Government of the People's Republic of Bangladesh
Bangladesh Water Development Board

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River Training Studies of The Brahmaputra River

Draft Final Report

January 1993

Technical Annexes

FAP- 1

Annex 1
Analysis of Sediment Data

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Sir William Halcrow & Partners Ltd.
in association with

Danish Hydraulic Institute
Engineering & Planning Consultants Ltd.
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RIVER TRAINING STUDIES OF THE BRAHMAPUTRA RIVER

DRAFT FINAL REPORT

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GOVERNMENT OF THE PEOPLE'S REPUBLIC OF BANGLADESH
BANGLADESH WATER DEVELOPMENT BOARD

RIVER TRAINING STUDIES OF THE BRAHMAMPUTRA RIVER

DRAFT FINAL REPORT: ANNEX 1

ANALYSIS OF SEDIMENT DATA

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ABBREVIATIONS

BIWTA	-	Bangladesh Inland Water Transport Authority
BRE	-	Brahmaputra Right Embankment
BRTS	-	Brahmaputra River Training Study
BWDB	-	Bangladesh Water Development Board
DHI	-	Danish Hydraulic Institute
EIA	-	Environmental Impact Assessment
EIRR	-	Economic Internal Rate of Return
EMP	-	Environmental Management Plan
FAP	-	Flood Action Plan
FIDIC	-	Federation International des Ingenieurs-Conseils
FPCO	-	Flood Plan Coordination Organisation
GOB	-	Government of Bangladesh
ICB	-	International Competitive Bidding
IDA	-	International Development Association (World Bank)
JMB	-	Jamuna Multipurpose Bridge
JMBA	-	Jamuna Multipurpose Bridge Authority
LCB	-	Local Competitive Bidding
LWL	-	Low Water Level
NPV	-	Net Present Value
PIANC	-	Permanent International Association of Navigation Congresses
RE	-	Resident Engineer
RRI	-	River Research Institute
TOR	-	Terms of Reference

ANNEX 1 - ANALYSIS OF SEDIMENT DATA

1. INTRODUCTION

This Annex report deals with analysis of the sediment transport and bed topography data collected in Test Area 1 during June, July and November 1990 and in Test Area 2 in December and August 1991. The hydraulic data (flow velocities and water levels) collected in Test Area 1 are discussed in Annex 1, Part 4 in the First Interim Report.

The scope of the Test Area 1 data collection programme is described in the mission report of BRTS's sedimentologist (BRTS, 1990). The main purpose of the Test Area 1 survey was to prove the data for calibration of a 2-D mathematical model, which describes the flow and sediment transport in the Brahmaputra River. The data are of great importance not only for the 2-D mathematical modelling, but also for providing insight into the hydraulics and morphology of the river.

One of the main problems with most data from the Brahmaputra River is that they often are uncorrelated and only give information about one cross-section of the river at a time. The present data set gives a nearly instantaneous picture of what takes place in a entire reach of the river.

The surveyed area in Test Area 1 covers the entire width of the river for a length of about 12 km. The area is located south of Sirajganj and includes the proposed site for the Jamuna Multi-purpose Bridge (JMB), see Figure 1.1. This area has been selected because it contains both fairly straight and wide reaches as well as one major confluence and one bifurcation. Moreover, the data will complement those collected by the Jamuna Multi-purpose Bridge Authority (JMBA) in connection with the feasibility study for the bridge.

Test Area 1 has been surveyed three times during 1990 (June, July and November) with the purpose of covering rising stage, flood and falling stage. The observed discharges at Bahadurabad during the survey periods are depicted in Figure 1.2. The data collected during the three survey periods are :

June :
- Bathymetry
- Dune Tracking

July :
- Bathymetry
- Velocities
- Suspended Solids
- Bed Samples

November :
- Bathymetry
- Velocities
- Suspended Solids
- Bed Samples

Test Area 2 was surveyed in December 1990 and in August 1991. The aim was to monitor the development of bend scour and bank erosion in a place with severe bend scour. The collected data are:

December :

- Bathymetry
- Float Tracking

August :

- Bathymetry
- Velocity
- Suspended sediment
- Bed Samples

The bankline has been monitored at different times after December 1990 in order to obtain the bank erosion rate.

Nearly all the data have been organized in a LOTUS based data base for easy access to the data. The survey programme is described in Annex 1 of the Second Interim Report, which also contains information about:

- the data collection methodologies adopted
- data processing procedures
- the structure of the data base
- the logistic problems associated with a monsoon survey in the Brahmaputra River

In this Annex the data will be analysed and discussed in the light of some general observations regarding the hydraulics, sediment transport conditions and morphology of the Brahmaputra River. These observations are presented in Chapter 2.

Chapters 3 through 6 deal with analysis of the data while in Chapter 7 a detailed discussion of the sediment transport conditions in the river is presented. The main conclusions are summarized in Chapter 8.

2. GENERAL OBSERVATION

2.1 Introduction

Reviewing the literature on the Brahmaputra River, one comes across various theories and observations concerning the river which are presented as being representative for the entire river. Some of these theories and observations can be discussed in the light of some general considerations and order of magnitude estimate of the processes in the river.

2.2 Order of Magnitude of Bed Level Changes

In connection with the JMBA feasibility study, extremely useful "regime" relations" for the Brahmaputra River have been established based primarily on the compilation of a large amount of field data. According to RPT/NEDECO/BCL (1990) the sediment transport in the Brahmaputra River can be approximated by

$$S = 4.5x10^{-6}\ Q^{1.38}$$

where S and Q are total discharge of sediment (including pore volume) and water, respectively.

The flow duration curve for Bahadurabad suggests an annual sediment transport of $V = 1.4x10^{8}\ m^{3}$ (RPT/NEDECO/BCL, 1990) of bed material load.

Assuming an average width of the Brahmaputra River of 7 km and a length (within Bangladesh) of 200 km the area covered by the river is $A = 1.4 \times 10^{9}\ m^{2}$. Provided there is no significant net increase of the width of the river (i.e. bank erosion is balanced by bank deposition) and that wash load is not depositing the average change of bed level must be an order of magnitude smaller than $DZ = V/A = 0.10$ m. (the amount of sediment contained in suspension is insignificant). The very dramatic changes of the river bathymetry which can be observed in the Test Area 1 data as well as in many other data sets (see e.g. Coleman, 1969) must therefore be attributed to local redistribution of the sand deposits rather than to any seasonal and/or long term general change of bed level. This also implies that the widespread assumption that the river is subjected to significant general scour during flood is incorrect.

2.3 The Role of Coriolis Forces

The Coriolis force has often been mentioned as an agent for westward migration of the Brahmaputra. Due to the Coriolis force a moving particle will be subjected to a force directed to the right on the northern hemisphere and to the left on the southern. In a river this force will be balanced by a transverse (perpendicular to the flow) water surface slope so that the water surface Brahmaputra in general will be slightly higher along the western bank than along the eastern. The transverse water surface slope can be approximated by

$$I_y = 1.46 \times 10^{-4} \times \sin(25^\circ) \times U / g = U \times 6 \times 10^{-6}$$

(25° is the approximate latitude of Bangladesh).

Assuming a mean velocity of U = 1.5 m/s and a width of W = 7000 m the difference in water level between the two banks is only about 6 cm. This transverse pressure gradient in itself will not give rise to migration of the river. However, the Coriolis force also gives rise to a secondary current in the river. The flow velocity generally increases from the river bed towards the water surface, hence the Coriolis force will be larger close to the surface than at the bottom. This non-uniform distribution of the Coriolis force will induce a secondary current quite similar to the one found in river bends where it is caused by non uniform distribution of the centripetal acceleration.

In a bend the transverse water surface slope is given by

$$I_y = U^2 / (g \times R)$$

where R is the radius of curvature, which typically is of the order of magnitude 2500 m in aggressively eroding anabranches in the Brahmaputra. Again with U = 1.5 m/s the transverse slope becomes 1×10^{-4}, i.e. approximately 10 times larger than the slope due to the Coriolis force.

The driving force for secondary flow due to the Coriolis force and flow curvature are:

Coriolis: $1.46 \times 10^{-4} \times \sin 25^\circ \times (u - U) / g$

Bend flow: $(u^2 - U^2) / (g \times R)$

where u is the flow velocity (a function of level) and U is the depth averaged flow velocity.

The strength of the secondary current is approximately proportional to the force which is driving it. It is therefore possible to assume that the ratio between the force driving secondary flow in bends and the force driving secondary flow due to the Coriolis force is more or less equal to the ratio between the strength of the respective secondary flows. The ratio can then be computed from the forces described above to be:

$$\frac{1}{1.46 \times 10^{-4} x \sin(25)} \cdot \frac{1}{R} \cdot \frac{u^2 - U^2}{u - U}$$

$$\approx \frac{1}{1.46 \times 10^{-4} x \sin(25)} \cdot \frac{1}{R} \cdot 2U$$

$$\approx 20$$

This implies that bend scour will be in order of magnitude of 2 x 1/20 = 10% larger for curves of similar radius on the west bank than on the east bank, and hence bank erosion attacks will be more severe.

This could be an explanation for a net erosion of the right bank (i.e. westward migration) of the Brahmaputra River (and all other rivers in the northern hemisphere with large widths and flow velocities). This effect seems quite significant but it should be recalled that the analysis is based only on order of magnitude estimates.

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3. BATHYMETRIC DATA

3.1 Test Area 1

The bathymetry has been surveyed three times as a part of the Test Area 1 survey:

June 18th to 26th, 1990
July 9th to 18th, 1990
November 13th to 26th, 1990

The surveys were carried out using echo sounders to record the depths and the Decca system to determine the position. The surveys were carried out along Decca lines crossing the river at a small angle, see Figure 3.1.

The accuracy of the position fixing with the Decca system is about 30 m in any direction. Each minute as the vessel moved a mark was put onto the sounding chart and the corresponding position recorded in a log book. In between the markers the position has been determined by assuming the survey vessel moves with a constant speed.

The distance between the surveyed lines are ½, 2 and 1 Decca lines for the June, July and November survey, respectively. The distance between adjacent Decca lines is approximately 530 m.

The data are available in digital form in the BRTS data base. Further details concerning the methodology followed can be found in Annex 1 of the Second Interim Report.

In this report the results of the bathymetric surveys are presented in three different ways:

(a) Contour maps of the bed level for the June, July and November surveys are presented in Figures 3.2 through 3.4.

(b) One reason for carrying out the surveys along fixed cross-sections was that a detailed picture of the erosion and deposition pattern can be obtained. In Figure 3.5a through 3.5j superimposed cross- sections (i.e. June - July and July - November) are plotted with an indication of areas of erosion and deposition.

(c) The variation of cross sectional area, width, depth and "conveyance" with levels for some selected cross-sections are plotted in Figures 3.6a through 3.6j. The "conveyance "K has been defined as

$$K = \int_w D^{3/2} \, dy$$

where D is the water depth

This implies that the discharge, Q, is given by

$$Q = C \; I^{1/2} K$$

where C is the Chezy roughness coefficient and I the longitudinal water surface slope.

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The figures give rise to the following observation.

The thalweg (main channel) is entering Test Area 1 along the right bank, crosses the river in the central part and leaves the area along the left bank. The thalweg around the crossing is relatively diffuse: the thalweg bifurcates into an upper and lower thalweg, where the lower one seems to be the dominant. Where the left bank channel meets the upper thalweg a deep scour hole is observed, which may be interpreted as confluence scour or a combination of bend and confluence scour.

The superimposed cross sections depicted in Figures 3.5a through 3.5j identifies areas with severe bank line retreat. Particularly in Sections B66, B64 and B62 severe bank erosion has taken place; from June to July the bank retreat has been of the orders of magnitude of 300 m. It is observed that the bank erosion is accompanied with a comparable (sub-surface) deposition on the right side of the thalweg.

The very large bank erosion rate has a significant influence on the bend scour observed in the thalweg in front of the bank. This can be demonstrated by some simple formulas.

The bed load sediment transport direction, tan ψ defined as the deviation angle between the bed load sediment transport vector and the channel axis (see Struiksma et al, 1985) and is given by:

$$\tan \psi = - a D + f(\Theta) . I_y$$

where a is about 10, f (Θ) generally between 0.2 and 2 and I_y is the transverse bed slope (see Figure 2.1).

Material eroded from the banks will be transported by the flow. Close to the bank the bank erosion gives rise to a trannserse sediment transport component, which reads:

$$S_{BE} = (1-\varepsilon) \frac{DW.D.L}{T}$$

Where,
ε = the porosity of the sediment = 0.4
DW= bank line retreat; DW is about 300 m
T = period over which the bank erosion takes place; T = 1 month
L = length over which the bank erosion takes; L is about 1200 m

Then:

$$S_{BE} = 1.5 \text{ m}^3/\text{s}$$

The longitudinal sediment transport rate can be approximated by the JMBA relation:

$$S = 4.5 \times 10^{-6} Q^{1.38}$$

with Q = 50,000 m^3/s and f (fraction of the total transport carried in the anabranch in question) estimated to be 0.85, which is equal to the fraction of the total discharge carried in the anabranch.

$S = 4.5 \times 10^{-6} \times 50{,}000^{1.38} \times 0.85$

$= 12\ m^3/s$

The ratio between the transverse and longitudinal transport component (i.e. the direction) is

$$\tan \psi = -\frac{S_{BE}}{S}$$

$$= -\ 0.125$$

Along a protected bank (with no bank erosion) the sediment transport will be parallel to the bank, thus:

$$\tan \psi = 0.$$

The effect on the transverse slope of bank protection is therefore:

if D = 18 m, R = 1000 m

$$\frac{I_y \text{ (Bank Erosion)}}{I_y \text{ (No Bank Erosion)}} = \frac{-0.125 + 0.18}{0.18} = 0.3$$

i.e. the near bank transverse slope will be 3 times larger without bank erosion.

This is naturally an extremely simplified analysis, disregarding that the bend is not infinitely long, that a large amount of the sediment is carried in suspension and that an increased slope will give rise to redistribution of the flow. However, in spite of this it is very likely that bank protection will give rise to a significant increase of the transverse bed slope and hence the bend scour.

From June to July very large deposition takes place in the right channel in cross section C50. In B78 (downstream of C50) a high degree of sedimentation is observed from July to November. This can be an indication of migration of large subsurface bars. The same phenomenon, though less pronounced, is observed in section B72 and the subsequent section.

The deepest scour in the river is found in section B72 during November. This scour may be interpreted as confluence scour. The left anabranch in the downstream reach forms a large bend.

The most dramatic change of cross-section is observed from July to November in cross-section B74. The deep scour hole (confluence scour) in the left side is completely filled up and the right side of the section has eroded considerably. This can be interpreted as a downstream migration of the crossing.

The Figures 3.6a through 3.6j should be interpreted with caution. The sections only cover the part of the cross section that was accessible with the vessels. The figure therefore does not include information about chars and shallow areas (say depths less than 1 meter) and especially during the November survey some minor channels were not accessible by the survey vessels. This implies that differences between the elevation-area curves may not reflect only sedimentation or erosion. However, some trends are persistent.

- heavy deposition has taken place from June onwards in section C50 and B72

- Sections B78 and B76 have been remarkably stable during the entire period in terms of total cross-sectional area and conveyance although significant re-distribution has taken place within the cross-sections.

- the downstream sections (B70-B62) have been subjected to sedimentation from July to November

Comparison of the findings in Test Area 1 with other investigations reveals some discrepancies.

The central part of Test Area 1 is a so-called nodal point, where the main anabranches meet. According to Coleman (1969) such a section should have larger mean depth than other sections of the river. However, the surveyed sections around the crossing are not in general deeper than the remaining sections.

Coleman also reports a persistent pattern in the cyclic development of the cross-section:

> "As discharge increases, two channels, generally located adjacent to the river banks, tend to scour, while the central part of the channel is the site of deposition. As flood waters subside, one channel tends to fill rapidly, forcing water down the other, thus maintaining a single deep channel. After the flood has passed, little change takes place except for some filling and reduction in cross-sectional area of the main channel."

This pattern cannot be verified with the Test Area 1 data:

- both erosion and deposition take place in the central part of the cross-section

- there is no general increase of the main channels adjacent to the banks from June to July.

- from July to November there is no significant decrease of the minor channels.

RPT/NEDECO/BCL (1989) reports that the scour depth (bend and confluence) does not vary systematically with stage, (the inference being that scour statistics can be derived from dry season data. The Test Area 1 data shows that some scour holes increased in depth between the flood season and the dry season whereas others decreased. This does not conflict with the assumption that dry season data can be used to derive scour statistics but does demonstrate that the location of maximum scour is a dynamic function.

The contour maps of bathymetry have been used to estimate the migration speed of the major bed forms. First the maps have been smoothed out in order to remove the influences of dunes. Then the downstream movements of contour lines have been extracted from the bathymetry maps at different times. The migration speed varies considerably, see Table 3.1. However, it gives a valuable estimate of how fast the overall river bed bathymetry changes.

Table 3.1 Migration of Bed Elevation Contour Lines

Contour Lines m PWD	Approx. Location C/S #	Distance		Approx. Speed	
		Jun-Jul m	Jul-Nov m	Jun-Jul(22) m/day	Jul-Nov(123) m/day
3	B76 Right	50	1500	2	12
6	B78 Right	300	300	14	2
6	B78 Left	400	1200	18	9
3	B74 Left	450	1150	20	9
6	B66 Middle	1450	1750	66	14
3	B64 Left	150	400	7	3

The mean value from June to July is 21 m/day. From July to November, the discharge varies greatly and the derived average migration speed 9 m/day is more uncertain.

A theoretical expression for the migration speed c reads

$$c = \frac{b.s}{h.(1-F^2)} \qquad \text{(Vreugdenhil)}$$

where the sediment transport rate per unit width is expressed as $s = a.u^b$, u is velocity, b is exponential power (3-5), h is the depth and F is the Froude number $F = u/\sqrt{gh}$. If u=1.2 m/s, Q = 50000 m^3/s, S = 12 m^3/s, $s=1.8\times10^{-3}$ m^3/s, h = 6.6 m, and b = 3, then

$$c = 8.10^{-4} \text{ m/s}$$

$$= 72 \text{ m/day}$$

The calculated speed is relatively high. The parameters are very uncertain and the equation itself is an approximation from a linearised analysis. However, the comparison shows that from theory it can be demonstrated that the migration speed is inherently high.

Bank erosion rates can be derived from the cross sections in Figure 3.5a -3.5j. These also will only show order of magnitude because of the attached uncertainty, see Table 3.2. From June to July (22 days) the maximum erosion rate that occurred was 330 m or 15 m/day.

There is no clear relationship between velocity, depth, and bank erosion rate. The data however confirm that in general, bank erosion takes place where the banks are concave and the velocity is high.

3.2 **Test Area 2**

The bathymetry has been surveyed in Test Area 2 in December 1990 and August 1991, see Figure 3.7 and Figure 3.8. The migration speed of the chars and the scour hole is difficult to derive because the flow conditions are changing from high to low flow in that period. The scour hole migrated about 800 m downstream during the period and this was associated with high but not severe bank erosion. The near bank char just upstream the scour hole was also moved downstream about 800 m indicating a close relationship between these two processes. Assuming the majority of changes took place during the last two months of the period, the migration speed was approximately 14 m/day.

Table 3.2 Observed bank erosion in Test Area 1

Lane	Period	Left Anabranch		Left Bank A sqm	Right Anabranch		Right Bank A sq.m
		L m	D m		L m	D m	
C50	June	-80	7	-560	140	10	1400
C50	July	0	0	0	300	8	2400
B78	June	60	10	600	230	8	1840
B78	July	150	6	900	220	6	1320
B76	June	100	5	500	-110	5	-550
B76	July	360	6	2160	180	6	1080
B74	June	0	0	0	100	5	500
B74	July	0	0	0	270	3	810
B72	June	0	0	0	0	0	0
B72	July	0	0	0	370	2	740
B70	June	0	0	0	0	0	0
B70	July	-220	-2	-440	0	0	0
B68	June	0	0	0	0	0	0
B68	July	0	0	0	70	5	350
B66	June	300	20	6200	100	5	500
B66	July	160	7	1120	300	2	600
B64	June	220	15	3300	100	3	300
B64	July	370	11	4070	0	0	0
B62	June	340	12	4200	0	0	0
B62	July	370	14	5180	0	0	0

Notes: JUNE is June-July (22 days), JULY is July-November (128 days)
L is bank line retreat (negative number is deposition) in metres
D is depth in front of the bank (m)
A is eroded cross sectional area (m^2)

The bankline movements at Kazipur in 1991 is shown in Figure 3.9. Almost all the changes took place from June to October where upto 400 m had eroded in the southern part of Test Area 2 where the flow velocity was very high and the bed slope was steep. In the northern part (not shown), the bank line is stable. The maximum bank erosion rate was approximately 3 m/day in the monsoon period.

4. BED MATERIAL SAMPLES

Bed samples were collected in Test Area 1 during both the July and the November survey. 76 samples were collected in July and 19 in November. In the July survey two sample methods were used. At depths less than 4 m, which were served by the tenders (too shallow for the mother vessel), a grab type sampler was used. At depths greater than 4 m a US-GS sampler with a scoop released by a spring was used. In the November survey only the simple grab type sampler was used. A typical sample size was 300 g.

The collected samples have been sieved analyzed and the finer (silt) fraction analyzed in a settling column. Grain size distribution curves have been worked out for all the samples. Further details about sampling and analysis methods can be found in Annex 1 in the Second Interim Report.

The results of the bed sampling program in terms of spatial variation of d_{50} are depicted in Figure 4.1 and 4.2. The July data (Figure 4.1) show that, apart from a few outliers, the d_{50} does not vary much. The two very coarse samples (d_{50} > 0.40mm) have been collected in the thalweg where the flow velocities are high and the flow path curved (bend scour).

The data from the November bed sampling programme exhibit larger scatter than the July data. This is not surprising because both large scale sorting processes, as for instance in bends, and local sorting processes in sand dunes, are more pronounced when the bed shear stresses are small (see Olesen, 1987 and Ribberink, 1989).

The result of the bed sampling programme is summarized in Table 4.1. The values in this table are not based on all the data. A few outliers have been discarded. From the July data the two very coarse samples discussed above and one sample collected in still water containing almost entirely silt have been omitted. From the November data a few very fine samples have been omitted. The geometric standard deviation (or gradation) has been calculated as d_{84} / d_{16}, where d_{84} is the grain size of which 84% of the weight of the total sample has a smaller diameter.

Table 4.1 Summary of Bed Sample Data from Test Area 1.

	July	November
Mean d_{50} (mm)	0.15	0.19
Max d_{50} (mm)	0.19	0.33
Min. d_{50} (mm)	0.11	0.06
Mean Geom. Standard Dev.	2.8	2.1
Max Geom. Standard Dev.	8.8	5.4
Min Geom. Standard Dev.	1.8	1.4

The results summarized in Table 4.1 show that the sediment is very uniformly graded. The fact that d_{50} in the July data do not vary greatly emphasizes that grain sorting processes, such as for instance preferential transport of fine particles, play only a modest role in the local (i.e. on reach basis) morphology during the monsoon period.

The increase in observed mean d_{50} from July to November cannot reflect any general change in d_{50}, because the time scale for general morphological changes is much larger than the period covered by the data (cf. Section 2). The apparent increase in d_{50} may be attributed to:

- Lateral redistribution of sediment. It is very likely that sediment deposited at chars and banks during, amongst other, the falling stage is somewhat finer than the mean grain size due to segregation in the suspension profile. As a results char sediment will be slightly finer than the river bed sediment during the dry period. During the monsoon period the sediment is then partly re-mixed. Similar phenomena have been reported by RPT/NEDECO/BCL (1987).

- The limited number of samples.

Bristow (1988) reports significant seasonal change of grain diameter. His data from Chilmari (close to the Bangladesh - Indian boarder) suggest a d_{50} of approximately 0.06, 0.15 and 0.35 mm in April, July and November respectively. No information is available as to whether the above data are the mean value of a large number of samples or the results of only three samples. It is observed that the results are within the range found in the November data from Test Area 1.

The above results can also be explained if the samples are collected in the outer part of a bend. In line with the theories, and also illustrated by the Test Area 1 data, the sediment becomes coarse during falling stage in the outer bend. This could explain the observed significant increase of grain diameter from July to November. During the dry period the water can be almost stagnant at very deep sections (small discharge in combination with large depth) and hence fine sediment (including silt) may deposit. At the end of the dry season the top layer of the bed of a deep section may therefore consist of very fine sediment. This sediment is easily re-eroded at the beginning of the flood season and has therefore no significant effect on the morphology.

Seven Bed samples were also collected from Test Area 2 in August 1991 and the results are shown in Table 4.2.

Table 4.2 Summary of Bed Sample Data from Test Area 2

Mean d_{50} (mm)	0.17
Max d_{50} (mm)	0.23
Min d_{50} (mm)	0.09
Mean Geom. Standard Dev.	2.1
Max Geom. Standard Dev.	2.5
Min Geom. Standard Dev.	1.9

The results are consistent with those of Test Area 1. The coarse material was collected in the deep channels and the fine material was found at the chars.

5. SUSPENDED SEDIMENT SAMPLES

5.1 Test Area 1

Suspended load samples were collected in both the monsoon and the post monsoon survey in Test Area 1. In July a total of 360 samples and in November 75 samples were collected.

In general the samples were collected at 20% of the water depth below the surface and 20% above the river bed, however at selected representative locations up to 5 samples distributed over the depth were collected.

