be incorporated into future generations of mathematical models of sediment transport.

The result that the quantity of silt settling and re-eroding is small compared to that which remains in suspension has led to a revision of the rational model of silt transport in that sources are identified as likely to be areas where settlement takes place during one half tide followed by rapid erosion when the flow reverses. Such places exist in the lee of bends.

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1 INTRODUCTION

1.1 Background

Research over the last 10 - 15 years has radically changed perceptions of how cohesive sediment is transported in estuaries. Cohesive sediment is that in which there is a cohesive bond between particles which gives aggregated particles different properties to those of the individual. Cohesionless particles are those which have no such bond and behave with individual properties. The difference between the two is fundamentally due to particle size and the dividing line is usually taken as about .063mm particle diameter. Above this are sands and gravels, below it are silts and clays, the latter having diameters less than .002mm. Mixtures of silt and clay often also containing organic material, are loosely defined as mud.

Prior to the recent research it was generally assumed that mud in estuaries behaved the same way as sand at least qualitatively if not quantitatively. With sand transport for example the concentration of sand in suspension at a point is likely to be a function of the velocity of flow at that point. If the flow speeds up it picks up more sand : if it slows down it deposits some. This gives rise to the concept of a 'saturation' concentration for flow of a given velocity.

Early attempts to quantify the carrying power of flow in muddy estuaries failed because no general correlation could be found between flow velocity and suspended silt concentration. Failure was generally attributed to the large variability of concentrations and the difficulty of obtaining sufficient data to establish reasonable average values. The latter is certainly true and it led to substantial monitoring programmes in a number of estuaries, but it transpired that the explanation was more connected with a lack of understanding of the physical processes involved : mud in estuaries behaves differently to sand in estuaries.

1.2 Silt Monitoring

The proposal to construct the Thames Barrier to prevent flooding of London by surge tides gave impetus to the establishing of a comprehensive silt monitoring programme. In order to measure the effects of the barrier on silt movement in the Thames it was realised that it was first necessary to find out what the silt movement was without the Barrier. The programme began in 1970/71 with the establishment of four silt monitoring stations each recording at two heights above the bed every 15 minutes. It was made possible by the advent of magnetic tape data logging and computer processing of data.

At the time of writing this report 17 years of almost continuous data exists. Other studies of shorter duration were carried out in the River Crouch, River Parrett, Firth of Forth and many other estuaries. These all contributed to understanding the principals on which the silt regimes of estuaries work.

Suspended silt concentrations were observed to vary on a number of different time scales. Substantial variations could occur over a few seconds as 'clouds' of sediment passed the measuring sensor. Peaks and troughs of longer duration say 15 - 90 minutes occurred during a tidal cycle. Tidally averaged values varied from one tide to the next apparently in accordance with the range of the tide during a two-week spring-neap cycle. Values averaged over a spring-neap cycle appeared to vary from one cycle to the next on a seasonal basis, apparently influenced by, but not directly correlated with the amount of fresh water flow passing through the estuary.

It became apparent that values measured at a point were not so random as had been previously supposed. Thorn and Burt (1978) showed that for any one silt monitor station there was a unique characteristic repeating pattern of suspended silt variations during a tidal cycle. Over a single spring-neap cycle the time variation during successive tides could be normalised in terms of the mean concentration during each tide revealing a consistent pattern of peaks and troughs of approximately the same amplitude. The mean itself correlated well with the tidal range, highest values occurring during spring tides when the flow velocities are also highest. From month to month the relative heights of the peaks changed; sometimes a peak would not occur for a while then reappear, but always the peaks occurred at the same phase during the tidal cycle.

From station to station these peaks of concentration could occur at any time during the tidal cycle, not necessarily in phase with the velocity. In one case, the River Crouch, maximum concentrations occurred consistently around the time of high water when the velocity was almost zero. This led to the conclusion that silt seen in suspension at a point in an estuary must, in some cases, have travelled a considerable distance in suspension. This in turn led to the hypothesis of sources and sinks described briefly in Section 1.4.

Before discussing the interpretation of the silt regime of an estuary it is useful to examine the other development which has taken place over the last 10 -

15 years, the research into the physical properties of silts.

1.3 Physical processes

Research into the behaviour of mud in estuaries has been funded under a number of DOE contracts and is fully described in research reports. It is only necessary to describe here the main conclusions as they effect interpretation of silt regimes from silt monitor records.

Settling

Work using the HR Carousel has shown that settling from suspension only occurs when the near-bed flow velocity is very low. In the case of the Thames in mid-stream this means perhaps only during a half hour period around slack water at high and low water. For the rest of the tidal cycle velocities are able to maintain silt in suspension. This means that a particle of silt may travel up to about 20 km during a flood or ebb tide. The Carousel work has further shown that this deposition threshold is virtually independent of the concentration of silt in suspension up to at least 50,000 mg/litre. In other words if there is a saturation limit, the Thames, with maximum concentrations in the region of 5,000 mg/l, is operating well below it and is therefore capable of carrying a much higher suspended silt load than it does.

When conditions allow settling to occur it happens at a rate dependent on the concentration. This is a result of the process of floculation by which particles aggregate together to form larger particles which then have a settling velocity higher than the individual particles. High concentration suspensions give more opportunity for particles to collide hence producing larger flocs which then settle faster. A substantial field measurement exercise in the Thames sponsored by DOE, using a field settling column known as the Owen Tube, has given the best data set available in the world at the present time.

Consolidation

Silt having settled on the bed begins to consolidate but there is an intervening period lasting from a few minutes to a few hours, depending on the thickness of the layer, when it is still in a semi-fluid state. If it is left for longer it quickly gains in strength as it reduces in thickness and increases in density.

Erosion

Erosion takes place when the flow velocity, or more precisely the bed shear stress, exceeds the threshold value. The threshold value depends on the density of the silt deposit. If it is still in the semi-fluid state it is entrained easily back into suspension in much the same way as would occur at the interface of two fluids of different density. The longer a deposit remains on the bed the more resistance it develops to re-erosion. The erosion rate is proportional to the excess shear, i.e. the amount by which the applied bed shear stress exceeds the threshold for erosion. In practice the rate of erosion is modified by the fact that the bed itself has a density profile and therefore becomes progressively more difficult to erode as each new surface is exposed by erosion of the one above.

1.4 Silt movement

On the basis of this improved knowledge of silt behaviour it is thus possible to hypothesise a rational model for silt movement in an estuary which explains the time variation of suspended silt concentrations as observed at a silt monitor site.

To simplify the estuary hydrodynamics we can consider the tidal movement of water as a piston action, a body of water oscillating with a 12½ hour period such that any particle of water in that body will move upriver about 18km (in the case of the Thames) with a flood tide and return the same distance on the ebb tide back to it's starting point. If we take slack low water as a starting point and assume initially that the suspended silt concentration is uniform throughout the estuary, settlement from suspension would be taking place evenly along the bed. As the flow accelerates at the beginning of the flood tide deposition stops as soon as the threshold velocity for deposition is exceeded. At this stage a uniform bed of semi-fluid mud exists on top of the underlying consolidated bed. As the velocity increases the erosion threshold is exceeded and the surface of the newly deposited mud is eroded. Further increases in velocity increases the rate of erosion until all the recently deposited silt has been eroded. The underlying consolidated bed is much more difficult to erode and, unless there is an underlying trend of net erosion in the estuary, is therefore likely to contribute little to the sediment dynamics. The source of sediment is thus limited and further increases in velocity achieve little. The concentration as observed at a silt monitor would thus show a decreasing trend at slack water and slightly into the early flood tide followed by a rapid rise up to a peak about 2 hours into the flood tide. Concentrations would then remain constant until the next low velocity period around high water when the same pattern would repeat in the reverse direction.

If we now impose a <u>discontinuous</u> bed of easily erodible sediment it becomes apparent that this will give rise to peaks of concentration generated simultaneously in discreet stretches of the river while other areas yield little or nothing. Thus a concentration profile taken longitudinally in the body of water say 2 hours into the flood will show peaks of concentration in the water occurring just upriver of the sources and nothing elsewhere. A silt monitor at a fixed point would see a series of peaks as the body of water moved passed it, unrelated to the local time of maximum velocity.

It follows that at slack high water deposition will only take place where there is silt in suspension. In this simplified rational model therefore each source must have a reflected or secondary source.

This hypothesis of the interpretation of silt monitor records is fully described by Thorn and Burt (1978) and has to some extent been confirmed by the more recent research on the physical properties of silts.

1.5 Objectives

The purpose of the research described in this report was to validate and refine the interpretation of continuous long-term silt monitor data in terms of sources and sinks of sediment in an estuary regime. The predictive capacity of a mathematical model is limited to the extent to which it truly represents the physical processes involved. An experiment was devised in which we would

a) simulate the physical processes along a 1D streamline
b) check the predictions against measured results in the field.

If reasonable agreement was obtained it would lend confidence to building these processes into future generations of numerical models.

It was considered appropriate to ascertain whether, within a reasonably short stretch of the estuary, it is possible to identify and quantify the processes of cohesive sediment transport by detailed field measurement of the suspended solids concentrations and tidal velocities. Hence, measurement throughout the water column during an entire tidal cycle would enable the sediment flux to be calculated. By monitoring simultaneously the suspended solids concentration and velocity at a number of positions along a streamline in the Thames Estuary it would be possible to identify the location of any silt sources and sinks which may exist between the monitoring stations as well as quantify to some extent the sediment transport processes. Furthermore, such a monitoring exercise should also be helpful in verifying the location of the principal sources and sinks of cohesive material identified by Thorn and Burt (1978).

Accordingly, in Autumn 1985, a field survey was undertaken in Long reach in the Thames Estuary (Fig 1) in which simultaneous measurements were made at three survey positions during both flood and ebb tides. A simple cohesive sediment transport model was employed to simulate the physical processes of advection, erosion and deposition on the streamline on which the monitoring positions were located.

This report is divided into three main sections. The description of the field survey and the results pertaining to the tidal level, velocity and suspended solids concentrations are presented in Section 2. The analysis of field data is made in Section 3 in which peaks (termed events) in the suspended solids concentration-time data are identified and described. A sediment transport model is outlined in Section 4 together with results from the model for movement of cohesive material within the Long Reach. Conculsions and recommendations follow in Section 5.

2 FIELD SURVEY

2.1 Scope of Survey

Field measurements were taken from 6 positions in Long Reach between 28 September and 1 October 1985 during a period of mean spring tides of almost identical range and shape. The fresh water discharge into the tidal Thames at Teddington had been low for some time prior to the survey and the river was therefore considered to be in a dry weather state.

On each of the 4 days of observations, suspended solids concentrations were recorded throughout the water column using jetty mounted optical instruments at position 1 at the seaward end of the reach and at position 2 some 600m landward (Fig 1).

Anchored-vessel observations were taken throughout the water column from the Hydraulics Research vessel 'Triton'. Suspended solids concentrations and current-velocities (using a Severn current meter) were recorded. The vessel was anchored about 1050m landward of position 1 on 28 September and approximately 1620m, 2160 and 2660m landward on the subsequent days at positions 4, 5 and 6 respectively.

Measurements on the first three days of the survey were made during complete tidal cycles. On the final day, 1 October, observations were restricted to the flood tide, a period of about 6 hours. During each day of the survey water levels were recorded every 15 minutes from a tide board erected on the jetty at position 2. Suspended solids concentrations and current velocity observations were taken, where possible, every 15-20 minutes through the water column, with measurements being recorded at between five and eleven different heights above the bed. The number was dependent upon the water depth but in all cases included measurements at ½m, 1m and 2m above the bed.

The weather conditions remained good during the survey period. The tidal range and period were very similar on each day of the survey, and hence, it was not necessary to apply any compensatory factor to the data to allow for differences in the suspended solids concentrations and velocities caused by changes in tidal range and period. Therefore, direct comparison of data from each day of the survey was possible.

2.2 Tidal conditions

The tidal water levels on each of the four survey days were almost identical in shape and range (Fig 2). The average tidal range was 5.7m and represents a mean spring tide.

The velocities recorded at positions 3,4,5 and 6 are shown in the form of velocity contours on a time-height above bed graph in Figures 3 to 6 respectively. With the exception of the results obtained at position 6, (Fig 6) where the water depth was at least 2m below that at the other sites, the contours show that the velocities were very similar in both magnitude and in the timing of maximum and minimum values.

For the majority of the tide the velocities near the surface of the water were slightly greater than that at mid depth and considerably greater than those near to the bed. There was a period, however, from about mid flood to high water, when this was not the case. At all positions during this period the magnitude of the near surface velocities fell below those at mid depth, and, in a few instances, below those near to the bed. It is not clear what caused this phenomenon but it is known to occur in other stretches of the Thames on the flood tide.

A comparison between the velocities 6m above the bed recorded from the survey craft 'Triton' at positions 3-6, and those obtained in mid channel during the 1968 and 1969 surveys (Hydraulics Research 1971) appear in Figure 7. At the landward end of the reach, positions 5 and 6, it could have been expected that the bend effect would have been sufficiently diminished to have produced results of a more comparable nature. This difference may be attributed to the effect of the bend at Stoneness which would tend to reduce the velocities in the lee of the bend during the flood tide. On the ebb tide the three sets of data show a remarkable degree of similarity. However, although the shape of the velocity curves are similar during the flood tide, the magnitude of velocities recorded in 1985 are somewhat lower than 1968 and 1969 velocities for the four hours from LW+1hr to LW+5hrs.

2.3 Suspended solids concentrations

The suspended solids concentrations for each measuring position and tidal cycle are presented as contours on time after low water and height above bed axes in Figures 8 to 19. At both positions 1 and 2, suspended solid concentrations were recorded on each of the four days. The results from these two positions appear in Figures 8 to 11 and 12 to 15 respectively and show good day to day agreement at each position. The results from positions 3, 4, 5 and 6 are shown in Figures 16 to 19.

By considering Figures 8 to 19 it may be seen that the major flood and ebb suspended solids events (i.e. peaks) occurred throughout the water column with the suspended solids concentrations rising and falling within a very short space of time at any given position. After the initial increase in values at the start of the ebb tide, the suspended solids concentrations decayed to no more than a background reading for the remainder of that part of the tidal cycle. At position 1 during the second half of the flood tide some slight inconsistencies are evident with respect to the 200ppm contour. It is probable that this was caused by lateral dispersion of fine material as it circulated around the eddy which is known to form on the landward side of Stoneness in the latter stages of the flood tide (Hydraulics Research 1970).

Comparisons of the suspended solids concentrations at bed +3m of each of the six positions monitored in 1985 with the 1968 and 1969 surveys are presented in Figure 20 (Positions 1, 2 and 3) and in Figure 21 (Positions 4, 5 and 6). Similarities between the 1985 data and the 1968 and 1969 surveys exist during the latter half of the flood tide and at the start of the ebb tide. The principal difference between the 1985 survey and the earlier work occurs after the initial peak in suspended solids concentrations at LW +7½hrs during the ebb tide. Whereas, in the 1968 and 1969 surveys the suspended solids concentrations rose steeply after LW +8hrs and maintained a reasonably high level for 2 to 3 hrs, the suspended solids concentrations in the 1985 survey fell away to very low values during the period LW +8hrs to LW +10hrs.

Preceding the 1968 survey the fresh water discharge into the river at Teddington, the tidal limit, was abnormally high when compared with that of 1969. Previous work by Kendrick and Derbyshire (1976) investigated the factors influencing estuary sediment distribution and provides an explanation as to the effects of fresh water flow upon suspended solids concentrations. From their conclusions it is clear that many of the discrepancies, between the 1968 and 1969 data can be accredited to the differences in the fresh water discharge preceding the surveys.

3 ANALYSIS OF DATA

3.1 Introduction

The objective of the analysis of the field data was to determine the relationship between the suspended solids concentrations and current velocities with the view to identifying the 'events' during the tide at each position. An event is defined as the passage along a part of the estuary of a moving body of water containing a relatively high quantity of suspended solids. Its movement past a particular point is characterised by a peak in the suspended solids concentrations which may occur throughout the whole water column or in only the lower region of the flow. The 'source' of an event, i.e. its starting geographical location within the estuary may be estimated from a knowledge of the mean flow velocities through the tidal cycle. The 'sink' location of an event may also be identified to some degree in a similar manner.

To enable the suspended solids concentrations and velocities to be considered together a number of graphs were produced in which both parameters are shown for bed +½m, bed +2m and bed +6m. Each survey position was analysed and Figures 22 to 27 give the results for Position 1 to 6 respectively. It will be noticed that for position 1 and 2 only the suspended solids concentrations are shown as no velocity measurements were made at these two positions.

Considerable care has been taken in the data analysis to identify the timing of an event. Although the surveying conditions were ideal, small discrepancies in the timing of events probably do exist as the readings were instantaneous rather than continuous.

The time associated with an event was, in the majority of cases, taken to be the time at the peak of the suspended solids concentration. This was found to be a more reliable method of identifying an event than trying to locate its beginning and end. All timings are related to low water (LW).

3.2 Event 1

Position 1 (Fig 22) is the first position to feel the effect of the flood tide as it is at the seaward end of Long Reach. At the start of the flood, an event is detectable at bed + ½m and + 2m that occurs just after LW + 1hr. Moving landward to position 2 (Fig 23) at the same time there is only a slight indication of this event at bed + ½m, whereas at position 3 (Fig 24) it is of a similar magnitude to that at position 1. Further up the reach this event is not detected. As the timing of the event at positions 1 and 3 is identical and occurs when the velocities are low this tends to suggest that the increase in suspended solids concentrations is of a local rather than transient nature. It is probable that this event results from the resuspension of material deposited during slack water periods.

3.3 Event 2

At position 1 (Fig 22) 2hrs after low water at bed + ½m there is a very considerable increase in suspended solids. This increase is detected up to bed + 3m (Fig 9). This event also occurs at positions 2 and 3 at the same time but with much lower concentrations (see Figures 23 and 24 respectively). Between positions 3 and 4 there is a time delay of ½hr which at first sight indicates that the event is moving landward without being supplemented by the erosion of further local material. This picture, however, is not altogether maintained further along the reach as the timing of the event becomes erratic. However, if the distance between positions 3 and 6

(1590m) is divided by the time taken for the event to travel between those two positions (2100s) an average velocity of 0.76m/s is obtained. This agrees favourably with the average recorded mean depth velocity of 0.73m/s. This indicates that overall the event probably moved consistently with the tidal current between positions 3 and 6.

In Figures 25 to 27 it can also be observed that at positions 4-6 the increase in suspended solids concentrations penetrates further up into the water column than at any of the first three positions. It is likely that this indicates a degree of vertical mixing of the material as the event migrates upstream on the flood tide.

3.4 Event 3

This is the major event on the flood tide and it is clearly defined throughout the water column at positions 1 to 5 and in the lower part of the water column at Position 6. The velocities have passed their peak by the time it appears at position 1 and so it may be reasonably assumed that any local material available for erosion has already been removed. Therefore, the material in suspension during event 3 is most probably derived from a distant source.

It may be seen from Figures 20 and 21 that this event is a common feature throughout the reach. It is interesting to note that the peak in 1985 at position 3 coincided with the 1968/9 peaks abeam of position 6. This indicates that the event passes through the reach much quicker in mid river, where the velocities are higher, than along the line of the 1985 survey positions.

From inspection of Figures 22-27, it is evident that event 3 generally progresses landward with time.

The event is identified at position 1 at LW + 2¾hrs and at position 6 at approximately LW + 4½hrs. The simultaneous arrival of the event at positions 1 and 2 is probably generated by the recirculation that occurs at the seaward end of Long Reach during the flood tide (Hydraulics Research 1970) which effectively feeds these positions from a mid river source.

At position 3 (Fig 24) the suspended solids concentrations of event 3 are the highest of the six survey positions. The peaks at each of the three depths shown in Figure 24 occur at the same time in the tide.

The situation at position 4 is somewhat different. The peak of the event is ¼hr later at bed + ½m than at bed + 2m or at bed +6m which occur at the same time (Figures 17 and 25 and Table 1). This may indicate that vertical layering takes place above 2m from the bed. However, this does not explain why the event at bed + 2m and bed + 6m occurs at the same time at positions 3 and 4. Peak values of concentrations are lower at position 4 than at position 3 which suggests that material has begun to deposit from suspension as a result of the reduced velocities.

Following the event up the reach to position 5 the conclusions determined from position 4 are apparently thrown into confusion. Not only does the event arrive at bed + 2m and bed + 6m after bed + ½m but the suspended solids concentrations increase at the above depths, although the velocities have continued to decrease as indicated on Table 1. From Figure 18 it is evident that there is a reduction in the near surface concentrations with those found at position 4 (Fig 17). Material has therefore been settling out of suspension from the upper layers of the water column between positions 4 and 5, which, in conjunction with higher near bed concentrations, will tend to confuse the timing and magnitude of the event.

By the time the event reaches position 6 the velocities (Fig 27) have generally decreased throughout the water column and material continues to settle out of suspension so producing lower concentrations in the upper layers (Fig 19).

Table 1 summarises event 3. It clearly indicates that the timing of the event at bed + ½m is related to the flow velocities in that there is a certain degree of correlation between the velocity of propagation of the wave and the measured velocity of the flow.

The interpretation of the results at bed + 2m and bed + 6m as already outlined is not so clear. The timing of the peaks at successive positions shows no clear pattern of progression. However, if the overall distance between positions 2 and 6 is divided by the time taken for the event to travel between them (2040m and 2700s respectively) the resultant average velocity is 0.76m/s which is in good agreement with the average measured velocity of 0.8m/s.

3.5 Event 4

Following event 3 there is evidence of a fourth event at positions 1, 2, 3 and 4 (Figs 22-25). The event is first recorded at position 1 at LW + 4½hrs and ends at position 4 at LW + 5½ hrs. This event occurs during the generally declining concentrations found towards the end of the flood tide. It travels only in the lower part of the water column at an average propagation velocity of 0.46m/s which is similar to the average of bed + ½m velocities at positions 3 and 4 of 0.4m/s. This may be interpreted to indicate that the event is probably of a transient nature derived from a distant source. It may be seen in Figure 20 that this event also occurred in 1968 and 1969.

3.6 Event 5

A fifth event may also be detected at LW + 5¼hrs. The data shows traces of this event between LW + 5hr and LW + 5½hrs (Figs 22-27) at several positions but it is not sufficiently defined to justify any detailed analysis.

3.7 Event 6

On the ebb tide the water will begin its passage through the study area at position 6 at the landward end of Long Reach and progress seaward to position 1.

No data was recorded at position 6 on the ebb tide as previously reported, and hence it is difficult to determine from where event 6 started. However, as no trace of an event can be found at position 5 it seems likely that its origin was in the vicinity of positions 4 and 3. The event passed these positions at LW + 7hrs, before proceeding past positions 2 and 1, passing the latter at LW + 7¾hrs (Figs 22-25). At positions 4 and 3, event 6 may be detected principally at bed + ½m (Figs 25 and 24) whereas at positions 2 and 1 (Figs 23 and 22) the concentrations also show a slight increase at bed + 2m and bed + 6m. It would seem, therefore, that this event picks up material in the middle of the reach and then transports it seaward.

3.8 Event 7

Event 7 is somewhat easier to identify as it was recorded through most of the water column at all five positions (Figs 8 to 18). Event 7 was also clearly evident in both 1968 and 1969 as shown in Figures 20 and 21. The peaks of the event at bed + ½m progressed seaward with time, starting at position 5 at

LW + 7½hrs and passing position 1 at LW + 8½hrs as shown in Figures 25-22. As with event 3 the propagation of the event at bed + ½m may be correlated to the flow velocities at that depth. Between positions 5 and 3, it travelled a distance of 1110m in 1800s, resulting in a calculated mean velocity of propagation of 0.62m/s. This compares well with the average near bed measured flow velocity of 0.55m/s.

At greater heights above the bed the progression of the peak of the event is not so straightforward. At position 5, the peak in the concentrations at bed + 6m appears after that at bed + ½m (Fig 26) which implies that the event is of near local origin as the material has not had sufficient time to become well mixed throughout the water column.

3.9 Summary of events

The following summarises the analysis of the 1985 data and identifies the probable "sinks" and "sources" which contributed to the events outlined. A schematic illustration of the events is given in Figure 28.

Event 1, Flood:

Originates from a source at the seaward end of the reach. It disperses as it passes through the reach.

Event 2, Flood:

At the seaward end of the reach it is of local origin, becoming transient through the remainder of the reach with additional material being supplied from a further source at the landward end.

Event 3, Flood:

This event is of distant source travelling through the reach to a sink just landward of the study area as local velocities fall during the latter stages of the flood tide.

Event 4, Flood:

Again of distant source passing through the reach to a sink at its landward end.

Event 5, Flood:

As event 4 but with a small amount of material settling out of suspension to form a sink in the middle and landward sections of the reach.

Event 6, Ebb:

Probably originating from the flood sink formed during Event 5 and so of local source.

Event 7, Ebb:

Originates from landward end of reach from sink of Event 4. It progresses through the reach with time.

4 SEDIMENT FLUX MODEL

4.1 Introduction

If it is assumed that the survey positions adopted in Long Reach are along the same streamline of flow, then an analysis of the time varying sediment flux at the survey positions during a tide may reveal some insight into the nature and rate of the cohesive sediment physical processes. For instance, if the flux of sediment at position 2 was greater, for example, than the sediment flux at position 1 in the early part of a flood tide, then it would be reasonable to conclude that there was a source of material between positions 1 and 2 which was being eroded. The rate of erosion could be estimated provided the advection of suspended sediment along the reach was taken into account.

In effect, the section of Long Reach covered by the survey positions may be treated as a very large flume. The flow may be assumed to be one-dimensional with the flow velocity representing the depth-averaged velocity. The movement of cohesive sediment within the reach will be governed principally by three physical processes - advection, deposition and erosion.

