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

PAP-1

River Training Studies of the Brahmaputra River

10

Final Report

1994

Technical Annexes

Annex 2
Morphology

MPN-5
A-5

Sir William Halcrow & Partners Ltd.
in association with

Danish Hydraulic Institute
Engineering & Planning Consultants Ltd.
Design Innovations Group

HALCROW

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

River Training Studies of the Brahmaputra River

Final Report

1994

Technical Annexes

Annex 2
Morphology

A 7

Sir William Halcrow & Partners Ltd.
in association with

Danish Hydraulic Institute
Engineering & Planning Consultants Ltd.
Design Innovations Group

FOREWORD

The BRTS Draft Final Report was issued on 31 January 1993. Comments from BWDB and FPCO were received from March 1993 onwards, and responses to those comments were issued in a single volume on 25 October 1993. The report was approved at the 20th FAP Technical Committee Meeting on 9 August 1994 subject to certain amendments. The amendments have duly been incorporated and the report was reissued in its present form as the Final Report in December 1994.

RIVER TRAINING STUDIES OF THE BRAHMAPUTRA RIVER

FINAL REPORT

GENERAL CONTENTS

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

RIVER TRAINING STUDIES OF THE BRAHMAPUTRA RIVER

FINAL REPORT: ANNEX 2 - MORPHOLOGY

CONTENTS

5

REFERENCES

TABLES

FIGURES

PLATES

APPENDICES

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

10

ANNEX 2 - MORPHOLOGY

1. PLANFORM CHARACTERISTICS

1.1 Data Sources

The principal sources of data that have been utilised for the BRTS analysis of river planform characteristics are:

(a) Survey of Bangladesh 1:50,000 scale topographic maps published in 1951-57, 1967-69 and 1978-79. These are considered to be the most reliable record of bankline for the period prior to the commencement of satellite image coverage and are in ready to use form.

(b) Rectified photographic prints at 1:50,000 scale obtained from the November 1989, March 1990 and November 1990 SPOT satellite imagery. This is high quality high resolution data but the short time span limits its value for morphological analysis.

(c) Partial coverage of the area by photographic prints of 1:50,000 and 1:20,000 scale aerial photography flown in December 1989 by Finnmap. This provides a potentially valuable complement to the SPOT imagery for interpretation of features which are not well defined on the former. Its use is limited by the security restrictions imposed by the Ministry of Defence and coverage for certain key areas, such as Sirajganj, is not available.

(d) Good quality copies obtained from the India Office Map Room, London, of the Rennell map of 1765, the Wilcox map of 1830 and the Survey of India map issued in 1914, the latter two at a scale of 1 inch to 4 miles. The 1914 map is a detailed topographic map showing a large number of villages and features in a similar style to modern maps and it may be assumed that its reliability with regard to bankline planform and major char outline is of a high order. The Wilcox map covers only the river and a narrow strip on either side; it is drawn to a high standard with good detail and referenced to longitude and latitude. There are doubts about the datum used by Wilcox but cross-reference to villages on modern maps is satisfactory and there is no reason to presume that the map is not reliable with regard to planform. The Rennell map is also well drawn and detailed; it is not referenced to longitude and latitude but after adjustment to a common scale it is possible to relate it satisfactorily through village and town locations and thereby establish a common reference with the other maps. The outline of the river fits well with major bend scars and other features identified on the 1:50,000 SPOT imagery and it is reasonable therefore to accept it as a reliable record of the approximate location of the main banklines at that time.

(e) River cross-sections surveyed by the BWDB Morphology Division between 1964 and 1989 with a break from 1970 to 1976. These were mainly received in the form of rather indifferent quality ammonia prints and were digitised in the BRTS office. Systematic quality checks revealed significant datum anomalies that set severe limits on the quantitative interpretation of the analyses carried out using this data set.

(f) Landsat MSS imagery for 02/73, 01/76, 02/78, 02/80, 02/84 and 02/87 and TM imagery for 01/90 and 03/92, which has been rectified, enhanced and processed by ISPAN under the FAP-19 project. This is high quality data on which much of the quantitative analysis has been based.

(g) Photographic prints at approximately 1:250,000 scale of unrectified Landsat imagery for 02/73, 01/76, 01/77, 02/78, 02/80, 12/81, 03/84, 03/85, 03/86, 02/87 and 02/88.

1.2 The Evolution of the Present River Planform Characteristics

1.2.1 Introduction

It was recognised prior to the start of the study that the morphological character of the river varied from north to south, with the section south of Sirajganj showing a lower braiding intensity and a greater tendency towards a meandering pattern.

Further scrutiny under the BRTS indicated that the river could be split into seven reaches which displayed distinctive patterns of braiding (Figure 3.16) as reported in the First Interim Report. Up to this point the focus had been on the number and pattern of anabranch channels in each reach (see Section 3.2.2 for an analysis); more recently the focus has turned to the islands or chars and as a consequence a complementary set of patterns has been identified that fits almost exactly with the early divisions but changes the perspective considerably with regard to channel evolution. This pattern is closely consistent with the theory of braid bar or island evolution proposed by M.S Yalin (1972) and it is therefore reasonable to use this thesis in conjunction with the known behaviour over the past 160 years to gain insight into the likely future behaviour of the river in terms of planform evolution.

In the following sections the process by which this pattern was positively identified will be described and the implications discussed.

1.2.2 Definition of Bankline, Chars and Sandbars

As a part of the BRE assessment survey the BRTS has prepared an accurate map of the existing BRE alignment and the bankline as in December 1990 at a scale of 1:50,000. A plan of the bankline in March 1989 at the same scale has also been prepared from the SPOT image. The definition of bankline in each case has been taken as the interpreted interface between the main river flow surface and the main body of the flood plain at a water level corresponding to dominant discharge. Where a minor channel forms an island whose surface is the same as the flood plain then the island is taken as part of the flood plain unless the channel width at dominant discharge exceeds 100m.

Chars are defined as meta-stable islands with their surfaces well above dominant discharge level and typically close to flood plain level; they are characterised by their well established vegetation cover. Sandbars are are normally submerged at dominant discharge and consequently show up on imagery as largely free of vegetation. The former typically evolve through a combined process of bank erosion, cross-channel cutting and attached bar formation, whereas the latter experience a high level of sediment transport over the whole of the submerged surface and consequently experience major geometry changes over a single season. The meta-stable islands can be clearly distinguished from the lower chars by

12

inspection of the river cross-sections, except in the immediate vicinity of "cross-overs" or "nodes" where the surface elevations of the two tend to merge (see Figure 3.14) This is discussed further in Chapter 3 of this Annex.

1.2.3 The Present Pattern of Bank Erosion

Inspection of the 1989 and 1990 bankline planform, for which the high resolution SPOT imagery is available, shows up two distinctive features. Firstly there are a number of pronounced embayments in the bankline that follow a very regular pattern as shown in Table 1.1. The mean wavelength of this pattern is 7.25 km with an SD of 1.59 and the mean amplitude is 1.8 km with an SD of 0.6. Secondly there are reaches which display the distinctive characteristics of active bank erosion alternating with relatively quiescent reaches. These characteristics are multiple smaller scale scars with a radius of about 2000 to 2500m which may or may not be associated with active low flow channels. Where these smaller scars are active they are typically associated with a large sandbar, having a length of 3000 m to 4000 m and an aspect ratio of between 2 and 3, which splits the anabranch flow. These active reaches correspond very closely with those lengths of the BRE that have experienced multiple retirements.

When the active and quiescent reaches are marked in plan it is apparent that in recent years there has been a very distinct pattern with the alternating reaches each being of the order of 13 km long. The pattern breaks down between Chandanbaisa and Sirajganj where the indications of recent active erosion are more or less continuous. This pattern is mirrored by the plot of numbers of retirement of the BRE as shown in Figure 1.1 and is completely consistent with the magnitude of net bank movement shown in Plate 3. It is also noteworthy that the length of the active reach between Chandanbaisa and Sirajganj can be divided into five units of about 13 km each, thereby maintaining the notional pattern of active/quiescent reaches.

1.2.4 Braiding and Island Evolution on the Brahmaputra

The distinctive pattern of meta-stable islands, with its associated string of unstable sand-bars, that is apparent today appears to have been developing steadily since the major avulsion that took place in the period 1780-1830.

Rennell's map, dated 1765, shows very distinctly that the river adopts one of two forms over different reaches. Upstream of the Dharla river confluence the form is predominantly meandering with a wavelength of about 19 km and a sinuosity of around 1.24. The bank to bank width was about 4 km with pronounced point bars or chars formed on the inside of the meander bends. This contrasts with the braided pattern today with a bank to bank width which is nowhere less than 6km and in several places is greater 14 km.

Downstream of the Dharla confluence the Rennell map shows a relatively sharp change to a strongly braided pattern with three groups of islands, of length around 20, 18 and 24 km respectively, separated by two necks, or cross-overs. The island groups display characteristics similar to those found today in the middle reaches of the Brahmaputra, with outer bank to bank width of up to 11 km. This braided reach has a length of about 100km and the river then returned to a predominantly single thread meandering pattern in the vicinity of Mymensingh.

It is possible to register the 1765 map with that of the Survey of India Quarter Inch series, published in 1944, by the comparison of common place names and this indicates that the earlier map is reliable to an order of 1km in 50km. It is therefore reasonable to suppose that the major river morphological detail has a similar level of reliability.

The map prepared by Wilcox in 1830 has also been checked against more recent maps and found to correspond. Morphological features are well described on the 1 inch to 4 miles scale version of the map and the triangulation lines are marked on some sheets. Moreover, the limits of the river meanders correspond closely to scars discernible on both the Landsat and SPOT imagery. All this evidence indicates that the map may be considered reliable within the tolerances stated above and is almost certainly a valuable record of the major planform of the river circa 1830.

The Wilcox map shows the river to be heavily braided upstream of the Teesta confluence and rather less so to the point where the Old Brahmaputra river offtakes. Downstream of this the river is essentially a single thread meandering channel down to the Ganges confluence, with an overall sinuosity of about 1.27.

The situation around the turn of the century is illustrated by the Survey of India map issued in 1914, which is stated to be based on surveys from 1848 to 1868 updated to 1913. This shows that cut-offs have formed across the large bends shown on the Wilcox map causing the overall planform of the river to be very much straighter at high flow but introducing strong braiding for about 36 km south of Sariakandi and 24 km south of Sirajganj. It may be inferred that the meandering sinuosity has been translated into braiding in order to maintain the same effective streampower at dominant discharge. The high sinuosity meandering pattern being inherently unstable in the longer term because of the tendency of the river to create cut-off channels during periods of out-of-bank flow.

The outer bank to bank width in these braided reaches was of the order of 7km. The map distinguishes between the higher level islands that have named settlements and the lower level shifting sand-bars. The former constitute somewhat over 50 percent of the island area, which is of the same order as at the present time during the low flow season.

Compared to the relatively irregular planform pattern of the river at the turn of the century, that of 1956 was beginning to show the development of the more regular pattern that is apparent today. In fact in some respects the 1956 planform displays more symmetry than seen today. Meta-stable island clusters were forming at all the sites of the present day major islands, although the area of the high level char tops was in total rather less than it is today and the outer bank to bank width was overall less. Perhaps more importantly the majority of the cross-over points (nodes) were consistent with the present pattern, suggesting that these features have a reasonably long life (see Plates 9 and 16).

Features representing a departure from the present pattern were:

(a) The equivalent of Island C was located about 12 km north of the present position in a zone that is currently a poorly defined cross-over.

(b) An additional 9km long island cluster existed south of Sirajganj in the reach that presently forms a distinct throat. The northern limit of this cluster coincided with the proposed Jamuna Bridge centre line. This cluster appears to have coalesced with the left bank soon after 1956 and the river has remained predominantly single channel since then.

(c) A small island cluster just north of the Hurasagar confluence that had virtually disappeared in 1968 but which has reformed recently.

Limited map coverage for 1966-67 shows that while the location and shape of the individual islets had changed very substantially the clusters were themselves in much the same positions.

The first satellite imagery became available in 1973 and it is possible thereafter to track the evolution of the chars into their present pattern, which is shown on Figure 1.2.

1.2.5 Features of the Present Char Pattern

Some features of the present pattern of meta-stable chars that are of relevance for both predicting planform evolution and for designing large scale river training works are:

(a) Prior to the 1988 monsoon Island A consisted of two distinct groups of upper level chars divided by a strong cross-over feature. Following that season the main flow channel split the northern cluster in two resulting in some compensatory accretion on the left bank. The southern cluster was also severely dissected and by December 1990 there was little more than a ragged collection of char fragments in this zone but the cross-over at latitude 25° 25' appears to be reforming and it is the consequent growth of the southern portion of Island A that is associated with the current bank erosion in the vicinity of the Manas Regulator. This trend is confirmed by the latest (1992) satellite imagery.

(b) Island B has been growing steadily in size since at least 1956 and has now become elongated to form a tail that stretches almost down to the Sariakandi macro-planform bend, where it terminates at a poorly defined cross-over. This tail could be considered as a vestige of the island cluster in this vicinity seen on the 1956 maps. One possible inference is that the stability of the Sariakandi cross-over is being affected by the proximity of the macro-scale bend.

(c) Island C has moved downstream about 12 km since 1956. It is currently associated with the bank erosion in the Mathurapara/Chandanbaisa reach.

(d) Island D has grown considerably since 1956 to the extent that in the satellite imagery of 1973 to 1980 it appears to be almost attached to the right bank. In 1985 the division of flow at the head of the island changed substantially and the right hand anabranch rapidly grew in size. Recently second order chars have formed in this anabranch and it is with these that the erosion at Kazipur and Sonali Bazar is associated. Since the location of these secondary chars corresponds to the char evolution theory outlined above, it may be expected that further bank erosion will continue to take place in these vicinities until the new regime is established.

(e) The second significant feature of Island D is that it has almost merged with Island E to the extent that the cross-over between them is now effectively uni-directional (east to west flow only). Island E has also grown substantially since 1956 and it is now distinctly pushing into the throat formed by Sirajganj and Bhuapur. If the position of this cross-over is artificially maintained then it seems possible that ultimately the Bhuapur channel will become starved and Island E will then merge with the left bank flood plain. The question is then whether the right anabranch would remain as primarily a single channel or whether it would tend to recreate a braided channel by cutting into the right bank. Given the history of the river, the latter seems a distinct possibility.

(f) Plate 11 shows that island F has been growing steadily since 1973 and with the trend of increasing width and braiding observed during this same period it seems probable that the right anabranch will tend to grow rather than decline. However much will depend on the future development of islands D and E. If they become attached to the left bank this may encourage flow to concentrate on the left bank south of the Jamuna Bridge Site.

Figure 1.3 shows the evolution of islands C, D and E during the period 1973 to 1990.

1.3 The Principal Morphologically Distinct Reaches of the River

From the plot of BRE retirements (Figure 1.1) it can be seen that there is a pattern to the number of retirements. Over certain reaches there have been no retirements to date while in others there have been multiple retirements. This pattern corresponds closely to that seen on the maps showing the bankline movements during the periods 1953 to 1973 and 1973 to 1992 (see plates 4 and 5).

Combining this evidence leads to the division of the river in the study area into five main reaches associated with major islands and the respective inter-island or cross-over reaches. The word "node" to describe the cross-over reaches has been deliberately avoided because of the implication of fixity and uniqueness that may be misleading. In fact according to some opinion the shorter the cross-over reach, and therefore the more node-like it may appear at any point in time, the less stable it is.

The five reaches are described in Table 1.2 and shown on Figure 1.4. It will be noted that Reach 4 is associated with both Islands D and E, which are now almost combined into one.

Reach 1 has the least well defined of the major islands. In many years the islands appear as two distinct clusters with a secondary cross-over at latitude 25° 25', just north of Kamarjani, while at other times these appear more as a single island. Following the 1988 flood flow the islands were heavily dissected and even after the 1990 monsoon season they had not regained any form. Despite this apparent instability of form, the reach has experienced well below average bank erosion since 1956. Indeed it is probably the absence of consolidated island growth that is the reason behind the relative stability of the bankline.

The only significant bank retreat has taken place between Gidari and the Manas Regulator which was the cross-over reach in 1956 but is now occupied by the downstream portion of Island A. It seems possible that this Island is still at a relatively early stage of evolution and that if this is the case then bank erosion north of the current cross-over at latitude 25° 15' may

4

become worse during the next decade. For the present however mean erosion rates should remain below average, although localised rapid bank retreat can be expected for short periods at a time in the vicinity of the Manas Regulator and immediately south of the Teesta confluence.

The cross-over reach between Islands A and B is fairly well defined with its centre point at about 25^0 15', although in many years there is actually little cross-over of flow in this zone. Bank erosion here since 1956 has been minimal and while the cross-over remains laterally stable there is no reason to expect any significant change.

Reach 2 has undergone major change in the last 30 years as Island B has consolidated from a modest cluster of islands and grown to its present length of more than 23 km. The two main anabranches are now spawning secondary islands, some of which have distinct meta-stable elements. The recent serious bank erosion at Fulchari and the current erosion at Bahadurabad are related to substantial secondary islands and further localised erosion may therefore be anticipated at both these locations, and also at points 7 to 8 km upstream and downstream, as further secondary islands develop.

The future evolution of the river over this reach will depend on whether the braid belt as a whole shifts westward. Since the cross-over at the downstream end of the island has scarcely moved since around 1914 and has been remarkably stable since 1973, and the upstream cross-over has been laterally stable since 1956 (see plate 10) there seems a strong likelihood that any westward drift of the river's centreline will be, at most, relatively slow. If this is the case then a possible model of evolution may be the massive complex of islands that has developed north of the Dharla confluence. This heavily braided reach of the river has an outer bank to bank width of about 18 km compared to the 15km maximum width for Reach 2 at present.

The downstream limit of Island B is currently at about Latitude 25^0 04'. Downstream of this the pattern is confused with a mass of fragmented islands, some of which have meta-stable elements, occupying the centre of the channel and a substantial char consolidating towards the right bank. The downstream limit of this reach is the poorly defined upper end of Island C at about latitude 24^0 53'. It is interesting to note that in 1956 a cluster of islands also occupied this reach but never developed into a consolidated island.

Of probable significance is the fact that the cross-over immediately upstream of Island C, which is an important anabranch bifurcation point, has shifted westward by as much as 3km over the past 30 years. This cross-over coincides with the apex of the macro-form braid-belt bend and it is the behaviour of this hinge point that has a considerable influence on the river reach downstream.

1.4 Brief History of Bankline Movement

1.4.1 Bankline Retreat/Accretion

The processes of bankline retreat and accretion on the Brahmaputra river are seen to be dominated by the dynamics of anabranch evolution, which in turn is strongly influenced by the pattern of sediment and fluid transport. Since the latter are stochastic by nature it is necessary to look for significant trends that may be used to predict behaviour within specified confidence limits.

When analysing historic data it is important to keep in mind that bank movement is a combination of two distinct processes: widening of the braid belt related to char evolution and lateral shifting of the river channel centroid, related to long-term planform evolution and migratory trends.

It has been found that in almost all cases short-term bank erosion is associated with the concave face of anabranch bends which typically migrate only a relatively short distance downstream before dying out from one of several causes. This results in clearly defined embayments that are distinct features of the bankline and produce a scalloped appearance. However over a period of time it appears that the consecutive embayments are displaced by several kilometres, resulting in a relatively uniform average rate of bank retreat in any one reach, being of the order of 100 m/y, over a timescale of about 30 years.

The total bank movements for the periods 1953 to 1992, 1953 to 1973 and 1973 to 1992 has been plotted by FAP-19 and is illustrated in Plates 3,4 and 5 respectively. The movement is described in more detail in the following Section.

On a longer timescale, whatever the underlying cause, and tectonic movement is an obvious candidate, there is convincing evidence that the river as whole has moved consistently westward during the last 200 years over most of the study reach (see Plate No. 2). It is also apparent that the channel centroid can oscillate about its mean position by as much as 10 km, as the major anabranch switches from one side of a major char to the other. The notable exceptions to this westward drift are the very stable node south of Island B, Northing 780,000, already mentioned and the Island D reach. The future stability of the latter would seem to be less certain than the former.

1.4.2 Bankline Movements Since 1765

The combination of dramatic change in planform that occurred around 1830 and the inherent difficulty of defining the position of a braided river prior to the availability of high resolution imagery, makes it impracticable to think in terms of quantifying average movements at this scale. It is however possible and useful to infer some broad indicators from comparison of the older maps with the present day planform, particularly when such inferences can be corroborated by visual interpretation of the morphological features that show up clearly on the 1:50,000 scale SPOT imagery.

<u>Island A</u>

On the Rennell map of 1765 the Brahmaputra is shown hugging the Shillong hills for a distance of about 20 km north of the present confluence of the Kongkhal and Jinjaram rivers (see Figure 1.5). Taking the centreline of the braid belt as a reference, the Brahmaputra between the Teesta confluence and Bahadurabad has moved westward by a fairly uniform 14 km during the 225 years. Further north, in the vicinity of the present Dharla river confluence, the shift is less at about 8 km. The Wilcox map of 1830 shows the river as becoming considerably more braided, and therefore much wider, but the centre of the braid belt had only moved by the order of 2 to 3 km since 1765. This suggests that the river is capable of sustaining an overall westward migration at a rate of the order of 60m/y. It may be expected that over shorter time-spans, such as 30 years, the rate could be considerably higher or lower than this average.

Inter-Island Zone a-b

The centreline at the downstream end of the island A group, immediately north of island B, shows an overall westward movement since 1765 consistent with that described above, some 6 km of which has occurred since 1830. Since 1953 the centreline position has remained very stable, although there has been some minor widening.

Island B

Westward movement of the centreline since 1765 is again consistent with the reaches to the north, although by 1830 the centreline in the southern part of this reach was much nearer its present day position. Widening increased from 1830 to 1914, then more markedly so to 1953. Since then there has been a less general widening overall, although the embayments at Fulcharighat result in a continued westward bankline movement.

Inter-Island Zone b-c

South of the Old Brahmaputra bifurcation the situation is very different. In the upper portion of the present cross-over zone between Islands B and C (Latitude 25° 05' to 25° 00') the centre of the braid belt appears to have remained almost static between 1830 and 1914 while in the southern portion it shifted less than 2 km (20 m/y). Since then the width of the braid belt has increased but there has been only an insignificant shift of the centreline westward. As the indications are that this cross-over has been relatively stable laterally for 150 years it is likely therefore to remain so for at least the next few decades.

The lower portion of this cross-over zone (Latitude 25° 00' to 24° 54'), where most of the flow bifurcation currently takes place, the situation is again different. In this reach the river as shown on the 1830 map flowed in a large bend, of which the scar is still clearly visible on the SPOT imagery, with its apex 7 km east of that of the present day large bend south of Gaffargaon. This major feature had disappeared by the time of the publication of the 1914 map, to be replaced by a relatively straight braided reach and leaving only the Chatal river as a vestige of this abandoned course. It has been noted elsewhere that the size and shape of this old bend is remarkably similar to that of the present day large bend opposite the Hurasagar confluence and the scars left by other old bends.

The centreline of the 1914 braided reach was very close to that of the present braided channel but the outer bank to bank width was only at most 5 km compared to the present day equivalent of about 11 km. This width increase is the equivalent of a bank retreat rate of about 40 m/y. The averaged movement of the right bank of about 70 m/y in this reach is therefore probably composed of a combination of widening and overall westward movement of the centreline of the braid belt during this period, which is consistent with the lesser accretion rate experienced on the left bank.

67

Island C

The next reach downstream is that of Island C (Latitude 24° 54' to 24° 45'). On the 1830 map a small cut-off channel is marked which corresponds closely with the centre of the braid belt on the 1914 map. The latter is close to the current braid belt centreline - opposite Sariakandi it actually appears to have been marginally further west than the current centreline but given the difficulty in defining the centreline, this is not significant (see Plate 2). The outer bank to bank width has however increased from 6 km in 1914 to 11.5 km today (an average of 73 m/y). The change since 1956 however presents a contrasting picture. In 1956 the width was still of the order of 6 km and the centre of the channel was about 2 km further east than that of 1914. Most significantly, the reach contained no meta-stable islands. The implication is that the islands shown on the 1914 map fused to the right bank creating a zone of temporary accretion. As the islands reformed post 1956 the earlier centreline was retained but the overall width almost doubled to that of today. The net bank erosion since 1914 is thus of the order of 2.5 km (average 33 m/y).

Since there is no sign that would suggest that the island might either disintegrate or coalesce to one or other of the banks within the coming decade, it must be anticipated that erosion of both banks will continue. Since the right anabranch is still evolving a stable planform, it should be expected that more of the erosion will take place on the right bank. An averaged rate in excess of 100 m/y during the next decade would seem likely, with far higher short-term rates locally if an aggressive bend develops (i.e. up to 700 m/y).

Inter-Island Zone c-d

Very little net movement of the centreline of this reach appears to have taken place since 1914; a westward drift of the order of 1 km is suggested by the FAP-19 plot (Plate 10). However in the period since 1956 the changes that have taken place in the Island C reach have resulted in the cross-over at its downstream end effectively moving westward by about 2.5 km. This has had a commensurate affect on the Island D reach. The narrowest point of the cross-over has during the same period increased from 6 km to 8 km and has shifted some 10 km downstream.

Island D

The Island D reach has also seen relatively little change in overall width since 1953 but there has been a steady drift of the centreline westwards, amounting to about 5 km. The most important feature with regard to future behaviour is that the split of flow around Island D at present is such that the right anabranch takes a substantially higher proportion of the bankfull flow. If this trend continues, and the pattern of growth of islands D and E since 1953 makes this an increasingly likely occurrence, then the two islands could merge with the left bank, leaving the right anabranch to evolve into a braided channel itself. The present anabranch width of between 3.5 and 4.5 km would certainly tend to increase quite rapidly to at least 6 km and this would be at the expense of both right bank and the newly formed left bank. Combined average bank retreat rates would probably be the of the order of the highest recorded for sustained movement at the reach level which is about 200 m/y, split equally between the two banks.

Island E

It has been noted that the cross-over between Islands D and E is poorly defined to the extent that in recent years the flow has only been from east to west and the two islands have tended to overlap and are now near to merging. If this trend continues, the two islands may coalesce to form one island of about 36 km length. This implies a major anabranch wavelength of about 72 km or around double that of the theoretical single thread wavelength for dominant discharge, the nearest equivalent of a single anabranch bend of this scale being the 33 km long reach to the east of the current extended Island B. From the time snapshots of the river available it may be inferred that such a bend is not a long term stable feature, in which case there are two principal modes of evolution:

(a) the island might become attached to the left bank;

(b) the two anabranches might develop individually on either side of the island to form a multiple channel anastomosed system. The feature north of the Dudhkumar river, which has a major island length of about 36 km, may represent such an evolution.

In either case the right bank would come under increased attack, with the former probably creating the more aggressive condition. An average bank retreat rate of over 100 m/y over the reach could be expected and the upper part between Kazipur and Simla, where the current anabranch width is only about 3.5 km, experiencing more attack than the lower wider section.

For reference: the maximum widths of the "Dudhkumar" feature scaled off the 1765, 1830 and 1988 maps were 6, 12 and 15 km respectively, giving averaged widening rates of 92 and 19 m/y and a longterm average of 40 m/y.

Inter-Island Zone e-f

The lower end of Island E is currently at about Latitude 24° 25', although the lower 8 km are not as well defined as the remainder. The next 10 km down to Latitude 24° 19' comprises the well known throat or node reach which has remained effectively a single thread channel with little change in width over a period of about 20 years. However this reach has not always been so stable. In 1830 a large double meander with a wavelength of 17 km and an amplitude of 12 km was the main feature, and the scars from this period are clearly visible on the SPOT imagery. By 1914 cut-offs had formed across the meanders and the pattern had become coarsely braided with an overall width of about 11 km. The major island length was about 20 km.

By 1956 the eastern channels were clearly dying, in the period 1956 to 1973 both banks accreted and by 1978-79 the island complex had become attached to the east bank, leaving a single channel in more less the present position. Since 1989 there has been significant bank erosion on both sides and it is an open question whether this presages the start of the reestablishment of an 1830 type bend, which could create a 3 km embayment on the left bank (similar to that formed at Gaffargaon in 1990/92), or whether this is the start of a new island. In the latter case the sequence of evolution would probably be similar to the recreation of Island C between 1956 and the present day. Either way greater erosion on the left bank than the right bank would be the prognosis. The main difference being in the short-term rate of erosion, the large bend being far more aggressive (up to 600 m/y) but affecting a shorter reach.

Island F

This reach has seen some substantial changes in planform since 1830. The present major anabranch is the eastern one and this occupies a channel that parallels that of 1830 but is about 2 km to the west. The similarity between these two channels in terms of straightness and width is quite marked, all the more so when compared to the 1914 channel which had formed a large sweeping bend to the east with its apex some 9 km east of the present left bank-line; again, the scars from this period are clearly visible on the SPOT imagery.

The movement of the right bank by about 5 km appears therefore to have taken place since 1914. At Belkuchi the bankline in 1956 was scarcely different to that of the present day, which implies that bank retreat in this reach took place at the high average rate of well in excess of 120 m/y.

The shape of this island is at present more elongated than would be expected from either theory or comparison with other major islands described above. Since its length corresponds to the norm, the inference is that it will tend to continue to grow in width (see Plot 11).

The General Pattern of Bank Erosion

From the discussion in the previous sections it can be seen that there are at least four major processes with different timescales occurring concurrently and that this in part explains the apparent randomness of bank erosion in terms of both location and severity.

The process with the shortest timescale is the evolution of major aggressive anabranch bends. These can result in local erosion rates of more than 500 m/y but such rates are seldom sustained for more than 2 years and rarely more than 6 years (see Figure 1.6, especially Fulcharighat, sheet 1, and the Jalalpur bend downstream of Betil on sheet 4). Rates of 200-250 m/y are more common but from the preliminary analysis of anabranch bends identified on the Landsat imagery over the period 1973 to 1990 it has been estimated that only 10 percent of bends produced erosion rates in excess of 500 m/y and on average only 3 bends a year have been labelled as aggressive. Thus although major bends may be seen to be very destructive because of the speed of attack they do not comprise the main mechanism of bank retreat over a period of time.

The second process, which is allied with the first, is the systematic eating away of the bankline due to the widening of the braid belt associated with the formation of both chars and sandbars. The formation of major aggressive bends may play a part in this process but attack by less aggressive bends seems to be the main mechanism. Average rates of retreat due to this process have historically been of the order of 75 to 150 m/y and this may be sustained over 30 or more years.

The third process is the shifting of the centre of an inter-island cross-over (node). There is some evidence that this may be a cyclical process in some situations and in others it may be a drift in one direction, in which case it is probably more appropriately classified in the fourth category. An example of the apparent cyclical movement is the history of Inter-island zone c-d (Figure 1.7). This shifting may be associated with the attachment of islands to one or the other bank, in which case the transfer may be more abrupt than shown on the Figure. The effect of this process is superimposed on the widening trend but the erosive power of the river will place a limit on the maximum sustainable erosion rate. The timescale for this process seems to be of the order of 30 years.

The fourth process is the larger scale migration of the centreline of the braid belt. Because of its scale and the masking effect of the other three processes, this is the hardest to quantify. It is apparent that north of Bahadurabad/Fulchari the river has moved westward by between 8 km and 14 km since 1765 but it is not known whether the major avulsion was the initiator of this movement or, conversely, that the movement prompted the avulsion. The fact that the centreline of the river at Bahadurabad has scarcely moved since 1830 and that the Island A reach has been similarly stable since at least 1956 suggests that the former is the more likely. This clearly has major implications with regard to the future pattern of erosion in this upper portion of the river.

Between Island A and Island F the cross-overs have all, with the possible exception of cross-over b-c, shifted westward in relation to the centreline of the 1830 and 1914 alignments but the magnitude of the movement is relatively small and of the same order as potential registration error in the case of the 1830 map.

From Island F southward the situation becomes even less clear, with the river behaving more like a meandering river but with strong, and probably increasing, braiding tendencies. The scars of big bends very similar to those of the present day indicate that the river centreline is now at least 7 km west of its position in the early 1900's; this is consistent with the westward movement of the right bank by this same order over that period. This is the equivalent of a movement rate of the order of 100 m/y, which suggests that the erodibility of the Atrai/Gur deposits south of the Hurasagar is little different to the less clayey material further north.

1.5 Quantification of Bankline Movement

The sources of data on bankline position over different periods have been set out and their limitations described in Section 1.1.

The approach adopted in order to draw as much quantifiable data as possible from these sources, within the limits set by the scope and resources of the study, centred on the following tasks:

(a) Superimposition of the bankline shown on the Survey of Bangladesh 1:50,000 maps issued in 1956-57, 1967-69 and 1978-79 with that on the rectified SPOT imagery for March 1989, which has been published in sheets to coincide with the SoB mapping. This gives a very reliable measure of the bankline changes over these periods, with the proviso that it is not always clear as to the precise hydrological year to which the bankline refers. It has not proved possible to collect all sheets for all years and so the analysis has been perforce a bit patchy. The procedure was subsequently refined by the FAP-19 team using only the 1956-57 mapping (referred to as 1953 on the grounds that was the year in which aerial photography is reported to have been flown) and rectified 1973 and 1992 Landsat imagery; in all three cases the banklines were digitised and overlain to produce composite maps.

(b) Comparison of the 1 inch to 4 miles (approximately 1:253,400) scale maps published in 1830 and 1914 with the 1953 and present day bankline. Areal distortion and measurement error become significant at this scale and so the banklines from the earlier maps were digitised by the FAP-19 team and adjusted to register with the present day maps.

(c) Surveyed river cross-sections for the period 1964 to 1989 were digitised by the BRTS team and the bank position defined, firstly by the automatic application of a simple rule and then checked visually. Although the accuracy with which the reference pillars is known is no better than 100 m to 300 m and survey error introduces a further error source, this data provides an independent check for the period prior to the commencement of the satellite image coverage.

(d) Interpretation of the Landsat imagery for the period 1973 to 1990 which was processed by the FAP-19 team. Banklines were plotted on the images by applying jointly developed criteria for the definition of what constituted a bankline. Even with specific criteria it occasionally proved difficult to decide, for example, at which moment in time a char became attached permanently to the main floodplain; following which the bankline would make a quantum movement. This problem related largely to the left bank where char attachment is a far more common occurrence but there have been examples on the right bank also.

By far the most detailed and reliably quantified data has been obtained from task (d). FAP-19 provided the data in two formats: firstly the intersections between a series of transect lines running east-west and the two banklines, at 500 m intervals; secondly, the areas of floodplain, sand-bar and char lying between consecutive 500 m interval transects and arbitary fixed boundaries on each bank. The former were used primarily for analysis of bankline movement and the latter for investigating relationships between erosion and accretion.

It has been confirmed that the right bank has experienced net erosion over its full length since 1953 and that some reaches have suffered more than others. The distribution of the total erosion over this period is shown in Plate 3 and for two intermediate periods in Plates 4 and 5, from which it can be seen that the distribution of bank erosion has varied considerably over the total period.

It was expected that there would be a some correlation between bank erosion and the position of the large islands since it is in these reaches that widening of the river has been most marked (Plate 9). Accordingly the rates of erosion were plotted on an annual basis averaged over 10 km lengths of the river with the result shown in Figure 1.8. Plots of the rates of erosion against time for each 500 m length showed remarkable consistency of form (see for example Figure 1.9 and it was concluded that the pattern of the last 20 years provided a reasonable basis on which to base a predictor of future movement. The rates for each 500 m reach of the river were grouped in sets of 20 and from each of these sets the mean erosion rate and standard deviation was calculated. The plot shown in Plate 13 was obtained by extrapolating the median and 95 percent non-exceedance values for each 10 km reach and calculating the respective banklines as they might appear in 19 years time. Lines that are close together are indicative of a very consistent erosion rate while those that wide apart indicate reaches where erosion and accretion have alternated. It is clear that the uncertainty is very much higher on the left bank than on the right.

The same data set was used to analyse the frequency distribution of different rates of erosion. For this purpose only those sections experiencing active erosion within a 500 m reach in any one year were considered. To simplify interpretation, the output was presented in the form of cumulative frequency plots for four reaches of the river (Figure 1.10): Reach 1 extending from the Teesta confluence down to the southern end of Island B; Reach 2 covering the length where the original BRE remains down to the upstream end of Island C; Reach 3 containing Islands C, D and E down to Sirajganj and Reach 4 the remainder of the study area down to the Hurasagar confluence. The distribution pattern was remarkably similar for all reaches and for all periods. Only two periods departed from the general pattern; these were 1980-84 and 1990-92 (see Figure 1.11). It can be seen that rates of erosion above 250 m/y may be considered unusual and above 500 m/y as relatively rare. The very high rates experienced at Kazipur and Jalalpur in the period 1989 to 1991 fall into this latter category and a link with the aftermath of the 1988 flood flows seems very probable. Two provisos need to be emphasised: the rates are averaged for the periods concerned, which ranged from two to four years, and may therefore underestimate peak rates; the frequencies relate to those portions of each reach that was experiencing some degree of erosion. The proportion of each reach that was being eroded during each period is shown in Table 1.3. Thus the inference is that if a section of the bankline is subject to erosion then it is possible to predict with a high level of confidence the risk of different rates of erosion occurring at any one time.

The analysis was taken one step further by investigating the duration of different levels of erosion. Again the results were very consistent for the four reaches. From the data set out in Appendix A and illustrated in Figure 1.12 it can be seen that for the whole study area the average duration of all categories of erosion rate lie between 3 and 3.5 years, with the extremes (extremely rapid) being closer to the 3 years.

The pattern for extremely rapid, very slow and rapid is very similar (very rapid is distorted by perhaps one or two special cases) with only 20 percent of cases lasting more than 4 years and less than 2.5 years. Thereafter about 5 percent last between 5 and 6 years and neither extremely rapid nor very rapid ever last more than 8 years.

The normal category differs significantly only in that the 5 percent level is extended to almost 7 years, after which the curve tails off rapidly. The slow category stands out distinctly from the others with 20 percent of cases lasting more than 6 years and the 5 percent level approaching 9 years.

In short: most of the time (80 percent) any state will not last more than 5 years, or 6 in the case of "slow", and the likelihood of it lasting more than 8 years is very low. There is however little difference between the categories with the notable exception of "slow".

The pattern is very similar for all reaches. The "slow" category consistently shows the somewhat longer durations but this is particularly exaggerated in Reach 4 and to a lesser degree in Reach 3.

A similar analysis was carried out for the periods of accretion with the results shown in Figure 1.13 and 1.14. The similarity with the equivalent erosion plots is very apparent and provides a very useful guide as to the probable maximum duration of periods of accretion. This has direct relevance to the planning of bank stabilisation works at locations such as Sirajganj and Sariakandi, which are currently experiencing periods of accretion immediately upstream.

1.6 Quantification of Eroding Bend Evolution

The primary objective of this analysis was to determine whether any consistent patterns of anabranch bend behaviour could be discerned as an aid to short-term prediction of bank erosion progression. The focus was on substantial bends that had their concave face contiguous to the bank at the time and were therefore known to be associated with severe bank erosion. For completeness, bends of similar significance eroding central chars and the left bank were also identified.

The only source of data on the planform of bends that is suitable for this purpose is the dry season Landsat imagery dating back to 1973. Bends were identified by comparing the low flow braid pattern in consecutive years and picking out bends that had a recognisable life of more than two years. There is an element of subjectivity in such an approach and this should be taken into consideration when interpreting the results. The first screening produced the following results:

(a) Over the period 1973 to 1990, with gaps in 1974, 1975, 1979, 1982, 1983 and 1989, 29 bends were identified as described earlier; of these 10 were concave to the right bank, 12 to the left bank and the remainder were contiguous to mid-stream chars. Although this is a small sample it may be inferred that there is an approximately equal distribution of bends between both banks.

(b) 6 bends concave to the right bank and 8 concave to the left bank were picked as having lives extending over at least 3 years. These represented only 60 percent and 25 percent respectively of all bends identified during the primary screening. The bend lives ranged from 3 to 7 years with a mean of 4.4 years and standard deviation of 1.2.

(c) The low flow channel widths ranged from 375 m to 1625 m and the radii from 1,000 m to 16,000 m. There was no discernible difference between the left bank and right bank in this respect.

(d) There was no obvious variation in the number of bends active in any one year, although the sample is rather small for such trends to become apparent unless they are very pronounced.

(e) The major active bends tend to be concentrated between Fulchari and Kazipur on the right bank and from opposite Sariakandi down to Bhuapur on the left bank, and a scattering on both banks south of Sirajganj.

(f) Of all bends analysed, only about one quarter displayed a complete life cycle (see Section 3.3.1) moving through steadily tightening radii until they died; it is these bends that do the most damage. Other bends were destroyed by other larger scale channel form developments before they could become fully aggressive.

26

(g) Only four persistent bends have been identified, that is bends that have died and then recurred at almost the same location a few years later. Two were on the right bank and two on the left; the right bank examples are the embayments to the north and south of Sariakandi; the left bank examples are north of Bahadurabad and near Tangail.

(h) Based on this information one could expect 12-15 bends to be active in any one year of which 6 would be on the right bank and 6 on the left. Since the average life span is about 4.5 years, normally only about half of the bends would be in their peak aggressive range at any one time. The situation in 1988 through to 1990 was on these grounds very unusual, with at least six major bends active on the right bank at one time. The 1991 monsoon season, with only three locations reporting severe erosion, is more normal.

Following the rectification and registration of the imagery by the FAP-19 team, a more rigorous selection of bends was made based on the following criteria as described in section 3.3.

The conclusion is that the practical prediction of bend development will always be limited by a low level of confidence. Certain characteristics have been identified that warn of impending development of an aggressive bend but there is a greater than 50 percent chance that any such bend will be overtaken by other developments before it can evolve further. With further analysis as more data becomes available over time it may be possible to identify secondary influences that affect the life expectancy of a bend and thereby to improve the prediction confidence. At present the data set is too small for this to be possible.

One characteristic that is of potential use for planning embankment alignments for relatively short life horizons is that in most cases the aggressive bends have a relatively low ratio of lateral to longitudinal movement. This means that they typically punch into the bankline rather than shave slices off it. However there are exceptions to this rule where the bend has followed the initially lateral movement by a downstream migration and actually regenerated again in a new location. The Kazipur bend is displaying such character traits at present.

1.7 Anabranch Planform Characteristics

The objective of this part of the study was to examine whether it was possible to discern within the very "noisy" low flow channel braid pattern any dominant waveform parameters that could be the basis for planning the long-term stabilisation of the river planform. The parameters of interest being wavelength, amplitude and sinuosity. Again, the most appropriate source of data for this purpose is the dry season Landsat imagery dating back to 1973.

Dominant Waveforms

The first step was to identify sequences of bends forming a clearly discernible cyclical waveform in plan and to trace these off the imagery. The minimum requirement was that one complete cycle was strongly pronounced. It was noticeable while doing this primary screening that in some years it was difficult to pick out any wave forms at all whereas in other years several were apparent. It has to be accepted that there is a strong element of subjectivity in such an approach and the interpretation of the results must be qualified accordingly.

The results of the preliminary sample screening are shown in Table 1.4 from which it can be seen that there appear to be at least two sets of waveforms, (see Figure 1.15) the mean wavelength of one being about double that of the other. It can also be seen that the range of ratio of amplitude to wavelength, which is a rough measure of sinuosity, is rather similar in both sets.

It has been noted earlier that the large bends now evident near Gaffargaon and opposite the Baral (Hurasagar) River confluence on the left bank are of a scale that is found repeated in many places, ranging from the bends on the Wilcox map to old valley edge scars and large scale embayment features on the 1914 map. There can be little doubt that this is a characteristic feature of the Brahmaputra that is persistent through time and which is perhaps its most distinctive fingerprint; it is also a fairly safe inference that these bends represent the limit of the meandering tendency of the river. These bends have reached their climax ratio of radius to low flow width of about 5 to 6 and can be expected to collapse through cut-off development. This evolution is clearly discernible in the case of the Gaffargaon bend on the November 1990 SPOT imagery and 1992 landsat.

The shorter wavelength forms appear to be less persistent and may be related to periods of lower river flow. They are particularly apparent on the March 1988 imagery (i.e before the 1988 floods).

A third set of shorter wavelength forms can be picked out from the larger scale imagery available for 1989. These correspond to the lower chars, or macro bedforms, that in 1989 at least had a characteristic length of 3 to 4 km and width of 1.5 km giving a waveform wavelength of 7 to 8 km and amplitude 2.0 to 2.5 km. This corresponds closely to the pattern of bedforms generated during the 2-D mathematical model applications which have a spacing of about 2 to 4 km. On the basis of the mathematical model results it appears that these macro-dunes can move downstream at a speed of about 30 m/d. It can be seen from the imagery that some cases of bank erosion are certainly associated with this level of char/sandbar (e.g. Chandanbaisa 1989, Jalalpur 1988/89).

As additional imagery data becomes available, further study may shed light on the relationship between these different sets of waveforms. There can be little doubt that they reflect the behaviour of the river in some way and a better understanding of their significance could assist with the prediction of planform evolution.

Bend Geometry

Of particular concern in relation to the hard-point concept of bank stabilisation is the shape of bend that may develop to occupy the reach between two adjacent hard-points. The ratio of bend chord length to the depth of the embayment created by the bend is of key importance when determining the set-back distance for the flood embankment. It had earlier been observed that embayments, which are the vestiges of bends, tend to fall into two categories: one with a chord length of between 8 and 12 km and a depth of about 2 to 2.5 km; the second with a shorter chord length of about 5 km and also of depth about 2 to 2.5 km. An example of the former being the quiescent embayment north of Sariakandi and of the latter the Jalalpur embayment. Preliminary designs were based on the Jalalpur bend as being the most severe embayment that had been identified on the available maps and imagery.

It was subsequently decided that a more systematic approach was required as means of assigning probabilities to the occurrence of embayments with different geometric properties. Since there are insufficient embayments alone for statistical analysis, all well defined bends were picked out from rectified Landsat imagery for the years 1978, 1980, 1984 and 1990 and their chord length, half-amplitude and mean low flow channel width were measured. The chord length was defined as far as possible as the distance between the points of inflexion of the outer bank bankline and therefore corresponds approximately to a half wavelength. Channel widths proved difficult to measure in any consistent manner and should be taken as indicative. The results are shown in Table 1.5 with the bends identified by a number that indicates which of four major morphological divisions of the river it belongs to.

Figure 1.16 shows the cumulative probability plot for the ratio of chord length to depth (half-amplitude). It is clear that while bends on the left bank and the centre of the river, most of which are in contact with chars, have broadly similar characteristics, those on the right bank are generally less sinuous. The median value for the right bank bends being 3.4 compared with 3.0 for the other two categories. Moreover of greater significance, whereas only about 10 percent of right bank bends have a ratio of less than 2.5 more than 30 percent of left bank and central bends fall into this category.

Since this analysis relates to all bends, most of which are very short-lived, whereas embayments can only be formed by bends of several years life, it seems reasonable to accept the ratio of 2.5 as the worst case for the design of hard-points on the right bank. It is also seen from the plot in Figure that very few bends have a chord length of less than 3.5 km and that this therefore provides a convenient indicator for the minimum spacing between hard-points (unless there are over-riding reasons, such as the maximum acceptable depth of the embayment). It is also consistent with the observation that embayments are most frequently associated with major sandbars of more than 3 km in length.

2. CROSS-SECTIONAL CHARACTERISTICS

2.1 Introduction

BWDB Morphology Division annually survey cross-sections across the Brahmaputra River at fixed locations for the length of the river (Table 2.1). During most years a minimum of 32 sections are surveyed and more often when a special need arises. Out of a total of approximately 1000 cross sections that have been surveyed, representing a substantial record of the river from 1964 to the present day, approximately 700 could be located. This data has been analysed by BRTS with the aim of establishing whether there have been morphological trends in the river's development over this period, both over the length of the river and with respect to time.

Cross-sections were surveyed at 2 km intervals during 1986-87 and this detailed record of the river topography has been used in the BRTS 1-D hydrodynamic model of the Brahmaputra River. It was found that the model calibrated with these sections gives a good prediction of water levels for the full 25 year period 1964 to 1989. This indicates that although the sections are continually changing the river was most probably in dynamic equilibrium over this period; that is to say changes over a particular reach may be very significant but properties over the full length of the river remain reasonably constant. Analysis of these cross-sections contributes to the understanding of the morphological changes that have taken place during the last 25 years.

2.2 Sources of Data

The position of each cross-section is defined by permanent pillars located on one or both river banks with the survey team starting from these pillars and traversing the river on a fixed compass bearing. Although the positions of the pillars are defined with respect to land holdings and other features, no longitude or latitude values were available and so, as described in Annex 1 of the Second Interim Report, the locations of 28 of these pillars were fixed to eastings/northings coordinates by a site survey with an accuracy of $\pm$ 100 m. Intermediate cross-sections were interpolated between these known positions to an accuracy estimated to be within 300 m. Figure 2.1 shows the location of the sections fixed by the survey.

All the cross-section data has been received in graphical form from BWDB Morphology Division over a period of approximately four months. The remaining 300 sections (covering years 1970-1976) could not be located despite extensive efforts by BRTS and BWDB staff during this period, including visits to BWDB offices at Bogra, Sirajganj, Gaibandha and Dhaka. Jahangirnagar University was also approached as work was carried out there in the late 1980's which included the appraisal of cross-section data from the Brahmaputra River, and BRTS acknowledge the time and help given by Dr Elahi. The cross-section data used in the study, however, was post 1980, and did not include the block of missing years.

During October 1991 an additional 24 cross-sections were located covering the years 1971-1976, but the coverage during any individual year was very sparse (2 to 8 sections per year) and only partially helped to fill the rather large gap in the database. The absence of these data has substantially limited the scope of the morphological analysis of the data and this in turn effects the confidence limits which apply to predictors of future channel change derived

30

from this analysis.

All the available cross sections have now been collected and incorporated into an extensive database which is included in the backup system used for all computer based files prepared during the BRTS study.

2.3 Data Preparation

2.3.1 Digitising of Cross-sections

All the cross-section data collected from BWDB were in graphical form presented at various scales depending upon the year of the site survey.

The information was transferred from the graphical plots into a database via a digitising tablet involving the following steps:-

- using the digitising tablet, y,z coordinates of the cross-section plot were taken off at points which correctly defined the shape of the section. This included all peaks and troughs and typically there were 150 to 250 pairs of coordinates for each section.

- an additional three points were also digitised from the graph to reference the axis of the plot. These points were referenced by the database programs described below to determine the absolute y,z coordinates. This meant that the graph did not need to be placed on the tablet in a fixed orientation which speeded up the digitisation process and helped maintain quality control. The data taken off using the tablet were input into an AUTOCAD drawing file.

- y,z coordinates of each section were exported from the drawing file as a DXF (data interchange) file which can be read by other software.

- data was read into a database file using a program written specifically for the purpose by BRTS staff; the program reads the DXF file, prompts for the scale of the graph and the coordinates of the origin of the graph's axis, and then uses this information to determine the metric y,z coordinates referenced to PWD datum.

2.3.2 Data Storage

In addition to the database containing the cross-section y,z coordinates other information referenced during the analysis of the sections is required such as the location of the cross-section, bearing of the section line and water levels for particular return periods. In order to store the information in an efficient manner three types of linked database files were set up:

- Physical data taken directly from the graphical output and which are time dependent (Table 2.2).

- Data which relate to the cross-sections, but which are not time dependent, eg bearing of the cross-section from survey pillars and water levels which relate to specific return periods (Table 2.3).

- Results files containing output from the analyses. The structure of these files vary depending upon the type of analysis.

All the data and program files have been stored in a structured set of sub-directories:-

- PROGS - Program files
- FIX - Files common to all years
- Y6465 - Files containing year specific data
  Y6566...

2.4 Preliminary Data Quality Checks

Once the cross-section data were digitised the following quality control checks were carried out:-

- each cross-section was plotted and compared to the original graph.
- a database was set up for each year containing all the cross-sections surveyed during that year. For ease of reference the file name included the survey year eg y8990.dbf for the 1989/1990 survey year.
- as shown in Table 2.2 the file also contains a reference to the number of y,z pairs applicable to each cross-section in the database.
- a program was written to carry out a series of checks on the information contained in each of the databases and also to establish that the databases were internally consistent.

After completion of these quality control procedures a high level of confidence has been established that the data entry was carried out correctly. The accuracy and consistency of the source data was reviewed following the initial analysis of the cross-section data.

2.5 Methodology

2.5.1 General

The key objectives of the analysis of cross section data were to establish whether there are discernable morphological trends between 1964 and 1989 and in particular to determine changes to:-

- cross-section hydraulic parameters with respect to time.
- cross-section hydraulic parameters according to location.

32

- conveyance characteristics longitudinally and with respect to time.

The analysis of the data was completed in two stages; in the first stage the data was pre-processed into a form which could then be rapidly analysed by further programs, each analysing different aspects of morphological change. As described below the pre-processing of the cross-sections involves a large amount of computational time and was carried out on the BRTS micro computers over night and during the weekends. Adopting this approach to the cross-section analysis has meant that a high utilization of the micro computers has been possible. Also having the pre-processed files available for reference allows future analyses to be extremely flexible as the run times are fairly short (usually less than 5 minutes per year of cross section data).

Despite the primary level quality control described in Section 2.4, some significant data irregularities have been identified. Measures taken to address this problem are described in Section 2.6.

2.5.2 Pre-Processing

A program was written to pre-process each cross-section data set into a form which provides information to allow subsequent analysis to be carried out very rapidly.

Each section was divided into a series of vertical slices, one for each y,z pair of coordinates and key parameters determined at a series of levels between thalweg level and 1.0 m above the 100-year flood. Figure 2.2 shows a portion of the results file which was produced by the analysis for each cross-section.

At the end of a run all the output files for a particular year were entered into an archive file (one for each year) for ease of storage - although the individual files are large (typically 50 kbytes each) the archived form takes up much less space (approximately 10 kbytes) and stores the large number of files in a manageable form.

2.5.3 Data Analysis

A series of data analysis programs were written to determine trends in cross-sectional data. This has included programs to determine the various cross-section parameters as described below. As the analysis is only preliminary and further checks on the data quality are required, the outputs shown in this report have been limited to representative samples. In general, "at a section" plots have been produced for sections J14 (approximately 7 km upstream of Fulcharighat) and J7 (adjacent to Sirajganj), while for long section plots the years 1964/65, 1976/77 and 1986/87 have been shown.

Thalweg level

The thalweg level (lowest point in the section) was determined directly from the cross-section data file and did not need to reference the pre-proceed file. A plot of the levels, both at-a-section (Figures 2.3 and 2.4) and also along the length of the river (Figure 2.5) show the large variation in this parameter.

Cross-section area

The total cross-section area was determined for each cross-section under a range of levels to PWD datum (Figure 2.2). To make a comparison between cross-sections the area under levels corresponding to water levels at three flows were determined:-

- 1 in 100 year event
- dominant discharge

Table 2.4 shows the variation for a typical year and Figure 2.6 shows the variation in area (under dominant discharge line) along the length of the river for a sample three years. The plot shows how much the cross section area varies both with respect to time and location on the river.

Figures 2.7 and 2.8 show at-a-section plots of cross-section areas for Sections J-7 and J-14. These sections are typical for most sections and illustrate the large variation in cross-sectional area recorded along the same traverse section line.

Location of centroid of area

The location of the centroid of area under the water levels used in the above analysis were determined and presented as dY and dZ plots, where dY and dZ are the horizontal and vertical distances respectively between the the centre of area of the cross-section area and fixed datums. The objective of this analysis was to give a measure of channel movement. A plot of dZ gives a better indication of the overall channel slope than the thalweg which is highly variable, while dY is a good indication of lateral movement of the channel or a change in which anabranch is dominant within the braid belt.

Figure 2.9 shows the location of dZ along the length of the river for the sample three years while Figures 2.10 and 2.11 show the variation in DY at Sections J-7 and J-14.

Volume of Channel

A direct indication of overall channel erosion or accretion is the change in channel volume below a fixed surface profile; an increase in volume indicates net erosion, while a decrease represents net accretion.

The dominant discharge line was taken as the upper level for the area calculation and the volume calculated by taking each cross-section to be representative of the reach of river up to the mid-way point between it and the adjacent sections. The variation in the total channel volume for the river is large, (Figure 2.12) and as discussed below there appear to be unrealisticly large variations in volume between consecutive years.

Cross-section conveyance

To complement similar work recently undertaken at the SWMC for the 1986/87 cross-sections the variation of hydraulic properties of the sections has been compared for all years by co-registering the plots of the conveyance factor ($AR^{2/3}$) versus depth; a relative stage=30m has

34

been set to correspond to a conveyance factor ($AR^{2/3}$) in each year equal to 140,000, which corresponds to near-bankfull flow (Figures 2.13 to 2.15).

2.6 Data Quality Confidence

The wide scatter of results obtained from initial analyses prompted a closer examination of the original data and this led to the conclusion that there were substantial and largely inexplicable datum shifts at some sections in some years but no obvious pattern to this.

A particularly strong indicator of datum errors is in the plot of total channel volume against time (Figure 2.12), which shows unrealistically large changes in channel volume. In most years the difference is greater than the total annual sediment load normally transported by the river, which, including silt, is of the order of 0.5×10^9 m^3. This is clearly not possible.

A large variation is particularly noticeable between the years 1978/79 and 1979/80 and further plots illustrate that it is likely that this is due to a systematic vertical datum shift between these two years:-

- Figure 2.16 shows a plot of the cross-section area below the dominant discharge line for both years and shows the plot for 1979/80 consistently below that for 1978/79.

- Figures 2.17 and 2.18 show the cross-section plot for two of the cross-sections (J-12-1 and J-13) and in both cases the levels of the flood plain are higher during the later year which could not occur in practice. Further checks of the original plots showed that the data has been correctly digitised from the graphical plots.

The reasons for the other variances are not so clear. A rigorous comparison of all sections from one year to the next revealed a large number of cases where lack of correlation of strong features indicated that there was either horizontal or vertical datum shift or both. In many other cases there was insufficient evidence to determine whether there was an anomaly. After attempts to make corrections were unsuccessful it was concluded that it would be better to accept that there was a substantial error element in the data, which appeared to be in practical terms random, and to interpret the results accordingly.

It is unlikely that the vertical error component exceeds one metre and so trends outside this limit may be considered significant. The sensitivity of area to elevation, particularly in the vicinity of dominant discharge water level means that computations involving area and volume have to be interpreted with great caution. As an example, a 1 m difference at around dominant discharge water level could result in a 20 percent change in the computed area. This is however less than the variation in cross-sectional area that can occur between adjacent sections and from one year to the next.

With the limits of these provisos, the following qualitative interpretations can be made:

- total channel width varies substantially at a section from year to year; the range is greatest in island reaches. The maximum variation is found associated with Islands D and E (5,000 to 15,000 m at dominant discharge level). 60 percent of all surveyed sections had overall channel widths within the range 5,000 to 10,000 m at dominant discharge.