At 20% below the water surface, a 400 ml bottle with a cork which could be released from the vessel was used. In the bottle a ping-pong ball sealed the bottle when it was filled. This arrangement was also used at 20% above the bottom in shallow water (total depth less than 4 m) where the mother vessel could not operate. At larger depths a 0.40 m tube with a diameter of 0.05 m was used at 20% above the bottom. At the desired depth the tube closed at both ends. Additional details about the survey and analysis method can be found in the BRTS First Interim Report.

The two sample methods only collect a small amount of water/sediment mixture. Due to the high turbulence in the Brahmaputra River especially during the monsoon period, the suspended sediment concentration field will exhibit very large variation. The collected data therefore only represent an instantaneous picture of this fast varying concentration field and consequently exhibit a large scatter.

The data are plotted in Figures 5.1 through 5.4. The spatial variation of mean concentration (defined as mean value of the concentrations at 20% above the bed and 20% below the surface) is depicted in Figures 5.1 and 5.2 for July and November respectively. The observed concentration plotted versus the observed depth averaged velocity are shown in Figures 5.3 and 5.4. All these figures reflect the large scatter; however the following observation can be made:

(a) Irrespective of the velocity the concentration is larger than 0.4 g/l in the July data. This is a clear indication that wash load concentration is about 0.4 g/l. The wash load is the very fine particles of the sediment (silt and clay) which are more or less uniformly distributed over the vertical and do not interact with the bottom. In non-tidal rivers wash load normally has no or insignificant influence on the bed topography.

(b) From the November data it is seen that the wash load concentration is significantly lower than in July (about 0.05 g/l).

(c) Figures 5.3 and 5.4 suggest that the vertical gradient in concentration is significantly larger in the November data where the flow velocities generally are lower. This conforms with the sediment transport models, see Section 7.

(d) The sediment concentration increases with the flow velocity. This trend is more pronounced in the November data.

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The suspended sediment samples have been sieve analyzed. Due to the small amount of sediment in each sample (generally between 0.2 and 1.0 g) it was necessary to mix a number of the samples before the sieve analysis were carried out. Samples collected in the vicinity of each other at the same relative depth were mixed. In total 26 mixed samples were analyzed from the July survey and only four from the November survey.

The sieve analyses showed that on average 45% of the samples consisted of silt (d<0.053 mm) in the July survey and about 67% in the November data. The mean concentration in the July and November samples were 1.08 g/l and 0.22 g/l thus the mean wash load (silt) concentration is 0.48 g/l and 0.14 g/l, respectively.

Given the inaccuracies inherent in suspended sediment sampling, these values are consistent with those noted above.

It was not possible to detect any clear trend in the variation of the sand/silt contents with depth in the July data, whereas the November data suggests (on average) a sand content of 35% at 20% above the bed reducing to 30% at 20% below the surface.

The suspended bed material load transport (d > 0.053 mm) can be estimated from the total fluid discharge multiplied by the mean sediment concentration. Using the Brahmaputra discharge the transport will be as shown in Table 5.1.

Table 5.1 Suspended Bed Load Characteristics

Characteristic	July	November
Fluid Discharge* m3/s	53,750	17,850
Sediment Transport: t/s	32	1.4
10^6 t/day	2.7	0.12
(incl. pore) m^3/s	20.0	0.90
(excl. pore) m^3/s	12.0	0.54

* Mean value of recordings during survey period.

5.2 Test Area 2

In Test Area 2 in the vicinity of Kazipur, a total of 35 samples of suspended sediment was collected at seven stations. The samples were taken at varying depths (usually 20% and 80% above the bed) by pumping up 25 litres at a time. The suspended bed load was extracted from the samples by sieving the water samples through a 0.063 mm sieve and collecting the retained material. Small 0.5 l samples were collected so that the concentration of wash load could be derived also.

The samples are all from a very small area (800 x 1000 m) inside Test Area 2. Hence they can not be used to derive a mean concentration representing the whole river. However the method of sampling may provide a better estimate of the total load and the proportion of silt.

The measured concentration of suspended bed material varied between 0.06 g/l and 0.54 g/l with a mean value of 0.21 g/l. The mean concentration of the total load, inclusive of wash load, was 1.00 g/l so the distribution between sand and silt was 21% and 79%.

The concentration of suspended bed material increased towards the bottom as expected. When the mean concentration was plotted against mean depth velocity at the seven stations there was no clear trend towards increasing concentration with increasing velocity.

The data from Test Area 2 only cover a small part of the river and in a channel only so it would not be reasonable to try to estimate the total sediment discharge on basis of these data as in Test Area 1.

5.3 Bahadurabad Sediment Transport Data

Data on coarse (i.e. suspended bed load material and excluding wash load) suspended sediment transport in the Brahmaputra River at Bahadurabad are available for the period 1968-70 and 1982-88. The observed suspended sediment transport plotted against discharge is depicted in Figure 5.5 together with a regression line reading

$$Q_{susp} = 9.1\ 10^{-6} x Q^{1.26}\ \text{(t/s)}$$

A closer analysis reveals that the data from the period 1968-70 suggest a significant (about 3 times) higher sediment transport than suggested by the 1982-88 data. The data are depicted in Figure 5.6. The regression lines are

1968-70:

$$Q_{susp} = 4.97\ 10^{-6}\ Q^{1.38}\ \text{(t/s)}$$

1982-88:

$$Q_{susp} = 15.2\ 10^{-6}\ Q^{1.184}\ \text{(t/s)}$$

It is most likely that the apparent increase in sediment transport is caused by either a change in measuring procedure or a change in data processing. An increase of sediment transport with a factor 3 normally would imply an increase of velocity of 30% to 40%. This could only be achieved if very significant morphological changes had taken place, and there is no indication of such morphological changes.

The following is noted:

(a) The high flow (July) data from Test Area 1 suggest a slightly higher transport rate than the 1968-70 data, although the November data agrees better with the 1982-88 data. It should be mentioned that the Test Area 1 data only represents two sets of observations of the total sediment transport, which is subjected to natural fluctuation due to migrating bars etc.

(b) Most sediment transport models will predict transport rates which agree better with the 1968-70 data than with the 1982-88 data, see Figure 5.7.

The 1968-70 data probably therefore provide a better description of the conditions in the Brahmaputra River, particularly during the monsoon season when the large majority of sediment transport takes place. This is consistent with the relations applied in the JMB feasibility study.

The sediment transport condition in the Brahmaputra River is discussed in more detail in Chapter 7.

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6. DUNE TRACKING

Dune tracking was carried out in Test Area 1 during June 1990. Two Decca lanes were sounded twice daily for the period 22 to 26 June. The location of the dune tracks are shown in Figure 6.1.

The dune tracking data have been used to estimate the migration speed of the dunes and to analyse the hydraulic resistance of the river channel.

6.1 Migration Speed of Dunes

Two different methods have been used to estimate the migration speed of the dunes.

(a) The position of individual dune crests were read from the sounding chart and plotted as a function of time. An example is shown in Figure 6.2. On some of the charts the selected dunes could not be identified. This could either be due to inaccurate positioning of the vessel, or a reflection of the fact that the dunes are relatively short crested.

(b) Dune profiles of a reach of around 500 m were transferred to transparent paper and the position of the best fit on the subsequent sounding chart were used as an estimate for the migration speed of dunes.

The results of the two methods were very consistent. The results using Method 1 for some selected dunes are given in Table 7.1. The mean value of the migration speed is about 10^{-3} m/s or around 90 m/day. Typical heights and lengths for the dunes were 3 m and 200 m respectively. The results are discussed in more detail in Chapter 7.

6.2 Hydraulic Resistance

The calculation of the flow resistance is far more complex in case of an alluvial river than in the case of a channel with a fixed bed. This is because a large part of the hydraulic resistance in the alluvial case may be caused by form drag on bed forms, which have a configuration determined by the sediment transport and the flow. The most important bed forms in natural rivers are dunes.

If the dimensions (height and length) of the dunes are known, the hydraulic resistance (bed shear stress) can be calculated from the water depth and the specific discharge. Furthermore, the position of the bed shear stress, τ', which is acting as skin friction on the gently curved upstream side of the dunes, can be determined.

The total bed shear stress, τ, is split up into the skin friction, τ', and a portion which is caused by the form drag on the dunes τ'':

$$\tau = \tau' + \tau'' \qquad [6.1]$$

The form drag is mainly caused by the expansion loss downstream of the dune crests, and can therefore be calculated as a Carnot loss (Engelund & Hansen, 1967)

$$\frac{\tau''}{\rho} = \frac{\alpha}{2} \cdot \frac{D}{L} \left(V_c^2 - V_c^2\right) \qquad [6.2]$$

where α is a coefficient which is close to unity for long crested dunes with steep lee sides, L is the dune length, D the water depth and V_c and V_T - the flow velocity over the crest and through respectively - can be approximated by

$$Vc = \frac{D}{D - \frac{H}{2}} . V$$

$$Vc = \frac{D}{D + \frac{H}{2}} . V$$

where H is the dune height and V the mean flow velocity. The remaining term of the right hand side of Equation 6.1, i.e. τ', can be obtained from a boundary layer equation (see Section 7.2.1). Thus for any combination of V, D, H and L the total bed shear stress can be determined, hence also the bed resistance coefficient.

In the Brahmaputra the dune pattern is probably highly 3-dimensional (short crested) as discussed in Section 6.1. In addition the lee side of the dunes is not very steep (RPT/NEDECO/BCL, 1989). This might be caused by the large amount of suspended material being deposited in the separation zone downstream of the dune crests, as discussed in Chapter 7. The implication of this is that the "expansion loss factor" in Equation 6.2 will be considerably smaller than unity.

In Figure 6.3 the Chezy resistance number - predicted using the model described above - is depicted as a function of the "expansion loss factor". A dune height of 3 m and length of 200 m were used. RPT/NEDECO/BCL (1989) reports Chezy coefficients of the order of magnitude of about 65 $m^{1/2}/s$, which with a water depth of 7 m corresponds to a Mannings n of 47 $m^{1/3}/s$. Hence the expansion loss coefficient is probably of the order of magnitude of 0.25. In that case about 60 % of the total friction is caused by form friction for a water depth of 6 m, and about 50 % for D = 8 m.

7. DISCUSSION OF SEDIMENT TRANSPORT DATA

7.1 Summary of the Main Findings from the River Survey

The suspended load in Test Area 1 was measured by an instantaneous sampler and this method will tend to show a large scatter due to the turbulence of the water. The depth integrated concentration of suspended bed load material in July 1990 varied between 0 (g/l) and 4.5 g/l with a mean value of about 0.59 g/l. This corresponds to a total suspended transport of about 32 t/s, see Chapter 5.

In Test Area 2 during September 1991, the suspended sediment was measured by pumping a large amount of water (25 l) over several minutes at each depth and extracting the suspended bed material on board the vessel. In this way the scatter in the data was reduced. Still the spatial differences in depth mean concentration were very large which indicates the high irregularity of the suspended sediment distribution locally. The mean value of concentration of suspended bed material was 0.21 g/l.

Usually the sediment transported in the migrating dunes is interpreted as the bed load and from the successive dune trackings it is possible to estimate the sediment transport in the dunes. If the shape of the dunes is taken to be triangular, the volumetric sediment transport is found as

$$q_d = \tfrac{1}{2} a H (1-n)$$

where H (m) = the dune height, n = porosity (= 0.4) and a (m/s) the migration velocity of the dunes. Table 7.1 gives the result of following some individual dunes from the tracks in the period 22nd - 26th June.

Table 7.1 Some Typical Results of Dune Tracking.

Lane	D (m)	H (m)	a (m/s)	½ a H(1-n) (m3/m/s)
34.9	8	3.25	1.0×10^{-3}	9.8×10^{-4}
34.9	8	2.75	9.3×10^{-4}	7.7×10^{-4}
34.9	5.5	3.0	1.1×10^{-3}	1.0×10^{-3}
35.2	7.5	3.5	9.7×10^{-4}	1.0×10^{-3}
34.9	5	3.5	9.4×10^{-4}	9.9×10^{-4}

The flow velocity was not measured at the same time, but from information of the water level, it can be estimated that the mean flow velocity is around 1.5 m/s, cf. Figure 7.1 which shows the variation in water level at Bahadurabad for the period of dune tracking and velocity measurements, respectively.

The sediment is characterized by its size and settling velocity. A large number of sieve analyses suggest a mean diameter of about 0.15 mm.

Fall velocity is estimated from ASCE Sedimentation Engineering (1975) and a water temperature equal to 20° C. This suggests a fall velocity equal to 2.0 cm/s.

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7.2 Selection of Sediment Transport Formula

A number of sediment transport formulae have been applied to attempt to describe the sediment transport in the Brahmaputra.

Based on dune trackings, it is apparent that dunes in the Brahmaputra migrate much faster than would be expected from any known bed-load formula. For this reason, it is necessary to estimate how large a proportion of the suspended sediment transport is deposited in the lee of the sand dunes and actively contributes to their movement. It is concluded that a substantial proportion (more than 50 %) contributes to the dunes' movement.

Two models, the Engelund-Fredsoe and the van Rijn models, have been used to calculate the sediment transport in the Brahmaputra. The advantage of these two models is that they are able to distinguish between bed load and suspended load, which is essential for mathematical modelling of bend scour. The two models predict slightly larger transport rates than the Engelund-Hansen model, which is a total load model.

However, the Engelund-Fredsoe model and the van Rijn models correspond very well with the measured field data

2b

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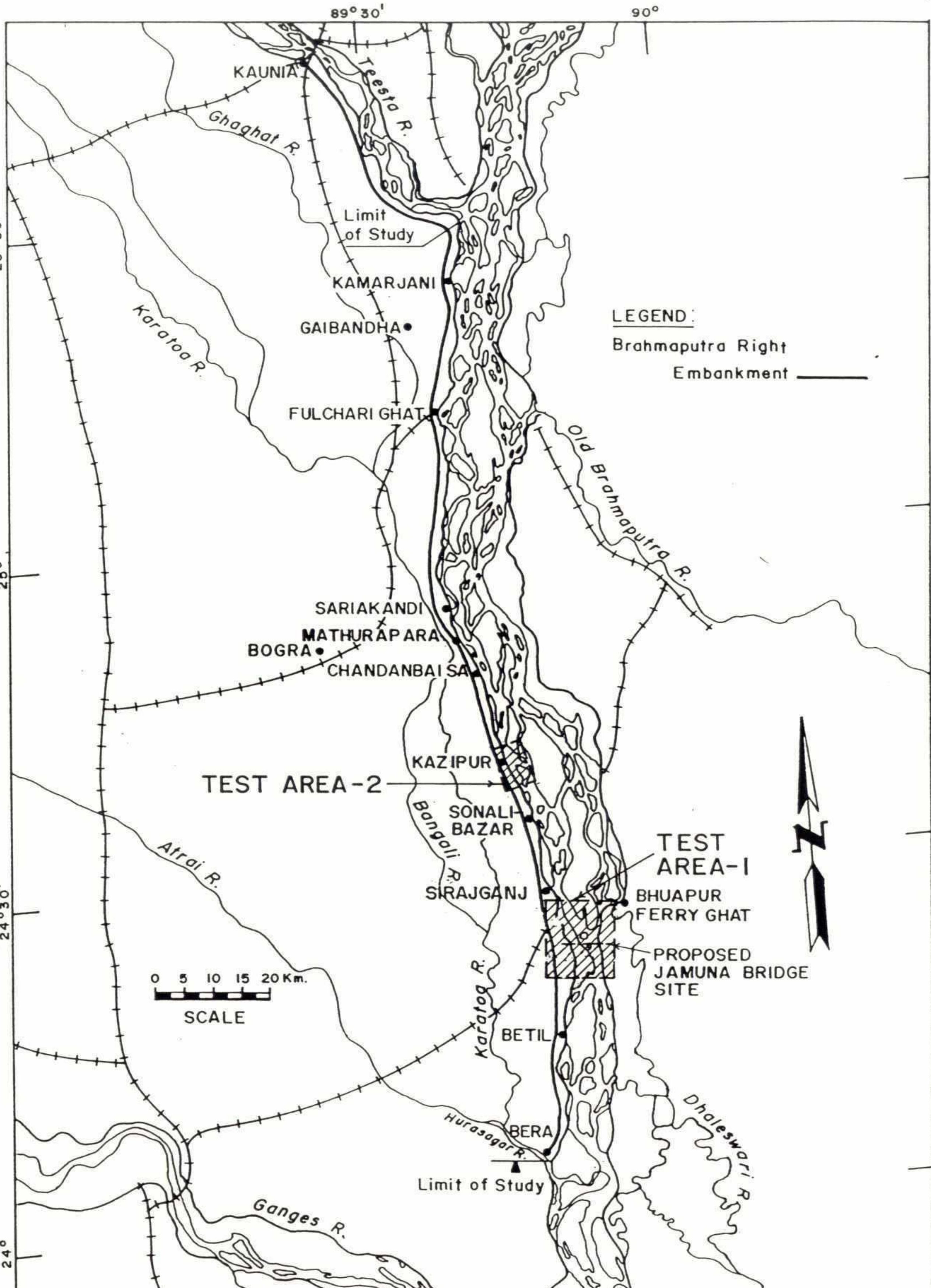
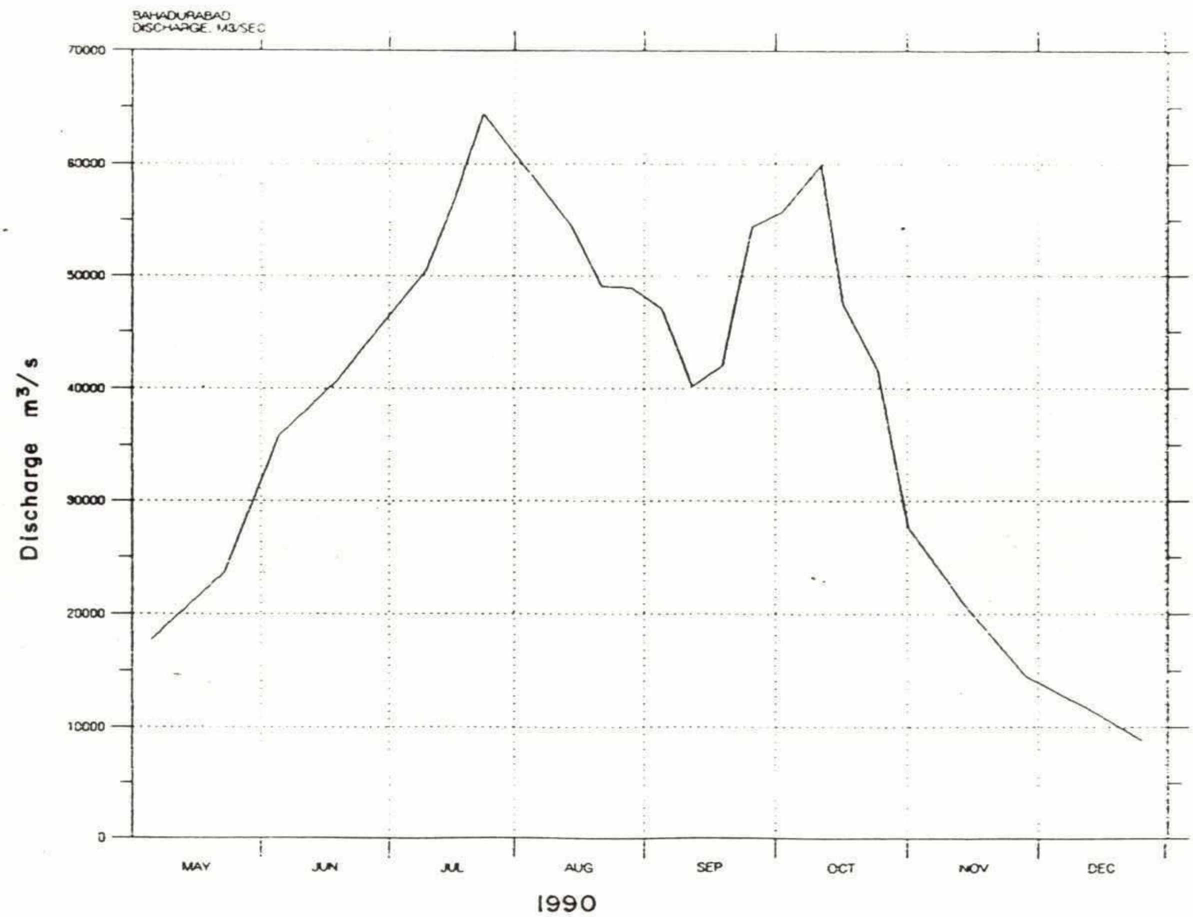
FIGURES



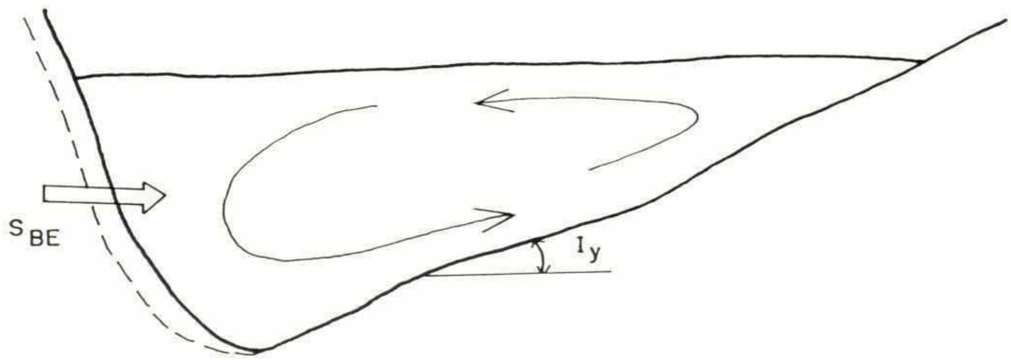
Location Plan of Test Area 1 and Test Area 2