The objective of the work described in this section was to develop a simple computational model of the sediment transport processes taking place within the surveyed reach. Using the sediment flux at one end of the reach and the measured depth averaged velocities as the inputs to the model it was intended to compare the results of the model at the survey positions along the reach with the field measurements. By adjusting the parameters which describe the rates of erosion and deposition it would be possible to identify the relative importance of these processes.

4.2 Description of model

The computational model was a simple one-dimensional representation of a unit width of river along the line of the survey positions. The processes of advection, deposition and erosion were modelled over 200m long sub-reaches. Within each sub-reach the depth of flow, velocity and suspended solids concentration were each constant at any instant during the tide. Continuity of discharge was assumed throughout the reach and the water level was taken to be horizontal and given by the average of the tide curves presented in Figure 2.

Advection of sediment from one sub-reach to an adjacent sub-reach was approximated for small ΔM by

$$\Delta M = \frac{V \ \Delta T}{L} M \qquad (1)$$

in which

M = mass of sediment in sub-reach
ΔM = mass of sediment advected
V = mean velocity of flow
ΔT = time step
L = length of sub-reach

The discrepancy in using depth averaged velocities and total sediment mass in calculating the advection of sediment was evaluated by comparing the flux of sediment calculated from the detailed field measurements with the sediment flux given by depth averaged velocity multiplied by depth-averaged concentration. In all cases the difference between the two was less than 5%.

Deposition of sediment from suspension was represented by assuming that above a certain critical velocity no deposition occurred and that below this critical velocity the rate of deposition was given by

$$\Delta M = \frac{W \ \Delta T}{d} \left(1 - \frac{V^2}{V_{cd}^2}\right) M \qquad (2)$$

in which

$\bar{W}$ = settling velocity of sediment
d = depth of water
V_{cd} = critical velocity for deposition

The settling velocity of the sediment was assumed to be proportional to the square of the near bed concentration, which in turn, was taken to be twice the depth-averaged concentration. Hence, the settling velocity was given by

$$W = 0.001\ (2C)^2 \qquad (3)$$

in which

C = depth averaged solids concentration (kg/m^3)

The erosion of material from the bed within a sub-reach was modelled by first assuming that there existed a critical velocity below which no erosion took place. When the velocity exceeded this critical value the mass eroded was given by

$$\Delta M = 0.9\ (V^2 - V_{ce}^2) \qquad (4)$$

in which

V_{ce} = critical velocity for erosion

4.3 Model results

4.3.1 Flood tide

The measured sediment flux passing survey positions 1,2 and 4 during the flood tide of 29-9-85 are shown as histograms in Figures 29 and 30. The sediment flux during a half hour interval together with a representative velocity is given in Figure 29. This clearly shows that the maximum flux occurs at around 3hrs after low water, whereas, the peak velocity occurs after only 1½ hrs. In Figure 30 the accumulated sediment flux depicts the gradual progression of suspended material upstream with the flood tide. At the end of the flood tide the accumulative mass which had passed each survey position was virtually the same and was approximately 42 T/m.

The sediment flux passing position 1 was used as input to the computational model to predict the sediment flux at position 2 through a flood tide. The histograms showing the results of the model and the field measurements at position 2 are presented in Figures 31 and 32. The model in this instance was run without allowing erosion or deposition to take place. Advection was therefore the only process modelled.

Throughout the early to mid part of the flood tide, the sediment flux predicted by the model was somewhat lower than that measured in the field (Fig 31). In terms of total mass which passed position 2 it is clear from Figure 32 that there is a consistent shortfall between the sediment flux predicted by the model and that which was measured in the field. However, this may be explained by reference to the analysis of the field data as reported in Section 3 which indicated that erosion was taking place between positions 1 and 3 in the early part of the flood tide.

Therefore, a more realistic run of the model was made in which erosion was allowed to occur up until LW + 2hrs. The critical velocity for erosion was taken to be 0.5m/s. The results of this run are presented in Figures 33 and 34. The difference between this run and the previous run in which only the advection process was modelled is that the flux predicted by the model during the first two hours of the flood tide is greater. The effect of this increase in sediment flux during the early part of the tide is to increase the accumulative flux to an extent that matches very closely the field measurements (see Fig 34).

A further run was made in which the third process, namely deposition, was modelled by setting the critical velocity for deposition to be 0.4m/s. Results from this run indicated that there was virtually no deposition occurring in the reach, and hence, the low concentrations were a result of water moving into and through the reach which had low sediment concentrations rather than deposition within the reach between positions 1 and 2.

Comparison of the model and field results for position 4 reveals that for the advection only computational model (Fig 35) the movement of flux is at first under-estimated up to LW + 2hrs, then over-estimated between LW + 2hrs and LW + 3½ hrs, and again under-estimated for the rest of the flood tide. The accumulative sediment flux (Fig 36) follows a broadly similar pattern. The total flux predicted by the model at the end of the tide is about 2T/m less than the field measurement of 42T/m.

To examine whether the shortfall in total flux could be accounted for by the absence of the erosion process in the model, a second run of the model was made in which erosion was represented. The critical velocity was again taken to be 0.5m/s and erosion was allowed to take place only up until LW + 2hrs. The results are presented in Figures 37 and 38. Although the total sediment flux to pass position 4 as predicted by the model is similar to that measured in the field (Fig 38), it may be seen that in the first half of the tide the model over-estimates the sediment flux and in the second half the model clearly under-estimates the flux (Fig 37). This suggests that the depth averaged velocity used in the model was somewhat higher than the velocity at which the sediment laden water was actually moving in the reach between positions 1 and 4.

4.3.2 Ebb tide

The sediment flux during half hour periods and the accumulated sediment flux passing positions 3, 2 and 1 on the ebb tide of 28-9-85 were calculated from the field data and are shown in Figures 39 and 40 respectively. Also detailed in Figure 39 is a representative flow velocity within the reach which illustrates the difference between the times of peak sediment flux and peak velocity. The accumulated sediment flux (Fig 40) has a consistent pattern in that more material initially passes position 3 than position 2 and likewise position 1. By the end of the ebb tide the total sediment fluxes are reasonably equal, each being about 30T/m.

The computational model was run for this tide using the field measurements at position 3 as the input. The event analysis given in the preceding section had concluded that there was little erosion or deposition occurring within the reach during the ebb tide and therefore only the advection process was represented in the model. The results for position 2 are shown in Figures 41 and 42 and for position 1 in Figures 43 and 44.

Although the accumulated sediment flux passing position 2 (Fig 42) and position 1 (Fig 44) show good agreement between the field and model results by the end of the ebb tide, the agreement during the early and mid part of the tide is not good. This is illustrated more clearly in the histograms of sediment flux during half hour periods shown in Figures 42 and 44. During the early part of the tide the flux predicted by the model at both position 2 and position 1 is greater than that measured in the field. Between HW + 2½ hrs and HW + 4½ hrs the reverse occurs with the model under-estimating the sediment flux.

It is reasonable to conclude that these discrepancies are probably due to the assumption in the model that the survey positions were on a streamline. Some lateral movement of sediment could well have been taking place which would account for the differences between the model and field results.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Field measurements were made within Long Reach in the Thames Estuary at three positions simultaneously for three complete and one half tidal cycles between 28.9.85 and 1.10.85. Two of the survey positions were fixed at jetties and the third position was an anchored survey boat which was moved further away upstream from the jetties on successive days of the survey. Suspended solids concentration readings were recorded throughout the water column at each of the three locations with velocity measurements also being made from the survey boat.

2. The suspended solids concentrations were consistent over the four day period at the two fixed survey positions and all the data was regarded to be of good quality.

3. Seven peaks in the suspended solids concentration against time graphs of a complete tidal cycle for the survey positions were identified. These peaks occurred repeatedly during each flood and ebb tide

and were termed events. The passage of these events through the reach was analysed and their likely sources and sinks identified.

4. With respect to the findings relating to the areas of sources and sinks of the earlier work on the Thames (Thorn and Burt, 1978) the results of the present work do not disagree.

5. At any given point, transient events tended to result in an increase in suspended solids concentrations throughout the water column, whereas local events were normally evident only in the lower waters.

6. A simple computational model of the movement of sediment within the surveyed part of Long Reach was developed. The processes of advection, deposition and erosion were incorporated into the model. The model indicated that at the site used in the study the principal sediment transport process was advection with little or no deposition and erosion taking place. This was confirmed by the field measurements. The implications of this result are very important. It indicates that run-of-the-river situations contribute and abstract very little silt. Conversely, a high proportion of the silt in suspension in the estuary stays there, oscillating up and down with the tides.

7. The above raises the questions of where and what are the sources which so clearly give rise to peaks of concentration. If the amount of silt which settles around the time of slack water is not enough to produce a source it follows that there must be other places where settlement can take place for longer. Such places may exist in

the lee of bends in the estuary. An area which is in the lee of a bend during the flood tide for example, may be, and in many cases is, fully exposed to the ebb tide. Sediment entering the area throughout a flood tide may settle to and accumulate at the bed to be rapidly re-eroded early in the next ebb tide. From this research it is further evident that the secondary sources referred to in Section 1.4 may well be 'apparent' rather than 'real' sources i.e. the majority of the silt in suspension stays there throughout the ebb tide, (except that which is abstracted in the lee of other bends), through slack low water and returns on the flood tide. However, during this time longitudinal mixing must occur and the existence of the peak must become blurred and probably simply contributes to a general background level of concentrations. New peaks are generated each flood and ebb tide by this method.

8. The benefits of this research are therefore twofold.

   i) It has confirmed that the physical processes as represented in the simple computational model lead to sensible predictions of the interaction between bed and suspended silt under the influence of tidal currents. These processes can therefore be more confidently incorporated into future generations of mathematical models of sediment transport.

   ii) The actual result that the quantity of silt settling and re-eroding is small compared to that which remains in suspension at a run-of-the-river position has lead to a revision of the hypothesis of a rational model of silt transport. The revision is that 'sources' must be areas where velocities are low for long periods during the tide and high when the flow reverses. Such places exist in the lee of bends. 'Secondary' sources need not be interpreted as temporary bed deposits since most of the silt can stay in suspension.

5.2 Recommendations

To locate 'sinks' and 'sources' more accurately it would be necessary to obtain data from mid channel in the reaches both up and down river within the predicted tidal excursion. It is suggested that such measurements should be made at ½m, 2m and 6m above the bed and 2m below the surface as this would be sufficient to identify events of both local and transient nature at any given position.

It would be prudent when conducting a further survey to consider carefully the detailed measurement of velocities at more than one position.

6 REFERENCES

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TABLE.

TABLE 1 Tabulated analysis of Event 3

Position	Height above bed (m)	Timing of peak LW + hr	Maximum suspended solids (ppm)	Recorded velocity (m/s)	Height above bed (m)	Time taken to next position (s)	Distance between positions (m)	Calculated velocity between positions (m/s)	Average recorded velocity between positions (m/s)
1	½	2.85	800						
	2	3.00	700						
	6	2.75	850						
					½	540	600	1.11	Unknown
					2	0	600	α	
					6	0	600	α	
2	½	3.00	740						
	2	3.00	650						
	6	3.00	540						
					½	900	450	0.5	Unknown
					2	900	450	0.5	Unknown
					6	900	450	0.5	Unknown
3	½	3.25	1000	0.65					
	2	3.25	950	0.8					
	6	3.25	700	0.9					
					½	900	620	0.67	0.58
					2	0	620	α	0.75
					6	0	620	α	0.85
4	½	3.5	750	0.5					
	2	3.25	700	0.7					
	6	3.25	600	0.8					
					½	900	450	0.5	0.45
					2	2700	450	0.16	0.60
					6	2700	450	0.16	0.75
5	½	3.75	950	0.4					
	2	4.00	750	0.5					
	6	4.00	700	0.75					
					½	3600	520	0.14	0.3
					2	0	520	α	0.48
					6	0	520	α	0.75
6	½	4.75	900	0.2					
	2	3.75	700	0.45					
	6	3.75	500	0.75					

FIGURES.