- Individual main anabranch channel mean depth varies from 3 to 10 m but generally lies between 4 and 8 m below the dominant discharge level. Overall channel mean depth varies from 3 to 8 m with a median value of 4.2 m.

- thalweg depth generally varies between 2 and 5.5 times the mean depth but can be as high as 8 times (these higher rates are generally associated with left bank bends). Higher ratios are associated with island reaches; the highest values being linked to Islands D and E. Inter-island reaches a-b and b-c have not experienced ratios higher than 4.0 during the period of the records.

- examination of the long section plots (thalweg and dZ) indicates that within reaches there may be net erosion or deposition occurring over the period 1964-1989, while in terms of overall change for the full length of the river there is no discernable trend.

- there is a marked variation in area at each cross-section; this may be indicative of dunes or sand waves moving through the cross-section. Two nodal sections, one upstream of Island B and the other one downstream of Jalalpur show consistently smaller cross-sectional area, linked with lower channel widths. The nodal sections between Islands B and C and between C and D are less well distinguished.

- Mean cross-sectional velocity during the peak of a 100 year flood varies substantially down the river, with the inter-island reaches displaying values of up to 3.5 m/s it does not normally rise above 2.0 m/s.

- the analysis of conveyance has indicated that, for the purposes of 1-D sediment transport modelling, it is feasible to adequately represent the river channel using one or more equivalent cross-sections.

3. ANALYSIS OF OTHER RIVER PARAMETERS

3.1 Channel Geometry and Dynamics

3.1.1 Determination of the Dominant Discharge

The dominant discharge concept was first put forward by Wolman and Miller (1960). Stated plainly, the concept hypothesises that in rivers which experience a highly variable range of flows, the dimensions and geometry of the channel are determined by the flow which performs the most work, where work is defined as sediment transport. There are other definitions of dominant discharge. For example, Ackers and Charlton (1970) defined it as the steady flow that would produce the same meander wavelength as the observed range of flows within which that steady flow lies. Wolman and Gerson (1978) extended Wolman's original contribution on dominant discharge in arguing that the effectiveness of a flow event reflects the morphological changes it causes through erosion and deposition, as well as the associated sediment transport. These are, however, complementary definitions in that it should be expected from basic principles that the flow doing most work on the channel would be responsible for forming and scaling the salient parameters of its geometry, size and sedimentary features.

A completely different definition, which is not consistent with Wolman and Miller's original concept or Ackers and Charlton's alternative view, was adopted in the JMBA study of the Brahmaputra. They define dominant discharge as "that steady discharge which, had it operated continuously for the period of record, would have transported the same amount of sediment as the range of flows which actually occurred" (JMBA Design Report, Volume II, page A1.2). This corresponds to the flow associated with the time average sediment transport rate. While this definition is often used by mathematical modellers (Olesen, personal communication) but it is not appropriate for use in the geomorphological analysis of river form and process. Although Wolman and Miller's concept has frequently been questioned on theoretical grounds, few people question its usefulness and validity as an analytical device in the geomorphological assessment of rivers and as an aid to river modelling and management.

The analysis was undertaken by the team from the Bangladesh University of Engineering and Technology (BUET) according to the approach suggested by Wolman and Miller (1960). The work was checked independently in the BRTS office. It was based on hydrological and sediment transport records from the Bangladesh Water Development Board (BWDB) gauging station at Bahadurabad. Daily discharge data for the period 1956/7 to 1988/89 were used to construct a flow frequency distribution (Figure 3.1). Sediment transport measurements taken between 1968-1970 for sand load and 1982 - 1988 for both sand and total suspended load could be used to construct a sediment rating curves (Figure 3.2, 3.3 and 3.4).

The equations were all selected for use, to give a comprehensive idea of their impacts on dominant discharge. The equations used are:

1) Total sediment transport (1982-88 data)

   $Q_{st} = 0.91\ Q^{1.38}$ t/day

2) Suspended sand transport (1982-88 data)

$Q_{ss} = 0.93\ Q^{1.25}$ t/day

3) Suspended sand transport (1968-70 data)

$S_l = 4.1 \times 10^{-6}\ Q^{1.38}\ m^3/s$

The last equation was tested specifically to address the fact that this is the curve favoured in the JMBA study (JMBA Report, Vol. 2, Annex B, pages B5/7 and 5/8) and the one preferentially used in the Mathematical Modelling component of the present BRTS study even though it is based on a relatively short period of record, on the grounds that the data quality is considered to be better. The distribution of flows and sediment loads are listed in Table 3.1. The three sediment rating curves are shown in Figures 3.2 to 3.4.

The flow frequency curve was divided into discharge classes with increments of 5,000 m^3/s and the frequency of each class was multiplied by the appropriate sediment transport rate, to produce a total sediment load transported by that discharge class during the period of record (Figure 3.5).

Examination of the total sediment transport distributions in Figure 3.5 shows that the choice of sediment rating has little impact. The distribution is bimodal. The main peak defines the flow doing most work on the channel through the transport of sediment: that is the dominant discharge.

The dominant discharge is defined by the analysis to be 38,000 m^3/s. The much smaller, secondary peak is associated with a discharge of 7,500 m^3/s, which corresponds to base flow for the river and it is possible that some characteristics of anabranch channel geometry, such as low bars and bed forms, may be adjusted to this discharge. The JMBA report quotes a figure of 23,200 m^3/s for dominant discharge. As pointed out earlier, their concept of dominant flow is quite different from that used here.

Noting that a large proportion of the measured sediment load at Bahadurabad is made up of wash load (silt), which notionally plays relatively minor role in forming the channel, the analysis was also performed using the sediment rating curve for suspended sand load only (Figure 3.3). While the absolute amounts of total sediment transported were reduced substantially (Figure 3.5) the distribution was not significantly altered and the dominant discharge was unchanged. It was, therefore, concluded that the dominant discharge of the Brahmaputra River in Bangladesh is about 38,000 m^3/s and this is quite a robust result which is insensitive to the precise nature of the sediment rating curve used to derive it. Comparison to the bankful discharge of 44,000 m^3/s quoted in the JMBA Design Report, shows the dominant discharge to be close to but a little less than this definition of bankfull flow.

This figure also agreed with the dominant discharge quoted in the Study Report by China-Bangladesh Joint Expert Team (CBJET), (1991) of 37,500 cumecs, which was derived in a similar fashion. Examination of the flow duration curve for Bahadurabad (Figure 3.6) indicates that the dominant discharge is equalled or exceeded 18 percent of the time. The return period for dominant discharge is a little less than one year.

These findings are consistent with results for other large rivers and are not at all unexpected. For example, Benson and Thomas (1966) found that the dominant flow in several streams with sediment transported predominately as suspended load, had exceedance frequencies in the range 7.6 to 18.5 percent, and that dominant flow was less than bankfull flow. More recently, Lee and Davies (1986) analysed dominant discharge in braided streams using a physical model. They found that the dominant flow was equalled or exceeded 22 percent of the time that the bed material was in motion, and concluded that dominant discharge is likely to be less than bankfull flow in a braided river.

3.1.2 Determination of Cumulative Sediment Transport Curve

The cumulative sediment transport curves for the three different sediment rating curves in Figures 3.2 to 3.4 and the distribution of flows in Figure 3.1 were determined by progressively accumulating the sediment loads for each discharge class from the lowest to the highest discharge. Each cumulative sediment discharge was expressed as a percentage of the total sediment load transported during the period of record. The data are listed in Table 3.2 and the cumulative curves are plotted in Figure 3.7.

The curves in Figure 3.7 are very similar. All show the distinctive "S" shape of hypsometric curves with a very steep, almost linear increase in cumulative sediment load for discharges between 32,500 and 50,000 m^3/s. Dominant flow (37,000 m^3/s) is also the medium flow for sediment transport with about 50 percent of the load being transported by both higher and lower flows. The Brahmaputra River experiences discharges ranging from 2,500 m^3/s to well over 90,000 m^3/s, but flows between 32,500 and 50,000 m^3/s, a range of only 17,500 m^3/s, are responsible for transporting about forty percent of all the sediment moved by it. Discharges less than about 10,000 m^3/s transport only about 10 percent of the load, and the cumulative contribution of all floods greater than 50,000 m^3/s is less than about 20 percent of the total load, while that of flows greater than 62,500 m^3/s is merely 5 percent and that of flows greater than 70,000 m^3/s, is less than 2 percent. The return period for 70,000 m^3/s is only about 3 years.

The very rapid flattening off of the curve after about 65,000 m^3/s is also of significance since this corresponds closely with both flood plain level and the tops of the major chars. Thus all but a small fraction of sediment transport takes place while the river is flowing within its banks.

These results may surprise many river engineers who view large overbank floods as having great long-term significance in doing work on the channel. The data do not support that conclusion. They do, however, highlight the importance of flows around the dominant discharge in forming the channel, and identify that high in bank flows between 25,000 and 48,000 m^3/s have a disproportionate impact on channel form since they transport about half of the total load.

3.1.3 Specific Gauge Analyses

When analysing the medium to long term behaviour of river, a specific gauge analysis can be used to determine if there are any trends with time in the elevation of the water surface corresponding to a given discharge. The analysis must be based on sound, historical stage-discharge records for a gauging station with an open-river section. In this study, the records from Bahadurabad between 1963/64 and 1988/89 were used. This is the only flow gauging station on the river in the relevant reach and it is the only place that a specific gauge analysis can correctly be performed. The work was carried out by the BUET team and checked by the

BRTS staff. Out of this period, rating curves for the years 1969/70, 1971/72 and 1978/79 were unavailable.

The method of analysis was based on discharges of 7,000, 14,000, 28,000, 42,000, 60,000 and 80,000 m^3/s and the corresponding water stages from the rating curves for the available years. For the 80,000 m^3/s flow, mostly extrapolated values of stage had to be used. Water stages were then plotted versus year of observation on an arithmetic plot (Figure 3.8).

The limitations of the gauging records must be taken into account when interpreting these results (see Annex 2 of the Second Interim Report for a discussion of the magnitude of errors) but with this proviso the following inferences can be drawn.

The results suggest a very slight overall rising trend in water stages for the period of observation. Lates (1988) showed that during the period 1956-68 low water levels (14,000 and 28,000 m^3/s) at Bahadurabad had a rising trend, while intermediate flows (42,000 m^3/s) were constant and the stage associated with high flows (70,000 m^3/s) fell slightly. In the period 1968/69 to 1985/86 the rising trend of the lowest flows (7,000 and 14,000 m^3/s) continues, while the intermediate flows fall slightly and the high flows rise markedly. Since 1985/6 all but the lowest flow (7,000 m^3/s) show a marked reduction in stage (Figure 3.9).

A similar analysis was carried out for Sirajganj but in this case some assumptions had to be made because at site flow measurements were not available. The main assumption was that while the flow remained within bank there was a simple unique relationship between the flow at Bahadurabad and that at Sirajganj on the same day. Best fit relationships were then generated between the water level at Sirajganj and the flow at Bahadurabad for each of the hydrologic years, two power curves were found to give a satisfactory representation in each case. The remainder of the analysis was as for the Bahadurabad data.

The results shown in Figure 3.10 indicate that there has been no significant change in water level for a given discharge and therefore probably no sustained aggradation or degradation of the section. The small trend gradients shown are small in relation to the measurement errors involved and inclusion of data from 1955 to 1960 would actually reverse the trend in some cases. The apparent cyclical trend in water levels is of possible relevance; the amplitude of around 1 m and wavelength of around 7 years is comparable to that observed at Bahadurabad. Although not conclusive this is additional evidence that the river appears to be in dynamic equilibrium.

Stage changes like this are characteristic of a large, braided river with a highly mobile bed. The passage of macro-scale bedforms such as sand waves, and the shifting of braid bars and chars can radically alter the resistance characteristics and water surface topography, so altering the stage-discharge relationship. Also, unsteady flow effects, varying sediment transport rates and bedform hysteresis can produce marked changes during a single annual hydrograph (Vanoni, 1975). The degree of variability observed in the stage-discharge relations is, therefore, to be expected.

Those trends in the data that are maintained for periods of five to seven years are probably not associated with hydraulic roughness or sediment transport effects: they may be representative of systematic trends in the bed level associated with the passage of pulses of sediment moving through the fluvial system. Pulsed movement of bed load is widely observed in rivers. It may be attributed to unsteady supply from outside the channel associated with non-fluvial events such as tectonic events. In the case of the Brahmaputra, sediment inputs associated with major landslides in Assam during earthquakes are known to have occurred (Goswami, 1985). However, bed load pulses are known to develop even in cases of steady sediment supply in flume experiments (Thorne et al., 1987) and so they would probably be a feature of the Brahmaputra with or without the effects of landslides upstream.

Any persistent trend in the stage-discharge relations over the twenty five years period of record could be indicative of net degradation or aggradation of the channel. When analysing the records to identify any trend it would be inappropriate to use least squares regression because of the high degree of `noise' in the data. Instead application of a robust assessment of trend and non-homogeneity based on 3-point moving medians was undertaken. The results indicate that the stage-discharge relations for all six discharges do not show any significant trend at a 5 percent confidence level. It may, therefore, be concluded that the records do not indicate net aggradation or degradation over the whole period of record.

3.1.4 Analysis of the Long-Profile

The long profile of the Brahmaputra River in the study reach has been investigated using the records for the surveyed, monumented cross-sections established by the BWDB (Figure 3.11). As described in Chapter 2 of this Annex, the sections were digitised and entered into a computerised data-base by BRTS. The period covered by available data spans from 1964 to 1989, but with a gap from 1970 to 1976.

The data were used to produce two measures of channel stability. These are the vertical and lateral movement of the centroid of cross-sectional area below the water level at dominant discharge at each surveyed section. In a river with a complex cross-section it is difficult to characterise any overall trends towards aggradation, degradation or lateral instability. The centroid is a good measure of the overall location of the channel and movement of its coordinates can be used to identify both vertical and lateral shifting.

Plots of the vertical (z) elevation of the centroid versus chainage for various periods are shown in Figure 3.12.

Examination of the plots indicates that within reaches there may be net erosion or deposition occurring over the period 1965 to 1989 while in terms of overall charge for the full length of the river there is no discernible trend. Inability to resolve datum errors that appear to be present in data sets for certain years limit any further conclusions based on this data.

3.2 Braiding and Char Building

3.2.1 Braid Bar Inundation

In the study of fluvial geomorphology, alternative definitions of the dominant discharge refer to the most effective flow in doing work on the channel through transporting sediment (Wolman and Miller, 1960) and the discharge responsible for forming the main features of the channel (Ackers and Charlton, 1970). Many researchers have concluded that these two definitions are complementary in that the flow responsible for doing most work and the "channel forming" discharge are one and the same (for example, Hey, 1978 and Andrews, 1980).

In single thread rivers which are in dynamic equilibrium (that is which have alluvial, mobile boundary materials but which are not aggrading, degrading or changing their width through time), the morphological expression of dominant flow is in the bankfull capacity. There is ample evidence from rivers with a wide variety of bed material types that dominant flow equates with bankfull flow in terms of discharge magnitude and, to a lesser extent, in terms of flow frequency (Richards, 1982; Knighton, 1984). However, in multi-thread or braided rivers this is not thought to be the case (Lee and Davies, 1986; Biedenharn et al., 1987). In fact dominant discharge is believed to be less than bankfull discharge in braided rivers.

Nonetheless, it should be expected that if the dominant discharge is actually significant in forming the channel, there should be major morphological features which reflect this through being adjusted to the dominant flow. Perhaps the most prominent features of a braided river are the braid bars (chars) which are responsible for the river's characteristic multi-channel cross-section, very high width/depth ratio, braided planform and shifting nature. Therefore, in this study topic the morphology of the braid bars was investigated in order to determine if there was a clear association with the dominant discharge identified from the analysis of total sediment transport to be 38,000 m^3/s.

A somewhat qualitative approach was adopted, based on visual examination of the water surface elevation corresponding to dominant discharge in relation to char top elevations at all surveyed cross-sections for the 1988/89 survey. Water surface elevations were taken from a preliminary run of the BRTS version of the Mike11 1-D General Model, for a flow of 38,000 m^3/s. The results are given in Table 3.3 and Figure 3.13.

It was immediately clear that there are two distinct char top levels along much of the course of the river. A typical section. (Figure 3.14) shows a high, central char at close to bankfull elevation and lower sandbars on each side, at a little less than dominant flow level. In practically all cases, the dominant flow inundates the lower bars but does not overtop the upper chars. On this basis, dominant flow corresponds to bar topping discharge of these lower level bars. A very close correspondence was found between the top of the upper chars and the bank tops, with the right bank tending to be slightly higher on average and the left bank being almost the same elevation as the upper char top. Hence, for the upper chars to be inundated requires "bankfull" flow of perhaps 60,000 m^3/s, compared to the JMB study estimate of 45,000 m^3/s.

In this respect, the lower chars are "adjusted" to the present dominant flow and are contemporary morphological features. The upper chars, or islands, divide the flow even at dominant discharge and their tops are inactive except during high magnitude, out-of-bank flow events. The upper char, or island surfaces are much more similar to fragments of contemporary flood plain within the braid belt then they are comparable to the contemporary chars. This is also evident from the satellite images and aerial photographs, which show mature vegetation and well developed settlements on the upper char (island) surface but not on the lower active char surfaces.

Closer examination of the lower sandbar elevations reveals a stepped profile with longer, steeper reaches where the elevation difference between the sandbars and chars is a metre or more and the sandbars are well inundated (Figure 3.13), separated by shorter, flatter reaches where the difference is much less and the sandbars are barely inundated at dominant flow.

Investigation of the locations of the steps shows them to be related to planform width and stability variations. At this stage it should be noted that "island reaches" show a clearer separation of upper and lower surfaces than the intervening "cross-over reaches".

It is appropriate to provide some rational explanation of the reason for inundation of chars by dominant flow based on the links between water level, sediment transport rate and channel morphology.

Figure 3.15 shows a schematic representation of flow in a braided channel. At low flow (stage 1), well below sandbar top stage, the active (mobile) width is limited to the anabranches. Even if the sediment transport rate per unit bed width is quite high, the total transport rate for the river is relatively low because of the small proportion of the actual bed width which is active. Even with a substantial rise in discharge and stage (stage 2), and a commensurate increase in unit sediment load, the total load increases only slowly because the active width has not increased substantially.

However, for a small increment of increase in discharge and stage which takes the river to sandbar topping discharge, it may be expected that the sediment transport rate will increase very markedly. This would occur because the active width increases and sediment becomes available for transport across a much larger width including the sandbar tops. The unit sediment transport rate on top of the sanbar may be fairly low, because the depth is small. However, due to hydrodynamic effects and relative roughness the slope will be greater for flow over rather than around the sandbar, so that boundary shear stress may be quite high. Even if the average unit transport rate falls somewhat, the total load increases substantially.

These arguments support the thesis that the sediment transport capacity of the river just above "bar-full" stage should be substantially greater than that just below "bar-full" stage. The increased transport capacity, coupled with much increased sediment availability from the sandbar surface, producing a very marked increase in sediment transport rate. For bankfull flows necessary to inundate the char (island) surface, the whole valley is flooded.

It may be concluded that the dominant discharge of 38,000 m^3/s is responsible for producing the major morphological feature of the Brahmaputra River, that is the contemporary braid bars. The sandbar height is adjusted to be close to, but a little less than, "bar-full" stage, which corresponds to dominant flow. Flows between "bar-full" and bankfull flow would, thus, be particularly important in transporting sediment and forming the channel because of their relatively high frequency and hydraulic efficiency in terms of transport capacity and sediment availability.

The results of the cumulative sediment transport analysis are fully consistent with this explanation, showing the importance of flows between 38,000 and 60,000 m^3/s, that correspond to the bar-full and bankfull range respectively.

Overbank flows are less important because of their lower frequency, low hydraulic efficiency and unchanged sediment availability. Sediment is deposited once stage drops below charfull owing to reduced transport capacity and a reduction in active width. This deflects the flow against the banks, promoting continued bank erosion at these stages, and deposition in anabranch channels.

The discussion presented here is, necessarily, much simplified. In the river the idealised case depicted in Figure 3.15 does not occur, as sanbars are not flat topped and there may be several sandbars of somewhat different elevations within the same reach of braid belt. However, it is remarkable how well the dominant flow discriminates between the sandbar and char (island) levels along the length of the river and at individual cross-sections.

3.2.2 Braiding Intensity on a Reach by Reach Basis

This topic was studied by the BUET team and independently checked and supplemented by BRTS staff.

Preliminary inspection of 1:250,000 scale satellite images of the Brahmaputra River suggested that the Brahmaputra river could be divided into reaches with distinctive and persistent geomorphological features. On the basis of this visual inspection, seven sub-reaches were identified as shown in Figure 3.16. Braiding intensities, number of anabranches and overall braid belt width analyses were carried out for the years 1973, 1978, 1981, 1987, 1989 and 1992. The results are listed in Table 3.4 and are shown graphically in Figure 3.17. The methodology is based on a paper by Howard et at., 1970, which was also used in the JMBA study.

There is a clear overall tendency for braiding intensity, number of channels and overall width to decrease downstream of Sirajganj. This result is consistent with the observation that the river downstream of Sirajganj is closer to adopting a single-thread, sinuous course. However, the results indicate that this is by no means a stable pattern, and the braiding index E is currently as high as 5.0 for the reach immediately downstream of Sirajganj. The width is 7.7 km, which is over 2.5 km wider than in 1989. Generally, however, the lower two sub-reaches have decreased in braid intensity and currently display relatively low E values, fewer anabranches and narrow widths than average for the last sixteen years.

This trend contrasts with that in the upper four reaches. Each has a much higher braiding intensity than in 1973, although the trend is never steady, and higher intensities have occurred in the period of record. Similar trends are also evident in the numbers of anabranch segments (N) and overall widths (C). There is in general a tendency for N and C to increase up to 1987 but then to decline somewhat in the period 1987/89. This could be part of the natural variability or it could be related to the high magnitude flood of 1988 (return period 100 years) which might have had the effect of silting in small char top, island top and flood plain channels and building attached bars at the flood plain margins to reduce both N and C.

However, the inevitable conclusions drawn from Figure 3.17 is that the braiding intensity upstream of Sirajganj is tending to increase, as is the number of anabranches segments and the overall width. Downstream of the Jamuna Bridge site the situation is different, with a slight overall trend towards less intense braiding perhaps, fewer channel segments and a somewhat lower width.

44

3.2.3 Prediction of Confluence Scour from Approach Channel Geometry

The JMBA report proposes a relationship between confluence scour depth (h_s) approach channel depth (h), and approach channel convergence angle (Θ):

$$h_s/h = 1.292 + 0.037\ \Theta$$

where $\bar{h} = (h_1+h_2)/2$ and h_1 and h_2 are the depths in the two approach channels. This relationship was tested using data from Test Area 1 and from the 1986/87 survey. The data and results are given in Table 3.5

Comparison of the monsoon peak and post monsoon surveys for Test Area 1 indicate that contrary to popular opinion bed level in confluence scour holes does not change appreciably with discharge. This was confirmed by the behaviour of the deep scour trench at Kazipur during the monsoons of 1990 and 1991; although the conditions that had created this feature were no longer extant, the depth of the trench was retained almost unchanged during the 1991 monsoon season, although it moved about 800 m downstream. The BRTS 2-D modelling system was able to simulate this movement and also able to create the deep scour downstream of a typical confluence that matched the JMB relationship very closely (see Section 3.5 of this report). However the 2-D modelling also showed that considerably deeper scour could develop depending on the distribution of flow between anabranches. The relationship must therefore be seen as representing the median value with the 95 percent confidence limit being perhaps of the order of 20 percent higher.

3.2.4 Hydraulic Geometry Analysis of Anabranch Channels

The JMBA study gives the following equations for downstream hydraulic geometry.

$$\bar{h} = 0.23\ Q_b^{0.32}$$

$$B = 16.1\ Q_b^{0.53}$$

where:
$\bar{h}$ = Mean depth at bankfull flow (m)
B = Water surface width (m)
Q_b = Bankfull discharge of the anabranch (m^3/sec)

The same study also suggest another set of equation for at-a-station hydraulic geometry.

$$\bar{h} = 0.56\ Q^{0.23}$$

$$B = 18.9\ Q^{0.51}$$

where $\bar{h}$ and B are as defined above and

Q = observed discharge corresponding to the observed values of width and depth.

The validity of the equations has been checked against the data from the surveyed cross-sections and found to be consistent. The degree of variance is however very clear from

45

Figures 3.18 and 3.19. Part of the scatter can be explained by data error; both width and mean depth are very sensitive to stage in the vicinity of dominant discharge as can be clearly from Figure 3.14.

3.2.5 Braiding Intensity Effect on Width and Depth

This study is intended to test whether maximum scour depth and sub-channel width can be predicted form braiding intensity.

The relationship corresponding to dominant flows are to be studied for:

A_L/A_{TOT} vs h_{max}/h_{mean}

A_L/A_{TOT} vs n

A_L/A_{TOT} vs w

where:
A_{TOT} = Total wetted area including all channels
A_L = Area of largest anabranch (=A_{an})
h = Average depth = Total Area/Width
hmax= maximum depth
n = nos. of anabranches

The first part of this analysis was carried out using the historic cross-section as described in Chapter 2 of this Annex. It was found that h_{max}/h_{mean} did not vary significantly with A_L/A_{TOT} (see Figure 3.20) confirming that this characteristic is largely a function of bend and confluence geometry and not anabranch size.

No significant correlation between anabranch size and width could be found other than that shown in Figure 3.18.

The number of anabranches plotted against the ratio A_L/A_{TOT} is shown in Figure 3.21. It can be seen that there is some trend towards a higher ratio as the number of anabranches reduces but this is overlain by a very wide scatter with almost the full range of possibilities covered to a uniform degree.

3.2.6 Comparison of Bank and Char Sediments

Bank erosion on the scale of that occurring on the Brahmaputra generates an enormous supply of sediment to the river, which then does one of three things with this bank derived sediment:

(a) transports it directly out of the study reach and into the Padma River and thence into the Bay of Bengal;

(b) transports it some distance before depositing it temporarily in a bed form (prior to re-eroding it soon afterwards or during the next high flow event);

96

(c) transports it some distance before depositing it into long-term storage in an upper level meta-stable char (island).

The purpose of this topic was to determine the approximate amount of sediment supplied to the river by bank erosion, and the relative amounts going into 1) wash load, 2) suspended and bed load, and 3) char building.
The pilot exercise was carried out using data from the 1986 and 1987 maps contained in the JMBA Report for the reach between sections J-11-7 and J5-6 and the measurements of sediment load at Bahadurabad made during the interval between mapping. The data are given in Table 3.6

The data may be used to calculate the supply of sediment from bank erosion as a percentage of the incoming load measured at Bahadurabad. The data are given in Table 3.7.

The results obtained would indicate that bank erosion in the study reach adds only 8 percent to the measured sediment load coming in from upstream, an amount which, although perhaps not negligible, may be within the margin of error of measurements of the type reported here. However, it is not only the total mass of sediment which is of particular geomorphic importance, but also the size distribution and the relationship between bank erosion and char growth.

The preliminary analysis suggested that the bank material is made up of about 60% sand and 40% silt. When the silt fraction is considered, the contribution to the silt load supplied from upstream is only 3%, which is negligible. But for the sand fraction the yield is 70% of the supply from upstream. That is, the river in this reach must accommodate 1.7 times the input from upstream, in order to remain in dynamic equilibrium. Examining the yield by bank, it is seen that 43% of the supply comes from right bank erosion, but only 27% from left bank erosion.

Additional data and investigation suggested that these figures might be misleading and the computation was accordingly repeated with the results shown in Tables 3.8 and 3.9

The question which immediately springs to mind is: how does the river deal with this large input of relatively coarse sediment. Mostly, it builds chars with it, effectively putting the sand back into the long-term flood plain storage from whence it came. In terms of the sediment pathways described earlier, a large proportion of bank silt yield follows path 1 directly to the Bay of Bengal, although some probably follows path 3 through being deposited on chars and on the flood plain during the falling stages at the end of the snowmelt runoff and monsoon floods. The bank sand yield follows paths 2 and 3, possibly with relatively short travel distances from bank source to char store given the relatively slow speed of movement of bed material load compared to wash load.

Examination of the data in Tables 3.6 and 3.8 shows that the amounts of sand fraction sediment involved in bank erosion and net char deposition are of a very similar order (that is the excess of char growth over char erosion are similar). This suggests that char growth and continued braid belt expansion are approximately balanced by bank erosion, with an almost complete exchange of sediment between the two. Thus sediment exchange is superimposed upon a much larger throughput of silt, and a throughput of sand which is of the same order as the exchange rate.

These results demonstrate the potential value of this form of calculation. Recognition of the intimate link between bank erosion and char growth, and of the pivotal role of the sand size fraction in both processes, have important implications for predicting the river's response to bank stabilization and river training.

Further analysis was therefore carried out using the data generated by FAP-19 from interpretation of Landsat imagery covering the period 1973 to 1992. The river was divided into 500 m wide strips down its length and for each of these the areas of flood plain, char and sandbar was computed by an automated pixel counting technique. The limit of the flood plain was taken as an arbitary fixed boundary on either side of the river. The change of area for each category was then computed by multiplying by the average depth of that element relative to mean level in order to derive the change of volume. These small elements were then aggregated by reach for ease of interpretation, using in this case the reach definitions drawn up by FAP-19/FAP-16 for their char study.

Change in volume of the right bank floodplain was then plotted against char volume change and sandbar volume change respectively. Plots were made for individual reaches for the full period of record, the total study reach for each period and the total reach for the total period.

It was found that there was generally very little correlation between bank volume change and sandbar volume change. In all cases except for Reach 6 (Mathurapara- Island C), where the apparent negative relationship is probably not significant, the best fit line is close or very close to horizontal. The least period change, which is of the order of 1×10^9 kg, is seen in Reach 2 (the Teesta confluence), despite this reach being 66 percent longer than the average, and Reach 10 (Island F - Betil). The others show changes which are about double this amount and Reach 13 (the Ganges confluence) has the highest variation at around three times.

The most striking feature is that the distribution between gain and loss is notably evenly balanced in all cases (see Figure 3.22 as an example) indicating no net change in sandbar volume over the full period in each reach over a period of decades, although substantial changes take place over a period of years. The modest trend indicated in Figure 3.23 cannot be considered significant.

The correlation between bank volume change and char volume change at the Reach level was found to have a somewhat closer correlation but with a wide scatter. The strongest correlation was again found in Reach 6 (Island C) as shown in Figure 3.24, also this time in Reach 10 (Island F). It may be significant that these are both chars at an early period of their development.

The fact that there is generally not a close correlation between floodplain erosion and char growth, nor the converse, suggests that the products of bank erosion travel further than previously thought before finding a suitable site for deposition.

This is reinforced by the plots of char volume change against floodplain volume change for the complete reach on period basis. This time there is a consistent close correlation in all periods except 1978-80, a period of notably little bank erosion activity but some significant loss of char land, and 1980-84 which was a period of both high erosion and high accretion

48

of both floodplain and chars. It is the overall plot for the whole reach for the full period that is of the most significance. This shows a very marked correlation between the products of bank erosion and the growth of chars over the 20 year period, each point on the plot representing the total volume change for one reach.

The overall pattern that emerges is that while the products of erosion in one reach may be transferred to storage in another reach, the balance is in the first reach is naturally redressed within a matter of a few years by the transfer of material from upstream. The overall system thus stays in balance with floodplain erosion being balanced by char growth and sandbar volumes , which represents the main mechanism of sediment throughput, remaining little changed.

The Plot shown in Figure 3.25 suggests that if bank erosion were to be stopped entirely then there would be a gradual reduction in the area of charland. This should not be given too much weight; firstly, the gradient of the line is strongly influenced by the two extreme points and secondly there methodology followed assumes that the effective heights of chars and floodplain are the same, whereas in reality the flood plain will in some reaches be marginally higher. The gradient of the line indicates that bank sand yield is greater than char sand storage by a factor of 16 percent. This small difference can be explained in terms of the proportions of sand to silt in the floodplain and chars assumed for the purposes of this calculation. If the floodplain silt content is taken to be marginally higher than assumed and the char silt content lower then a balance will be attained. (e.g an increase in floodplain silt from 40 to 50 percent would suffice). This is within the confidence limits of the available data. The balance of the silt fraction will become washload and be transported through the river system to the sea.

3.3 Bend Characteristics

3.3.1 Typical Bend Evolution

As a preliminary investigation, data on the migration of eight clearly defined and easily identifiable bends adjacent to the right bank were collected for the period 1987-89 based on cross-sectional records and unrectified Landsat satellite image interpretation. The inferences drawn from this first analysis (see Section 1.6) provide some useful qualitative guidelines but it was found that the quality of the data was not good enough for quantitative analysis. With the advent of rectified satellite imagery one of the main constraints was removed and a follow-up study was undertaken.

The earlier study has indicated the difficulty of finding relatively simple bends that were indicative of general patterns of erosion and that lent themselves to a systematic statistical analysis. More rigorous criteria were drawn up on the basis of the earlier tests to identify suitable "simple" bends that merited closer analysis. Only eight bends met all of the criteria, which were:

(a) the bend should not shift by significant steps but should only move by migrating steadily laterally or longitudinally;

(b) it should contain no confluences or bifurcations;

(c) its width should not change by more than a factor of three between consecutive images;

(d) its width should be greater than 125 m (0.5 mm at the 250,000 scale plots of the images used for this task).

Only eight bends could be identified that met these strict criteria: 3 on the right bank and 5 on the left bank. Short description of the bends and the methodology followed for the analysis are attached as Appendix B.

The bend parameters are described in Table 3.10. Measured migration distances were divided by the time interval to obtain annual rates. Meander bend radius of curvature and anabranch width (both at low flow) were measured for the starting and ending patterns and the values averaged.

The results display a considerable scatter reflecting the various stages that the bends were in at the time. Attempts to plot dimensionless parameters such as E/W and R/W, where E is the lateral displacement, R is the bend radius and W is bend width, generally produced wide scatter and inconclusive results. One possible exception is the plot of E/W against the Angle of Approach of the flow which is shown in Figure 3.26. This suggests that high erosion rates are related to angles of approach in the range 20° to 40° and that angles greater than 50° do not occur.

Some tentative inferences may also be drawn from Figure 3.27 which shows the radius of the centreline of the bend, at low flow, plotted against width. It appears that it is channels with low flow widths in the range 1,000 m and 1,500 m that are the most likely to develop into aggressive bends; smaller channels are unlikely to become aggressive unless their radius is less than 4,000 m. As the radius of the bend tightens beyond 2,000 m the width reduces rapidly and the bend dies. It is emphasised that these are tentative inferences but they are consistent with other observations.

The result of greatest value that emerged was the plot of erosion rate against bend radius shown in Figure 3.28. This shows a very distinct envelope of values illustrating that aggressive and sustained bends fall largely into a relatively narrow band. High erosion rates are associated with bends with radius less than 4,000 m but greater 1,900 m; if the bend radius decreases further the bend becomes unstable and is normally destroyed by a cutoff or washed out. The peak erosion rate shown in the Figure 3.28 relates to Bend H which reached a R_c/W of 2.5 during the 1991 monsoon after which it went into rapid decline. These results are completely consistent with the results of the 2-D mathematical modelling which demonstrated that typical anabranch bends with R/W of 2.0 produced no bend scour and would not sustain themselves.

3.3.2 Bend Scour Depth Prediction

The BENDFLOW computer programme (Developed by Dr. C. R. Thorne and Dr. A. J. Markham from the computer model written by J.S.Bridge) has been used as one approach to the estimation of bend scour. The input data required are:

5D

1) Darcy-Weisbach friction factor $f = \frac{8 g R S}{V^2}$

where:

g = acceleration due to gravity
R = hydraulic radius (approx. equal to mean depth)
S = water surface slope
V = mean velocity

2)	Mean Depth	$\bar{h} = A/W$
3)	Width	W = Water surface width
4)	Meander Wavelength	L = 2 x downvalley length of bend
5)	Sinuosity	P = $\frac{\text{channel length of bend}}{\text{valley length of bend}}$

The program has been used to produce dimensionless curves for the ratio of maximum scour depth to mean depth in the approach channel (Figure 3.29). These curves provide a convenient means of making a preliminary prediction of likely scour but are thought to moderately underestimate scour depths in the Brahmaputra because the computation is based on bed load only, whereas it has been found that suspended bed load also plays a significant role in bed form development.

3.3.3 Bend Velocity Prediction

Investigation of maximum possible near-bank bend velocity is an important aspect of the study because of its implications with regard to the design of bank stabilisation measures. While the main focus during this study has been on the use of 2-D mathematical modelling to investigate this subject, it could be useful to have a simpler tool available to produce less accurate but more readily obtainable values for planning purposes. Accordingly the BENDFLOW model was used to derive the relationships shown in Figure 3.29.

A comparison of predictions using this program with the 2-D hydrodynamic model simulation suggests that BENDFLOW tends to slightly overestimate velocity.

3.4 Bank and Flood Plain Characteristics

3.4.1 Assessment of Bank Condition

The survey of bank conditions along the right bank was performed in the period January-March 1991. The reconnaissance trip from Belka on the Teesta to the confluence with the Ganges was made mostly by boat, but with some land excursions to visit reaches of bank line not accessible from the river because of attached chars. A record of bank condition was made for the entire length of the reach, a distance of 270 km. Detailed assessments of bank condition were made at 28 locations along the reach. Locations were selected to be representative of the surrounding lengths of bank and to detail conditions at sites of particular concern.

Flow erosion and surface erosion (by wind, rain, run-off, ravelling) was observed on all eroding banks. Slab failure was the predominant failure mechanism, although significant sections of bank dominated by granular flow failure were also observed. In two locations the presence of a grey silt-clay layer at the toe of the bank caused seepage and some piping related failure. These locations, Niz Balai-Hatsherpur (119-121 km) and Deluabari-Mathurapara (135-139 km) are located where the bankline is close to the course of the Bangali River. It seems likely that the silt-clay deposit is associated with that river's alluvial valley fill materials.

A plot of the findings is presented in Figure 3.30. It will be noted that there is no obvious correlation between bank material characteristics, shown in Table 3.11, and mean bank erosion rates. In relation to the erosive power of the river, all bank material may be considered highly erodible and it is other factors that determine the erosion rate. Photographs illustrating some typical bank failure mechanisms are included as Figures 3.31 to 3.34.

3.4.2 Flood Plain Geomorphology

The geological and geomorphological maps have been obtained from the Geological Survey of Bangladesh but their scale is such that they have not provided any information that is considered germane to this study. The geomorphological map lacks detail and is probably not as useful as the geomorphic map in Coleman's paper of 1969 (Figure 3 in that paper, on page 136).

REFERENCES

Ackers, P and Charlton, F G (1970). Journal of Hydrology, 230-252

Benson, M.A. and Thomas, D.M. (1966) Bulletin IASH, 11, 76-80

Goswami, D.C. (1985) Water Resources Research, 21(7), 959-978

Lates, E. (1988) DHI Report UNDP/DTCD PROJECT, BGD/81/046, TCD CON 14/84, Part 1

Lee, A-L and Davies T R (1986) Publication 9, Hydrology Centre, Ministry of Works of New Zealand, ISSN0112-1197, 220-229.

Richards, K.S. (1982) Rivers : Form and Process in Alluvial Channels, Methuen.

Thorne C.R. Hey, R.D. and Bathurst, J.C. (1987) Sediment Transport in Gravel-Bed Rivers, J Wiley, Chichester, UK.

Vanoni, V.A. (1975) Sedimentation Engineering, ASCE Technical Manual 54, New York, USA

Wolman, M.G. and Gerson, R. (1978) Earth Surface Processes, 3, 189-208

Wolman, M.G. and Miller, J.P. (1960) Journal of Geology, 68, 54-74.

TABLES

Table 1.1 Spacing of Right Bank Embayments 1989/90

Serial No	Distance from Upstream Feature (km)	Location Name and Comments
1	4.5	Teesta distortion
2	6.5	
3	7.5	Kamarjani
4	8.5	
5	8.5	Fulcharighat
6	6.0	
7	6.0	
8a	8.0	Embayment absent
8b	8.0	
9	8.0	Sariakandi
10a	7.0	Embayment absent
10b	7.0	
11	7.0	Kazipur
12	8.0	
13	7.5	Simla
14	7.5	Sailabari
15	8.0	
16a	8.0	Embayment absent
16b	8.0	Belkuchi
17	3.0	Betil
18	5.5	Jalalpur
19a	7.5	Embayment Absent
19b	7.0	
20	2.5	
21	9.0	
Number of 24 Intervals	174.0	Mean 7.25 km SD 1.59

Table 1.2 Island Reach Parameters (km)

Reach	Island	Length	Width	Comment
1	A	31.0	-	I11 defined
2	B	25.0	7	
	b-c	16.0	-	
3	C	16.0	6	
	c-d	3.0	-	
4 {	D	18.0	6	D and E overlap
{	E	18.0	6	
	e-f	14.0	-	
5	F	18.0	5	
	f-g	12.0	-	
	G	18.0	4	I11 defined

Table 1.3 Proportion of Reach under Erosion, 1973-1992

Period	Reach 1	Reach 2	Reach 3	Reach 4
1973-1976	66.07 %	97.83 %	84.31 %	79.55 %
1976-1978	80.15 %	89.13 %	85.29 %	74.24 %
1978-1980	64.89 %	78.26 %	62.75 %	64.39 %
1980-1984	86.26 %	97.83 %	78.43 %	53.03 %
1984-1987	87.02 %	56.52 %	81.37 %	93.94 %
1987-1990	93.89 %	91.30 %	91.18 %	91.67 %
1990-1992	48.85 %	45.65 %	70.59 %	57.58 %
Mean	74.59 %	79.50 %	79.13	73.48 %

Table 1.4 Some Typical Waveform Characteristics

Image Date	Wave Length L (km)	Amplitude A (km)	L/A
Feb 1973	19.0	2.8	6.8
Jan 1990	17.0	1.8	9.4
Jan 1990	16.5	3.0	5.5
Jan 1976	10.5	1.3	8.1
Mar 1984	10.5	1.5	7.0
Mar 1985	10.0	2.0	5.3
Jan 1977	9.0	1.0	9.0
Dec 1981	8.5	1.5	5.7
Feb 1980	7.5	1.3	5.8
Mean SD	12.1 4.0	1.8 0.6	6.9 1.5

Table 1.5 : Brahmaputra Bend Analysis

(Sheet 1 of 3)

Year	Bend Ref No	L/R/C	Chord Length	Bend Depth	Channel Width	Remarks
1978	2/2	L	3300	1700	300	minor channel
1978	2/4	L	4600	2000	700	main channel
1978	2/5	L	3800	1500	300	abandonned
1978	3/2	L	4000	1700	500	main
1978	3/6	L	4800	1500	600	
1978	3/8	L	6400	3100	700	
1978	3/12	L	5130	1600	800	
1978	3/13	L	5230	2600	600	
1978	3/16	L	11800	3600	-	embayment
1978	4/1	L	14000	3000	900	
1978	4/2	L	8000	2000	-	embayment
1978	4/4	L	6700	2500	800	cutoff
1980	1/2	L	6500	1300	600	
1980	1/5	L	4500	1700	300	
1980	2/1	L	6000	1800	600	
1980	3/3	L	4200	2300	-	
1980	3/5	L	5500	1200	-	embayment
1980	3/6	L	3300	800	400)	
1980	3/7	L	3200	700	400)	same
1980	3/9	L	5300	700	500)	
1980	3/18	L	19300	5000	-)	Bhuapur embay-
1980	3/18b	L	17600	4200	-)	ment - three
1980	3/18c	L	17200	3000	-)	definitions
1980	4/1	L	7000	2500	1000	single channel
1980	4/2	L	8100	2100	-	embayment
1980	4/4	L	8300	2400	-	type embayment
1980	4/5	L	7800	2200	600	
1984	1/1	L	6500	1300	500	
1984	1/3	L	9500	2700	600	type embaymemnt
1984	1/8	L	3500	1200	200	minor channel
1984	2/3	L	5000	1400	-	embayment
1984	3/4	L	4600	1900	1000	
1984	3/10	L	7000	1300	600)	
1984	3/15	L	6400	2500	400	
1984	4/2	L	8000	2900	1000	
1984	4/4	L	8300	3300	1000	
1990	1/2	L	7000	2100	700	shallow
1990	2/1	L	6500	1300	900	
1990	2/6	L	8500	2600	700	
1990	3/1	L	2800	1100	600	
1990	3/4	L	9000	3500	700	v aggressive bend
1990	3/6	L	4200	2500	200	minor
1990	3/7	L	4700	2000	100	minor
1990	3/9	L	7000	1900	400	
1990	4/4	L	11300	4500	-	embayment
1990	4/5	L	9000	4000	800	shoaling, R=200

Table 1.5 : Brahmaputra Bend Analysis

(Sheet 2 of 3)

Year	Bend Ref No	L/R/C	Chord Length	Bend Depth	Channel Width	Remarks
1978	1/1	R	5020	1700	650	
1978	1/3	R	5100	1800	200	remnant
1978	1/5	R	5750	1500	200	remnant
1978	2/7	R	7200	2300	-	embayment
1978	2/8	R	5800	1800	-	embayment
1978	3/1	R	7800	2100	500	three
1978	3/5	R	7800	1800	600	major of 3
1978	3/7	R	2400	700	200	minor Chan
1978	3/10	R	5000	1500	200	minor chan
1978	3/14	R	5120	2000	300	abandonned
1978	3/15	R	15300	3500	800	notional
1978	4/3	R	13000	3500	1000	
1978	4/5	R	14000	4000	1000	
1980	1/3	R	9500	2500	-	abandonned
1980	1/5	R	11200	2400	500	
1980	2/2	R	2000	750	400	
1980	2/4	R	6400	1800	-	embayment
1980	3/1	R	7000	2200	400)	channel
1980	3/2	R	10200	3000	-)	embayment
1980	3/15	R	3000	800	300	
1980	3/19	R	3800	1000	-	embayment
1980	4/3	R	9000	3500	1000	
1980	4/6	R	11950	6200	1000	
1984	1/2	R	4700	1300	500	
1984	1/9	R	3800	1000	-	embayment
1984	1/10	R	3500	1200	-	embayment
1984	2/1	R	4700	1700	-	old embayment
1984	2/4	R	5000	1800	400	
1984	3/1	R	6500	1200	400)	
1984	3/2	R	4700	1100	400)	
1984	3/3	R	8300	2100	400	
1984	3/5	R	5200	900	-	embayment
1984	3/6	R	3700	1100	400)	
1984	3/9	R	8600	2500	-)	embayment
1984	3/13	R	7600	2400	-)	Sirajganj embay
1984	4/1	R	5000	1700	200	minor channel
1984	4/3	R	9200	2100	400	embayment
1984	4/5	R	16500	4600	1000	
1990	1/4	R	8500	2000	800	
1990	2/3	R	6800	1300	900	abandonned
1990	2/4	R	12000	3300	1000	
1990	3/3	R	8000	1800	-	embayment
1990	3/5	R	6000	1600	650	Kazipur
1990	3/8	R	6300	1800	700	Simla
1990	4/1	R	4300	2100	400	Jalalpur (cutoff)
1990	4/3	R	6800	1700	400	
1978	2/1	R(C)	10000	3800	1300	main channel

Table 1.5 : Brahmaputra Bend Analysis

(Sheet 3 of 3)

Year	Bend Ref No	L/R/C	Chord Length	Bend Depth	Channel Width	Remarks
1978	1/2	C	5370	1900	1100	indistinct
1978	1/4	C	4500	1400	700	
1978	2/6	C	4200	1400	600	
1978	3/3	C	4000	2600	500	channels
1978	3/4	C	6800	1800	500	
1978	3/9	C	5000	2900	400	
1978	3/11	C	15700	3500	900	
1980	1/1	C	10300	2900	700	main channel
1980	1/4	C	6600	1400	300	
1980	2/3	C	4000	1000	400	
1980	2/5	C	6000	1600	500	
1980	3/4	C	4400	1700	300	
1980	3/10	C	4400	1100	500	
1980	3/11	C	7200	2000	600	
1980	3/12	C	3000	1700	300	
1980	3/13	C	4200	1400	400	
1980	3/14	C	6500	1600	1000	
1980	3/16	C	3600	800	400	embayment
1980	3/17	C	3300	800	400	embayment
1984	1/4	C	4600	1400	600	
1984	1/5	C	4300	1600	600	
1984	1/6	C	4000	1800	400	
1984	1/7	C	4800	1600	400	
1984	2/2	C	5200	1100	700	
1984	2/5	C	4400	2300	400	
1984	3/7	C	6500	1500	500)	
1984	3/8	C	5300	1500	600)	
1984	3/11	C	5300	2000	400	
1984	3/12	C	6000	1500	600	
1984	3/14	C	4500	1600	400	
1990	1/1	C	7500	1700	400	
1990	1/3	C	8700	2200	1000	
1990	2/2	C	10000	2700	1000	
1990	2/5	C	5200	2000	700	
1990	3/2	C	3500	1800	400	
1990	3/10	C	5500	1800	300	minor
1990	3/11	C	5700	1800	300	minor
1990	4/2	C	5500	2000	600	
1990	4/6	C	4000	1900	200	minor
1978	2/3	C(R)	5700	1600	700	

Table 2.1 Cross Sections Surveyed Between 1964 and 1989

(Sheet 1 of 3)

Year	Description of Cross-Section	Total No. Cross Section	Approx Interv (mile)	Total No. Cross Section on Database
1964-65	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	17	8	16
1965-66	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	34	4	34
1967-68	Between Aricha & Indo-Bangladeh border C.S. No. J-0-1 to J-17	34	4	34
1968-69	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	34	4	34
1969-70	a) Between Aricha and Bahadurabad C.S. No. J-0-1 to J-12	24	4	34
	b) Near Bahadurabad C.S. No. J-12-4 to J-13	9	1	
	c) Between Bahadurabad and Teesta outfall C.S. No. J-13-8 to J-15-1	48	0.5	
	d) Between Teesta outfall and Chilmari C.S. No. J-16-7 to J-16-1	8	1	
	e) Above Chilmari C.S. No. J-17	1	4	
1970-71	a) Between Aricha and Bahadurabad C.S. No. J-0-1 to J-12	24	4	
	b) Near Bahadurabad C.S. No. J-12-4 to J-13	9	1	
	c) Between Bahadurabad and Teesta outfall C.S.No. J-13-8 to J-15-1	48	0.5	
	d) Between Teesta outfall and Chilmari C.S. No. J-16-7 to J-16-1	8	4	
	e) Above Chilmari C.S. No. J-17	1	1	
1971-72	a) Between Aricha and Bahadurabad C.S. No. J-0-1 to J-12	24	4	3
	b) Near Bahadurabad C.S. No. J-12-4 to J-13	9	1	
	c) Between Bahadurabad and Teesta outfall C.S. No. J-13-8 to J-15-1	48	0.5	
	d) Between Teesta outfall and Chilmari C.S. No. J-16-7 to J-16-1	8	1	
	e) Above Chilmari C.S. No. J-17	1	4	

Table 2.1 Cross Sections Surveyed Between 1964 and 1989

(Sheet 2 of 3)

Year	Description of Cross-Section	Total No. Cross Section	Approx Interv (mile)	Total No. Cross Section on Database
1972-73	a) Between Aricha and Bahadurabad C.S. No. J-0-1 to J-12	24	4	7
	b) Near Bahadurabad C.S. No. J-12-4 to J-13	9	1	
	c) Between Bahadurabad and Teesta outfall C.S. No. J-13-8 to J-15-1	48	0.5	
	d) Between Teesta outfall and Chilmari C.S. No. J-16-7 to J-16-1	8	1	
	e) Above Chilmari C.S. No. J-17	1	4	
1973-74	a) Between Aricha and Bahadurabad C.S. No. J-0-1 to J-12	24	4	2
	b) Between Bahadurabad and Chilmari C.S. No. J-12-4 to J-16-1	41	1	
	c) Above Chilmari C.S. No. J-17	1	4	
1974-75	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	34	4	1
1975-76	a) Between Aricha and Sirajganj C.S. No. J-0-1 to J-4	8	4	8
	b) Between Jagannathgonj and border			
1976-77	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	34	4	34
1977-78	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	34	4	34
1978-79	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	34	4	34
1979-80	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17	34	4	34
1980-81	a) Between Aricha and Bahadurabad C.S. No. J-0-1 to J-13	94	1	34
	b) Between Bahadurabad near Fulchari Cross Dam site and Teesta outfall C.S. No. J-13-11 t J-14-8/2	15	1	
	c) Between Teesta outfall and Indo-Bangladesh bordder C.S. No. J-14-8 J-18-3	34	1	

Table 2.1 Cross Sections Surveyed Between 1964 and 1989

(Sheet 3 of 3)

Year	Description of Cross-Section	Total No. Cross Section	Approx Interv (mile)	Total No. Cross Section on Database
1982-83	Nil			
1983-84	Between Aricha and Noonkowa Indo Bangladesh border from C.S. No. J-0-1 to J-17-1	34	4	34
1984-85	- do -	34	8	25
	Between Bir Bangabari, Upazila Islampur & Goaldoba, Islampur Jamalpur at barrage site C.S. No. JN-1 to JK-5 = 6 Nos. (6 Nos. x 4 rounds)	24	1.34	
1985-86	a) At Sirajganj C.S. No. JS-1 to J-6 = 8 Nos.	8	1	38
	b) As in 1984-85 C.S. No. JN-1 to JN-5 = 6 Nos. (6 Nos. x 2 rounds)	18	1.34	18
1986-87	a) As in 1984-85 C.S. No. JN-1 to JN-5 = 6 Nos. (6 Nos. x 2 rounds)	12	1.34	122
	b) Between Aricha & Noonkowa C.S. No J-0-1 to J-17-1	126	1	
1988-89	Between Aricha & Indo-Bangladesh border C.S. No. J-0-1 to J-17			33

Table 2.2 Sample of Cross-section Database
(taken from year 1988/89)

Node/ Nos of Coordinates	Coordinates	
	Y (m)	Z (m PWD)
JN3	0.00	18.64
249	60.96	18.50
	102.41	18.71
	103.94	18.88
	121.31	18.43
	122.83	18.99
	125.88	18.97
	127.41	18.05
	164.90	17.60
	286.82	18.43
	347.78	18.31
	408.74	18.66
	469.70	18.10
	530.66	18.29
	591.62	18.12
	919.28	18.17
	.	.
	.	.
	.	.
	12609.58	15.62
	12640.06	16.72
	12666.57	18.98
	12681.81	18.98
J15	0.00	21.64
249	60.96	21.34
	121.92	21.51
	182.88	21.47
	213.66	21.65
	218.54	23.37
	226.16	23.38
	233.48	22.16
	233.48	22.45
	259.69	21.42
	336.50	20.26
	397.46	20.41
	458.42	21.12
	546.51	21.55
	607.47	21.44
	.	.
	.	.
	.	.