Halcrow/DHI/EPC/DIG	November 1992	Annex 1 Figure 1.1



Observed Discharge at Bahadurabad

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 1.2

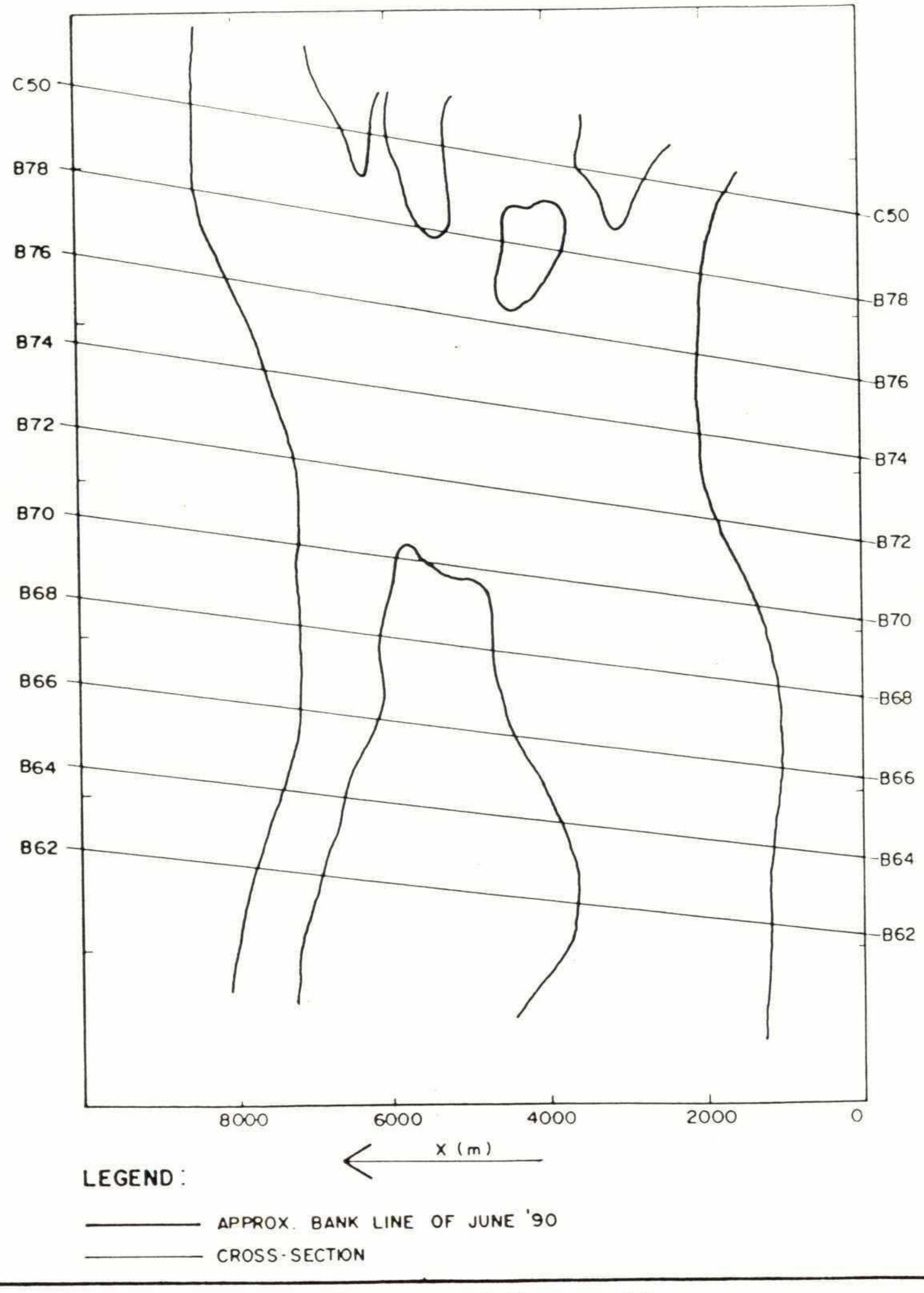


Flow and Bed Topography in River Bend Definition Sketch

Annex 1

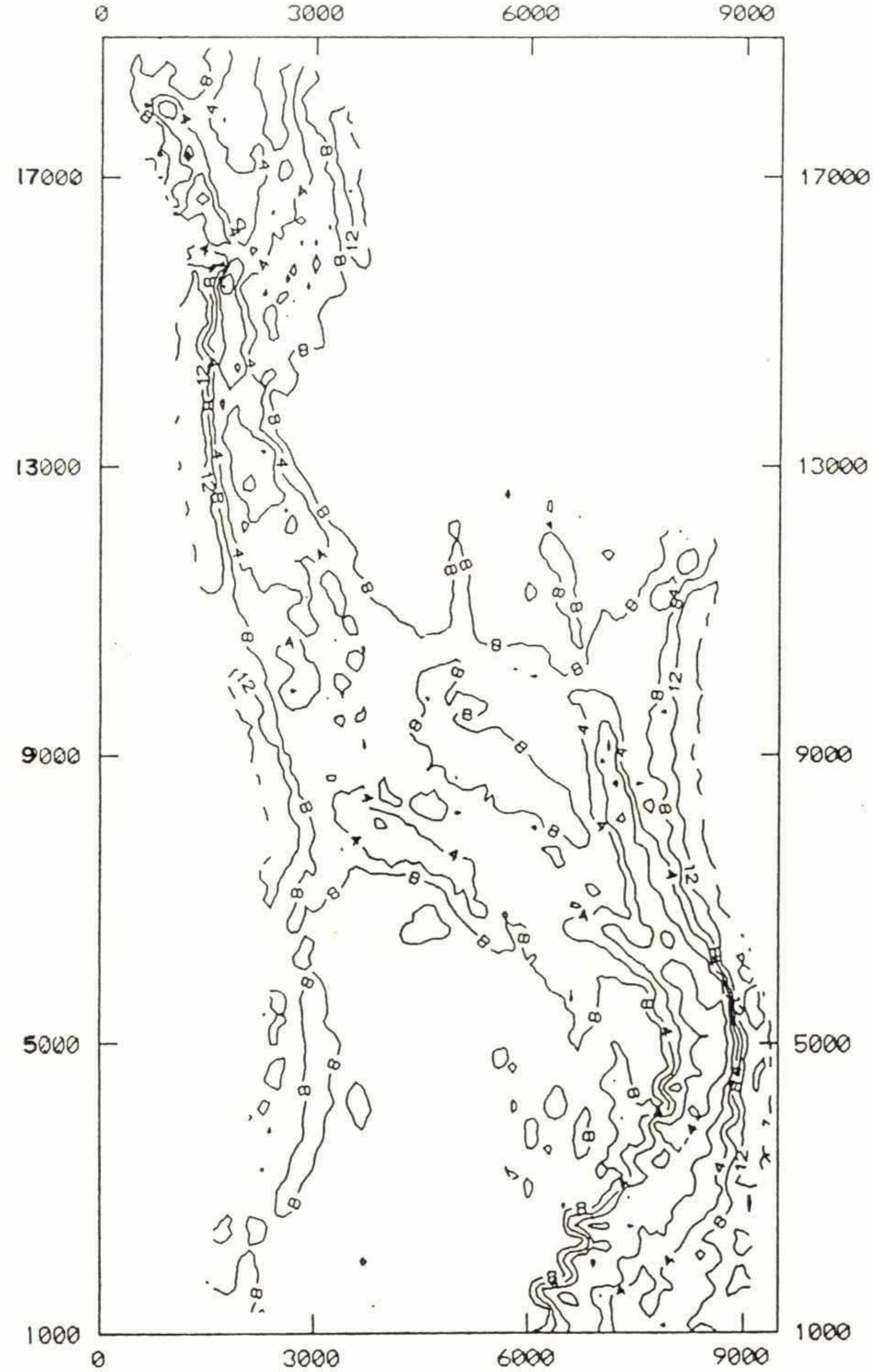
Figure 2.1

Halcrow/DHI/EPC/DIG *November 1992*



Surveyed Decca Lines

Halcrow/DHI/EPC/DIG	*November 1992*	**Annex 1**
		Figure 3.1



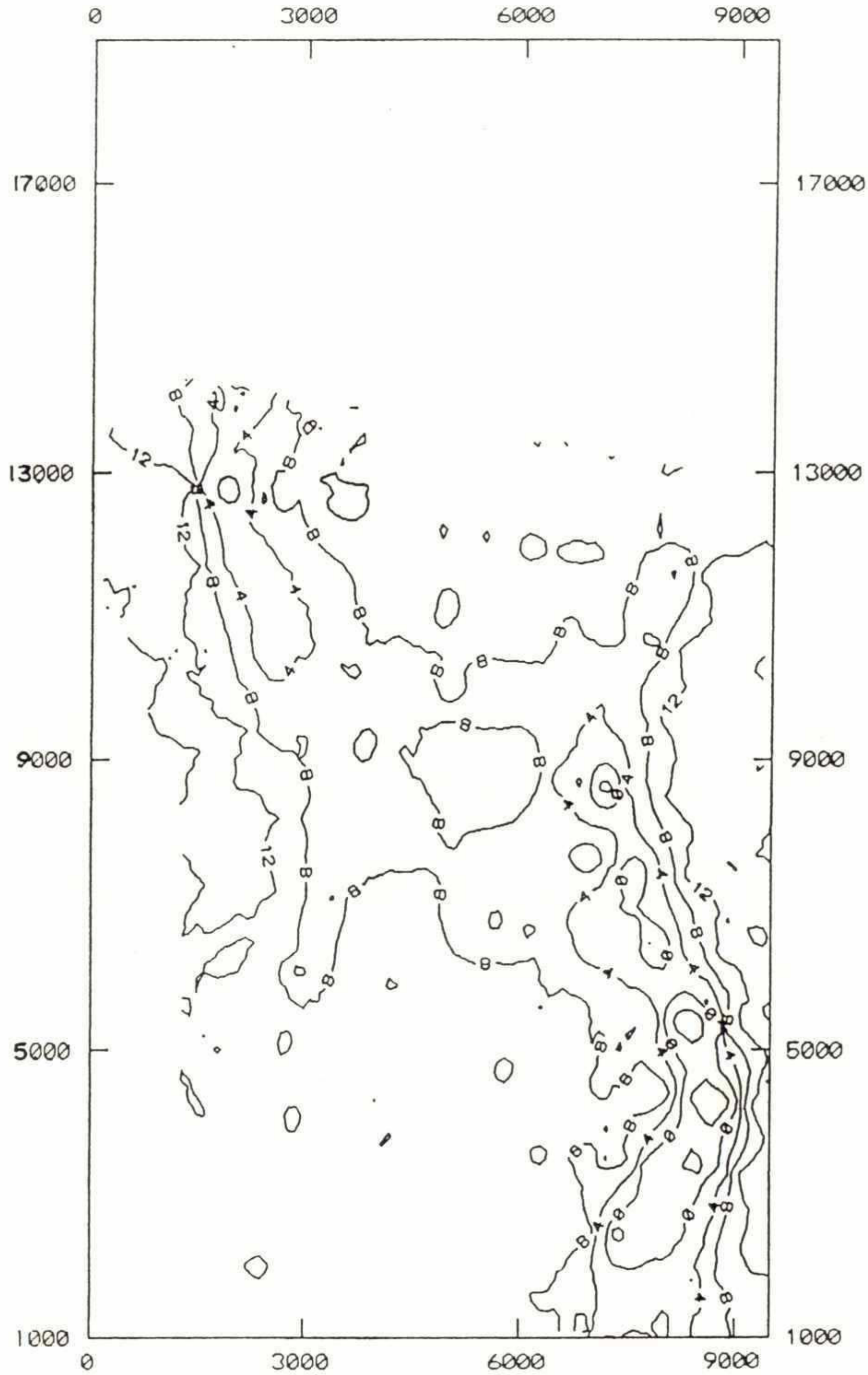
Contour Map of Bathymetry Surveyed in June 1990

Halcrow/DHI/EPC/DIG

November 1992

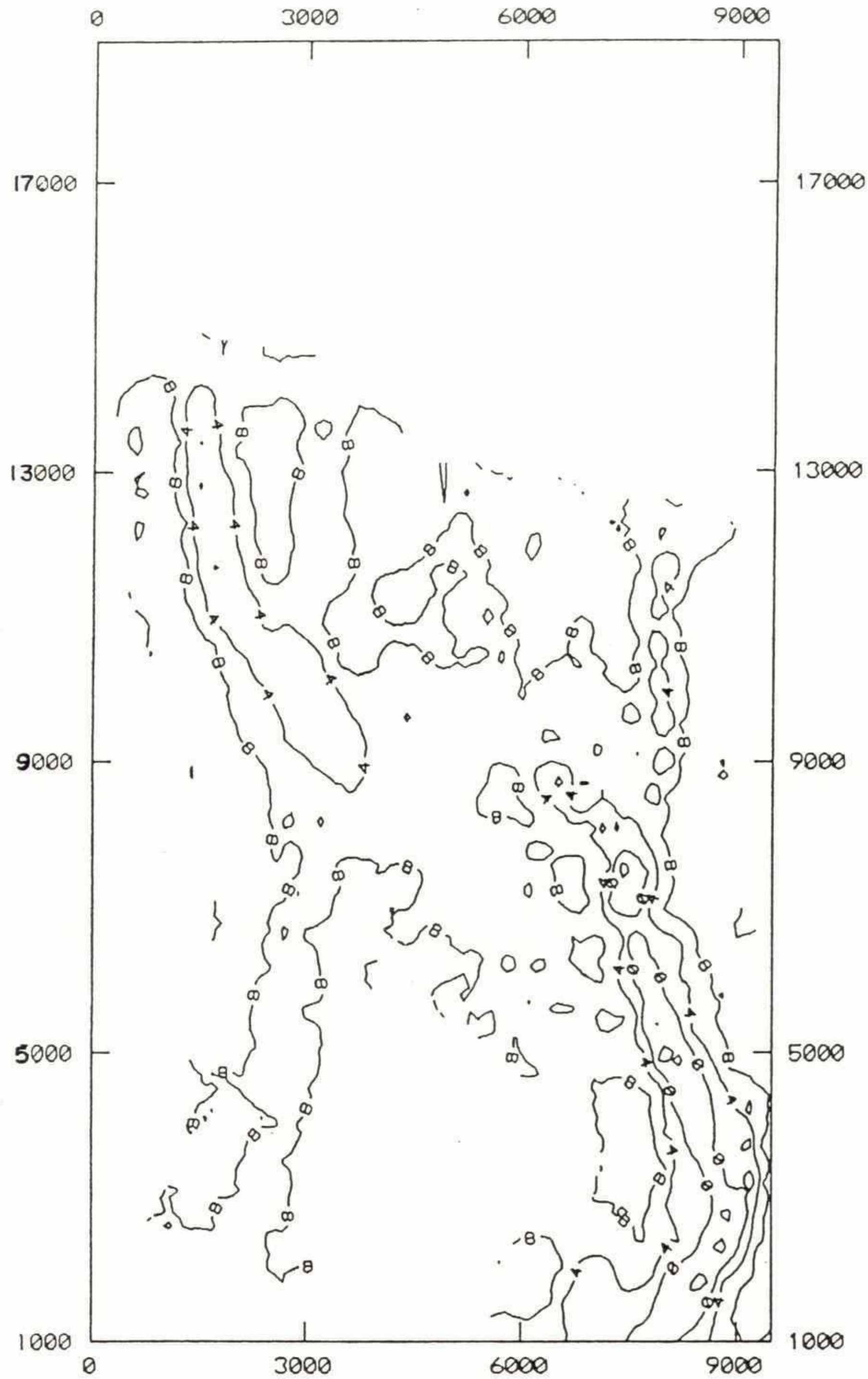
Annex 1

Figure 3.2



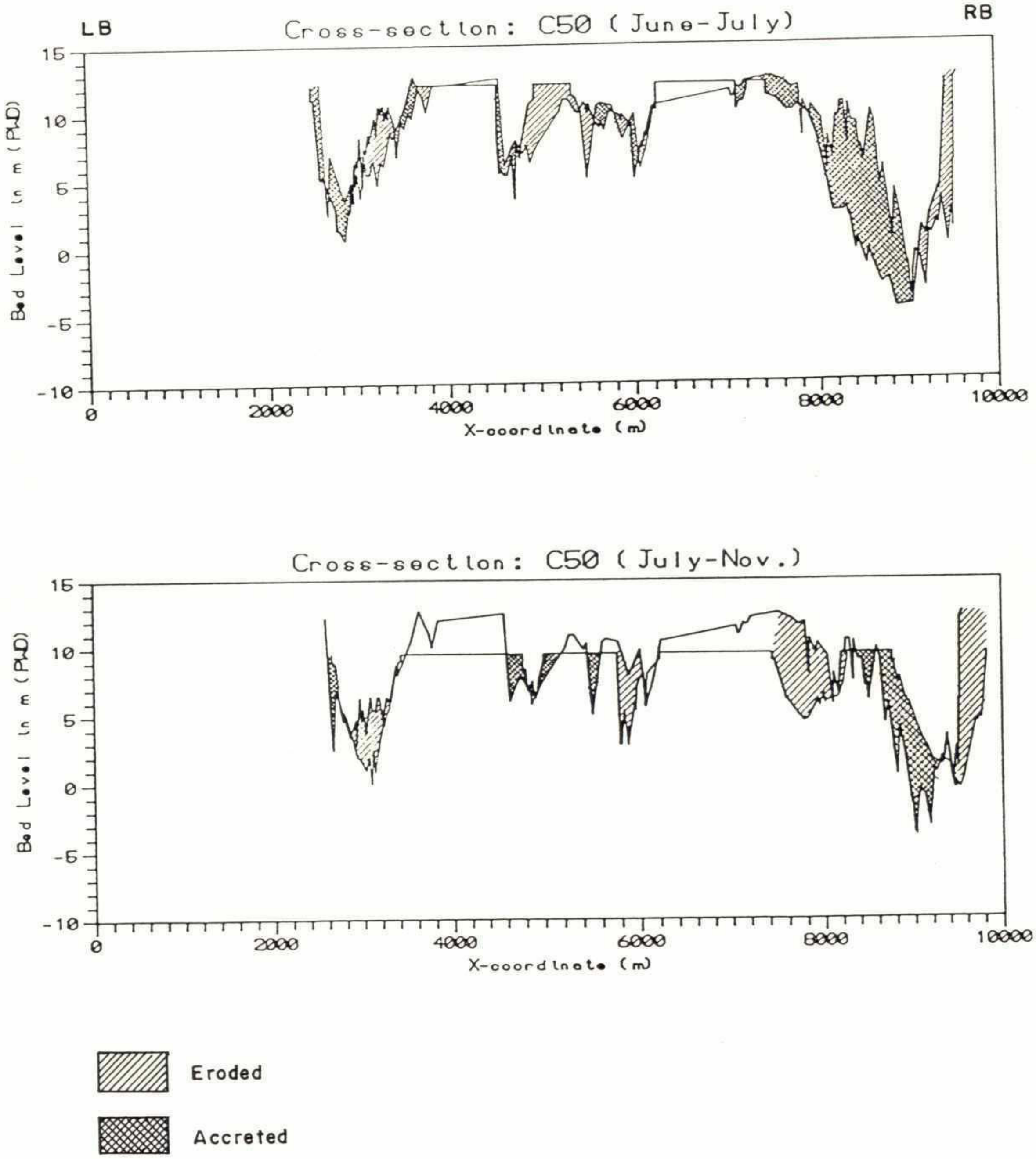
Contour Map of Bathymetry Surveyed in July 1990

Halcrow/DHI/EPC/DIG	*November 1992*	Annex 1
		Figure 3.3



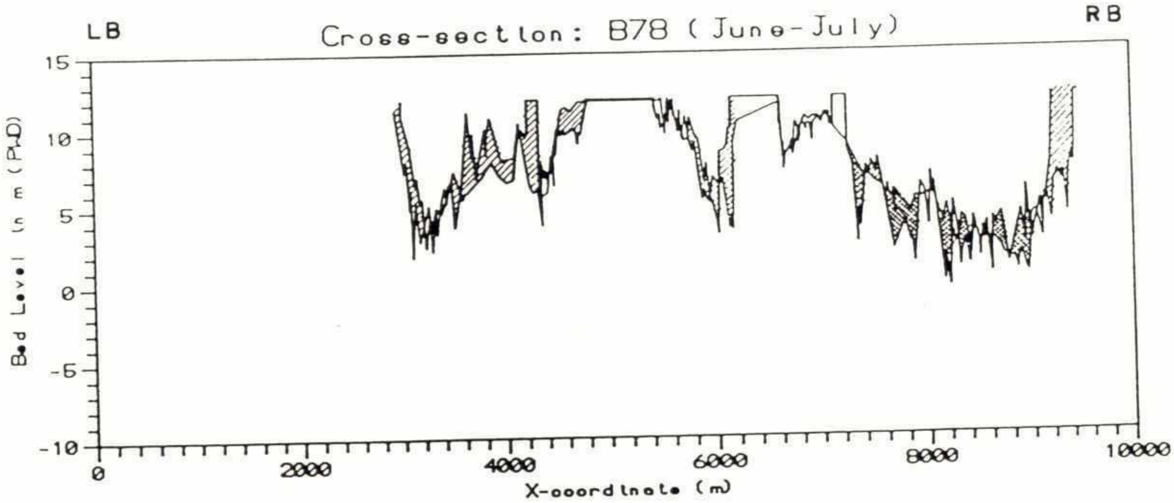
Contour Map of Bathymetry Surveyed in November 1990

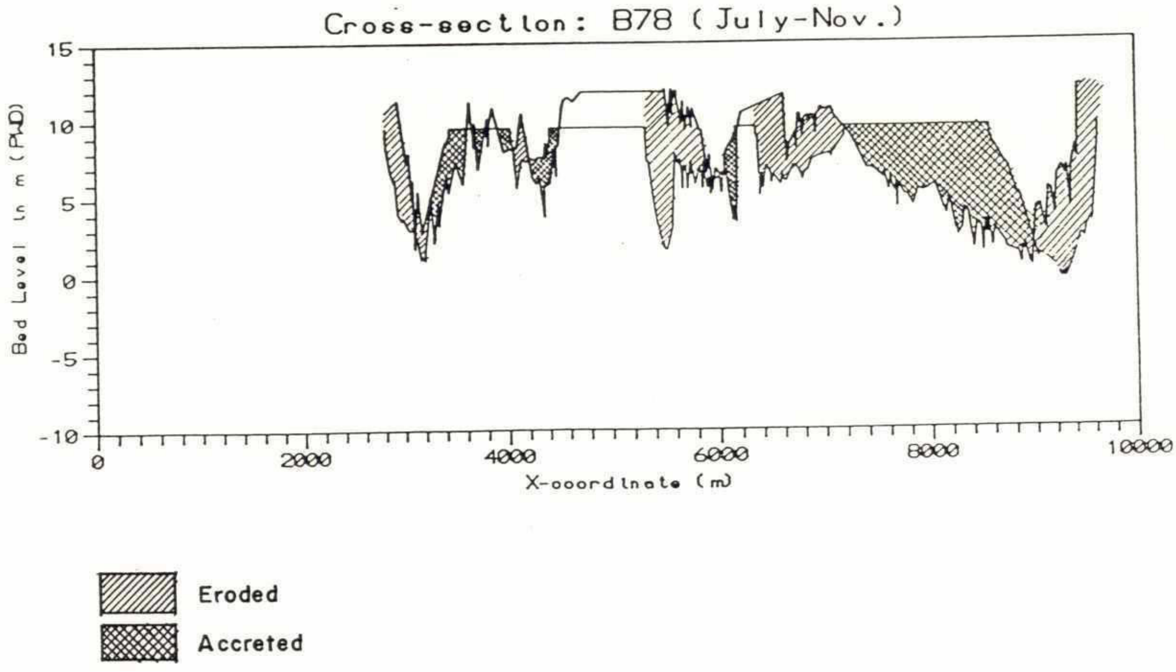
Halcrow/DHI/EPC/DIG	*November 1992*	**Annex 1**
		Figure 3.4



Cross Sections Surveyed in June, July and November

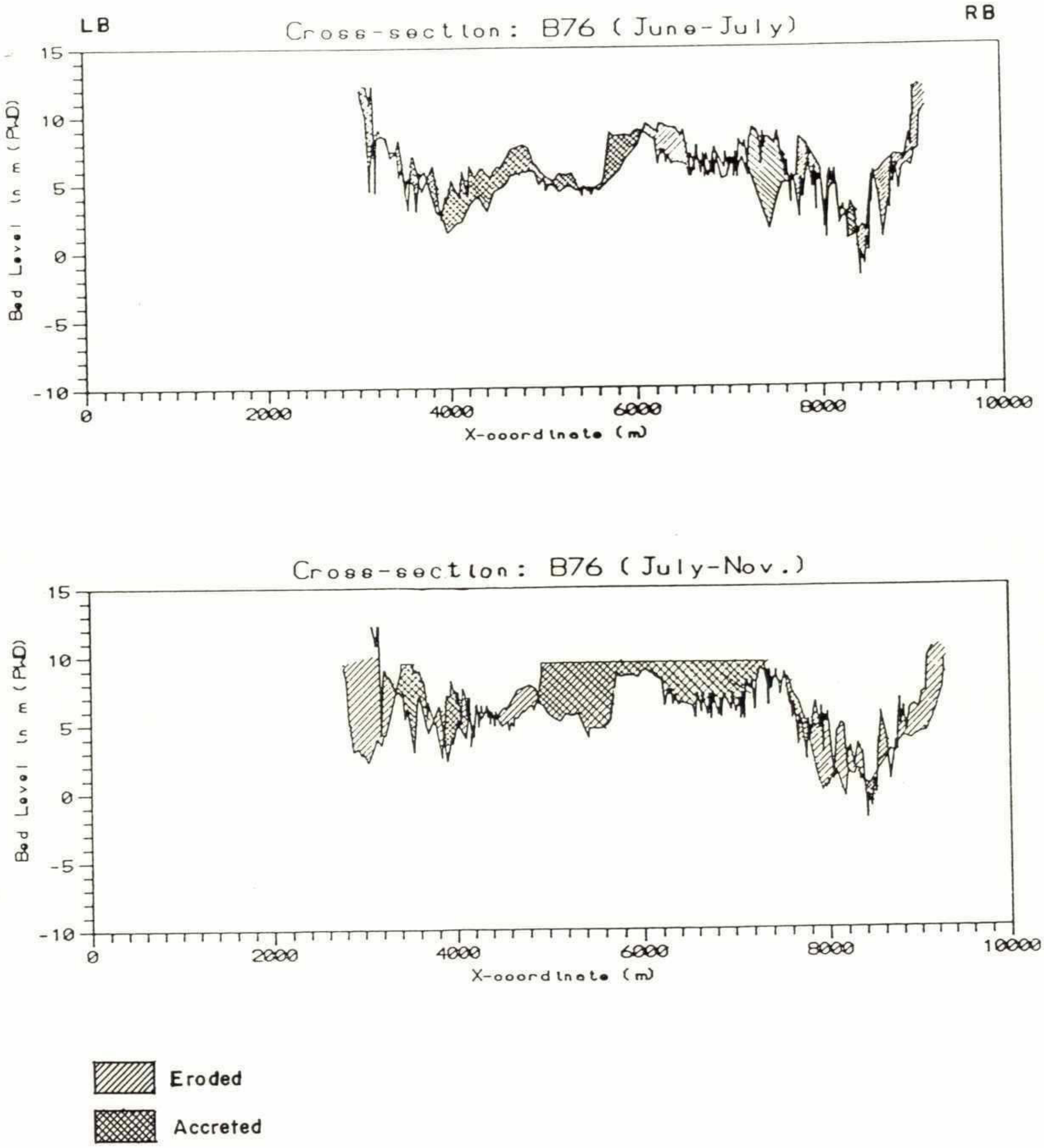
Halcrow/DHI/EPC/DIG *November 1992*	Annex 1 Figure 3.5a