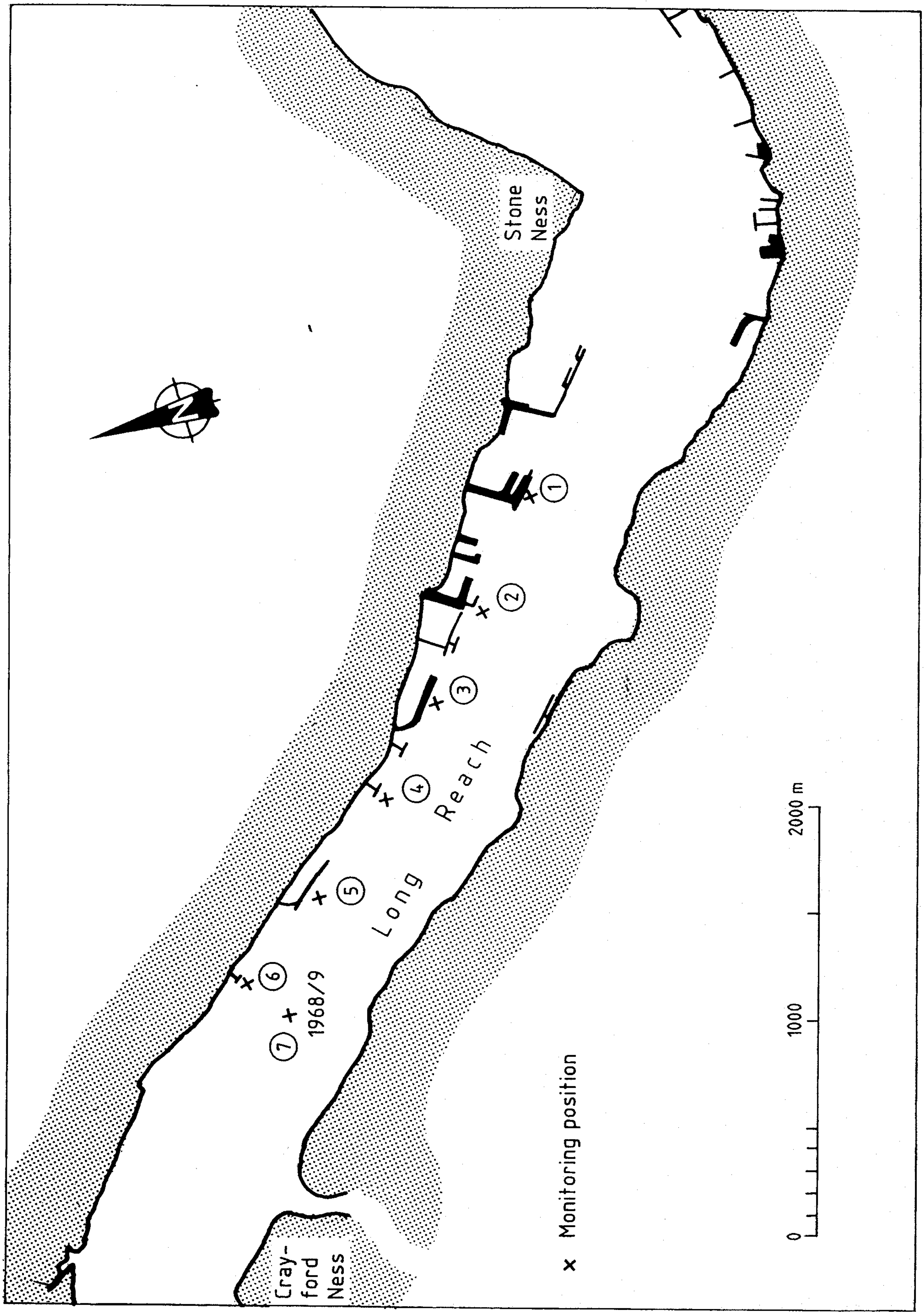

Fig 1 Location of monitoring positions

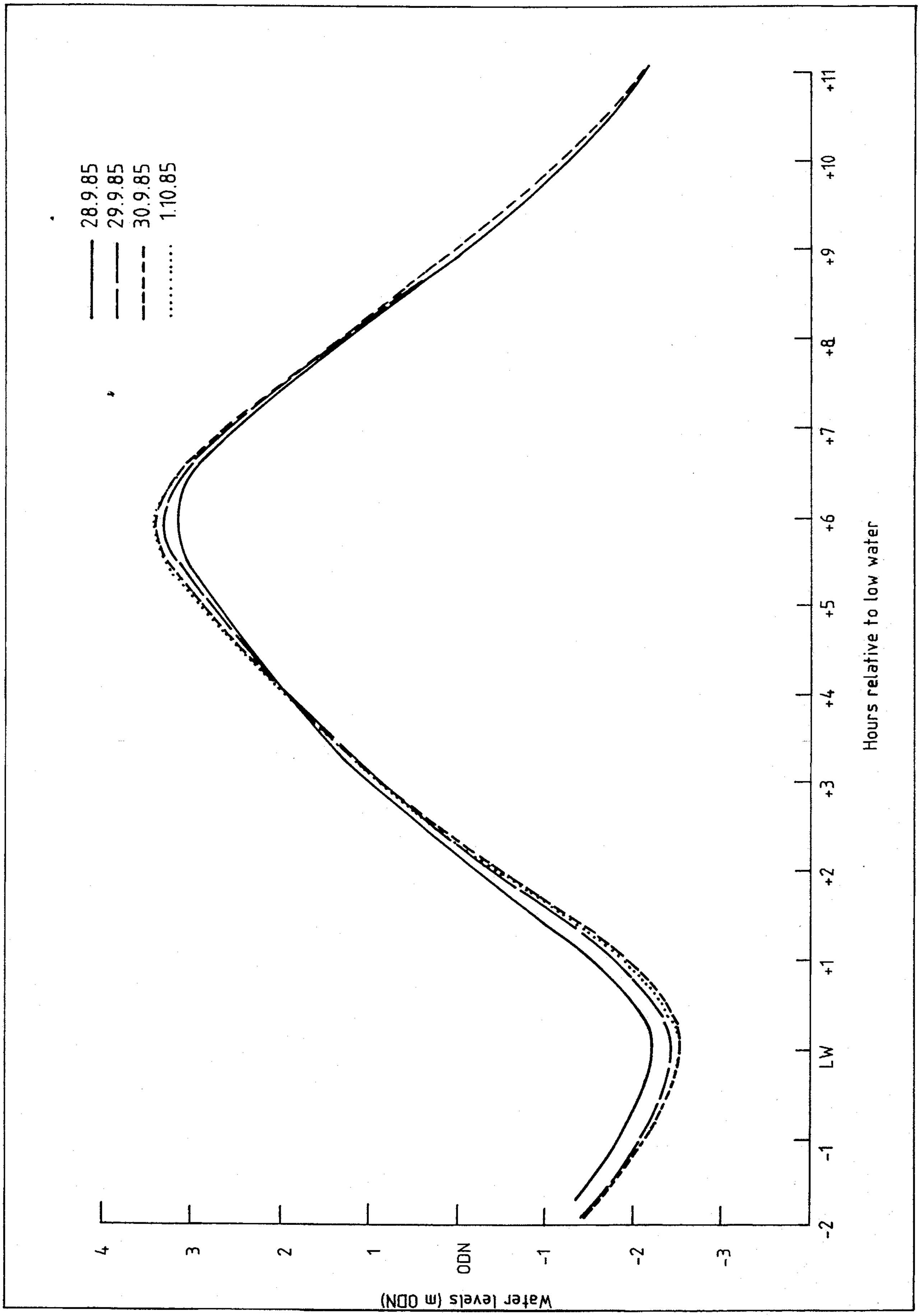

Fig 2 Comparison of tide curves during survey

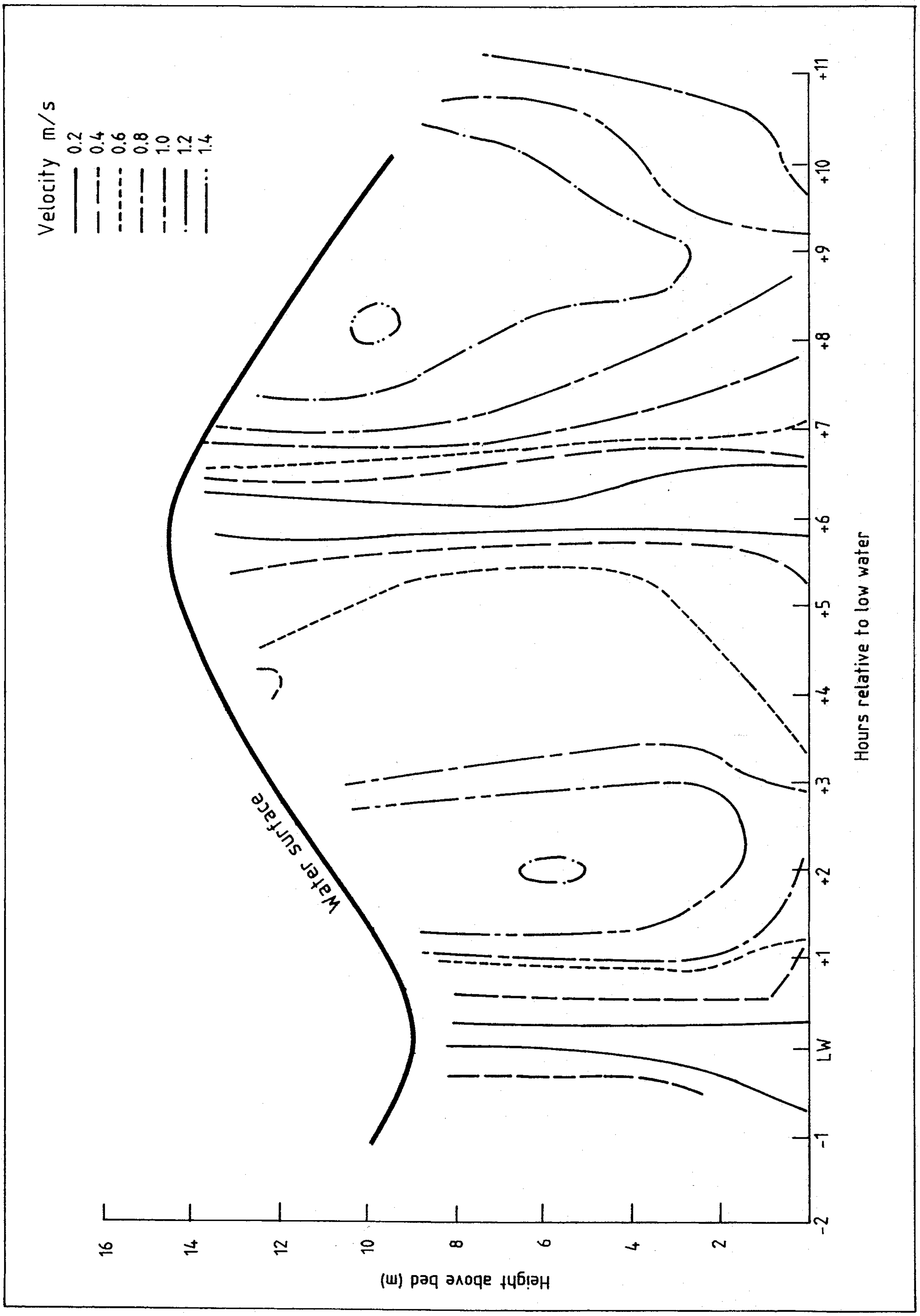

Fig 3 Velocity contours - Position 3

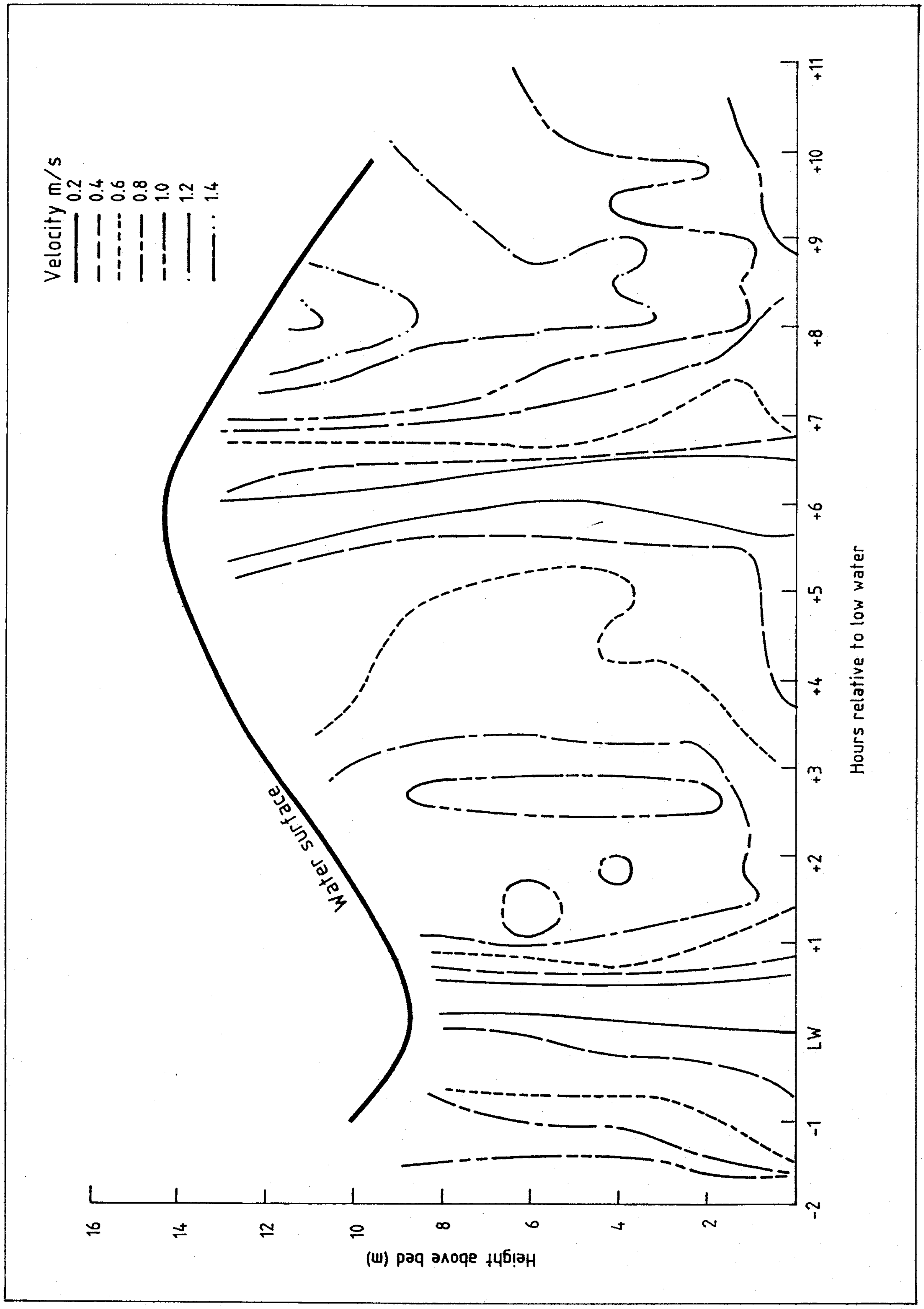

Fig 4 Velocity contours - Position 4

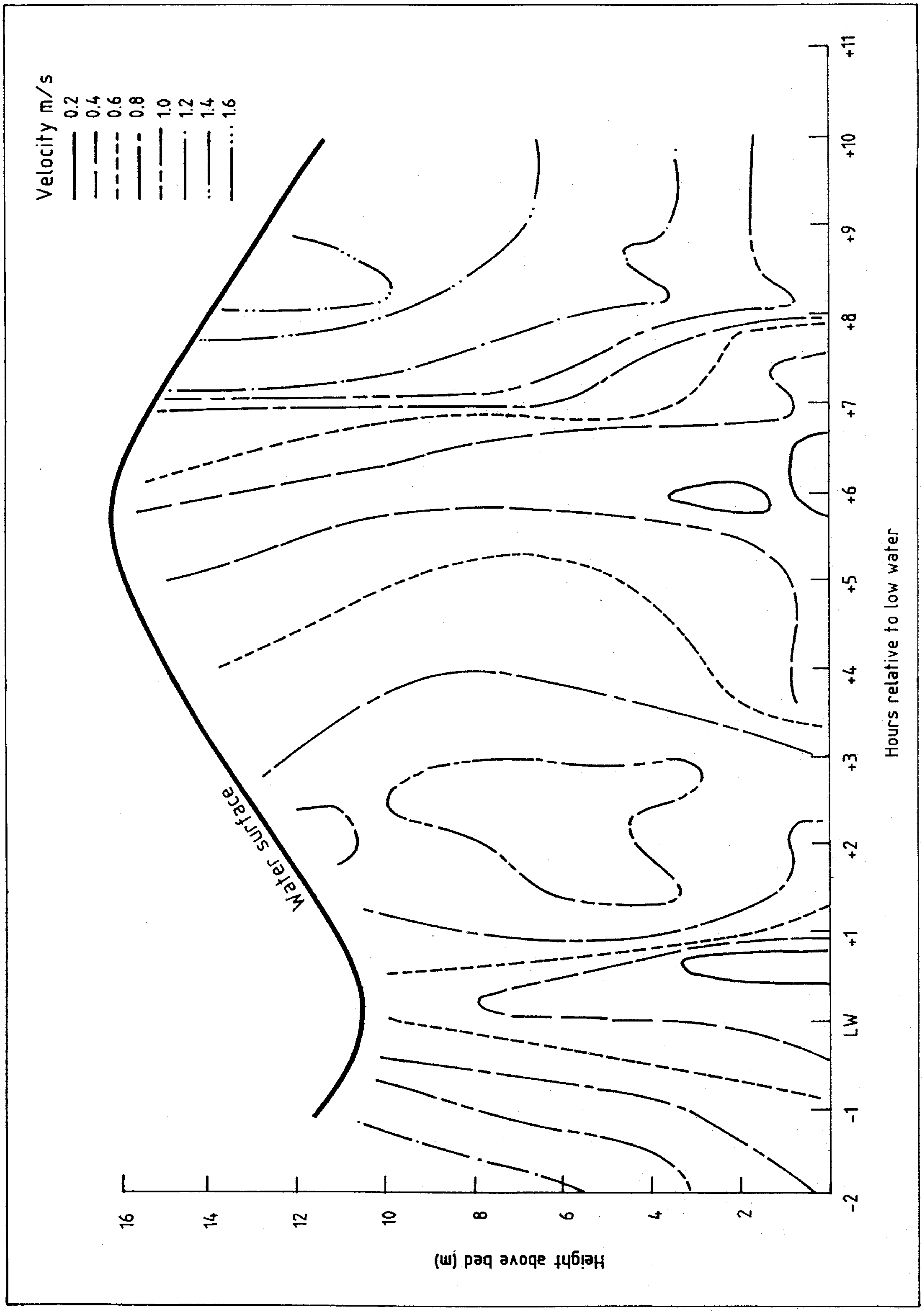

Fig 5 Velocity contours - Position 5

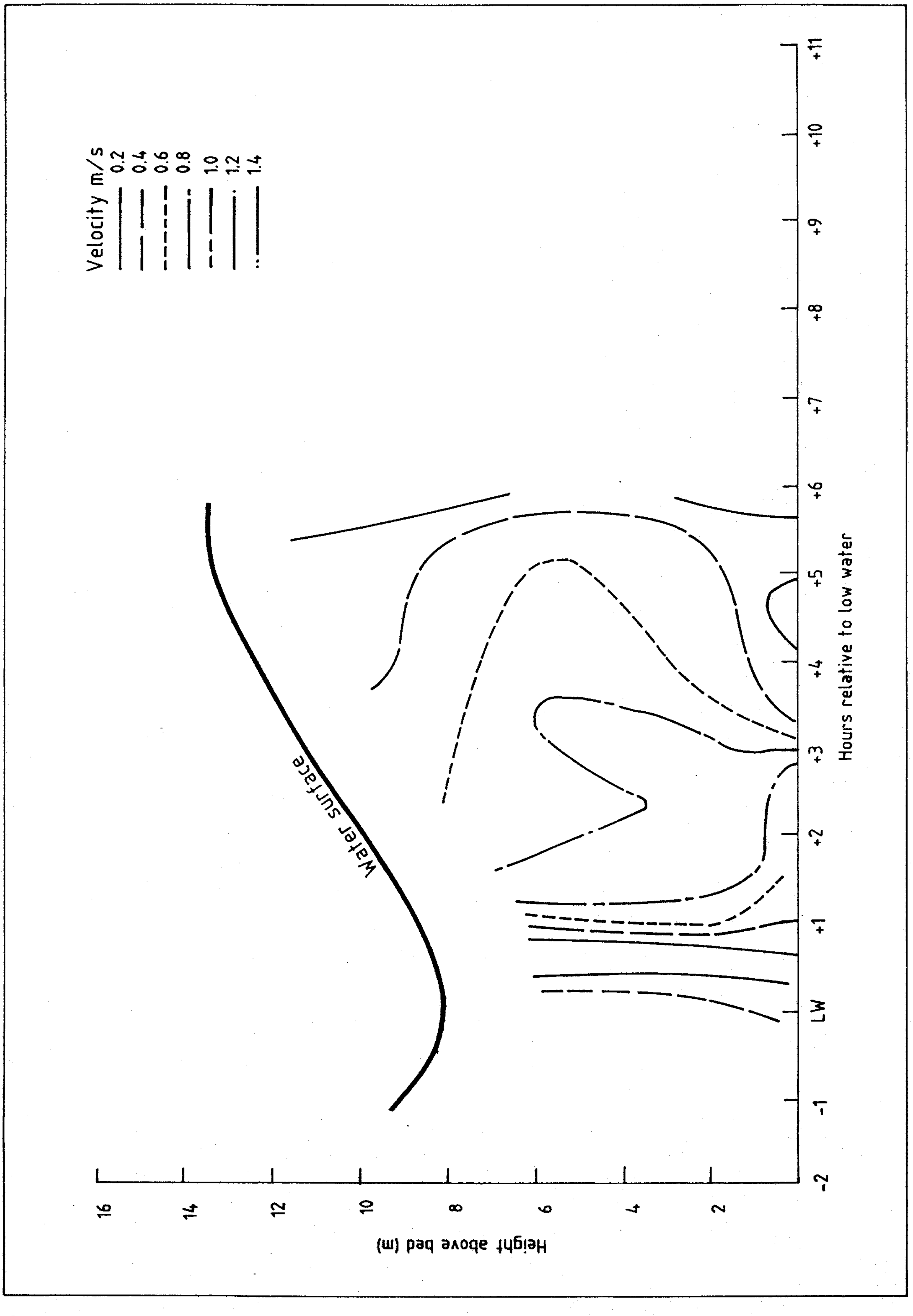

Fig 6 Velocity contours - Position 6

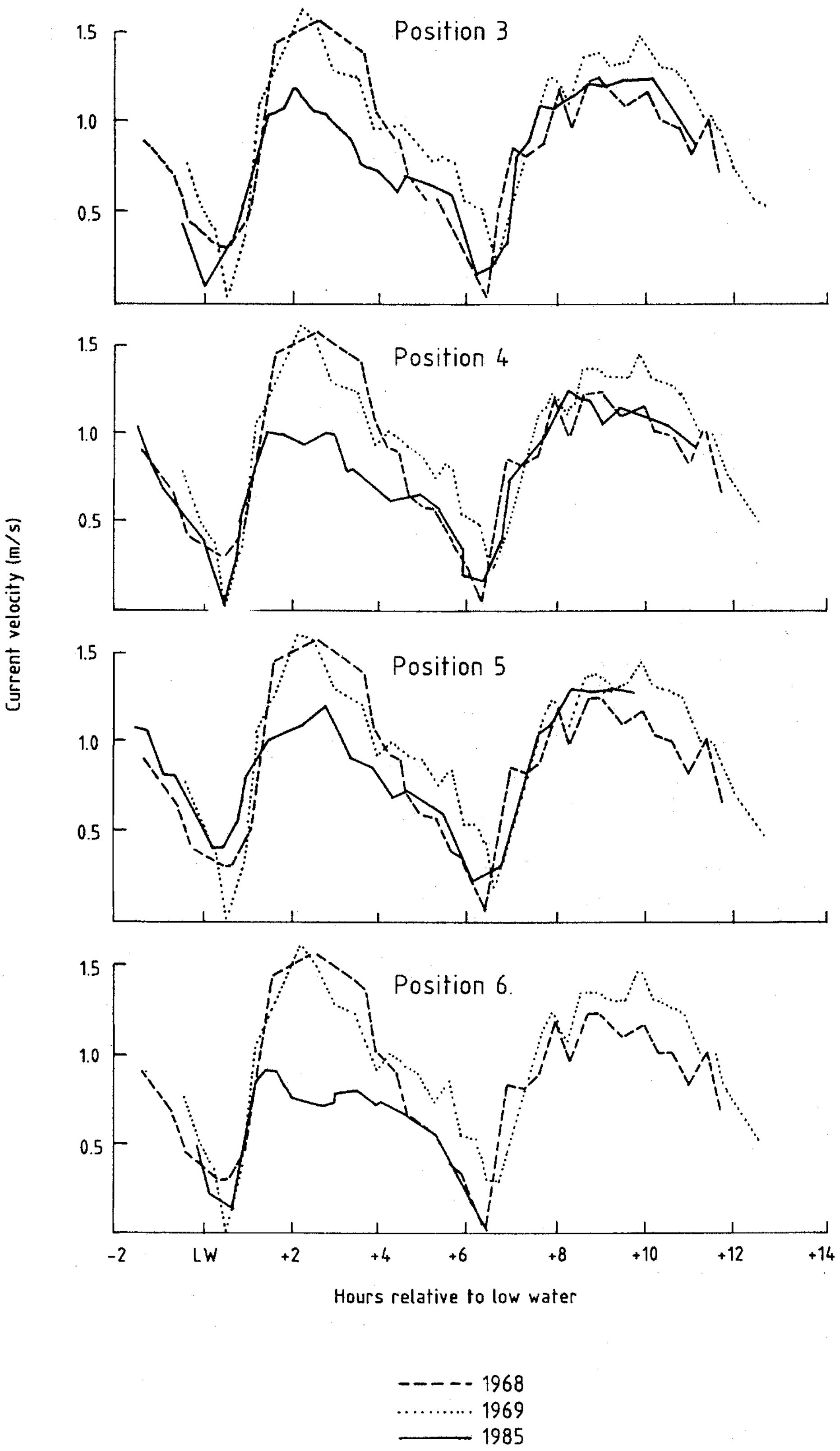

Fig 7 Comparison of 1968, 1969 mid channel & 1985 current velocities

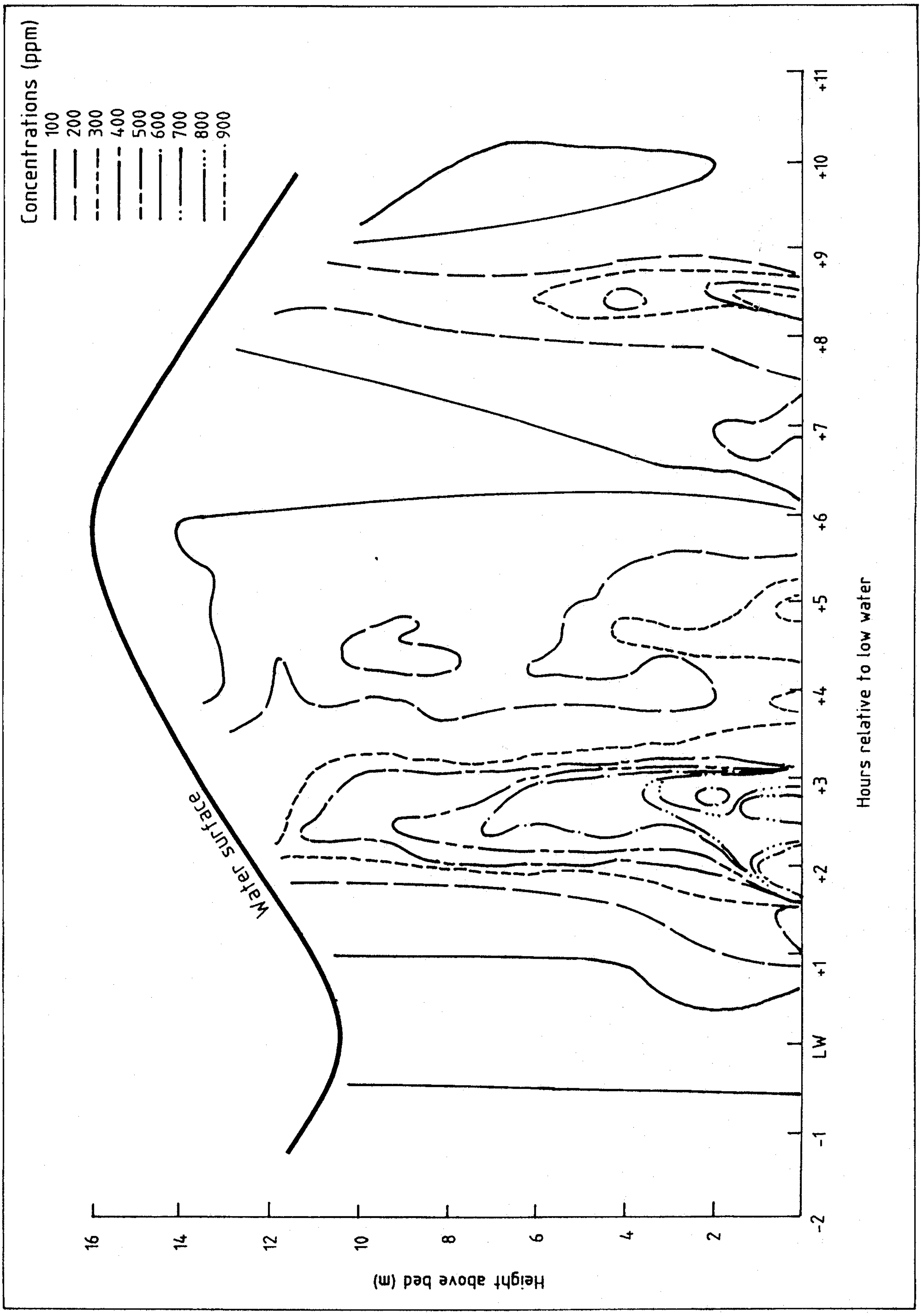

Fig 8 Suspended solid concentration contours - Position 1, 28.9.85

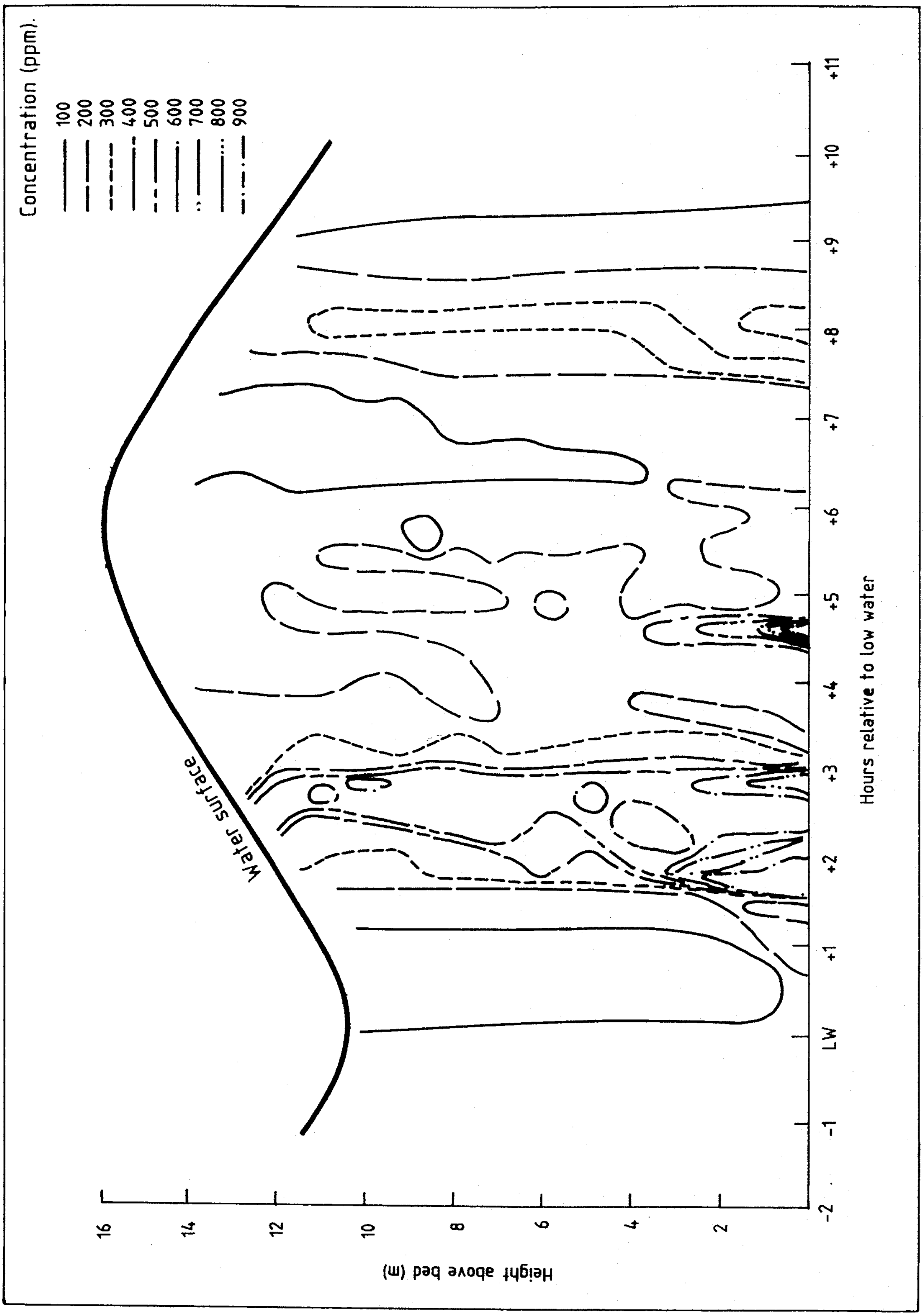

Fig 9 Suspended solid concentration contours - Position 1, 29.9.85