Table 2.3 Database Containing Non Time Dependent Variables

(Sheet 1 of 3)

Node	Chainage (BRTS km)	Pillar (LB/RB)	Bearing (deg to N)	Adjustment Factor	Water Levels (m PWD)		
					100 Year	Dom Disch	2 Year Dry
J17_1	16.60	R	89.00	0.94	26.81	25.33	20.60
J17_2	18.32	R	89.00	0.94	26.66	24.99	20.21
J17_3	20.05	R	89.00	0.95	26.52	24.66	19.82
J17_4	22.52	R	89.00	0.94	26.32	24.15	19.27
J17	25.00	R	89.00	0.94	26.13	23.65	18.71
J17_5	26.60	R	89.00	0.96	26.01	23.32	18.35
J17_6	28.05	R	89.00	0.98	25.88	23.02	18.02
J17_7	29.75	R	89.00	0.99	25.75	22.81	17.64
J16_1	31.35	R	89.00	0.99	25.62	22.62	17.28
J16_2	32.40	R	89.00	0.99	25.53	22.48	17.15
J16_3	33.60	R	89.00	1.00	25.43	22.33	17.01
J16_4	35.35	R	89.00	0.98	25.29	22.06	16.91
J16	37.10	R	89.00	0.97	25.14	21.84	16.72
J16_5	39.85	R	89.00	0.94	24.90	21.57	16.45
J16_6	42.60	L	269.00	0.91	24.65	21.30	16.18
J16_7	43.43	R	89.00	0.91	24.58	21.26	16.11
J15_1	44.25	R	89.00	0.91	24.50	21.21	16.03
J15_2	48.60	L	269.00	0.97	24.11	20.97	15.95
J15_3	53.15	R	89.00	0.99	23.70	20.73	15.88
J15_4	54.40	R	89.00	0.99	23.59	20.63	15.81
J15	55.65	R	89.00	0.99	23.47	20.52	15.74
J15_5	56.90	R	89.00	0.99	23.36	20.43	15.63
J15_6	59.10	L	269.00	0.99	23.16	20.28	15.43
J15_7	61.20	R	89.00	0.98	22.97	20.09	15.27
J14_1	63.30	R	89.00	0.98	22.78	19.89	15.11
J14_2	65.30	L	269.00	0.99	22.60	19.64	14.81
J14_3	67.30	L	269.00	1.00	22.42	19.38	14.51
J14_4	69.25	L	269.00	1.00	22.25	19.24	14.23
J14	71.20	R	89.00	1.00	22.07	19.09	13.95
J14_5	73.40	L	283.50	0.97	21.88	19.01	13.90
J14_6	75.60	L	283.50	0.95	21.68	18.92	13.84
J14_7	77.48	L	283.50	0.95	21.51	18.83	13.59
J14_7_1	80.10	R	103.50	0.96	21.27	18.67	13.50
J13_2	81.23	R	103.50	0.96	21.17	18.60	13.37
J13_1	81.70	L	261.00	0.97	21.13	18.57	13.31
J13_3	83.10	R	103.50	0.99	21.00	18.53	13.27
J13_4	83.20	R	103.50	0.99	20.99	18.52	13.26
J13	84.70	L	260.00	0.98	20.88	18.43	13.14
JN5	86.40	L	270.00	0.98	20.79	18.30	12.97
JN4	88.00	L	270.00	0.98	20.71	18.17	12.80
JN3	90.90	L	269.00	0.99	20.57	17.95	12.57
J12_1	93.80	L	269.00	0.99	20.42	17.72	12.34
JN2	95.50	L	269.00	0.99	20.33	17.62	12.22
JN1	98.00	L	269.00	1.00	20.21	17.48	12.10
J12	100.50	L	277.18	1.00	20.08	17.34	11.97
J12_5	101.55	R	95.00	1.00	20.02	17.26	11.90
J12_6	103.90	L	275.00	1.00	19.90	17.08	11.74
J12_7	106.40	L	275.00	0.96	19.78	16.95	11.64

Table 2.3 Database Containing Non Time Dependent Variables

(Sheet 2 of 3)

Node	Chainage (BRTS km)	Pillar (LB/RB)	Bearing (deg to N)	Adjustment Factor	Water Levels (m PWD)		
					100 Year	Dom Disch	2 Year Dry
J11_1	108.90	L	235.00	0.92	19.65	16.81	11.53
J11_2	111.50	L	235.00	0.93	19.52	16.62	11.41
J11_3	113.40	L	235.00	0.93	19.42	16.48	11.33
J11_4	115.15	L	235.00	0.96	19.27	16.11	10.84
J11	117.50	L	235.33	0.99	19.07	15.99	10.27
J11_5	119.88	L	235.00	0.95	18.87	15.82	10.15
J11_6	122.25	L	235.00	0.91	18.67	15.66	10.09
J11_7	124.38	L	269.00	0.95	18.48	15.57	10.06
J10_1	126.50	L	245.00	1.00	18.28	15.47	10.02
J10_2	128.50	L	245.00	1.00	18.10	15.36	9.97
J10_3	130.50	L	245.00	1.00	17.92	15.25	9.91
J10_4	132.50	L	245.00	0.98	17.75	15.06	9.77
J10	134.50	L	255.00	0.96	17.58	14.87	9.62
J10_5	135.65	L	255.00	0.96	17.47	14.73	9.49
J10_6	136.80	L	255.00	0.97	17.36	14.60	9.37
J9_1	139.00	L	245.00	1.00	17.16	14.45	9.27
J9_2	140.40	L	245.00	1.00	17.04	14.30	9.17
J9_3	141.80	L	245.00	1.00	16.91	14.14	9.07
J9_4	142.02	L	269.00	0.98	16.89	14.12	9.05
J9_5	142.23	L	245.00	0.97	16.87	14.08	8.98
J9	142.45	L	270.00	0.95	16.85	14.04	8.92
J9_6	143.45	L	270.00	0.95	16.76	13.87	8.78
J9_7	144.43	L	270.00	0.96	16.68	13.76	8.69
J8_1	145.40	L	274.08	0.97	16.59	13.64	8.60
J8_2	146.48	L	272.00	0.97	16.50	13.56	8.53
J8_3	147.55	L	272.00	0.97	16.40	13.47	8.46
J8_4	148.53	L	272.00	0.95	16.32	13.39	8.42
J8	149.50	R	100.00	0.93	16.23	13.30	8.37
J8_5	150.63	L	280.00	0.94	16.13	13.22	8.33
J8_6	151.75	L	280.00	0.95	16.03	13.14	8.29
JS1	153.37	R	90.00	0.97	15.89	13.04	8.11
JS2	154.98	R	90.00	0.98	15.75	12.93	7.92
J7_1	156.60	R	90.00	1.00	15.61	12.83	7.74
JS3	158.50	R	90.00	1.00	15.44	12.69	7.12
JS4	160.43	R	90.00	1.00	15.27	12.53	6.91
J7	162.35	R	90.00	1.00	15.10	12.36	6.69
JS5	164.48	R	90.00	1.00	14.98	12.21	6.59
JS6	166.60	R	90.00	1.00	14.85	12.05	6.48
J7_7	168.68	R	89.00	1.00	14.73	11.94	6.39
J6_1	170.75	R	90.00	1.00	14.60	11.82	6.29
J6_2	172.53	R	90.00	1.00	14.50	11.60	6.20
J6_3	174.30	L	270.00	1.00	14.39	11.38	6.11
J6_5	175.00	L	270.00	1.00	14.35	11.31	6.05
J6_4	176.00	R	90.00	1.00	14.29	11.21	5.96
J6	177.70	L	270.00	1.00	14.19	11.04	5.81
J6_6	179.20	L	270.00	1.00	14.10	10.96	5.60
J6_7	179.90	L	270.00	1.00	14.06	10.93	5.46
J5_1	180.60	R	90.00	0.99	14.02	10.89	5.32

Table 2.3 Database Containing Non Time Dependent Variables

(Sheet 3 of 3)

Node	Chainage (BRTS km)	Pillar (LB/RB)	Bearing (deg to N)	Adjustment Factor	Water Levels (m PWD)		
					100 Year	Dom Disch	2 Year Dry
J5_2	183.00	L	270.00	0.99	13.88	10.71	5.14
J5_3	185.70	L	270.00	0.99	13.72	10.51	4.94
J5	188.20	R	90.00	1.00	13.57	10.32	4.76
J5_5	189.98	L	270.00	1.00	13.47	10.15	4.53
J5_6	191.75	L	270.00	1.00	13.36	9.97	4.29
J4_1	195.75	R	89.00	0.99	13.12	9.71	3.52
J4_2	196.70	R	89.00	0.99	13.07	9.65	3.43
J4_3	197.65	R	89.00	0.99	13.01	9.59	3.34
J4_4	198.87	R	89.00	0.99	12.94	9.50	3.30
J4_4_1	200.08	L	269.00	0.99	12.86	9.40	3.26
J4	201.30	L	290.00	0.99	12.79	9.31	3.22
J4_5	202.23	R	108.42	0.99	12.73	9.30	3.21
J4_6	203.30	L	288.42	0.99	12.67	9.29	3.20
J4_7	204.19	R	108.42	0.98	12.62	9.26	3.20
J3_1	205.15	R	108.42	0.98	12.56	9.23	3.19
J3_2_1	207.18	R	112.53	0.97	12.44	9.21	3.18
J3_2	209.22	R	112.53	0.97	12.32	9.20	3.17
J3_3	211.25	R	112.53	0.97	12.20	9.18	3.16
J3_4	212.23	R	112.53	0.97	12.15	9.15	3.14
J3	213.20	L	292.50	0.97	12.09	9.11	3.12
J3_5	214.85	R	89.00	0.97	11.99	9.04	3.06
J3_6	216.50	R	82.58	0.97	11.89	8.96	2.99
J3_7	218.25	R	89.00	0.99	11.80	8.90	2.95
J2_1	220.00	R	82.58	1.00	11.70	8.87	2.89
J2	223.20	L	216.10	0.72	11.54	8.68	2.65
J1_1	229.40	L	231.60	0.97	11.24	8.49	2.29
J1	230.75	L	250.00	1.00	11.17	8.48	2.28
J0_1	235.50	L	266.00	0.82	10.94	8.05	2.22

Table 2.4 Sample Output Showing Cross-section Area and Centroid 1986-87

(Sheet 1 of 3)

Node	Chainage (Km)	1 in 100 Year Water Level					Water Level at Dominant Discharge					1 in 2 Low Water Level				
		WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)	WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)	WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)
J17_1	16.60	26.81	41783	23.45	4313	6850	25.33	31797	22.52	4065	6311	20.60	7698	18.95	3079	2915
J17_2	18.32	26.66	36610	23.31	4073	6585	24.99	26039	22.02	3906	5582	20.21	6465	18.85	3414	2860
J17_3	20.05	26.52	49335	23.38	5287	8735	24.66	33808	22.19	5109	7733	19.82	7427	18.08	4585	2602
J17_4	22.52	26.32	60917	23.28	6636	10908	24.15	38066	21.80	6233	10098	19.27	5002	18.41	3558	3885
J17	25.00	26.13	53827	23.26	6765	9744	23.65	30407	21.64	6663	8947	18.71	5226	17.25	3456	2051
J17_5	26.60	26.01	46997	22.57	5931	7664	23.32	27822	20.74	5832	6081	18.35	4419	17.35	1877	2773
J17_6	28.05	25.88	45240	22.91	7067	8607	23.02	23231	20.33	6752	6094	18.02	5669	16.41	2625	2036
J17_7	29.75	25.75	54309	22.36	6418	8542	22.81	30342	20.56	4997	7306	17.64	3427	16.66	2084	2234
J16_1	31.35	25.62	59113	22.08	5315	8800	22.62	33685	20.09	4504	7737	17.28	5432	15.86	3049	2631
J16_2	32.40	25.53	57002	22.05	5345	8632	22.48	31741	20.04	4214	7617	17.15	4708	15.72	2997	2338
J16_3	33.60	25.43	44611	21.91	4831	7097	22.33	24414	19.00	4817	5105	17.01	8493	11.84	4792	1577
J16_4	35.35	25.29	40229	22.28	3728	7506	22.06	18985	18.29	3065	4667	16.91	7626	13.08	2623	1218
J16	37.10	25.14	71530	22.30	11623	14500	21.84	32034	18.87	12092	7464	16.72	8819	14.35	11457	2626
J16_5	39.85	24.90	62899	21.42	7305	9767	21.57	32575	18.87	7304	7460	16.45	6844	14.47	3727	2792
J16_6	42.60	24.65	74556	21.15	8904	11815	21.30	38698	18.93	9178	9494	16.18	5571	15.17	4439	3461
J16_7	43.43	24.58	50457	21.91	7101	10032	21.26	20548	19.33	5172	6988	16.11	3630	14.06	4331	1148
J15_1	44.25	24.50	95455	21.18	10605	15946	21.21	48046	18.30	9926	9842	16.03	11250	14.19	8637	4333
J15_2	48.60	24.11	65078	20.56	7206	10694	20.97	35854	18.25	5599	8253	15.95	10776	11.39	4954	2080
J15_3	53.15	23.70	72428	20.40	6948	11447	20.73	39302	17.92	7410	10206	15.88	10774	14.02	4886	3659
J15_4	54.40	23.59	67485	20.27	6762	11298	20.63	37190	18.12	6235	9548	15.81	9483	13.81	6138	2912
J15	55.65	23.47	61059	20.45	7651	11287	20.52	31079	18.05	6919	7886	15.74	6692	14.27	5654	2622
J15_5	56.90	23.36	54513	20.23	5281	10326	20.43	28745	18.30	3927	7600	15.63	3017	15.01	1670	2148
J15_6	59.10	23.16	66432	19.34	6696	9465	20.28	40818	17.66	5619	8169	15.43	8084	14.26	3774	4122
J15_7	61.20	22.97	48666	19.28	5050	7109	20.09	29222	17.46	4950	6131	15.27	7376	13.19	4991	2277
J14_1	63.30	22.78	53456	19.97	9077	10920	19.89	26275	17.13	8453	6642	15.11	6966	13.45	5716	2670
J14_2	65.30	22.60	70713	19.69	8701	13202	19.64	34998	17.07	7048	8723	14.81	7868	13.03	4775	2703
J14_3	67.30	22.42	62910	19.86	8404	12595	19.38	27143	17.31	6368	8793	14.51	3465	13.41	4301	1947
J14_4	69.25	22.25	73629	19.43	10233	13846	19.24	34864	16.66	10675	9042	14.23	6010	13.16	6701	3624
J14	71.20	22.07	84133	19.33	12953	16862	19.09	39189	16.45	14250	10431	13.95	8609	12.33	8001	3019
J14_5	73.40	21.88	95446	18.86	14706	19103	19.01	49358	16.41	9161	12046	13.90	9335	12.36	4811	4261
J14_6	75.60	21.68	80815	18.77	10063	15137	18.92	41863	16.28	5998	10898	13.84	10639	11.63	5920	2999
J14_7	77.48	21.51	72381	18.86	9947	14173	18.83	35906	16.53	5490	12080	13.59	6268	12.10	3444	2400
J14_7_1	80.10	21.27	71502	18.43	10242	13413	18.67	38204	16.23	10240	11070	13.50	8513	11.33	9812	2722
J13_2	81.23	21.17	70383	18.29	10676	13082	18.60	38345	15.91	11488	10540	13.37	9113	11.71	10740	3408
J13_1	81.70	21.13	70091	18.58	11270	15687	18.57	34907	16.11	5943	9467	13.31	6947	11.76	4331	2571
J13_3	83.10	21.00	71749	17.80	8625	11792	18.53	43245	16.08	6867	10637	13.27	8053	11.50	1691	3048
J13_4	83.20	20.99	58921	18.37	9147	11580	18.52	31006	16.30	9065	10248	13.26	5891	11.47	9923	1964
J13	84.70	20.88	59935	18.12	6819	12360	18.43	32483	15.69	7134	8579	13.14	7764	11.41	2136	2833
JN5	86.40	20.79	53914	18.09	6790	11873	18.30	28547	15.45	6904	6905	12.97	6393	11.20	2026	2343
JN4	88.00	20.71	55080	18.25	6471	12251	18.17	26820	15.58	7025	7760	12.80	5585	11.36	2266	2482
JN3	90.90	20.57	63367	17.58	8066	12711	17.95	34424	15.39	7454	8349	12.57	4967	11.41	3653	2839

Table 2.4 Sample Output Showing Cross-section Area and Centroid 1986-87

Node	Chainage (Km)	1 in 100 Year Water Level					Water Level at Dominant Discharge					1 in 2 Low Water Level				
		WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)	WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)	WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)
J12_1	93.80	20.42	62417	17.76	8412	12577	17.72	30867	15.31	7790	8867	12.34	5423	10.87	5405	2268
JN2	95.50	20.33	68684	17.57	8854	13153	17.62	34802	15.14	8311	10227	12.22	5973	10.73	8726	2493
JN1	98.00	20.21	60457	17.88	9085	13465	17.48	26219	16.01	6289	10297	12.10	498	11.48	9122	333
J12	100.50	20.08	71577	17.43	8939	14901	17.34	34913	14.52	8794	9059	11.97	7463	10.49	7592	2948
J12_5	101.55	20.02	68531	17.59	6469	14762	17.26	30605	14.74	5918	8938	11.90	5417	10.36	4696	2365
J12_6	103.90	19.90	64499	17.62	8883	15172	17.08	26871	14.57	8620	7594	11.74	4592	10.34	7176	2142
J12_7	106.40	19.78	48382	17.89	8065	14239	16.95	18068	14.15	7255	4505	11.64	4385	10.07	6640	1677
J11_1	108.90	19.65	78154	16.55	10831	14321	16.81	41390	13.68	10848	9382	11.53	10483	10.14	6905	4135
J11_2	111.50	19.52	58636	17.17	8476	13462	16.62	24676	14.30	8554	7453	11.41	3618	9.68	6489	1592
J11_3	113.40	19.42	60329	16.84	9446	12689	16.48	27090	14.45	8545	8237	11.33	3799	9.50	9680	1374
J11_4	115.15	19.27	52744	16.89	9582	11663	16.11	20064	14.36	8278	6957	10.84	632	10.31	5315	865
J11	117.50	19.07	71994	15.62	8248	11395	15.99	38912	13.32	7065	8176	10.27	7157	8.53	5882	2562
J11_5	119.88	18.87	61123	16.01	7119	10884	15.82	29014	13.54	8512	9361	10.15	4245	8.44	8285	1567
J11_6	122.25	18.67	69514	15.93	11174	12874	15.66	32171	13.15	11264	10453	10.09	7246	7.63	11731	1899
J11_7	124.38	18.48	60008	16.16	7729	13842	15.57	24857	13.56	8249	8704	10.06	3581	7.96	13365	1028
J10_1	126.50	18.28	92193	15.21	11193	15343	15.47	49748	13.06	10620	13924	10.02	9225	7.06	14153	2972
J10_2	128.50	18.10	84113	15.31	11481	15715	15.36	42776	12.51	14591	12017	9.97	10722	7.73	14963	3330
J10_3	130.50	17.92	78144	15.35	11111	16068	15.25	37733	12.74	13877	10767	9.91	6225	8.44	7934	3128
J10_4	132.50	17.75	71968	15.41	10239	15862	15.06	31026	13.11	7683	11311	9.77	4937	8.10	6980	1696
J10	134.50	17.58	73657	15.17	9751	15847	14.87	33296	12.40	12773	11699	9.62	6497	8.23	5987	2893
J10_5	135.65	17.47	69664	15.02	7778	14800	14.73	31763	12.71	10899	10640	9.49	6199	7.48	5509	2017
J10_6	136.80	17.36	69287	14.81	10908	14208	14.60	32643	12.34	10707	9982	9.37	5094	8.13	4299	2432
J9_1	139.00	17.16	85762	14.20	11244	14875	14.45	46293	11.76	12786	12816	9.27	10934	7.54	12085	3882
J9_2	140.40	17.04	79544	14.17	10318	14615	14.30	41337	11.55	12613	11056	9.17	10389	7.34	3989	3422
J9_3	141.80	16.91	71796	14.47	9715	15651	14.14	31923	11.76	13638	10398	9.07	6638	7.08	4069	1992
J9_4	142.02	16.89	63573	14.47	8353	14702	14.12	28354	12.07	6629	9577	9.05	3689	7.85	3459	2060
J9_5	142.23	16.87	83498	13.59	10270	14441	14.08	46474	11.20	6463	10451	8.98	10808	7.66	4543	4876
J9	142.45	16.85	76358	14.09	7838	14715	14.04	37554	11.81	10403	10359	8.92	5349	7.54	4670	2579
J9_6	143.45	16.76	67503	14.13	7984	13706	13.87	31235	11.59	11199	9124	8.78	5000	7.41	5636	2535
J9_7	144.43	16.68	65669	13.93	10227	12886	13.76	31597	11.20	9836	8315	8.69	6150	7.32	6819	2919
J8_1	145.40	16.59	67245	13.63	9881	12199	13.64	33734	10.96	10270	8559	8.60	7431	7.23	7231	3139
J8_2	146.48	16.50	72850	13.64	10458	13621	13.56	35618	11.38	9665	10296	8.53	5435	7.27	8127	2698
J8_3	147.55	16.40	79270	13.61	9546	14254	13.47	39229	11.28	9039	11676	8.46	7433	6.97	9465	2920
J8_4	148.53	16.32	64096	13.56	8556	12292	13.39	30442	11.14	8216	9397	8.42	6896	6.65	8268	2409
J8	149.50	16.23	68076	13.47	9306	12998	13.30	32336	10.64	9439	9196	8.37	8633	6.41	9069	2659
J8_5	150.63	16.13	71506	13.47	10011	14428	13.22	33169	10.59	10125	9630	8.33	8193	6.67	9542	2890
J8_6	151.75	16.03	80205	13.27	10009	14780	13.14	38230	10.88	11668	12373	8.29	8595	6.77	9784	3332
JS1	153.37	15.89	61734	13.05	6173	12235	13.04	30785	10.20	4859	7321	8.11	8005	6.38	4581	2819
JS2	154.98	15.75	66903	13.10	7370	14709	12.93	31927	10.36	5743	8326	7.92	6064	6.73	4838	2816
J7_1	156.60	15.61	83060	12.86	11733	15543	12.83	41170	10.67	11540	13091	7.74	4136	7.01	3120	3449
JS3	158.50	15.44	74818	12.91	11809	15236	12.69	34957	10.72	11800	12101	7.12	4905	5.62	11878	1885
JS4	160.43	15.27	63169	12.80	9721	13774	12.53	29182	10.39	7906	9095	6.91	2946	5.47	1853	1437
J7	162.35	15.10	61070	12.76	10423	14269	12.36	27160	9.87	11894	7988	6.69	5270	3.75	12131	1563
JS5	164.48	14.98	65977	11.34	8385	10267	12.21	39504	9.17	8000	8036	6.59	8600	5.17	1210	3636
JS6	166.60	14.85	49891	11.45	6338	8085	12.05	28232	8.74	6507	6289	6.48	7690	4.68	5949	2373

Table 2.4 Sample Output Showing Cross-section Area and Centroid 1986-87 (Sheet 3 of 3)

Node	Chainage (Km)	1 in 100 Year Water Level					Water Level at Dominant Discharge					1 in 2 Low Water Level				
		WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)	WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)	WL(m PWD)	Area(m2)	Centroid Z (m PWD)	Centroid Y (m PWD)	Perimeter (m PWD)
J7_7	168.68	14.73	43813	11.20	5664	7545	11.94	25596	8.91	6096	5123	6.39	6674	4.30	4469	1960
J6_1	170.75	14.60	63086	11.94	8077	12587	11.82	30762	8.73	7666	7700	6.29	7899	4.28	6687	2286
J6_2	172.53	14.50	41060	11.08	5118	7439	11.60	22731	8.18	5235	4469	6.20	6573	3.61	5294	1849
J6_3	174.30	14.39	35173	11.57	3742	7433	11.38	16897	7.58	2454	3610	6.11	6048	3.89	2039	1516
J6_5	175.00	14.35	36316	10.91	5301	6252	11.31	19634	7.43	5204	3569	6.05	7302	3.68	5176	1667
J6_4	176.00	14.29	35924	10.84	5309	6252	11.21	19240	7.33	5204	3460	5.96	7150	3.63	5171	1651
J6	177.70	14.19	64794	11.97	11979	15590	11.04	24774	8.34	11791	5912	5.81	5006	4.37	10762	2316
J6_6	179.20	14.10	57176	10.21	5855	7749	10.96	33581	8.30	5258	6899	5.60	5493	4.39	2138	2871
J6_7	179.90	14.06	51791	10.98	7182	8956	10.93	25626	8.27	4316	5890	5.46	3640	4.48	2753	2245
J5_1	180.60	14.02	67824	11.41	9242	13546	10.89	28613	8.52	9432	7953	5.32	3770	4.16	8151	2044
J5_2	183.00	13.88	51707	10.65	4799	9060	10.71	26186	7.73	4046	5529	5.14	6326	3.25	2371	1903
J5_3	185.70	13.72	51417	10.82	7971	10138	10.51	24069	7.52	8071	5419	4.94	6286	1.51	9553	1589
J5	188.20	13.57	73766	11.27	9561	16604	10.32	26566	7.83	9997	8393	4.76	3649	3.68	9273	2102
J5_5	189.98	13.47	53063	10.98	7946	11355	10.15	21105	7.04	5463	5899	4.53	6135	1.77	5443	1464
J5_6	191.75	13.36	55277	10.42	4906	10343	9.97	24407	7.25	3610	6309	4.29	5020	2.31	2889	1475
J4_1	195.75	13.12	98218	10.53	13930	20351	9.71	38094	7.33	13226	10843	3.52	3770	2.09	13241	1675
J4_2	196.70	13.07	57563	10.01	7007	10733	9.65	26548	7.09	6554	6339	3.43	3572	1.91	8556	1495
J4_3	197.65	13.01	64898	10.12	6990	11470	9.59	27997	7.18	6889	8498	3.34	4059	1.51	2256	1277
J4_4	198.87	12.94	38433	9.48	2486	6467	9.50	19290	5.06	1811	3448	3.30	7402	-0.80	1300	1064
J4_4_1	200.08	12.86	37722	10.04	6324	7535	9.40	16810	5.50	6587	3091	3.26	5280	0.30	6609	1236
J4	201.30	12.79	50856	9.88	7499	9090	9.31	21883	5.08	7585	5294	3.22	7803	0.60	7541	1665
J4_5	202.23	12.73	42229	10.23	3279	8624	9.30	15965	5.83	1637	4342	3.21	4661	0.08	957	1096
J4_6	203.30	12.67	55545	8.63	5507	8346	9.29	30635	4.27	5314	4806	3.20	12832	0.12	4909	2238
J4_7	204.19	12.62	47555	9.33	6134	8196	9.26	23474	5.00	6100	4296	3.20	8627	-0.23	5758	1494
J3_1	205.15	12.56	55344	8.98	2699	8706	9.23	29049	5.80	2089	5061	3.19	10222	0.51	1580	2152
J3_2_1	207.18	12.44	55810	9.90	9922	11240	9.21	22682	6.01	9887	6090	3.18	6519	-1.17	10168	1188
J3_2	209.22	12.32	54825	9.46	10187	11039	9.20	25840	5.51	10334	5744	3.17	7869	0.46	10164	1969
J3_3	211.25	12.20	87136	7.36	6854	9938	9.18	57740	5.15	5742	8653	3.16	17243	1.24	2658	5458
J3_4	212.23	12.15	50712	8.43	6770	7863	9.15	29021	5.82	6983	5475	3.14	5326	1.47	6799	2627
J3	213.20	12.09	55923	8.94	7308	9230	9.11	29258	6.51	6546	7785	3.12	4745	1.87	1919	2298
J3_5	214.85	11.99	66645	7.95	7653	9256	9.04	40441	5.53	7005	7165	3.06	9124	1.77	2187	3742
J3_6	216.50	11.89	55571	8.59	8088	9262	8.96	29922	5.54	8556	6749	2.99	8082	0.83	8672	2224
J3_7	218.25	11.80	65761	7.59	7803	9255	8.90	40368	4.93	7572	7386	2.95	11584	1.15	6052	3947
J2_1	220.00	11.70	58164	8.36	7340	9118	8.87	32880	6.09	7382	8372	2.89	5680	0.76	8736	2037
J2	223.20	11.54	48126	8.38	5288	7899	8.68	26082	6.40	4482	7057	2.65	2902	1.60	3593	1722
J1_1	229.40	11.24	60259	6.84	6116	7313	8.49	40392	4.82	5973	6788	2.29	10984	-0.08	5451	2987
J1	230.75	11.17					8.48					2.28				
J0_1	235.50	10.94					8.05					2.22				

Table 3.1 Sediment Load for Different Discharge Classes

Discharge (Thousand m^3/s)	Frequency (Days)	1968/70 Land Load (Million tonnes)	1982/88 Sand Load (Million tonnes)	1982/88 Sediment Load (Million tonnes)
0-5	2,182	60	40	100
5-10	2,977	375	190	600
10-15	1,201	305	150	500
15-20	680	275	125	450
20-25	659	380	170	615
25-30	683	520	225	840
30-35	641	610	255	995
35-40	717	835	340	1,355
40-45	551	760	310	1,240
45-50	451	725	290	1,185
50-55	303	560	220	915
55-60	200	420	165	685
60-65	134	315	120	515
65-70	86	225	85	365
70-75	18	52	20	85
75-80	6	19	7	31
80-85	2	7	3	11
85-90	3	11	4	18
90-95	3	12	4	20
95-100	1	4	2	7

Table 3.2 Cumulative Sediment Loads

Discharge (Thousand m^3/s)	1968/70 Sand Load (%)	1982/88 Sand Load (%)	1982/88 Sediment Load (%)
2.5	0.9	1.5	0.9
7.5	6.7	8.4	6.7
12.5	11.4	13.9	11.5
17.5	15.7	18.5	15.7
22.5	21.6	24.8	21.5
27.5	29.6	33.0	29.5
32.5	39.0	42.4	39.0
37.5	51.9	54.9	51.8
42.5	63.6	66.2	63.6
47.5	74.8	76.9	74.8
52.5	83.5	85.0	83.5
57.5	90.0	91.0	90.0
62.5	95.0	95.4	94.0
67.5	98.5	98.5	98.4
72.5	99.3	99.3	99.2
77.5	99.6	99.5	99.5
82.5	99.7	99.5	99.6
87.5	99.8	99.8	99.7
92.5	99.8	99.9	99.9
97.5	100.0	100.0	100.0

Table 3.3 Relationship between Bank, Bartop and Chartop Elevations

Cross-Section Number	Reference Chainage (km)	Water Surface Elevation	Mean Bank Elevation	Bartop (Active Char) Elevation	Chartop (Inactive) Elevation
J-17	25.00	23.7	24.6	22.0	23.5
J-16	31.35	22.6	24.0	21.0	23.4
J-15	44.25	21.2	23.0	20.8	22.5
J-15	55.65	20.5	22.0	19.0	21.5
J-14-1	63.00	19.9	21.4	18.2	21.0
J-14	71.00	19.1	20.6	18.3	20.0
J-13-1	81.70	18.6	19.8	18.0	19.5
J-13	84.70	18.4	19.8	17.5	19.0
J-12-1	93.80	17.7	19.1	17.6	18.8
JN-2	95.50	17.6	18.9	17.3	18.8
J-12	100.50	17.3	18.6	17.0	18.1
J-11-1	108.90	16.8	18.0	16.8	17.5
J-11	117.75	16.0	17.2	14.8	16.8
J-10-1	126.50	15.5	16.6	14.6	15.8
J-10	134.30	14.9	15.7	14.6	15.5
J-9-1	139.00	14.5	15.2	14.4	14.9
J-9	142.45	13.9	14.9	13.8	14.8
J-8-1	145.40	13.6	14.6	13.5	14.3
J-8	149.50	13.3	14.2	13.8	14.0
J-7	162.35	12.4	13.4	13.0	13.0
J-6-1	170.75	11.8	13.0	None	12.5
J-6	177.70	11.0	12.5	11.3	12.0
J-5-1	180.60	10.9	12.2	11.0	11.0
J-5	188.20	10.3	12.0	9.8	11.7
J-4-1	195.75	9.7	11.4	9.1	10.7
J-4	201.30	9.3	11.0	9.0	10.2
J-3-1	205.15	9.2	10.6	8.6	10.55
J-3	213.20	9.1	10.1	8.5	8.5
J-2-1	220.00	8.9	9.9	8.0	8.0
J-1-1	229.40	8.5	8.8	5.0	None

Note: All Elevations are in metres above PWD datum.

Table 3.4 Braiding Indices of the Brahmaputra river, over period 1973-89

Date	21 Feb. 1973				22 Feb. 1978				27 Dec. 1981				27 Feb. 1987				March 1989				March 1992			
Parameter	E	Ei	N	C	E	Ei	N	C	E	Ei	N	C	E	Ei	N	C	E	Ei	N	C	E	Ei	N	C
Reach 1	4.25	3.25	35	7.80	4.59	3.59	43	7.40	5.18	4.18	33	7.35	5.83	4.83	45	8.63	5.26	4.26	39	8.34	5.85	4.85	54	9.96
2	3.79	2.79	18	9.40	6.75	5.75	37	9.10	5.03	4.03	35	9.63	4.66	3.66	49	10.12	6.32	5.32	37	9.33	5.29	4.29	42	11.76
3	4.91	3.91	32	8.25	4.79	3.79	30	7.70	5.72	4.72	46	9.04	7.72	6.72	53	9.52	5.60	4.60	44	9.12	6.64	5.64	64	10.96
4	4.54	3.54	34	9.50	5.07	4.07	38	10.30	7.09	6.09	68	10.90	6.68	5.86	68	11.06	6.19	5.19	63	10.67	5.60	4.60	81	12.40
5	3.90	2.90	18	5.75	3.06	2.06	11	5.10	4.27	3.27	18	6.30	4.89	3.89	28	6.81	3.98	2.98	20	5.12	5.04	4.04	26	7.70
6	4.27	3.27	22	5.56	4.60	3.60	18	4.80	3.98	2.98	14	6.60	3.86	2.89	16	5.10	4.70	3.70	23	6.72	3.92	2.92	19	8.97
7	4.30	3.30	17	8.42	4.41	3.41	18	7.80	3.76	2.76	19	6.80	4.43	3.43	20	7.38	3.12	2.12	12	9.67	-	-	-	-

E = NS/L = average number of segments bisected by the crosslines at the ends and interior of a river reach

N = total number of segments entirely within the section (reach) and entering the section from a lower numbered section

S = average length of all segments entirely within the section and those entering the section from a lower numbered section, in km

L = length of reach, in km

Ei = excess segment index, defined by Ei = E - 1 (for a purely meandering river Ei = 0)

C = average width of the stream between the outermost segments within the reaches, in km

Table 3.5 Confluence Scour Prediction

Location	Angle Θ (deg)	Mean Depth (m)	Scour Actual (m)	Scour Predicted (m)	Error (%)
B.78/C-50	55	5.39	20.2	17.9	11
J-6/J-7	40	7.34	17.8	20.3	- 14
J-12/J-13	55	4.21	11.5	14.0	- 23

Table 3.6 Sediment Balance for the Brahmaputra River 1986-87 Assumption 1

Sediment	Upstream Supply Yield	Left Bank Yield	Right Bank Yield	Total Bank	Char Deposition	Char Erosion	Net Char Growth	Net Addition
Sand	40	14	18	32	49	17	32	0
Silt	632	9	12	22	12	4	8	13
Total	672	23	31	54	62	21	48	13

Notes: All values have units of 10^9 kg

Assumes bank material is 60% sand and 40% silt, and char material is 80% sand and 20% silt, based on bank and char sediment samples.

Assumes char sediment density is 1,600 kg/m^3.

Table 3.7 Yield of Sediment from Bank Erosion as Proportion of Upstream Supply - Assumption 1.

Sediment Type	Left Bank Yield (percent)	Right Bank Yield (percent)	Total Bank Yield (percent)
Sand	27	43	70
Silt	1	2	3
Total	3	5	8

Table 3.8 Sediment Balance for the Brahmaputra River 1986-87 Assumption 2

Sediment	Upstream Supply Yield	Left Bank Yield	Right Bank Yield	Total Bank	Char Deposition	Char Erosion	Net Char Growth	Net Addition
Sand	162	14	18	32	49	17	32	0
Silt	504	14	18	32	5	2	4	28
Total	672	27	36	63	54	19	35	28

Notes: All values have units of 10^9 kg

Assumes bank material is 50% sand and 50% silt with density 1,600 kg/m^3 char material is 90% sand and 10% silt with density 1,400 kg/m^3

Assumes total sediment load is as measured but 25% silt and 75% sand

Table 3.9 Yield of Sediment from Bank Erosion as Proportion of Upstream Supply - Assumption 2.

Sediment Type	Left Bank Yield (percent)	Right Bank Yield (percent)	Total Bank Yield (percent)
Sand	8	11	19
Silt	3	4	6
Total	4	5	9

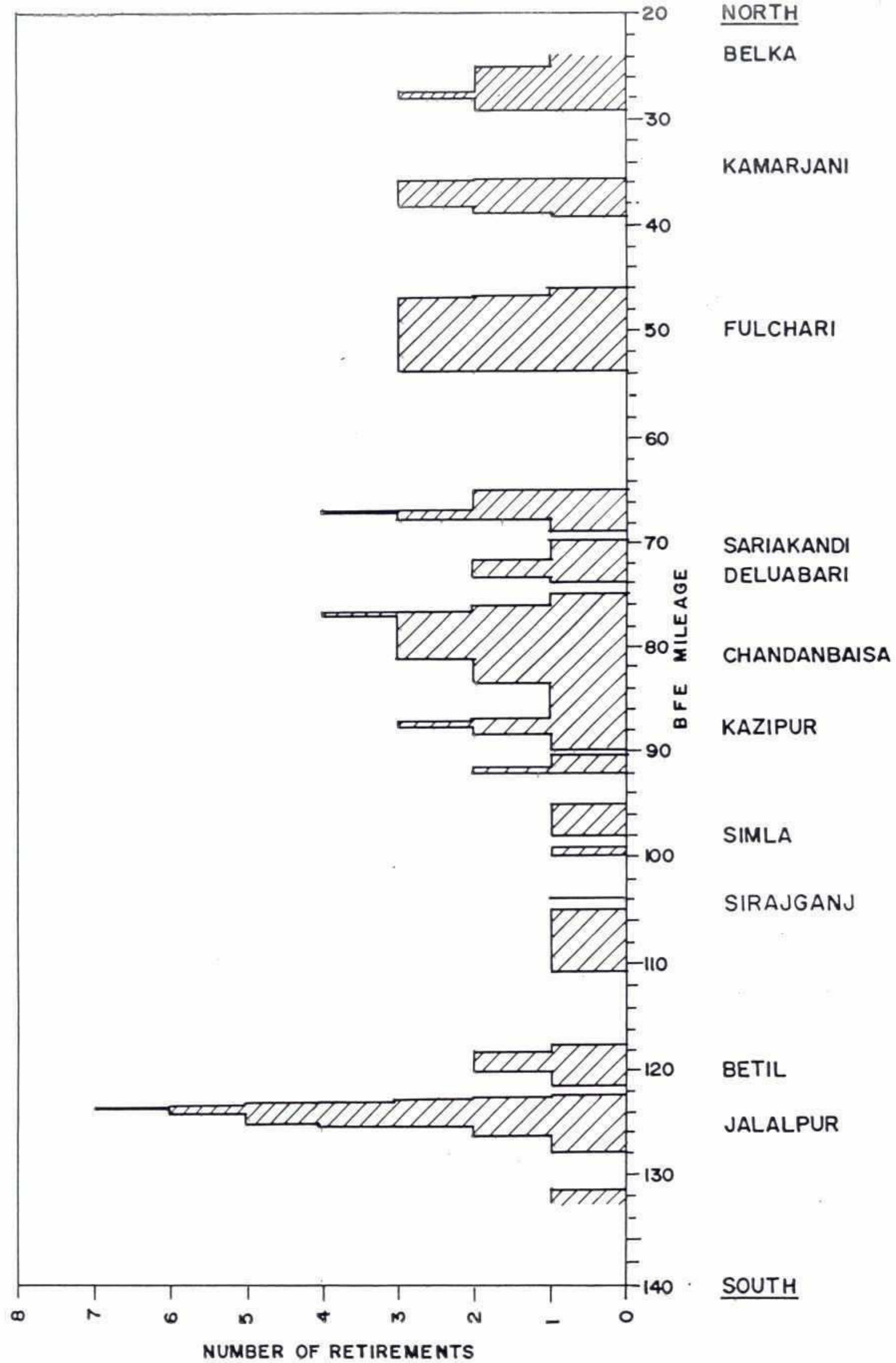
Table 3.10 Bend Evolution of Selected Brahmaputra Bends

BEND	YEAR	E	W	R_c	E/W	R_c/W	ANGLE
Bend A	1973	200	1013	1725	.197	1.703	42.5
	1976	127	563	1613	.226	2.865	25
	1978	-75	319	1425	-.235	4.467	50
Bend B i	1973	125	563	2475	.222	4.396	32.5
	1976	307	863	2081	.356	2.41	43.5
	1978	488	600	1725	.813	2.858	35
ii	1990	403	225	1481	1.791	6.582	27
	1992	403	225	2038	1.791	9.502	36.5
Bend C i	1973	88	593	1969	.148	3.32	29
	1976	82	450	2025	.182	4.5	41
	1978	99	690	1800	.143	2.609	34
	1980	122	390	2036	.313	5.221	32
ii	1984	107	728	2100	.147	2.885	41
	1987	96	1294	3638	.074	2.811	35.5
	1990	165	1470	1744	.112	1.186	50
	1992	244	863	1819	.283	2.108	41
Bend D	1978	422	1163	2906	.383	2.499	35
	1980	284	1290	2531	.22	1.926	31
	1984	148	479	2700	.309	5.637	23.5
	1987	200	285	1050	.702	3.684	24
	1990	144	319	900	.451	2.821	33
	1992	38	150	806	.253	5.373	0
Bend E	1973	50	1543	10350	.032	6.699	15
	1976	-125	1185	6825	-.105	5.759	18
	1978	94	1170	3375	.08	2.885	25
	1980	387	975	2674	.397	2.712	48
	1984	286	1097	1800	.261	1.333	44
Bend G	1990	169	1125	4031	.15	3.583	21
	1992	169	628	1163	.269	1.852	48
Bend H	1980	253	244	2194	1.037	8.992	0
	1984	167	473	2888	.353	6.106	50
	1990	397	610	1594	.651	2.613	36
	1992	713	694	1725	1.0127	2.486	29
Bend J	1973	275	1088	4369	.253	4.016	18
	1976	194	1163	8625	.167	7.416	21
	1978	151	938	6300	.16	6.716	17
	1980	104	623	3263	.167	5.238	19
	1984	19	1106	5531	.017	5.001	25

Table 3.11 : Bank Material Characteristics

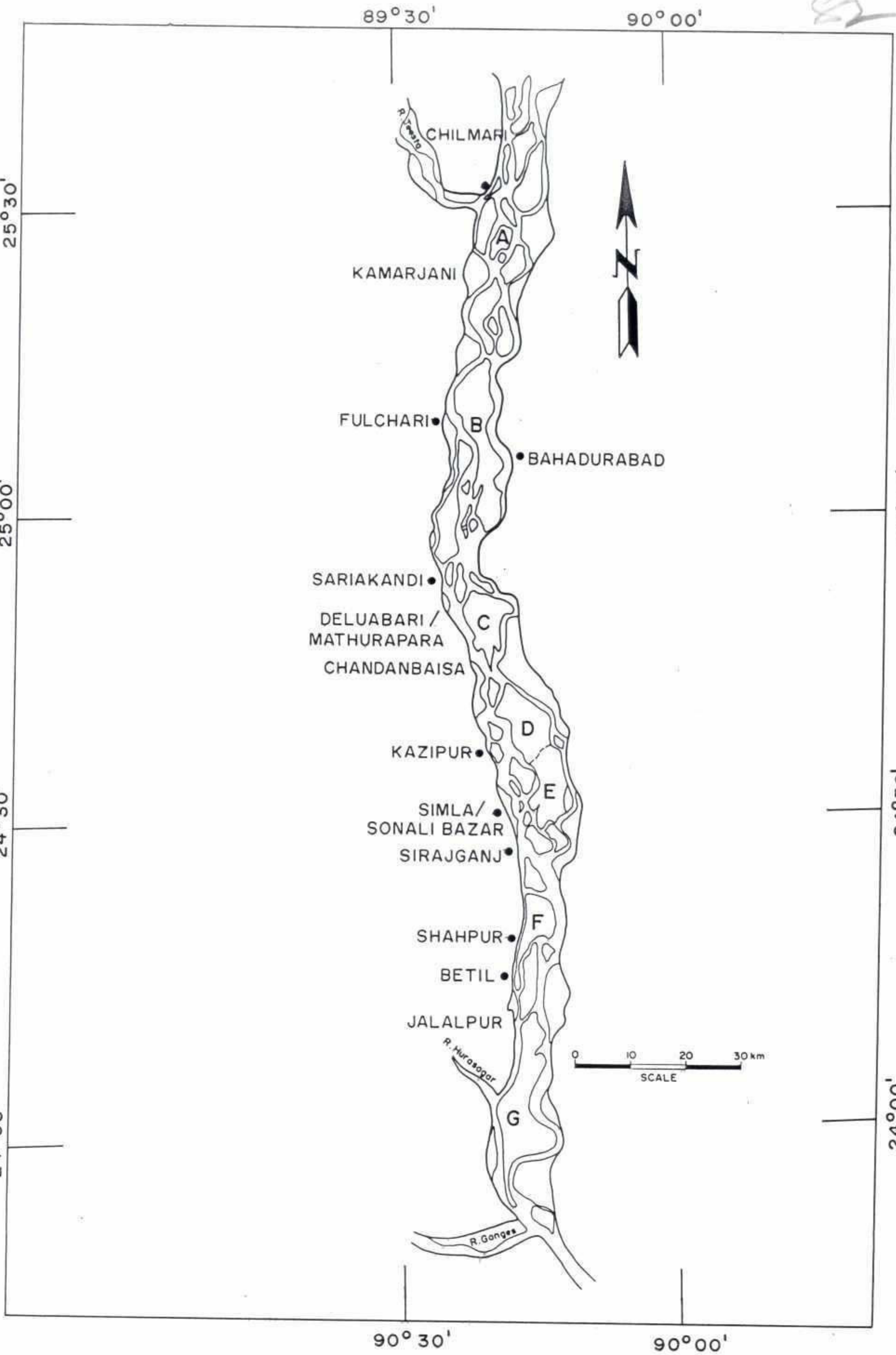
Reach No.	Sample No.	Sampling Location	Sand Content (%)	Silt Content (%)	Ratio (Sand/silt)	Remarks
A	4	Belka X-bar III	21.6	78.4	0.70	Silty Sand
A	5	Haripur (Sundarganj)	6.0	94.0		
A	6	Lalchamur (Sundarganj)	95.1	4.9		
A	7	Kamarjani (Gaibanda)	42.5	57.5		
B	S#1	Fulchurighat	19.4	80.6	1.07	Sandy
B	1	Ratanpur (Fulchari)	77.8	22.2		
B	2	Ratanpur (Fulchari)	61.1	38.9		
B	S#2	Patilbari	97.5	2.5		
B	3	Rasulpur (Gaibanda)	3.0	97.0		
C	S#3	Nizbalai	31.0	69.0	0.40	Operationally Cohesive Soil
C	S#4	Nizbalai	5.3	94.7		
C	S#5	Hatsherpur	33.0	67.0		
C	S#6	Kalitola	1.1	98.9		
C	S#9	Deluabari	77.4	22.6		
C	S#7	Deluabari	54.0	46.0		
C	S#8	Deluabari	9.0	91.0		
C	S#10	Mathurapara	13.6	86.4		
C	S#11	Chandanbisha	32.6	67.4		
D	S#12	Kazipur	38.1	61.9	0.18	Operationally Cohesive Soil
D	S#13	Kazipur	5.9	94.1		
D	S#14	Sonalibazar	1.8	98.2		
E	8	Sirajganj (L.ghat)	15.9	84.1	0.13	Operationally Cohesive Soil
E	9	Paikpara (Sirajganj)	13.3	86.7		
E	10	Agoria	5.6	94.4		
F	13A	Shahjadpur (lower)	1.0	99.0	0.05	Cohesive Soil
F	13B	Shajadpur (upper)	2.5	97.5		
F	11	Delua	14.3	85.7		
F	12	Betil	1.6	98.4		
G	14B	Upper Chitulia	35.5	64.5	0.71	Silty Sand
G	18A	Natakola and Nagarbari	96.4	3.6		
G	18B	Natakola & Nagarbari	83.7	16.3		
G	1A	Kabulibari	2.6	97.4		
G	1B	Kabulibari	64.7	35.3		
G	20A	Sariakandi (mid. char)	84.3	15.7		
G	20B	Sariakandi	96.5	3.5		
G	2A	Subarna khali	1.9	98.1		
G	2B	Subarnakhali	8.5	91.5		
G	3	Jagatpura	5.1	94.9		
G	4	Jagatpura (downstream)	19.4	80.6		
G	5	Original F ghat Bhuapur	22.0	78.0		
G	14	Chitulia Lower	2.7	97.3		
G	15	Nakalia	0.6	99.4		
G	16	Raghunathpur	3.8	96.2		
G	17	Natakola	27.4	72.6		
G	19	Teesta River Haripur	95.3	4.7		
G	21	Haripur Teesta River	94.4	5.6		

FIGURES



Number of BRE Retirements

	Annex 2
Halcrow/DHI/EPC/DIG November 1992	Figure 1.1



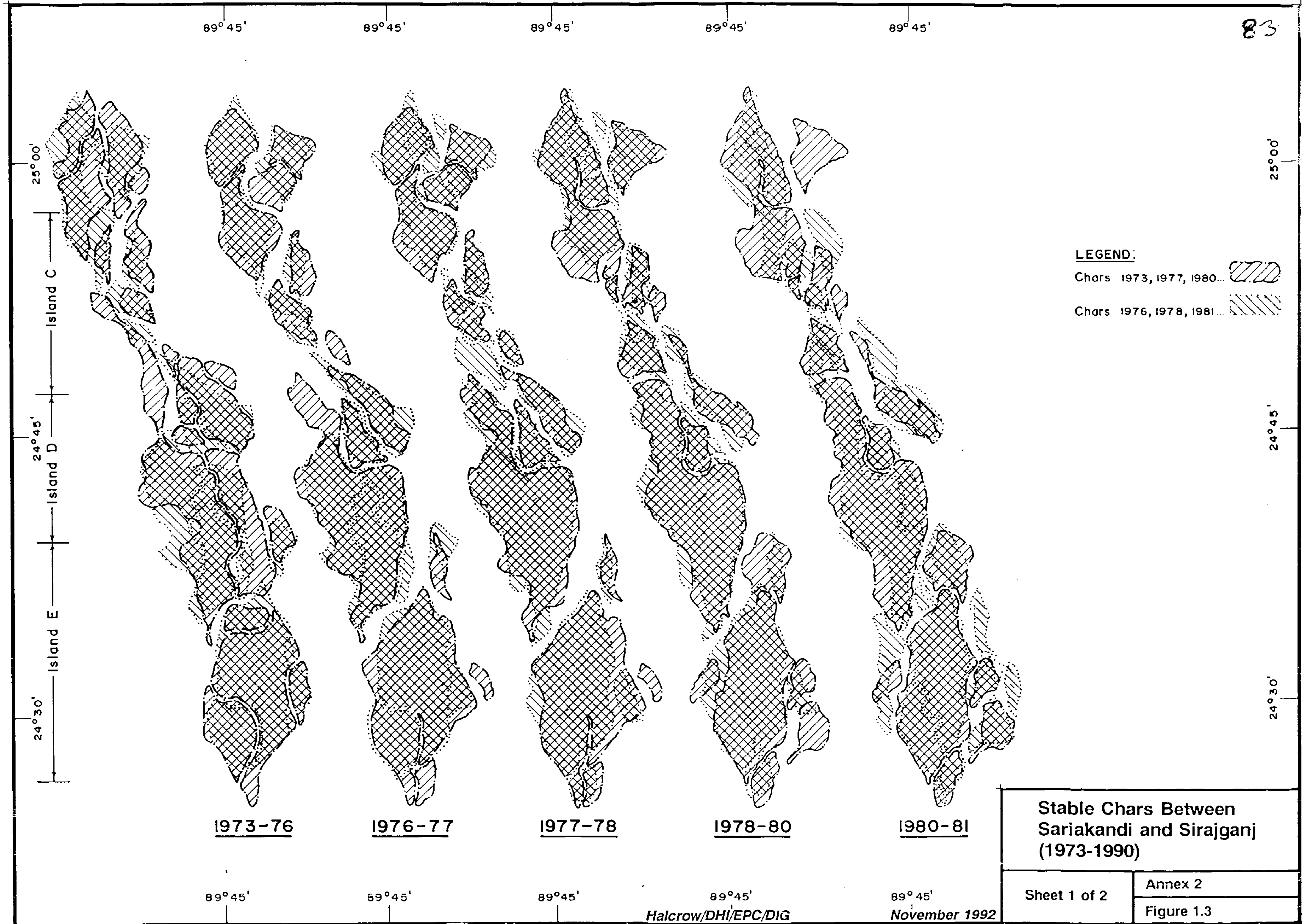
Present Island Pattern

Halcrow/DHI/EPC/DIG

November 1992

Annex 2

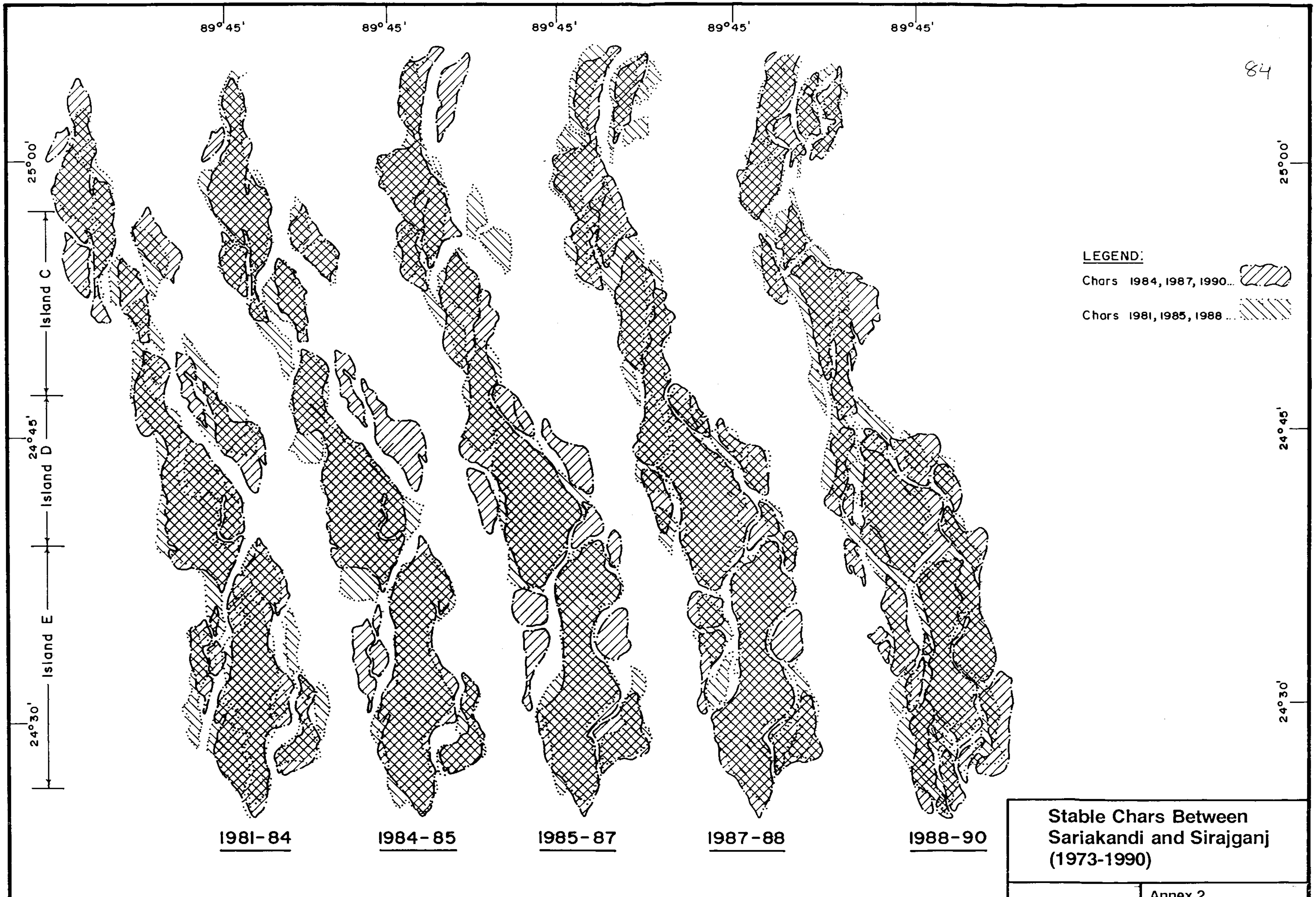
Figure 1.2



Halcrow/DHI/EPC/DIG

November 1992

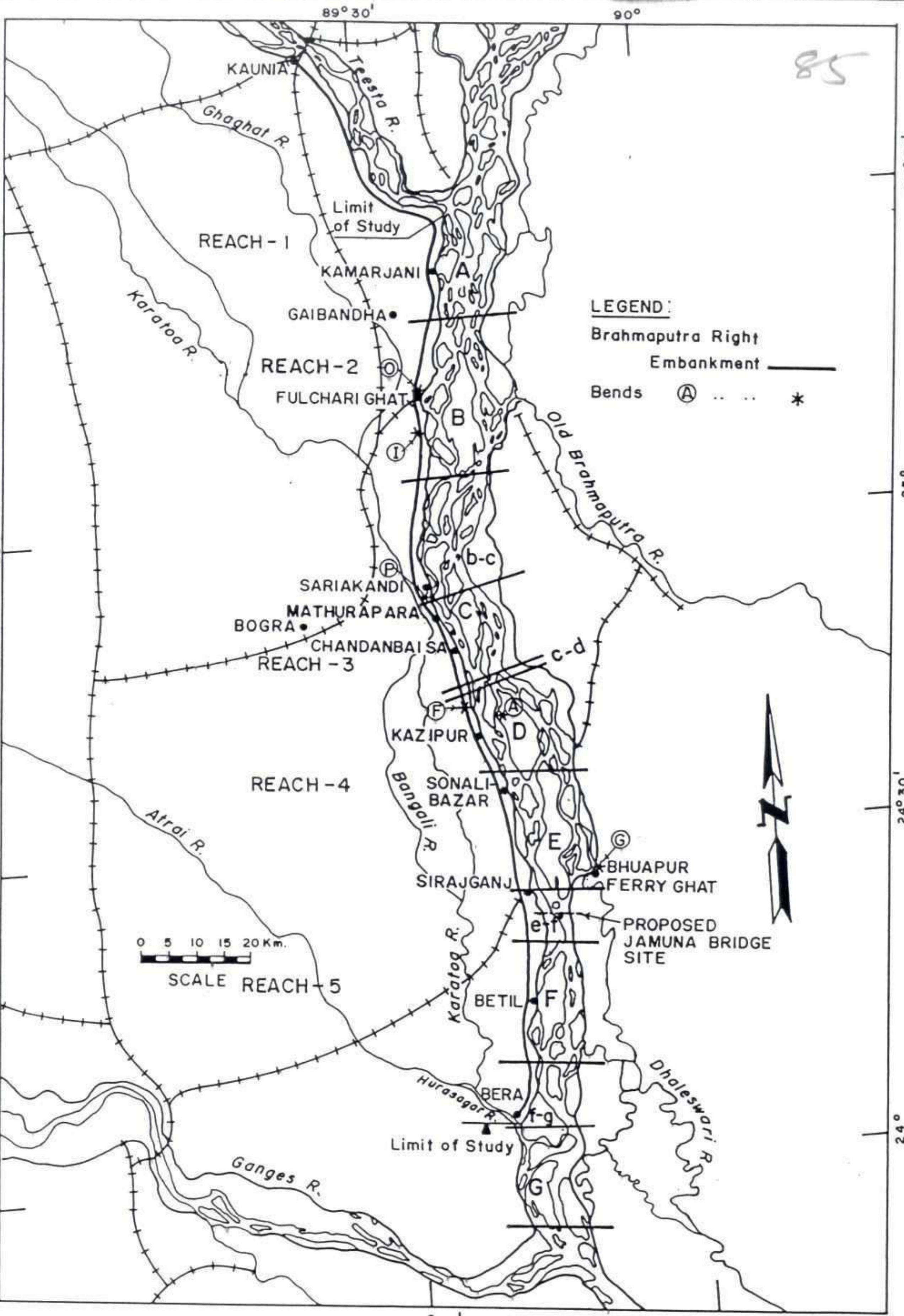
Stable Chars Between Sariakandi and Sirajganj (1973-1990)	
Sheet 1 of 2	Annex 2
	Figure 1.3



Stable Chars Between Sariakandi and Sirajganj (1973-1990)

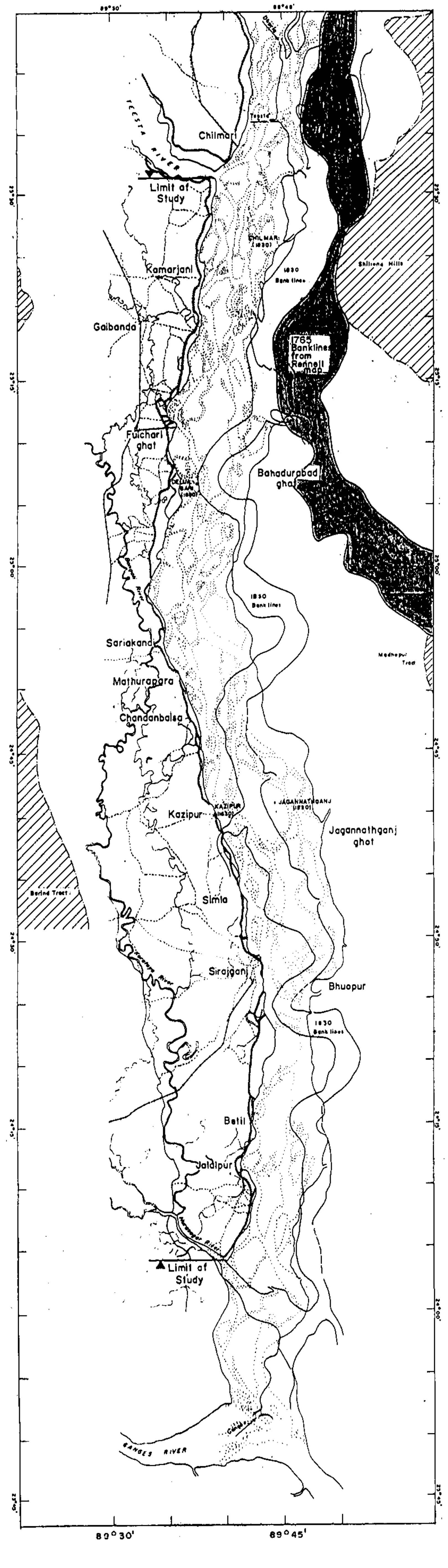
Sheet 2 of 2	Annex 2	Figure 1.3

Halcrow/DHI/EPC/DIG November 1992



Location of Island Reaches and Selected Bends

Halcrow/DHI/EPC/DIG November 1992	Annex 2 Figure 1.4



NOTE :

The Rennell and Wilcox banklines have not yet been formally registered with the 1990 plan form. This overlay is therefore to be treated as preliminary. See Plate 15 for 1830 bankline over 1992 image.