Cross Sections Surveyed in June, July and November

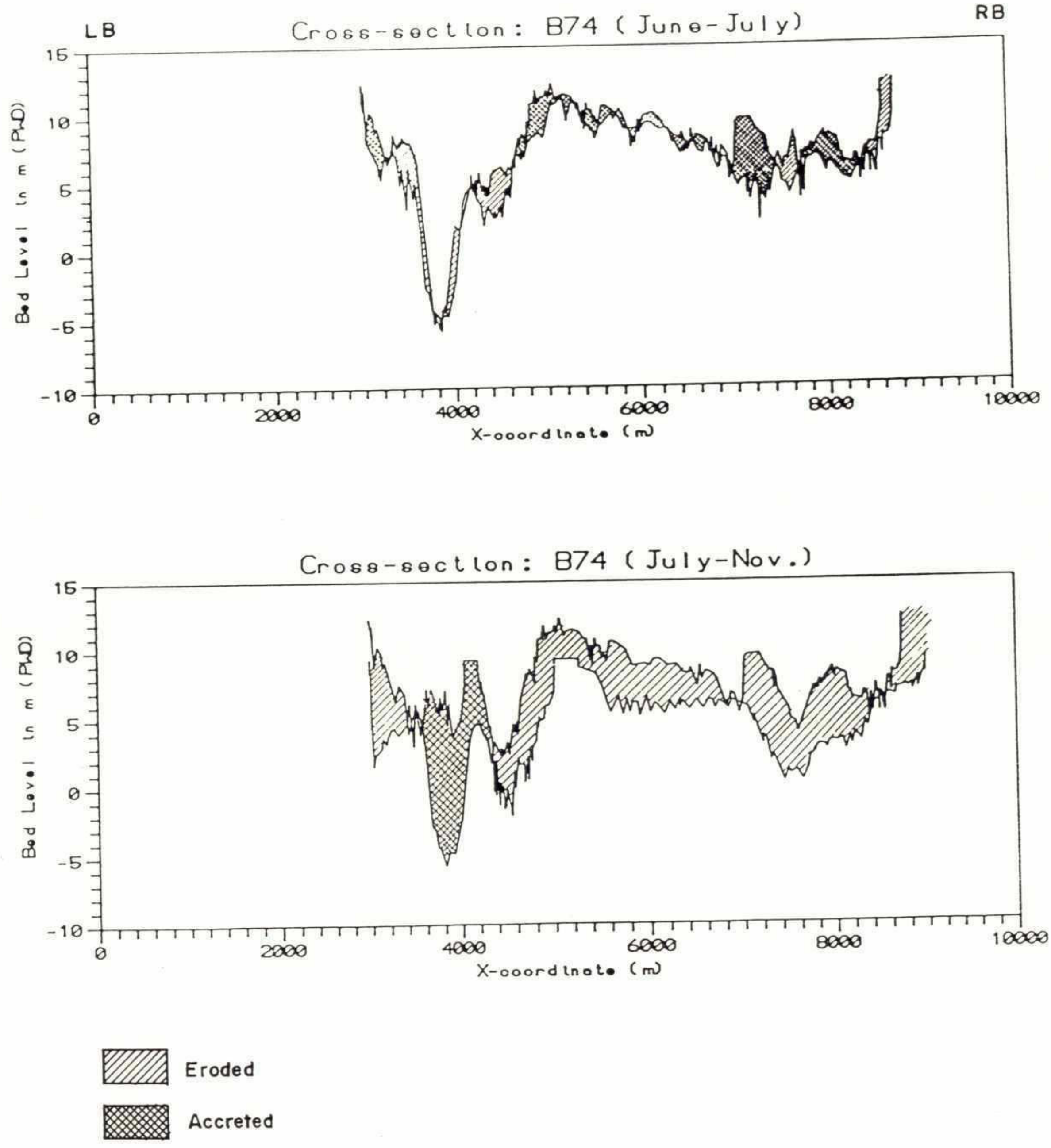
	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.5b



Cross Sections Surveyed in June, July and November

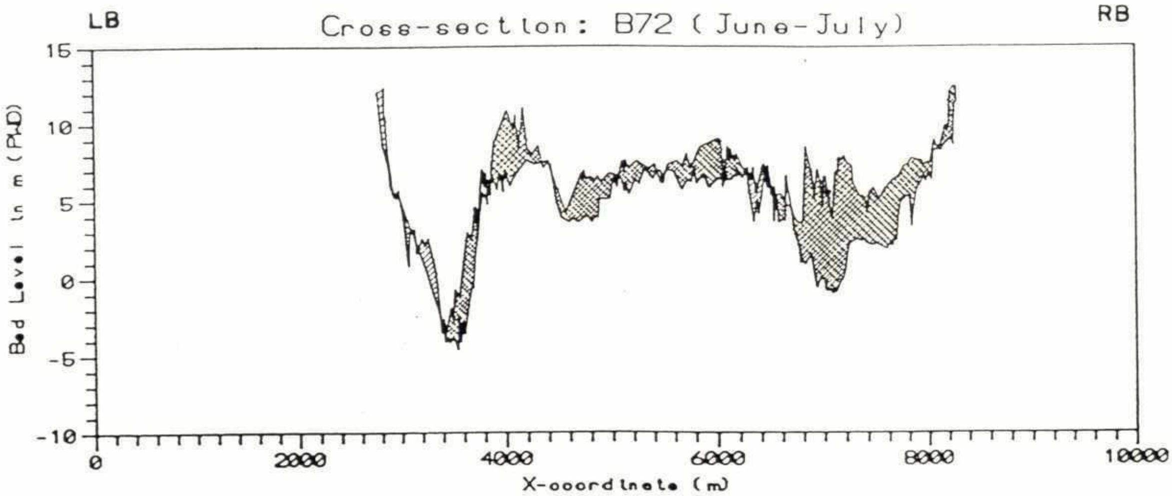
Annex 1

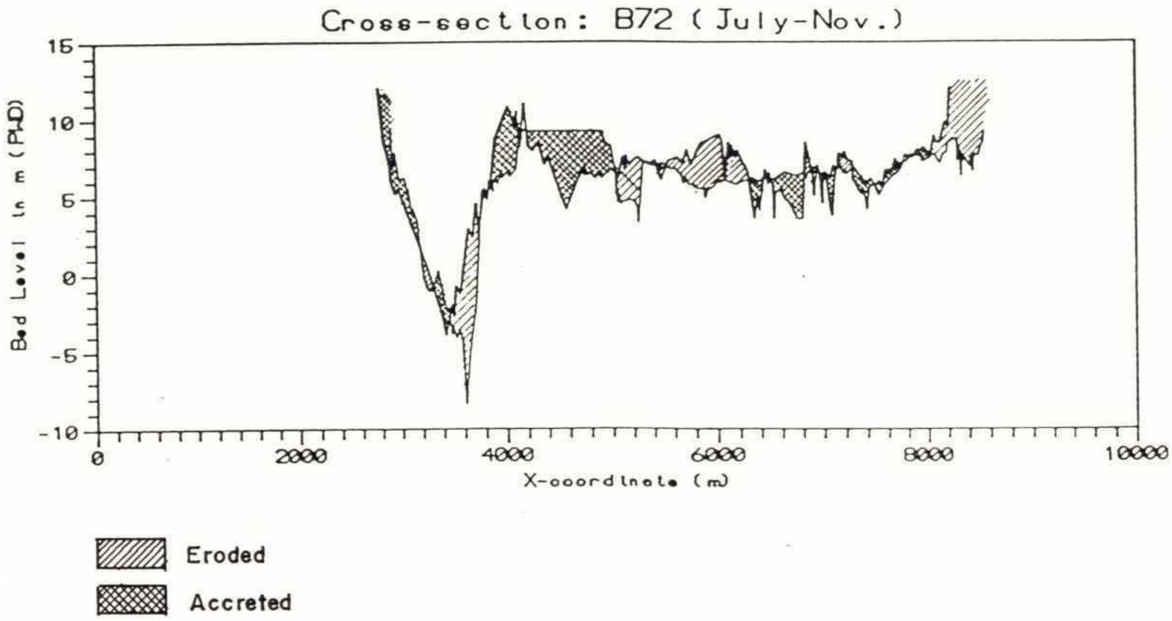
Halcrow/DHI/EPC/DIG *November 1992* **Figure 3.5c**



Cross Sections Surveyed in June, July and November

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.5d





Cross Sections Surveyed in June, July and November

		Annex 1
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 3.5e

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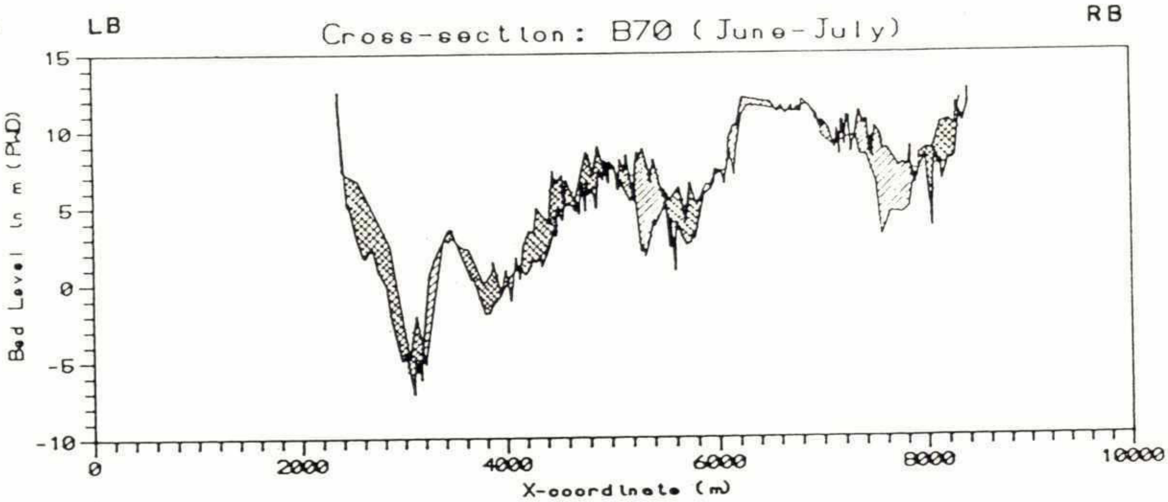
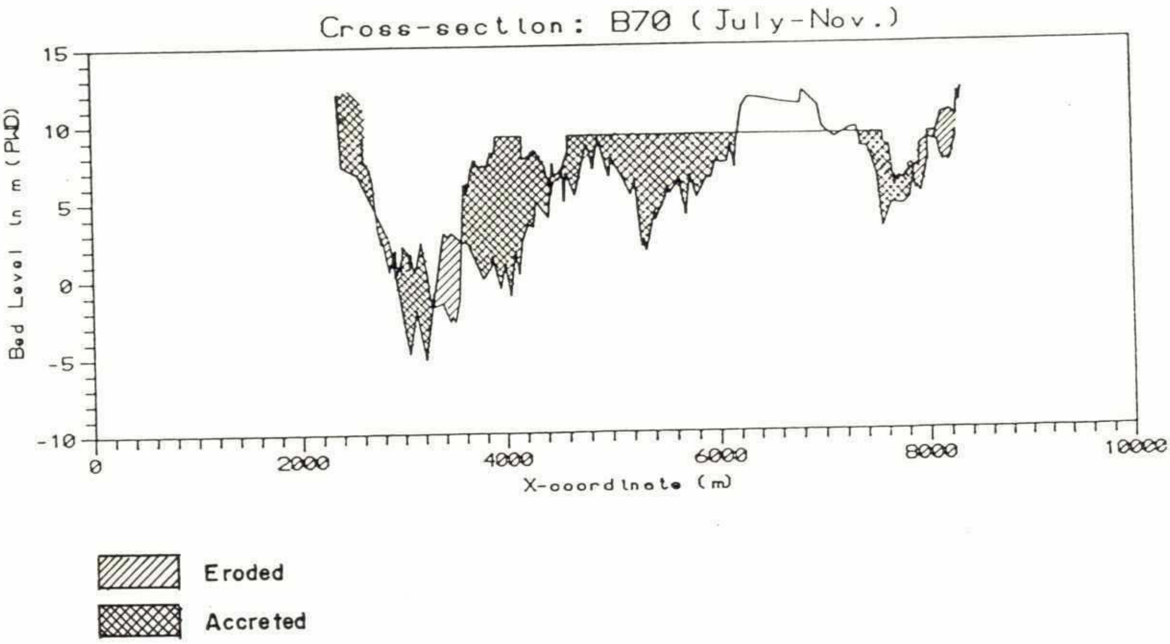
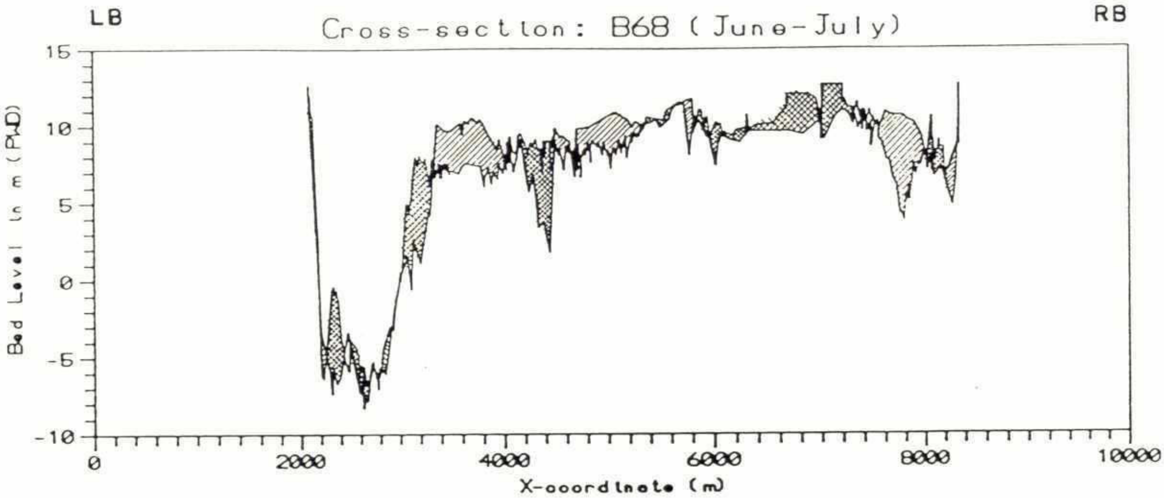
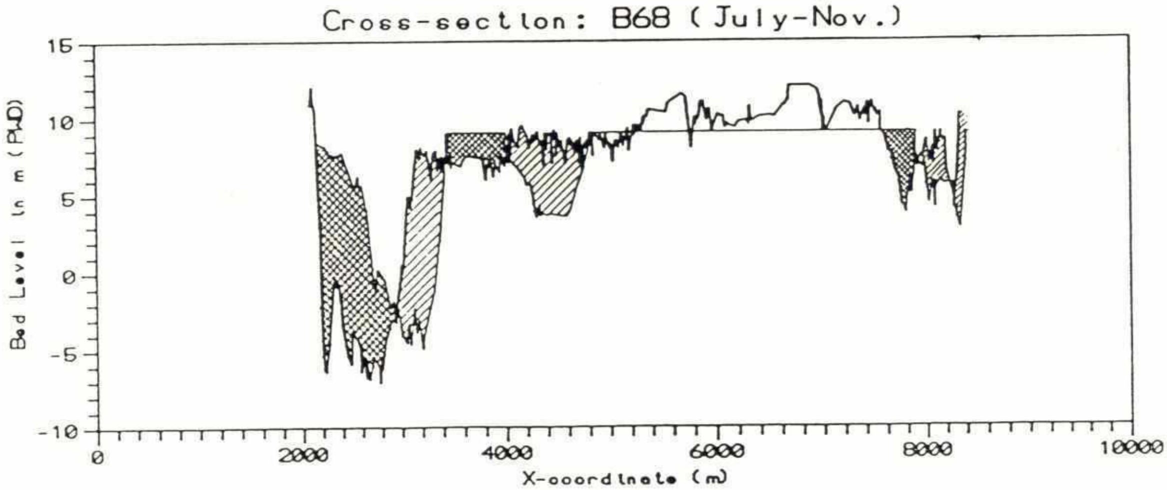




Cross Sections Surveyed in June, July and November





Eroded

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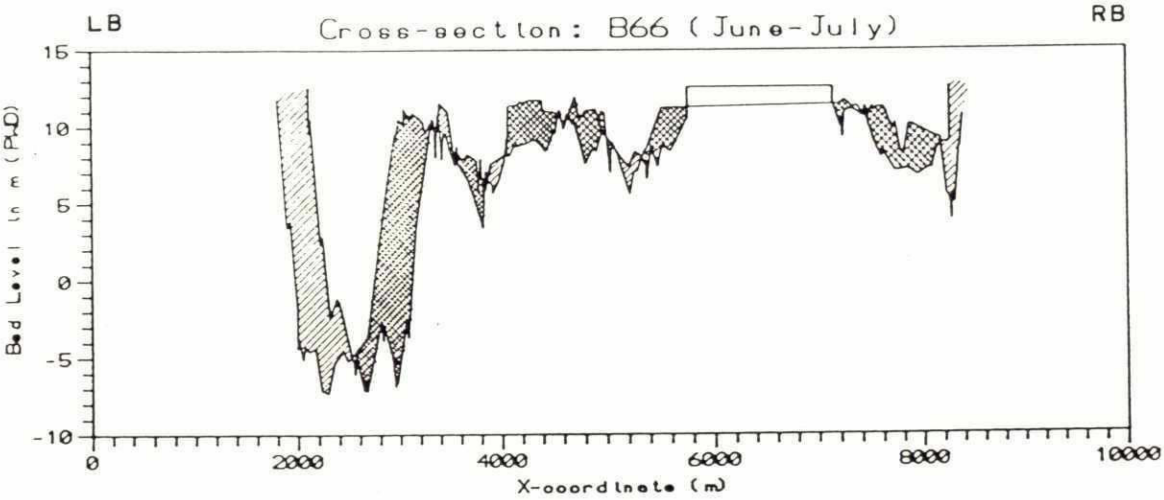
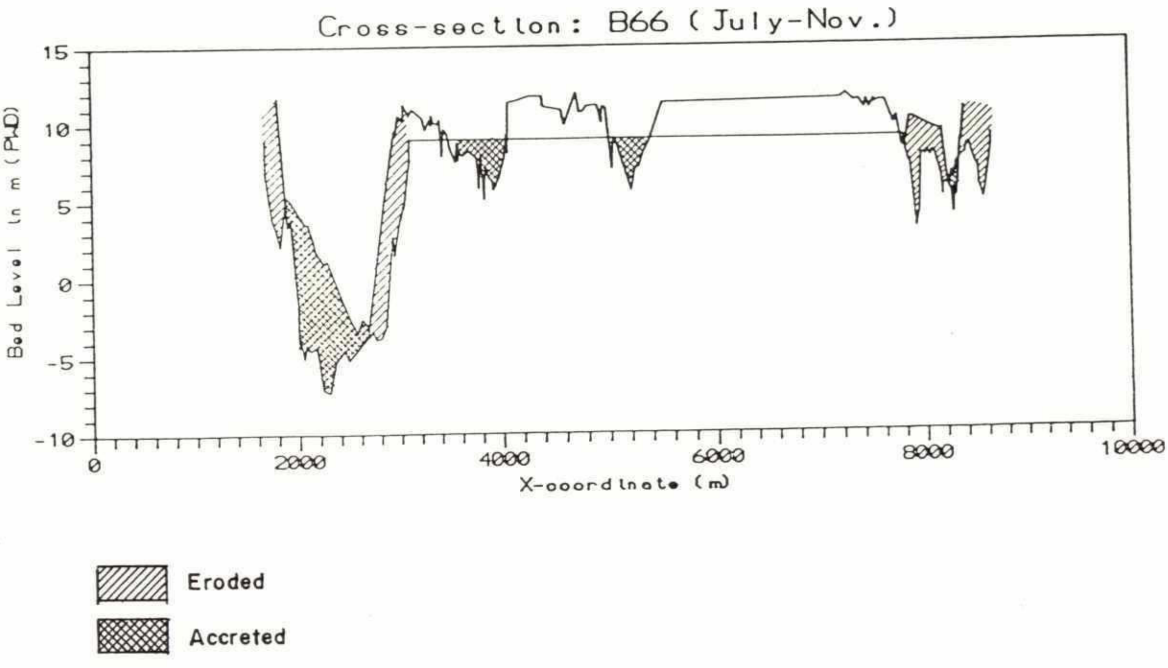
Cross Sections Surveyed in June, July and November

		Annex 1
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 3.5g





Cross Sections Surveyed in June, July and November

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.5h

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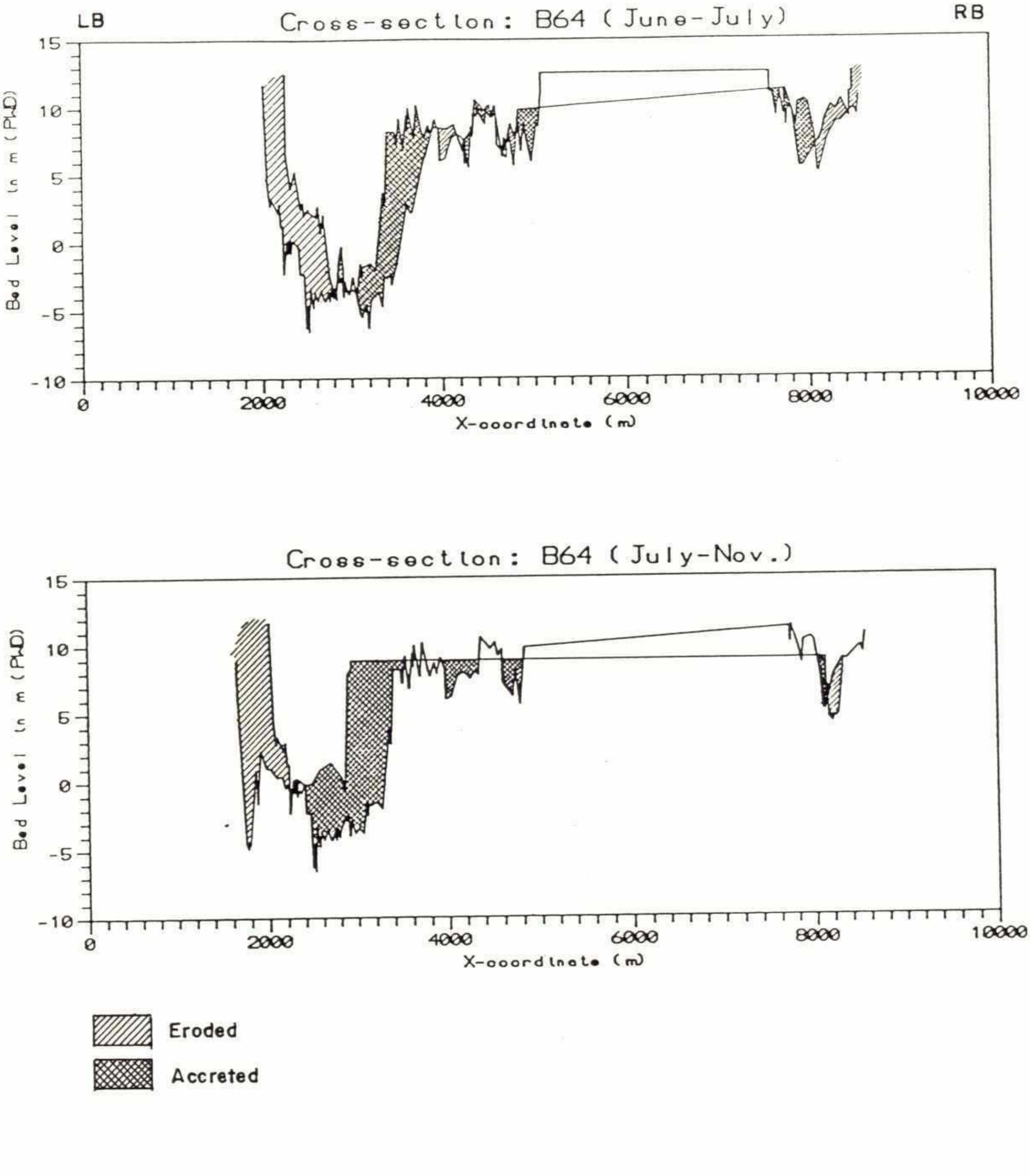
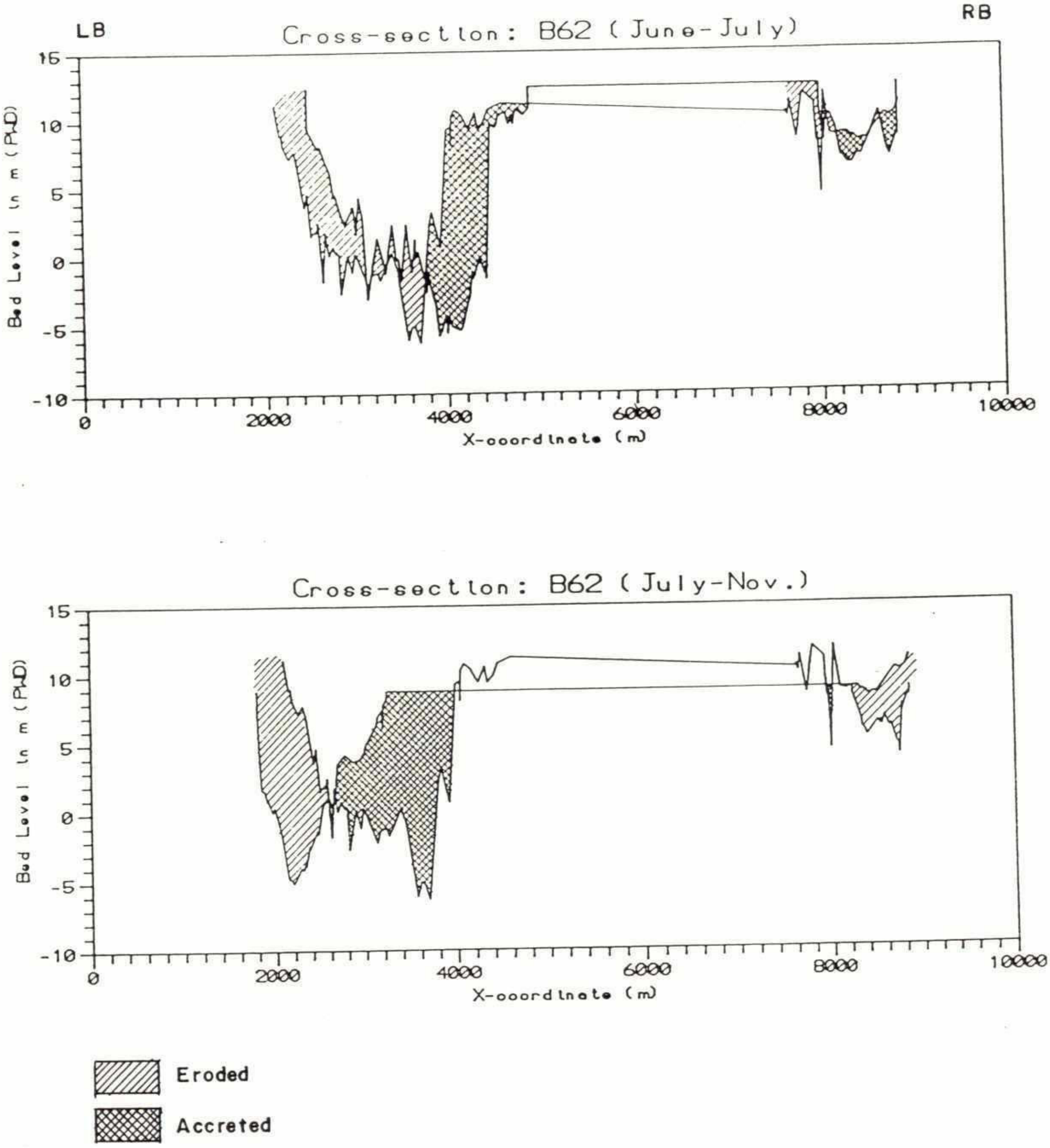
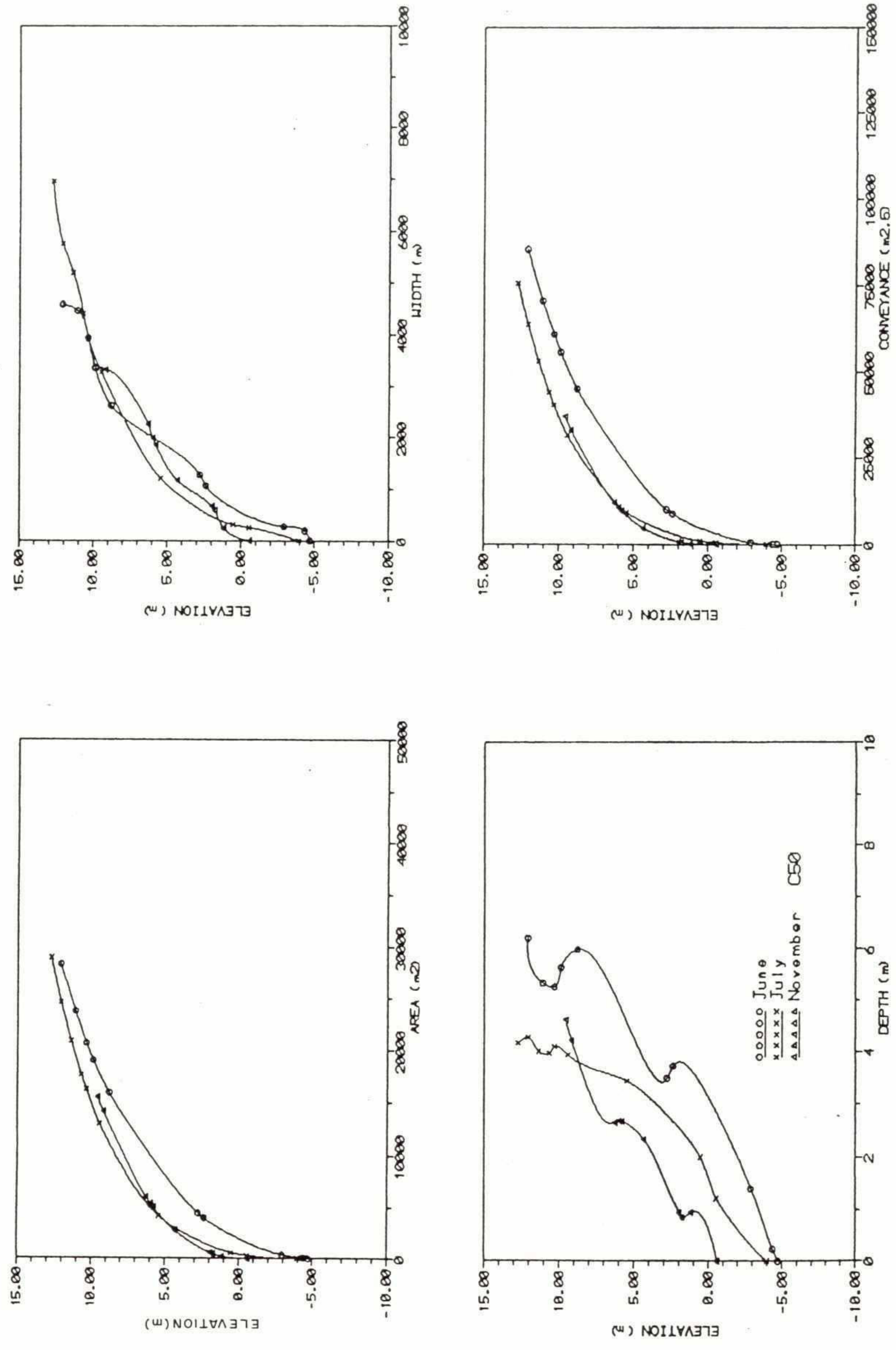