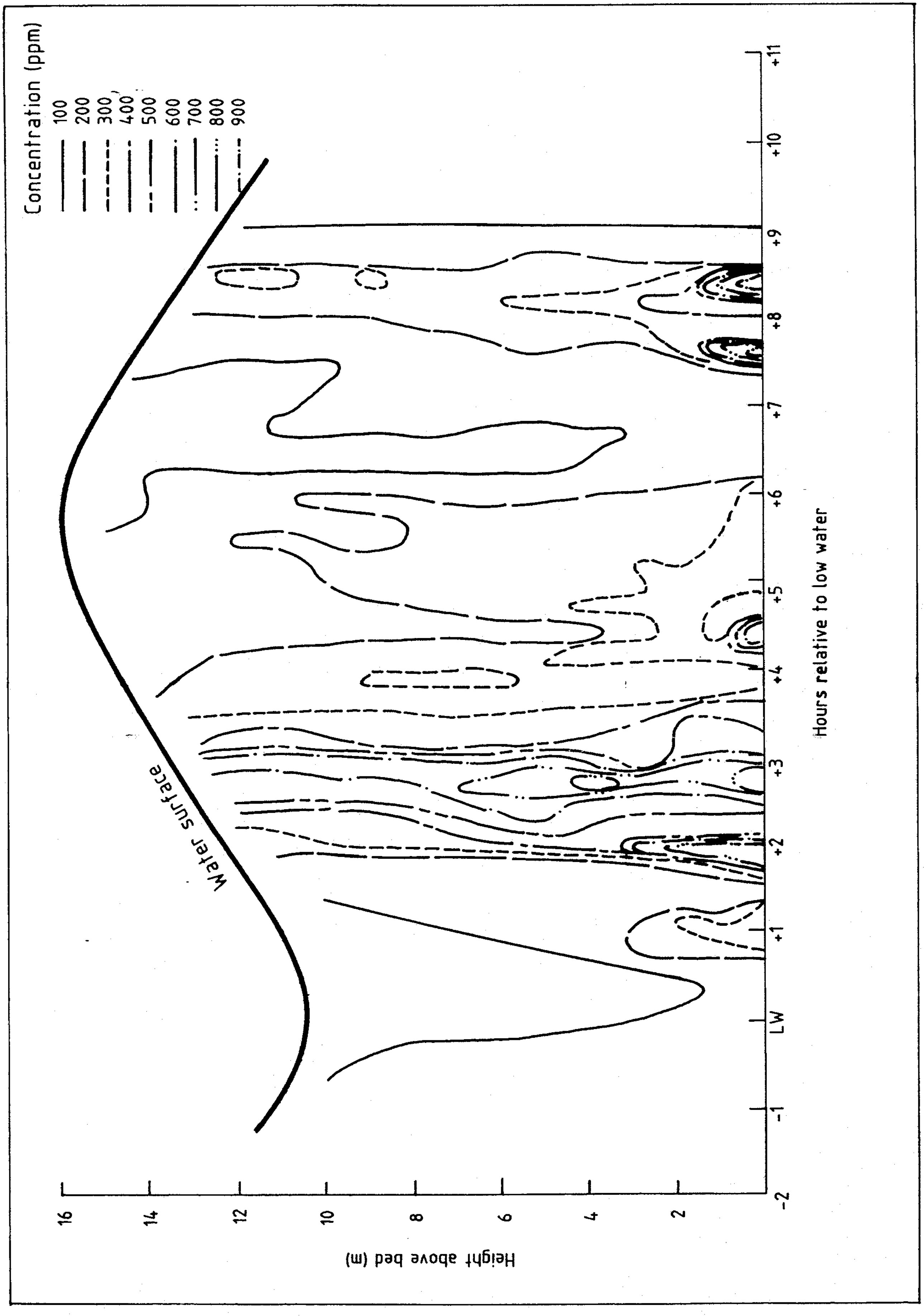

Fig 10 Suspended solid concentration contours - Position 1, 30.9.85

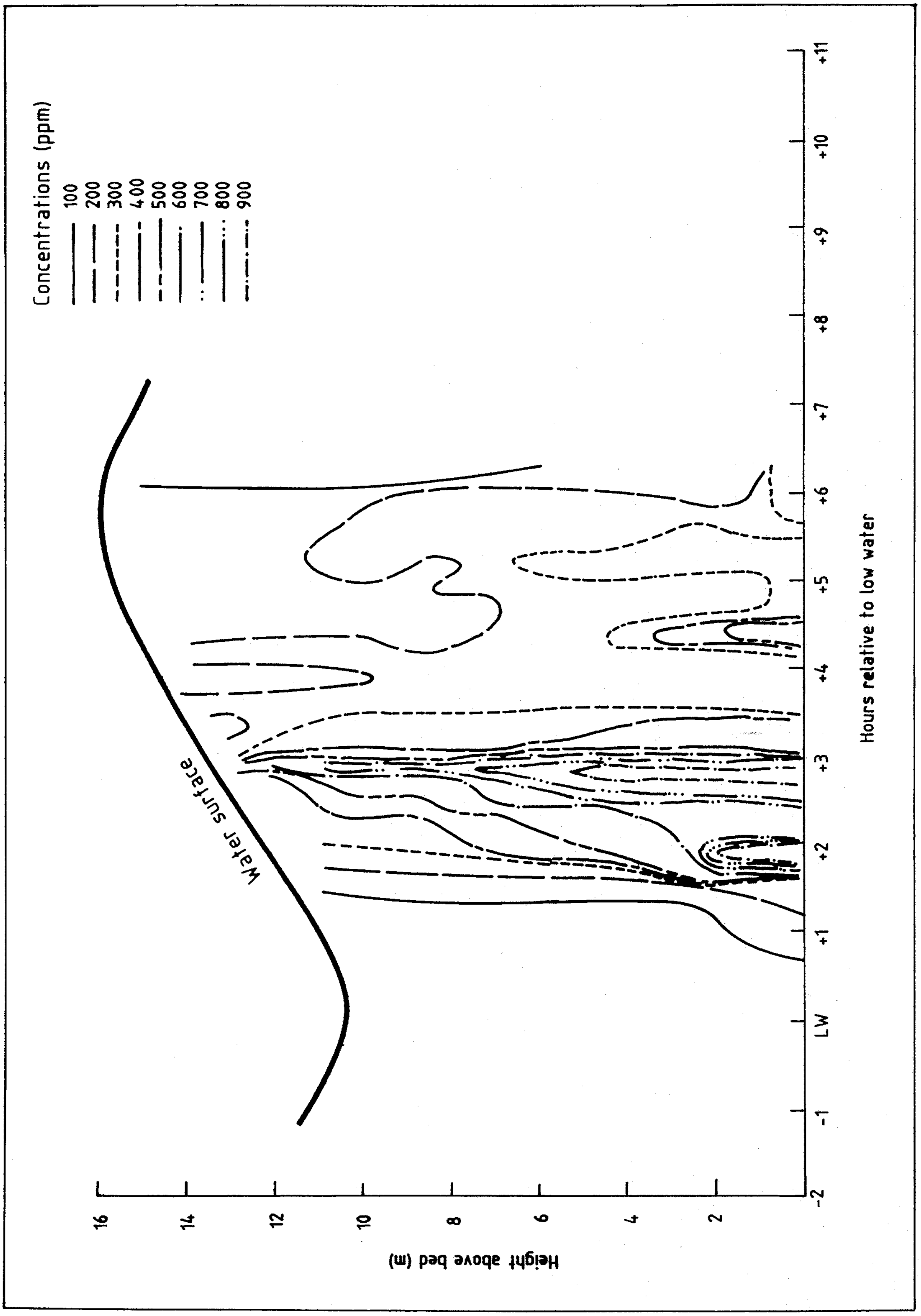

Fig 11 Suspended solid concentration contours - Position 1, 1.10.85

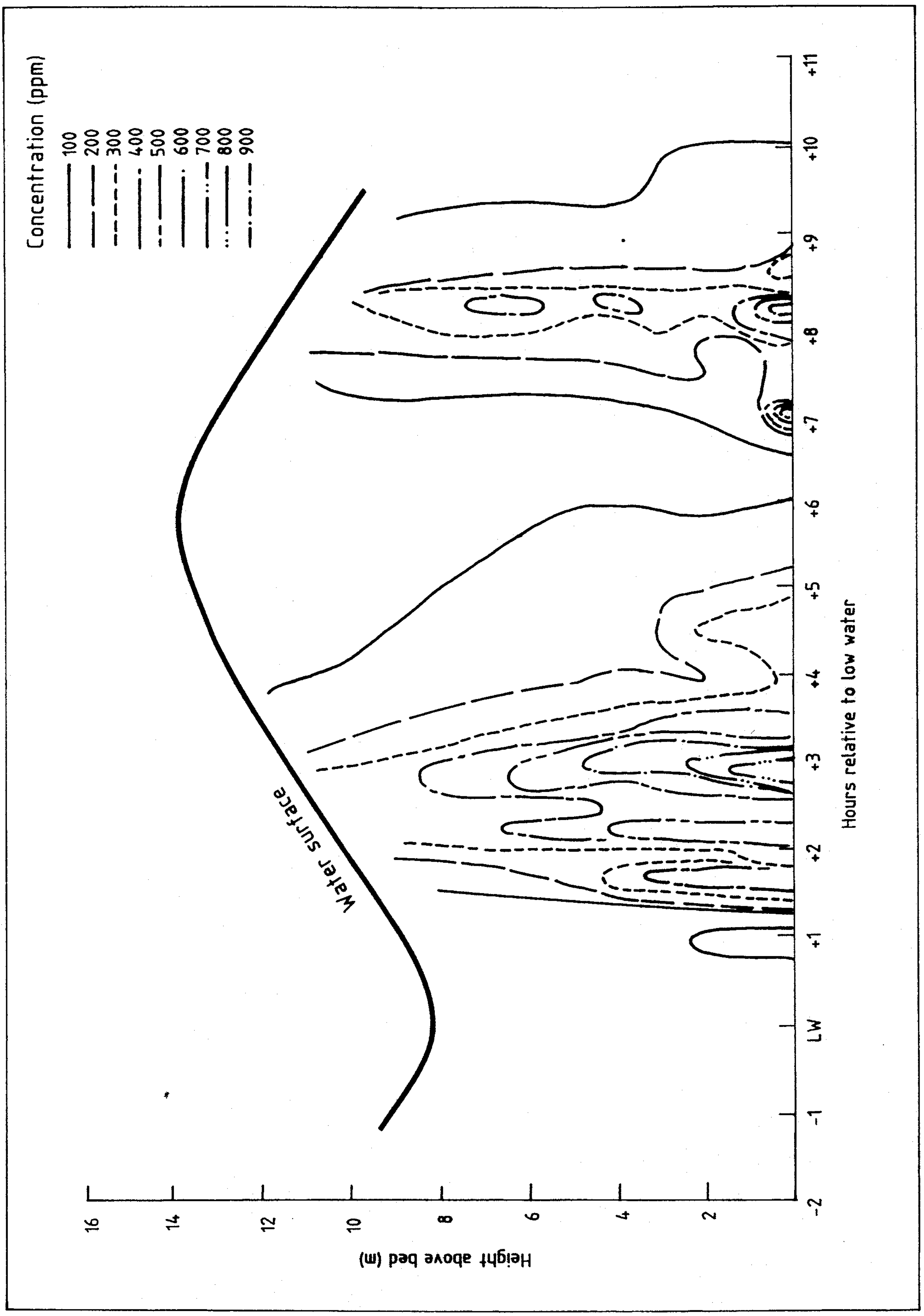

Fig 12 Suspened solid concentration contours - Position 2, 28.9.85

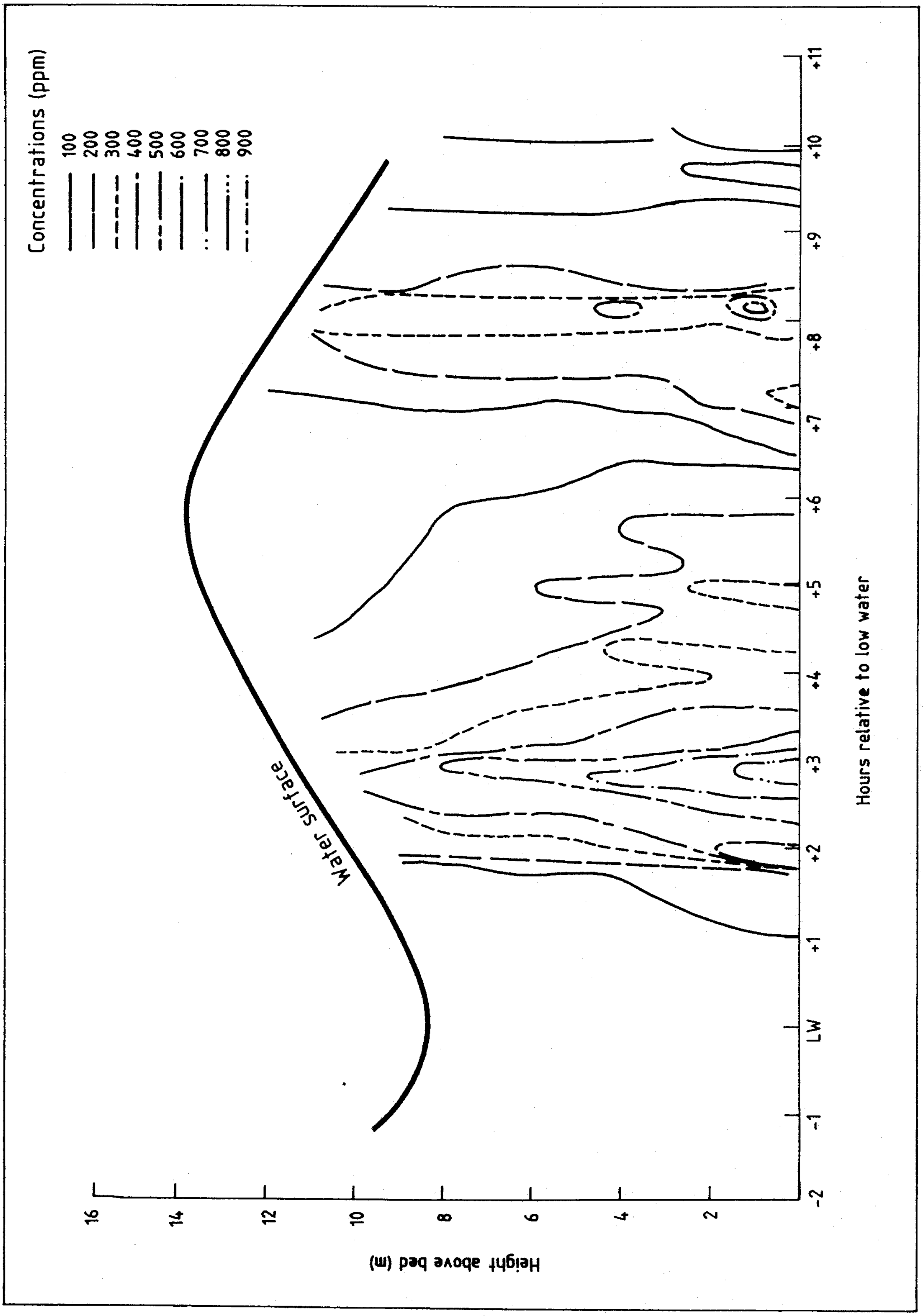

Fig 13 Suspended solid concentration contours - Position 2, 29.9.85

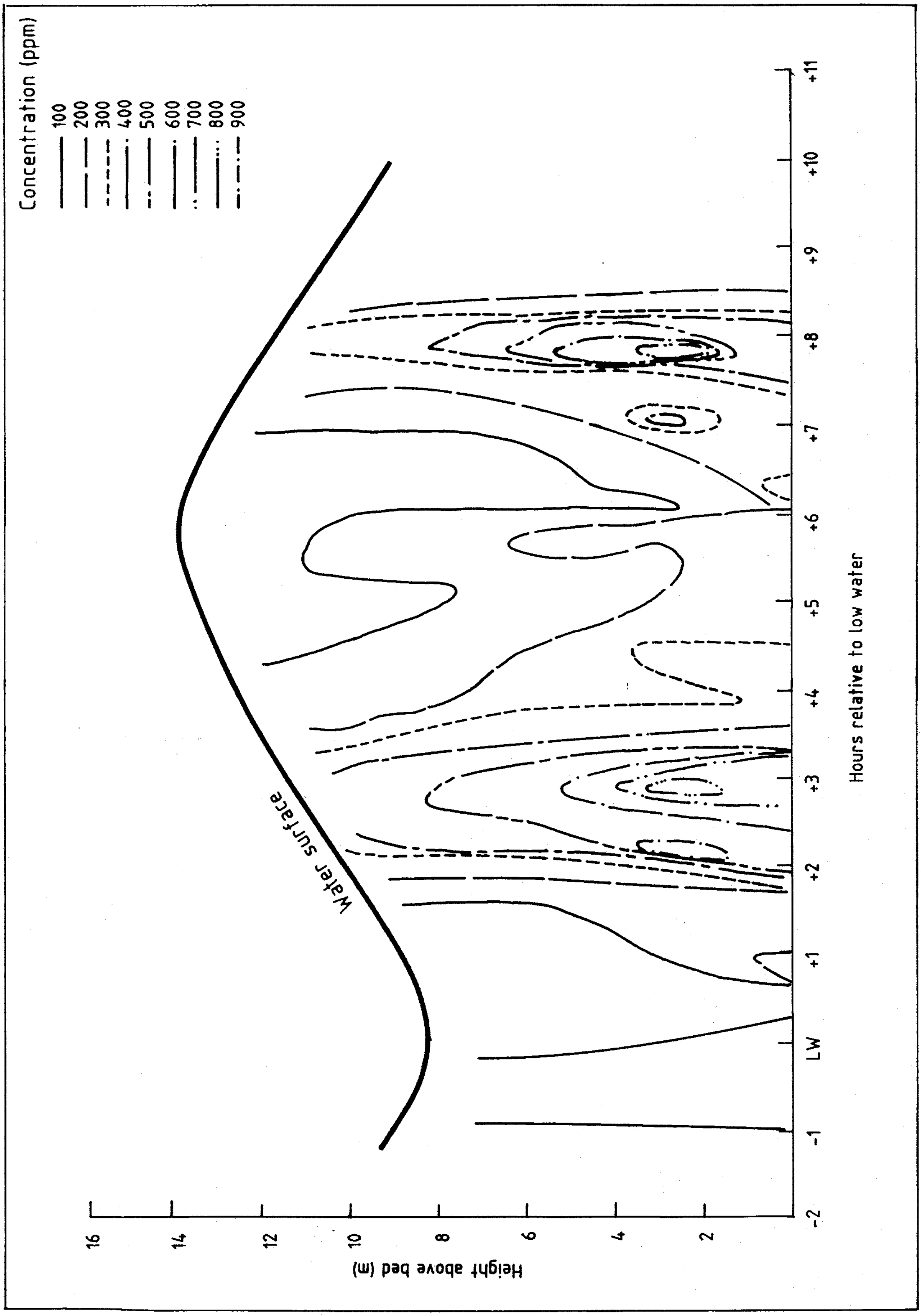

Fig 14 Suspended solid concentration contours - Position 2, 30.9.85

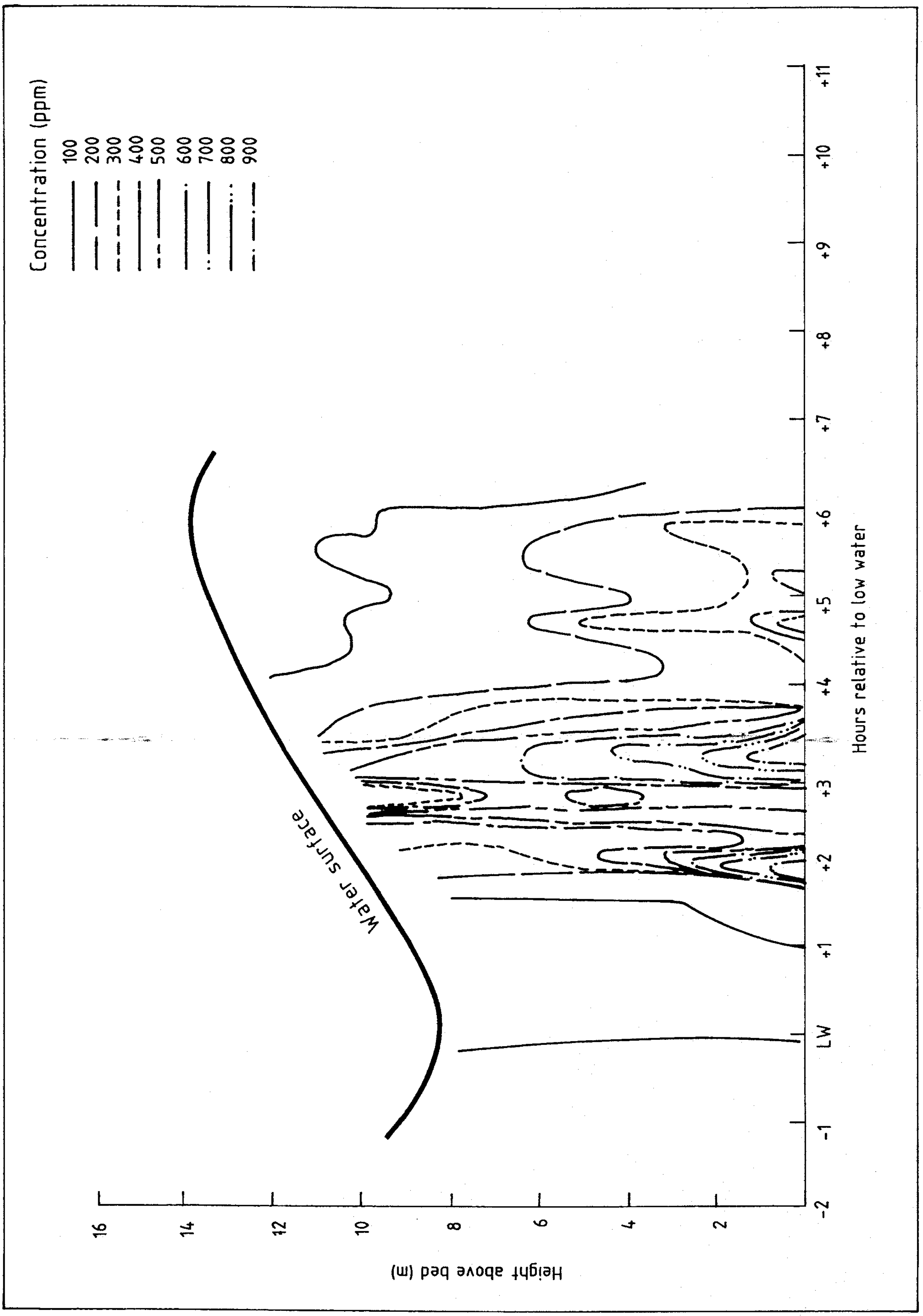

Fig 15 Suspended solid concentration contours - Position 2, 1.10.85

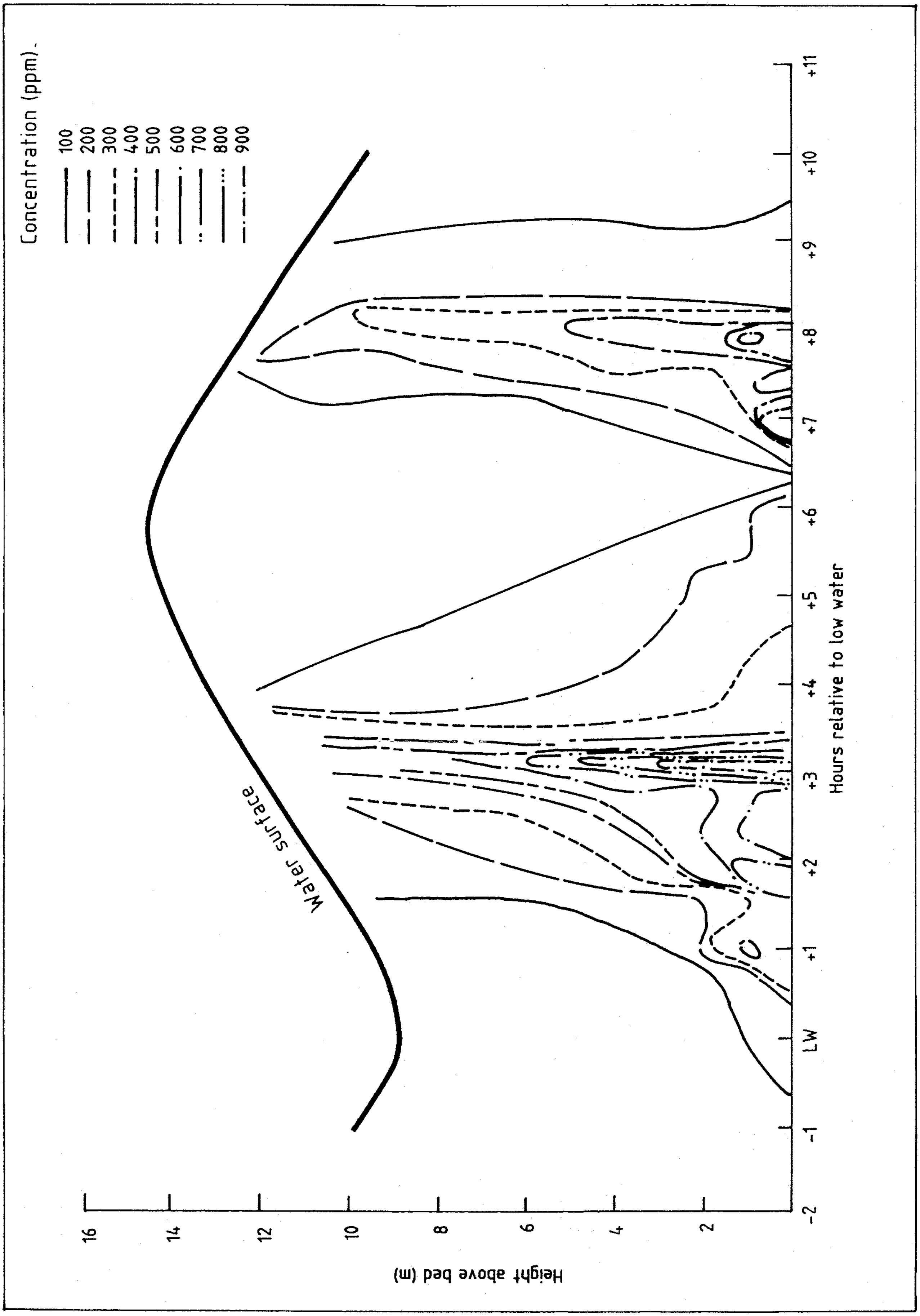

Fig 16 Suspended solid concentration contours - Position 3, 28.9.85

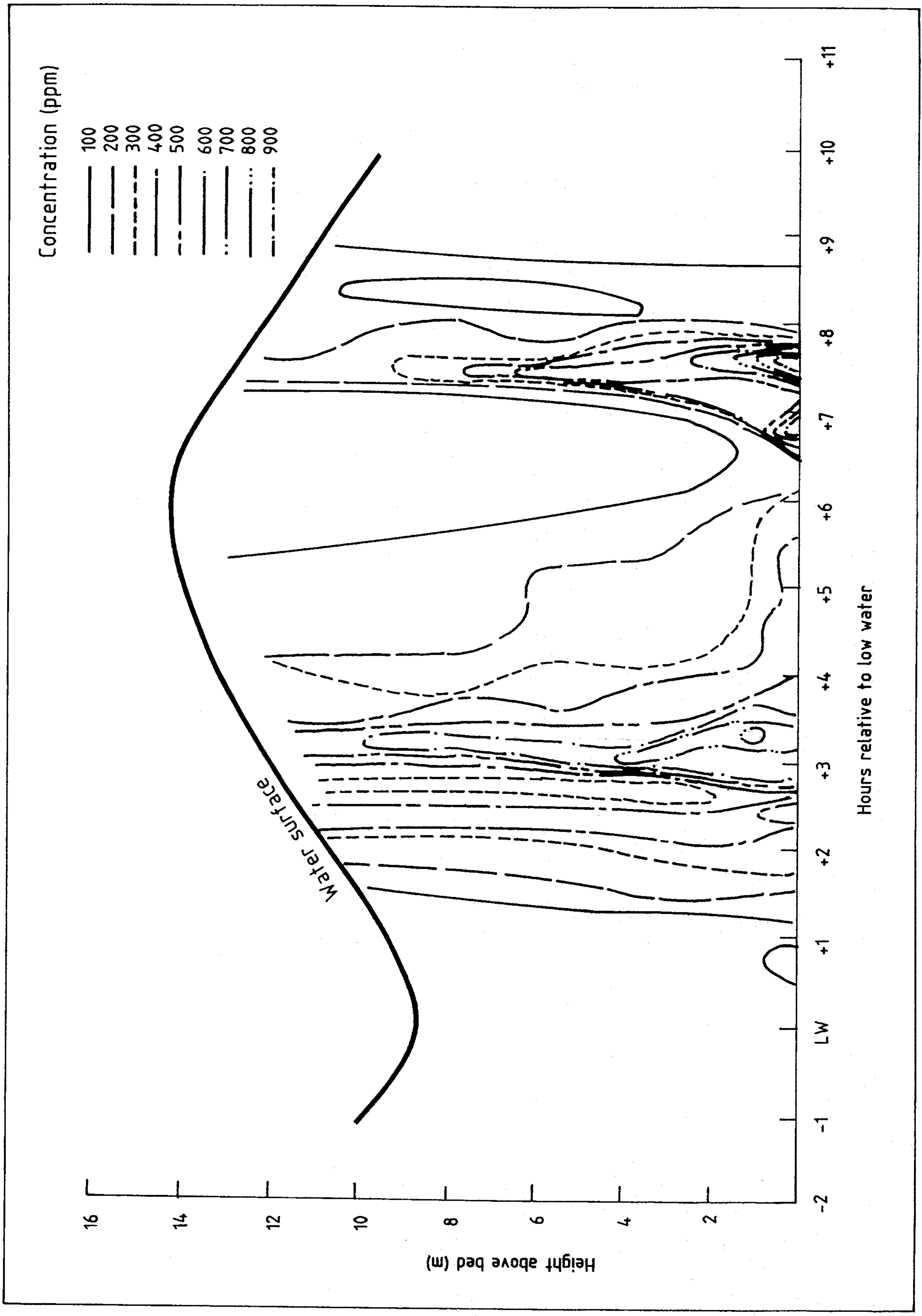