LEGEND :

- Bankline of 1989
- Bankline of 1830
- Bankline of 1765

0 10 20 Km.
SCALE

Superimposition of 1765, 1830 and 1989 Banklines

Annex 2

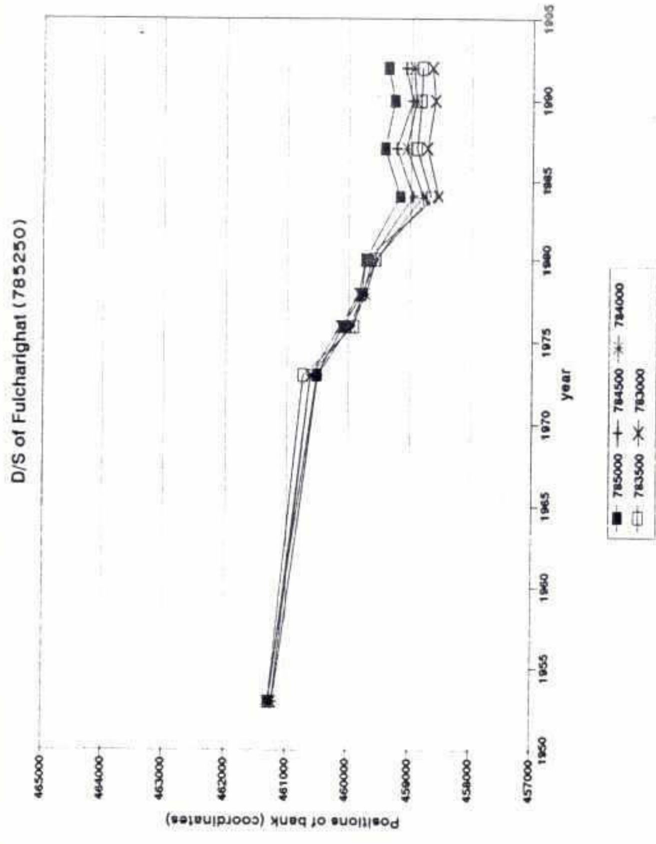
Figure 1.5

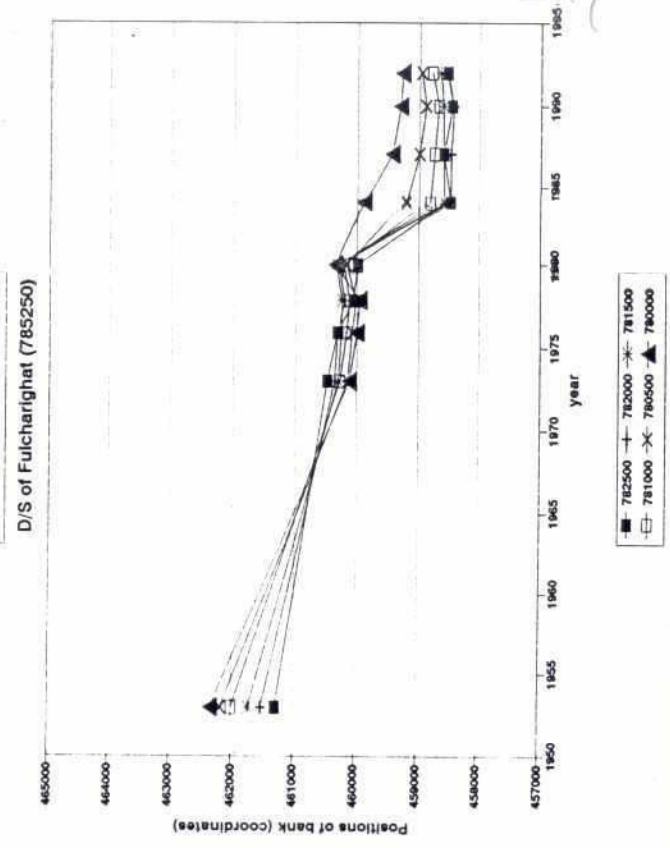
Halcrow/DHI/EPC/DIG

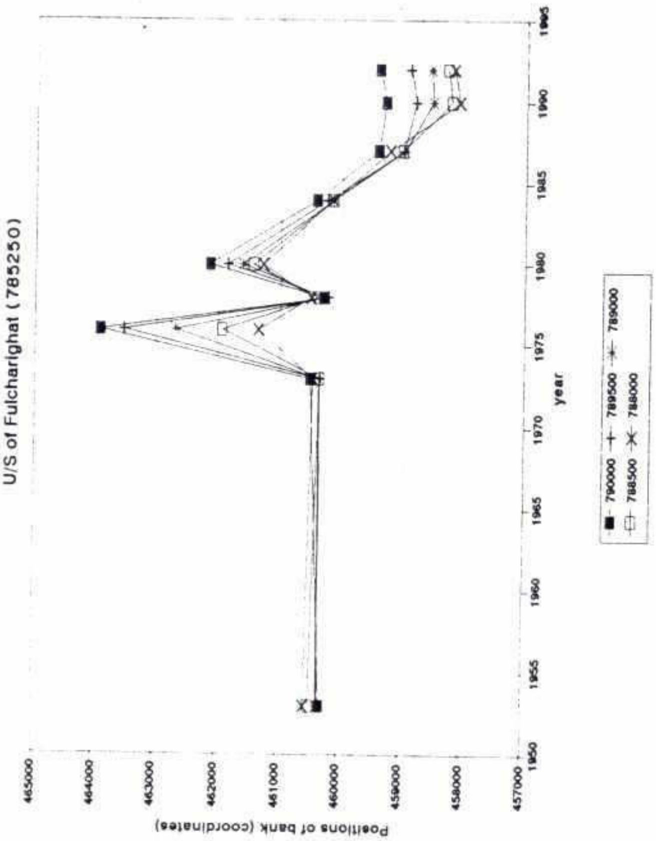
November 1992

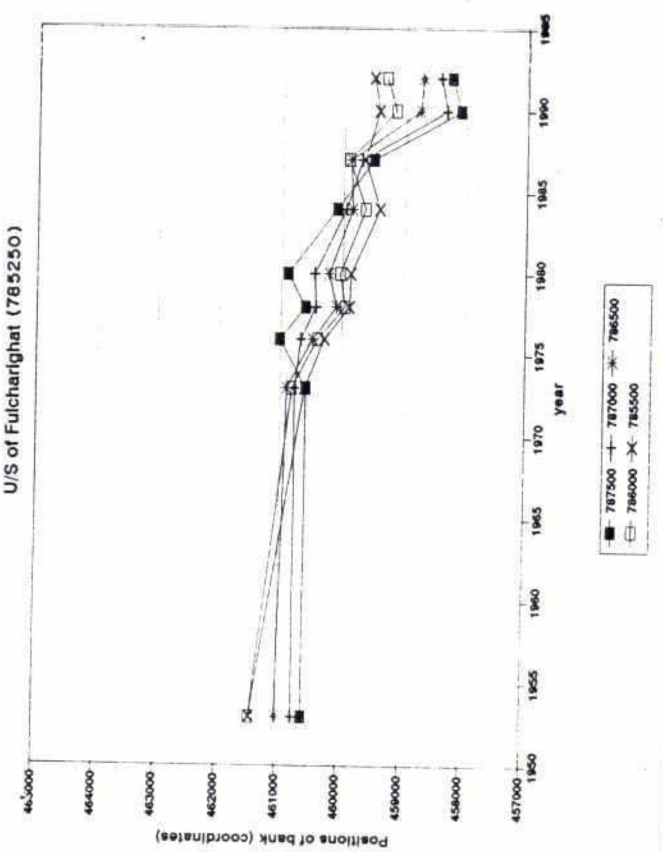
88

87







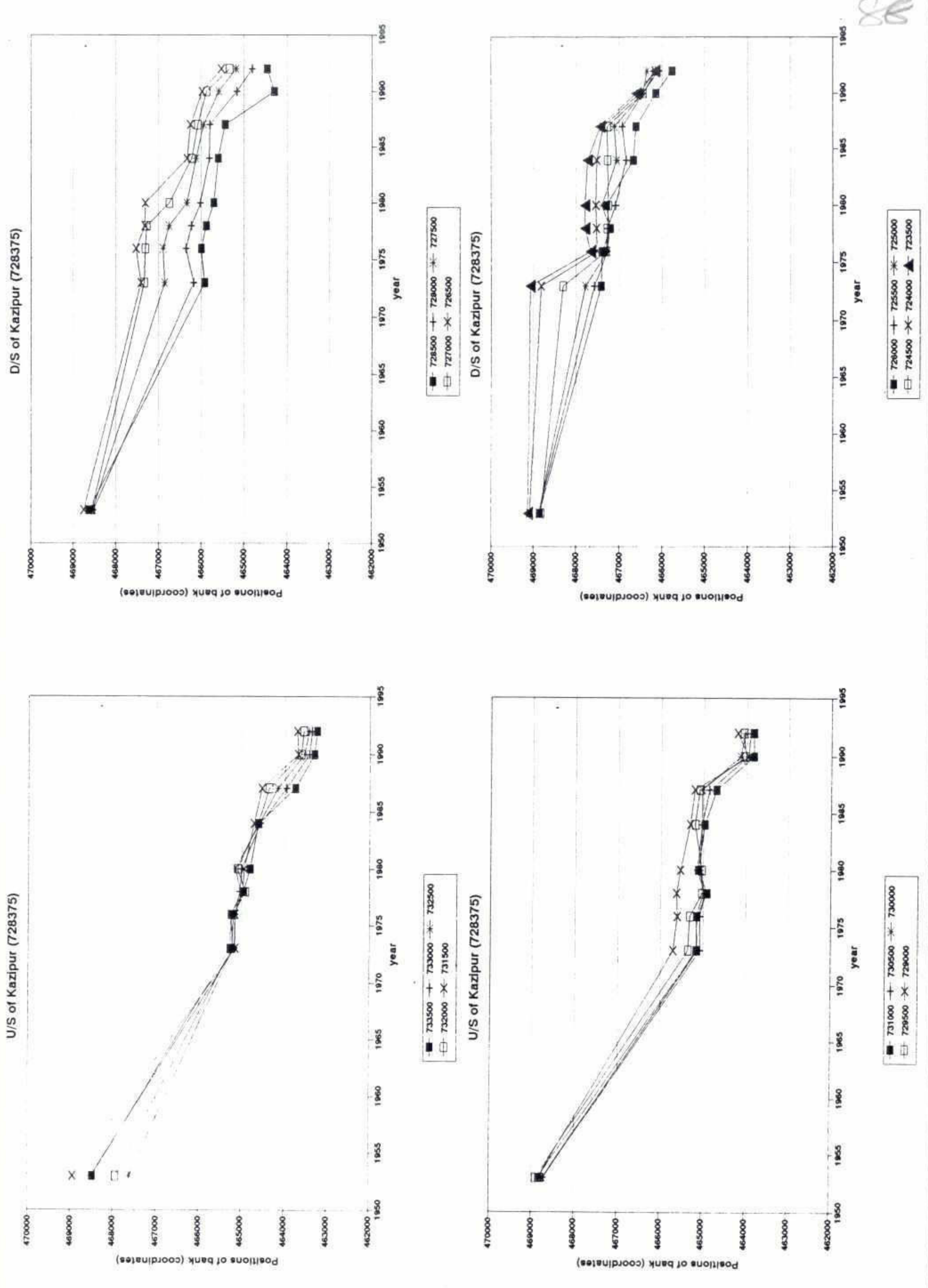


River Bank Erosion 1953-1992

Halcrow/DHI/EPC/DIG *November 1992*

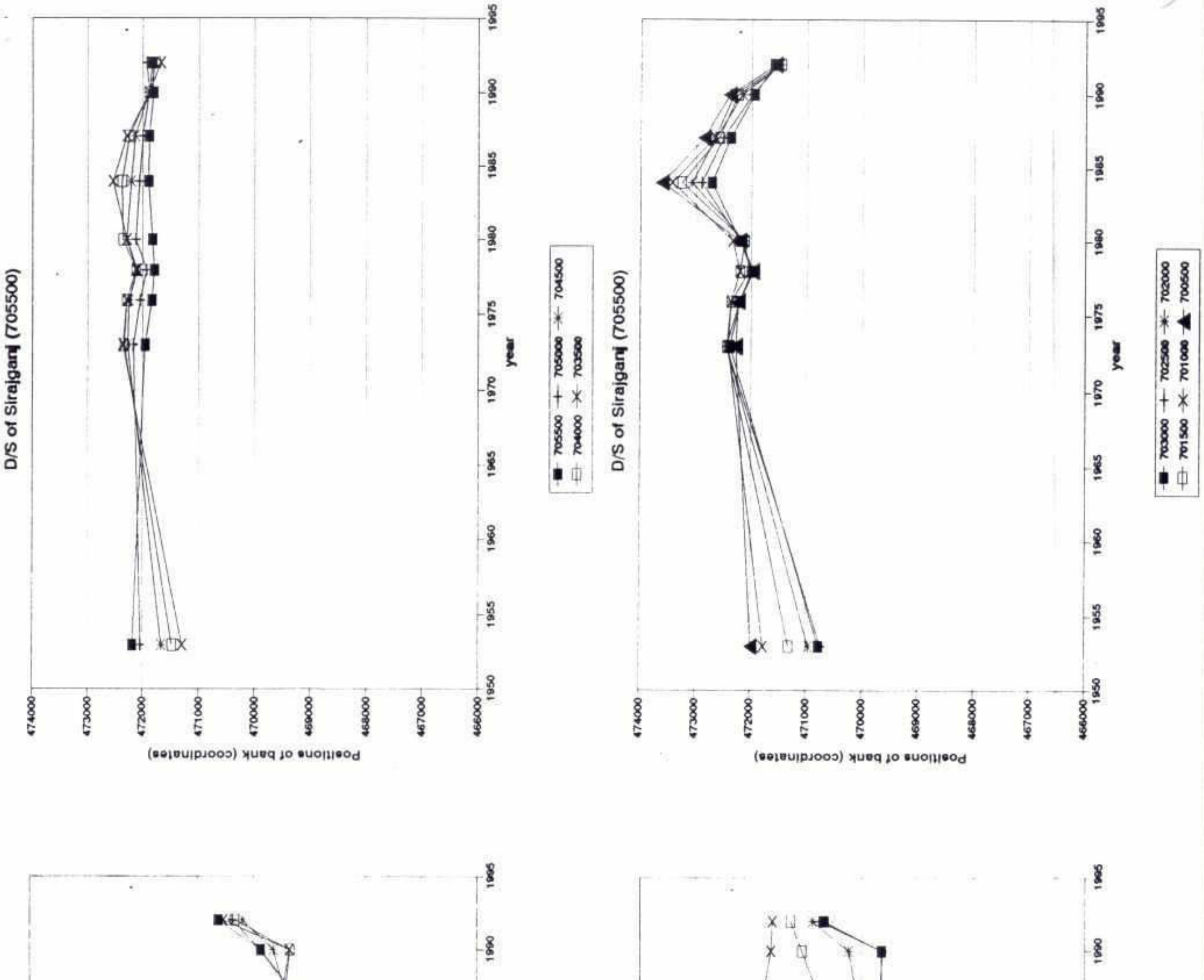
Annex 2

Figure 1.6 Sheet 1



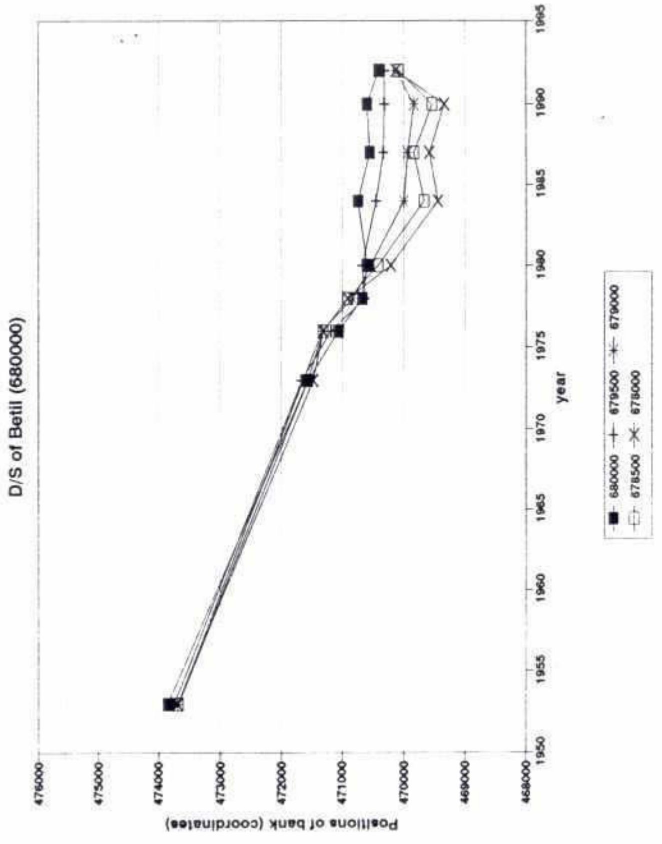
River Bank Erosion 1953-1992

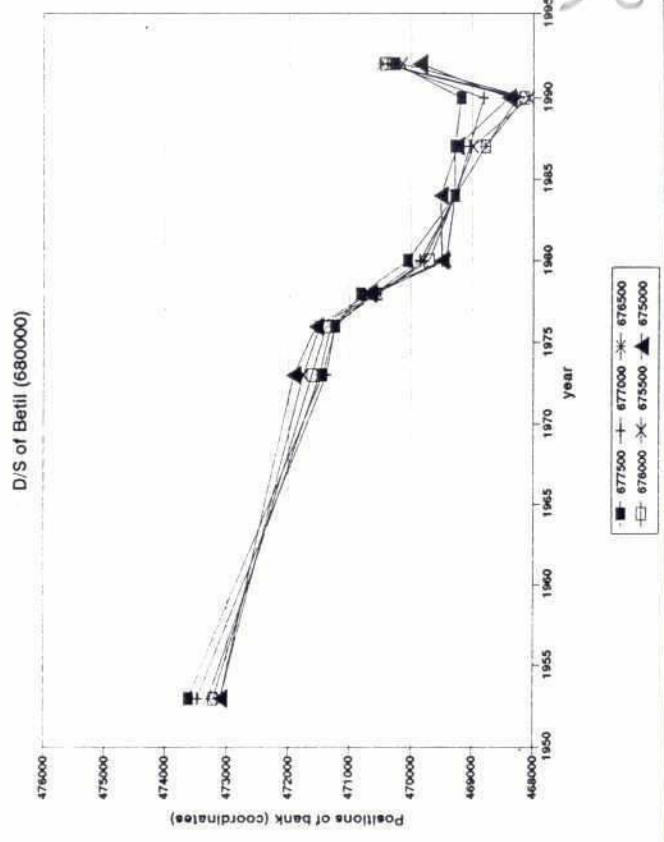
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 1.6 Sheet 2

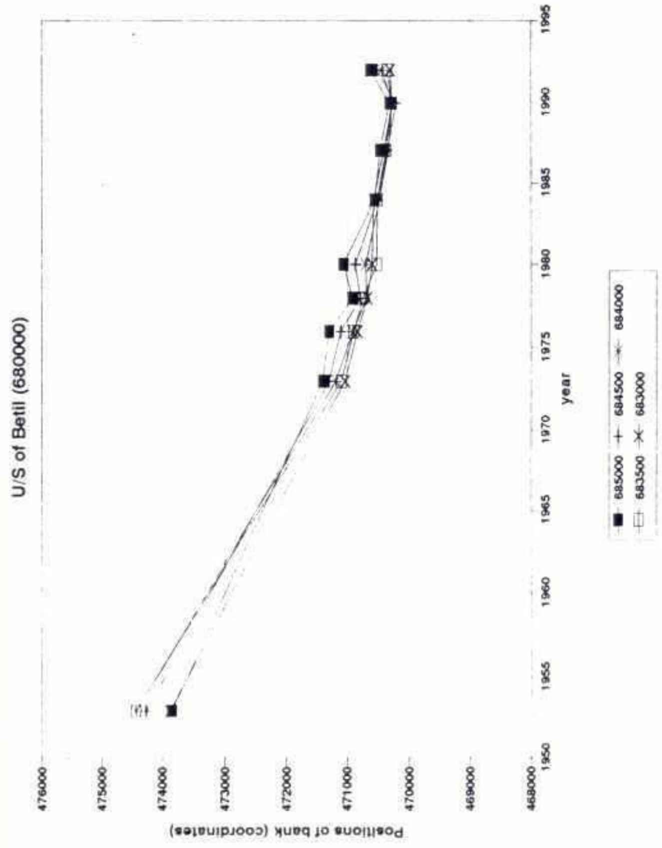


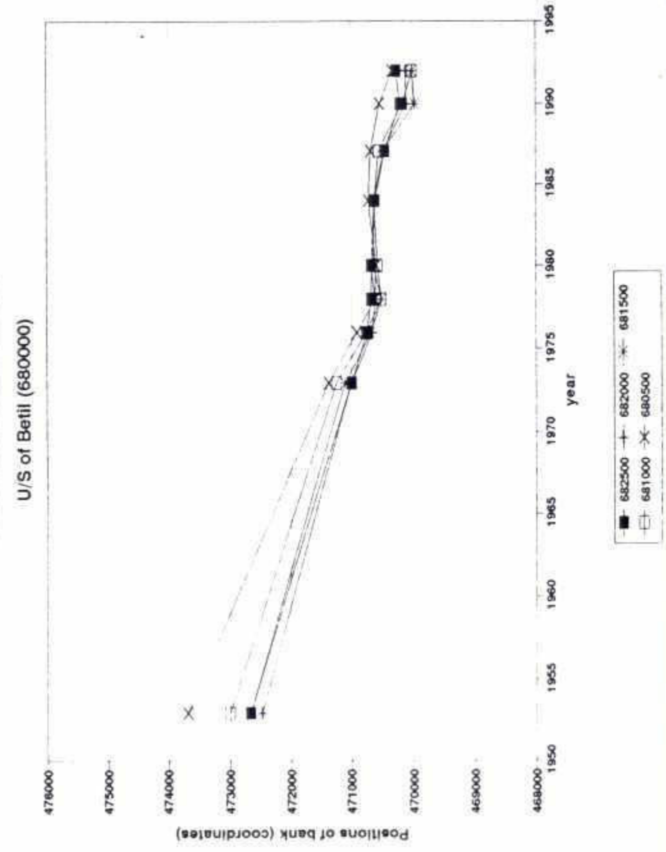
River Bank Erosion 1953-1992

	Annex 2	
Halcrow/DHI/EPC/DIG *November 1992*	Figure 1.6	Sheet 3



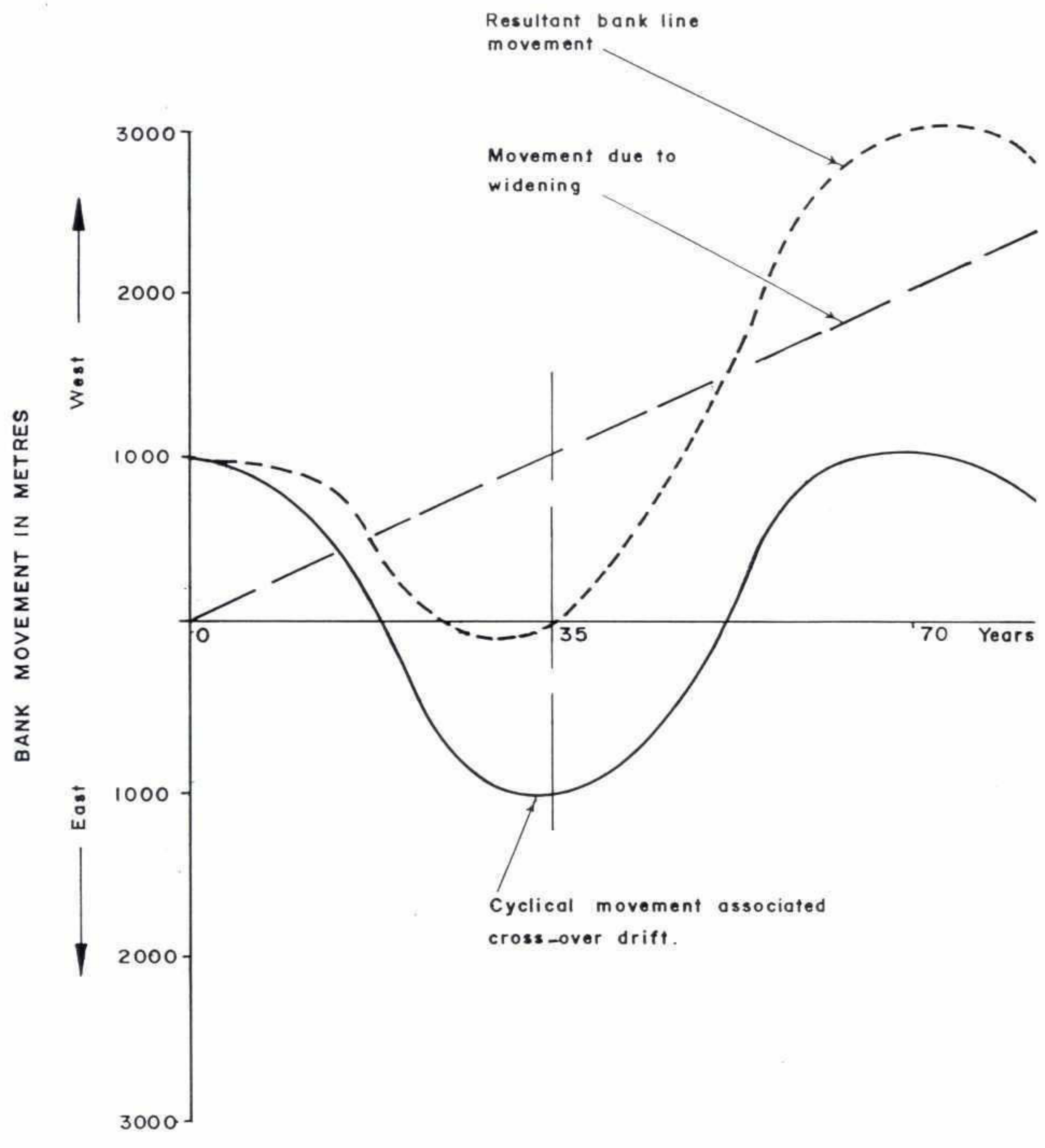






River Bank Erosion 1953-1992

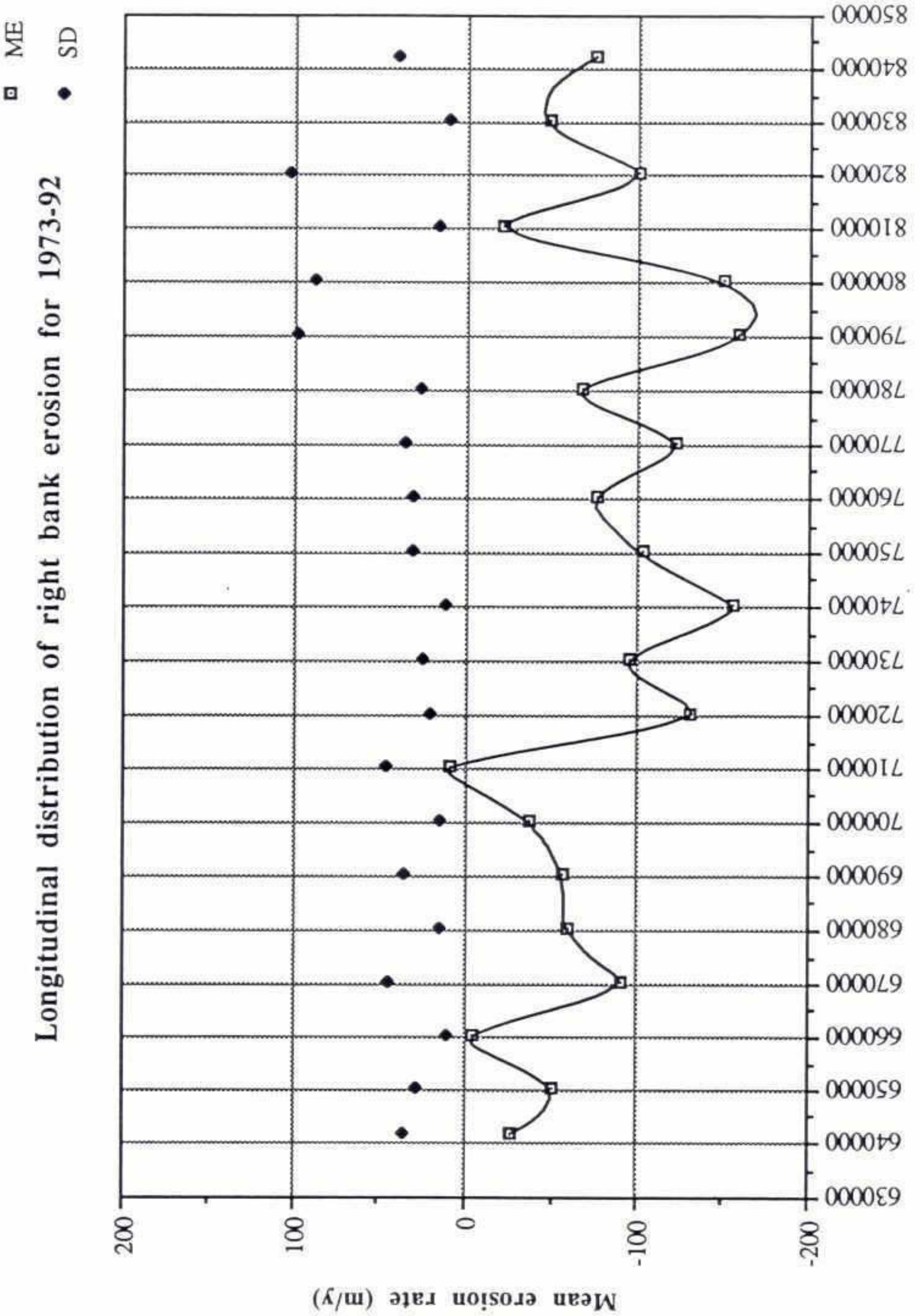
Halcrow/DHI/EPC/DIG	*November 1992*	Annex 2 Figure 1.6	Sheet 4



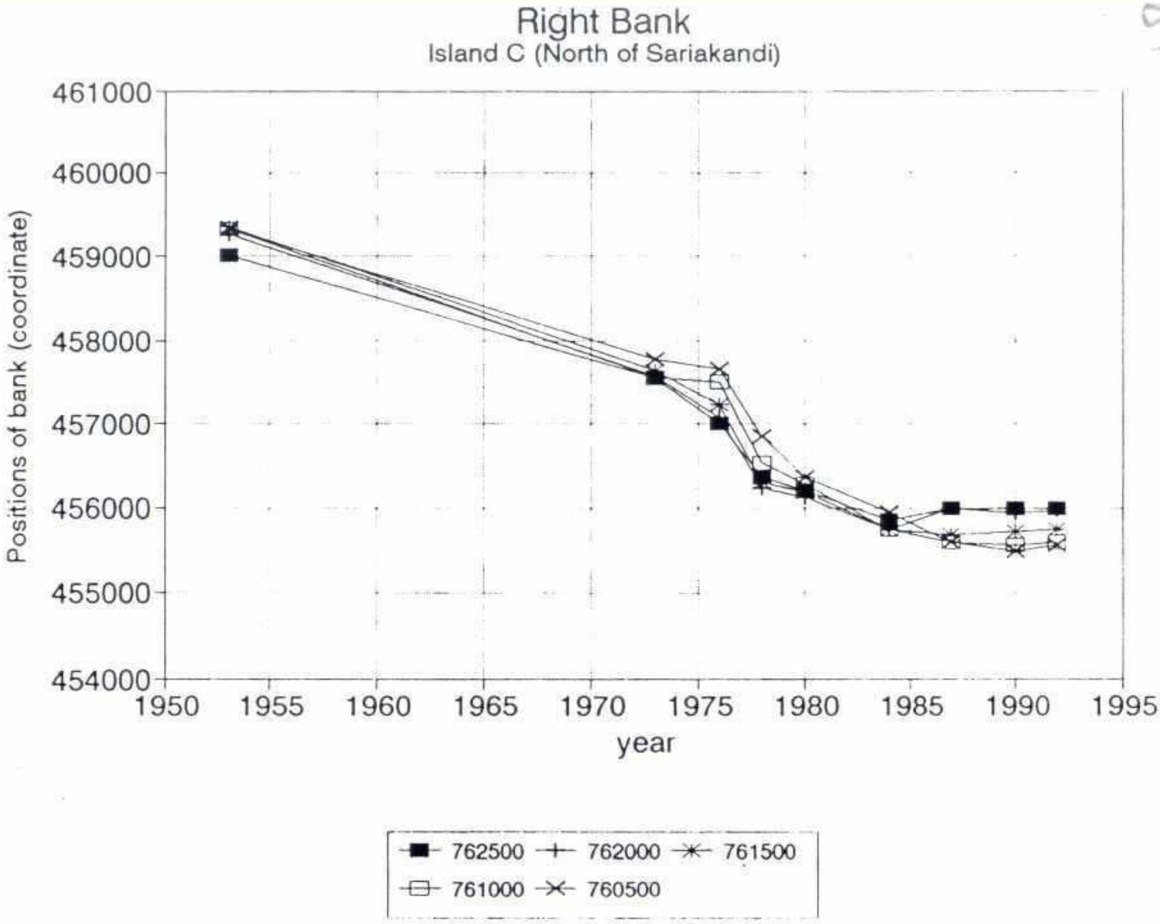
Conceptual Combination of Cyclical and Lateral Bank Movement

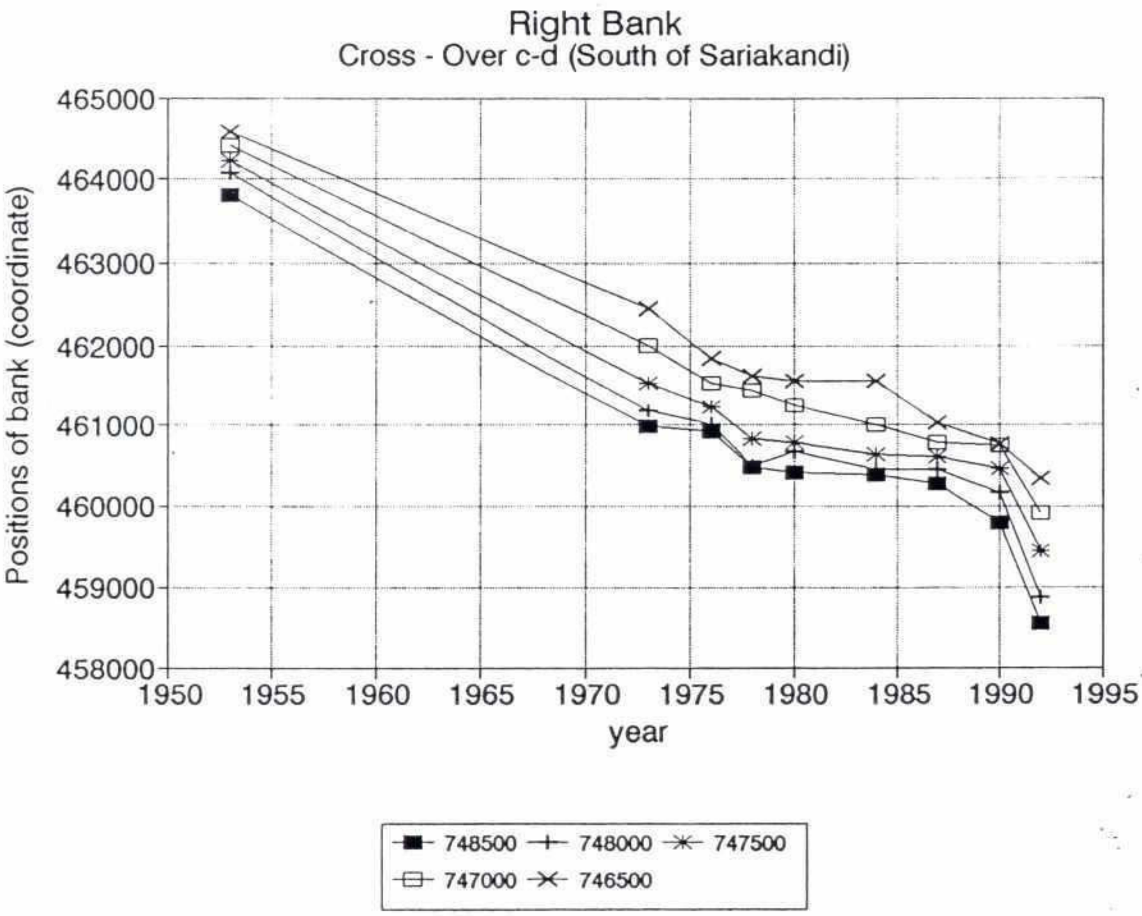
Annex 2

Figure 1.7



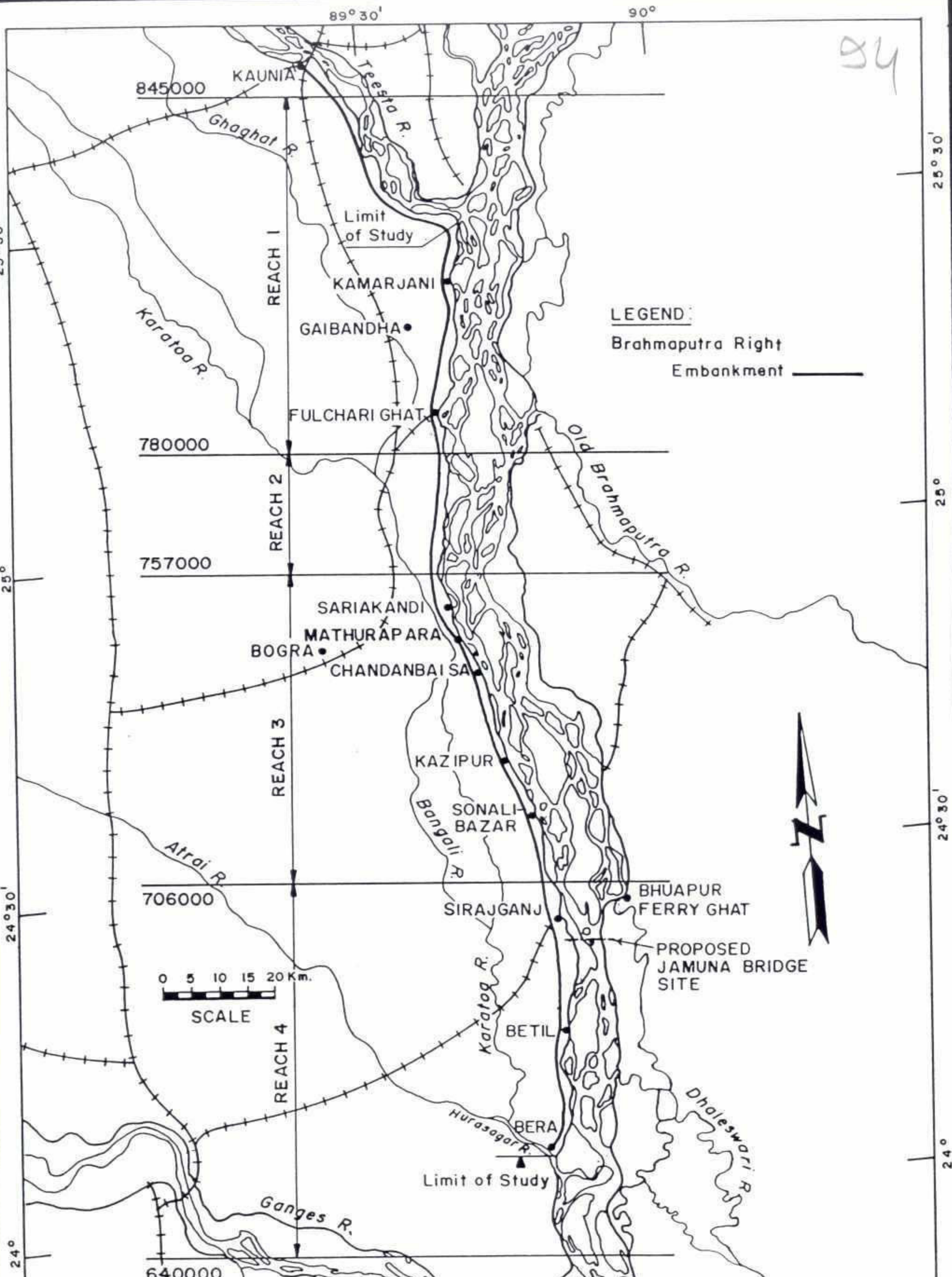
Longitudinal Distribution of Right Bank Erosion 1973-1992





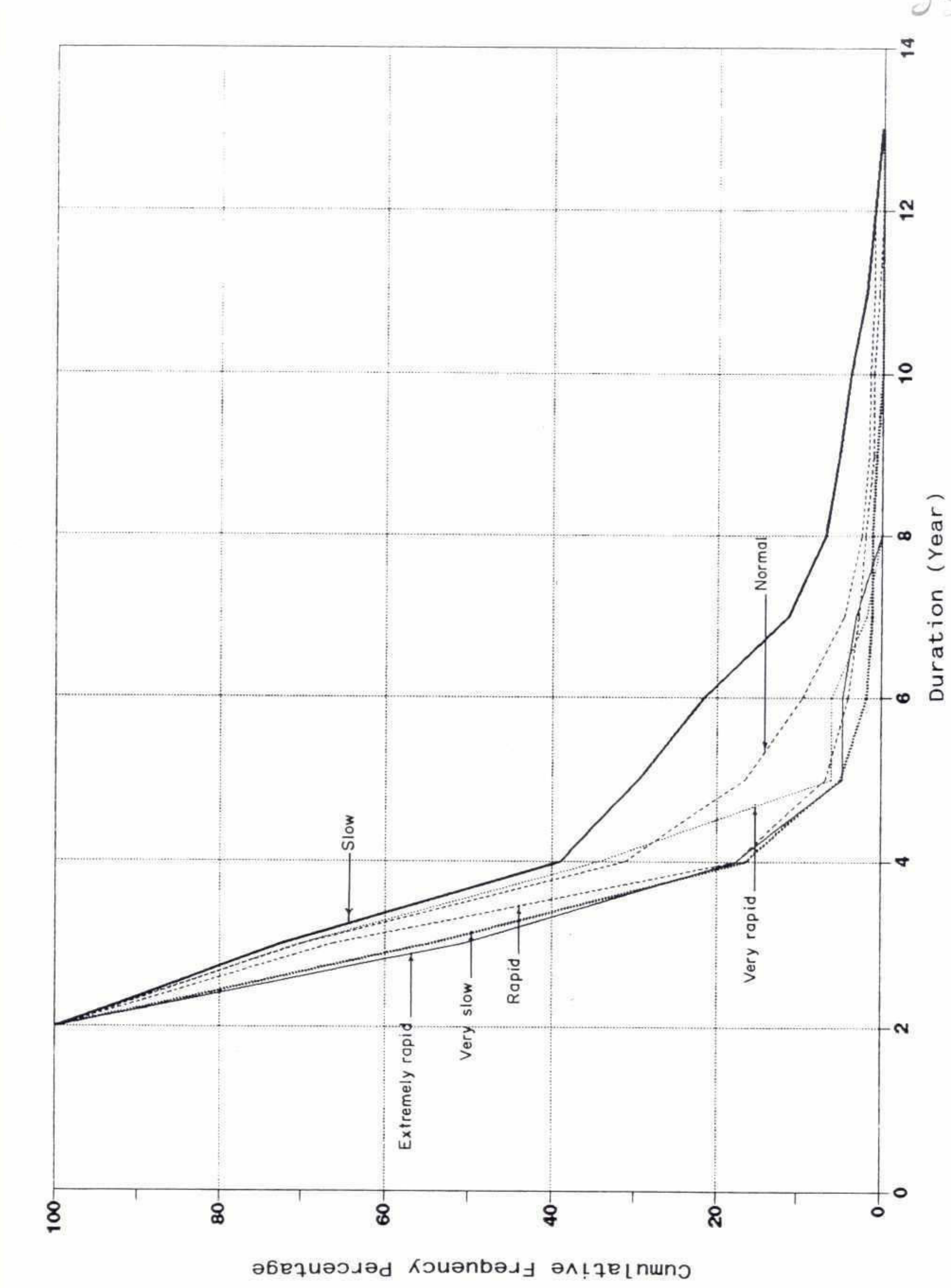
Bankline Movement 1953-1992 North and South of Sariakandi

		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 1.9



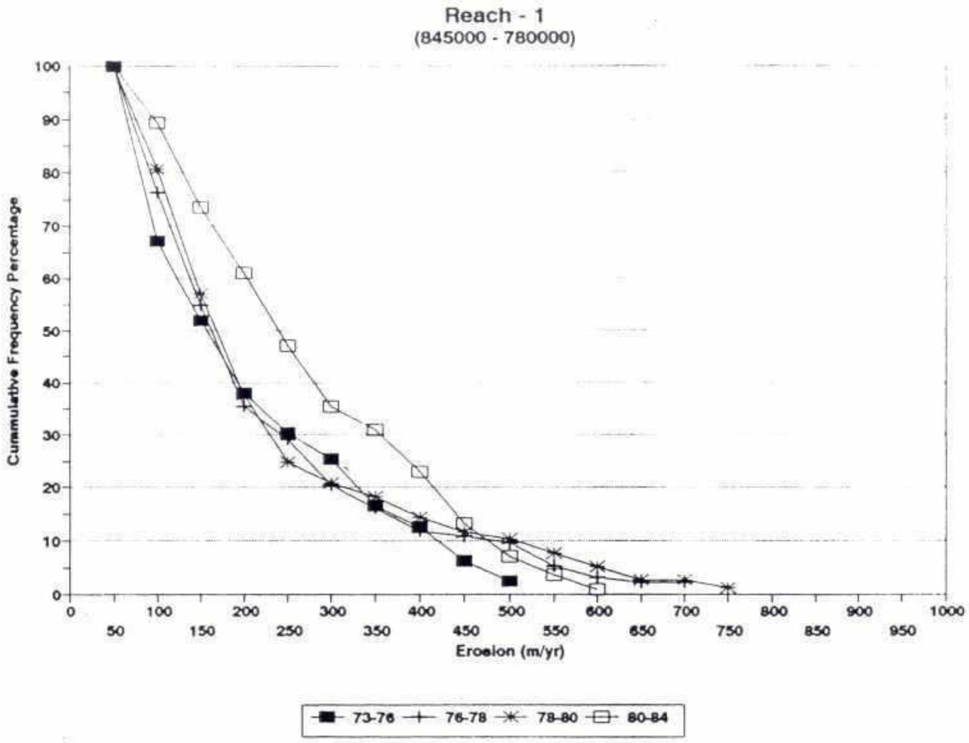
Definition of Reaches for Study of Rates of Erosion

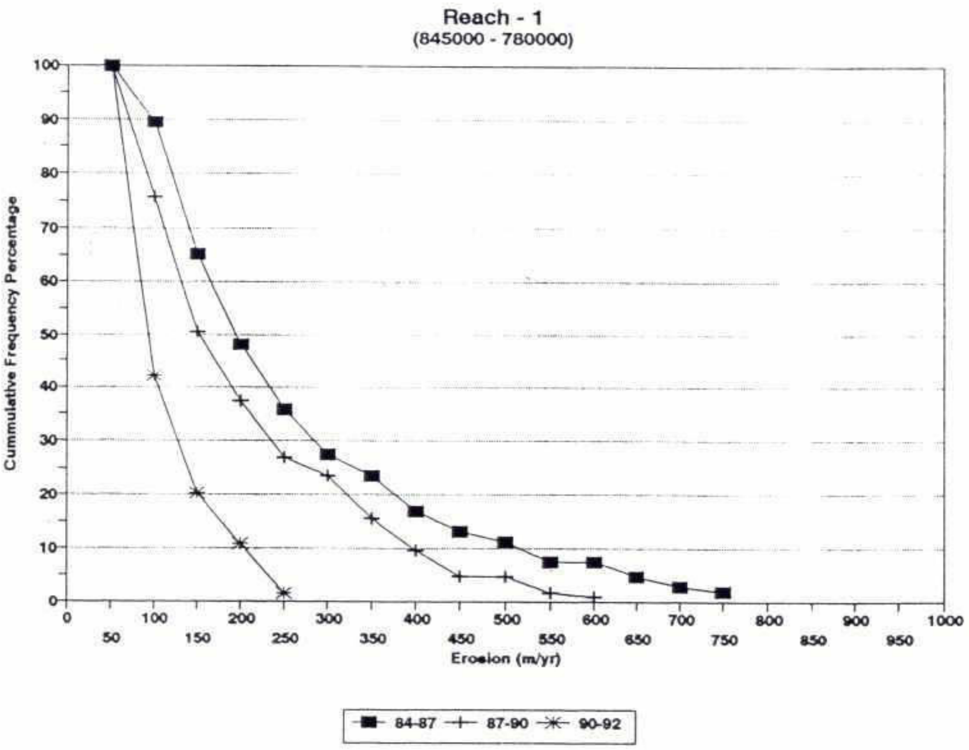
Halcrow/DHI/EPC/DIG	November 1992	Annex 2 Figure 1.10



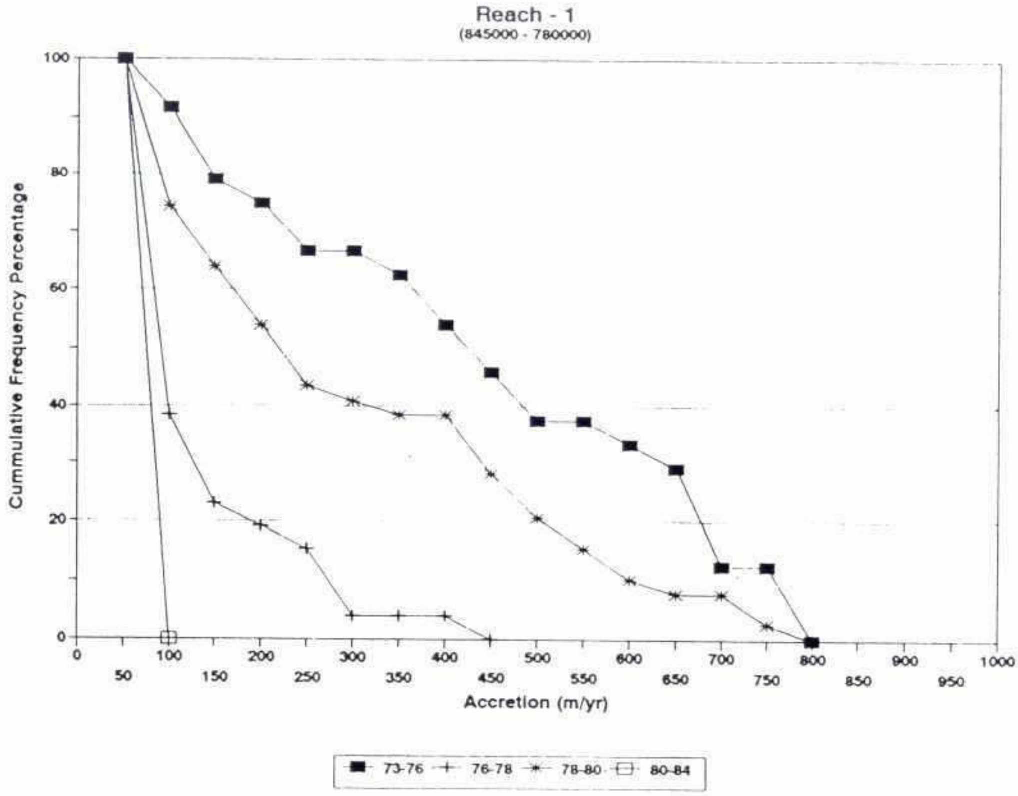
Duration of Erosion, Whole Study Area

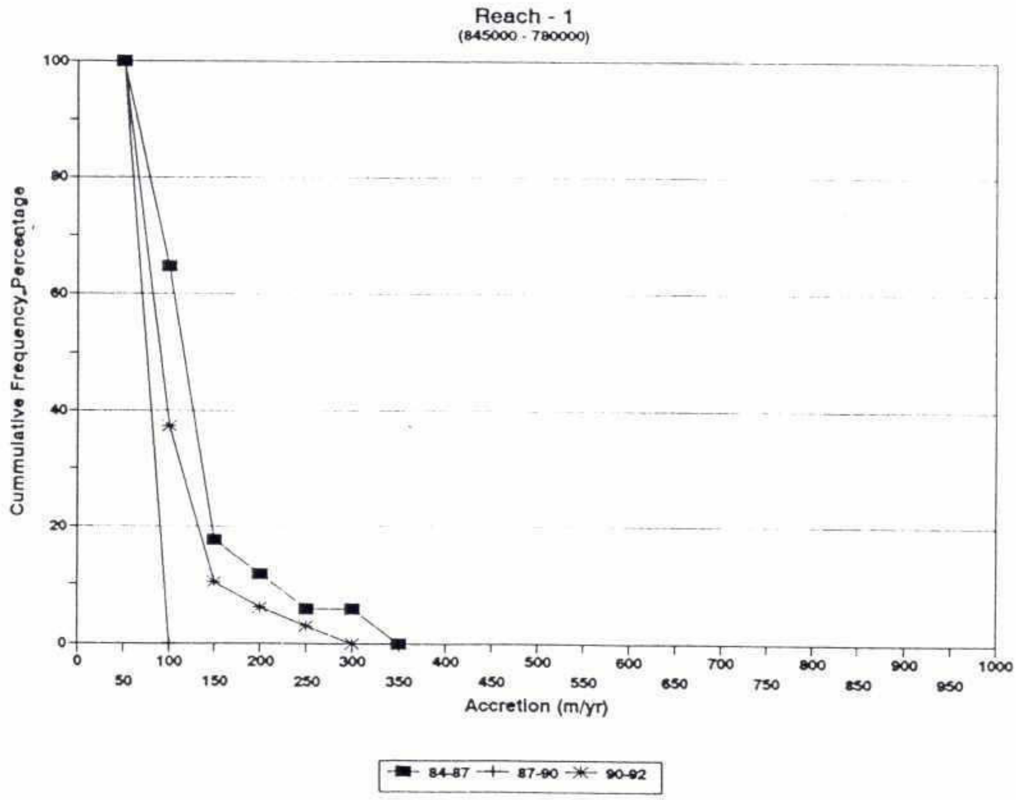
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 1.12





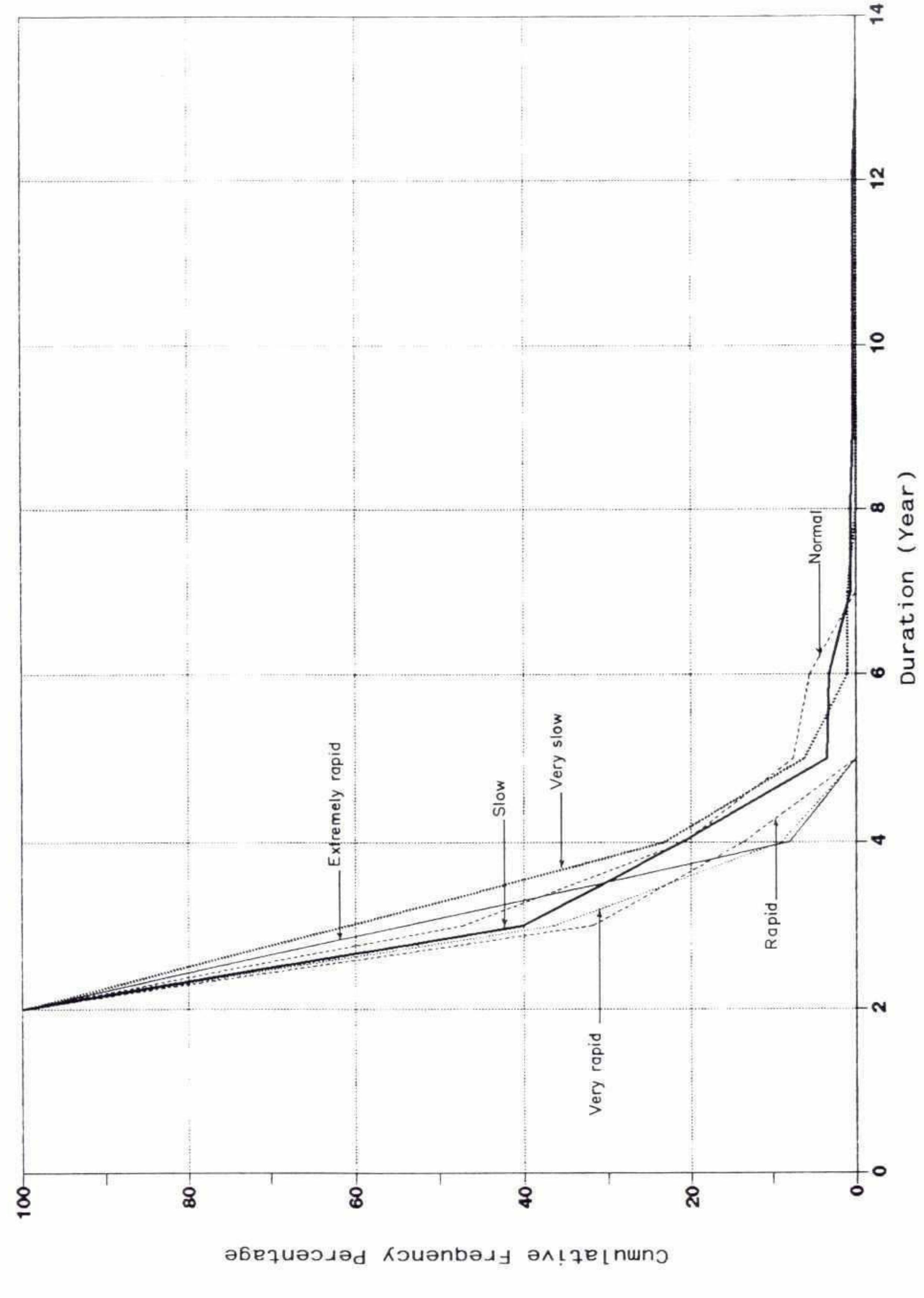
Frequency of Rates of Erosion, Reach 1





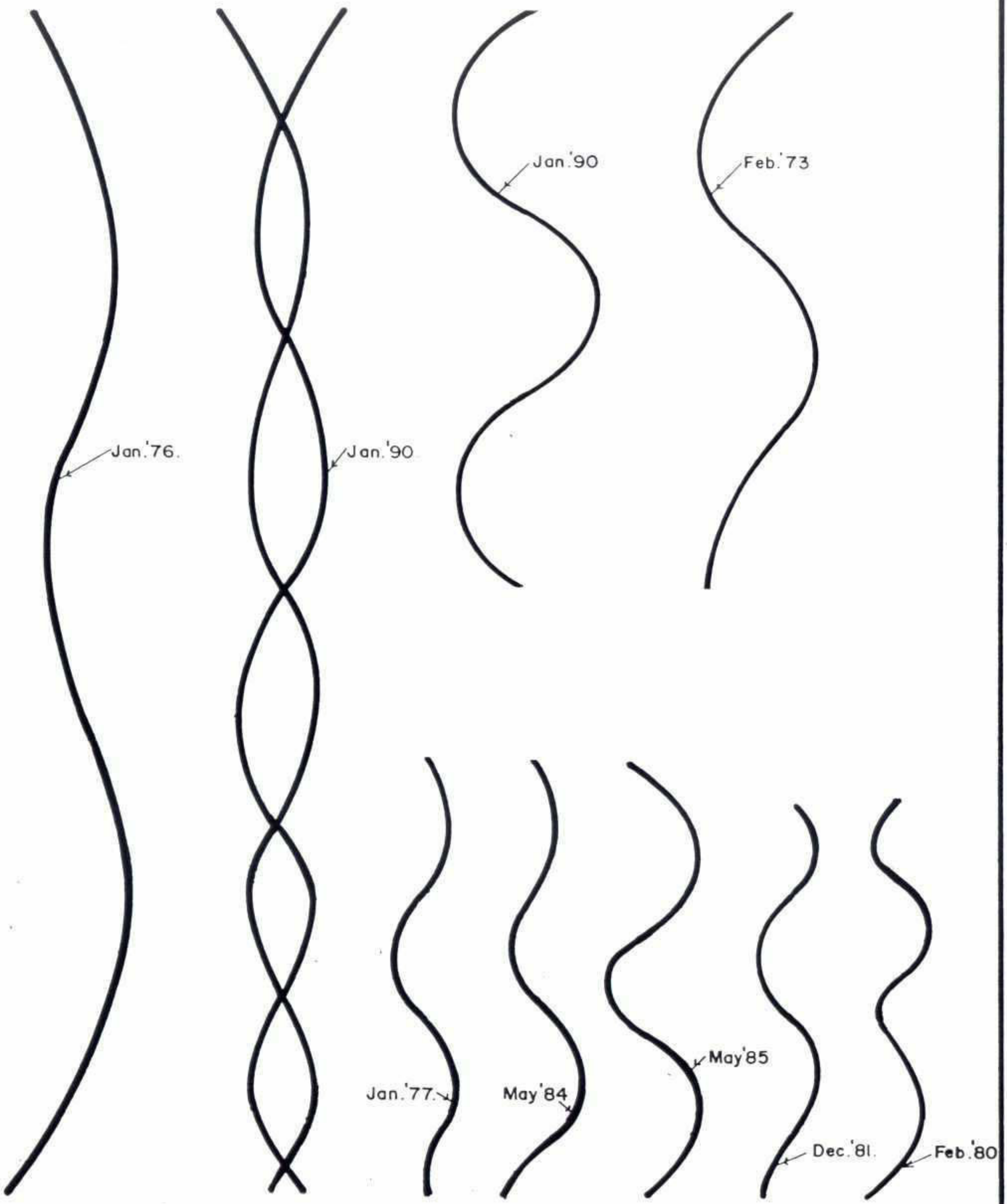
Frequency of Rates of Accretion, Reach 1

Halcrow/DHI/EPC/DIG	*November 1992*	**Annex 2** **Figure 1.13**



Duration of Accretion, Whole Study Area

Halcrow/DHI/EPC/DIG November 1992	Annex 2
	Figure 1.14



Interpreted from Land Sat images
of approximately 1:253400 Scale.