Cross Sections Surveyed in June, July and November

		Annex 1
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 3.5i

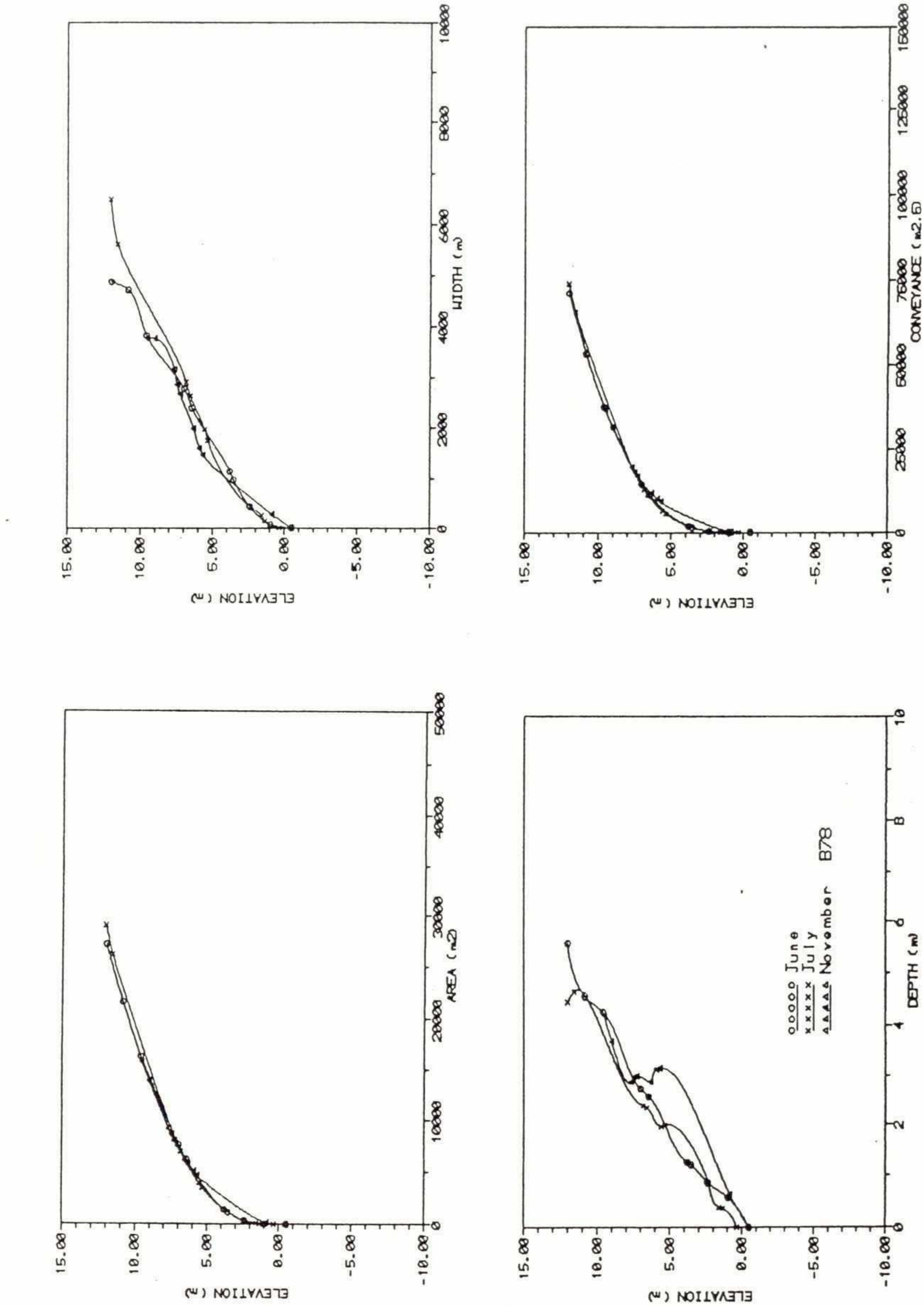


Cross Sections Surveyed in June, July and November



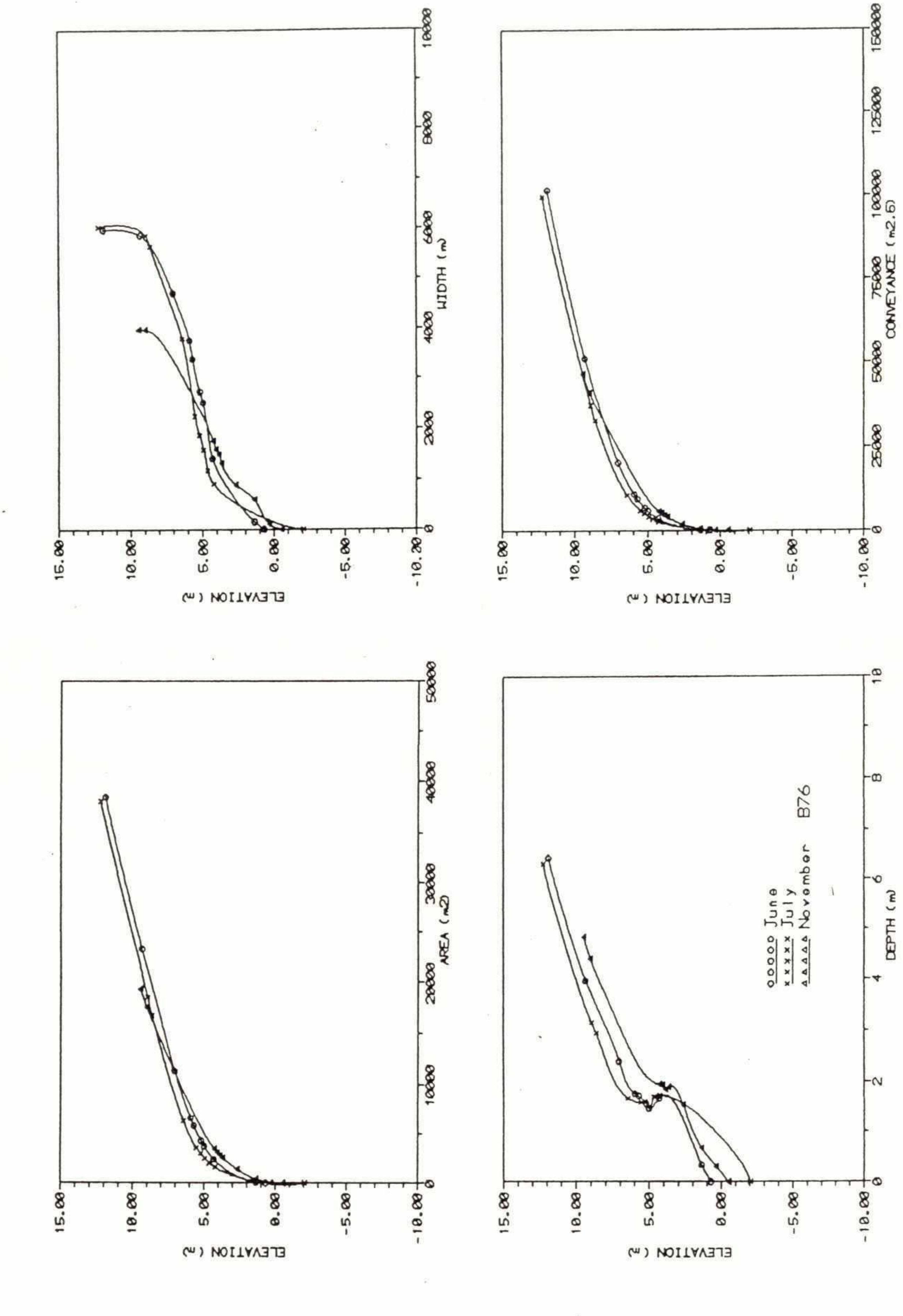
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.6a



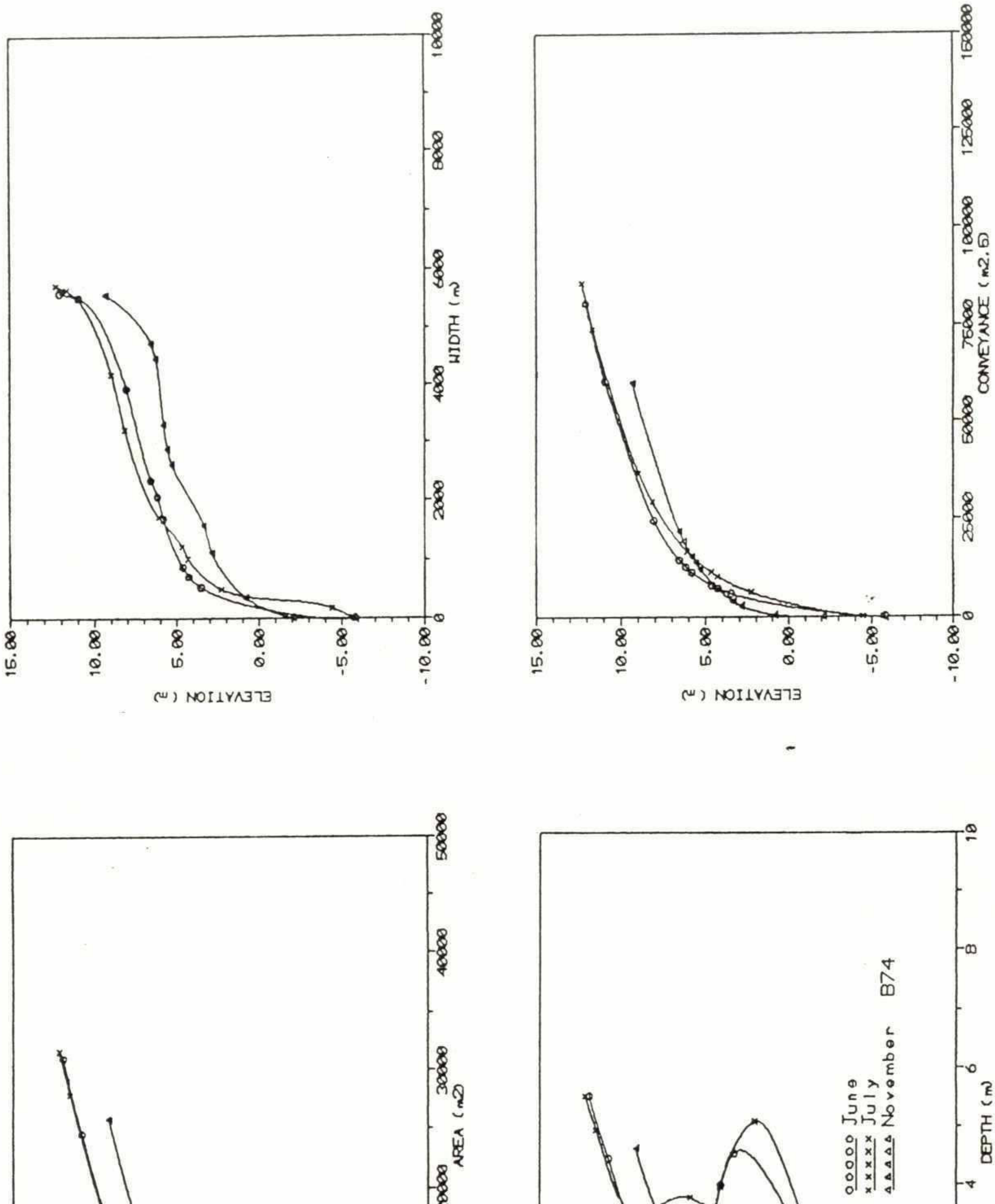
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.6b



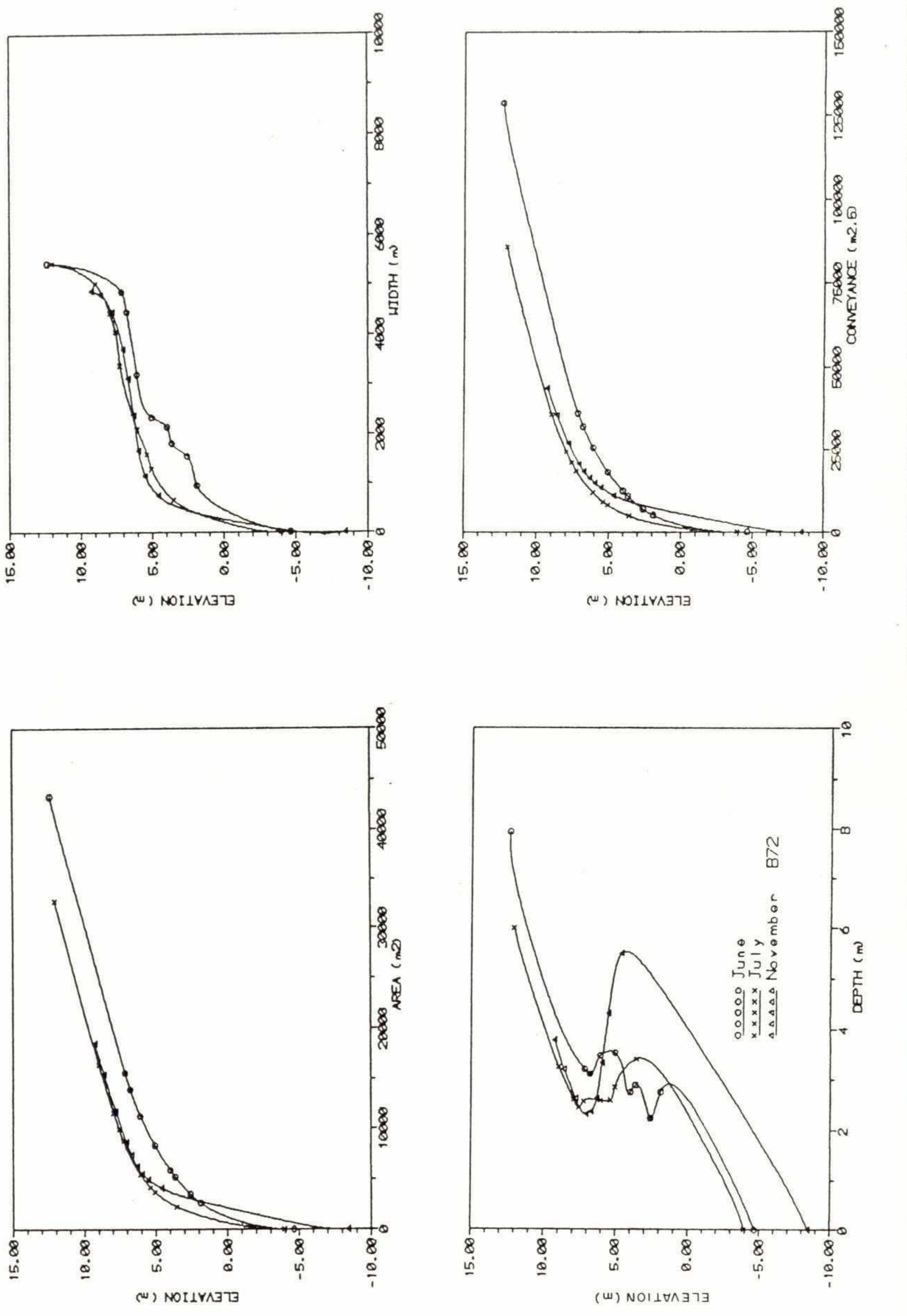
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.6c



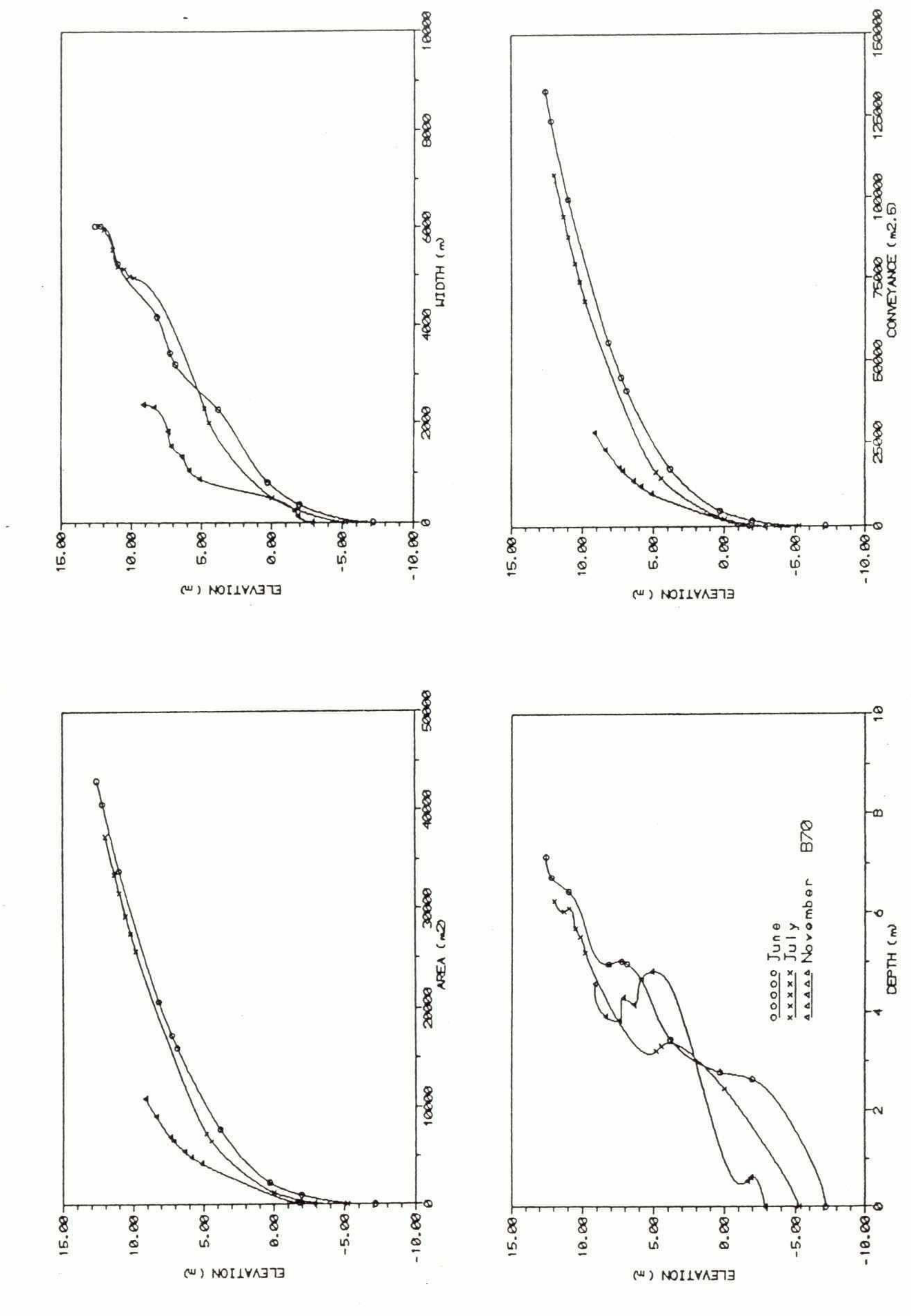
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.6d