Fig 17 Suspended solid concentration contours - Position 4, 29.9.85

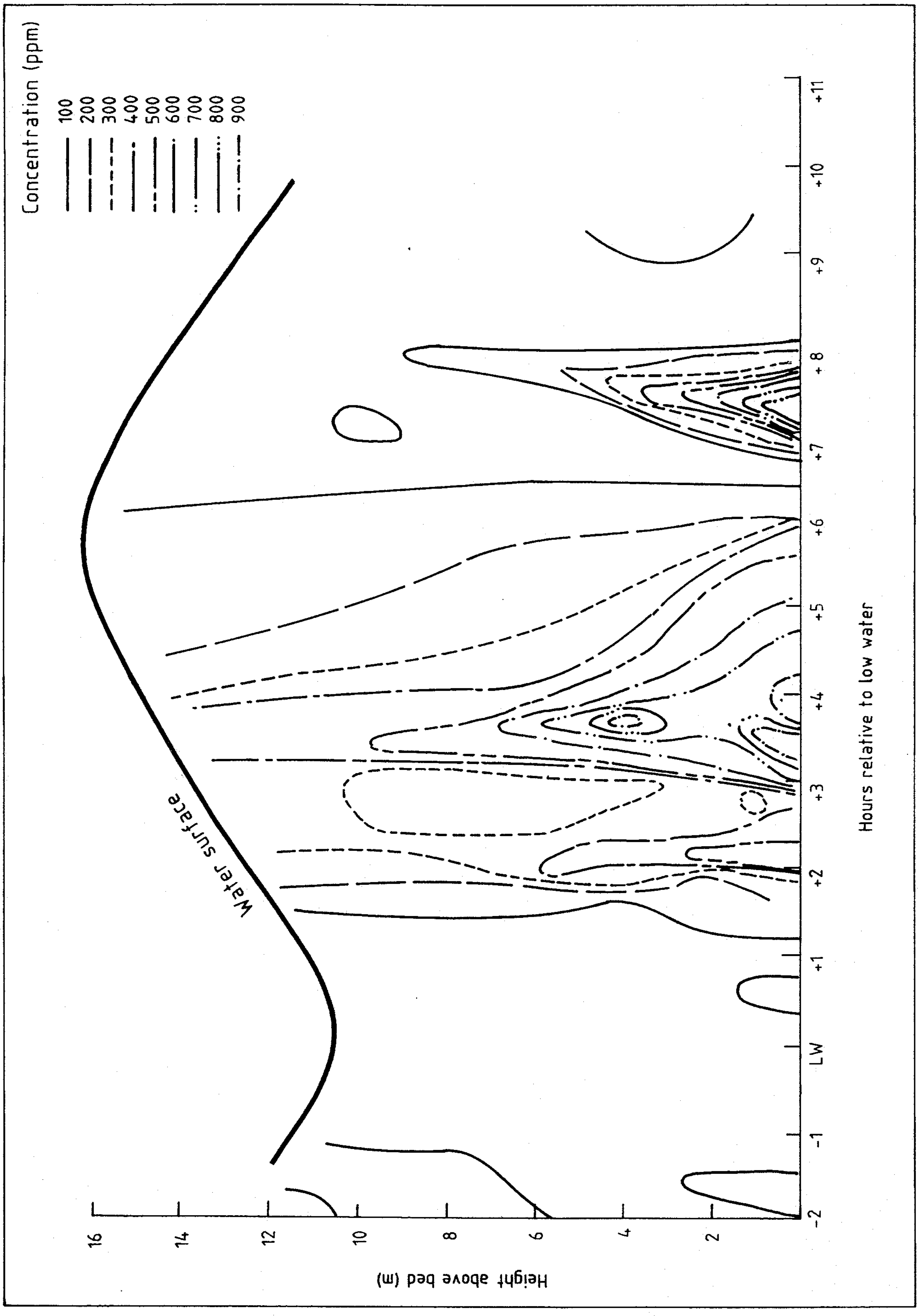

Fig 18 Suspended solid concentration contours - Position 5, 30.9.85

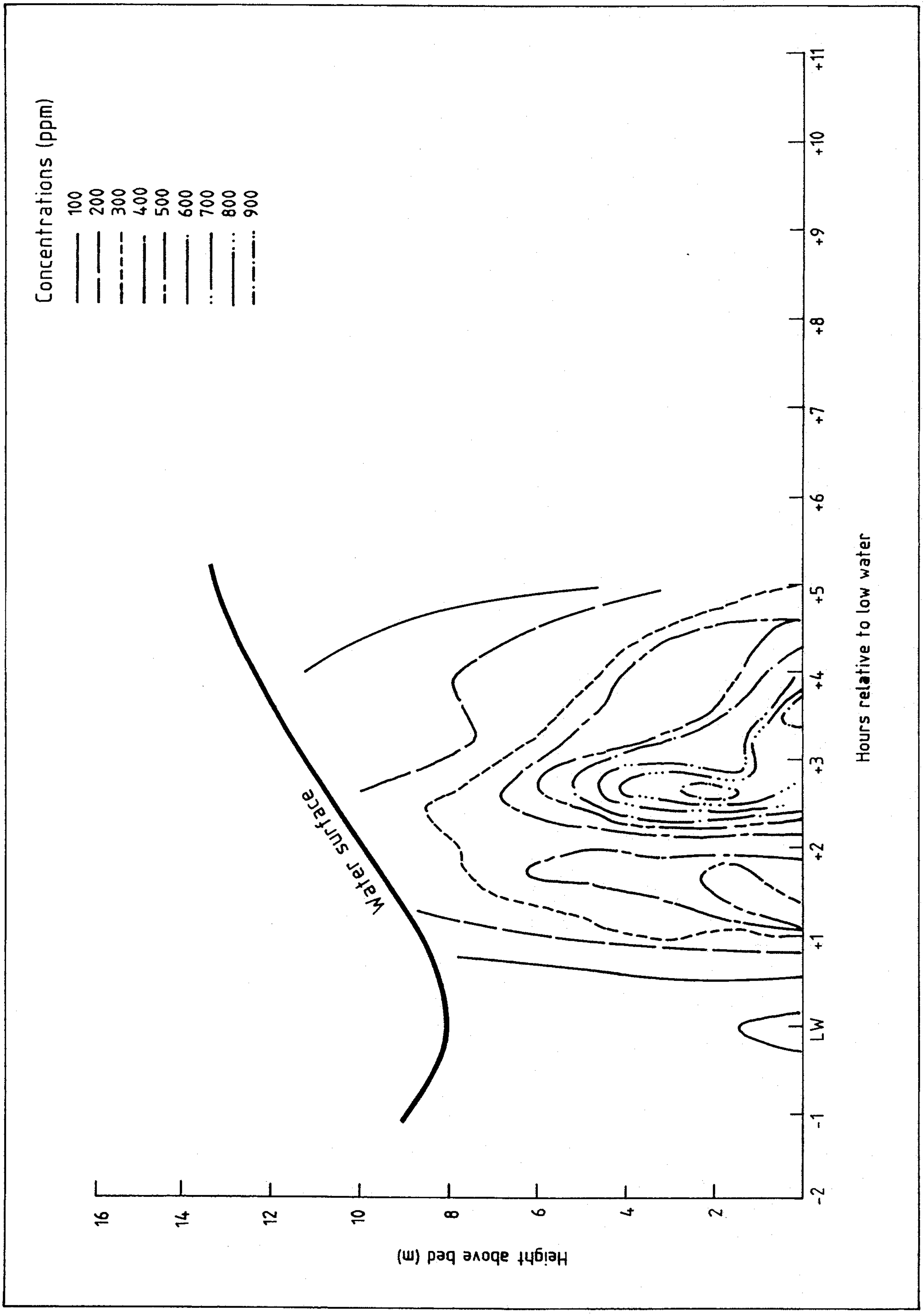

Fig 19 Suspended solid concentration contours - Position 6, 1.10.85

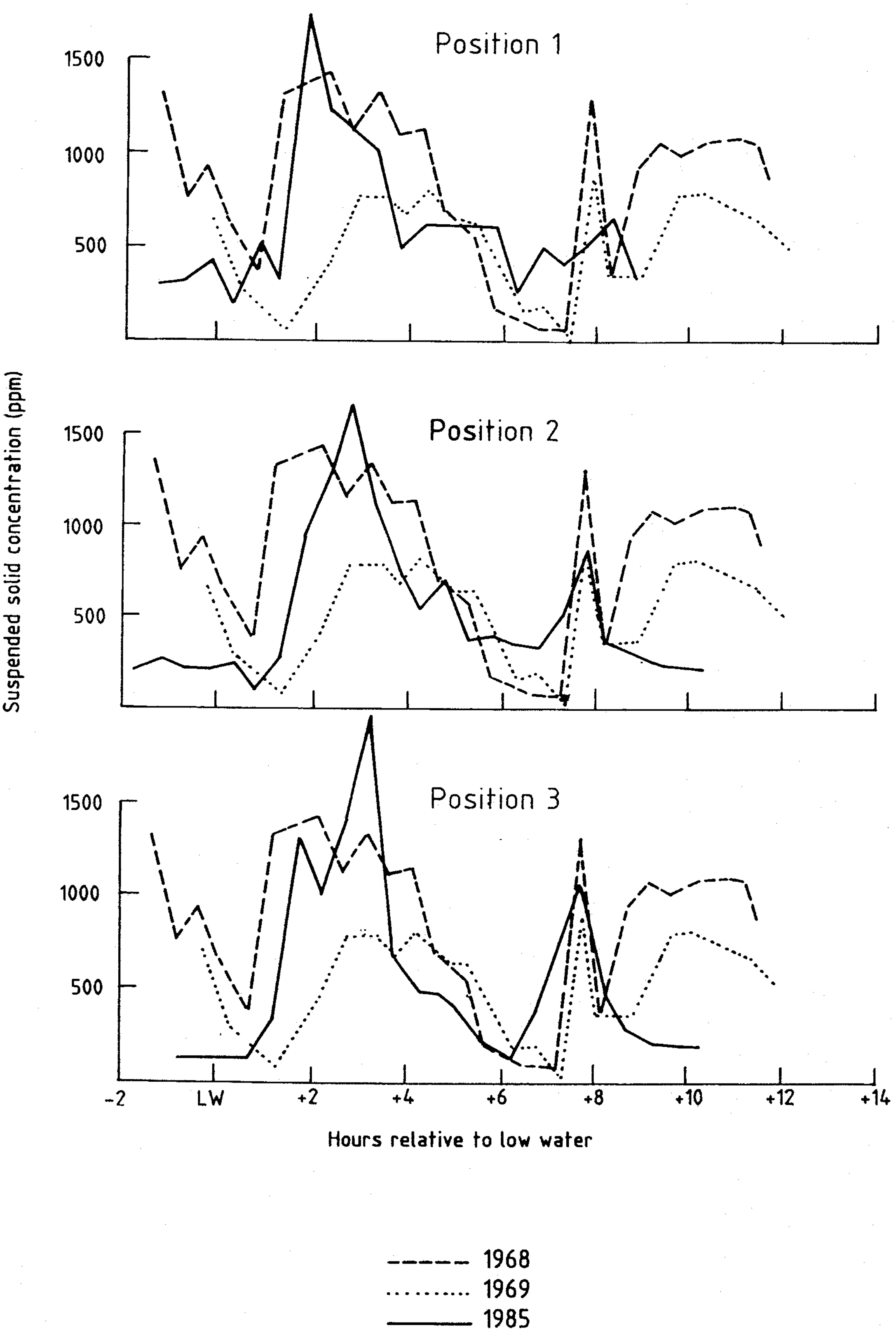

Fig 20 Comparison of suspended solid concentrations 1968-1969 - 1985

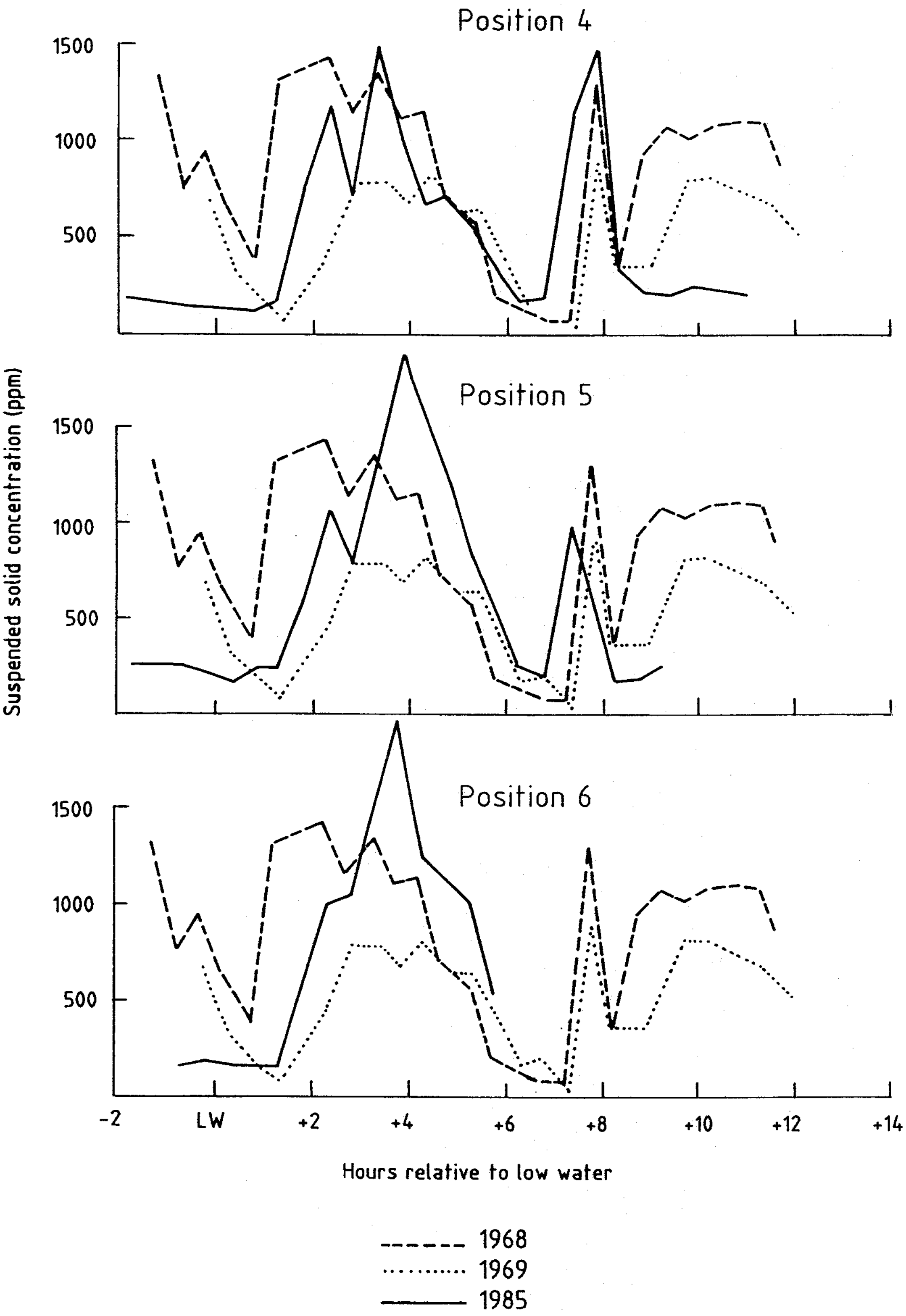

Fig 21 Comparison of suspended solid concentrations 1968-1969 - 1985

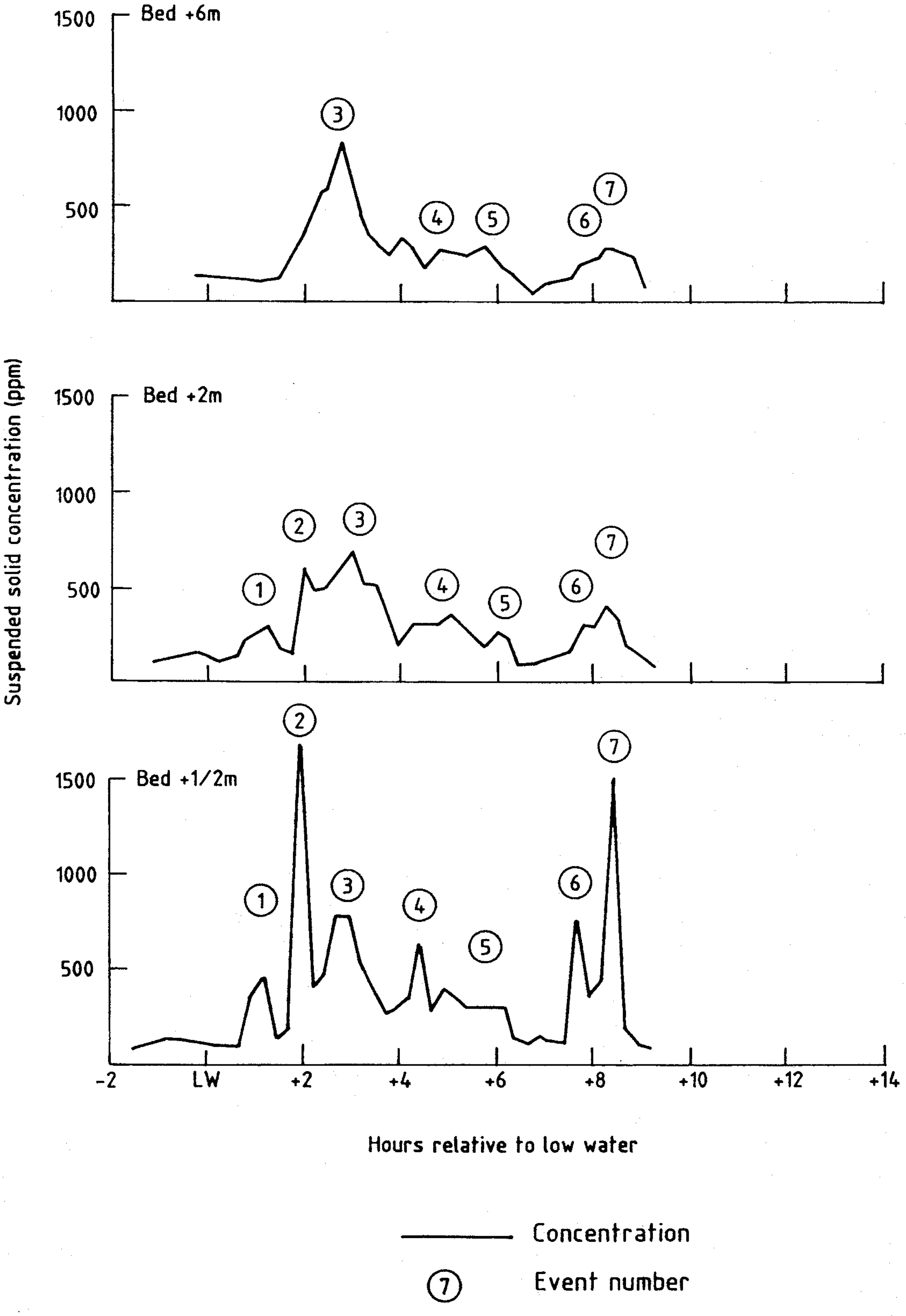

Fig 22 Suspended solid concentrations - Position 1

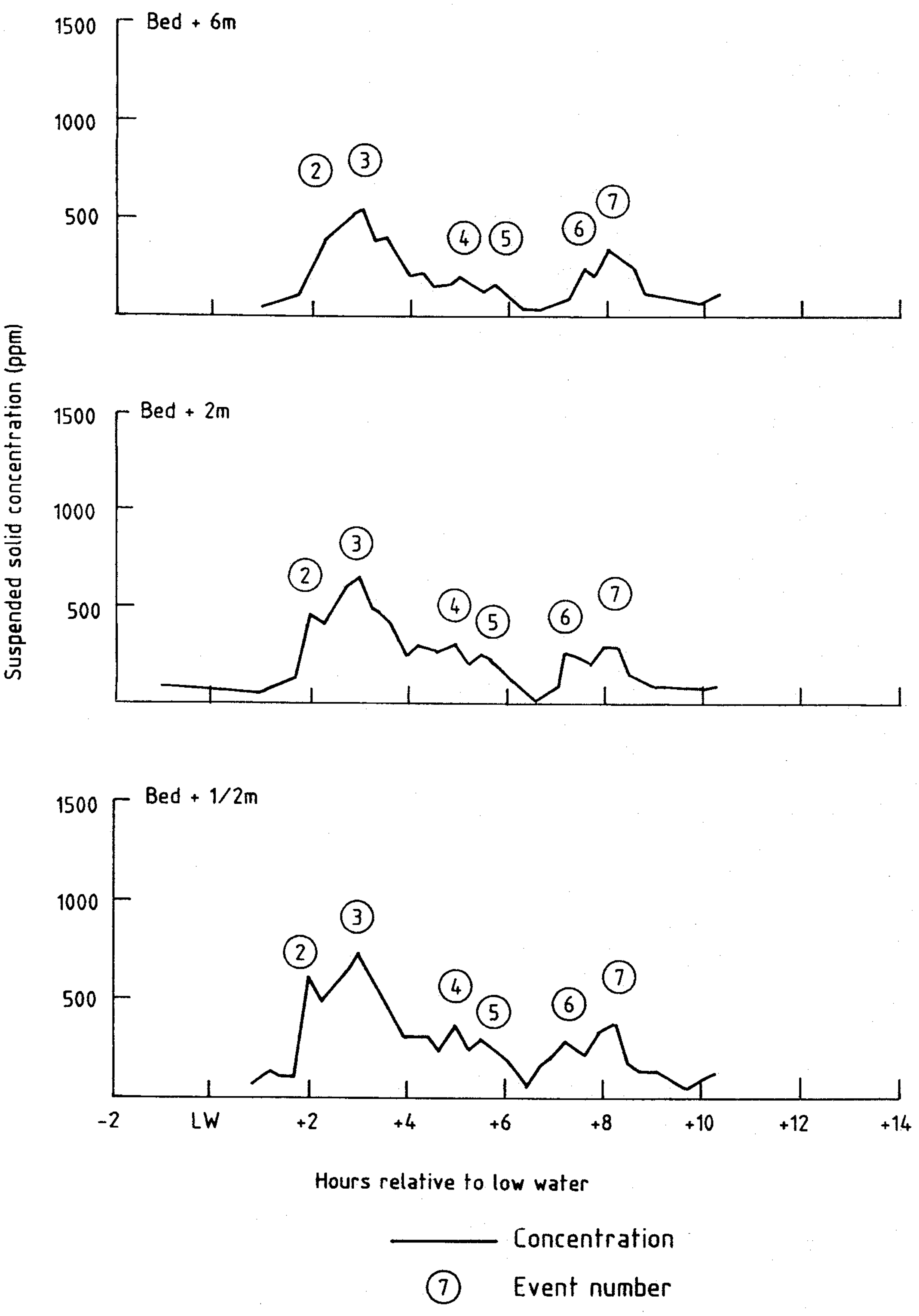

Fig 23 Suspended solid concentrations - Position 2

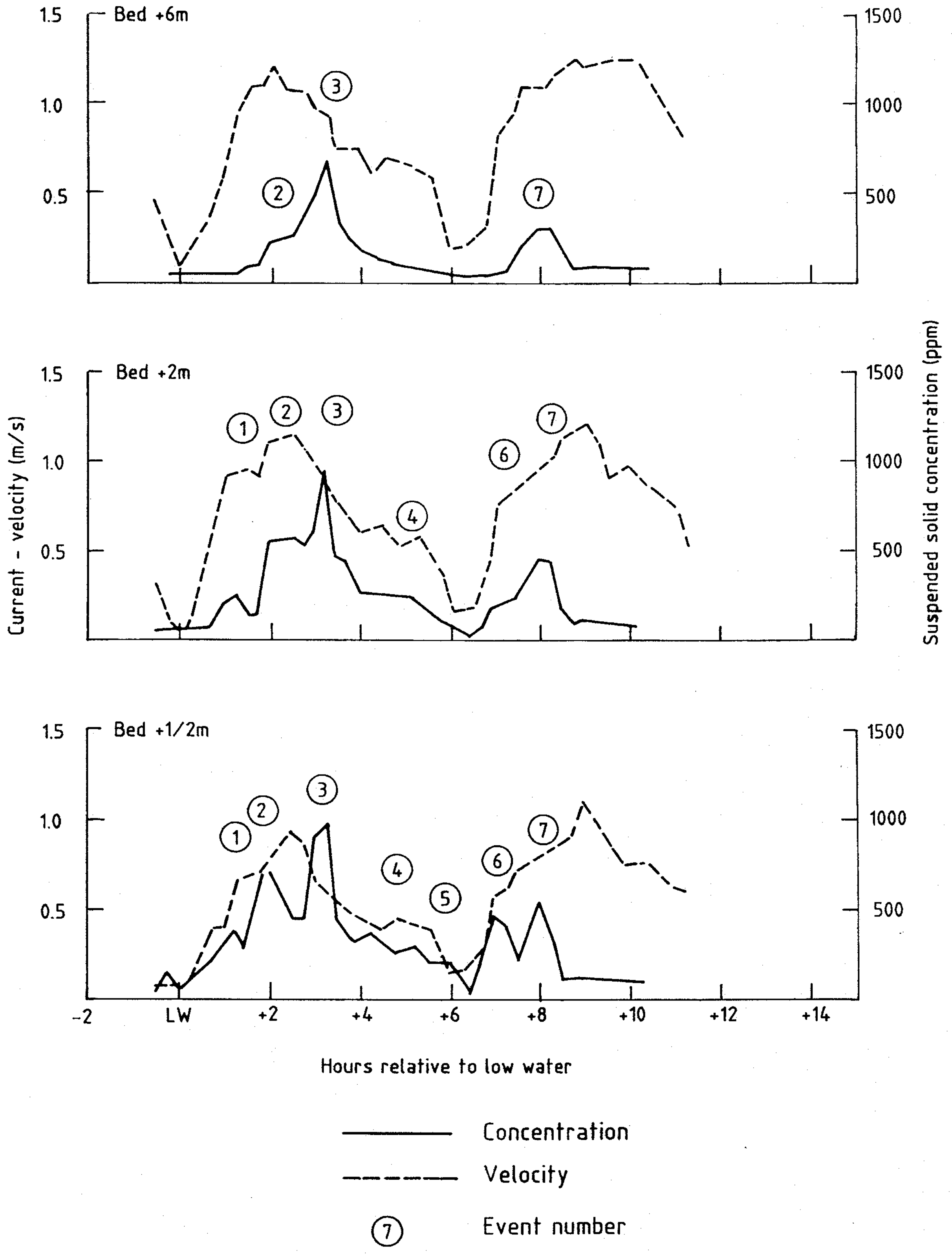

Fig 24 Comparison of suspended solid concentrations and velocities - Position 3