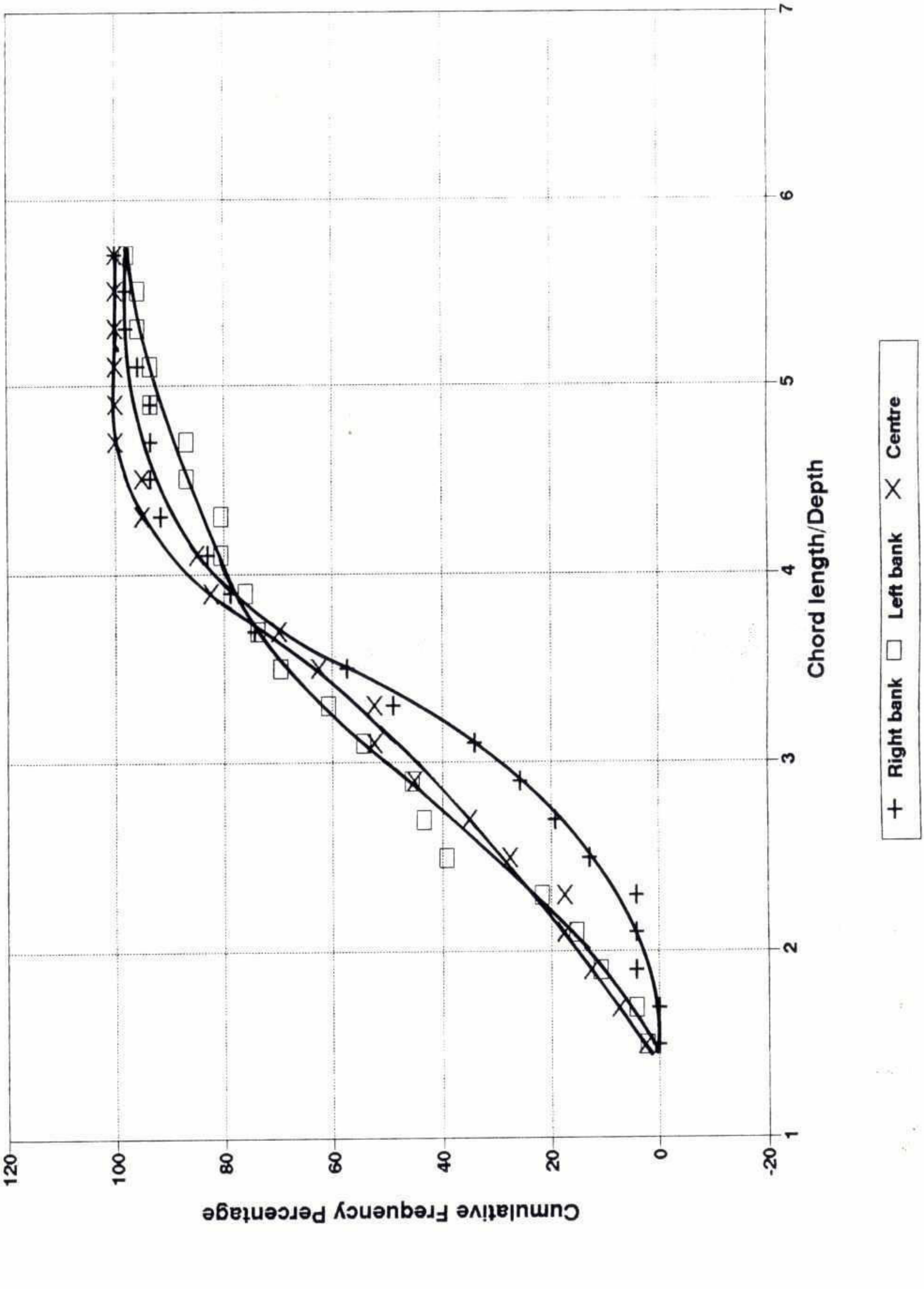
Typical Waveforms

Halcrow/DHI/EPC/DIG

November 1992

Annex 2

Figure 1.15



Probability of Exceedance of Chord length to Depth Ratio of Bends

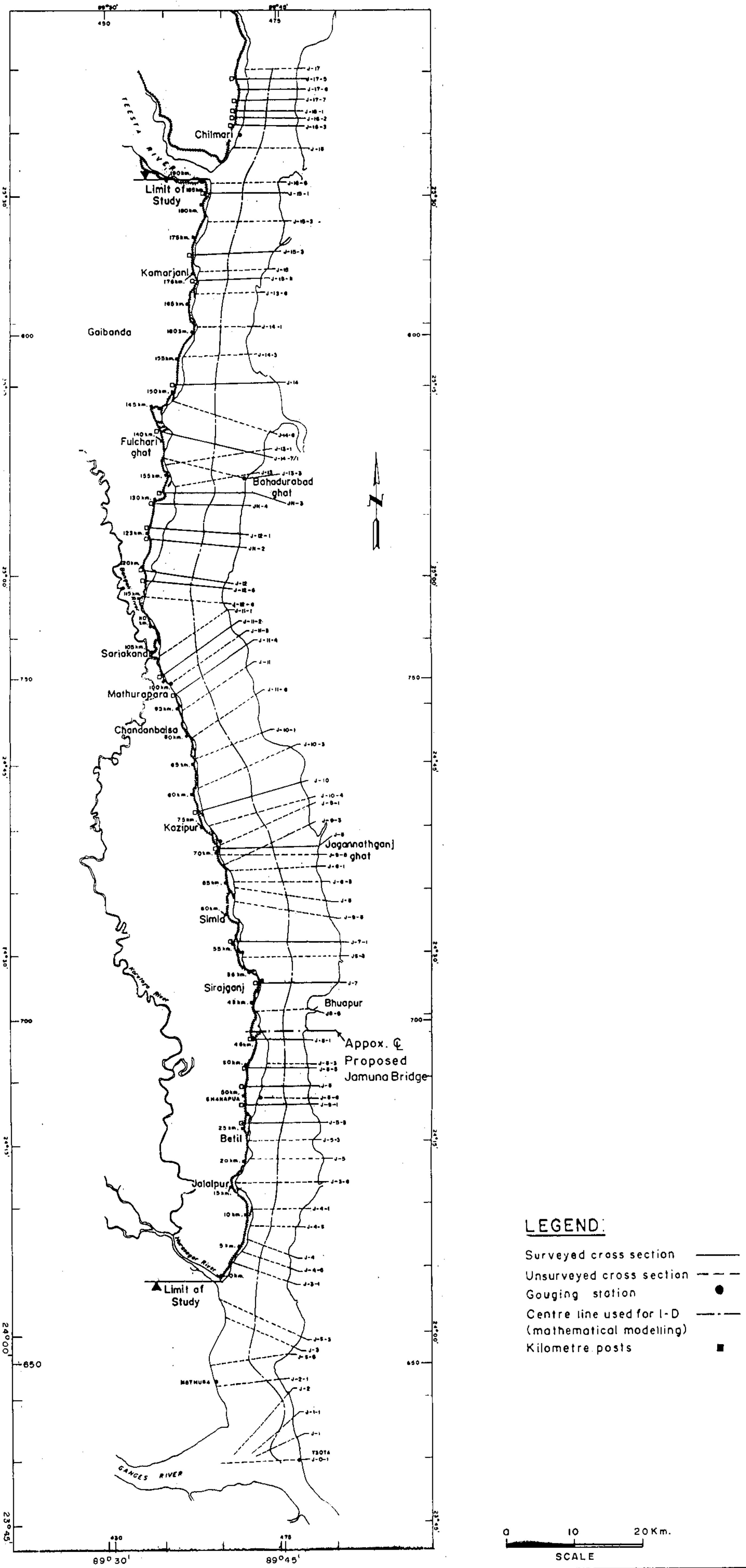
Location of Morphology Cross-sections and Gauging Stations

Halcrow/DHI/EPC/DIG

Annex 2

November 1992

Figure 2.1



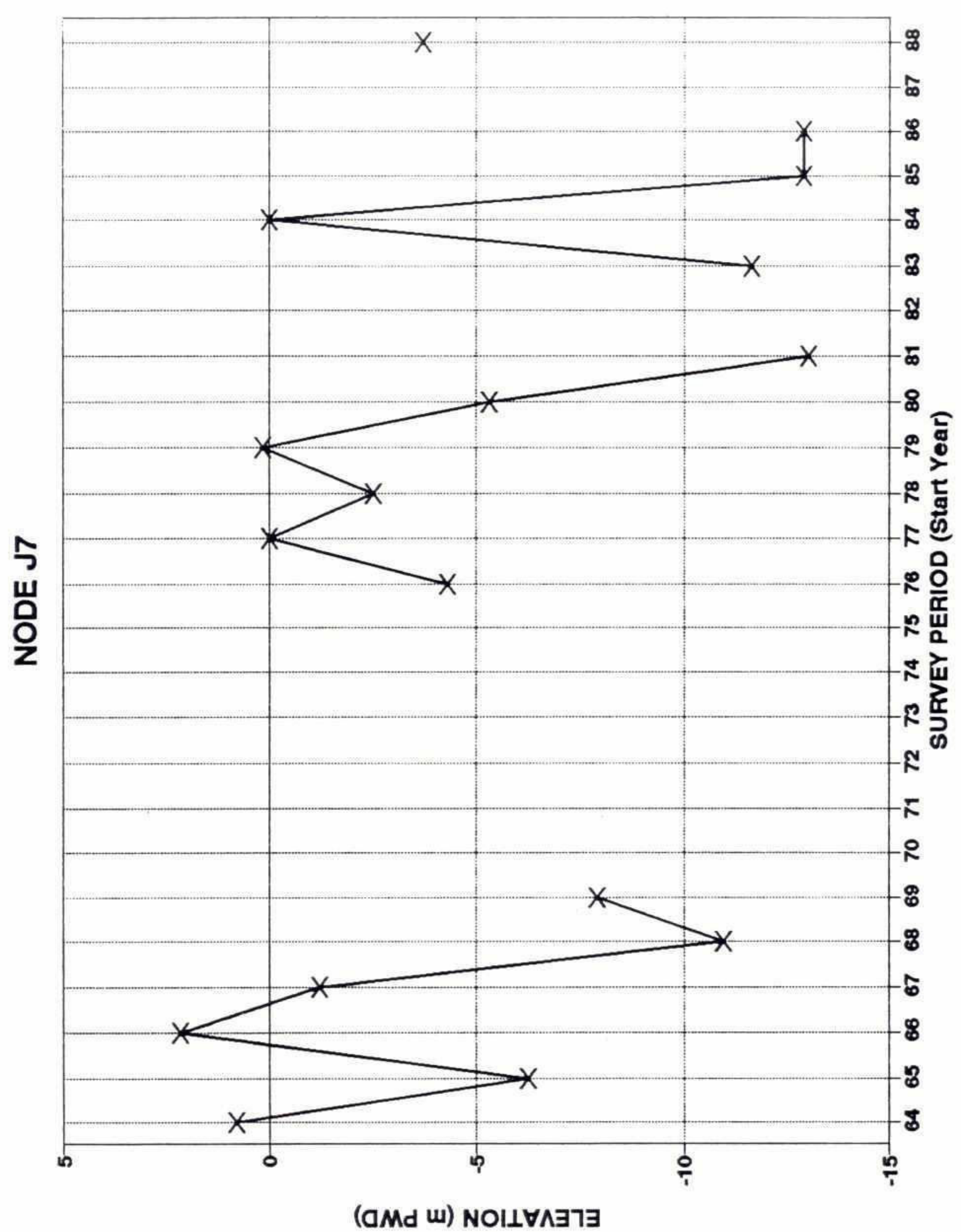
Typical Output After Pre-Processing Cross Section Data
Section JN3; 1988/89 Survey

Stage (m PWD)	Area Below Level (m2) Slice Number 1	2	3	4	5	6		Total	Wetted Perimeter (m)
21	148.133	99.273	3.374	40.733	3.481	6.161	- - - -	73307.06	12693.83
20	87.173	57.823	1.844	23.363	1.961	3.111	- - - -	60629.13	12684.64
19	26.213	16.373	.314	5.993	.441	.061	- - - -	48050.64	12350.75
18	0	0	0	0	0	0	- - - -	37093.62	9088.346
17							- - - -	28902.82	7589.201
16							- - - -	21648.43	6932.811
15							- - - -	15491.33	5197.179
14							- - - -	11100.52	3930.367
13							- - - -	7569.221	3293.999
12							- - - -	4604.872	2646.544
11							- - - -	2503.381	1773.248
10							- - - -	978.735	1286.76
9							- - - -	129.726	424.289
8							- - - -	0	0
							- - - -	0	0
Y bar	30.48	81.685	103.175	112.625	122.07	124.355	- - - -		
Z bar	18.57	18.605	18.795	18.655	18.71	18.98	- - - -		
Wetted P	60.96	41.451	1.539	17.376	1.62	3.05	- - - -		

Notes:-
Y bar - distance from reference pillar
Z bar - average bed level in slice
Wetted P - wetted perimeter of slice

102

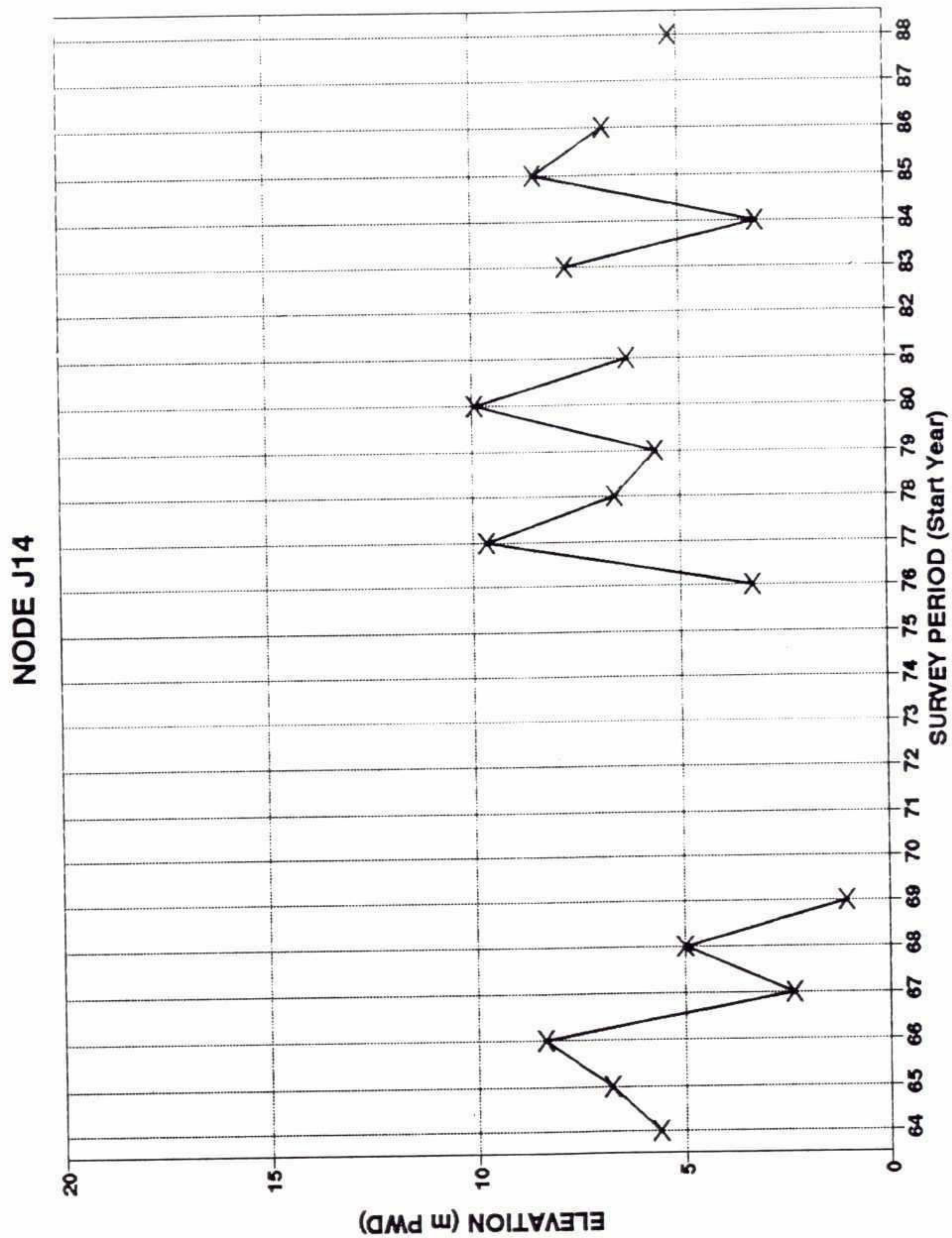
Sample Output After Pre-processing



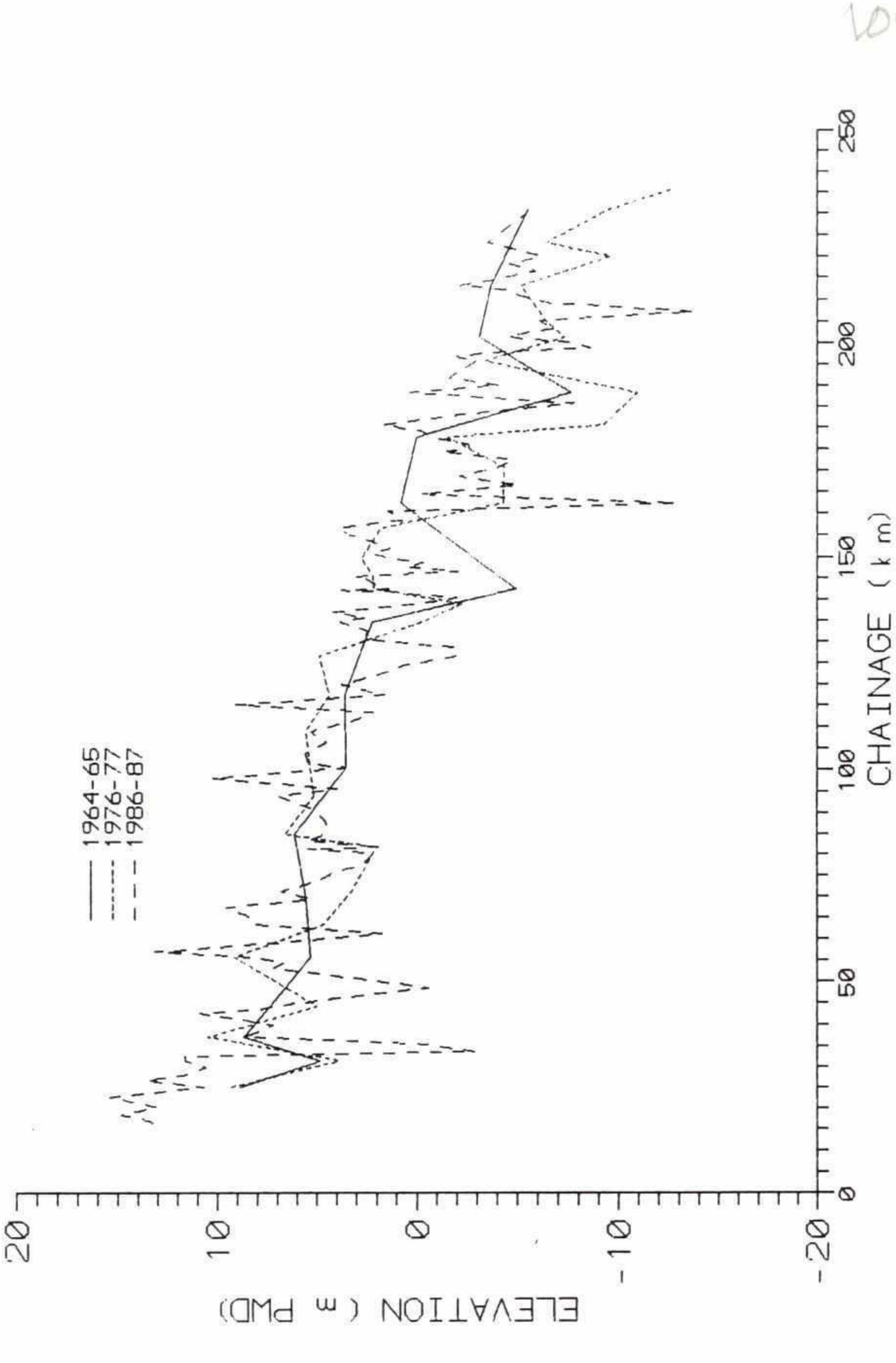
Varition in Thalweg Level with Time at Section J7

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.3

L04



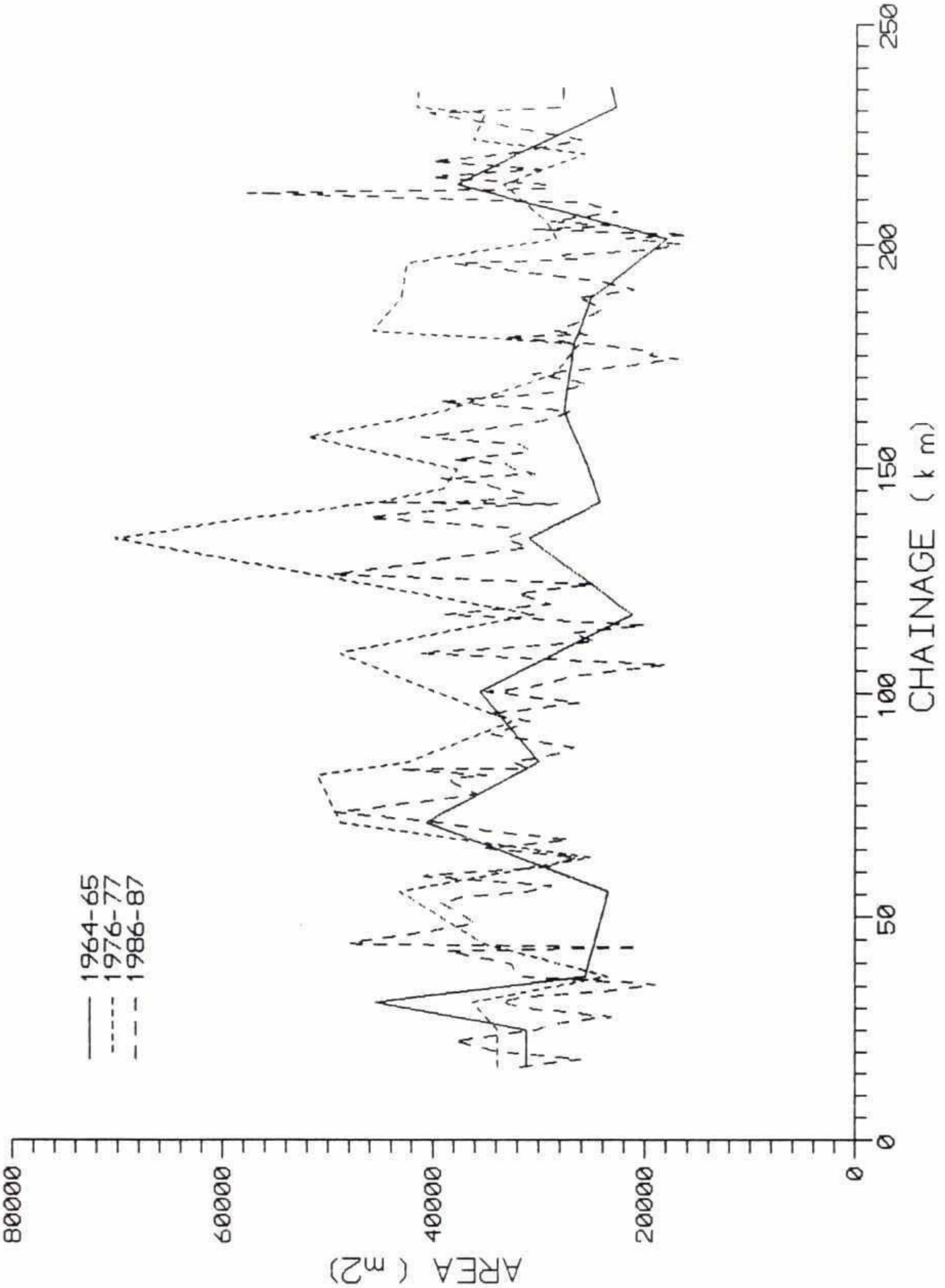
Varition in Thalweg Level with Time at Section J14



Variation in Thalweg with River Chainage

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.5

L06

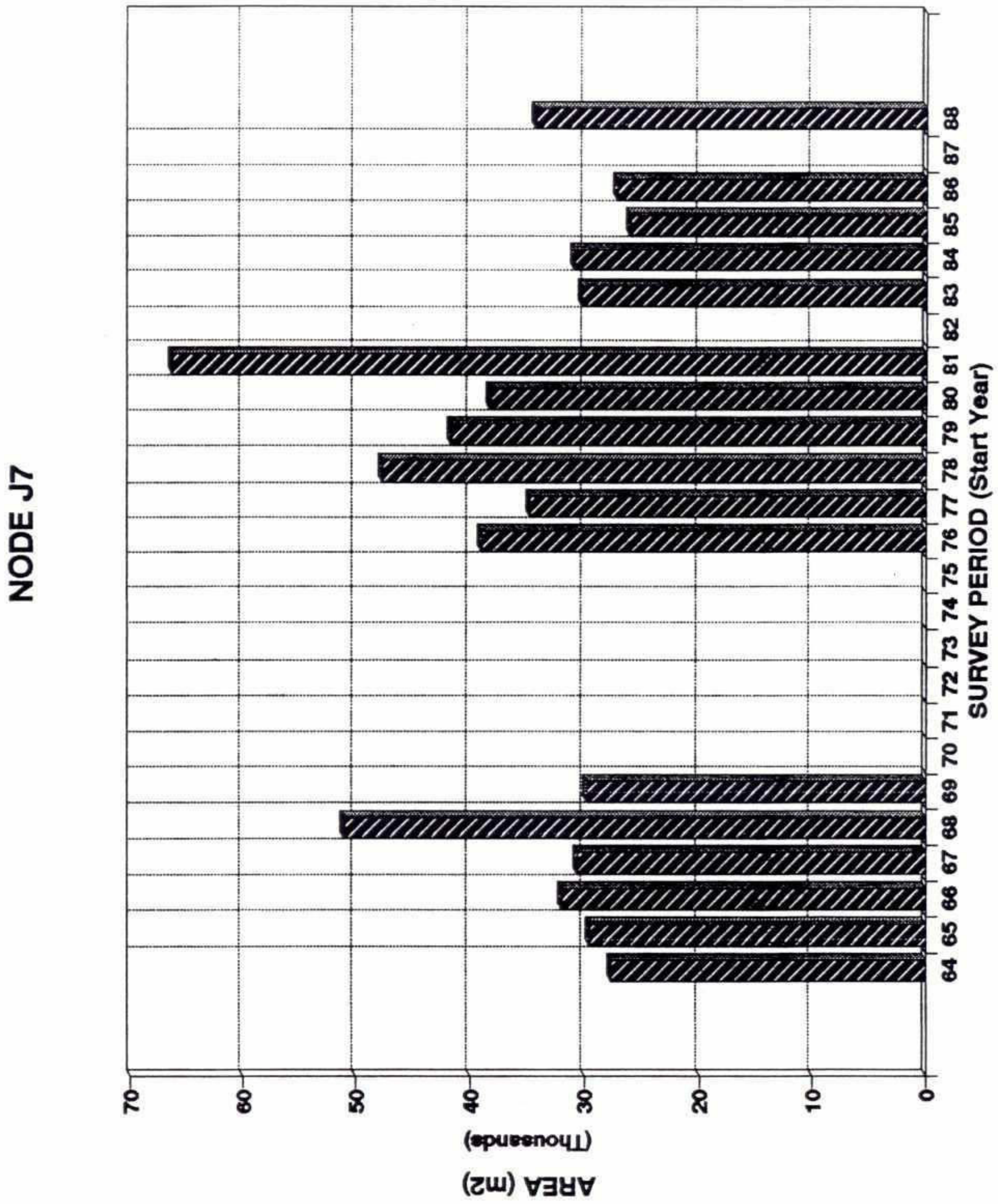


NOTE:

Area measured under water level at dominant discharge.

Variation in Cross-section Area with River Chainage

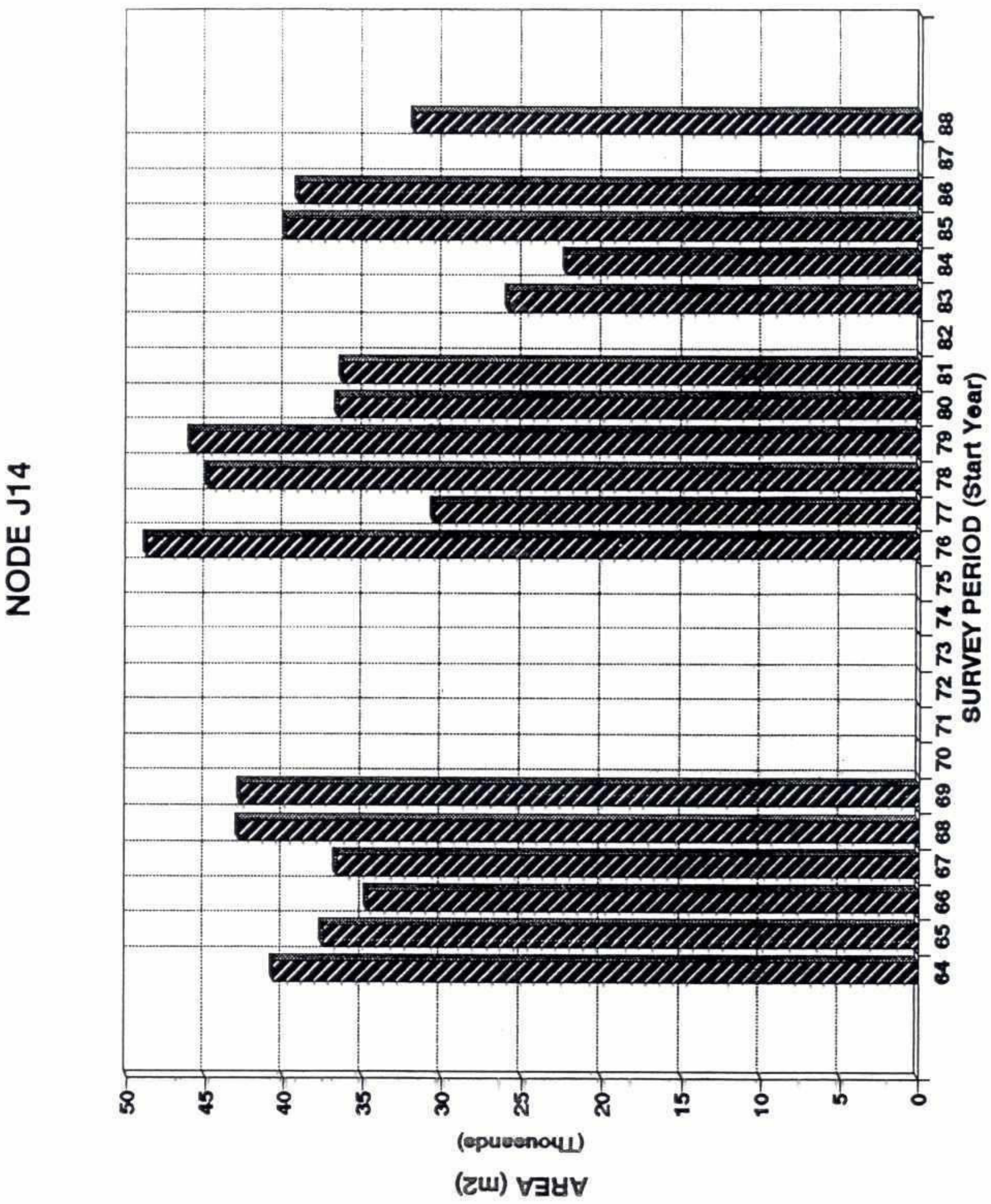
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.6



NOTE:

Area measured under water level at dominant discharge.

Variation in Cross-Section Area with Time at Section J7

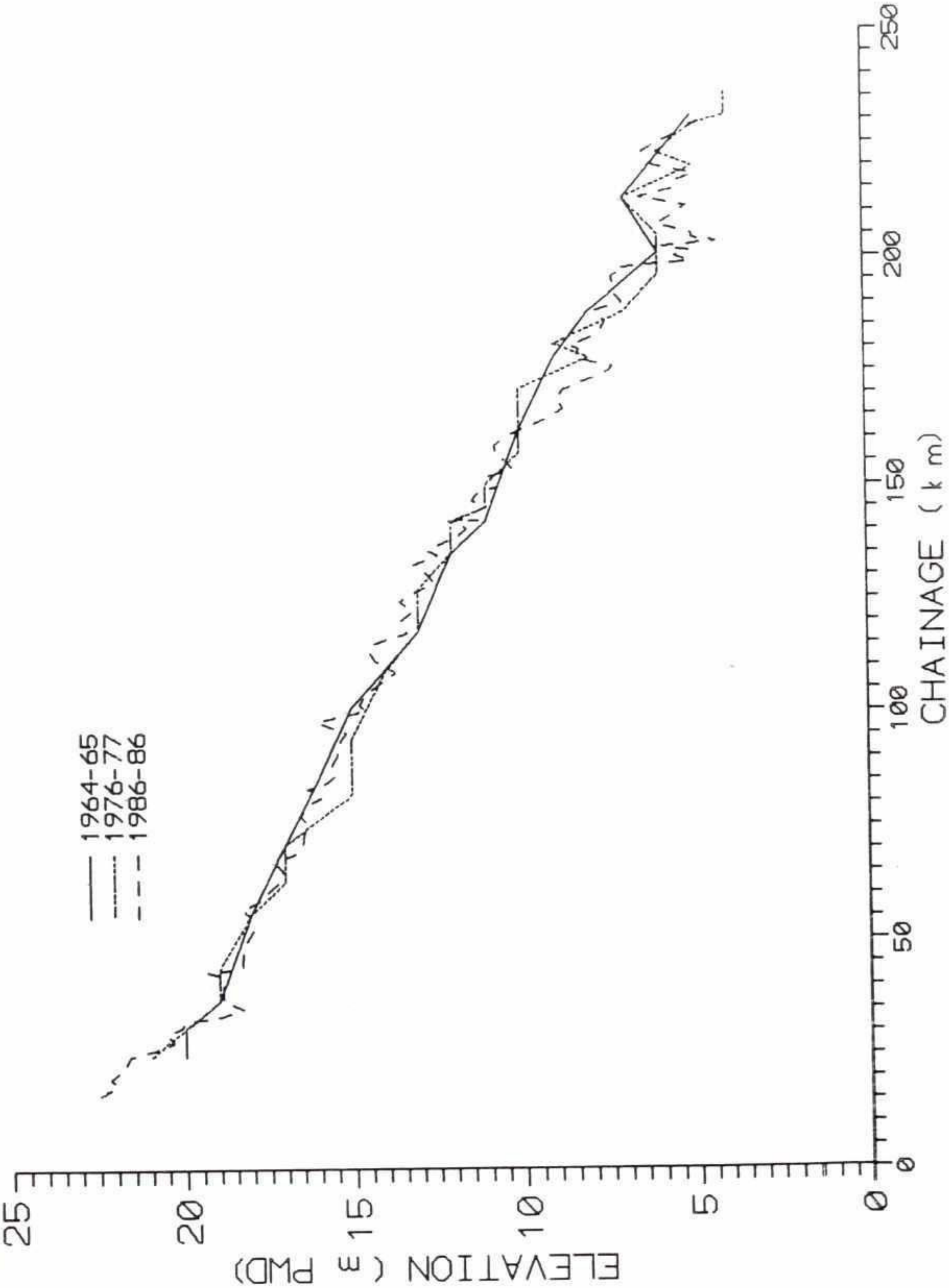


NOTE:

Area measured under water level at dominant discharge.

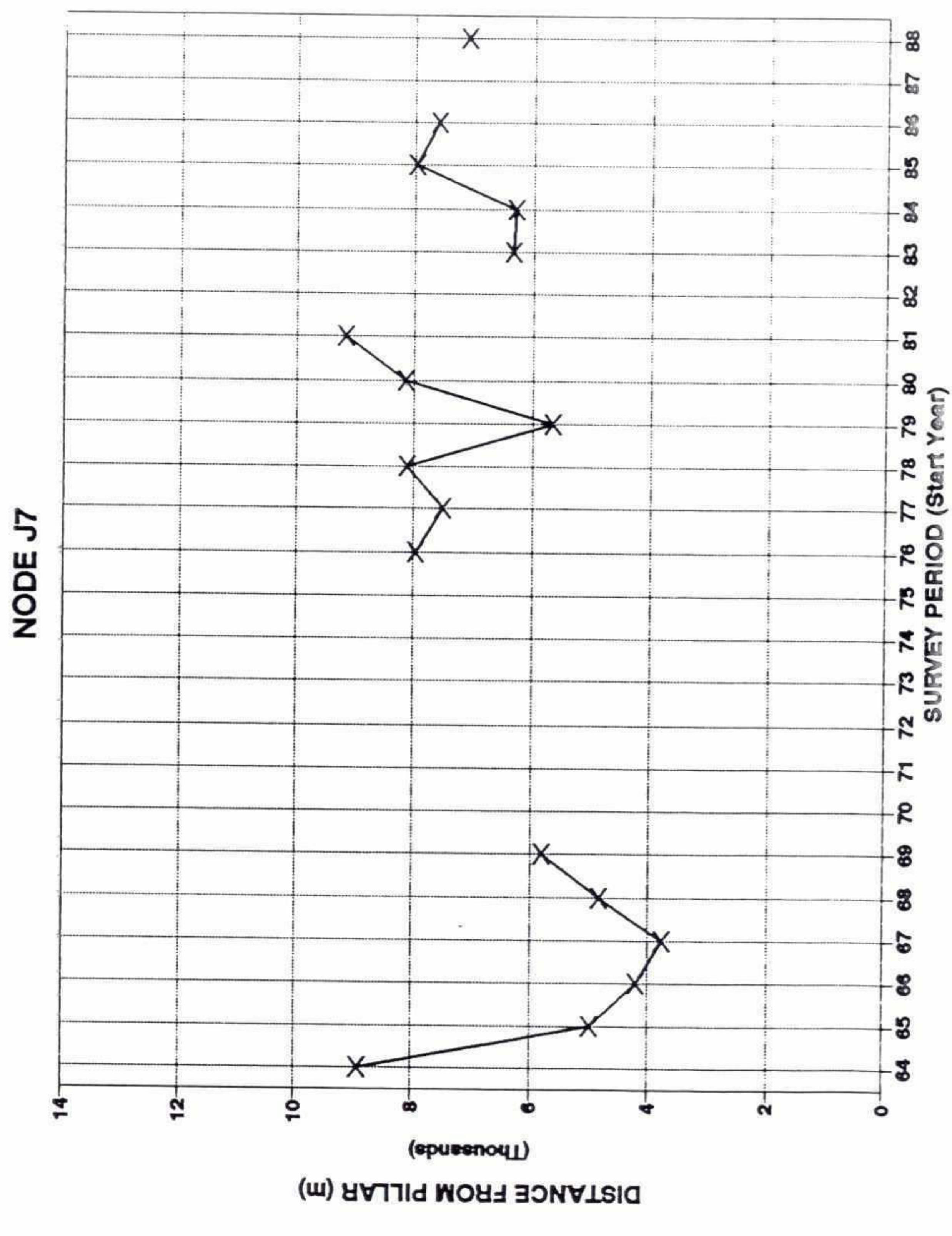
Variation in Cross-Section Area with Time at Section J14

(109)



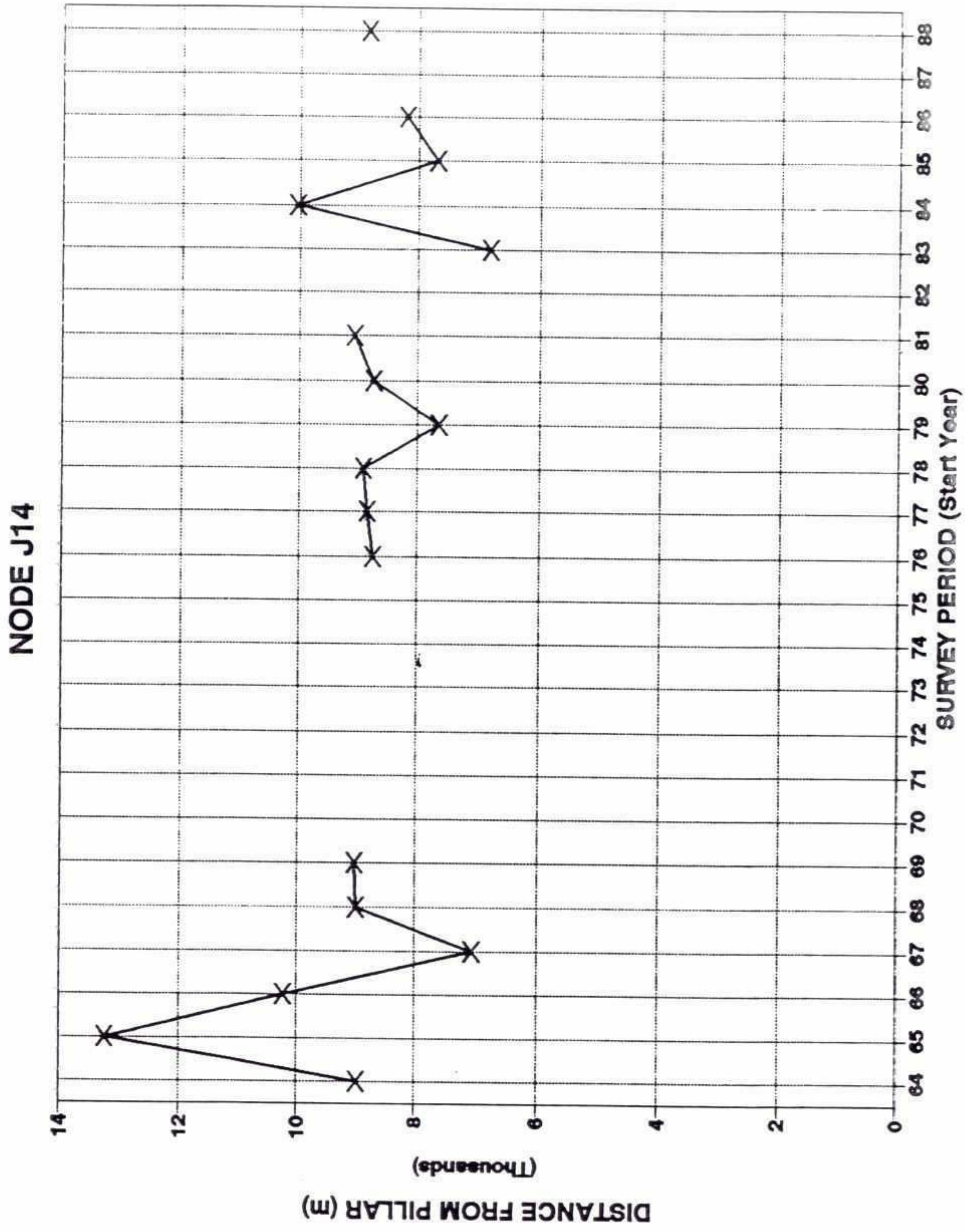
Variation in Centroid dZ With River Chainage

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.9



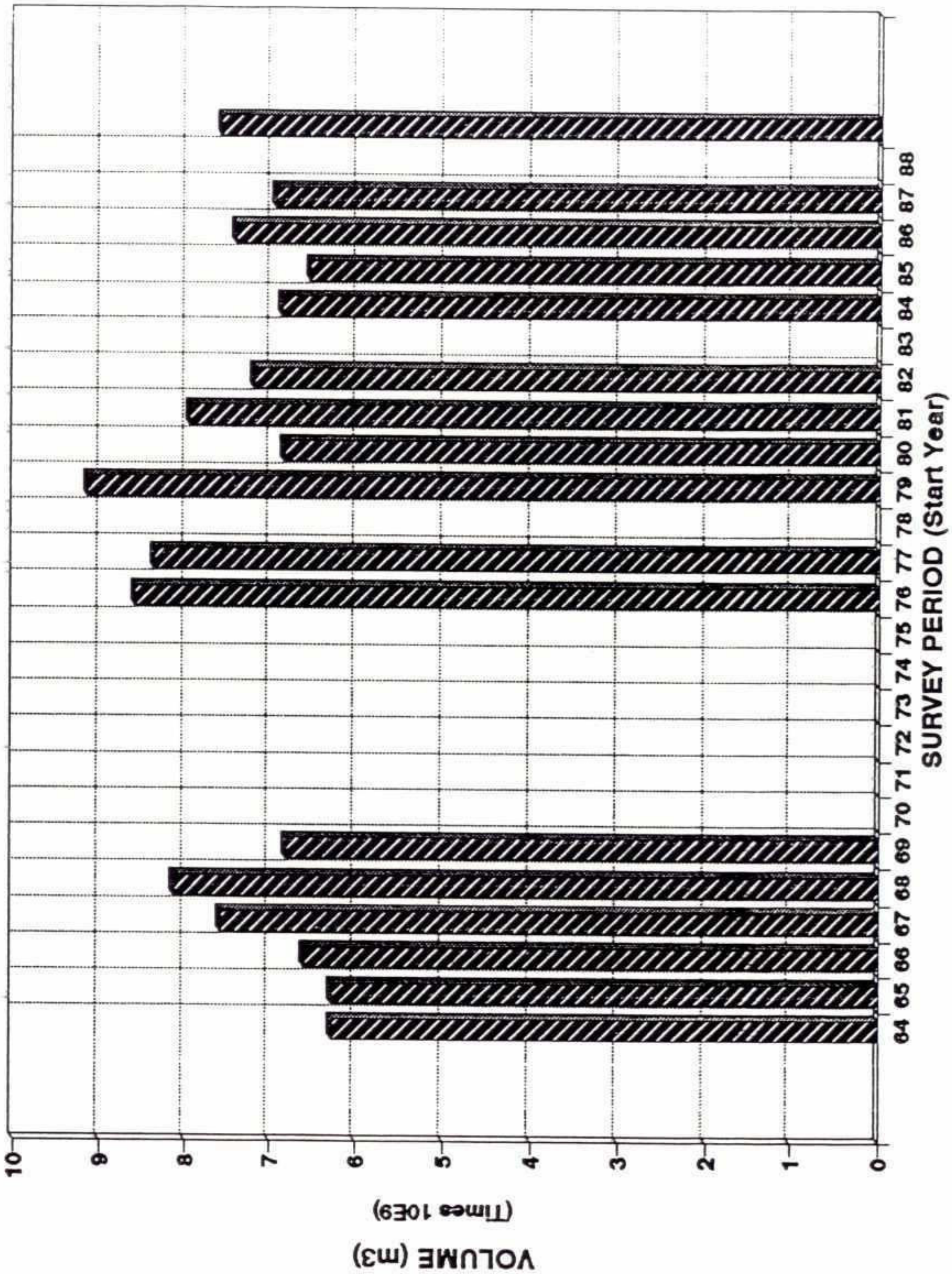
Variation in Centroid dY with Time at Section J7

		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 2.10



Variation in Centroid dY with Time at Section J14

Halcrow/DHI/EPC/DIG	*November 1992*	Annex 2 Figure 2.11



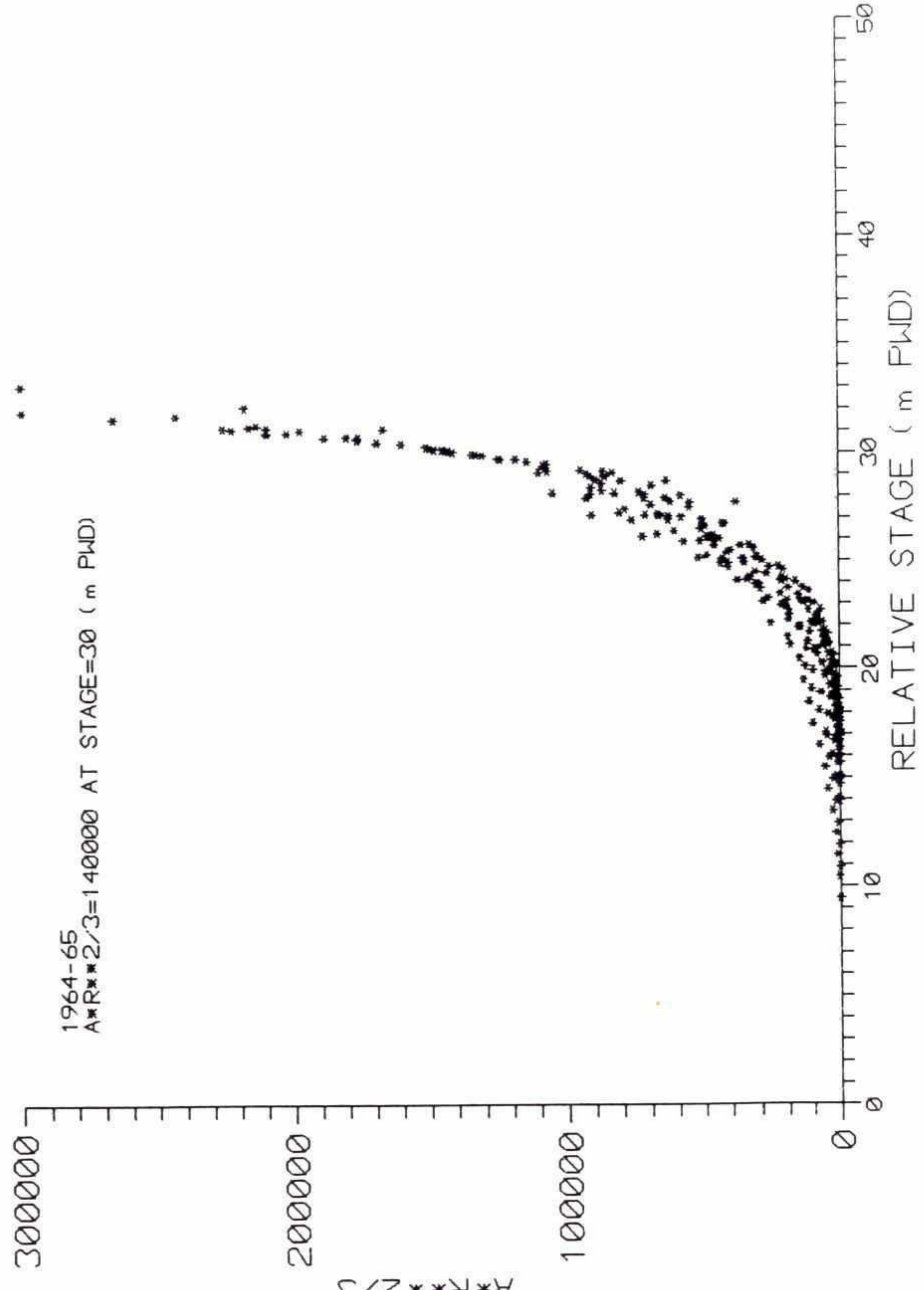
NOTE:

Volume measured under water level at dominant discharge.