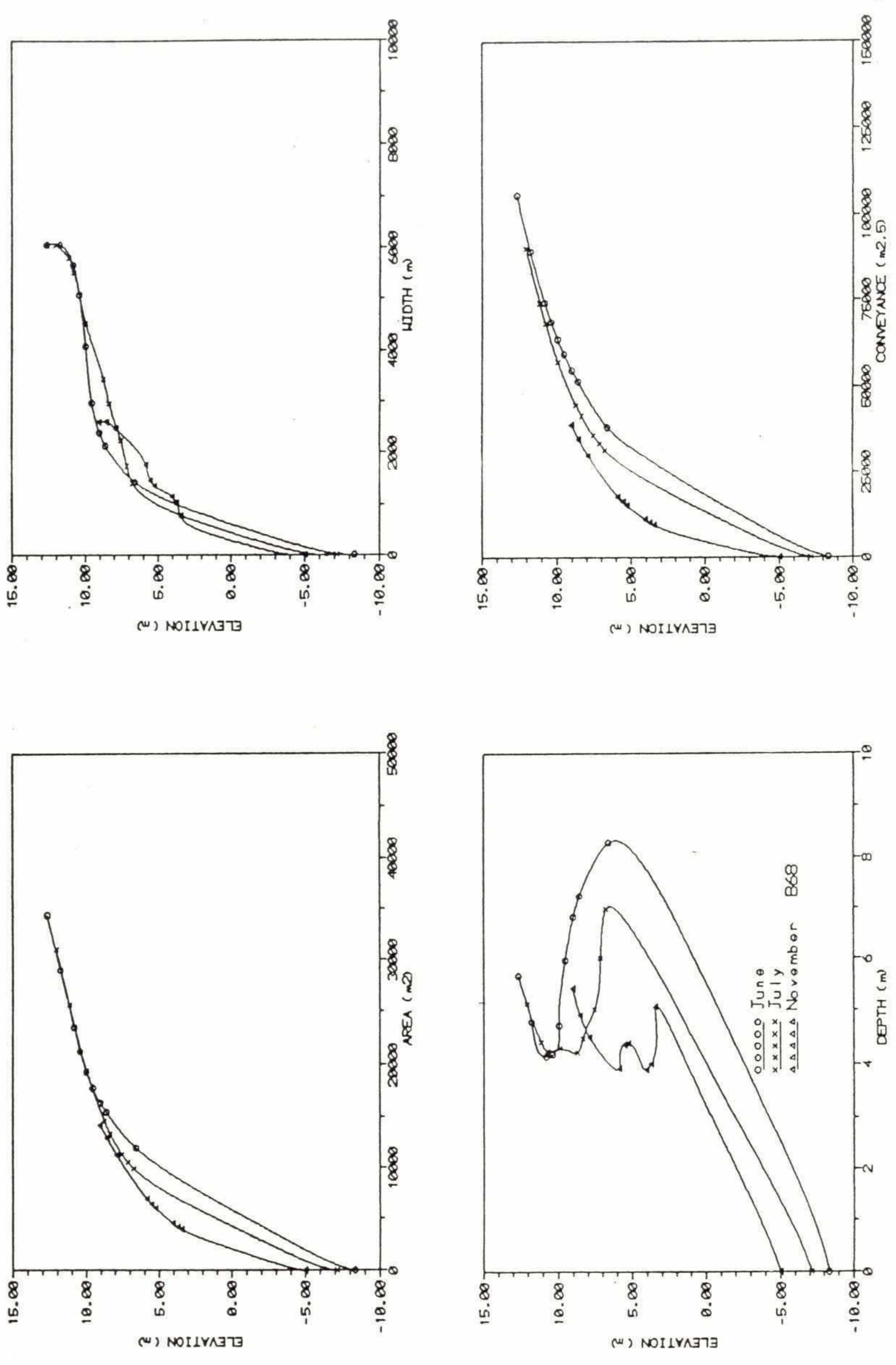


Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG ***November 1992***	**Figure 3.6e**

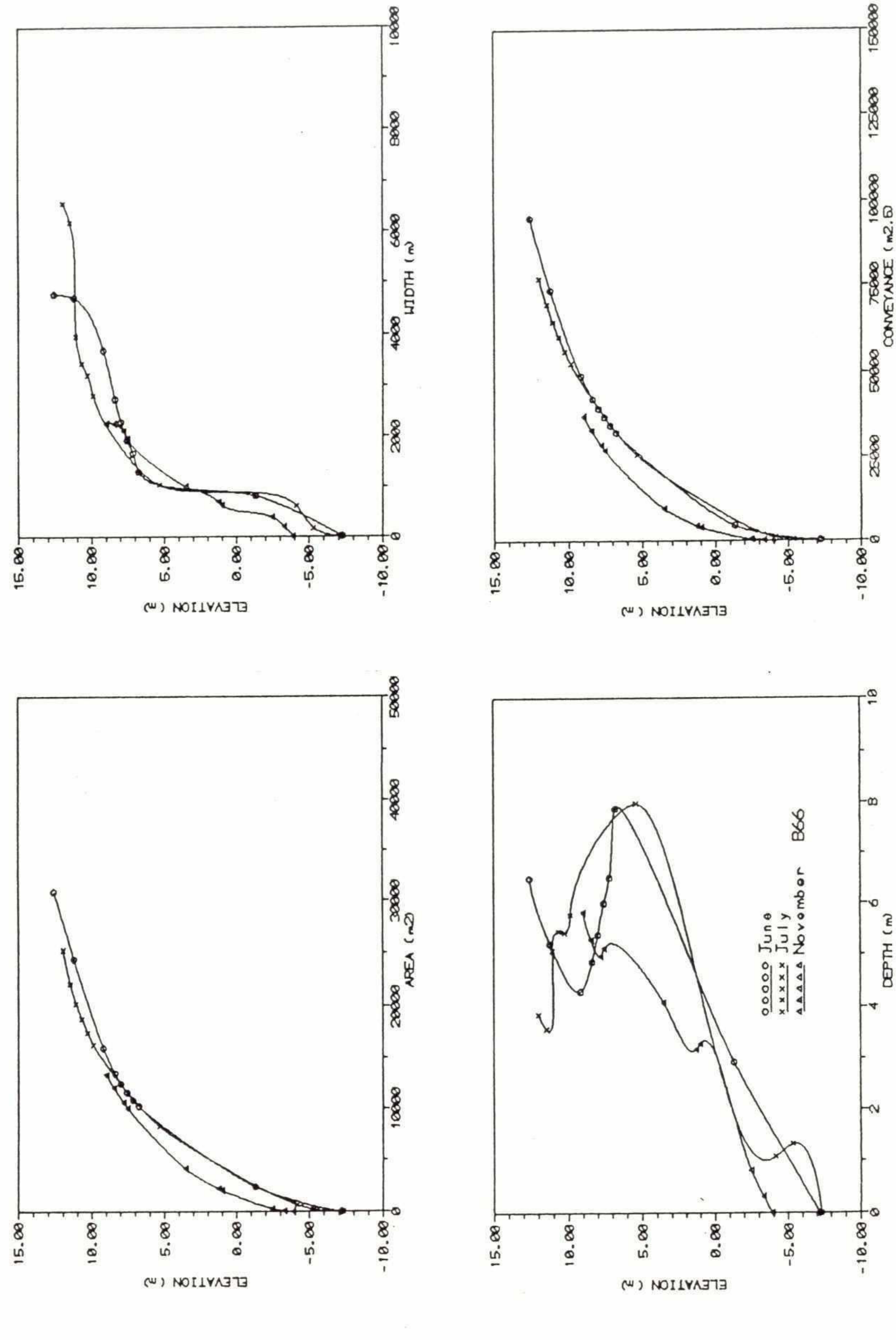


Variation of Area, width, Depth and Conveyance with Elevation



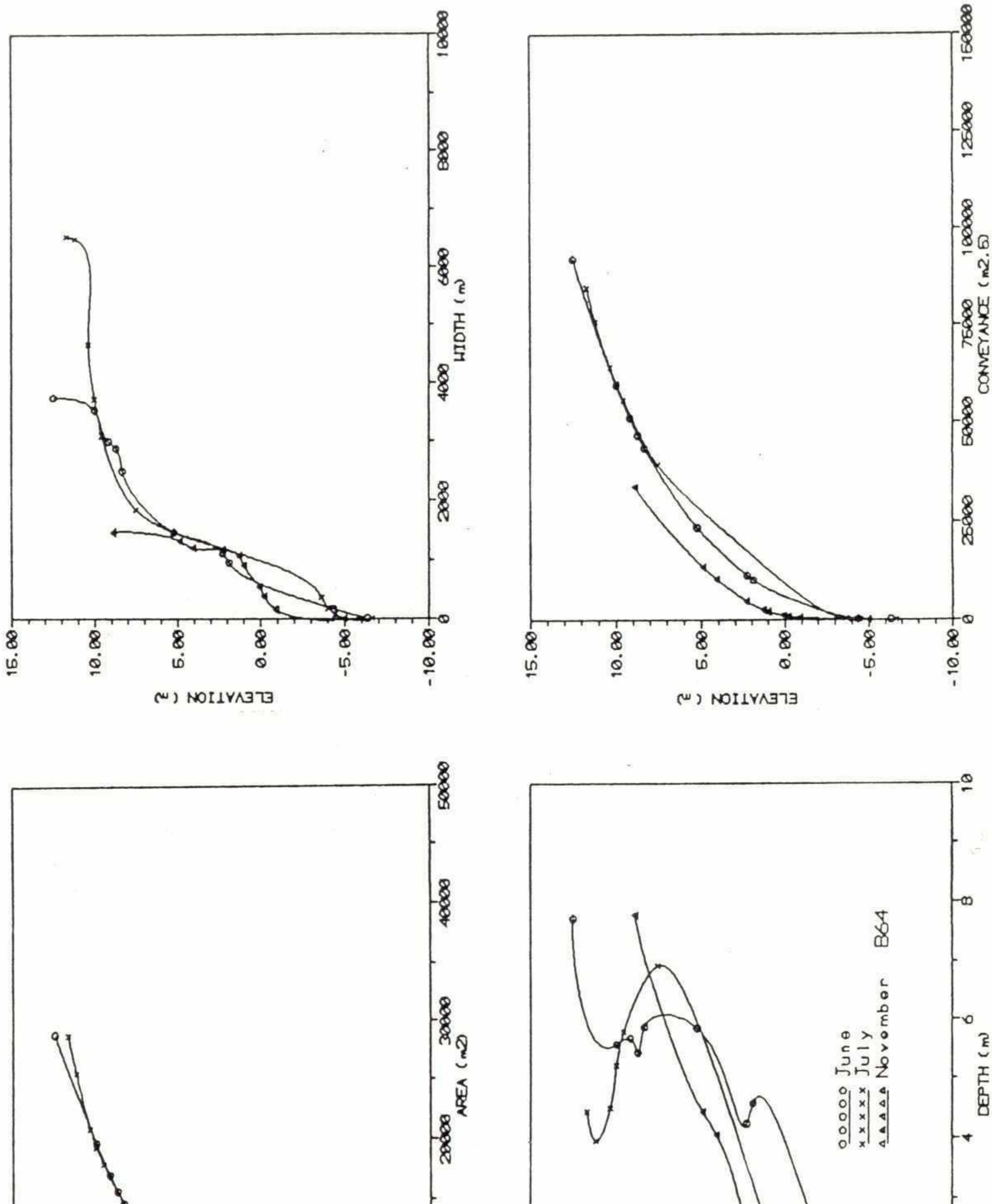
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.6g



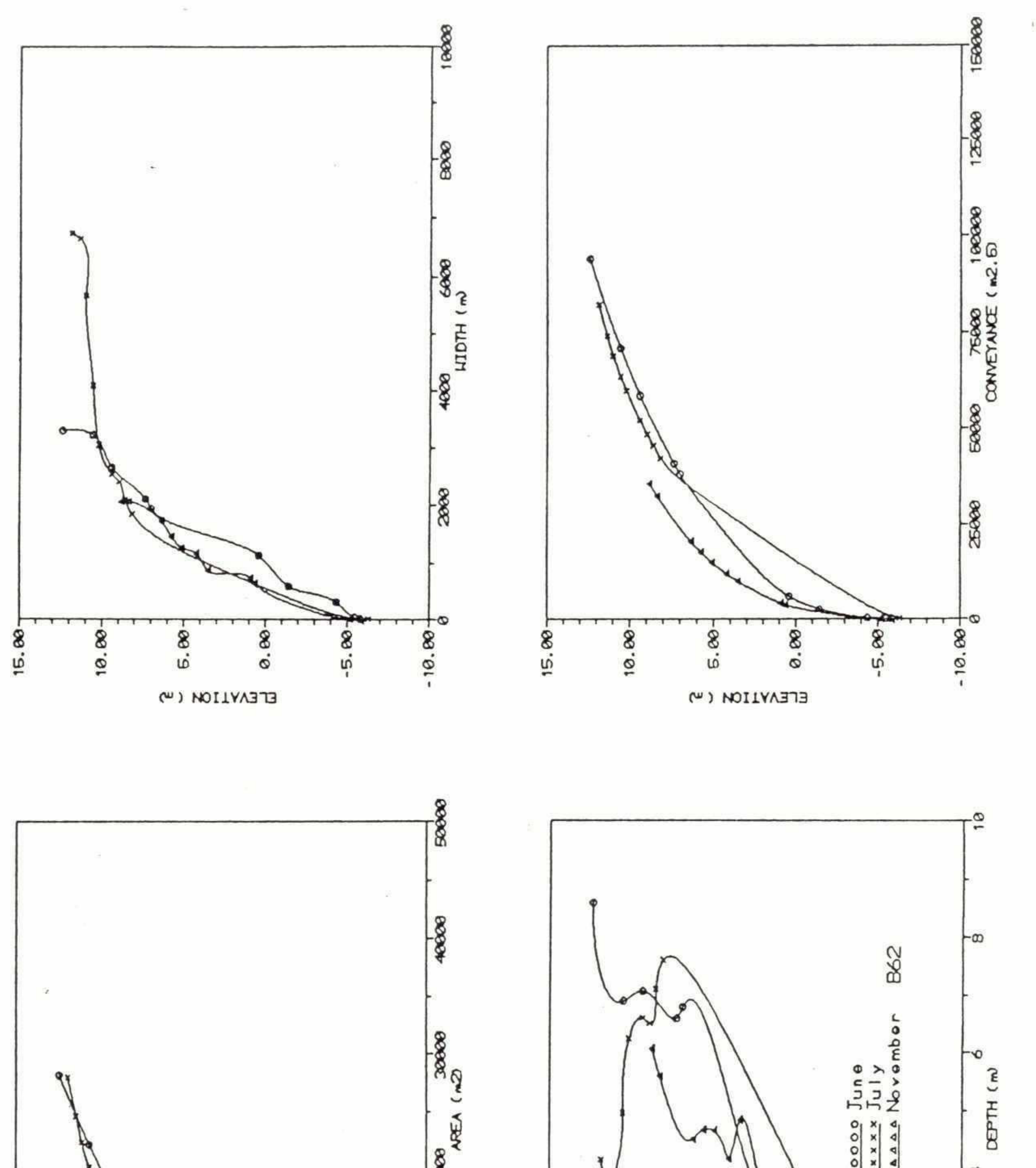
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG ***November 1992***	**Figure 3.6h**



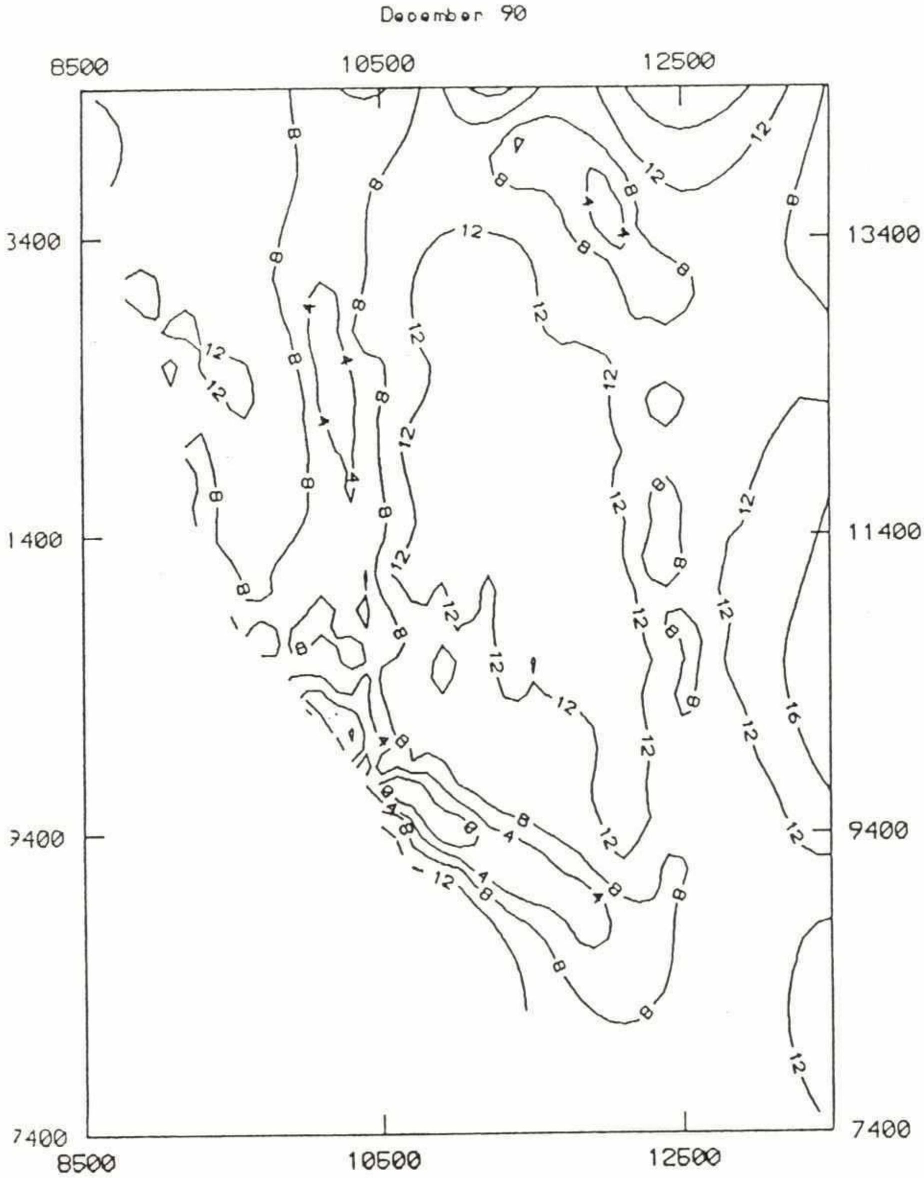
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.6i



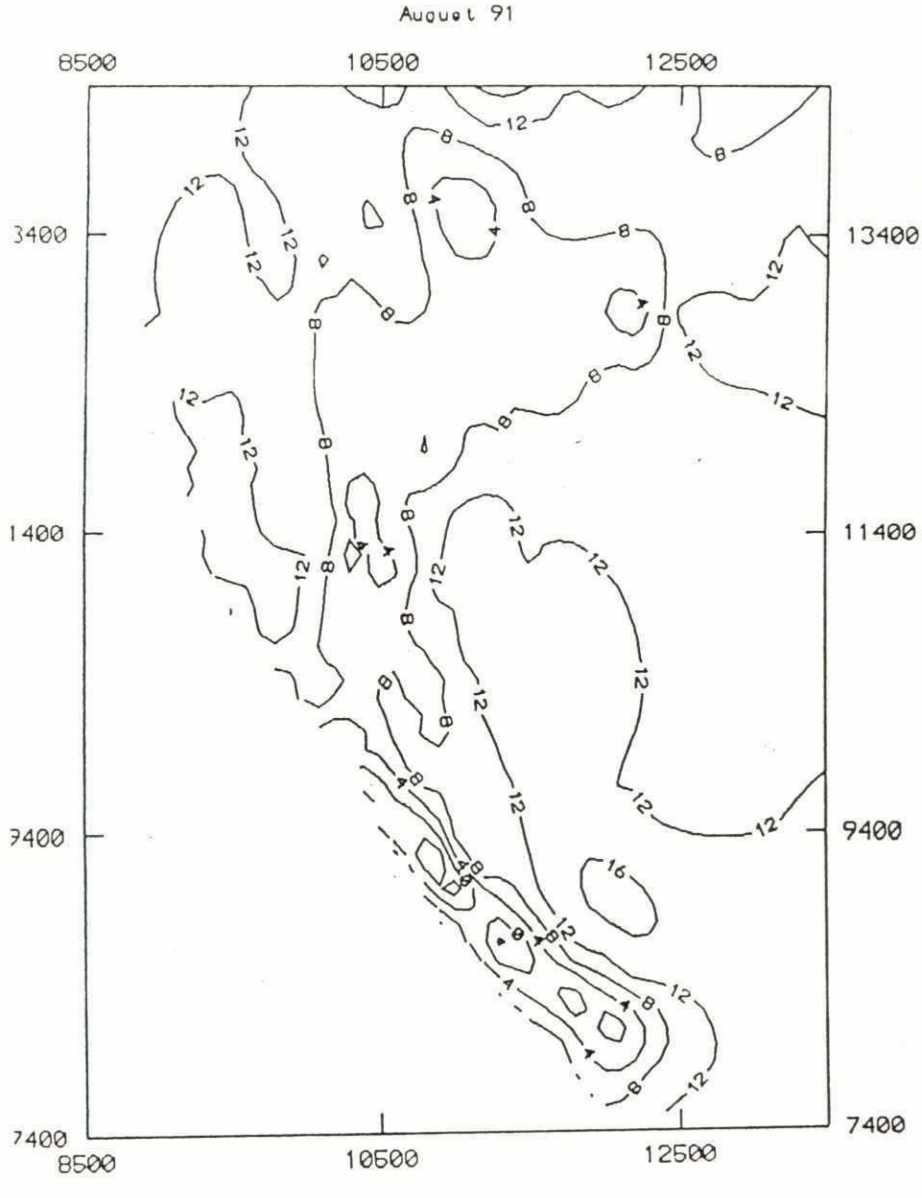
Variation of Area, width, Depth and Conveyance with Elevation