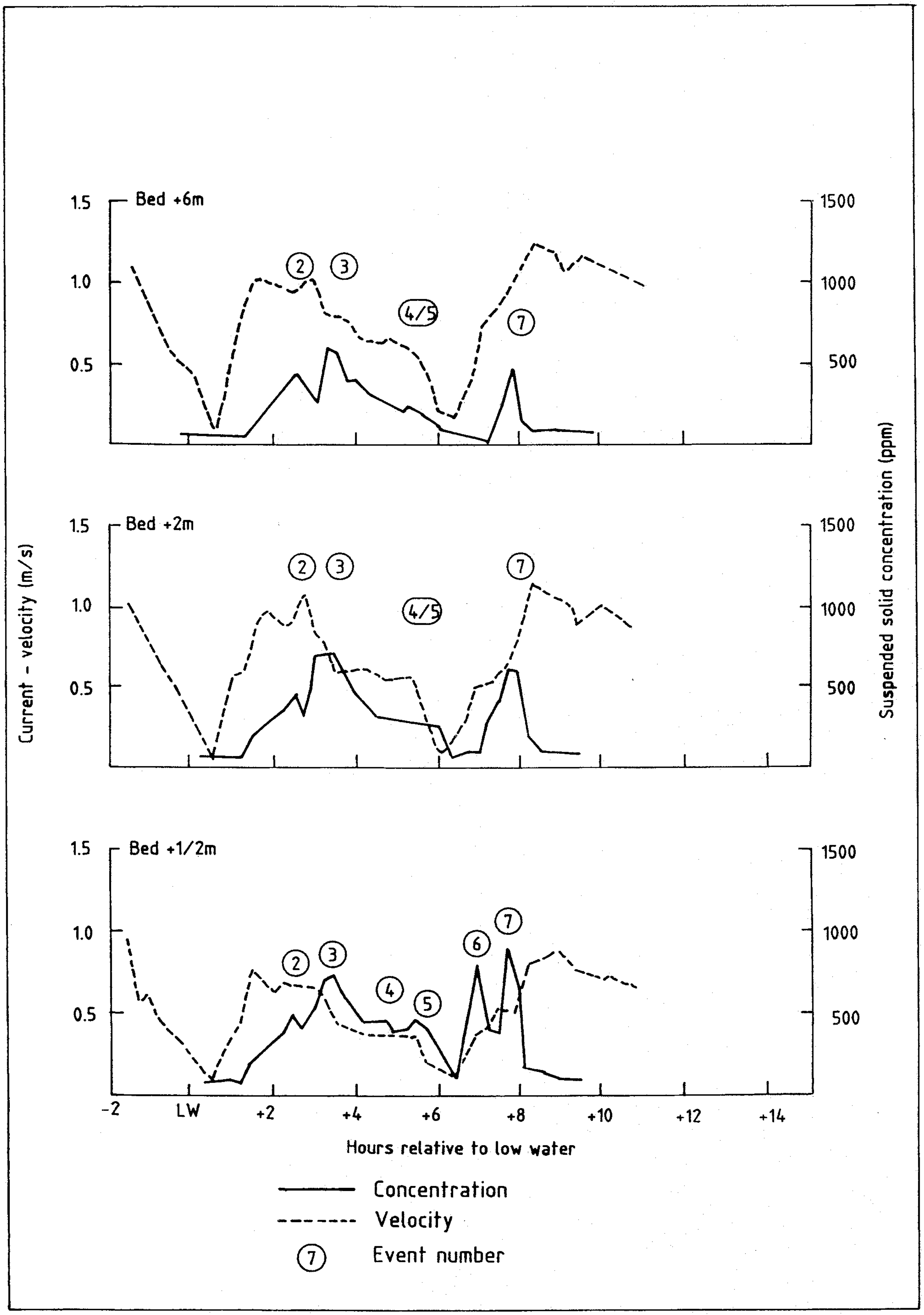

Fig 25 Comparison of suspended solid concentrations and velocities - Position 4

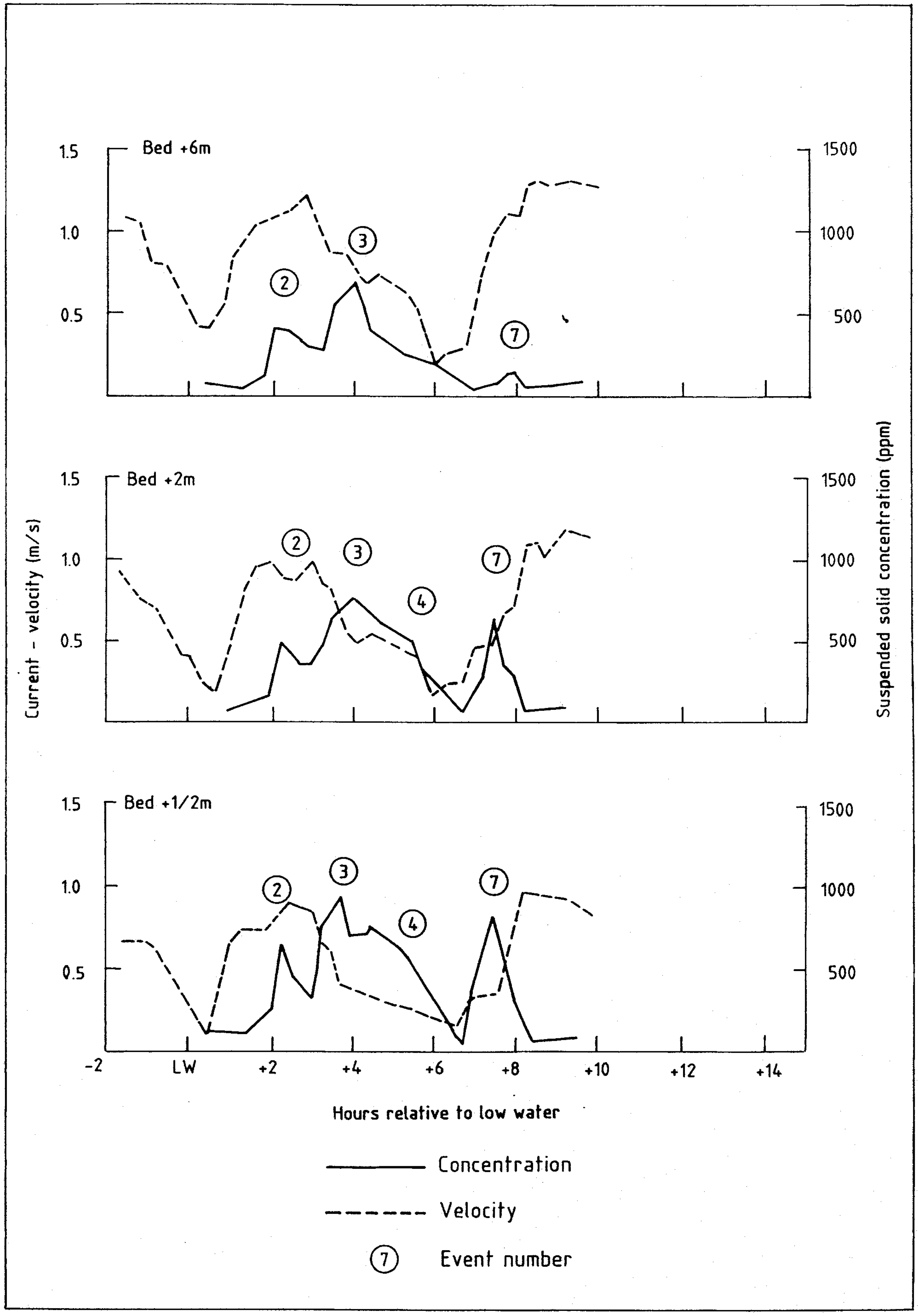

Fig 26 Comparison of suspended solid concentrations and velocities - Position 5

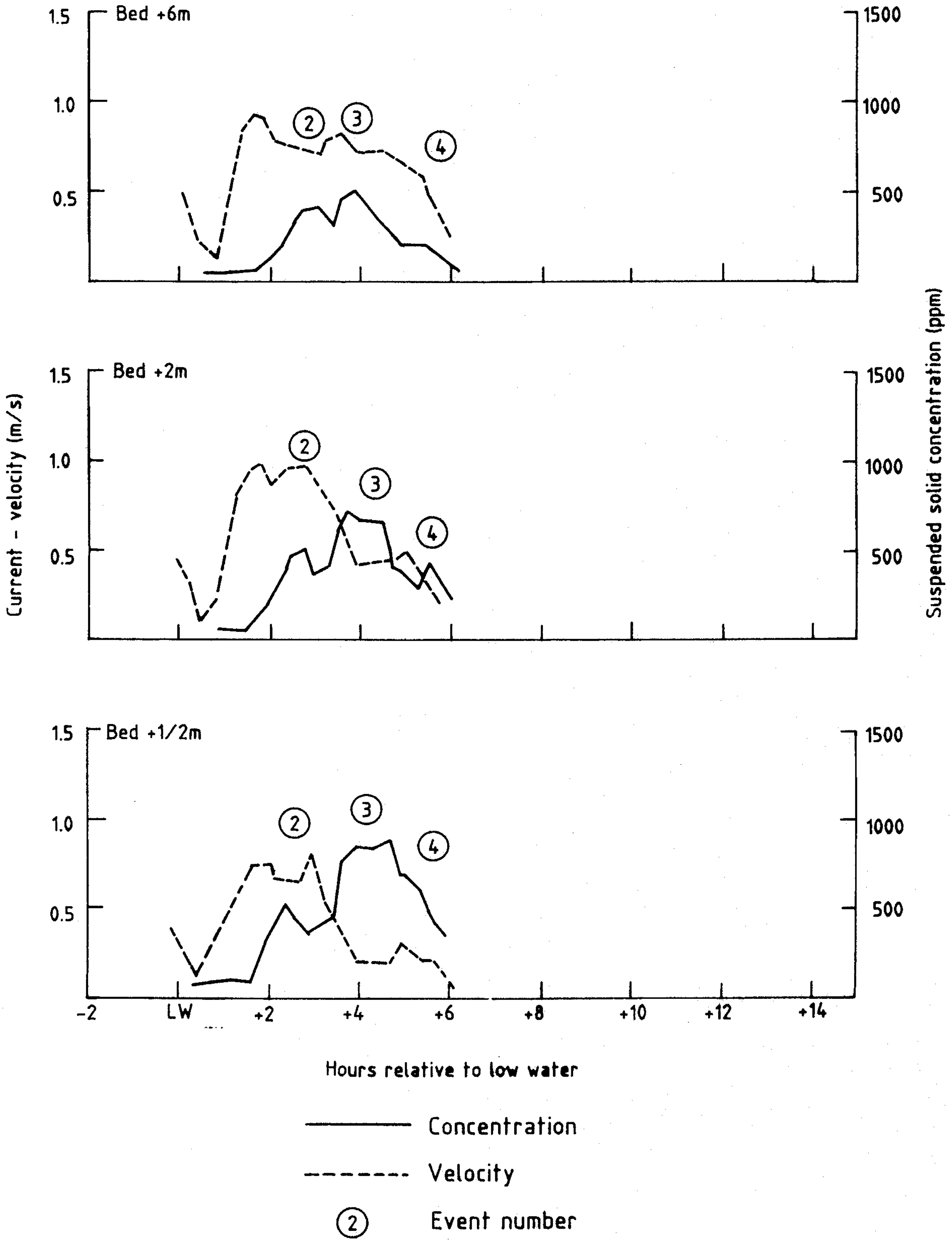

Fig 27 Comparison of suspended solid concentrations and velocities - Position 6

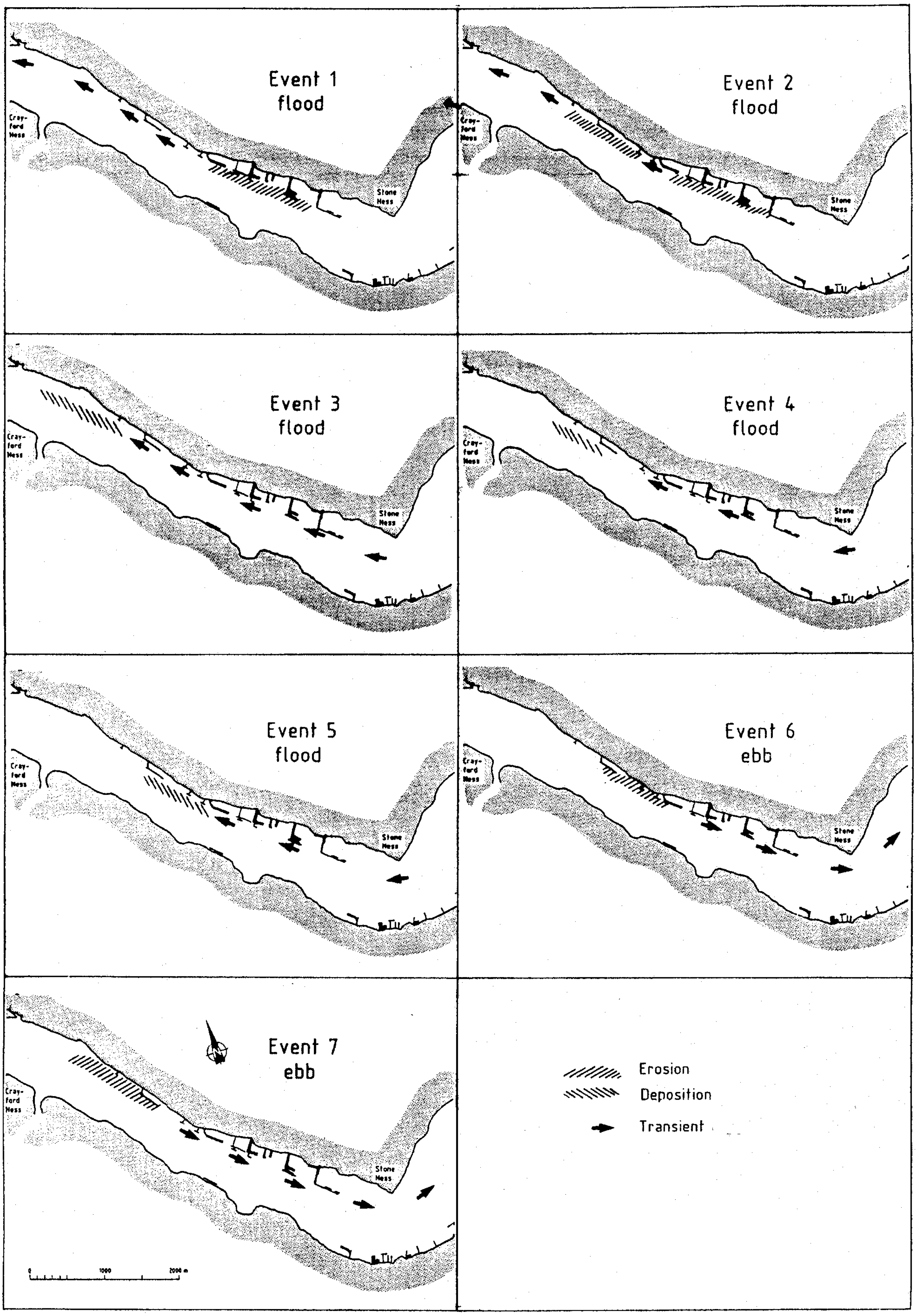

Fig 28 Schematic description of events

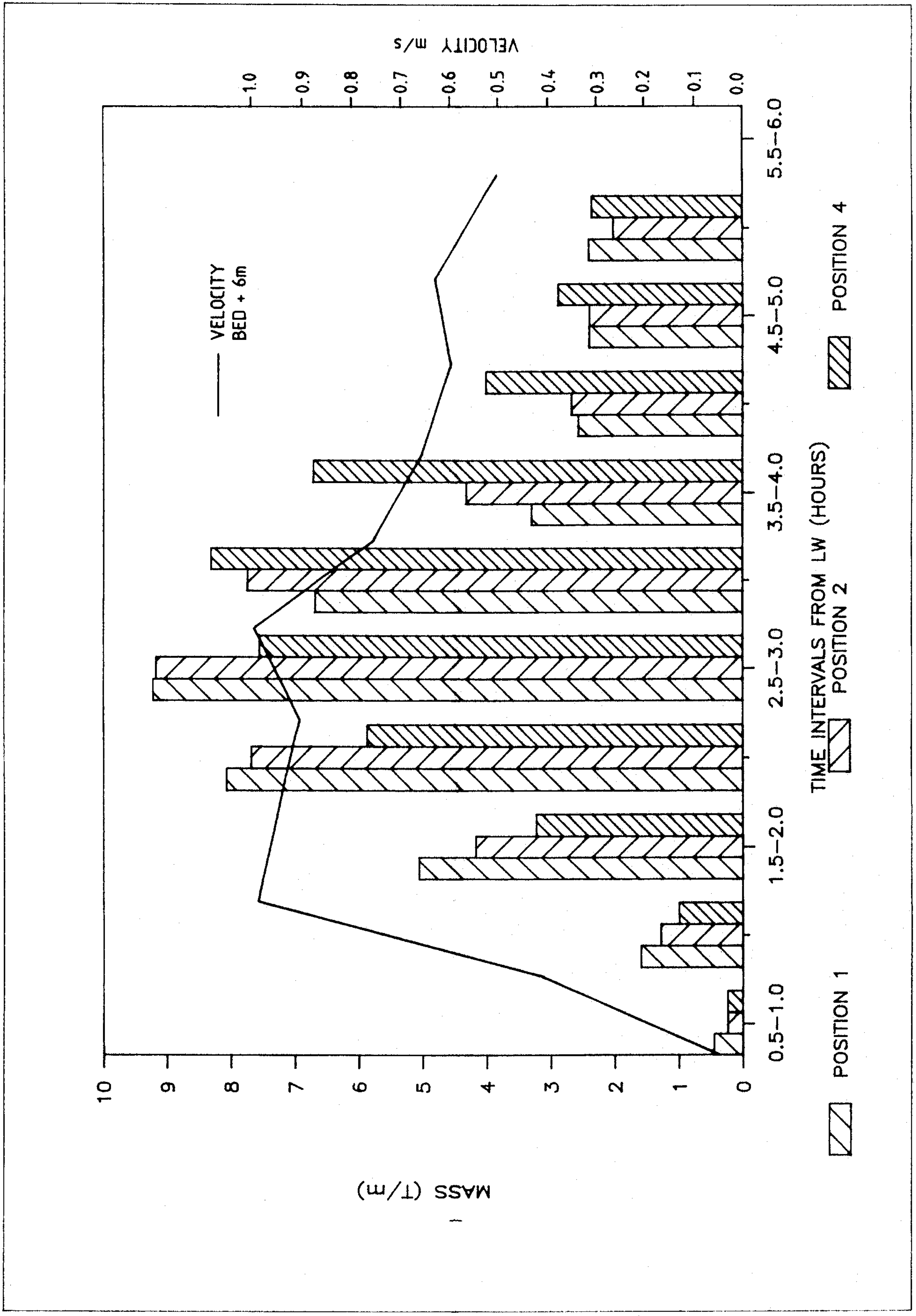

Fig 29 Sediment flux at positions 1, 2 and 4 and flow velocity : Flood tide 29-9-85

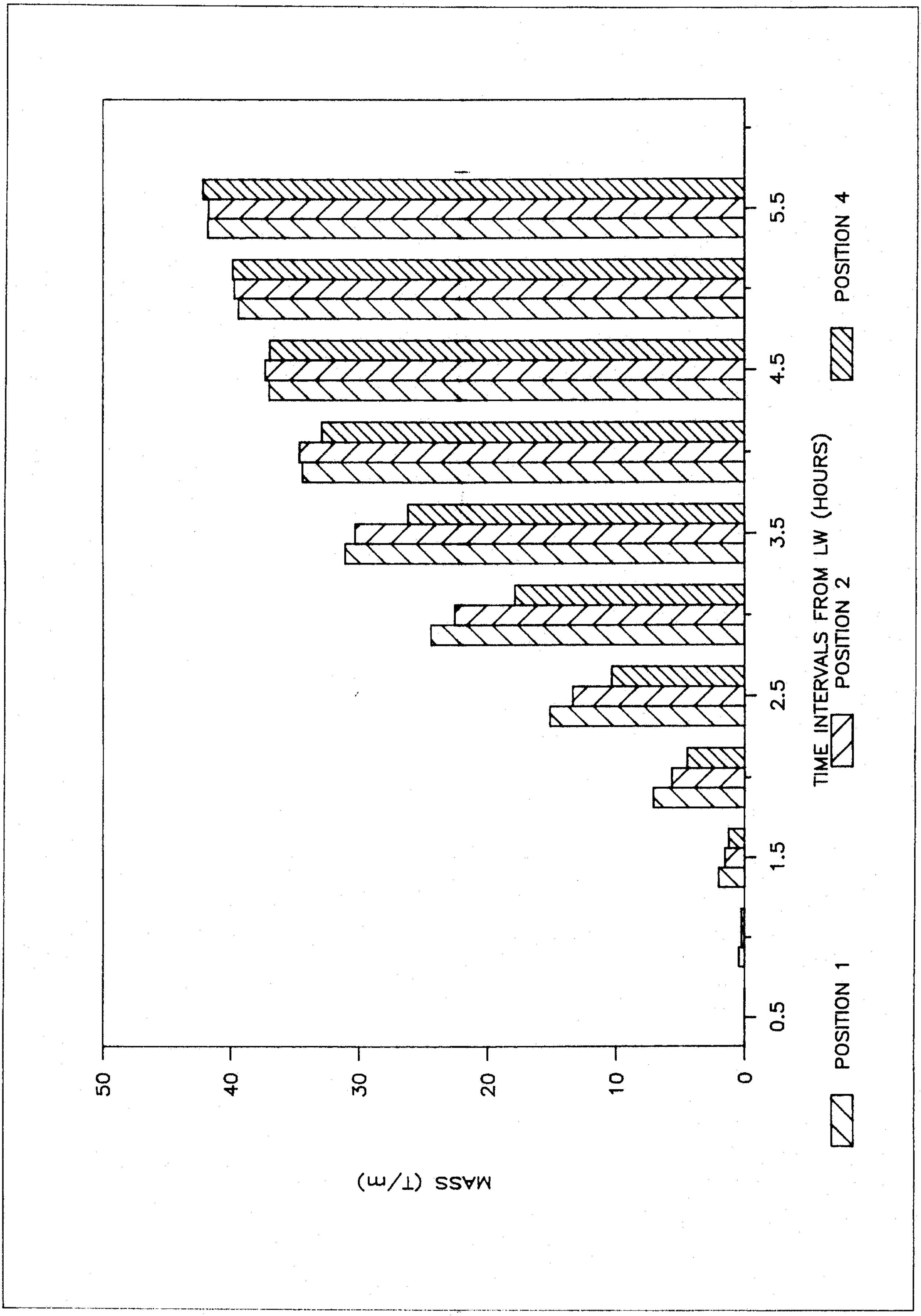

Fig 30 Cumulative sediment flux at positions 1, 2 and 4 : Flood tide 29-9-85

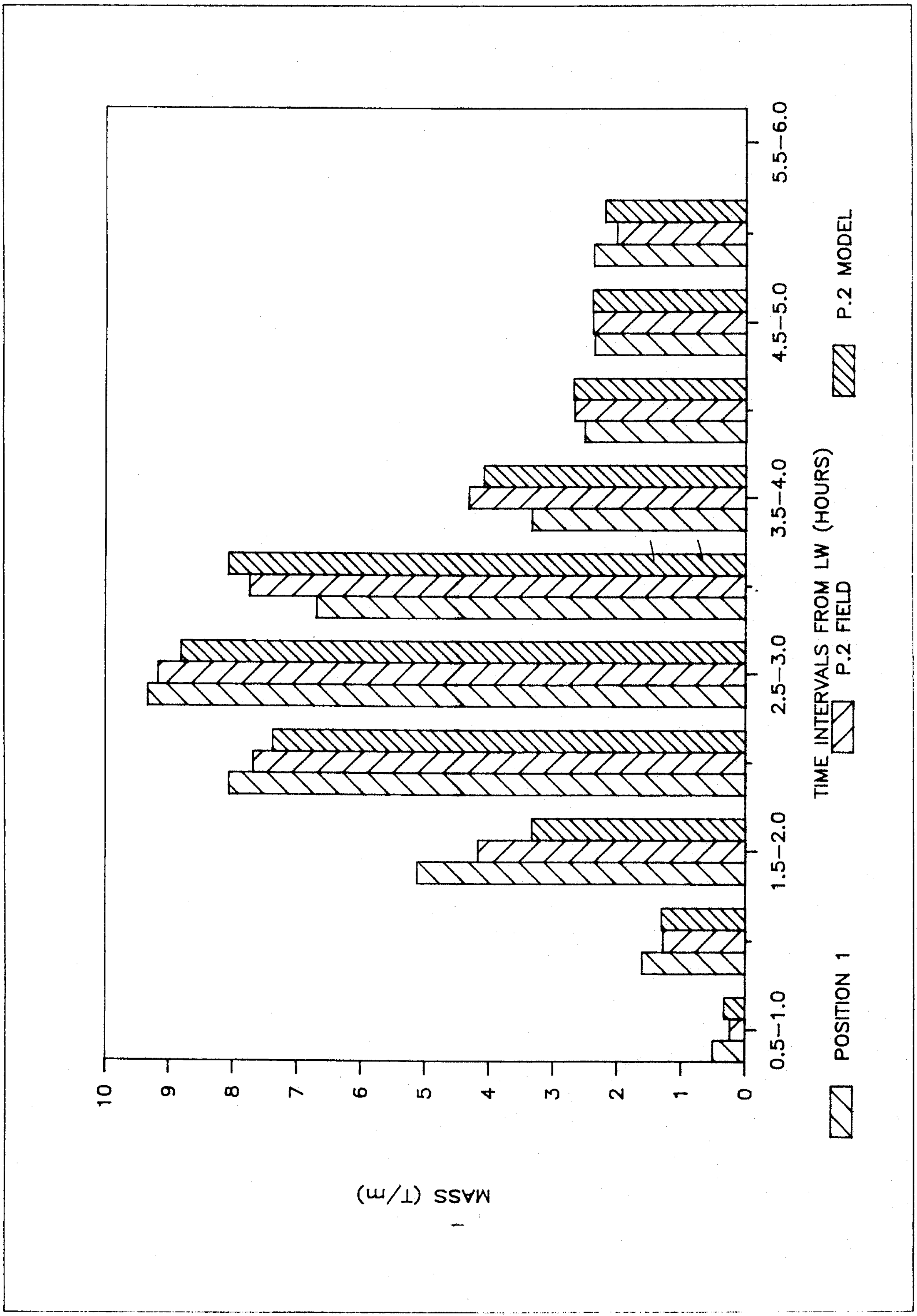

Fig 31 Predicted sediment flux at position 2 - no erosion; no deposition : Flood tide 29-9-85