Variation in Channel Volume With Time

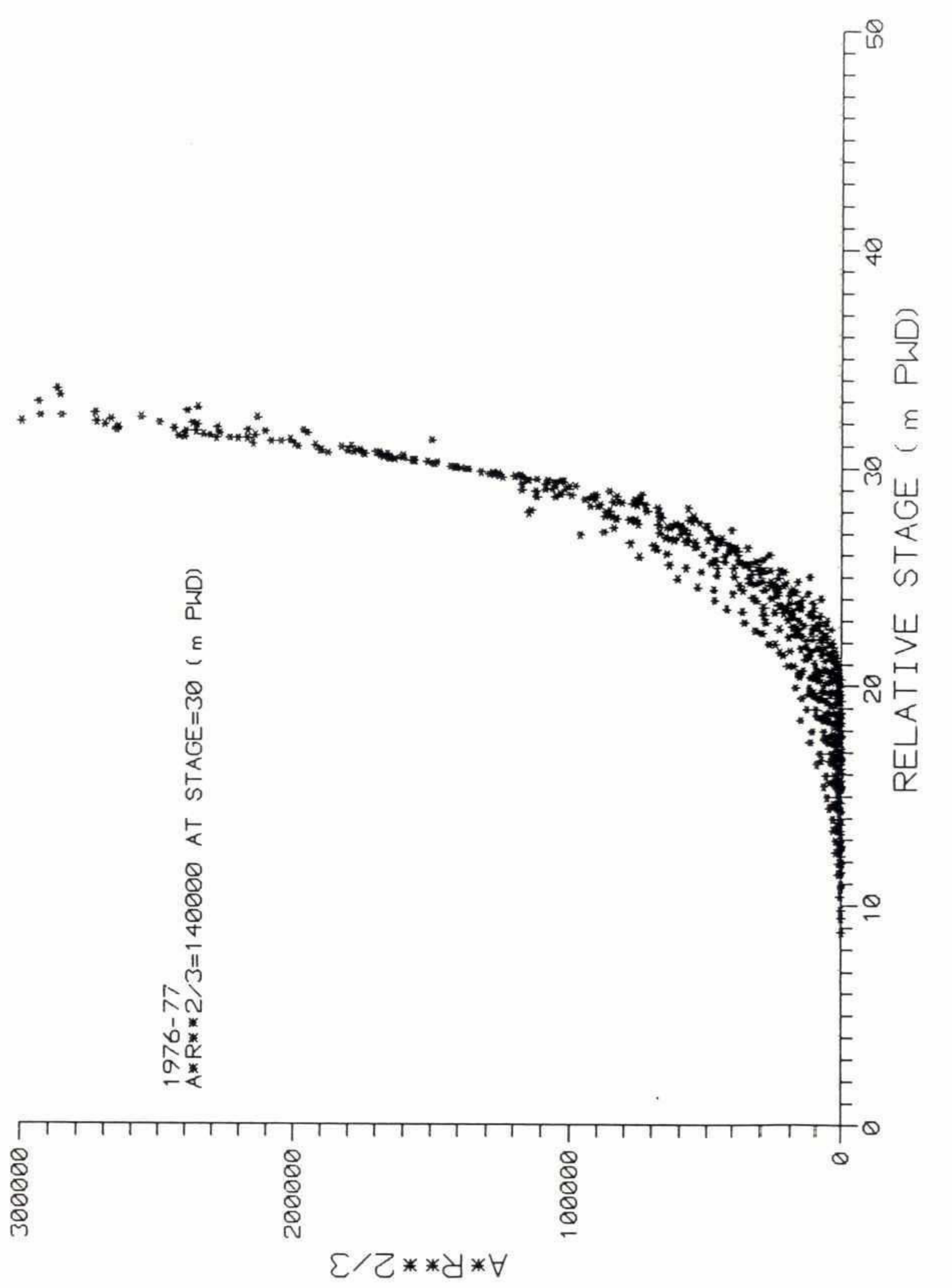
		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 2.12

43



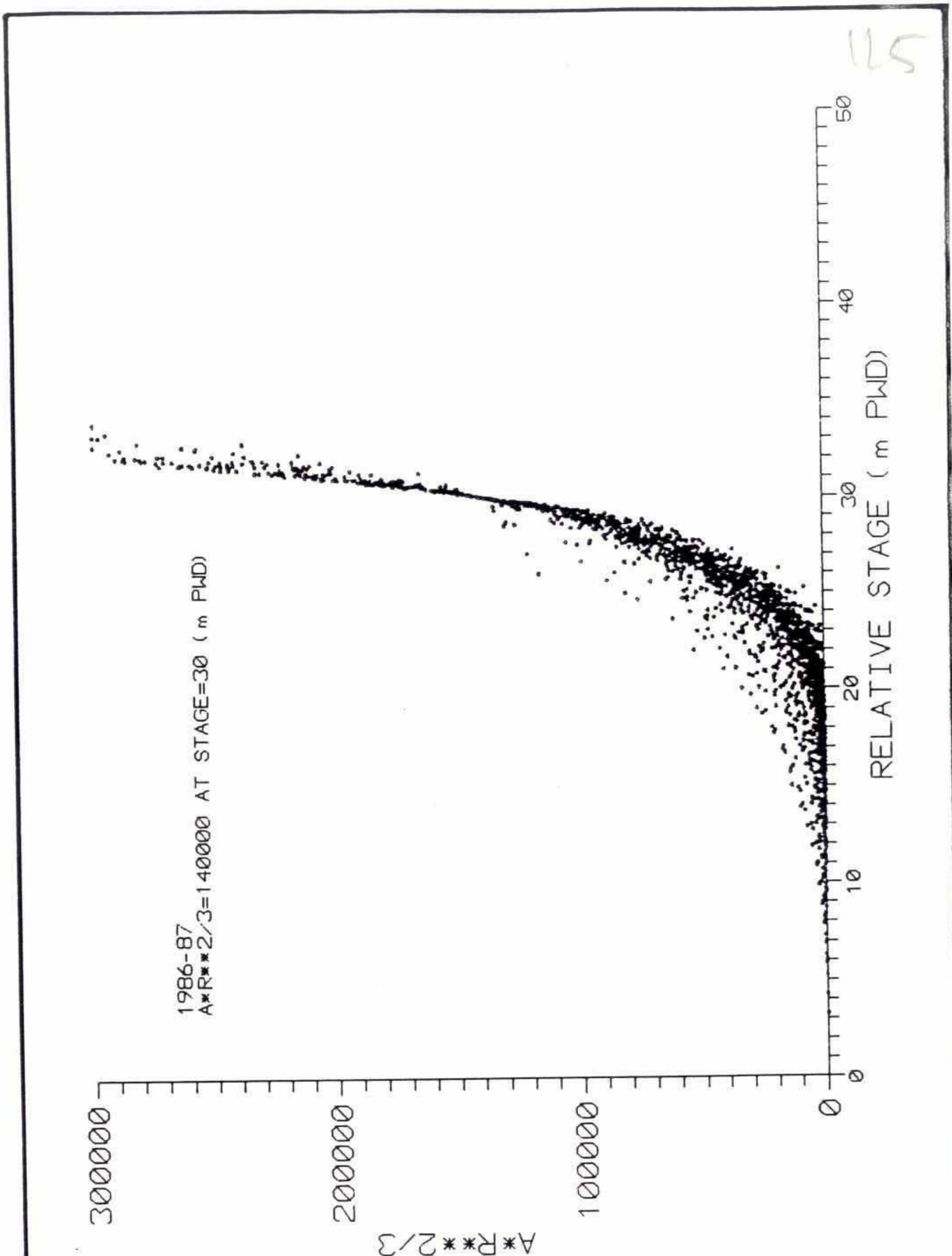
Conveyance Factor V Relative Stage 1964/65

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.13



Conveyance Factor V Relative Stage 1976/1977

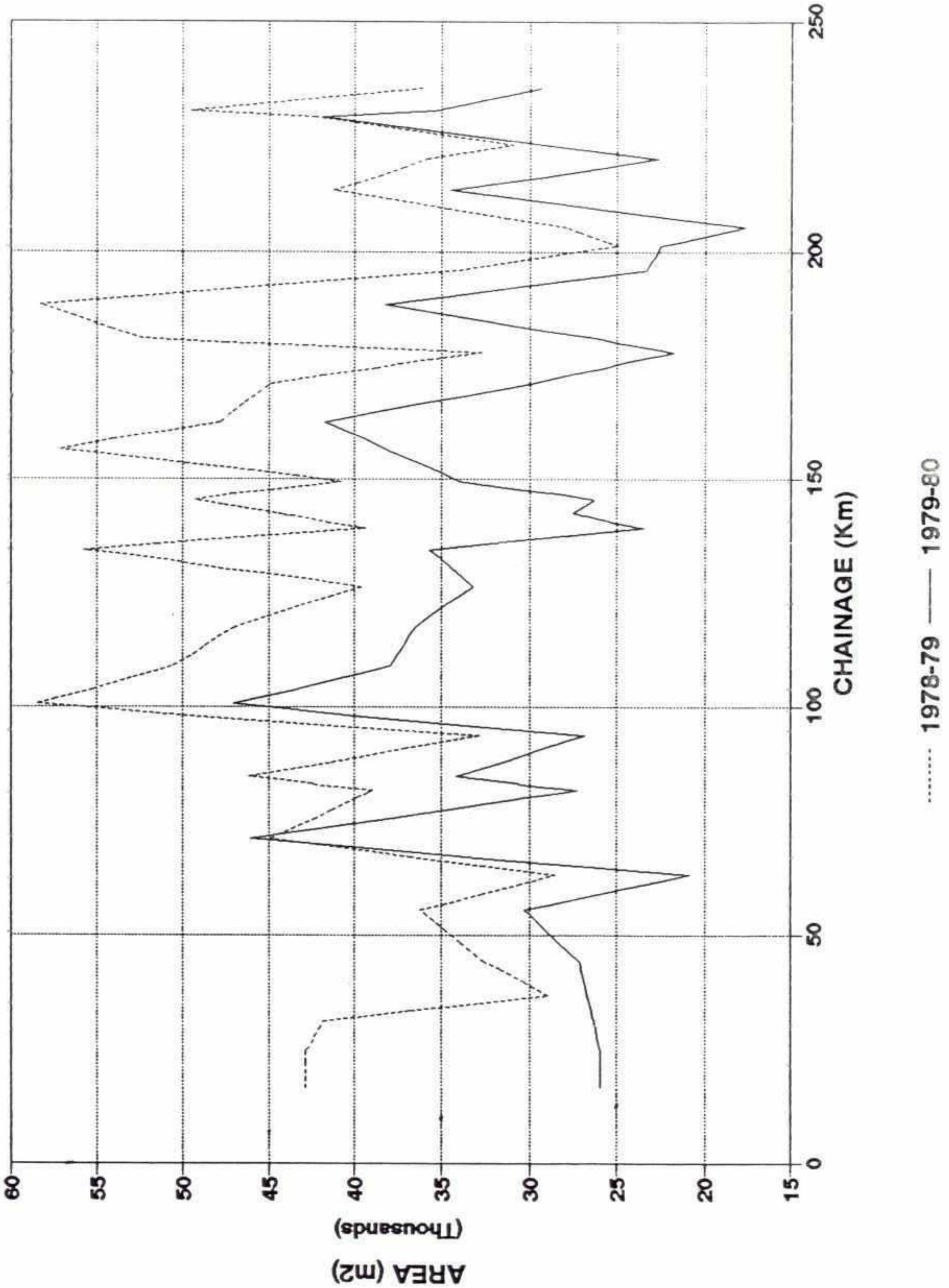
		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 2.14



Conveyance Factor V Relative Stage 1986/1987

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.15

116

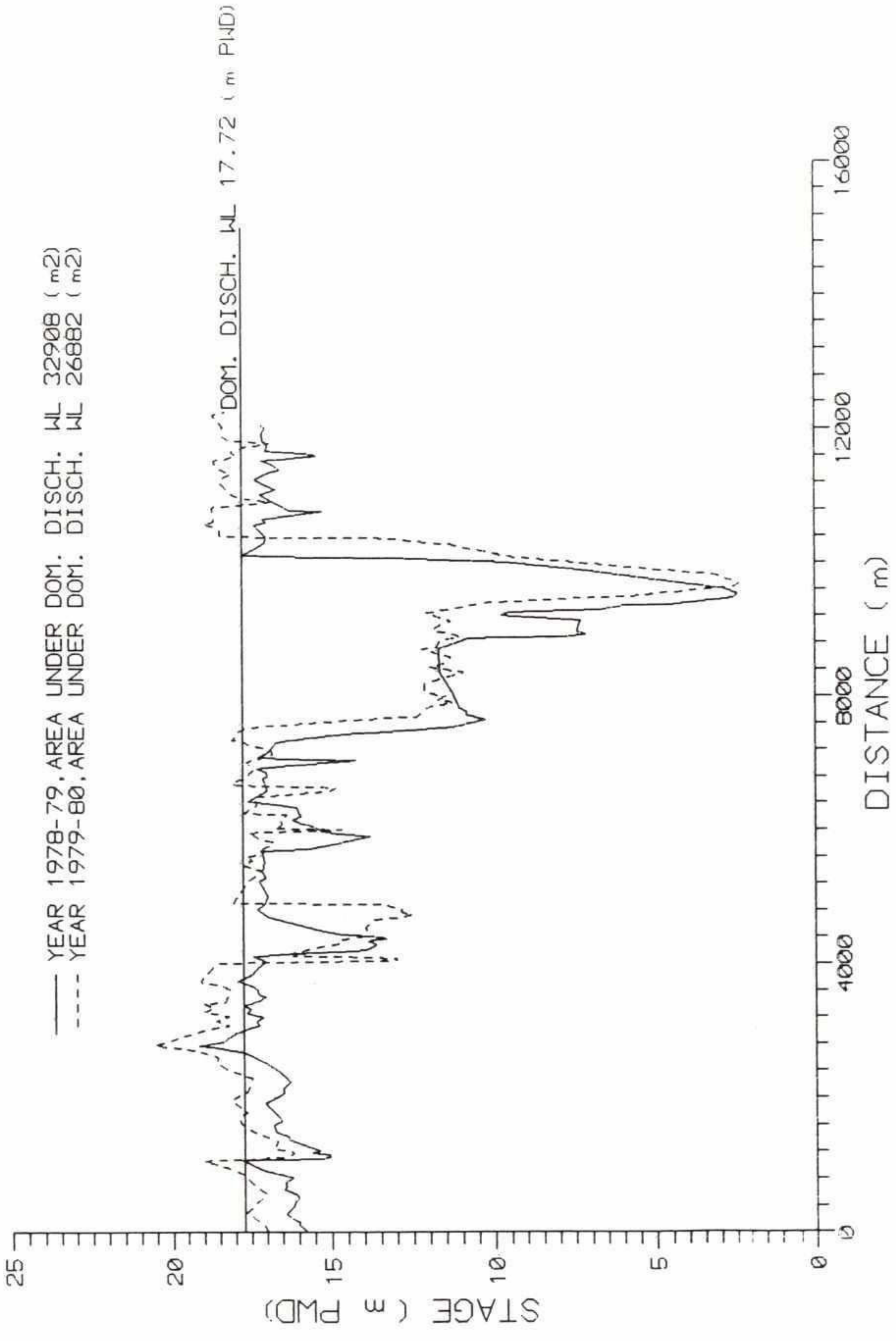


NOTE:
Area measured under water level at dominant discharge.

Cross-section Area V River Chainage (1978/79 and 1979/80)

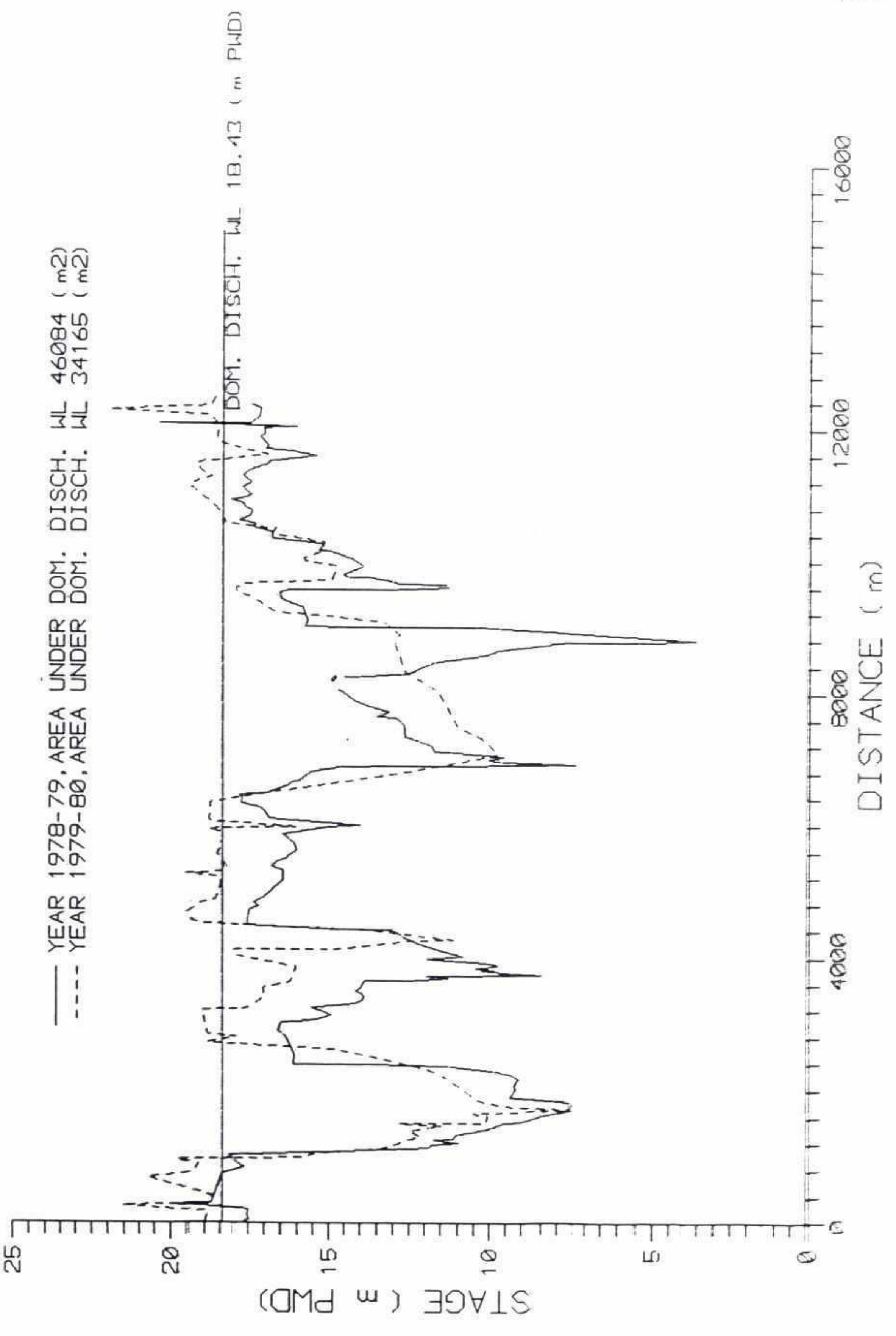
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.16

117



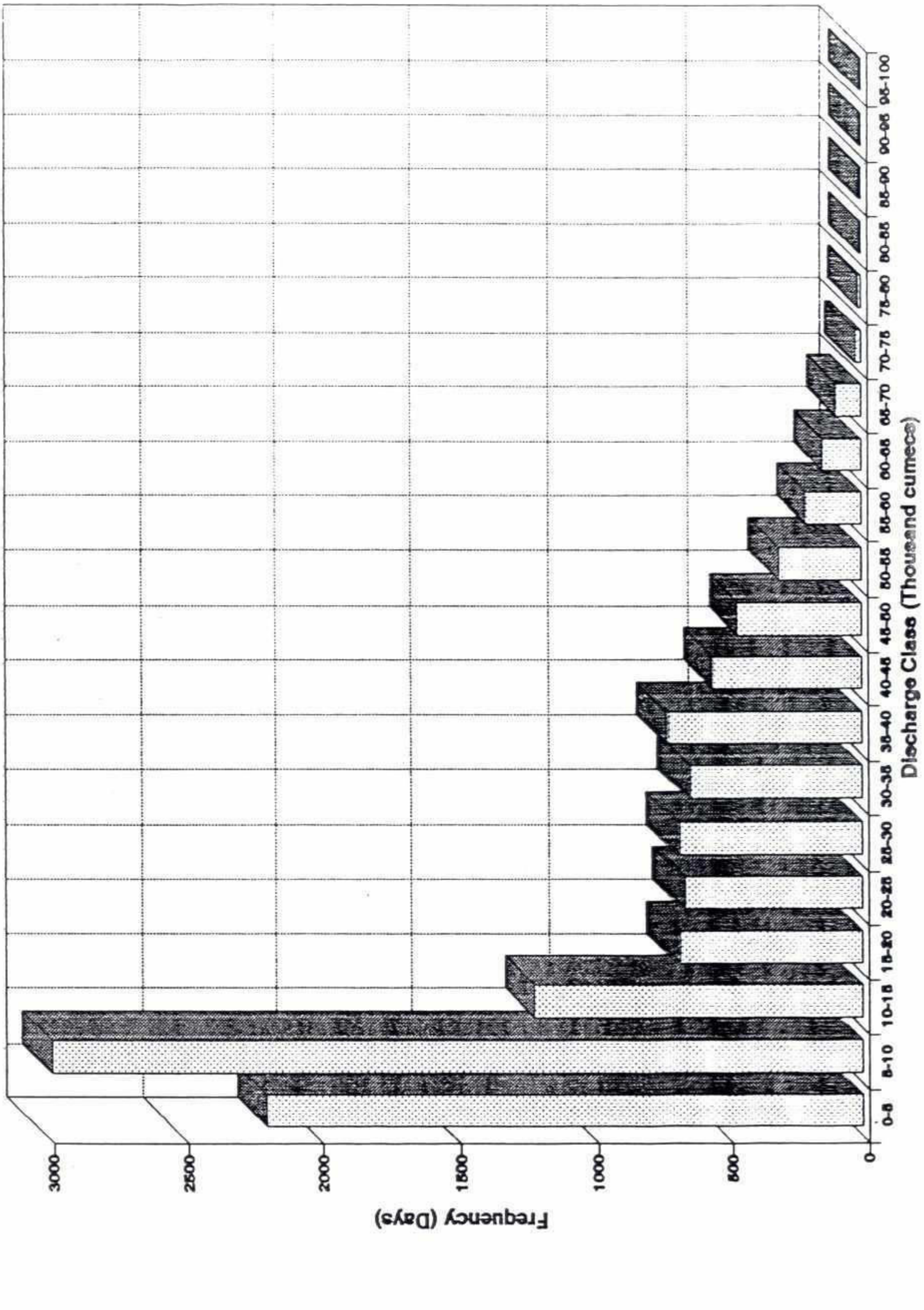
Cross-section Plot at J12-1 (1978/79 and 1979/80)

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.17



Cross-section Plot at J13 (1978/79 and 1979/80)

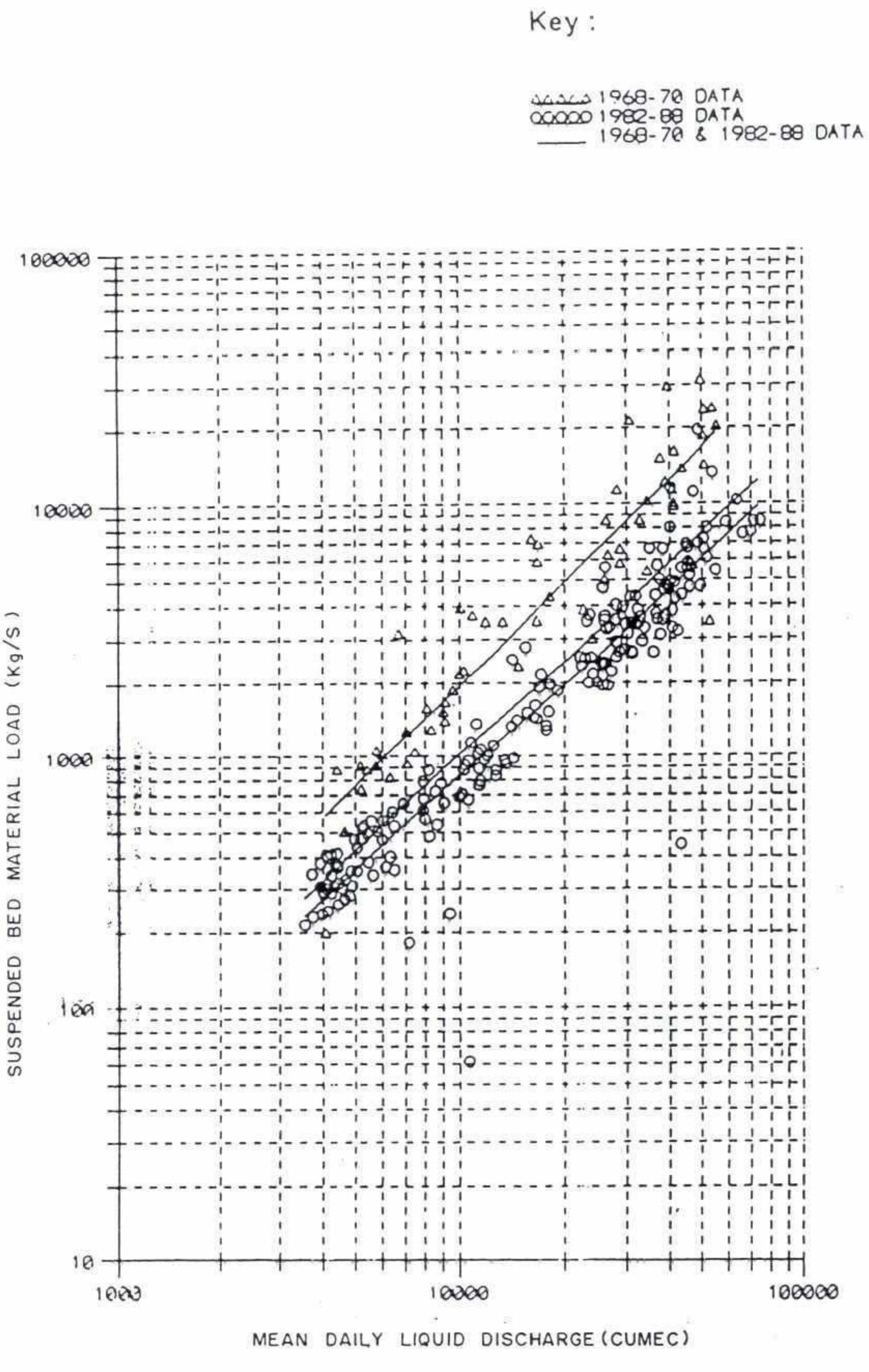
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 2.18



Frequency Distribution for Discharge at Bahadurabad (1956-89)

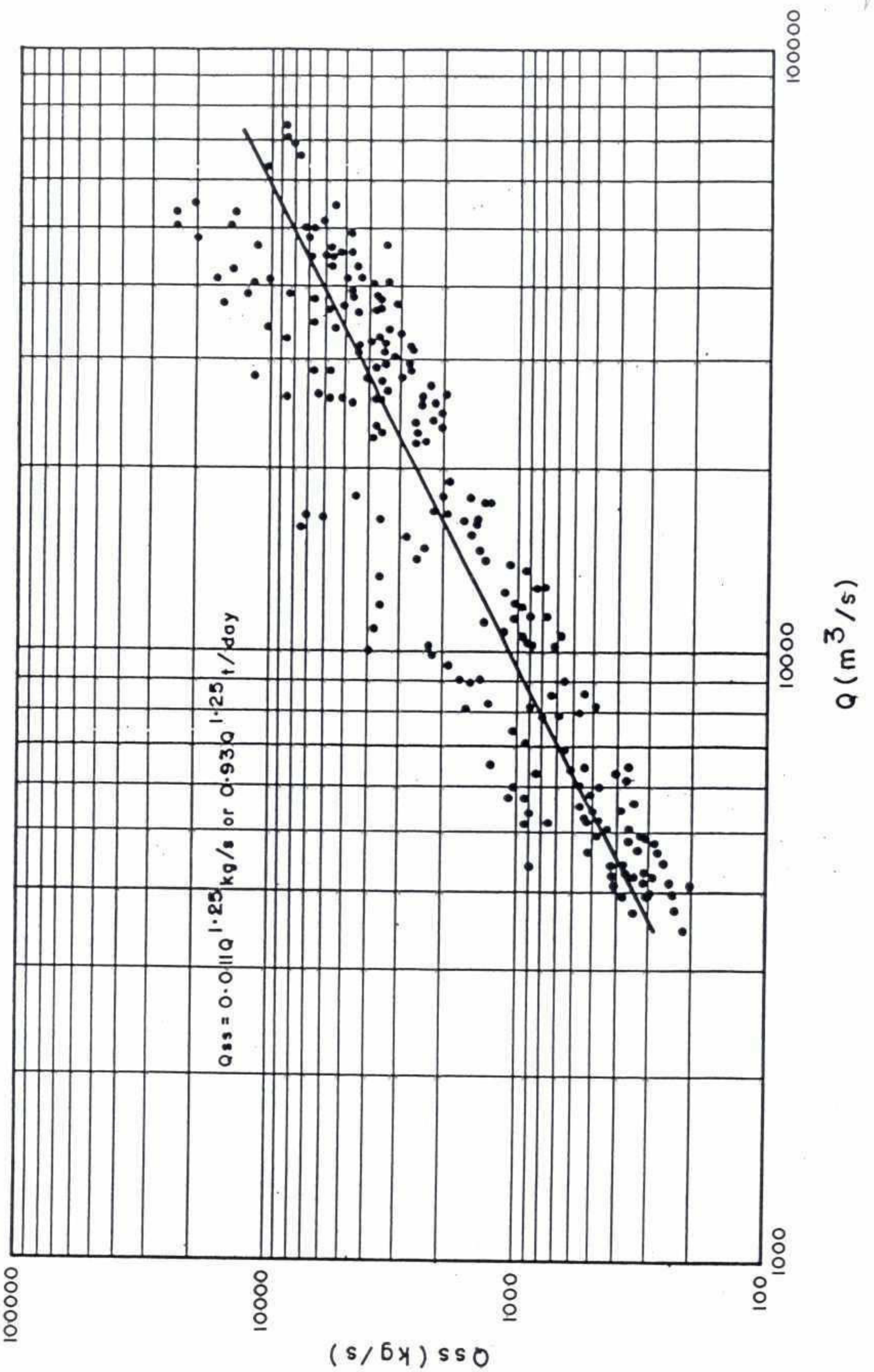
		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 3.1

V20



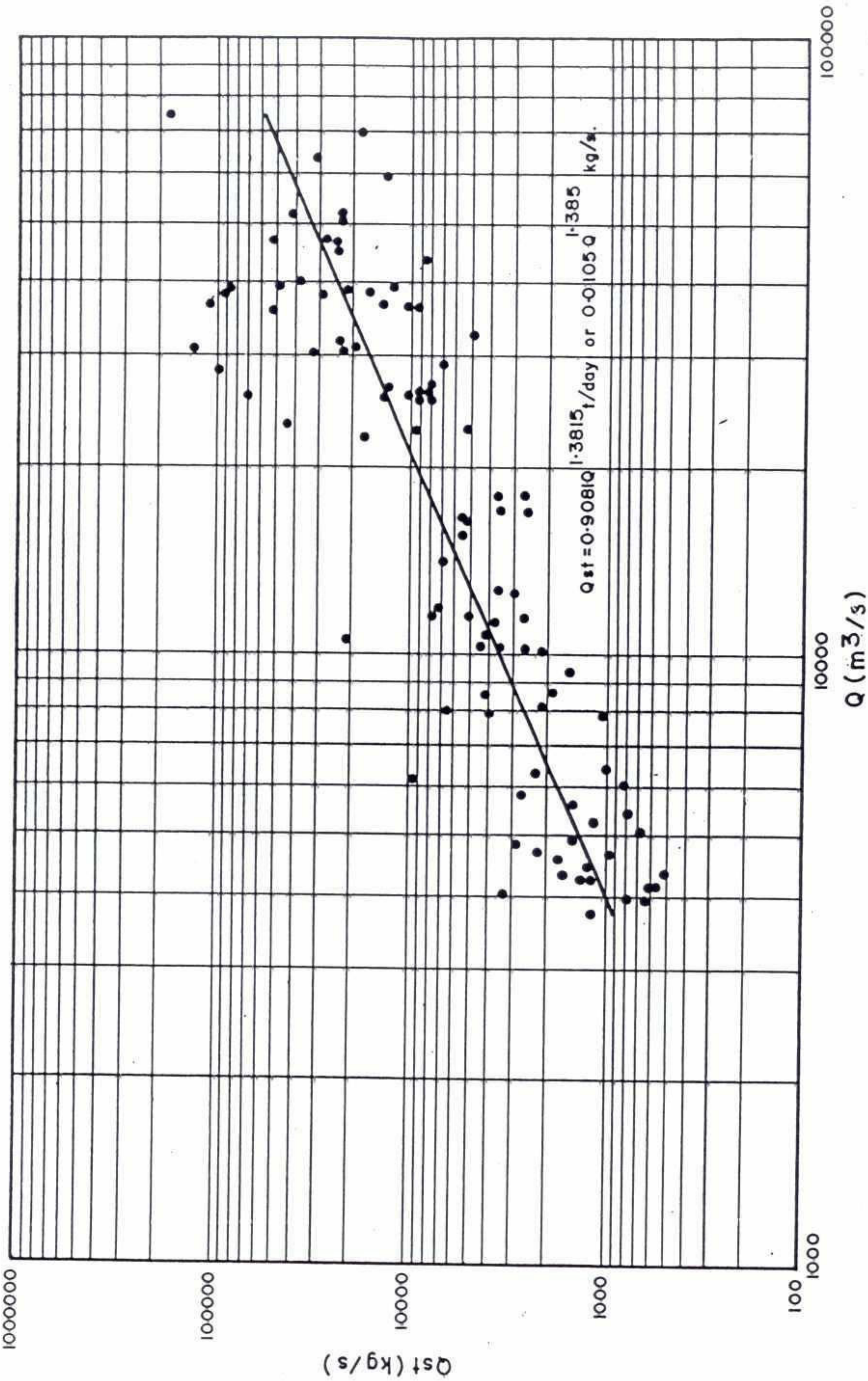
Suspended Bed Material Load Rating Curves at Bahadurabad

		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	**Figure 3.2**



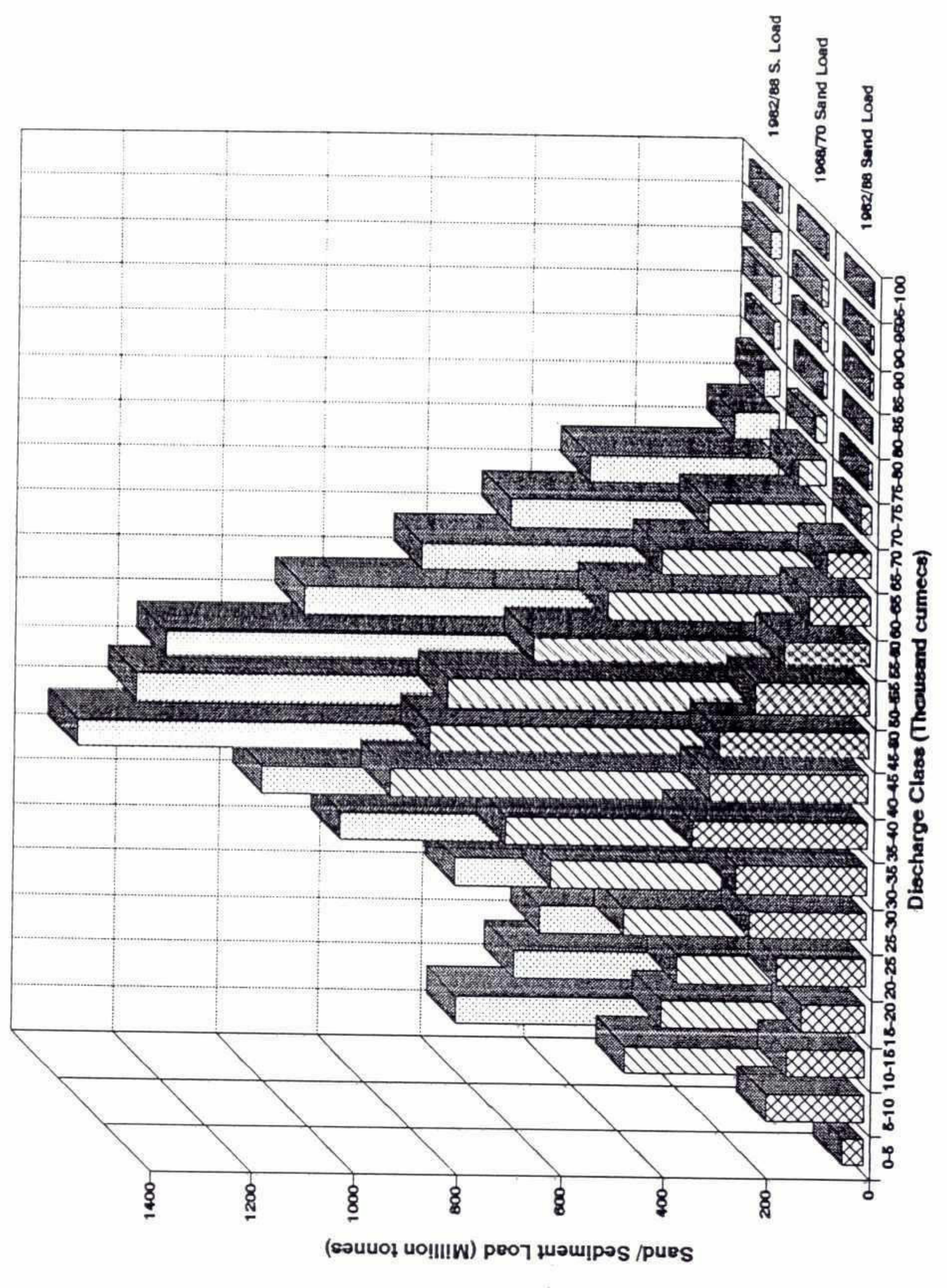
Suspended Sand Rating Curve at Bahadurabad (1982-88)

Halcrow/DHI/EPC/DIG	*November 1992*	Annex 2
		Figure 3.3



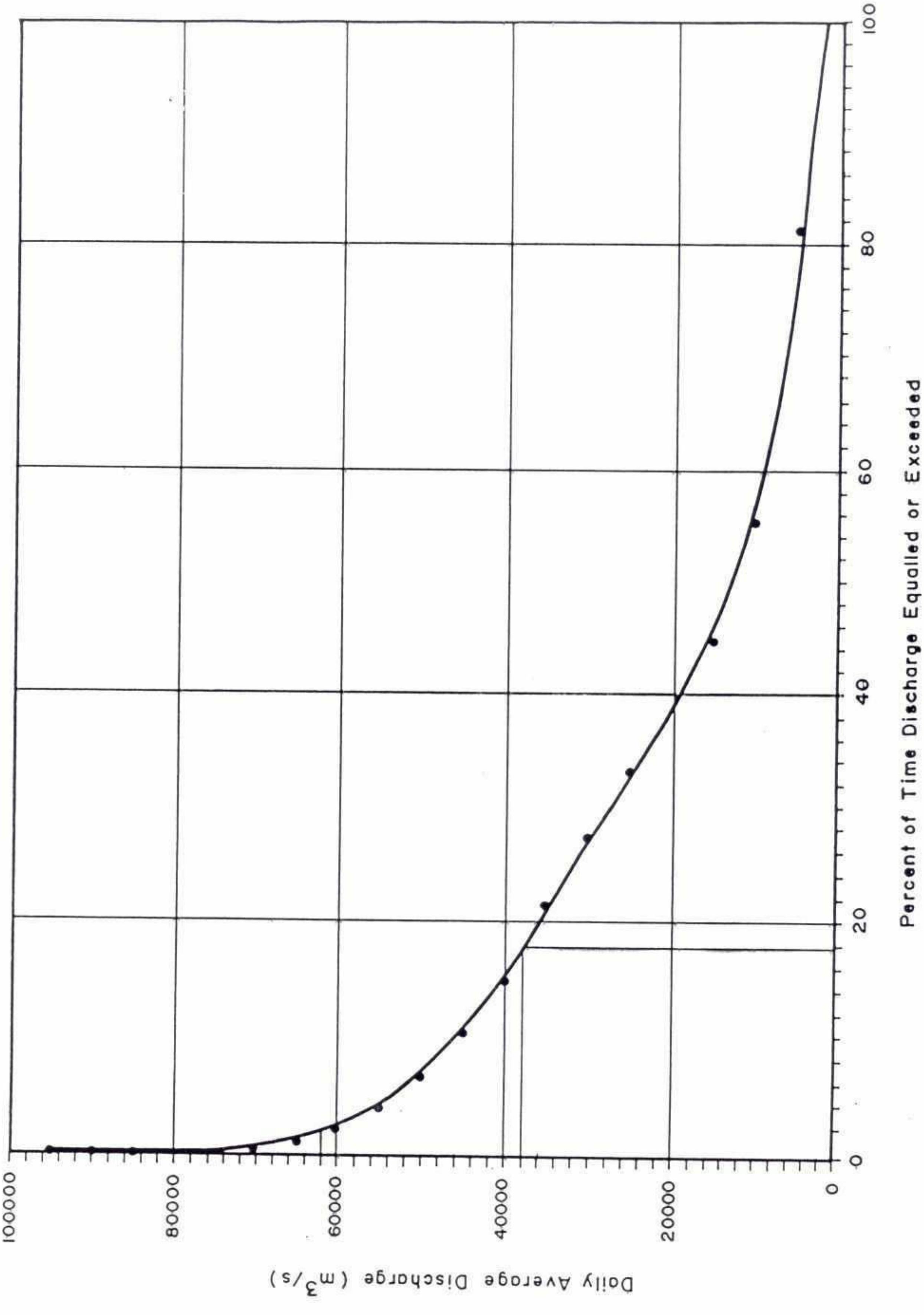
Sediment Rating Curve for Total Measured Load at Bahadurabad (1982-88)

Halcrow/DHI/EPC/DIG *November 1992*	Annex 2 Figure 3.4

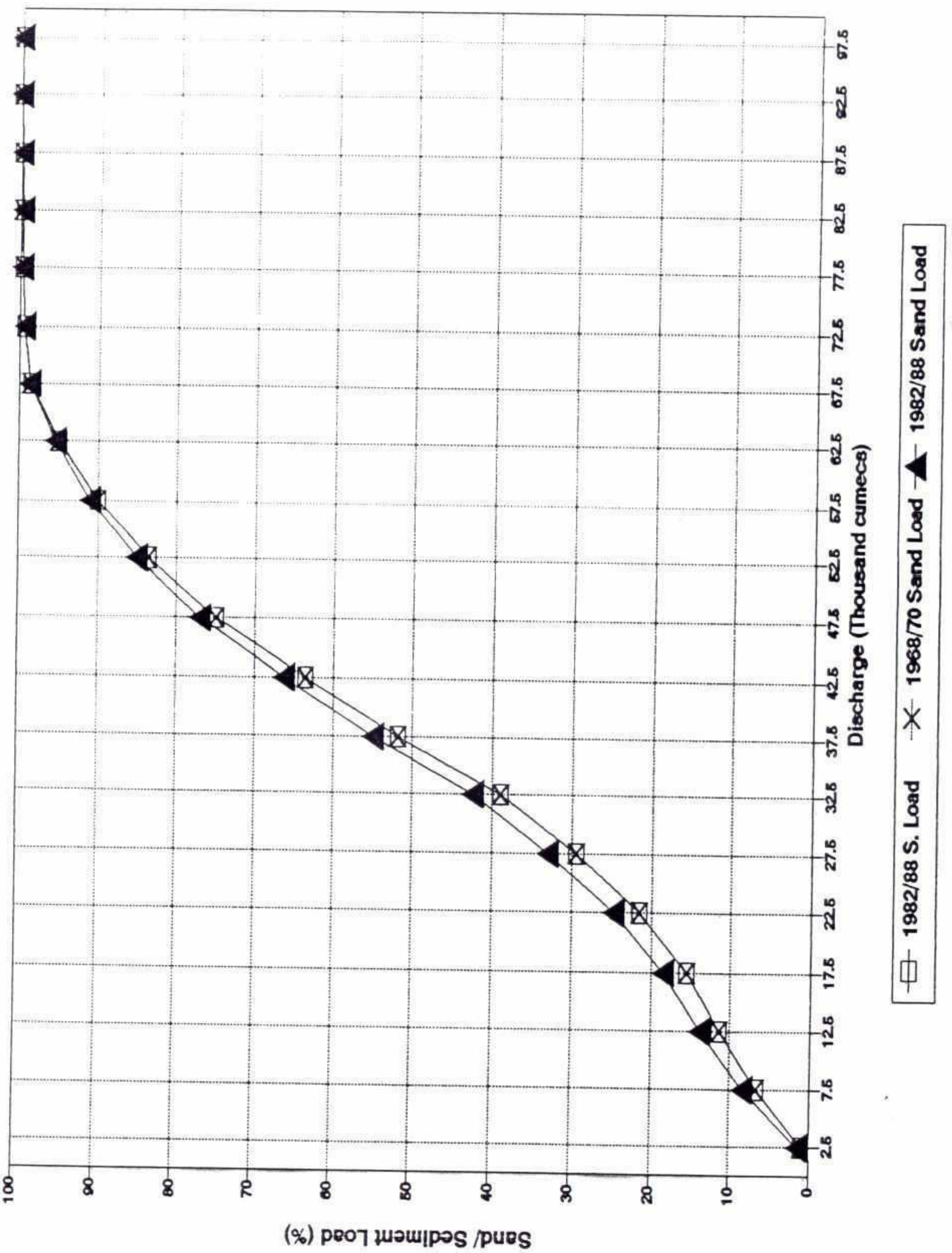


Total Sand/Sediment Transport Vs. Discharge Curves at Bahadurabad

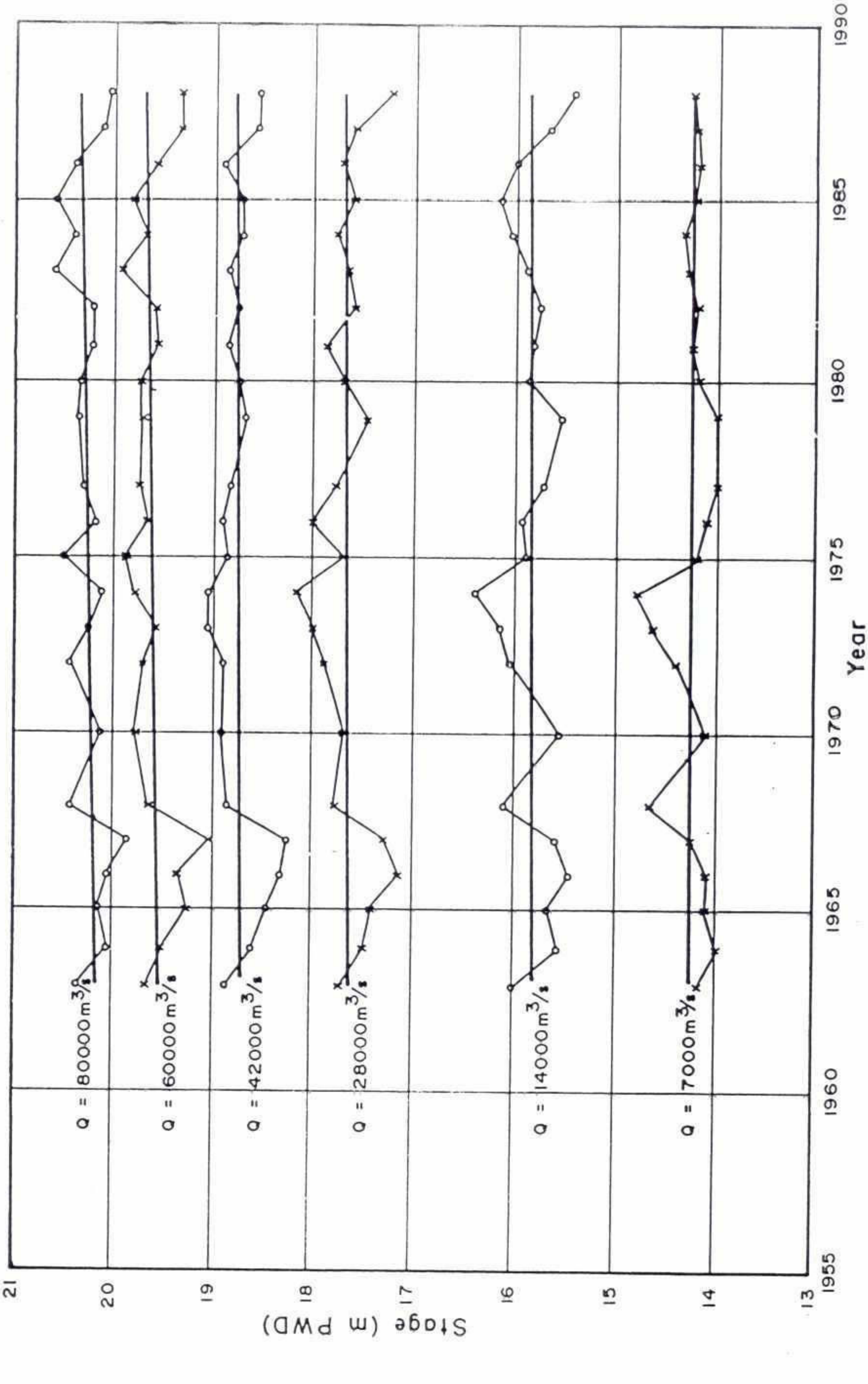
Halcrow/DHI/EPC/DIG	*November 1992*	Annex 2 Figure 3.5



Flow Duration Curve at Bahadurabad



Cumulative Measured Sand/Sediment Transport Vs. Discharge Curves at Bahadurabad

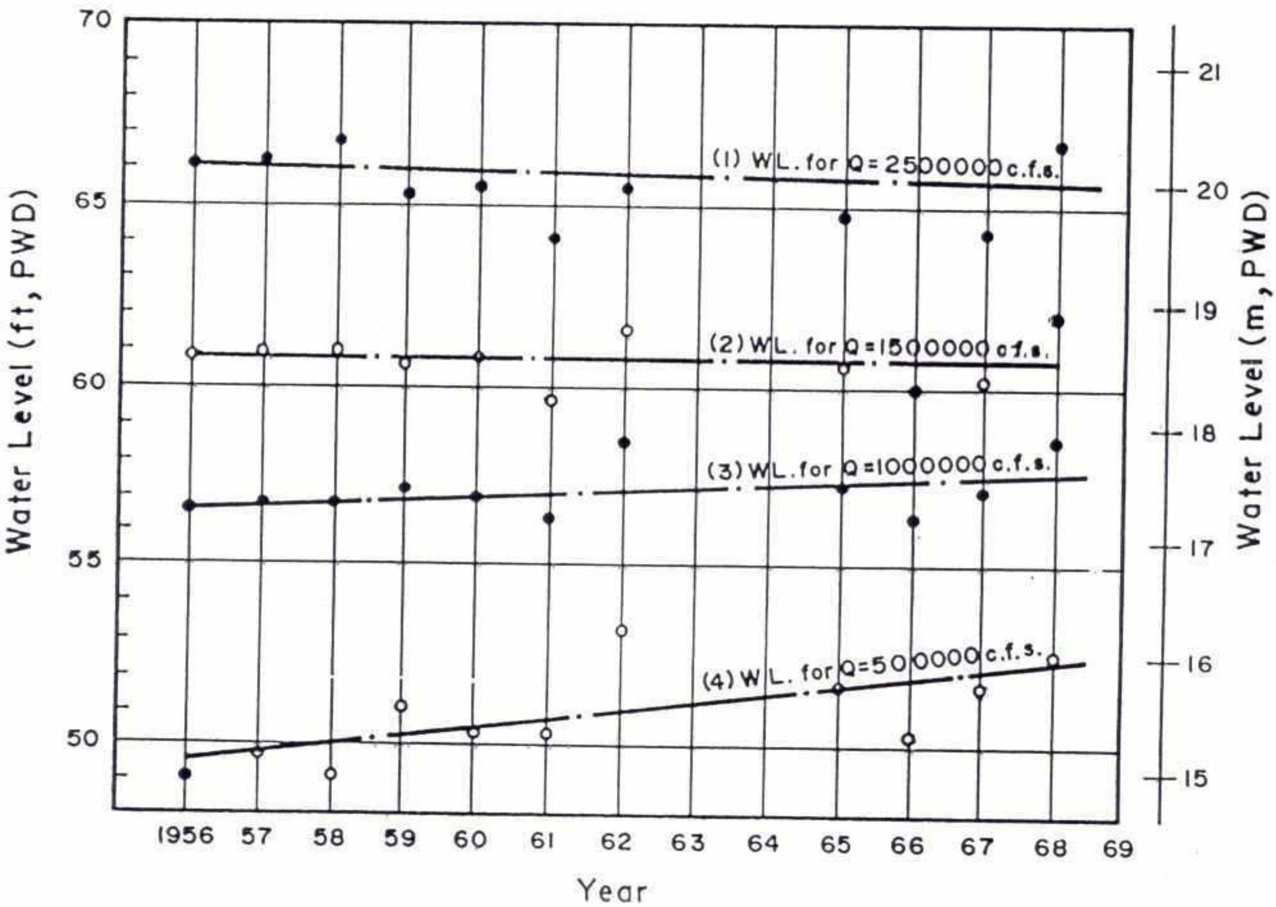


Water Level Variation for six Discharges at Bahadurabad for 1963-89

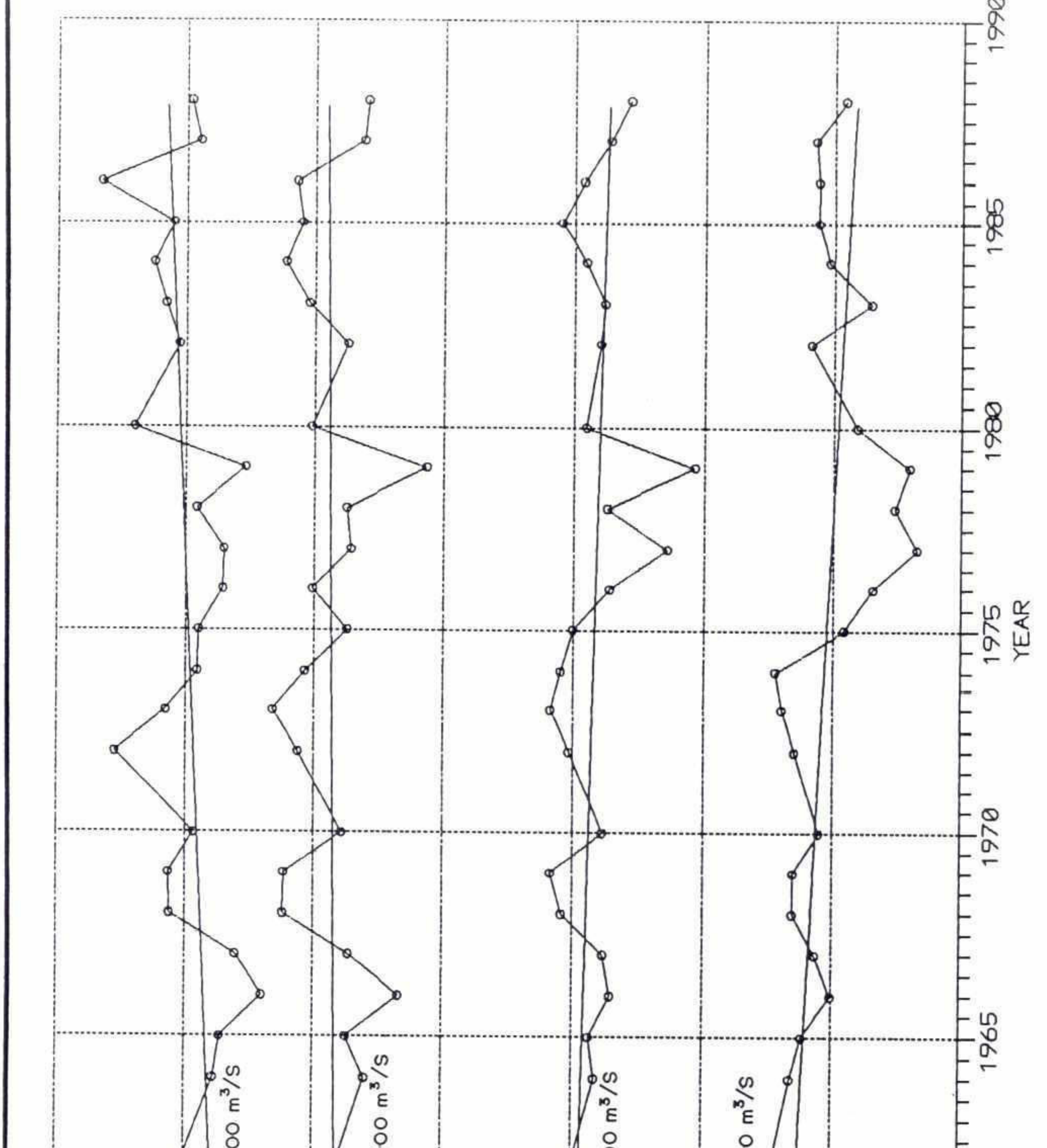
Halcrow/DHI/EPC/DIG	*November 1992*	Annex 2 Figure 3.8

127

(1) 70,236 m^3/s; (2) 42,142 m^3/s; (3) 28,094 m^3/s; (4) 44,047 m^3/s.