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	**Figure 3.6j**

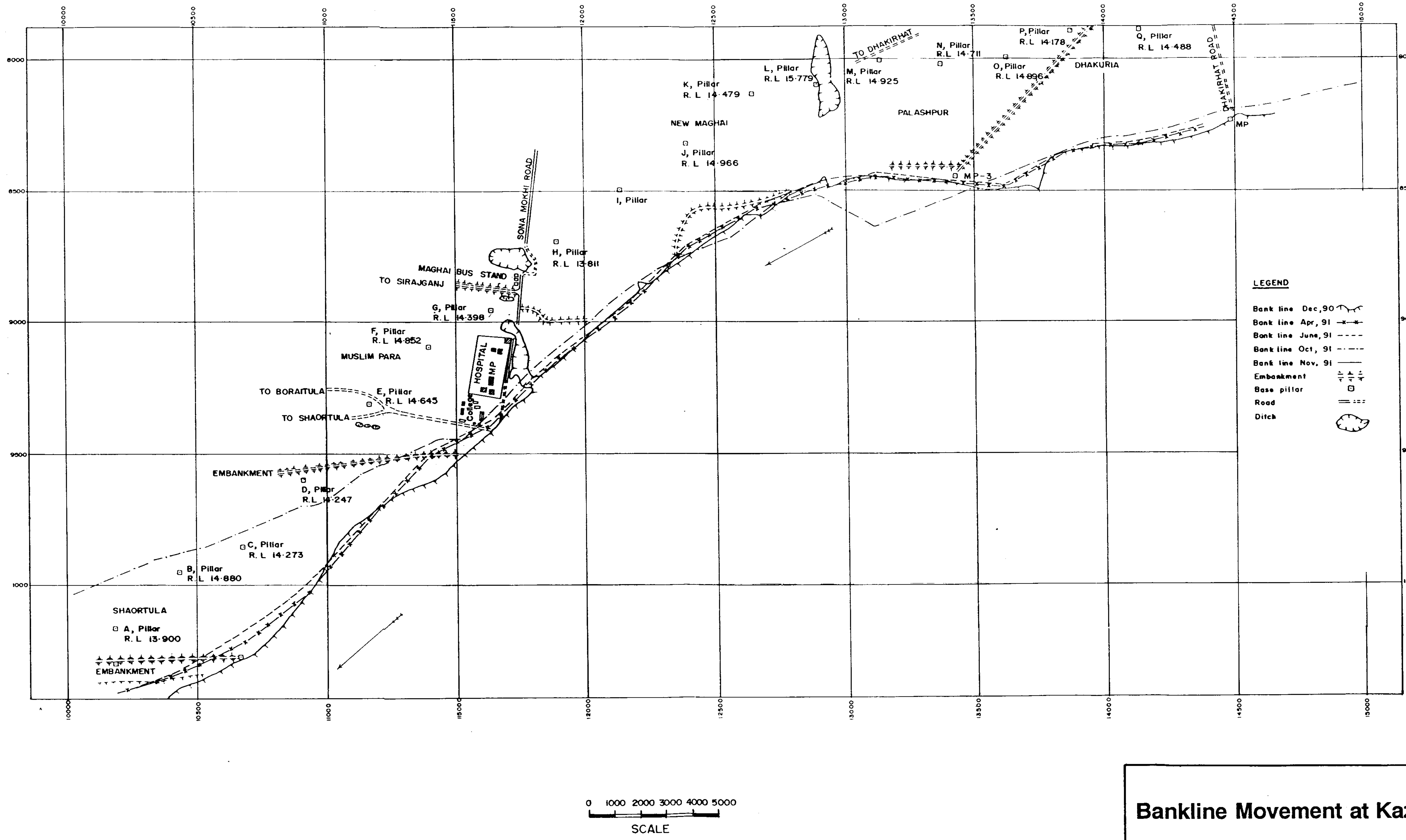


Contour Map of Bathymetry Surveyed in Test Area 2 in December 1990

Halcrow/DHI/EPC/DIG	November 1992	Annex 1
		Figure 3.7

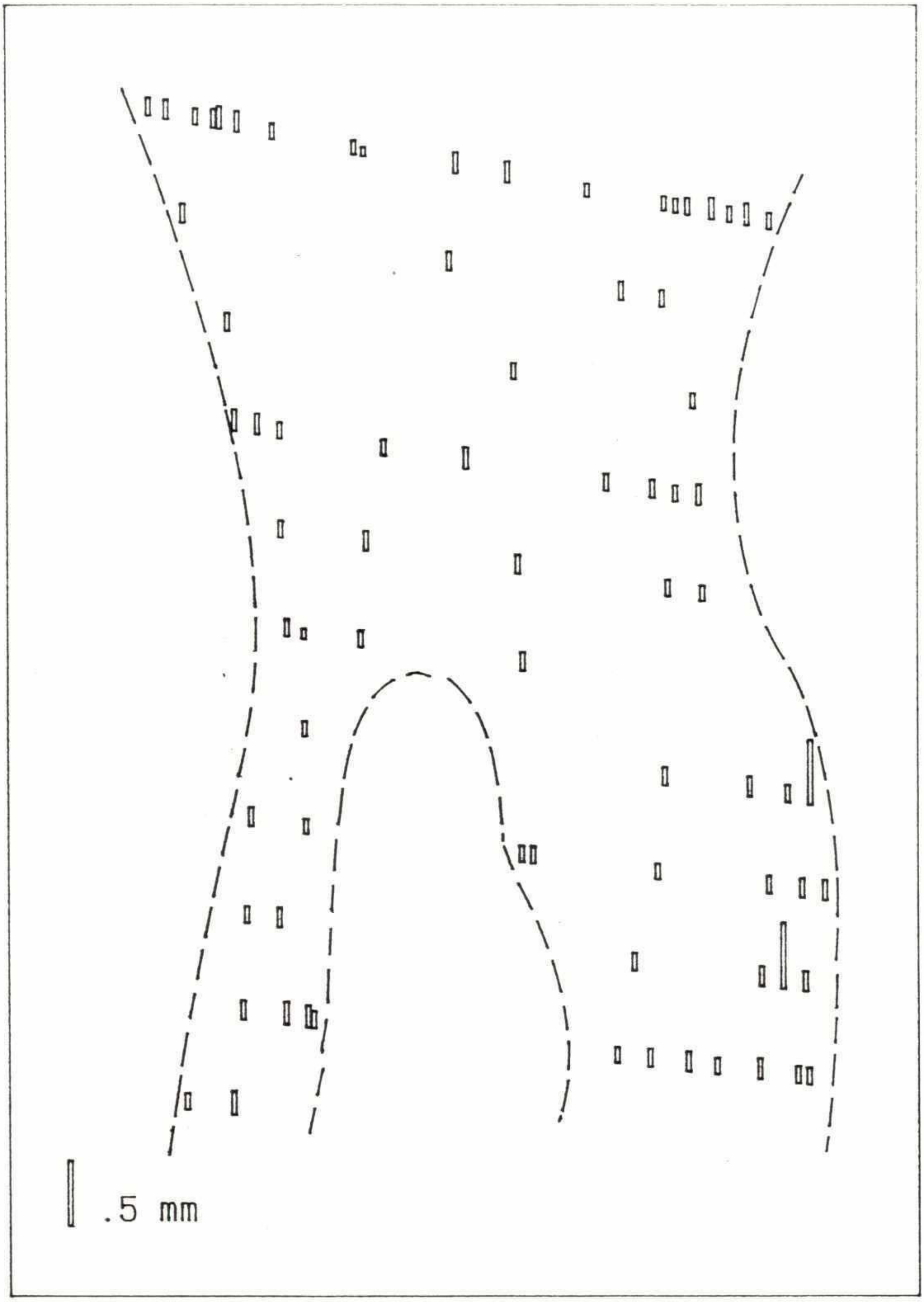


Contour Map of Bathymetry Surveyed in Test Area 2 in August 1991



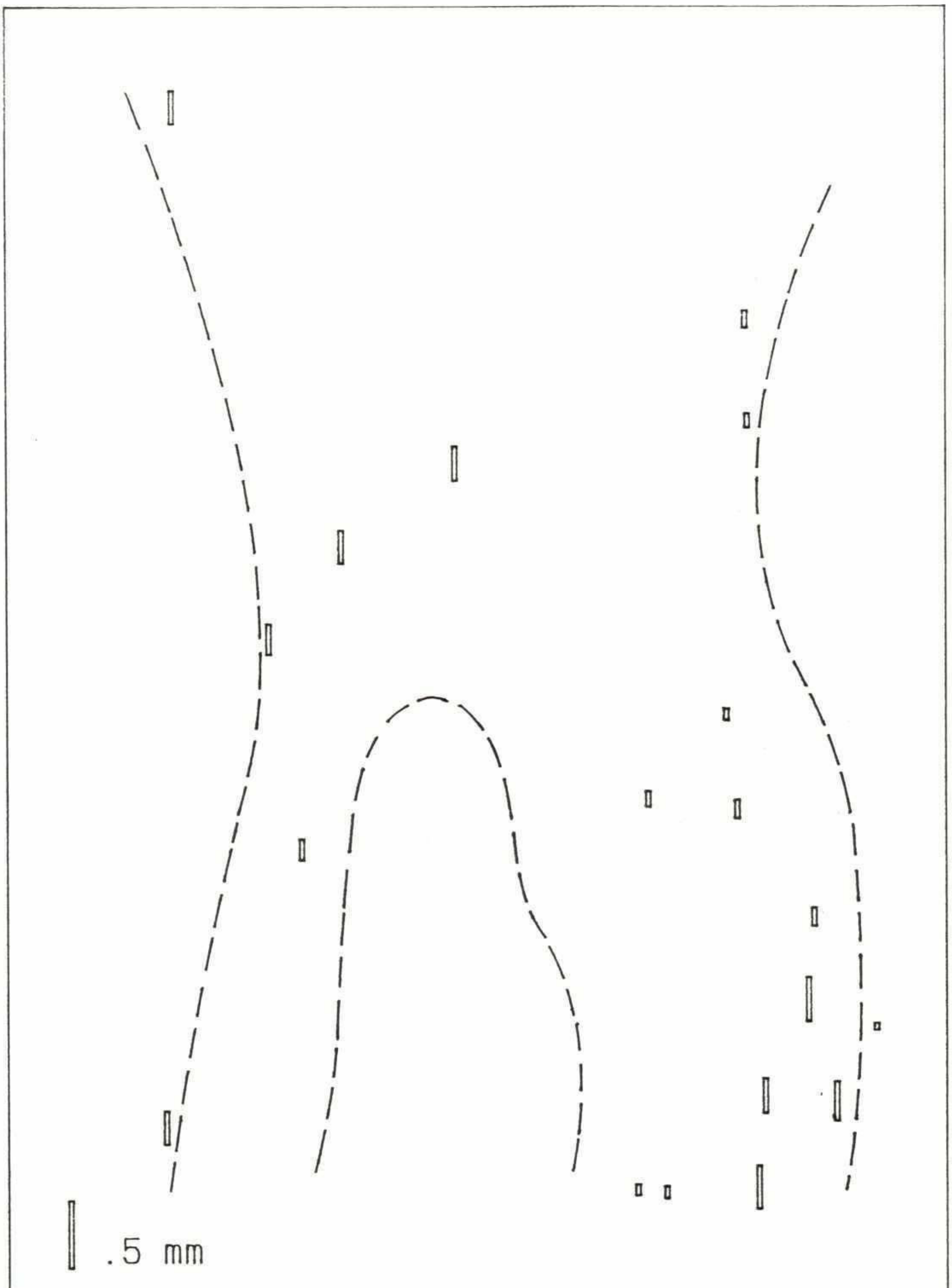
Bankline Movement at Kazipur

Halcrow/DHI/EPC/DIG	Annex 1
November 1992	Figure 3.9



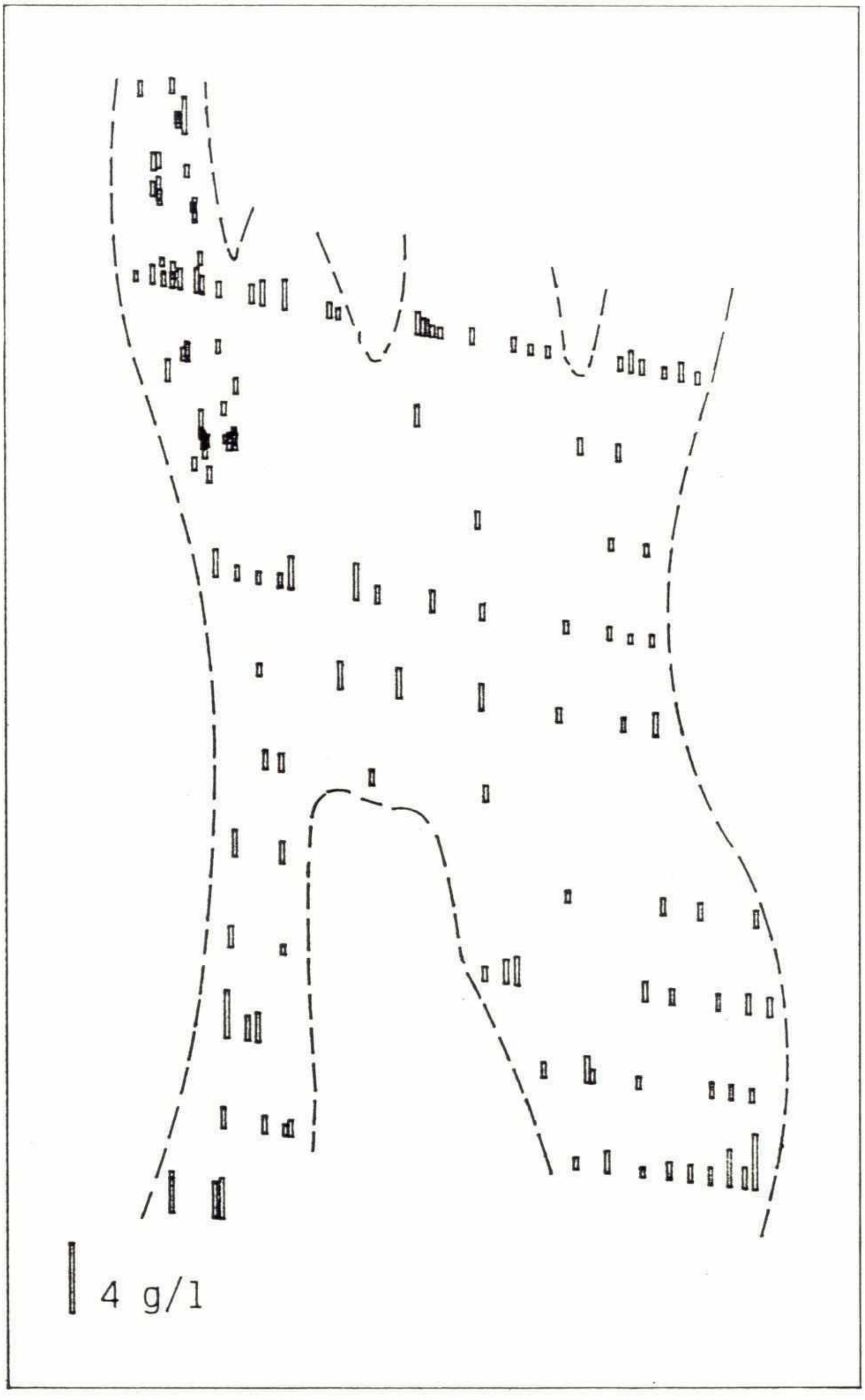
Spatial Variation of d_{50} (July Survey)

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 4.1



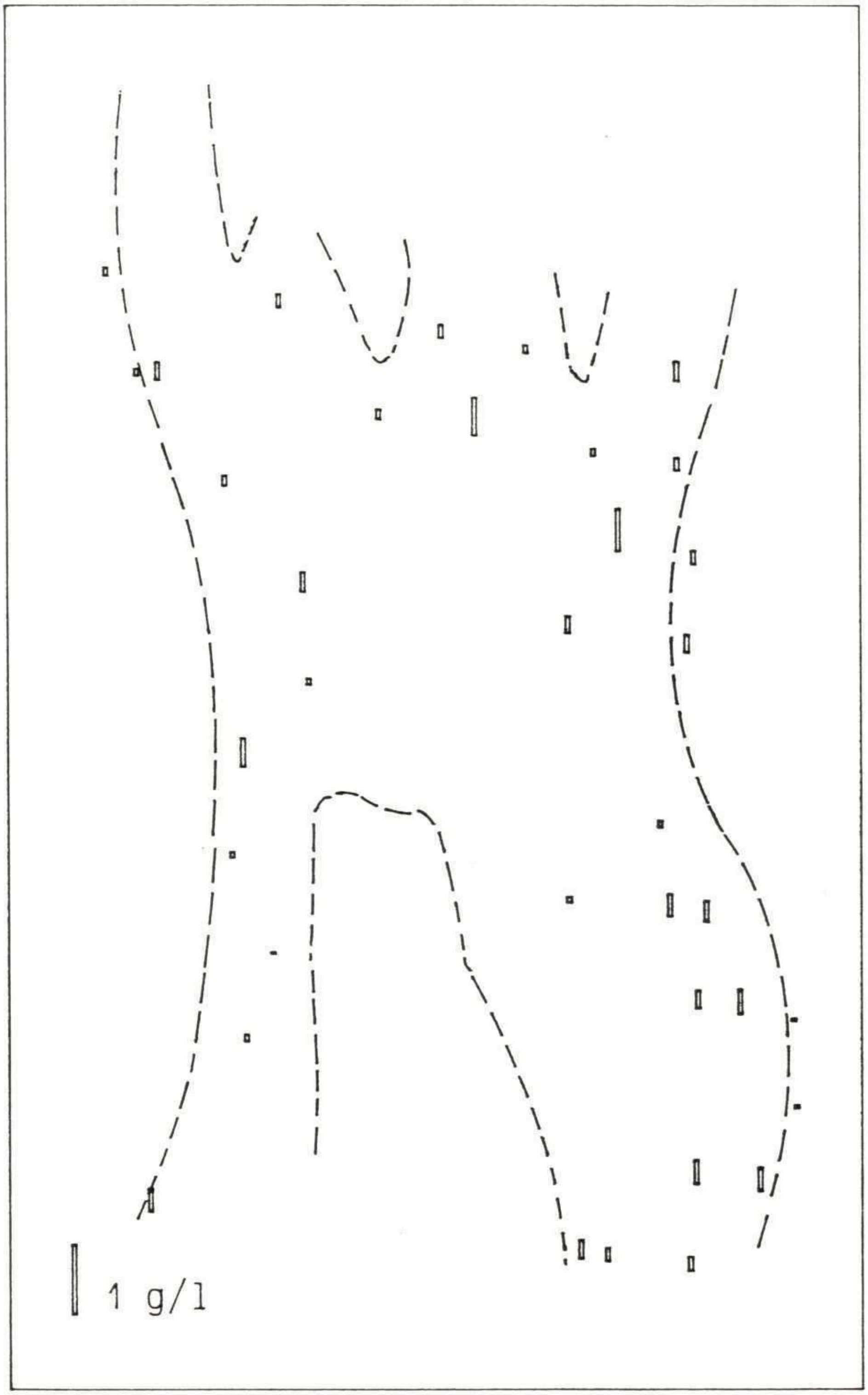
Spatial Variation of d_{50} (November Survey)

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 4.2



Spatial Variation of Mean Concentration (July Survey)

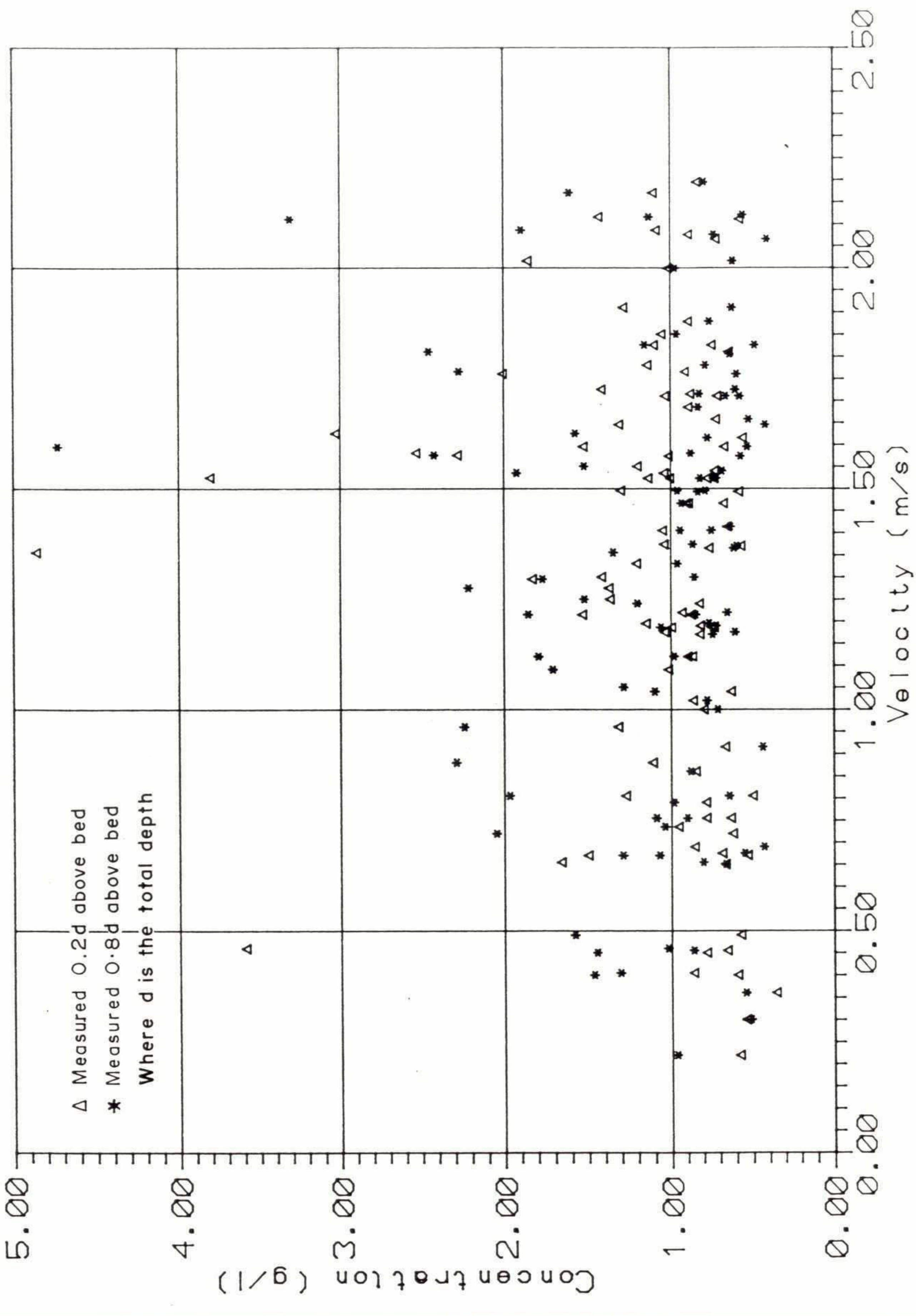
	Annex 1
Halcrow/DHI/EPC/DIG November 1992	Figure 5.1



Spatial Variation of Mean Concentration (November Survey)

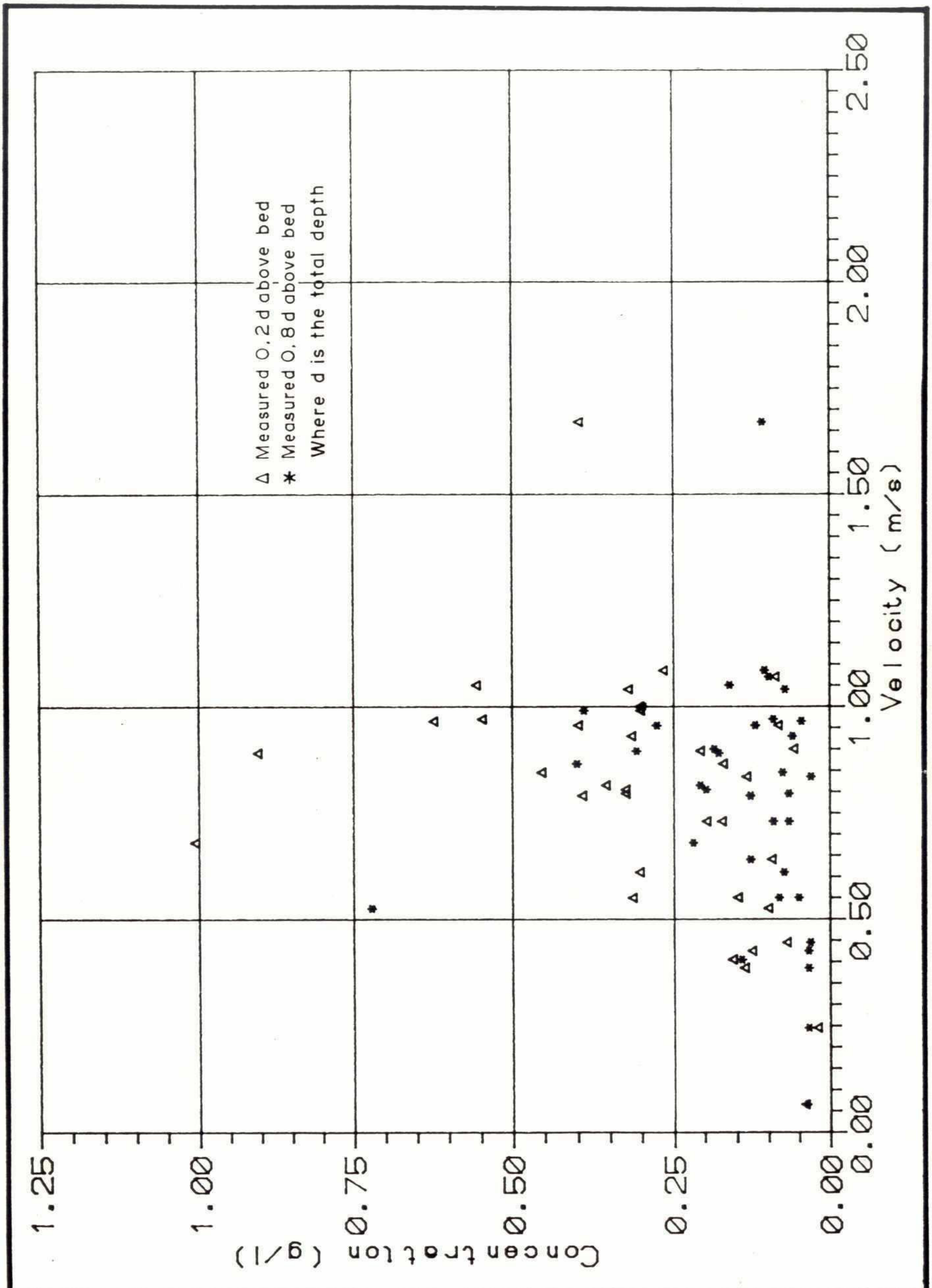
Annex 1
Figure 5.2

Halcrow/DHI/EPC/DIG *November 1992*



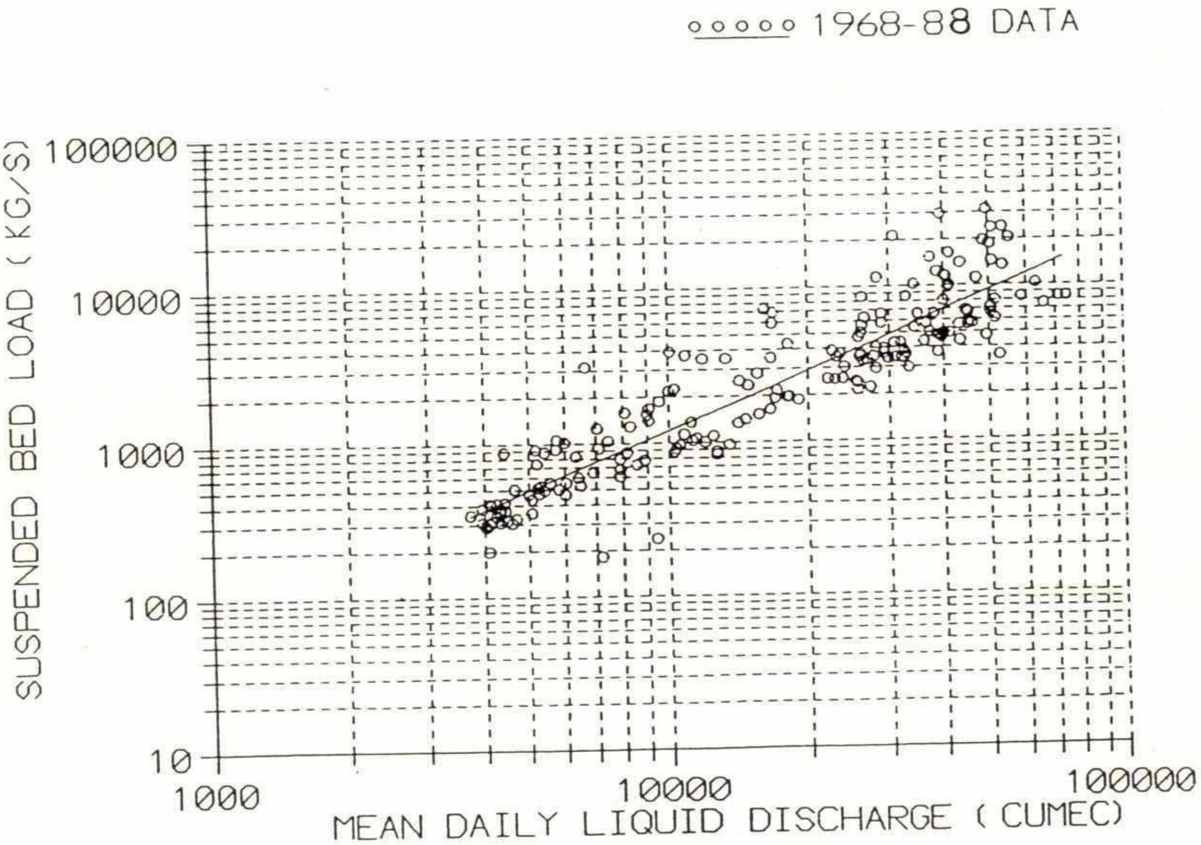
Variation in Measured Concentration with Flow Velocity (July)