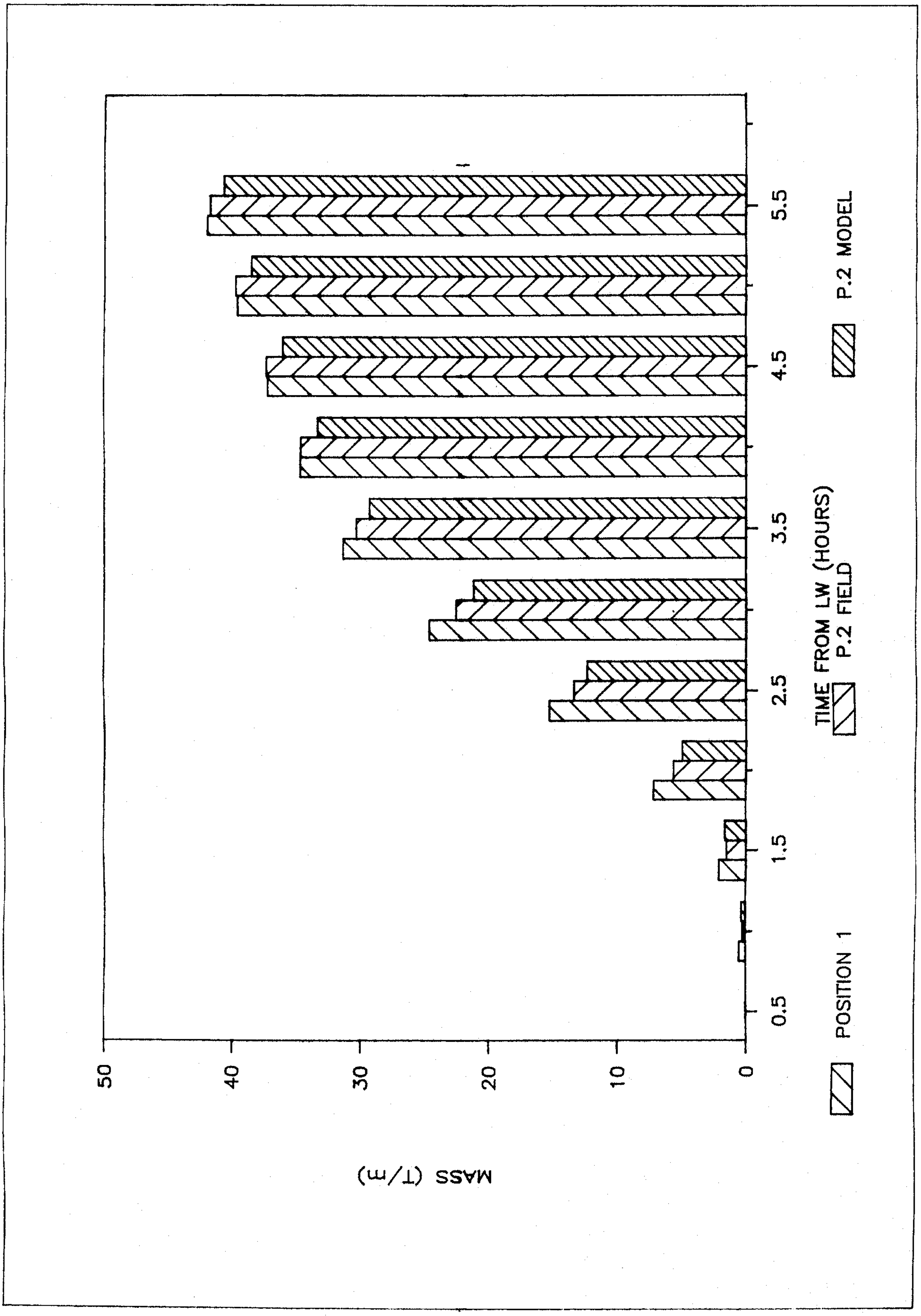

Fig 32 Cumulative predicted sediment flux at position 2 - no erosion; no deposition : Flood tide 29-9-85

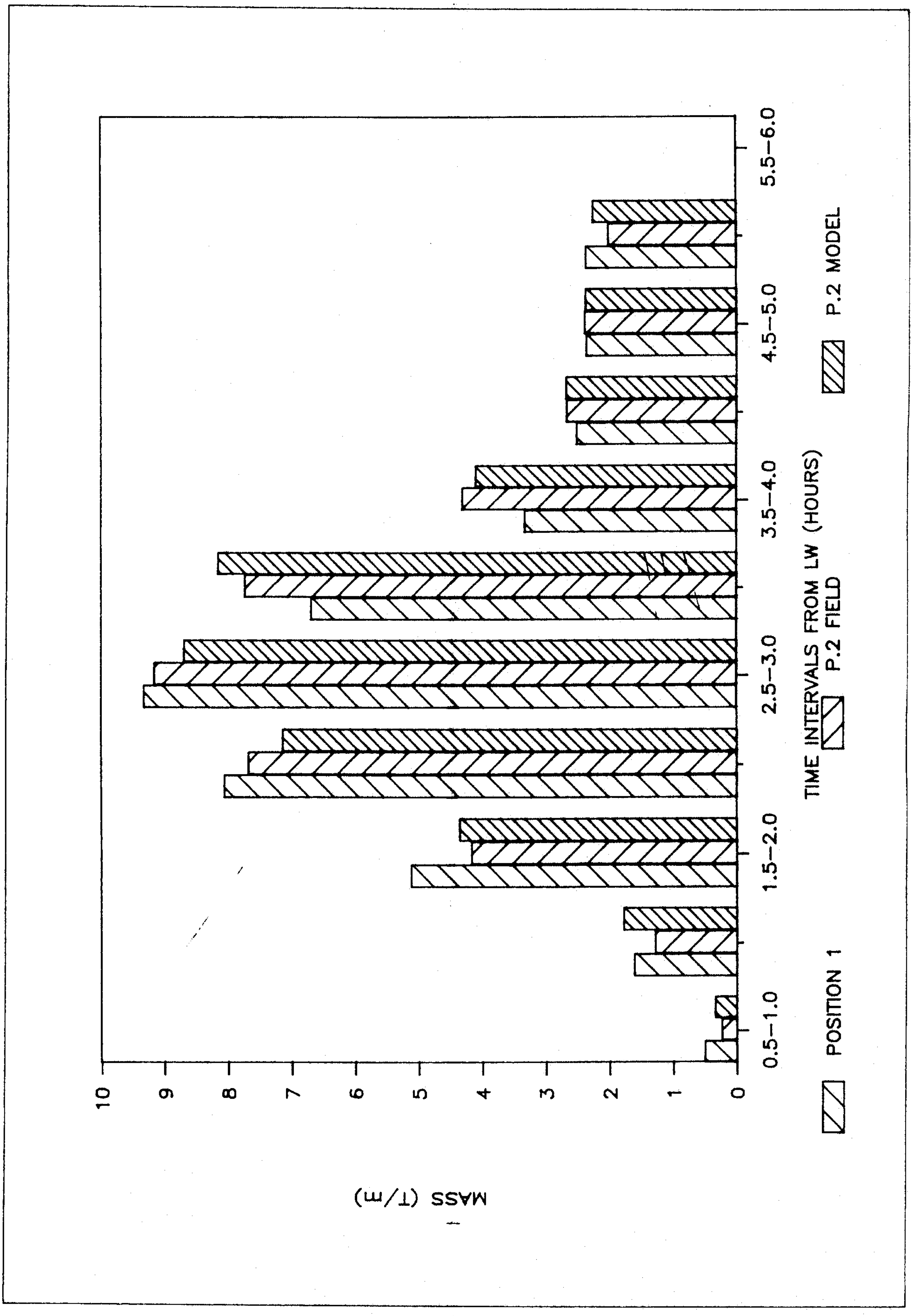

Fig 33 Predicted sediment flux at position 2 - no deposition : Flood tide 29-9-85

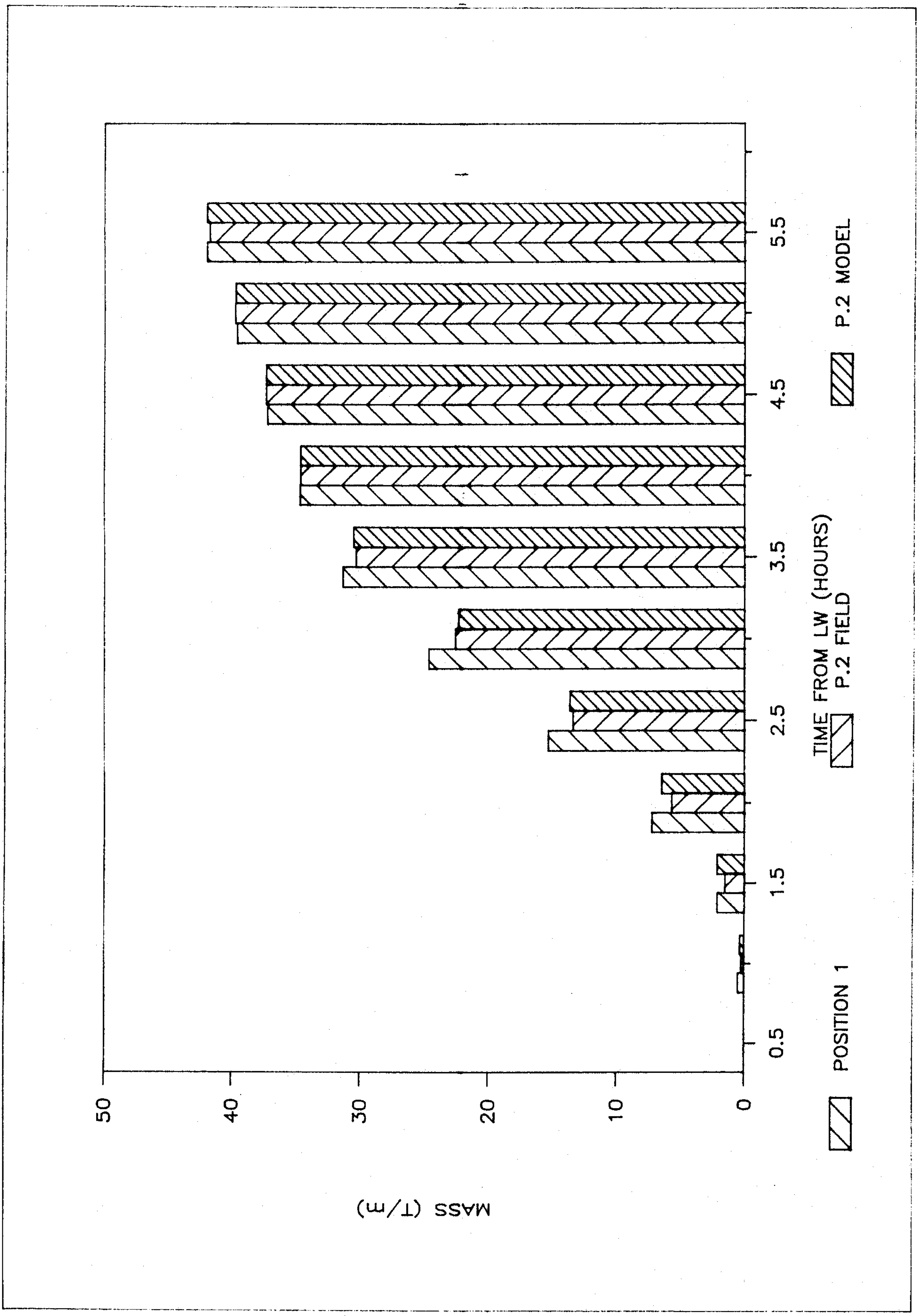

Fig 34 Cumulative predicted sediment flux at position 2 - no deposition : Flood tide 29-9-85

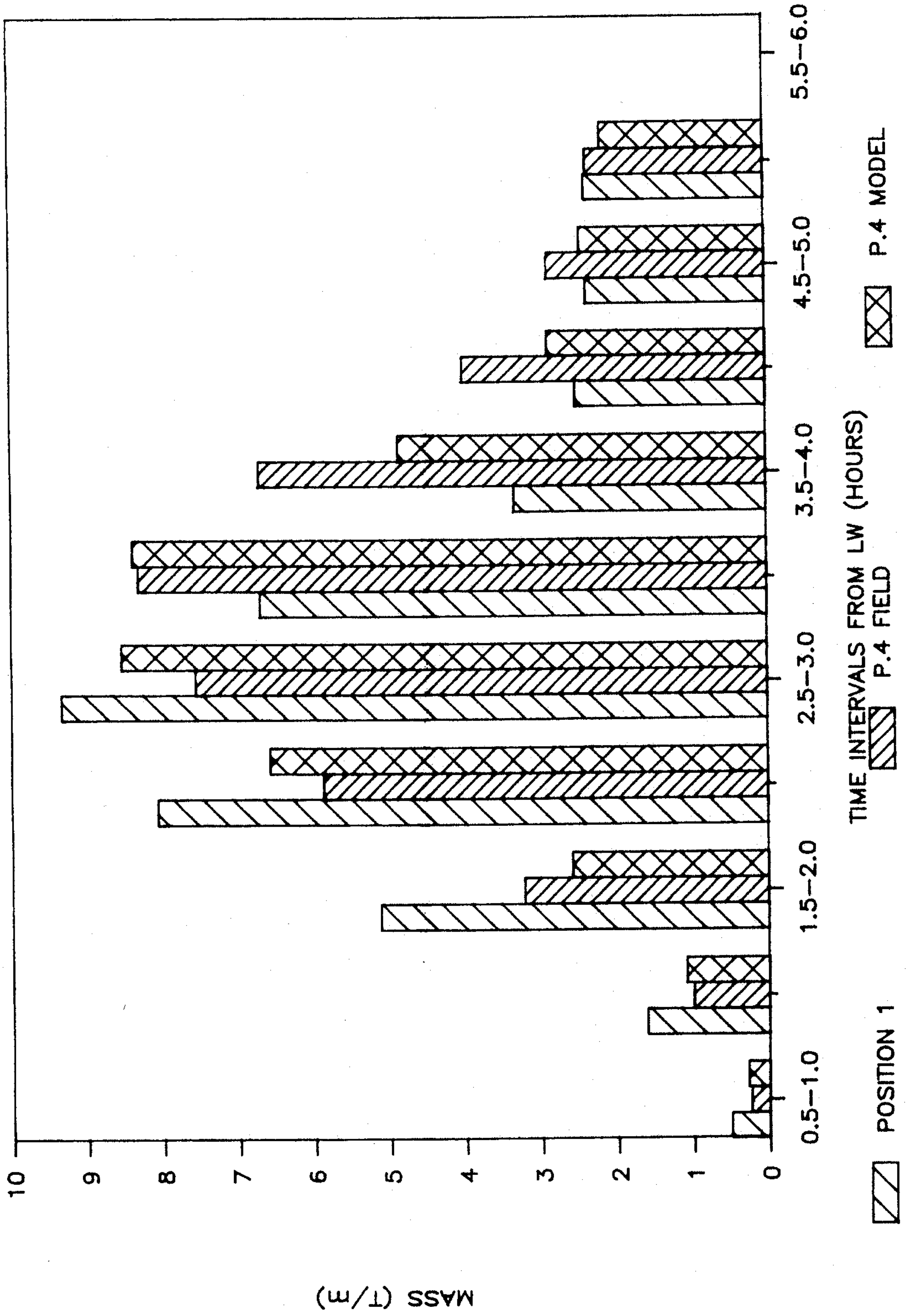

Fig 35 Predicted sediment flux at position 4 - no erosion; no deposition : Flood tide 29-9-85

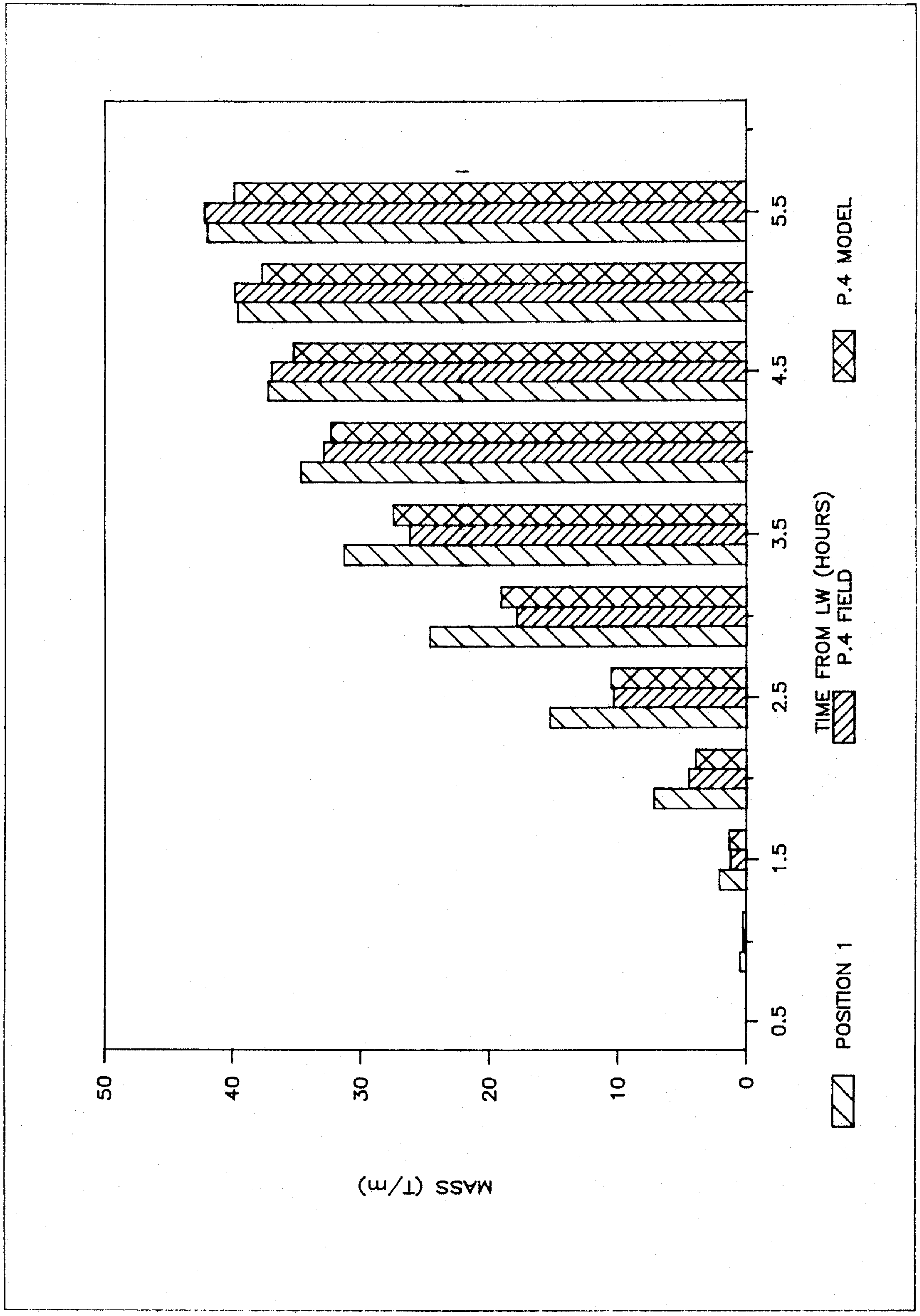

Fig 36 Cumulative predicted sediment flux at position 4 - no erosion; no deposition : Flood tide 29-9-85

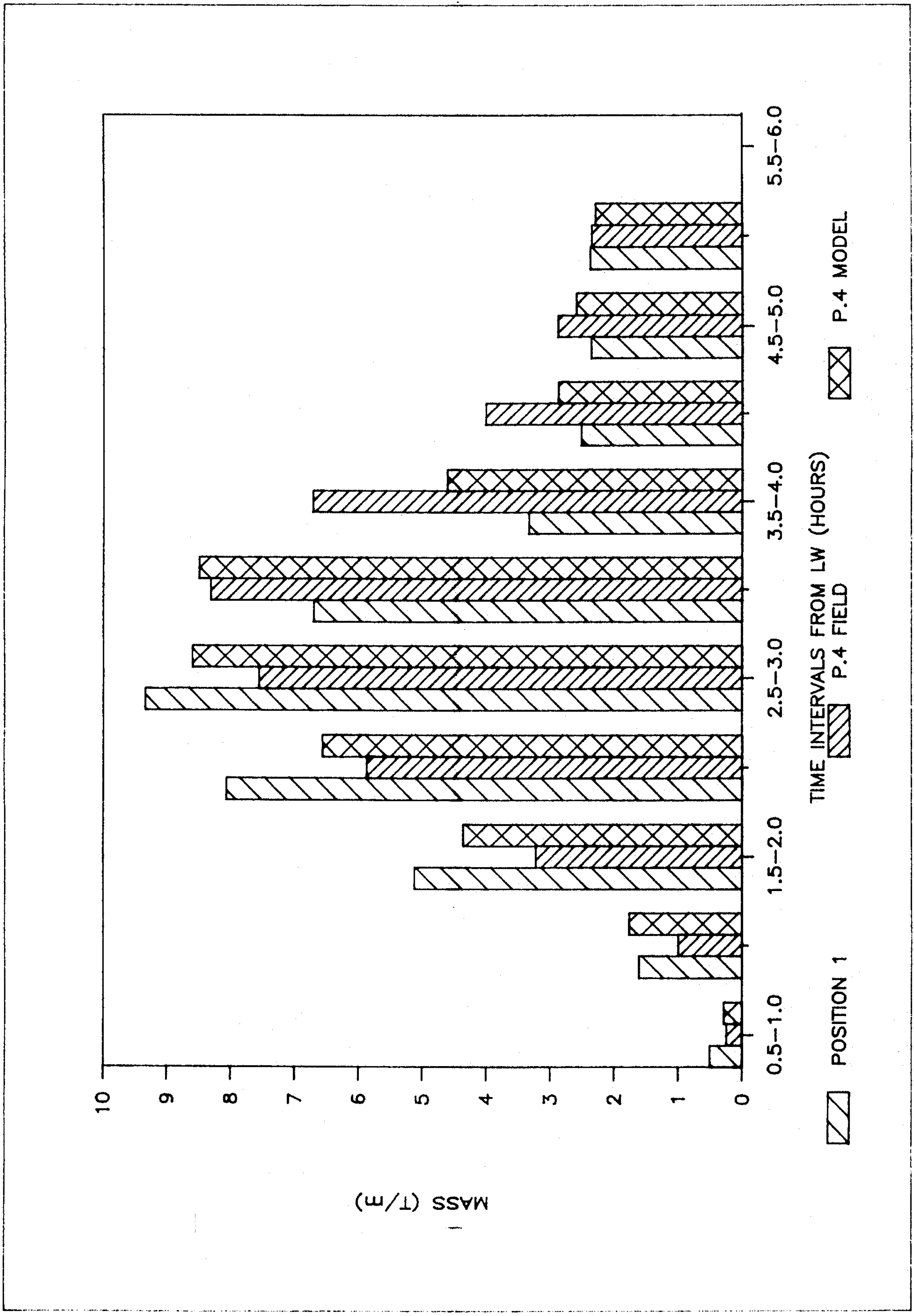

Fig 37 Predicted sediment flux at position 4 - no deposition : Flood tide 29-9-85