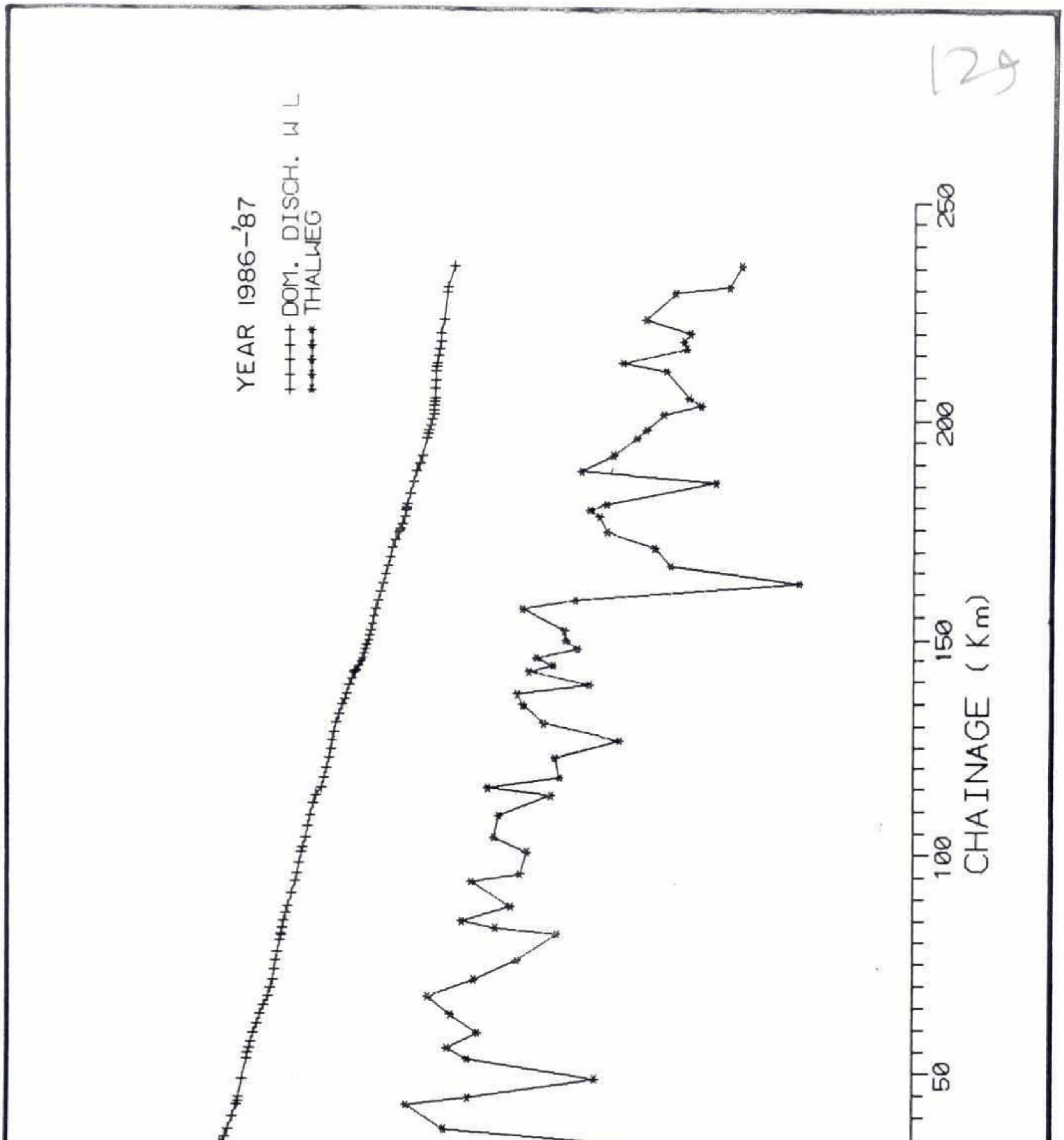


Water Level Variation for four Discharges at Bahadurabad for 1956-68 (After Lates, 1988)



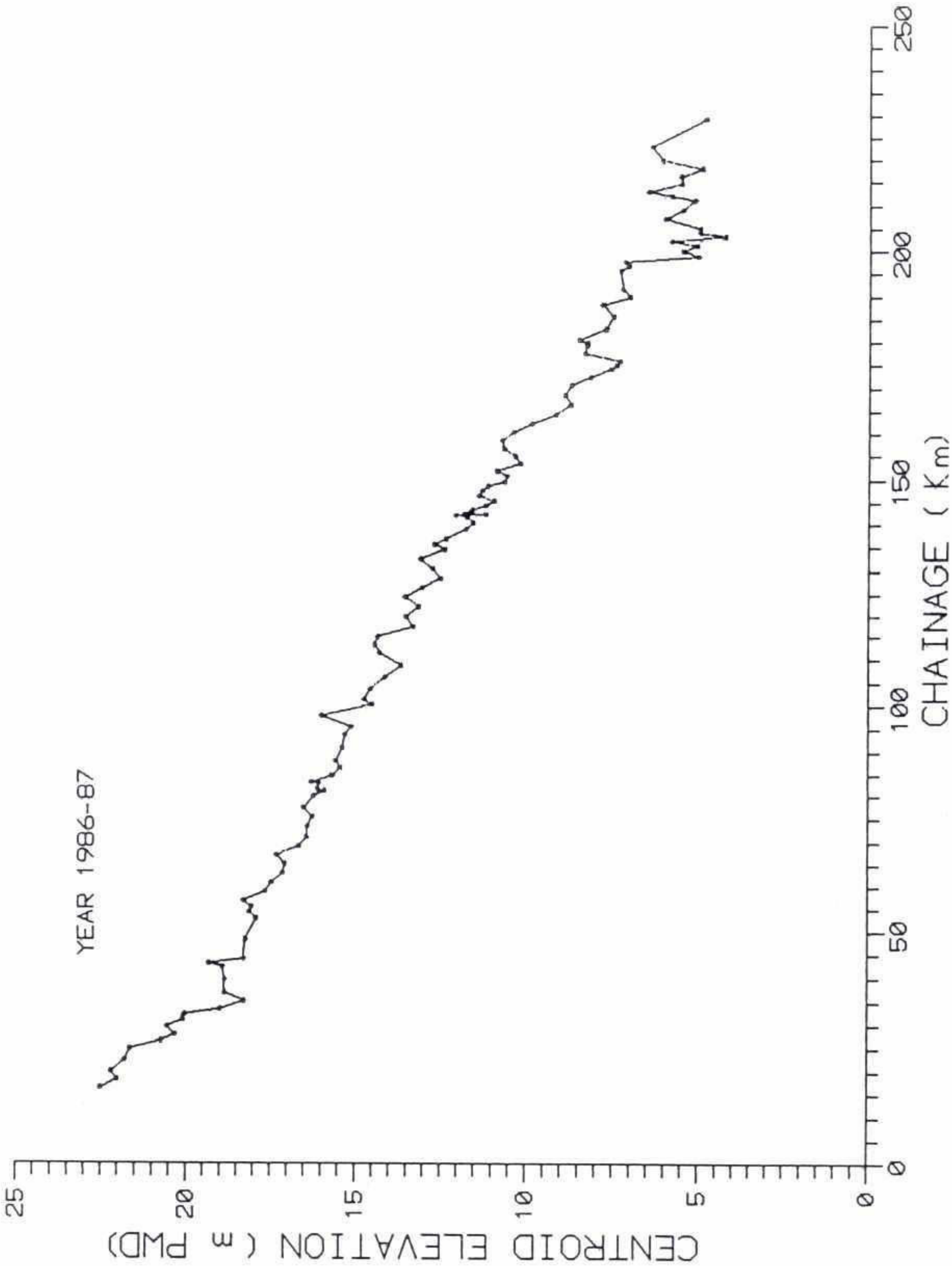
Water Level Variation for Four Relevant Discharges at Sirajganj for 1962-88

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.10



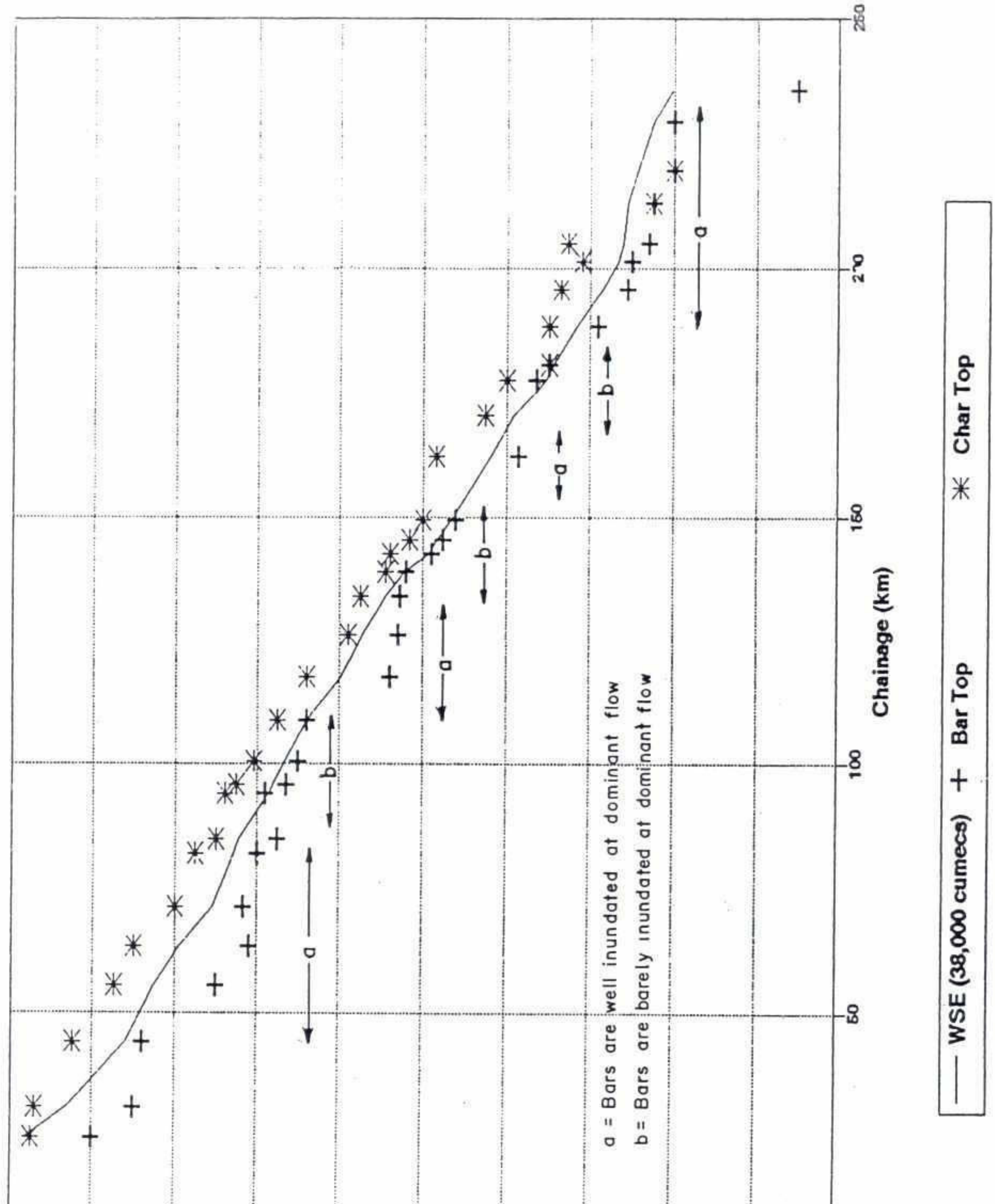
Longitudinal Profile of the Brahmaputra River 1986-87

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	**Figure 3.11**



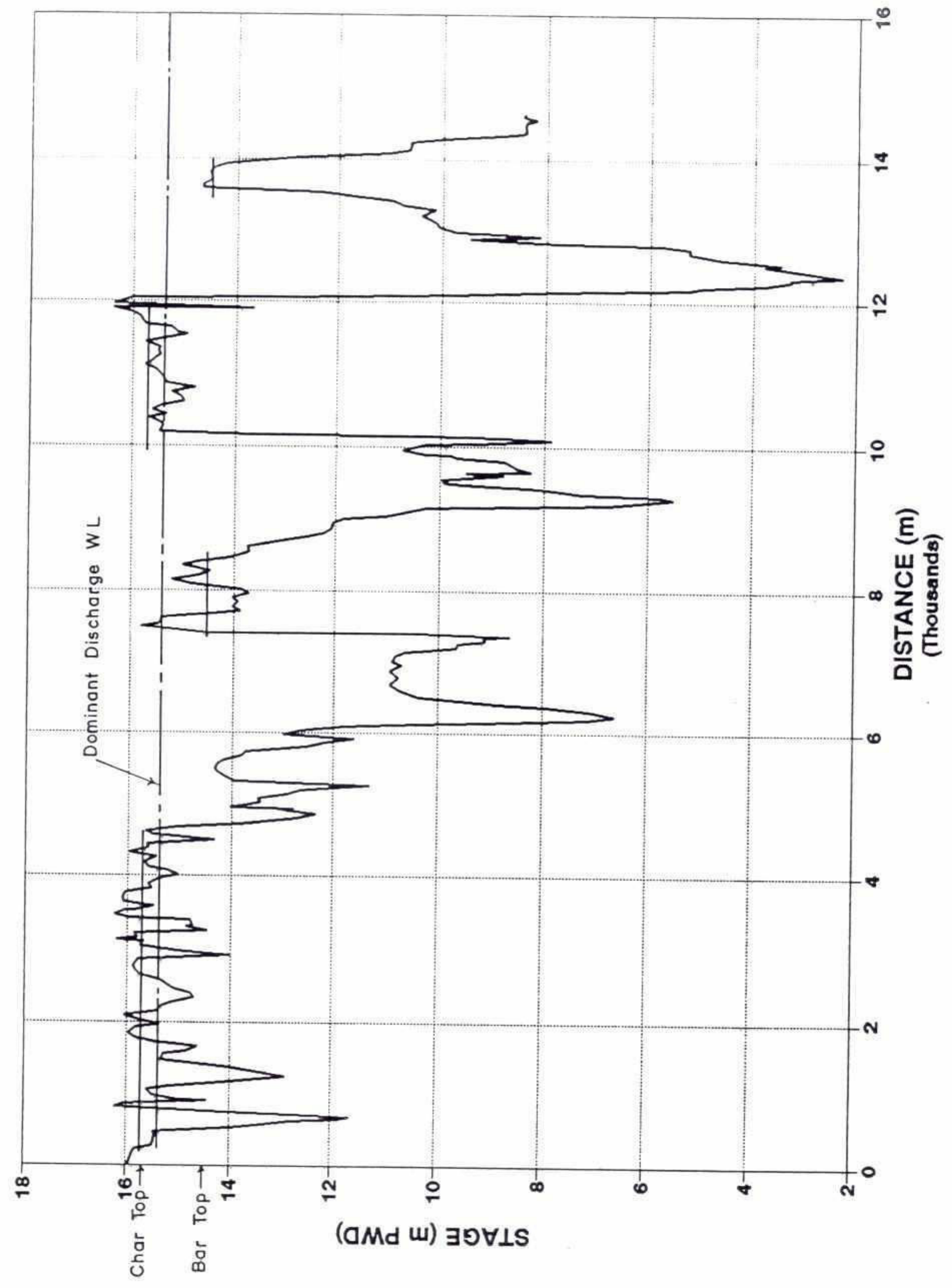
Variation of Vertical Elevation of Cross-sectional Centroid

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.12



Comparison of Dominant Flow and Barfull Flow Level

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.13



Typical River Cross-section showing Upper and Lower Char top Levels

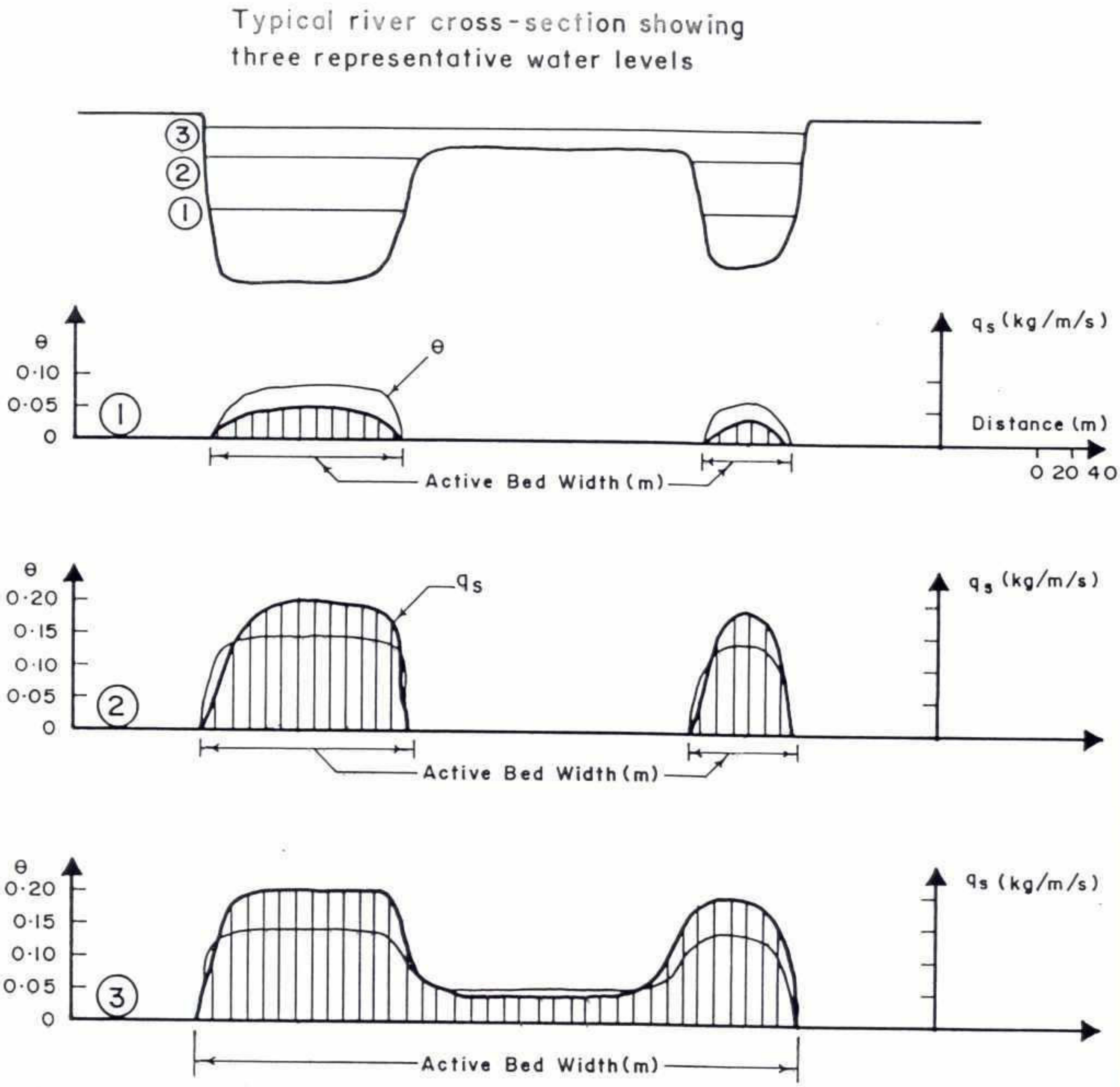
Halcrow/DHI/EPC/DIG

November 1992

Annex 2

Figure 3.14

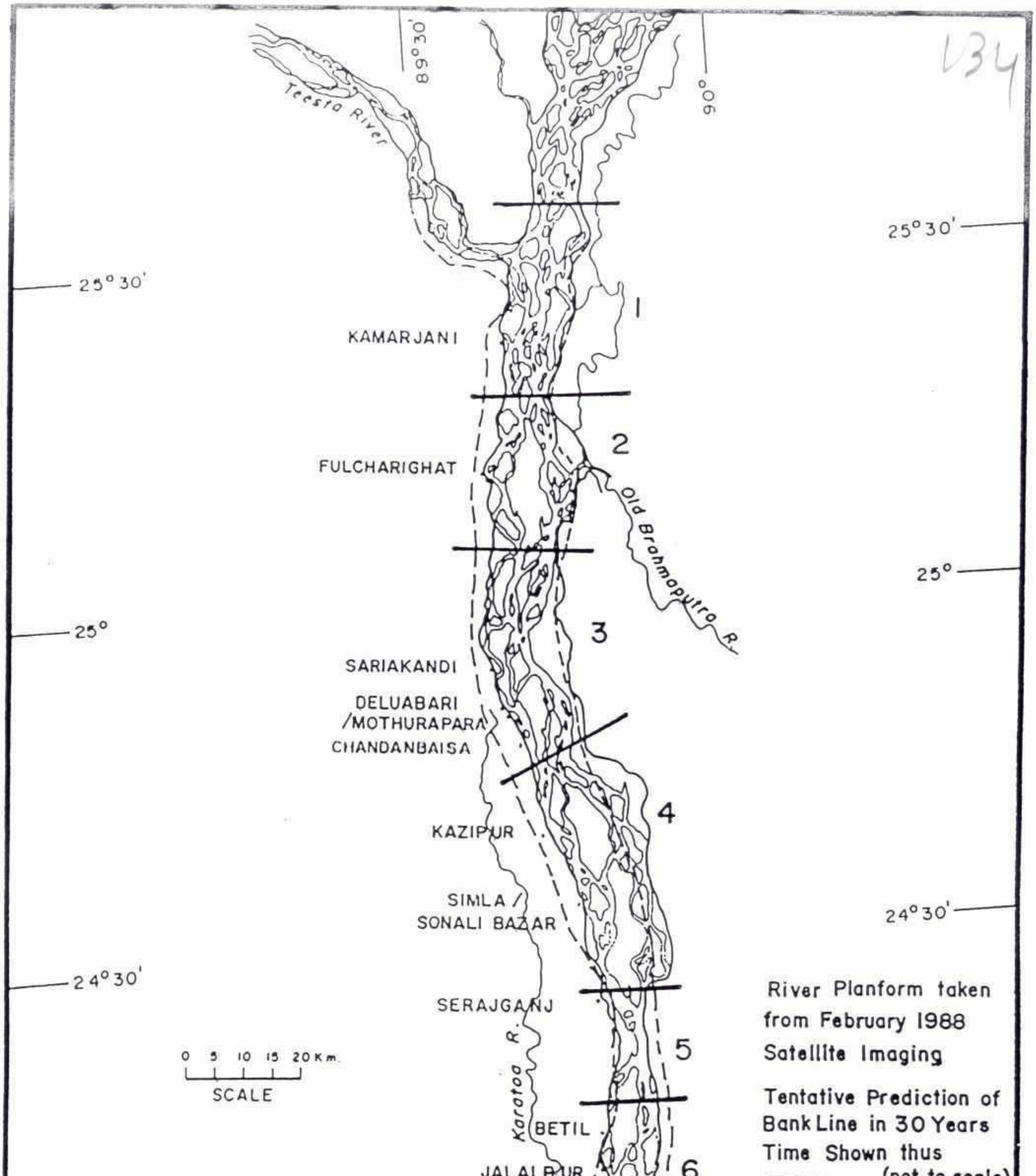
V33



Flow Stage	Ave. Unit Sediment Transport (kg/s/m)	Active Bed Width (m)	Sediment Transport Rate (kg/s)	Increase (%)
(1) Low Flow	3	170	510	—
(2) Just Below Barfull	3·5	200	700	37
(3) Just Above Barfull	3	370	1110	58

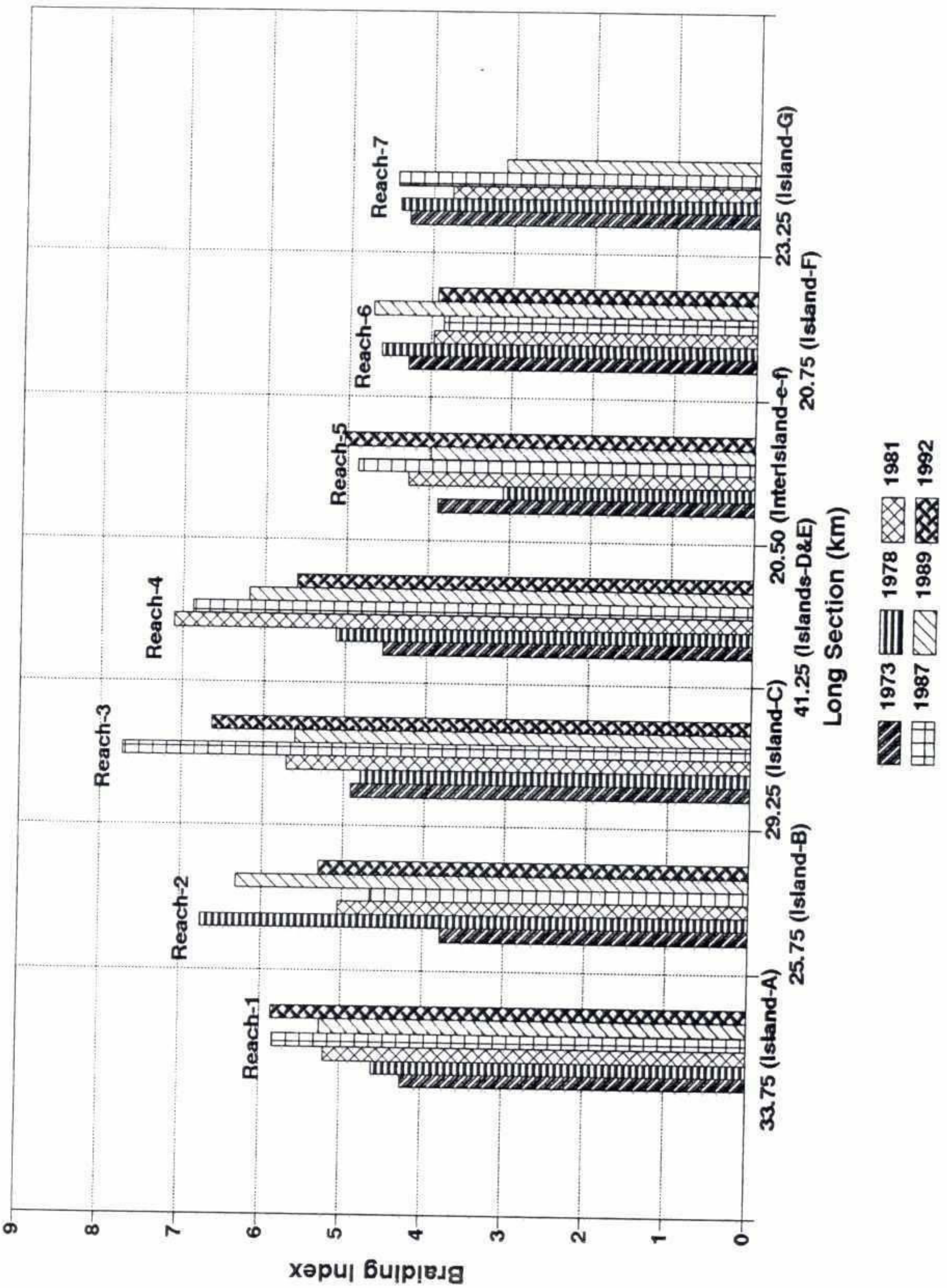
Relation Between Sediment Transport and Barfull Flow

Halcrow/DHI/EPC/DIG *November 1992* Annex 2 Figure 3.15



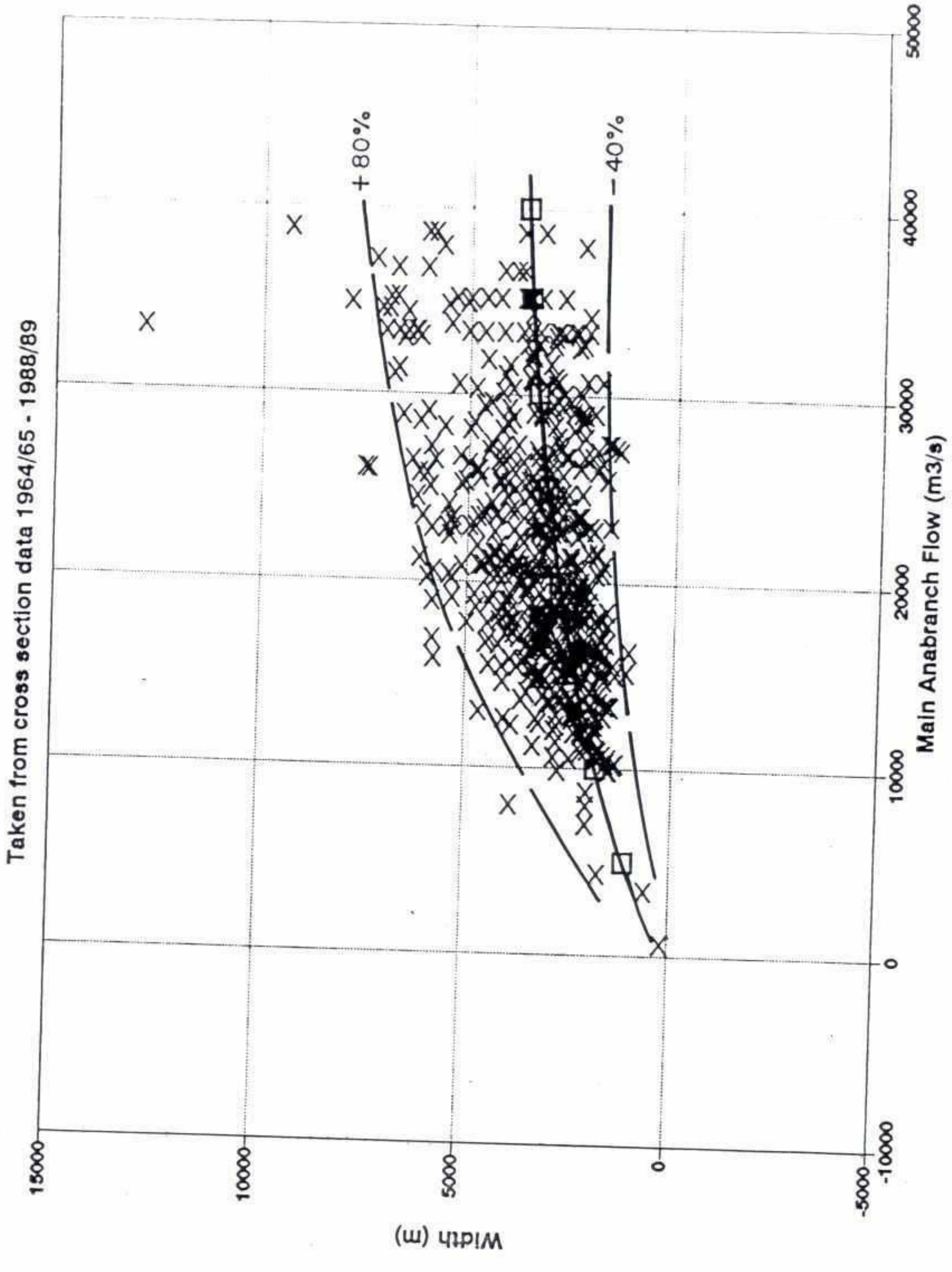
Definition of Reaches Used for Braiding Analysis

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	**Figure 3.16**



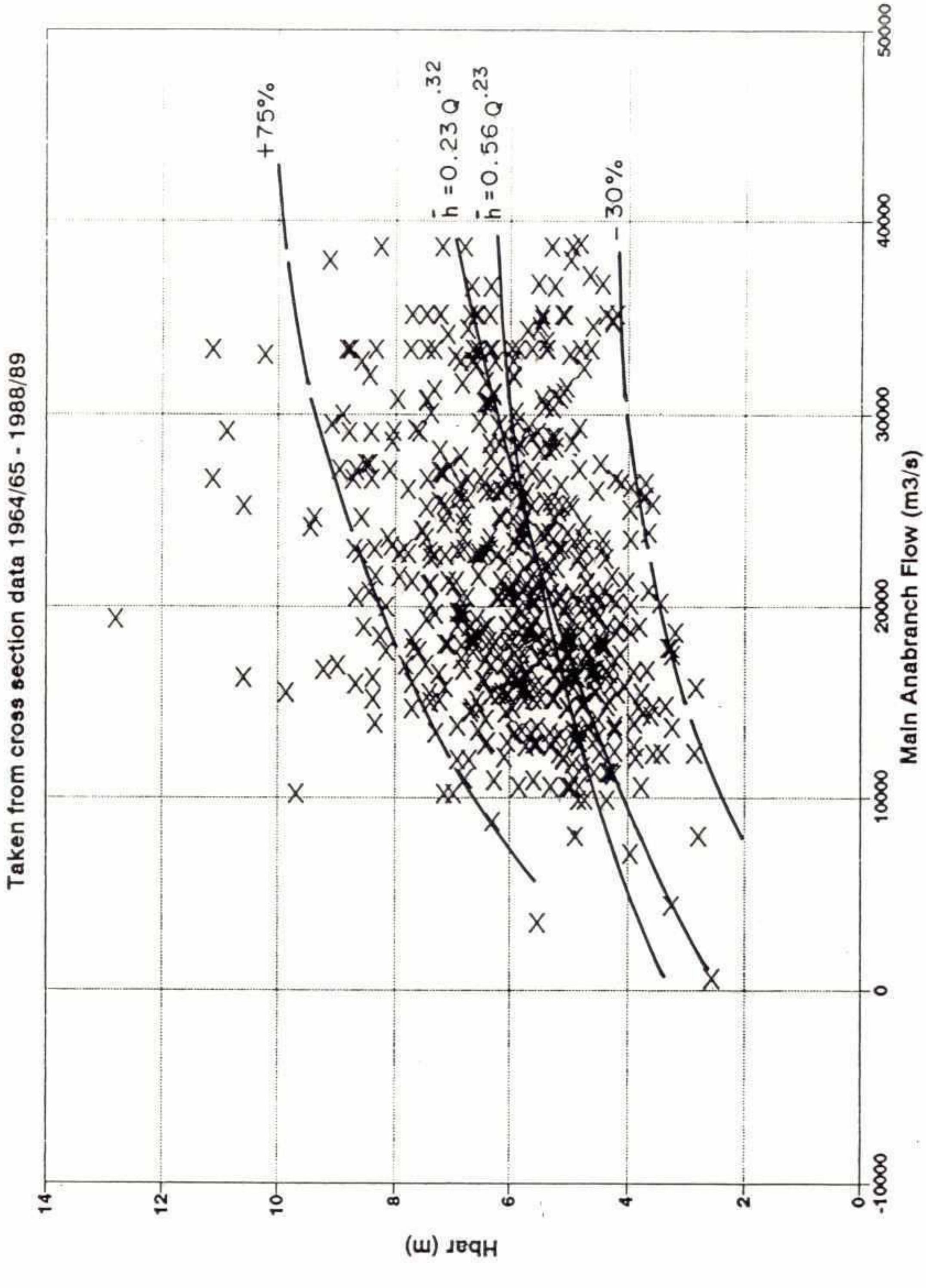
Braiding Indices for the Brahmaputra River, 1973-1992

136



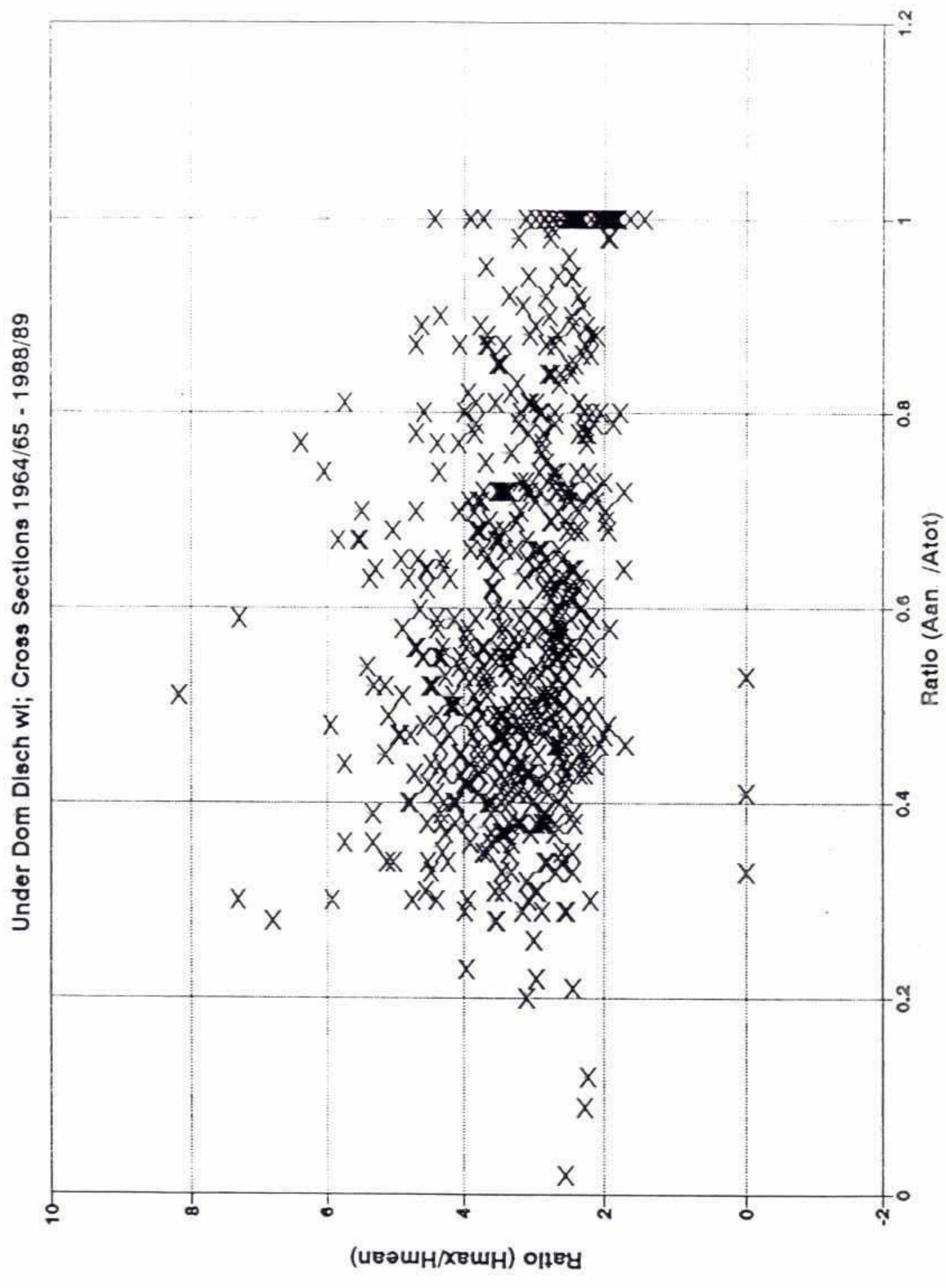
Relationship Between Anabranch Width and Discharge

Halcrow/DHI/EPC/DIG	*November 1992*	Annex 2
		Figure 3.18



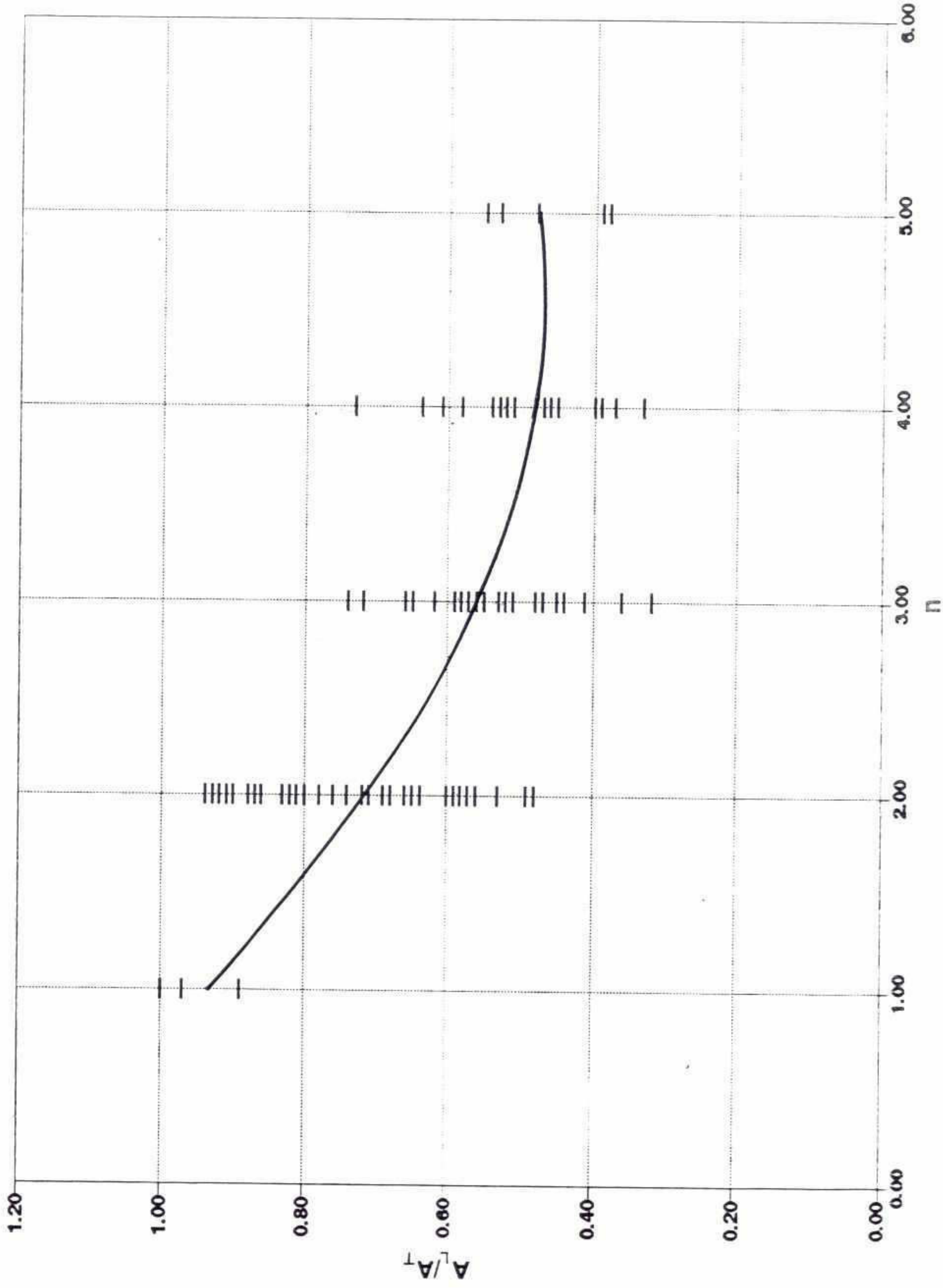
Relationship Between Mean Depth and Discharge

Halcrow/DHI/EPC/DIG	*November 1992*	Annex 2 Figure 3.19



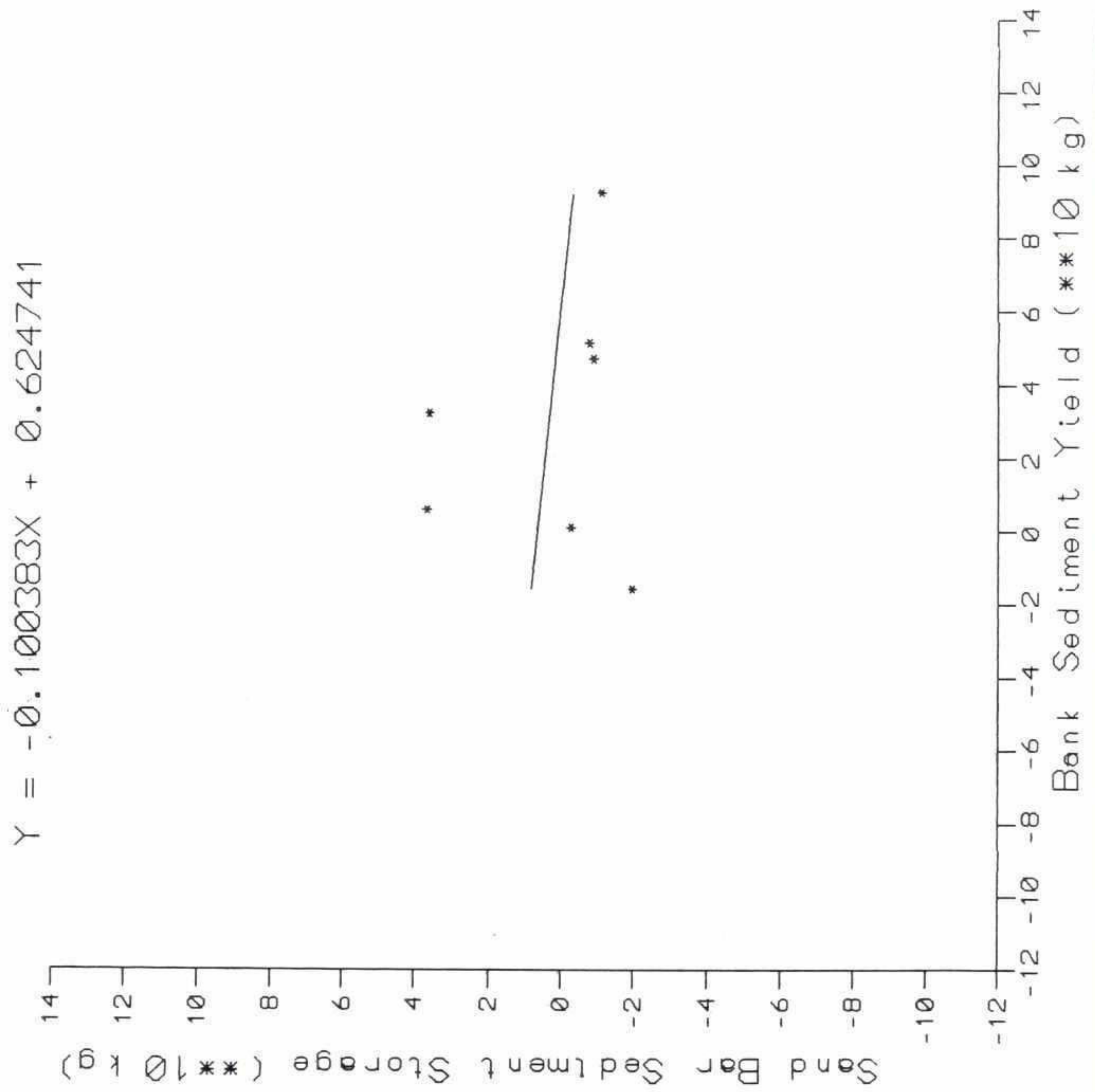
Relationship Between Maximum/Mean Depth and Area of Largest Anabranch/Total Wetted Area

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.20



Relationship Between Number of Anabranches and Relative Size of Major Anabranch

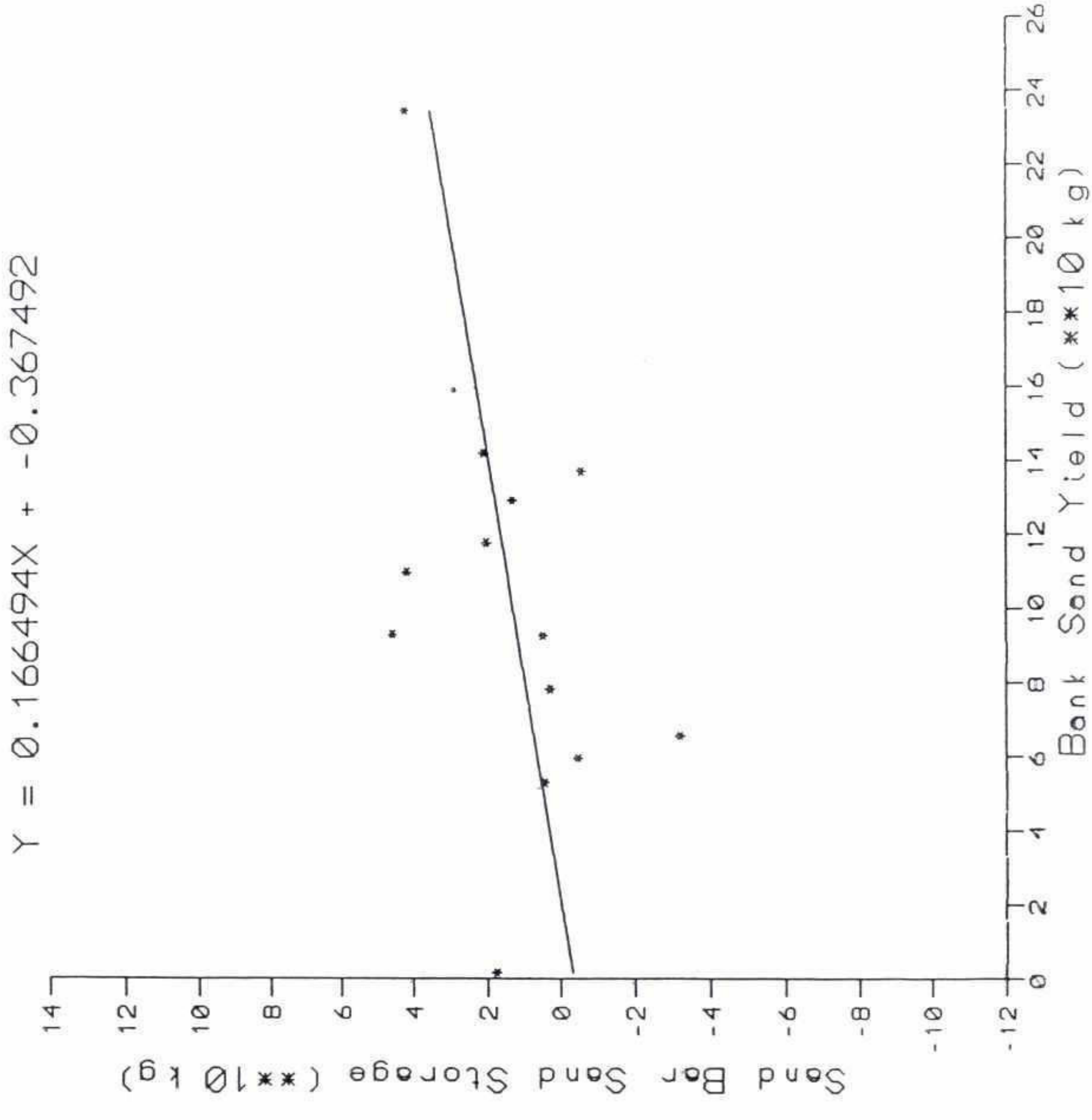
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.21



Note : ** 10Kg ≡ 10^{10} Kg

Relationship Between Floodplain and Sand Bar Sediment Volume Change, Reach 4

		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 3.22

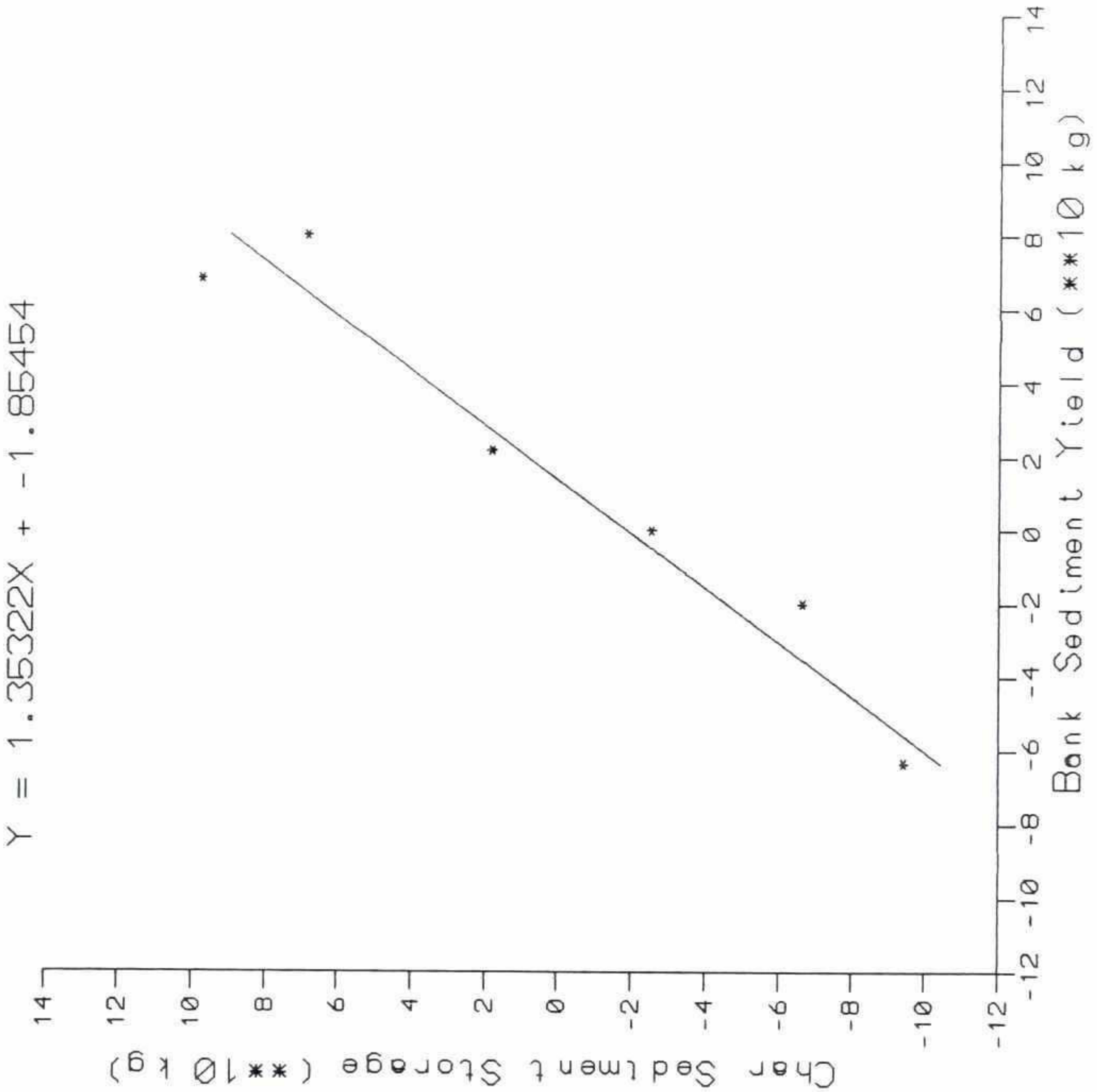


Note : ** 10 Kg. ≡ 10^{10} Kg

Relationship Between Floodplain and Sand Bar Sand Volume Change - Study Reach, 1973-1992

		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 3.23

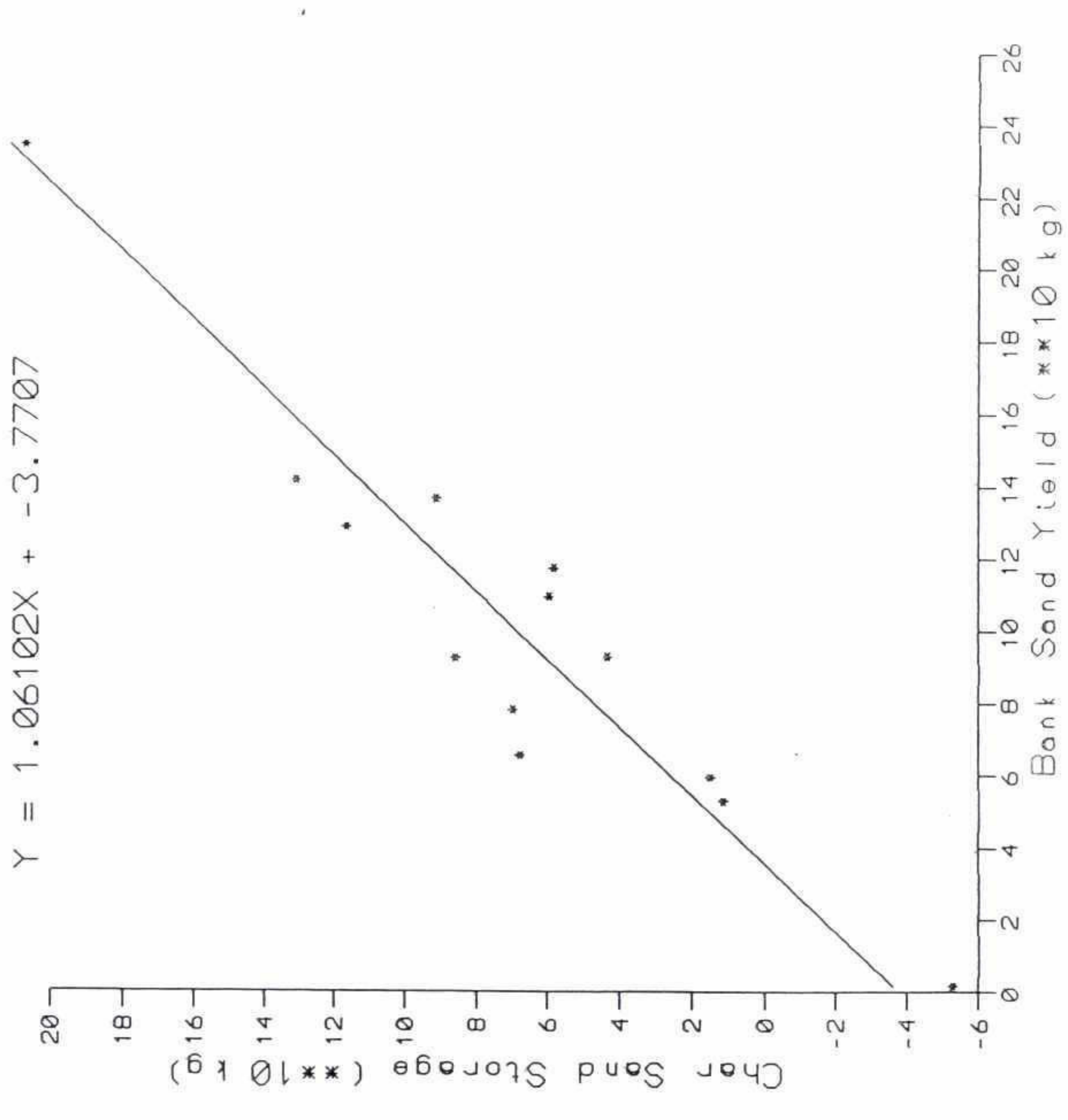
142



Note : ** 10 Kg. ≡ 10^{10} Kg

Relationship Between Floodplain and Char Sediment Volume Change - Reach 6

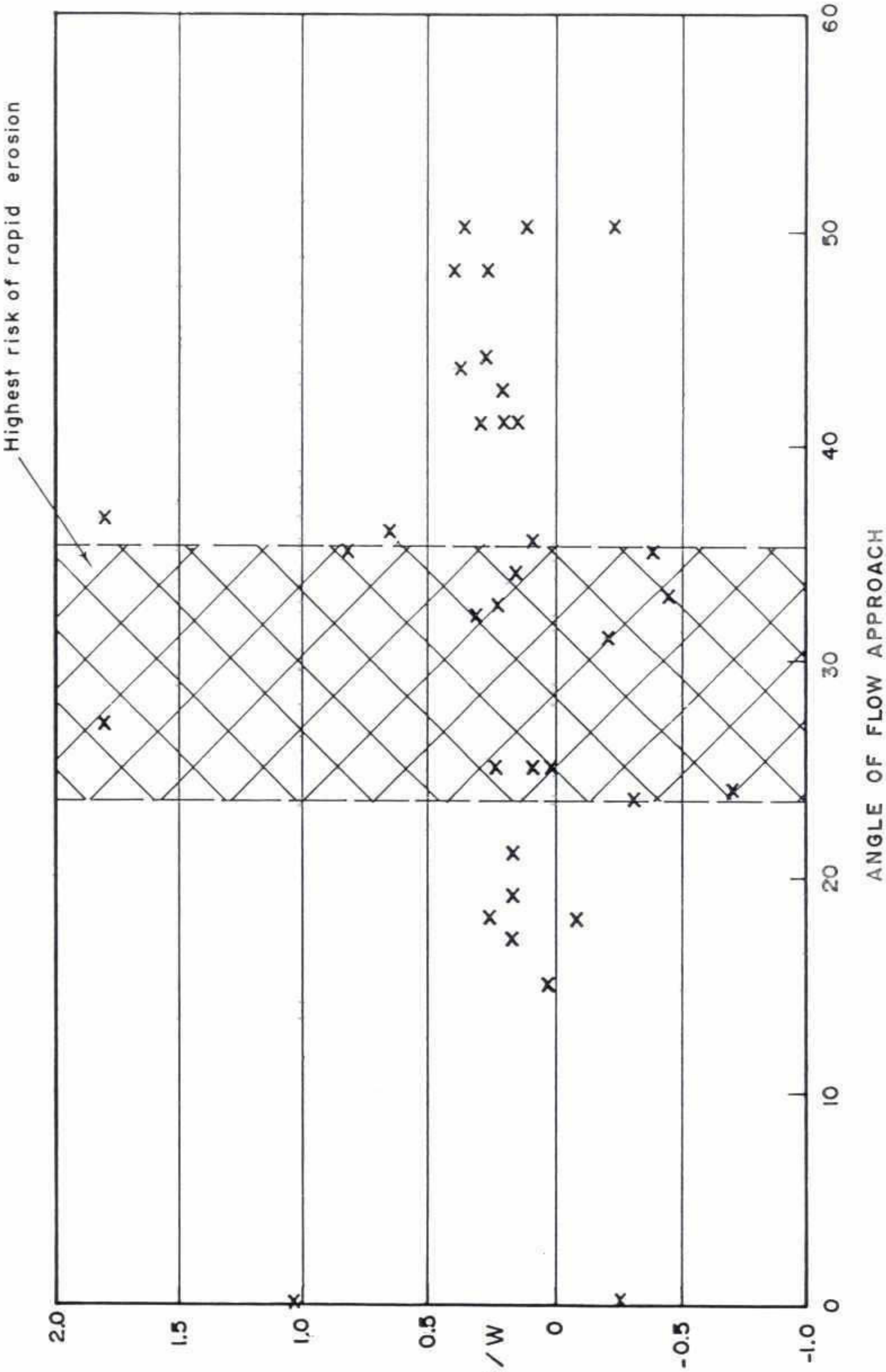
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.24



Note : ** 10Kg. ≡ 10^{10} Kg

Relationship Between Floodplain and Char Sand Volume Change -Study Reach, 1973-92