Halcrow/DHI/EPC/DIG	November 1992	Annex 1 Figure 5.3



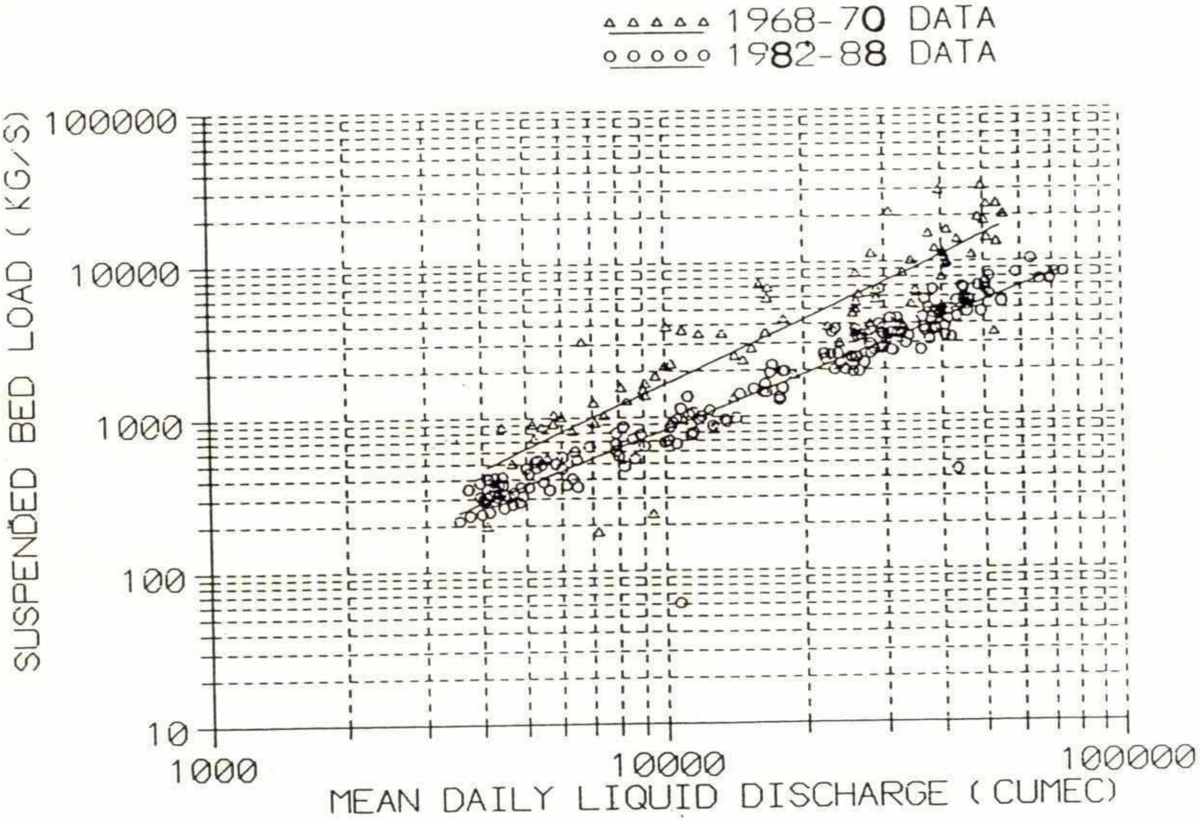
Variation in Measured Concentration with Flow Velocity (November)

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 5.4



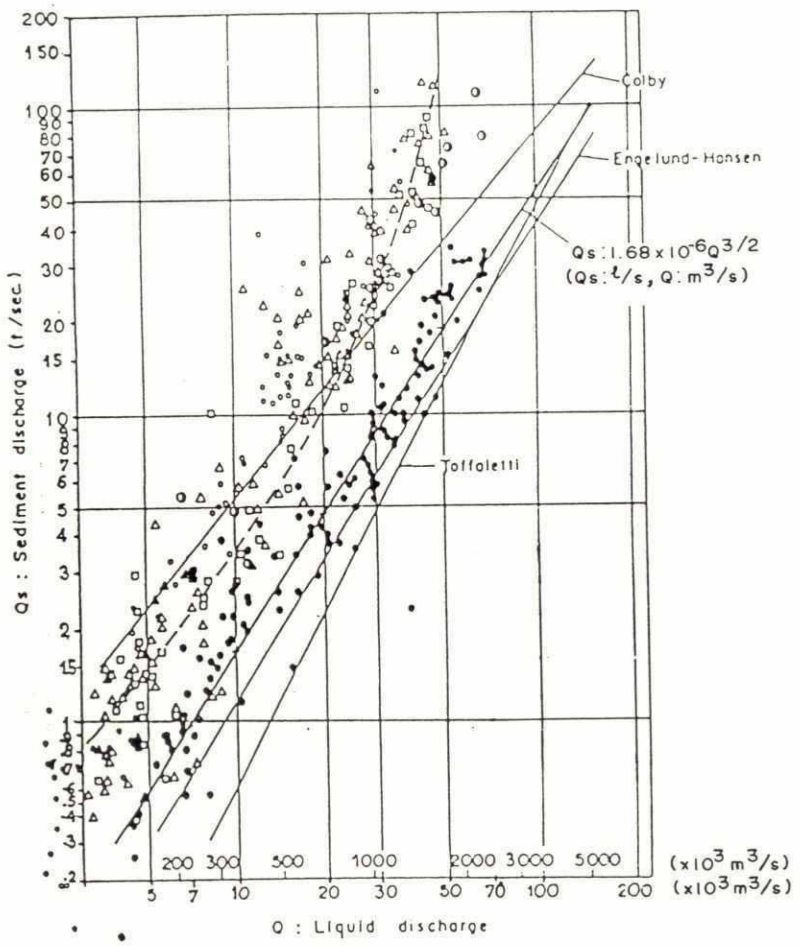
Measured Coarse Suspended Sediment Transport at Bahadurabad (1968-88)

	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 5.5



Measured Coarse Suspended Sediment Transport at Bahadurabad (1968-70 and 1982-88)

		Annex 1
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 5.6



Total Sediment

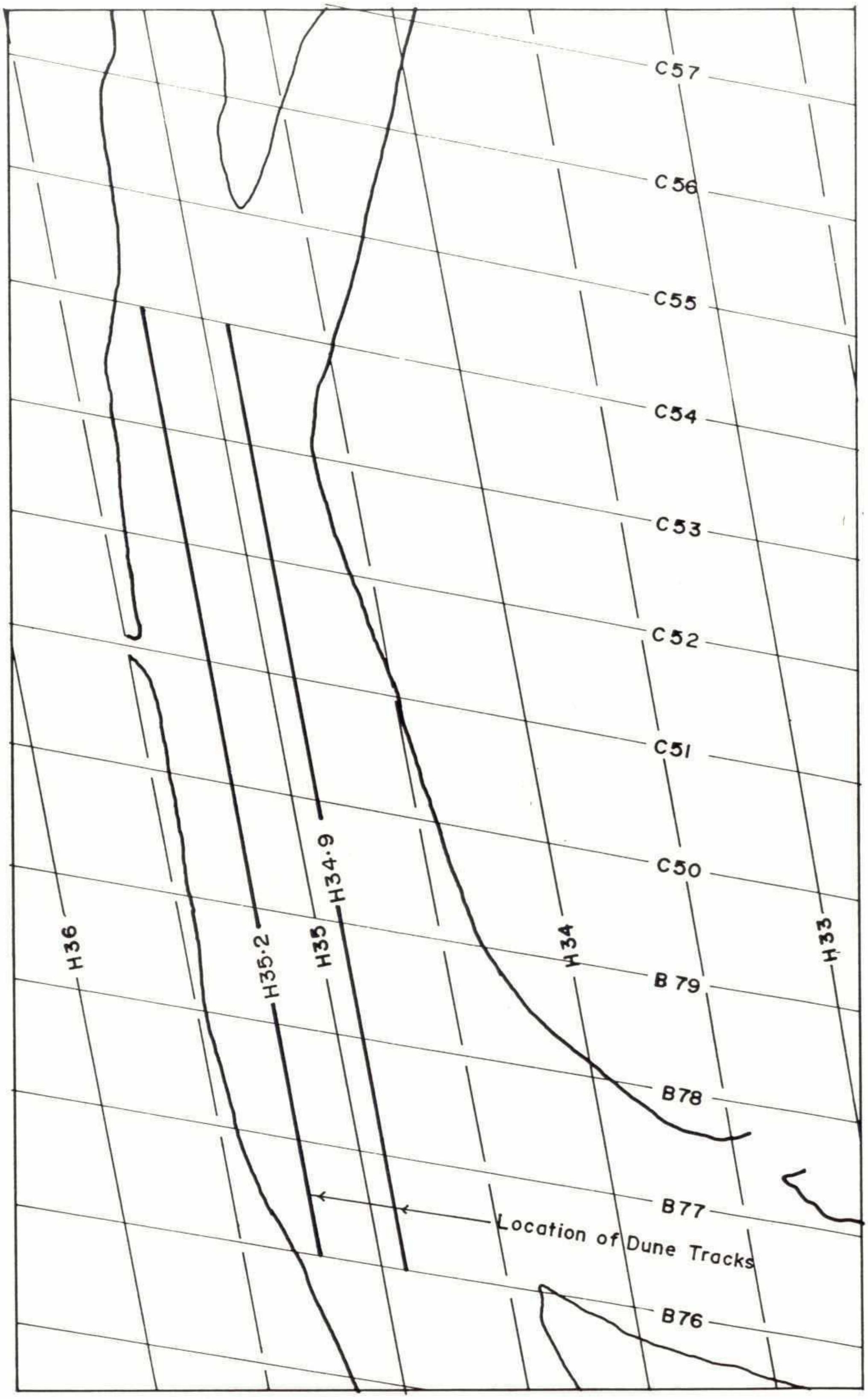
- ∘ Chilmari from 1966 to 1969
- ○ Bahadurabad in 1966
- △ Nakfater Char from 1965-69
- □----Nagarbari from 1967—69
- •——Bahadurabad from 1966—69

Coarse Sediment (d > 0.05 mm)

Relationship Between Discharge and Suspended Sediment Transport (after RRI, 1988)

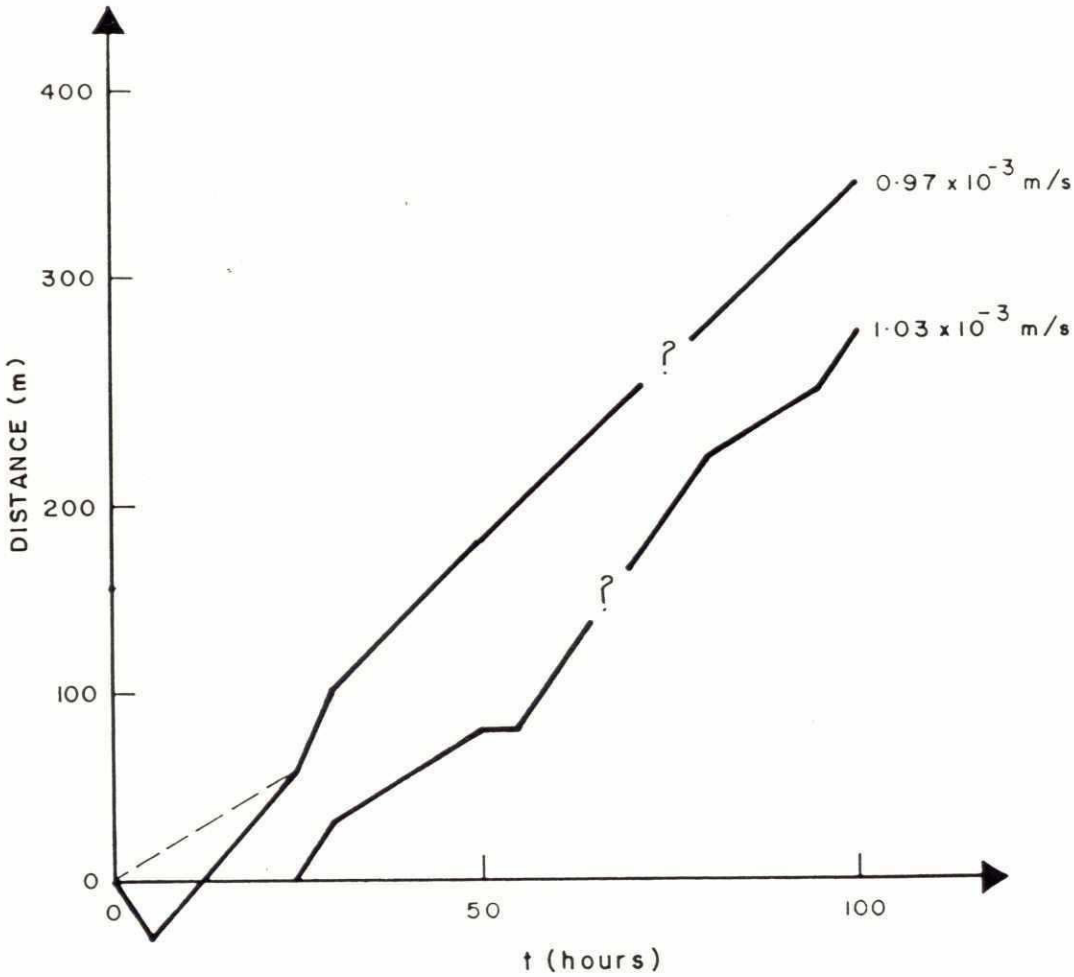
	Annex 1
Halcrow/DHI/EPC/DIG *November 1992*	Figure 5.7

90

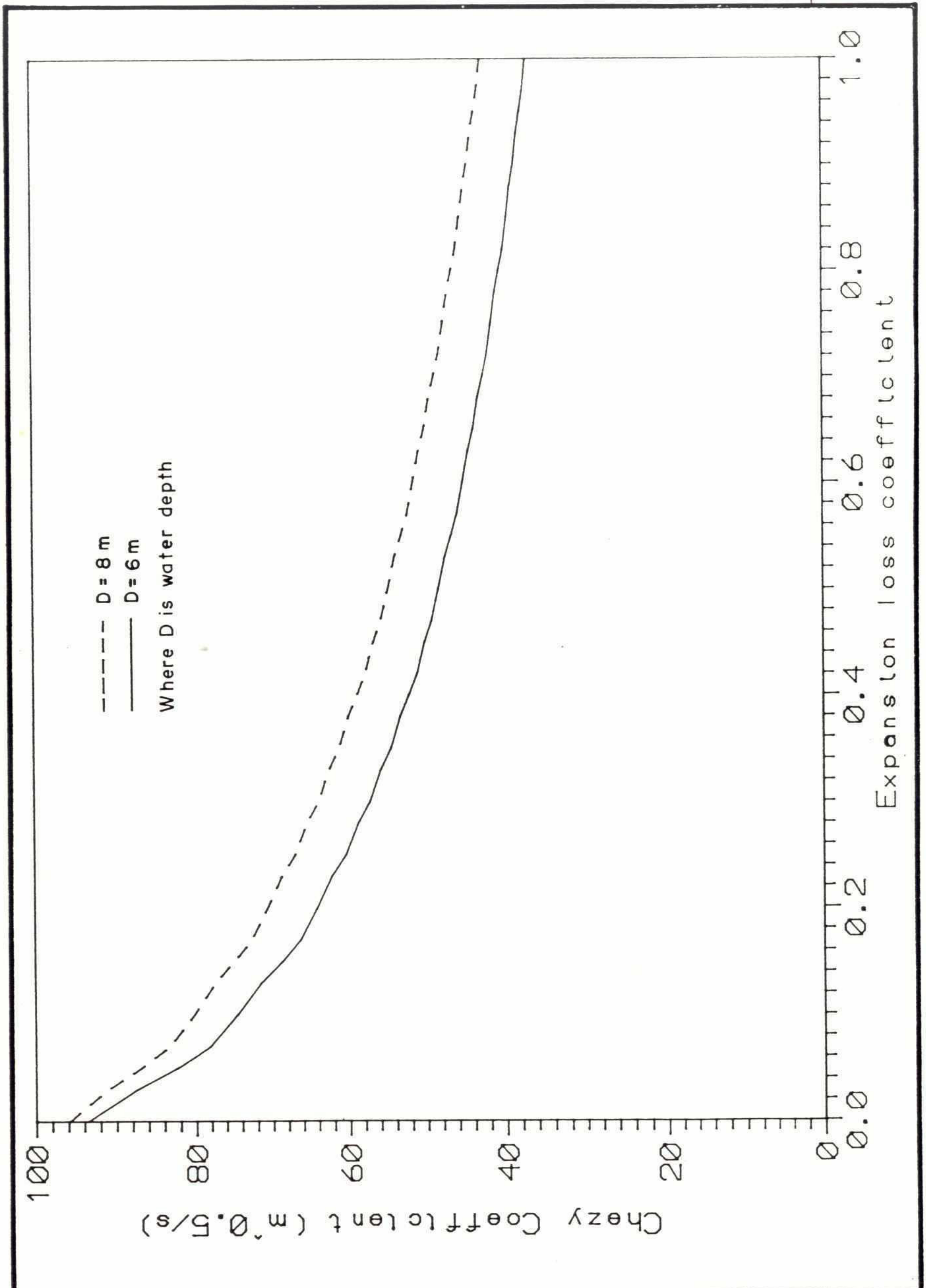


Location of Dune Tracks

Halcrow/DHI/EPC/DIG	November 1992	Annex 1 / Figure 6.1



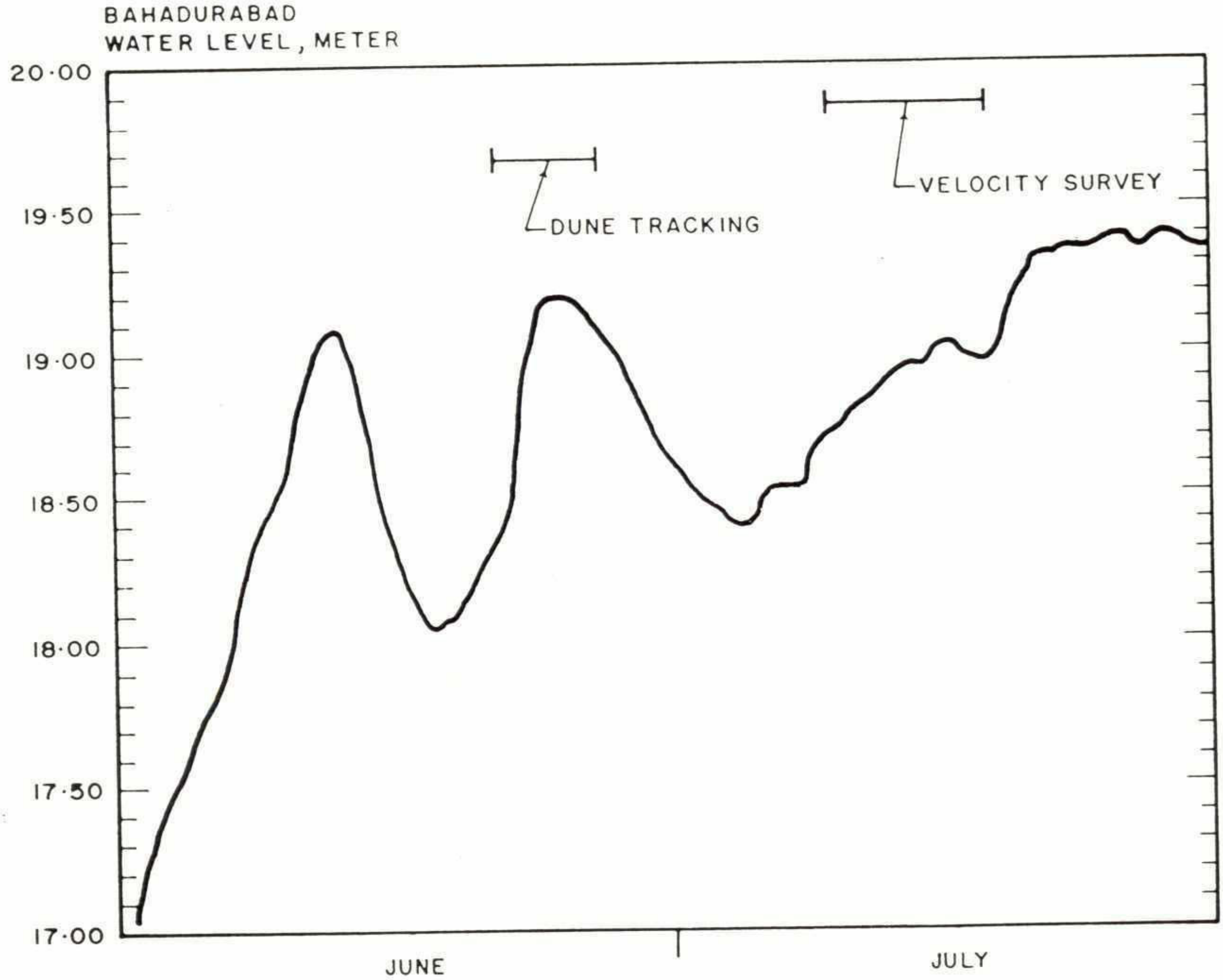
Relative Position of Dune Crests



Calculated Chezy Resistance Number As a Function of the Applied Expansion Loss Coefficient

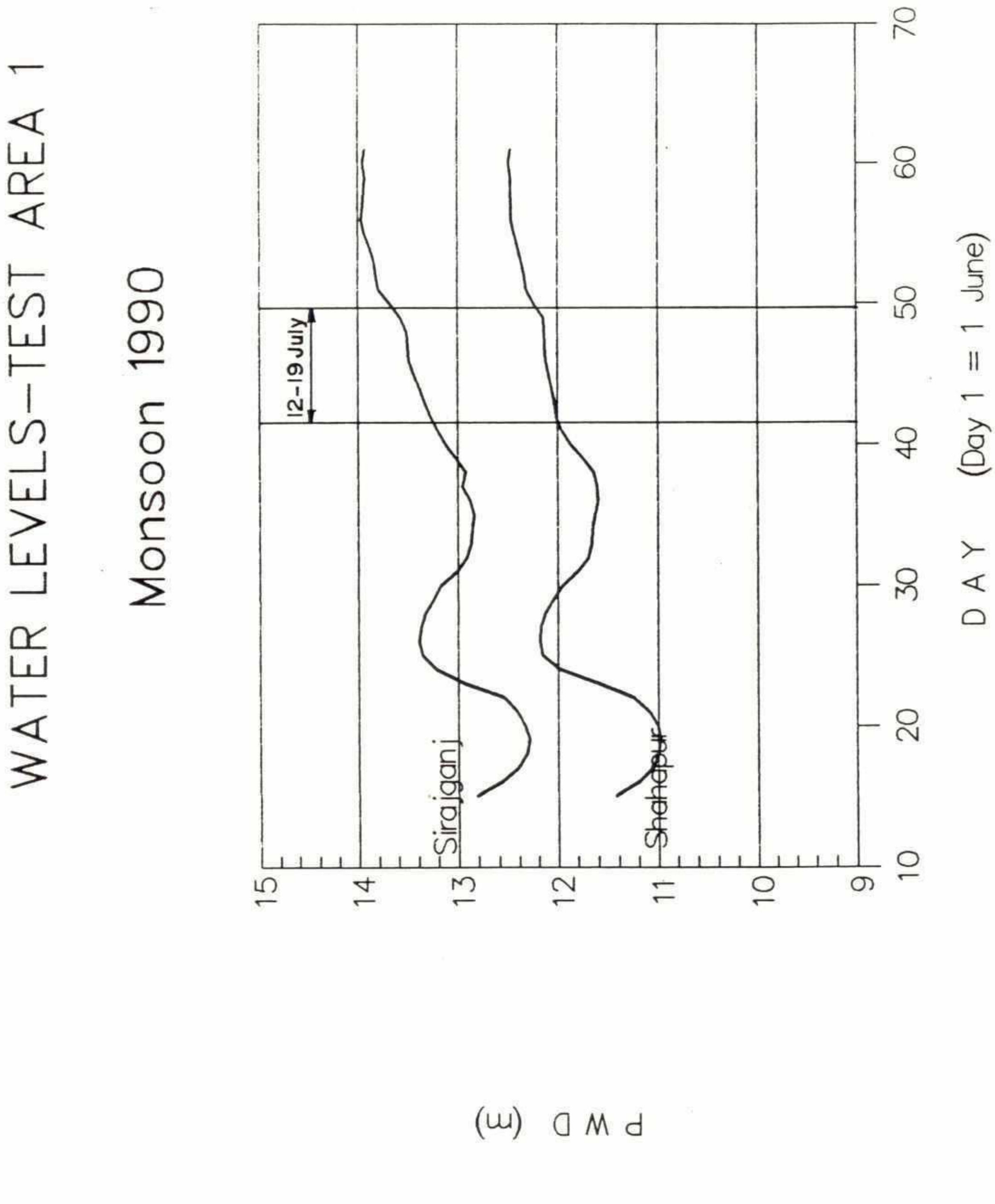
		Annex 1
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 6.3

96



Comparision of Water Level at Bahadurabad for the Period of Dune Tracking and the Period of Velocity Survey

		Annex 1
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 7.1



Water Levels in Test Area 1, During Monsoon Survey