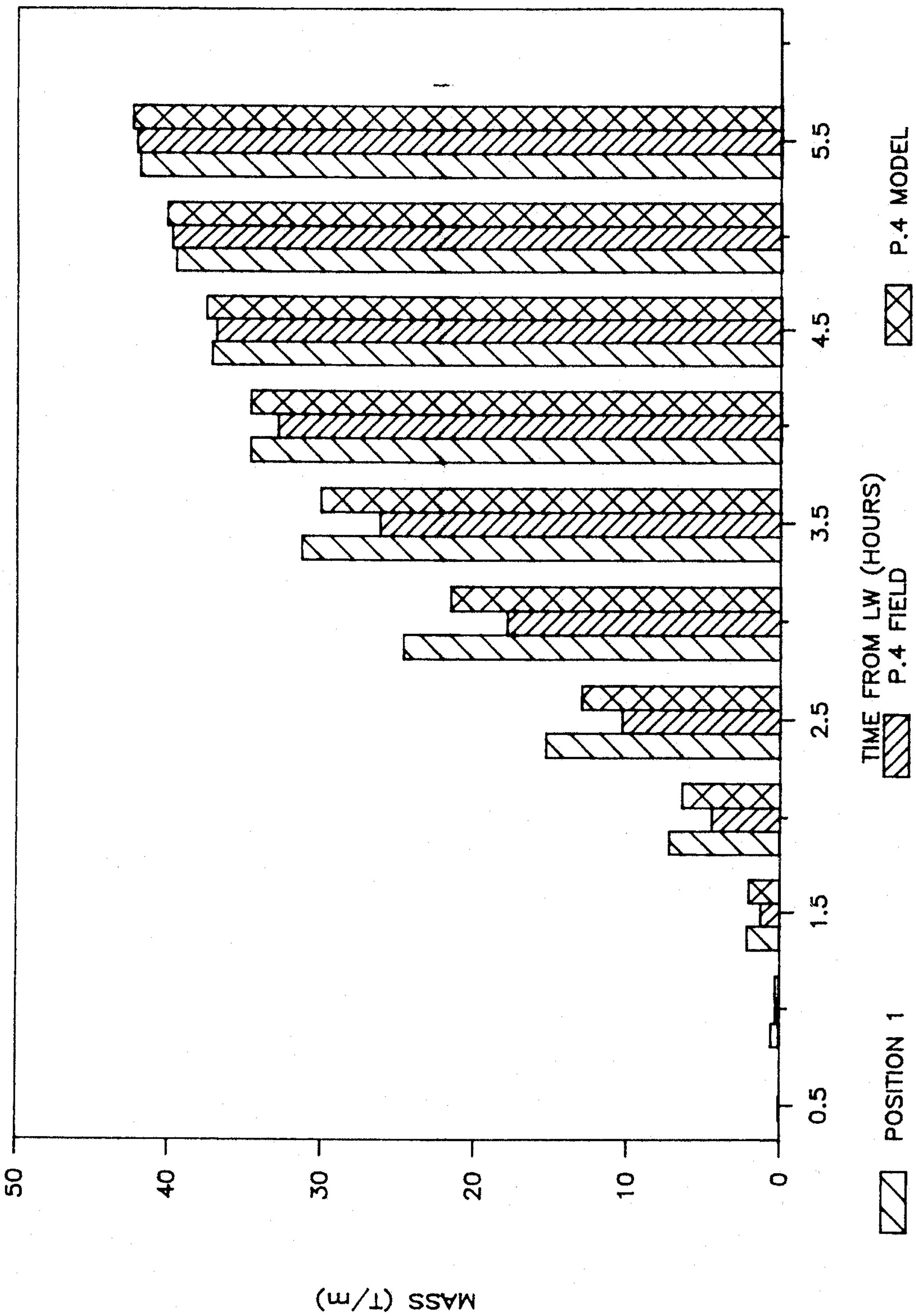

Fig 38 Cumulative predicted sediment flux at position 4 - no deposition : Flood tide 29-9-85

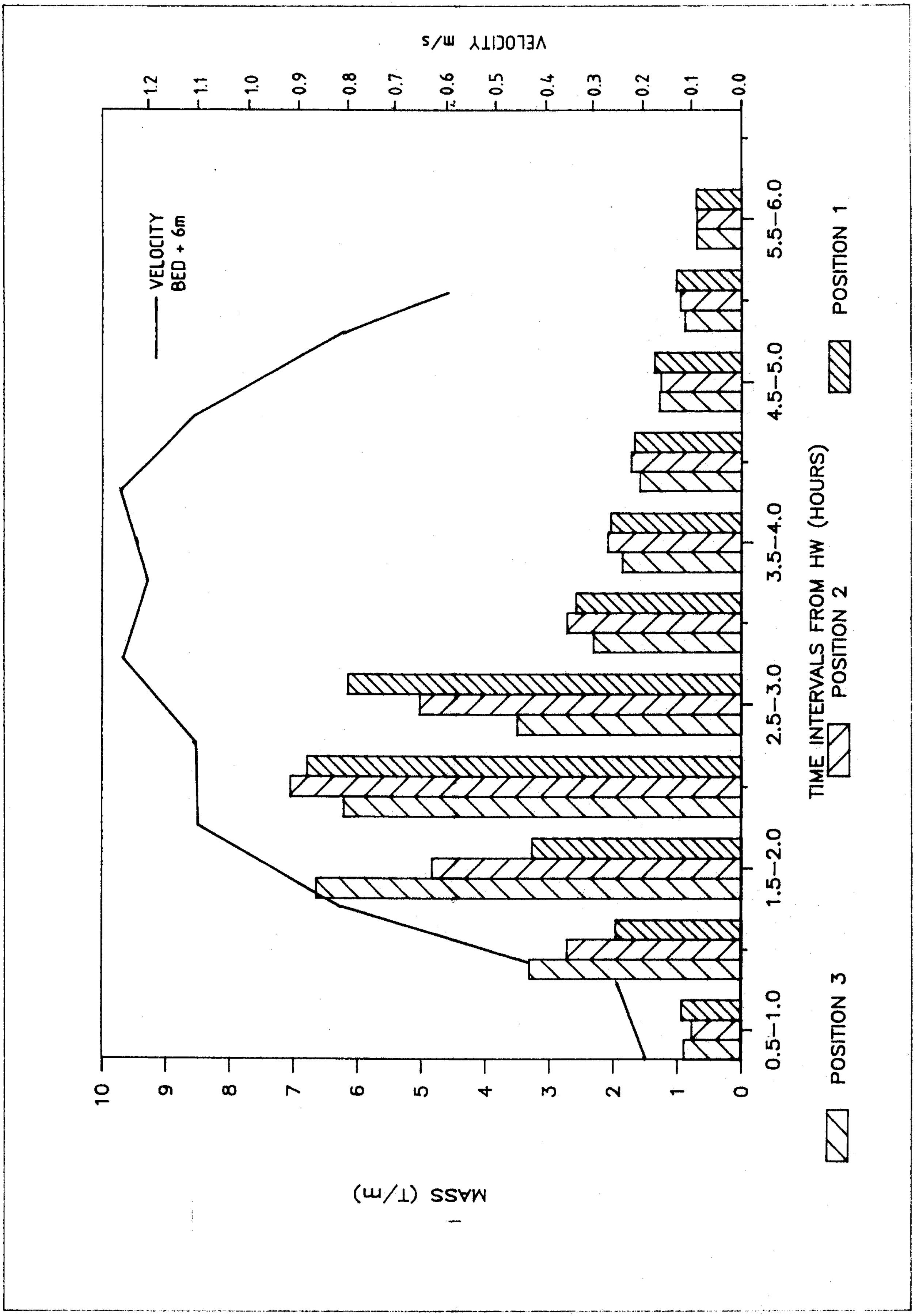

Fig 39 Sediment flux at positions 3, 2 and 1 and flow velocity : Ebb tide 28-9-85

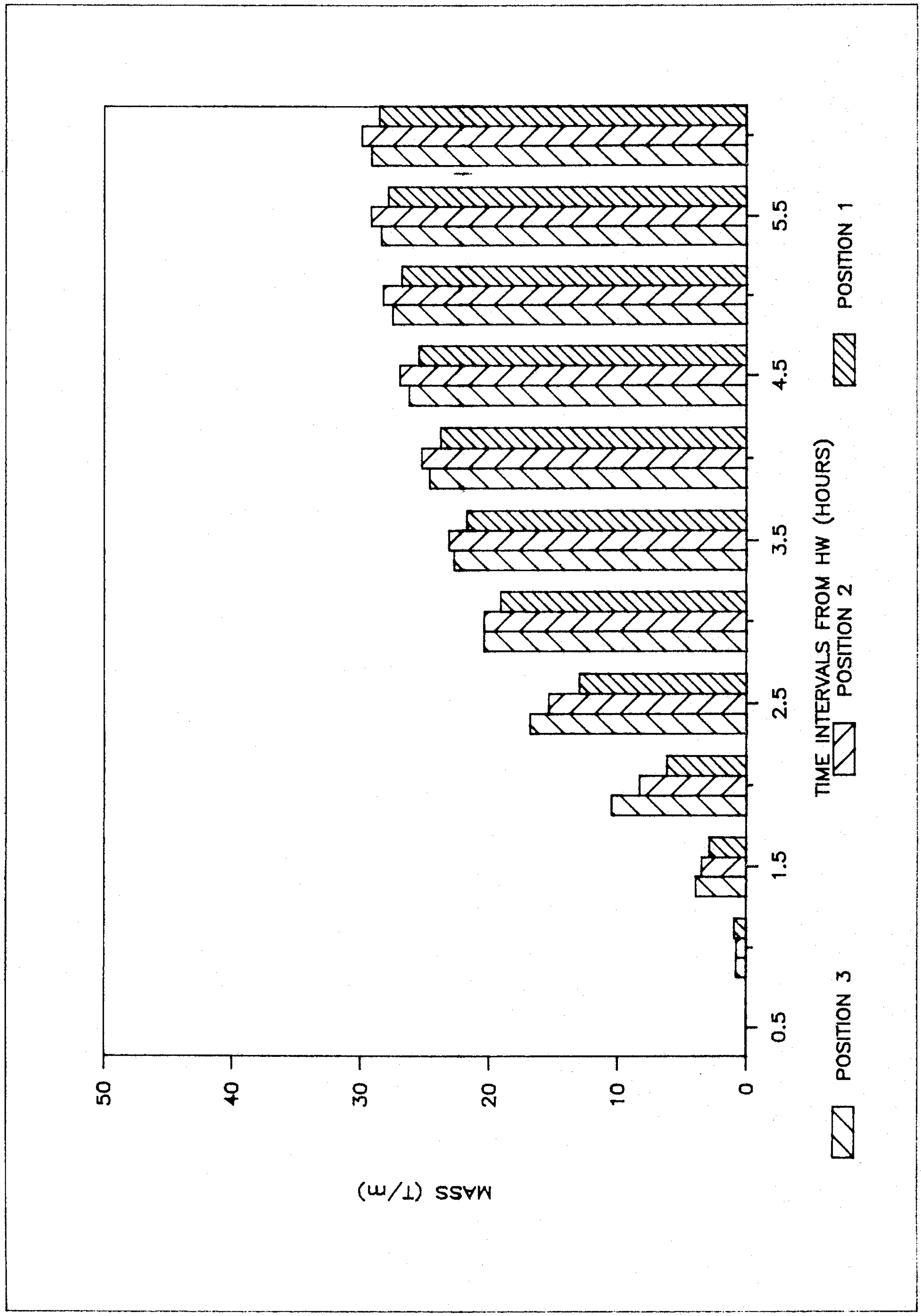

Fig 40 Cumulative sediment flux at positions 3, 2 and 1 : Ebb tide 28-9-85

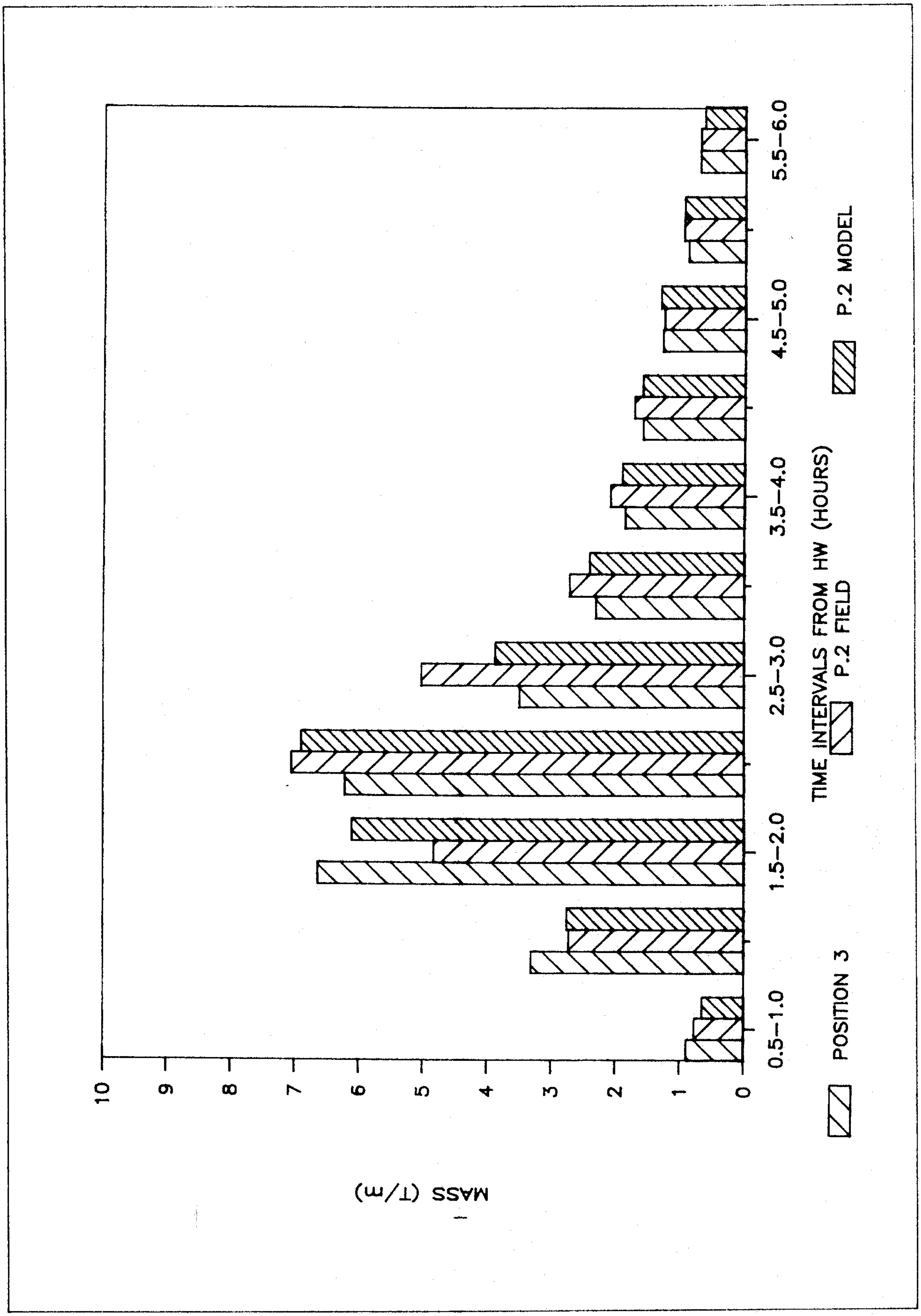

Fig 41 Predicted sediment flux at position 2 - no erosion; no deposition : Ebb tide 28-9-85

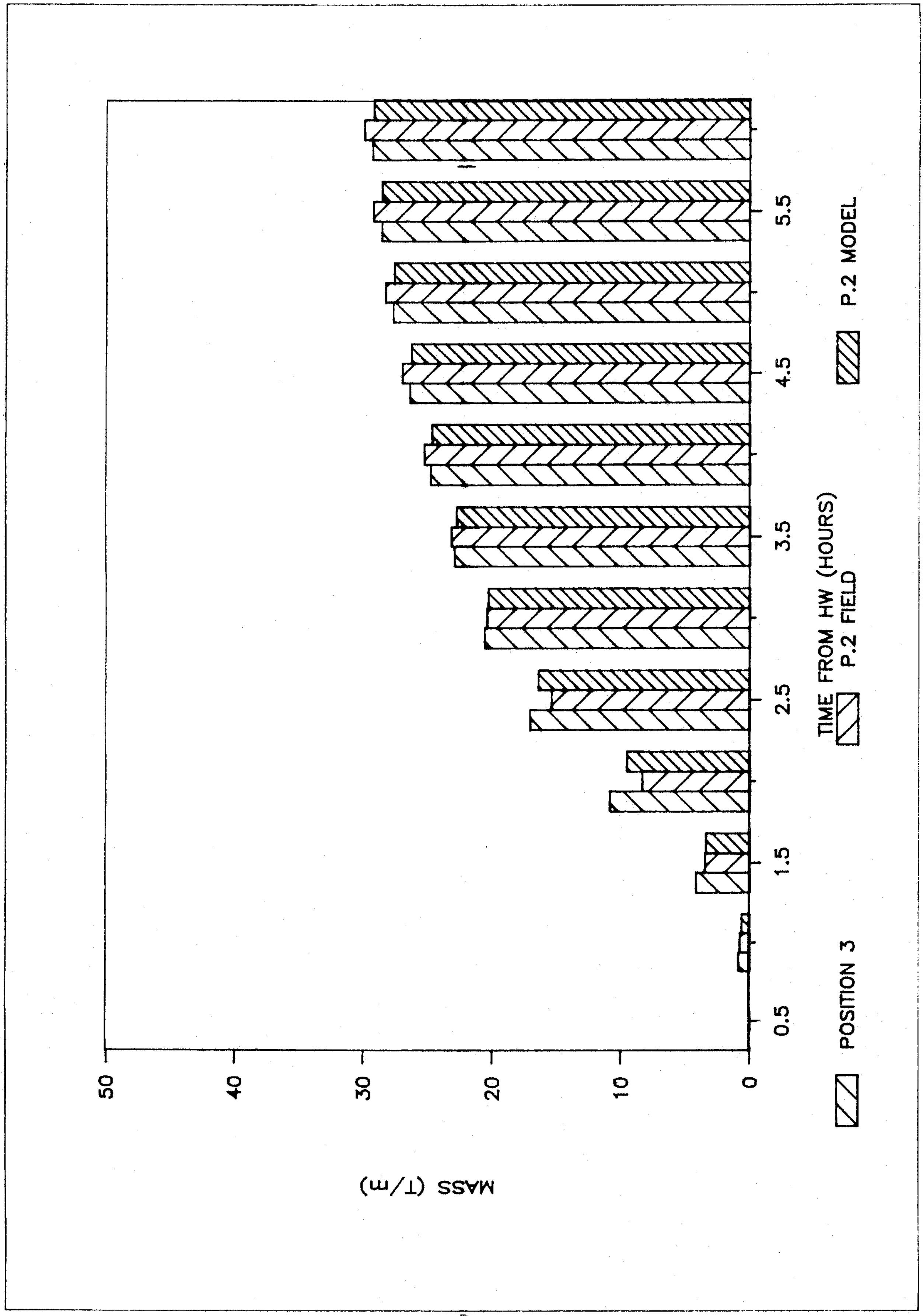

Fig 42 Cumulative predicted sediment flux at position 2 - no erosion; no deposition : Ebb tide 28-9-85

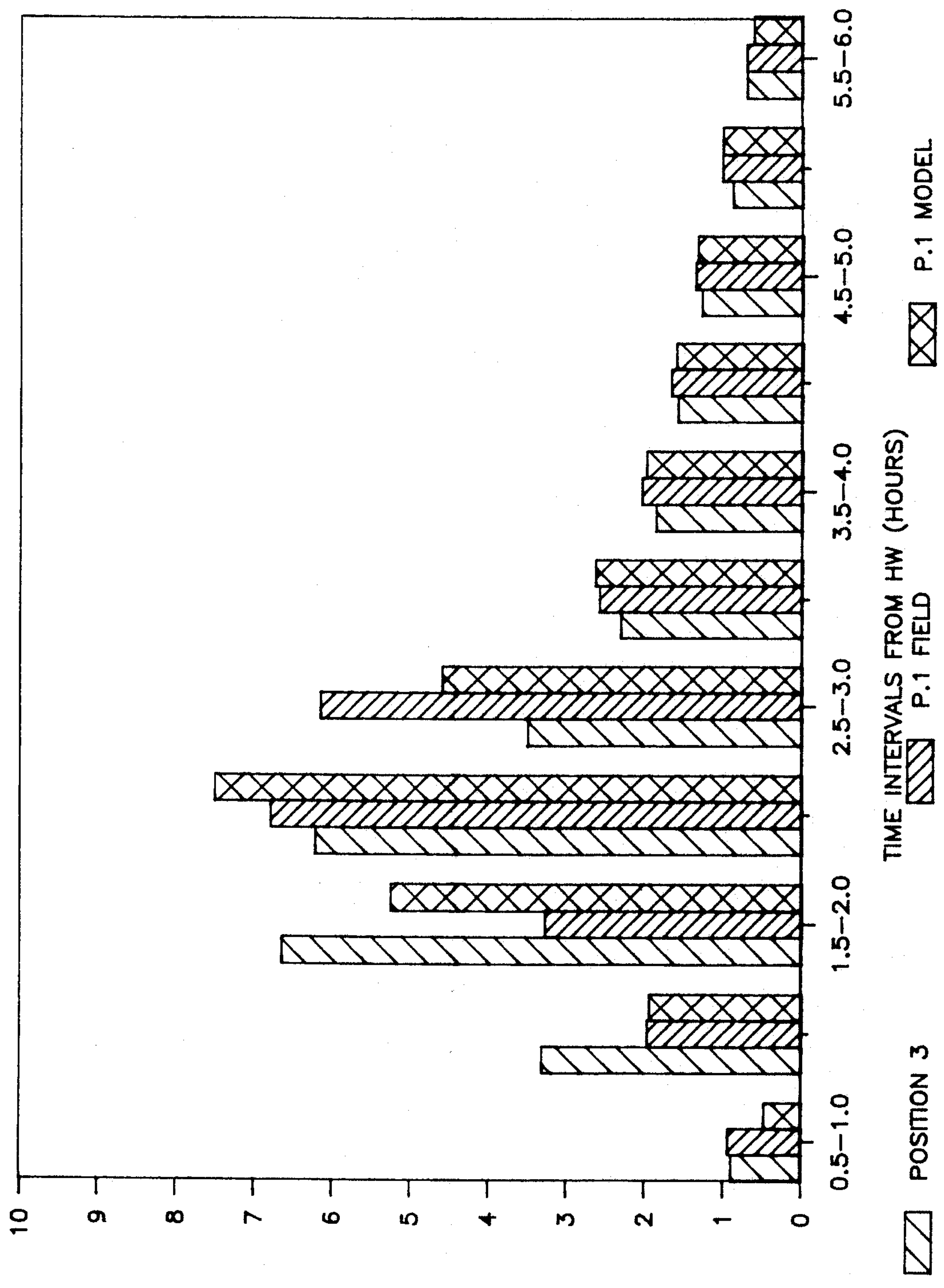

Fig 43 Predicted sediment flux at position 1 - no erosion; no deposition : Ebb tide 28-9-85

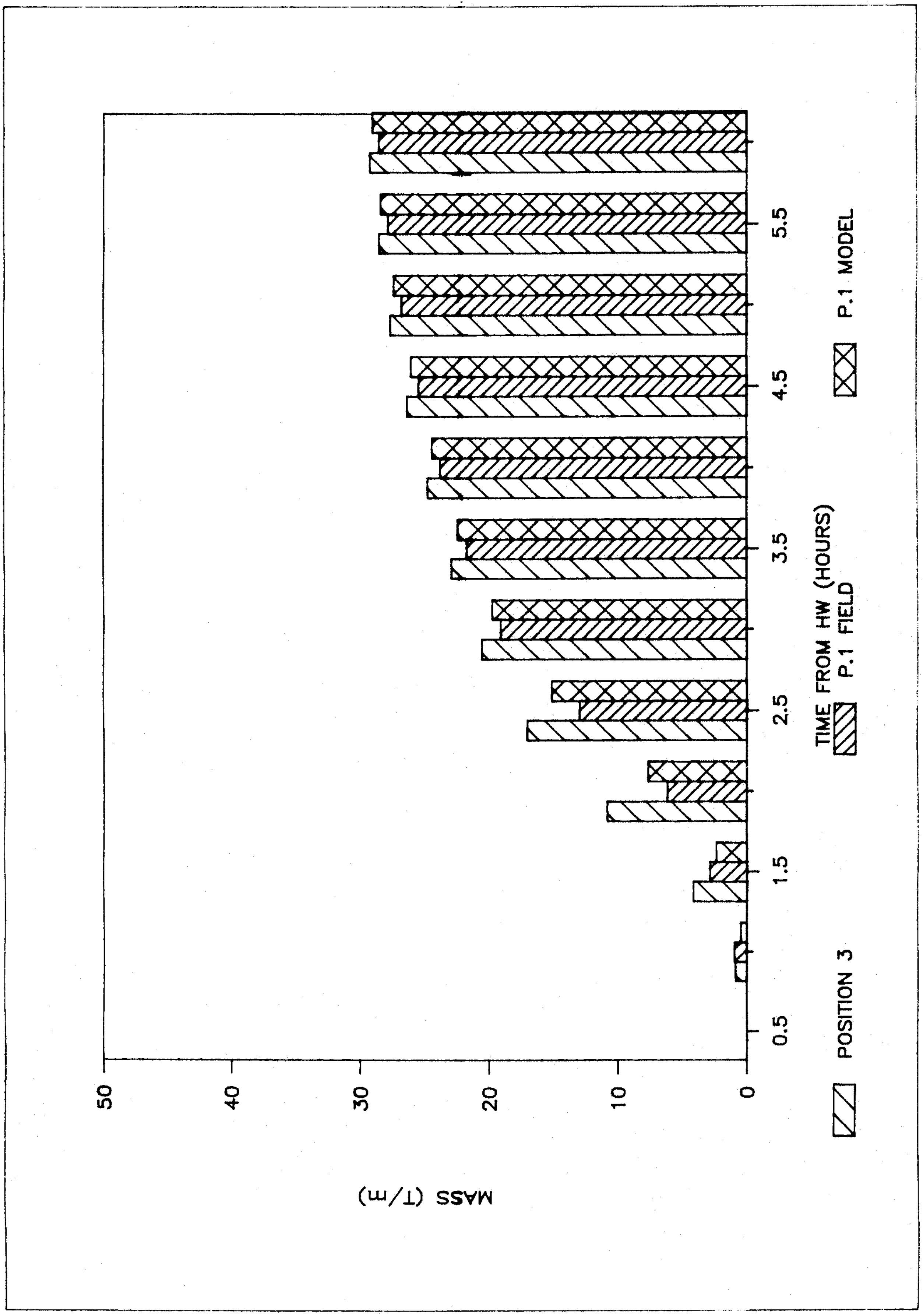

Fig 44 Cumulative predicted sediment flux at position 1 - no erosion; no deposition : Ebb tide 28-9-85