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.25



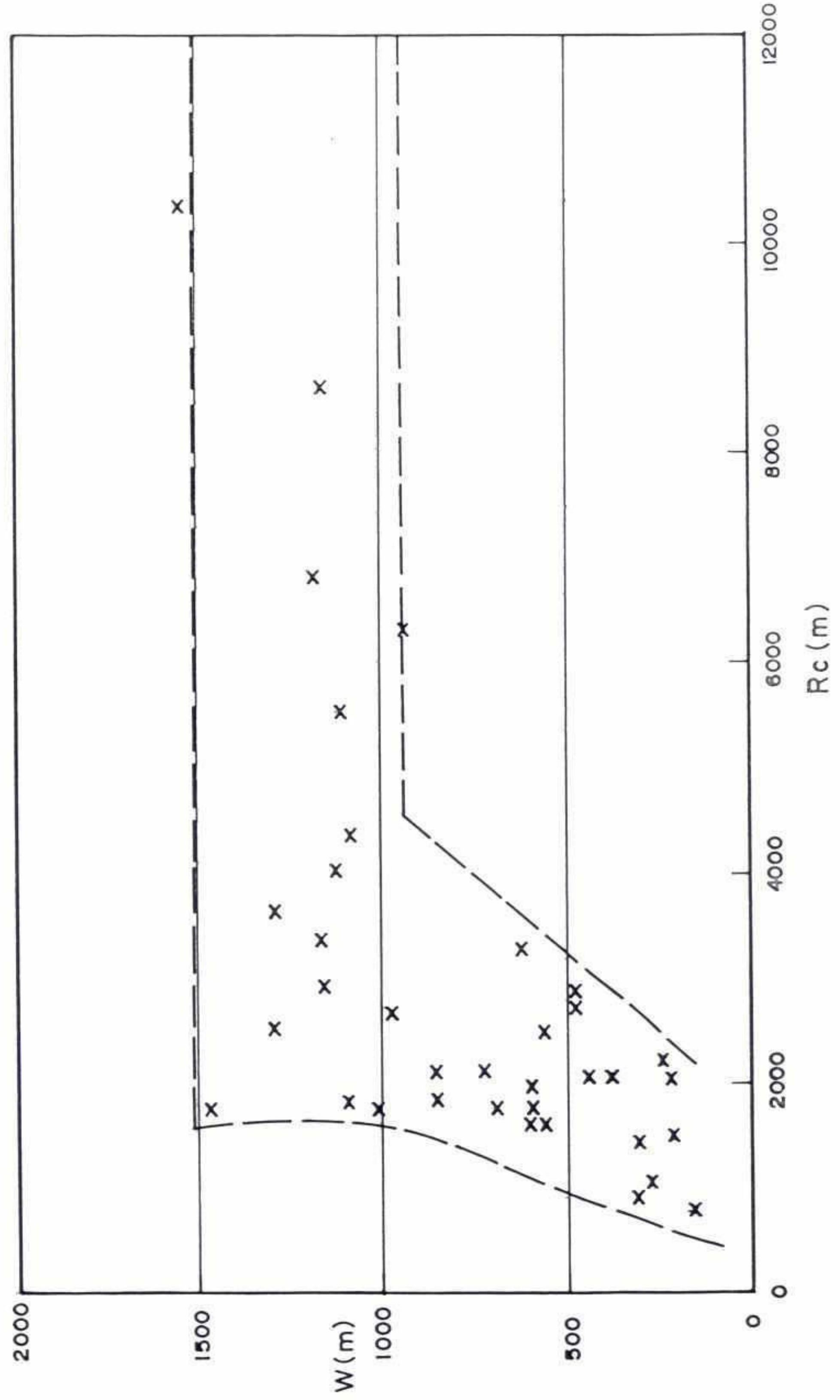
Notes : E = lateral displacement

W = bend width

Relationship between Bank Erosion and Angle of Flow Approach

	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.26

145

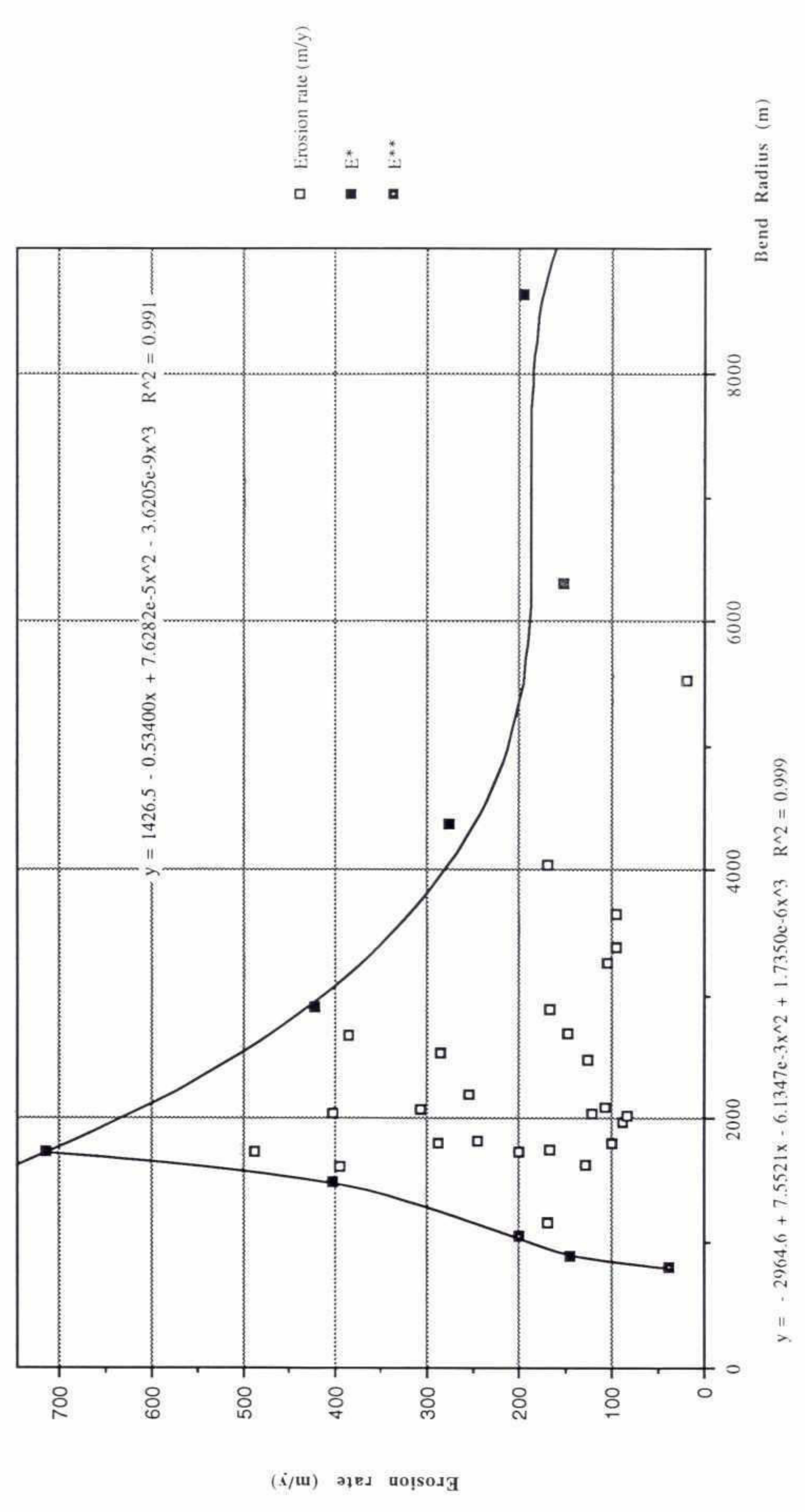


Notes: W = bend width

Rc = bend radius

Relationship between Channel width and Radius for selected Aggresive Bends

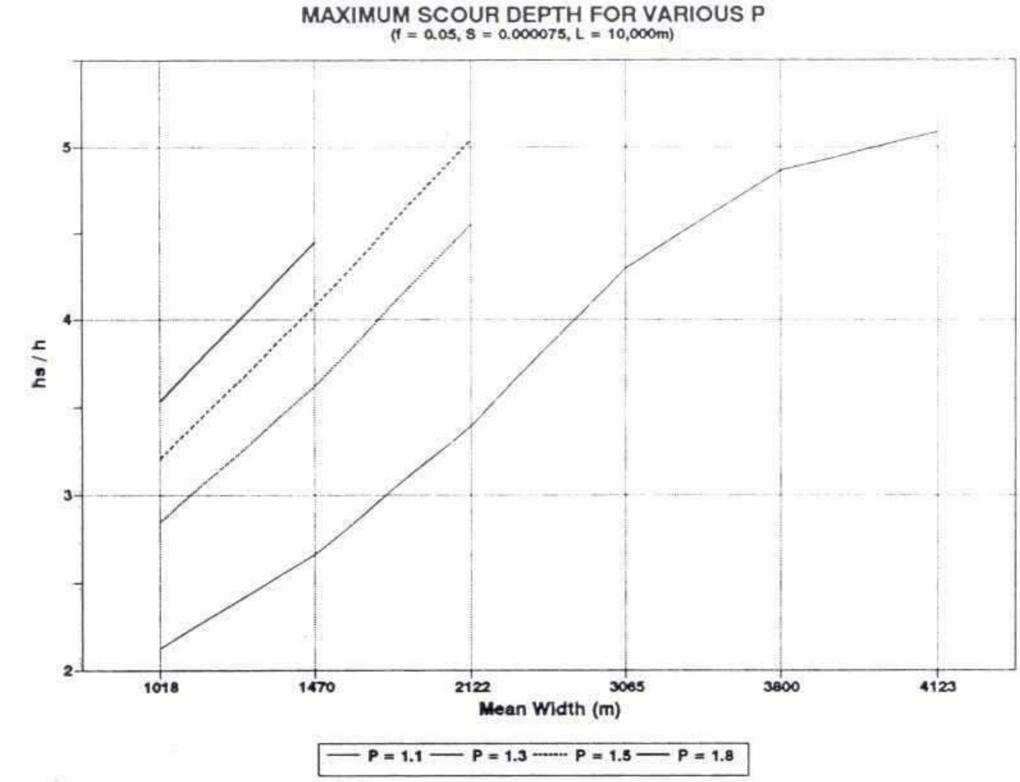
	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.27

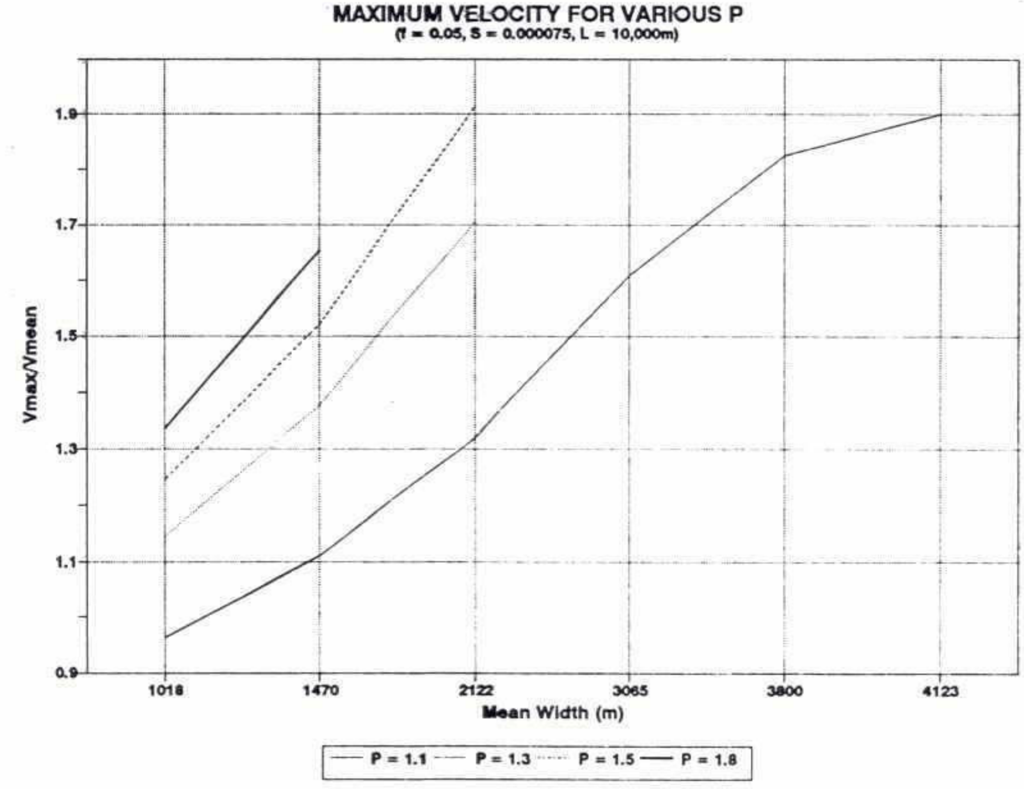


Bend Erosion Predictor for Brahmaputra Anabranches

	Annex 2
Halcrow/DHI/EPC/DIG **November 1992**	Figure 3.28

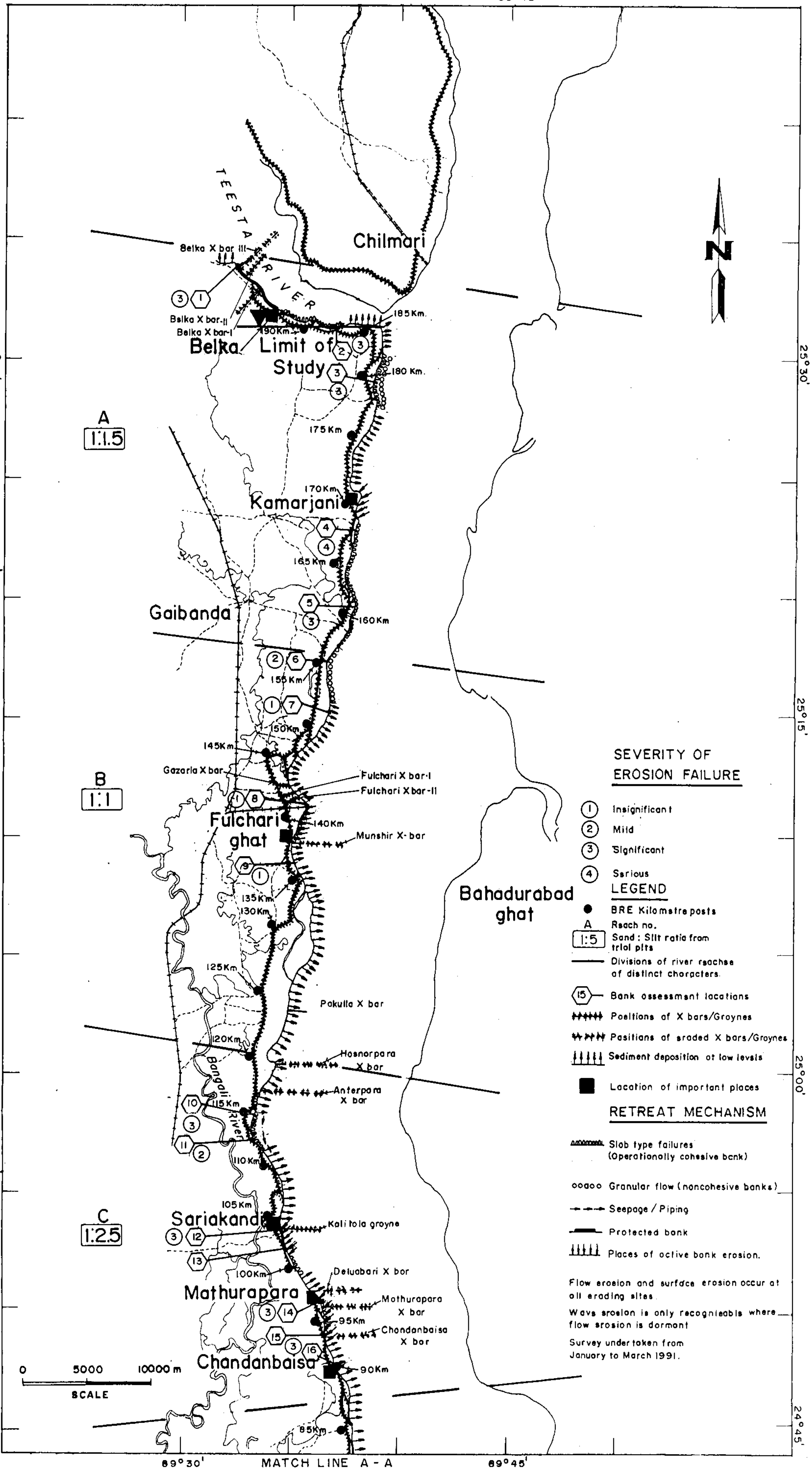
147





Relationships Between Bend Radius/Width, Scour Depth and Maximum Velocity

		Annex 2
Halcrow/DHI/EPC/DIG	*November 1992*	Figure 3.29



Halcrow/DHI/EPC/DIG

November 1992

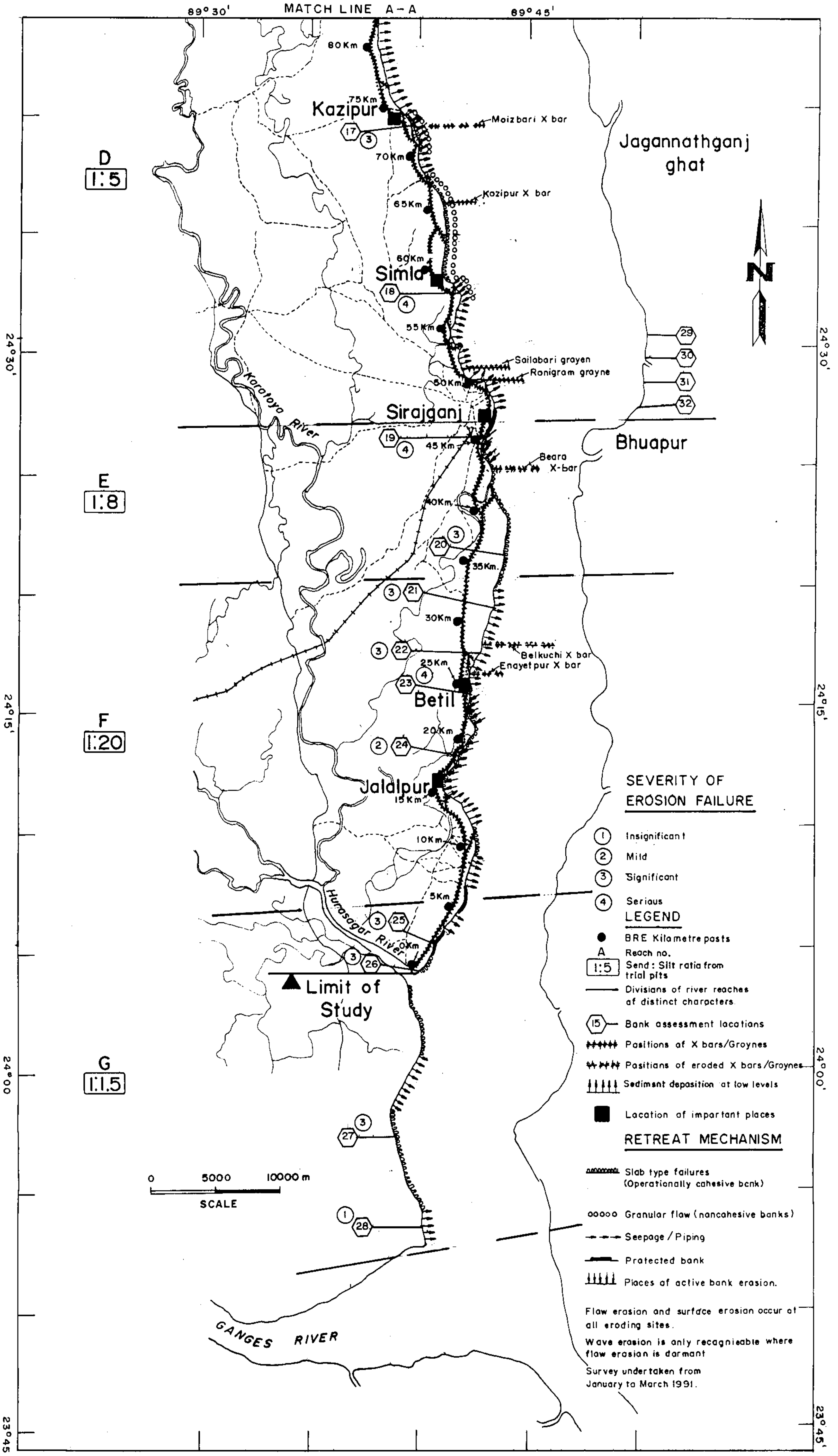
Sheet 1 of 2

Bankline Condition Assessment

Annex 2

Figure 3.30

148



Bankline Condition Assessment

Sheet 2 of 2

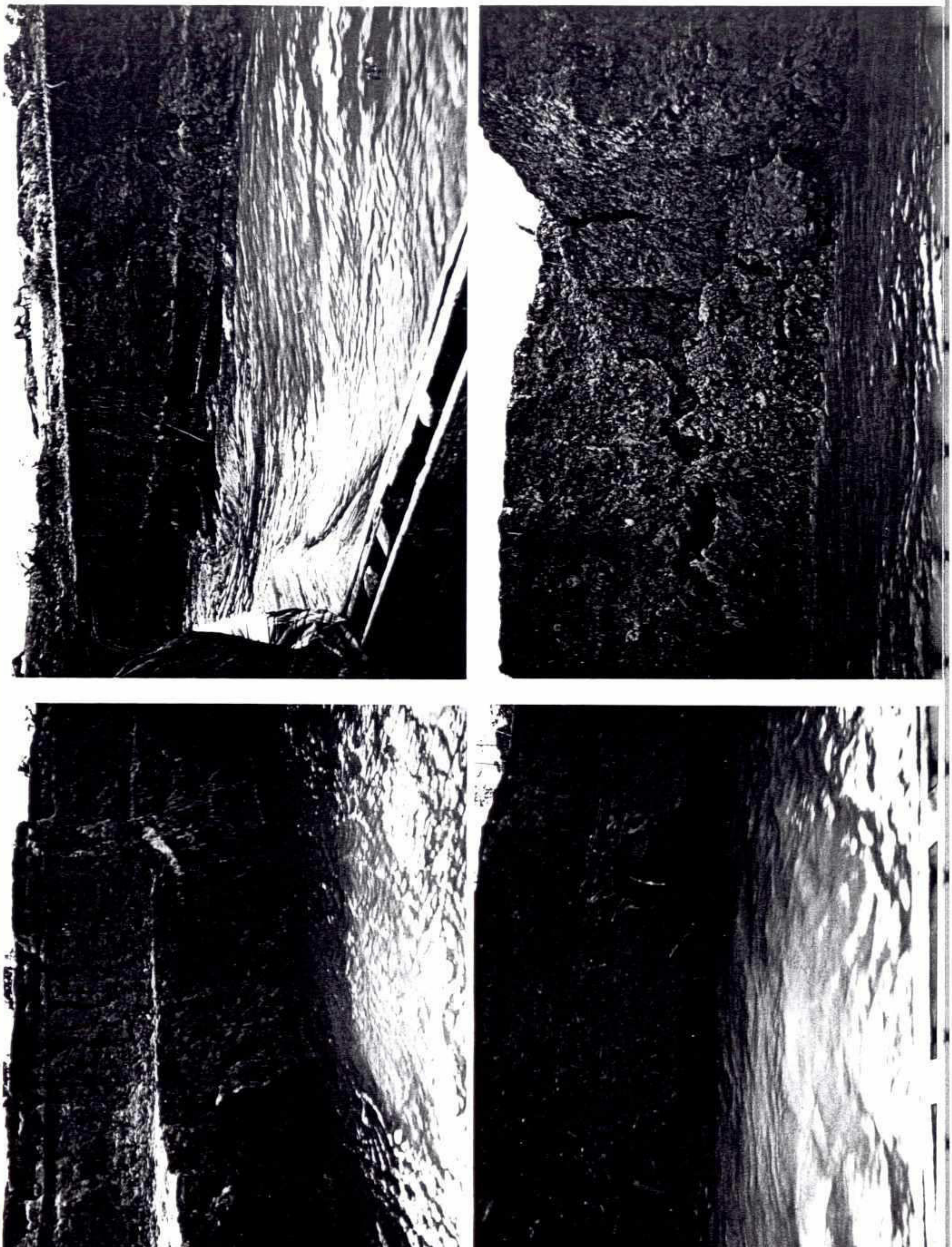
Annex 2

Figure 3.30

Halcrow/DHI/EPC/DIG

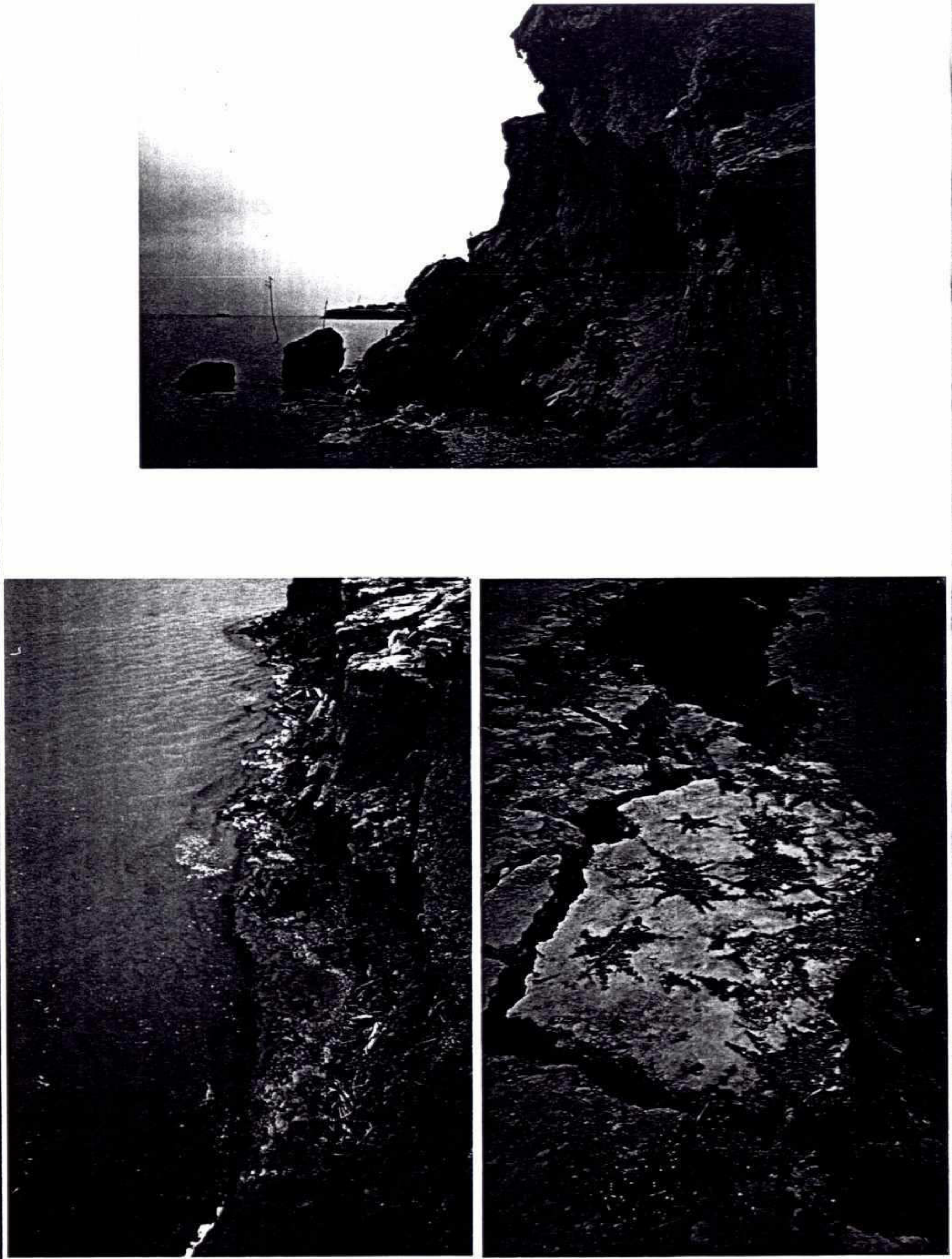
November 1992

150



Active Bank Erosion at Mathurapara

Active Bank Erosion at Mathurapara	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.31

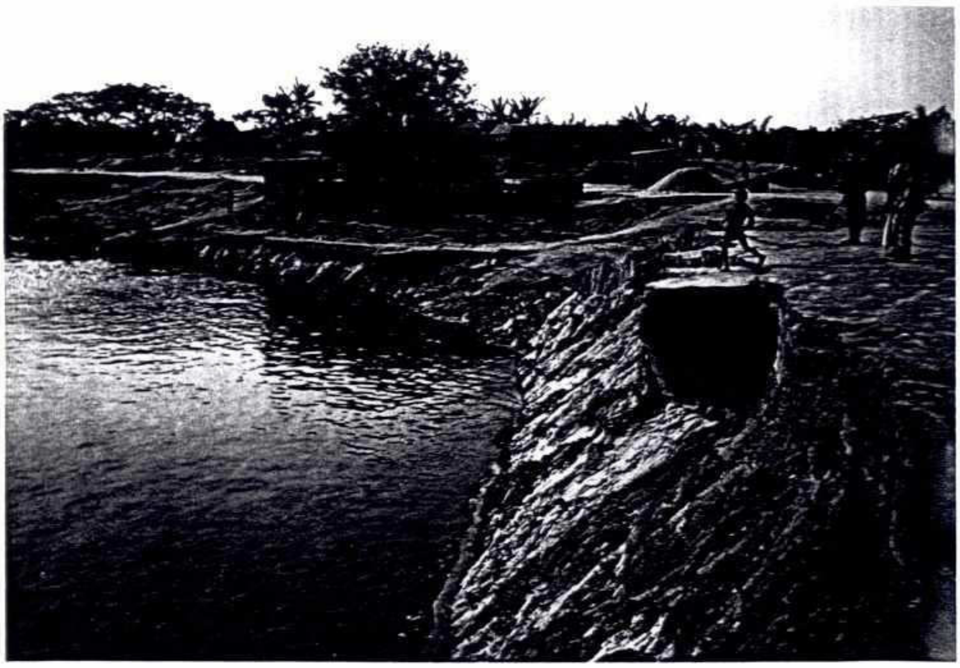


Slab Type Bank Failure at Kazipur

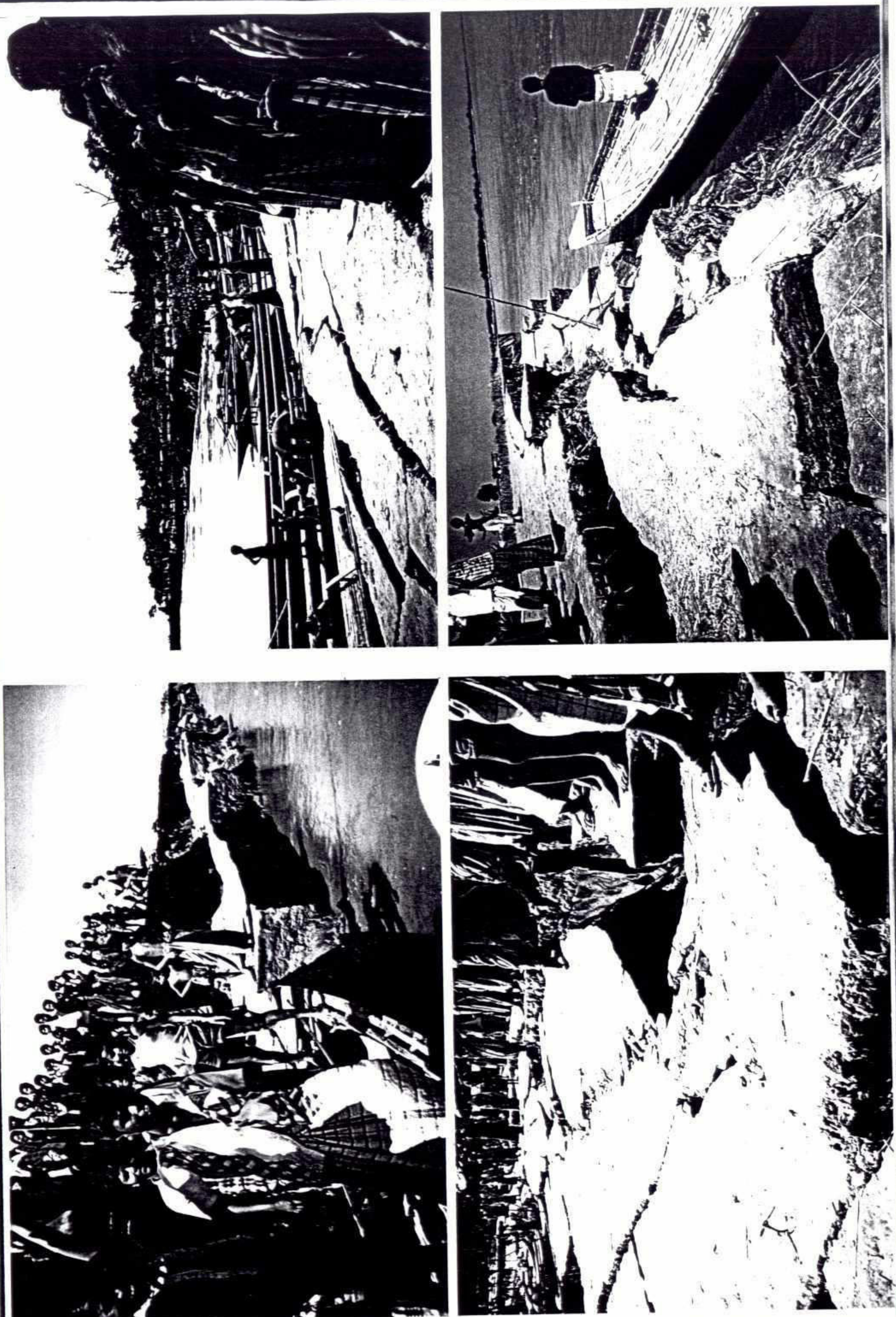
Annex 2

Halcrow/DHI/EPC/DIG *November 1992* Figure 3.32

152



Bank Failure North of Sirajganj	Annex 2
Halcrow/DHI/EPC/DIG *November 1992*	Figure 3.33

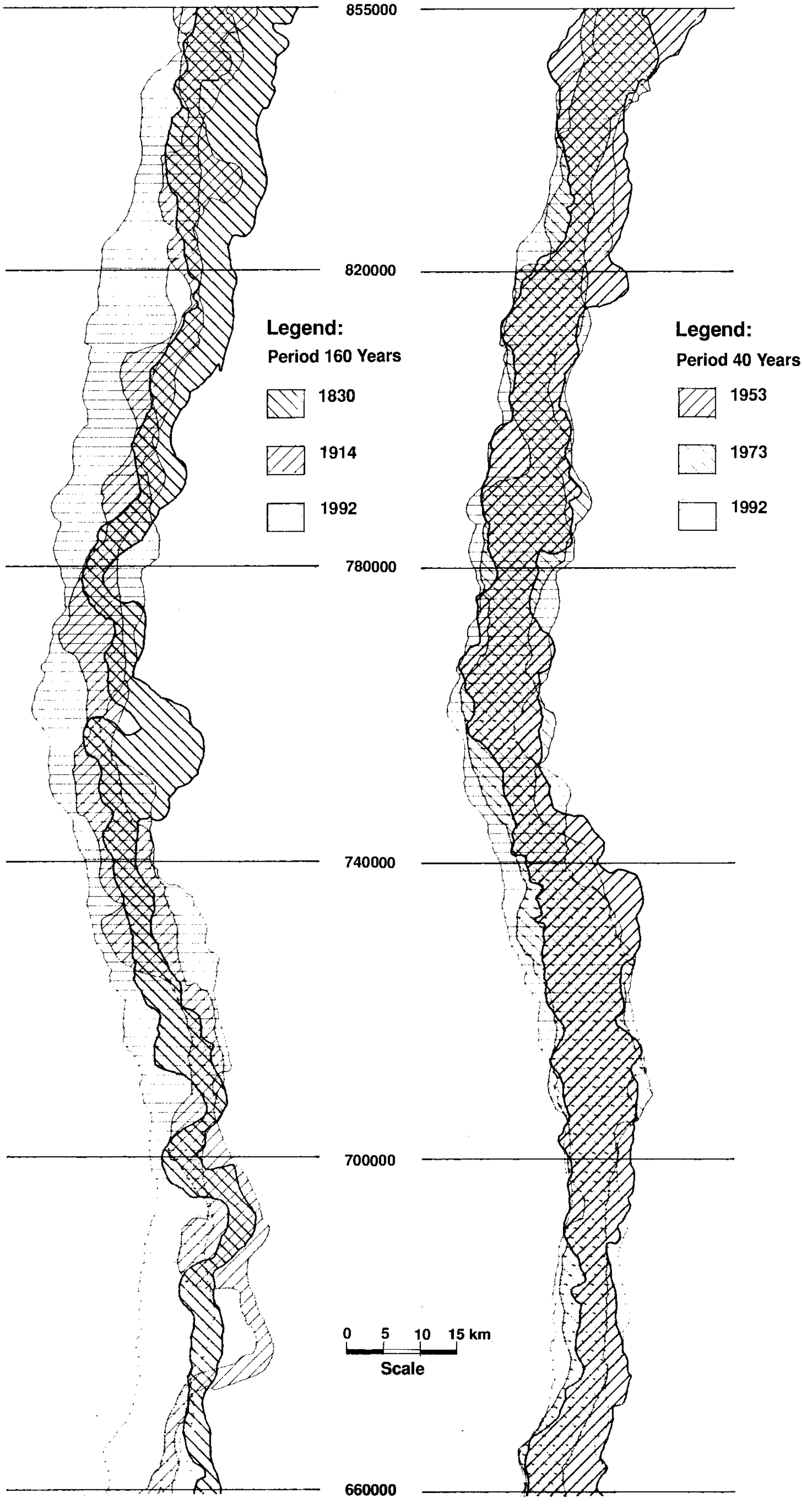


Slab Type Bank Failure at Betil

Annex 2

Figure 3.34

PLATES



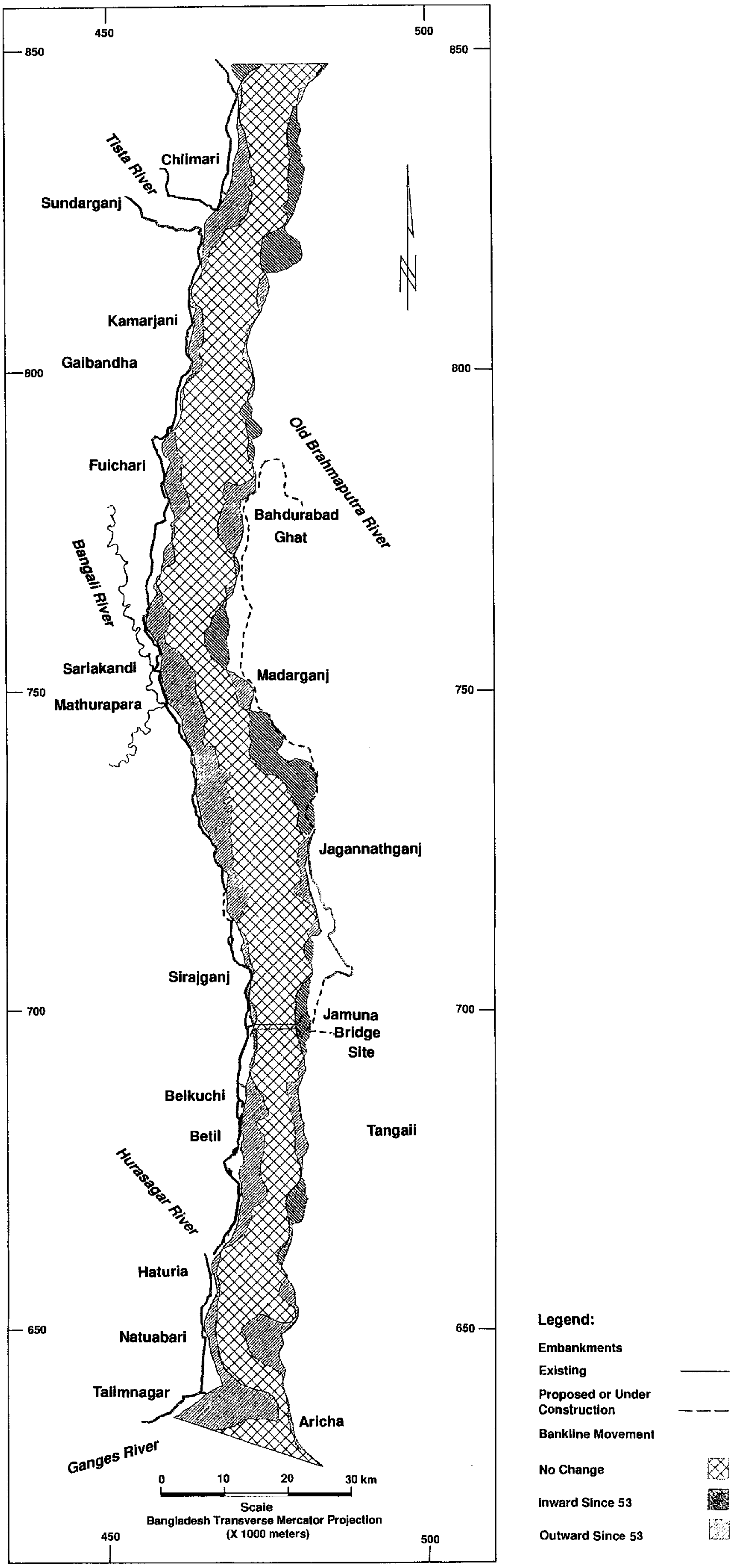
Source: USAID/ISPAN FAP-19

Historic Bankline Positions

Halcrow/DHI/EPC/DIG

November 1992

Plate 2



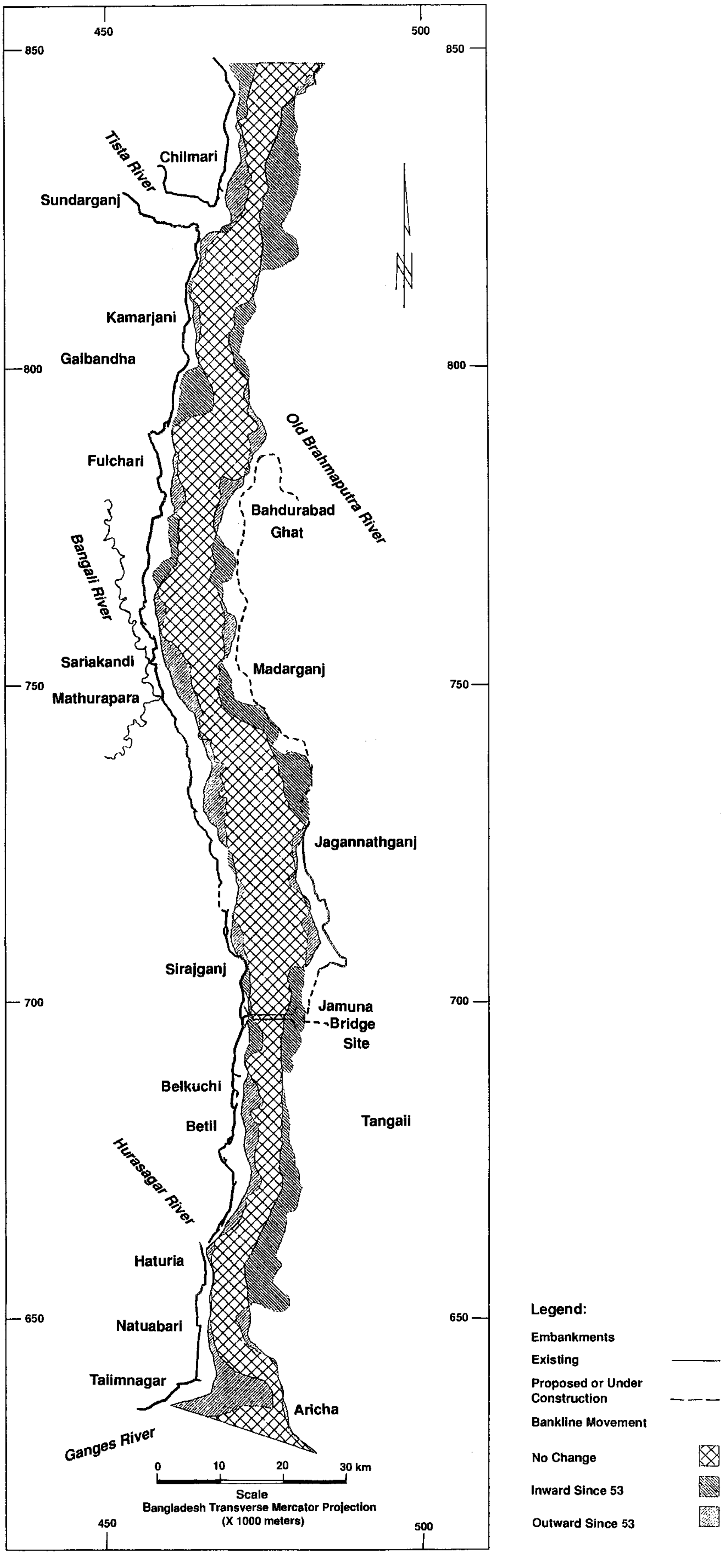
Source: USAID/ISPAN FAP-19

Jamuna River Bankline Movement 1953-1992

Halcrow/DHI/EPC/DIG

November 1992

Plate 3



Jamuna River Bankline Movement 1953-1973

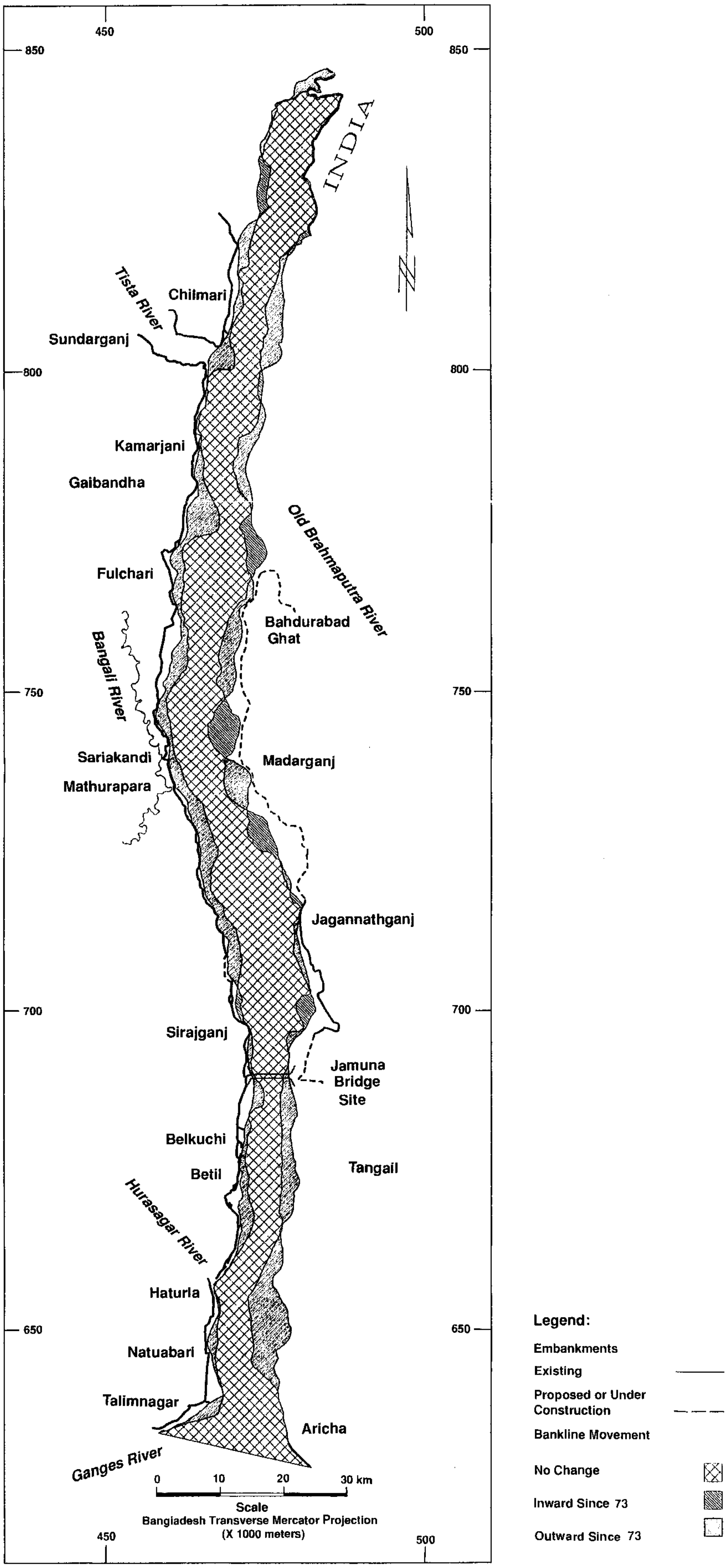
Halcrow/DHI/EPC/DIG

November 1992

Plate 4

Source: USAID/ISPAN FAP-19

152



Source: USAID/ISPAN FAP-19

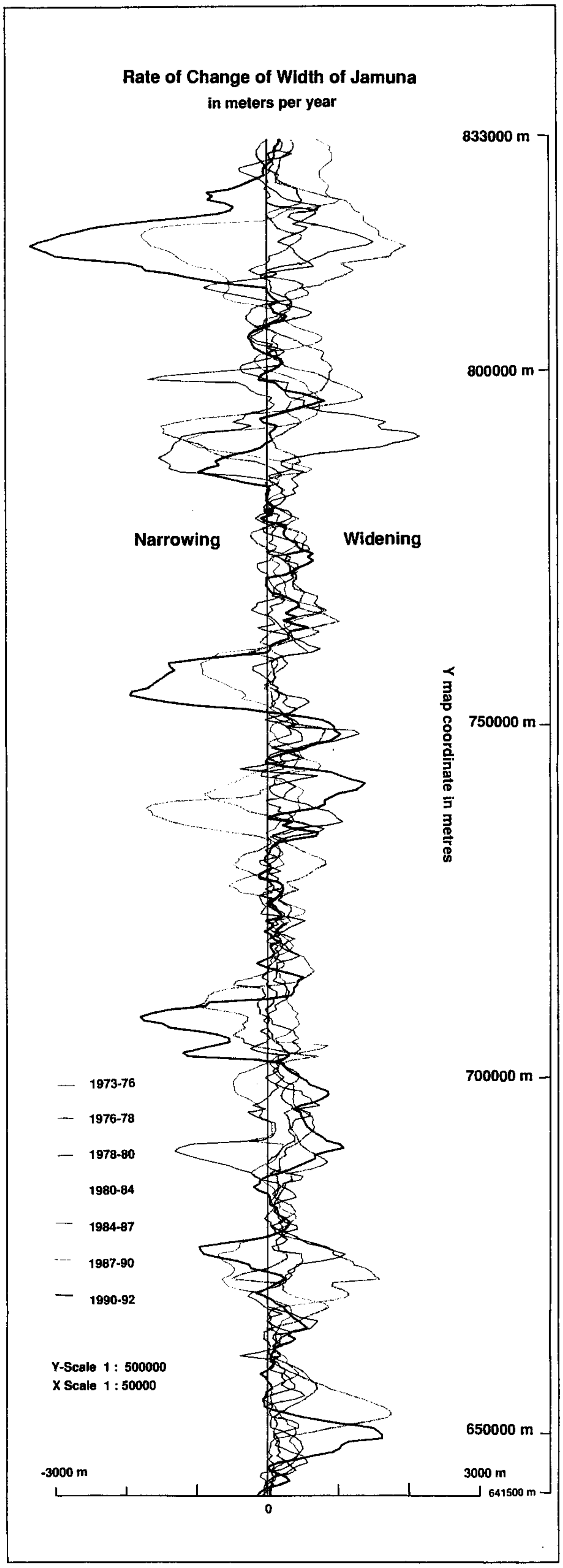
Jamuna River Bankline Movement 1973-1992

Halcrow/DHI/EPC/DIG

November 1992

Plate 5

158



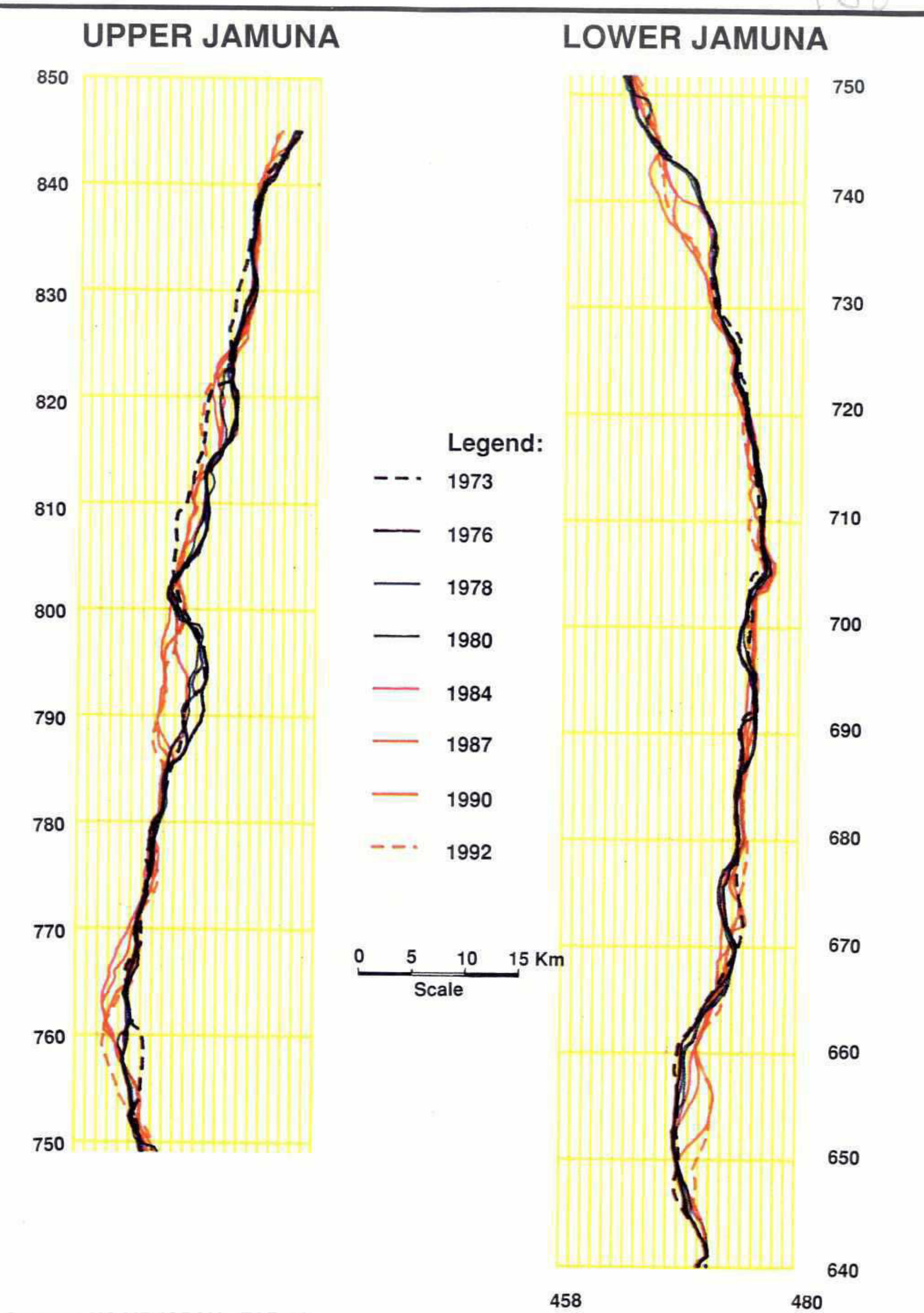
Source: USAID/ISPAN FAP-19

Rate of Change of Width of Jamuna

Halcrow/DHI/EPC/DIG

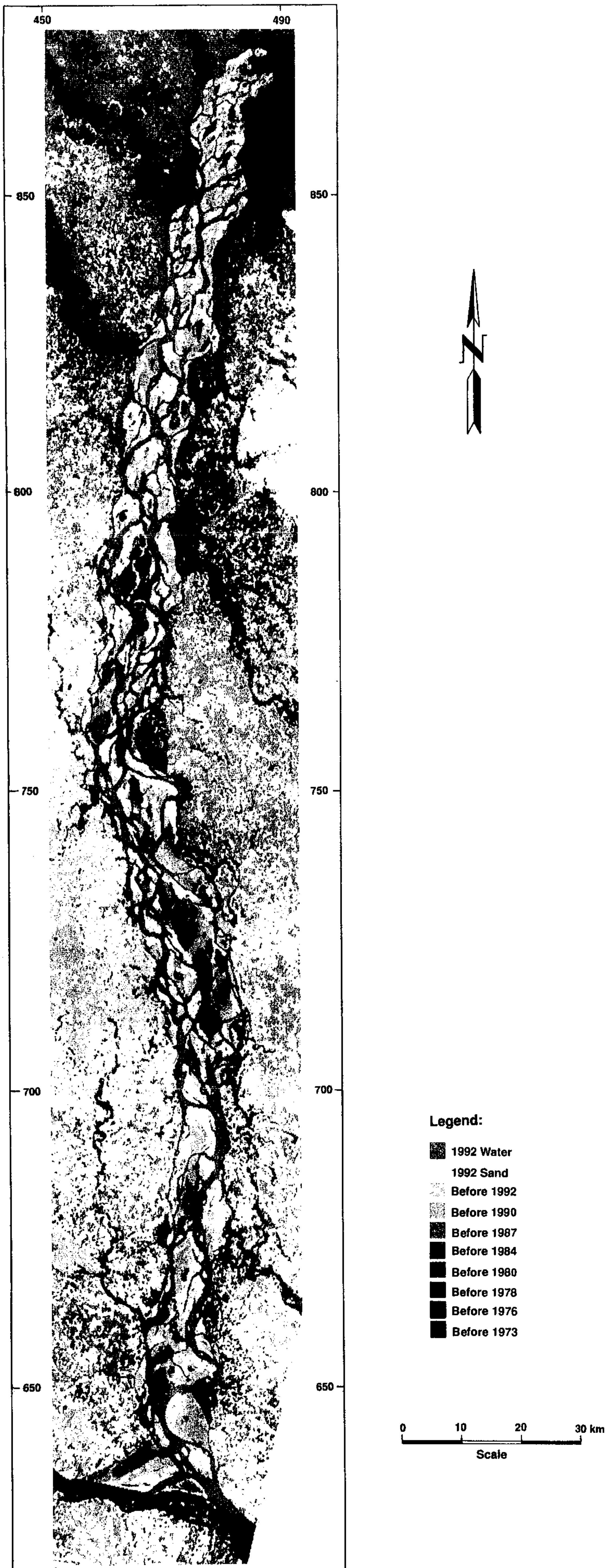
November 1992

Plate 9



Centre Line Migration

Halcrow/DHI/EPC/DIG *November 1992* Plate 10



Source: USAID/ISPAN FAP-19

Age of Chars Since Emergence

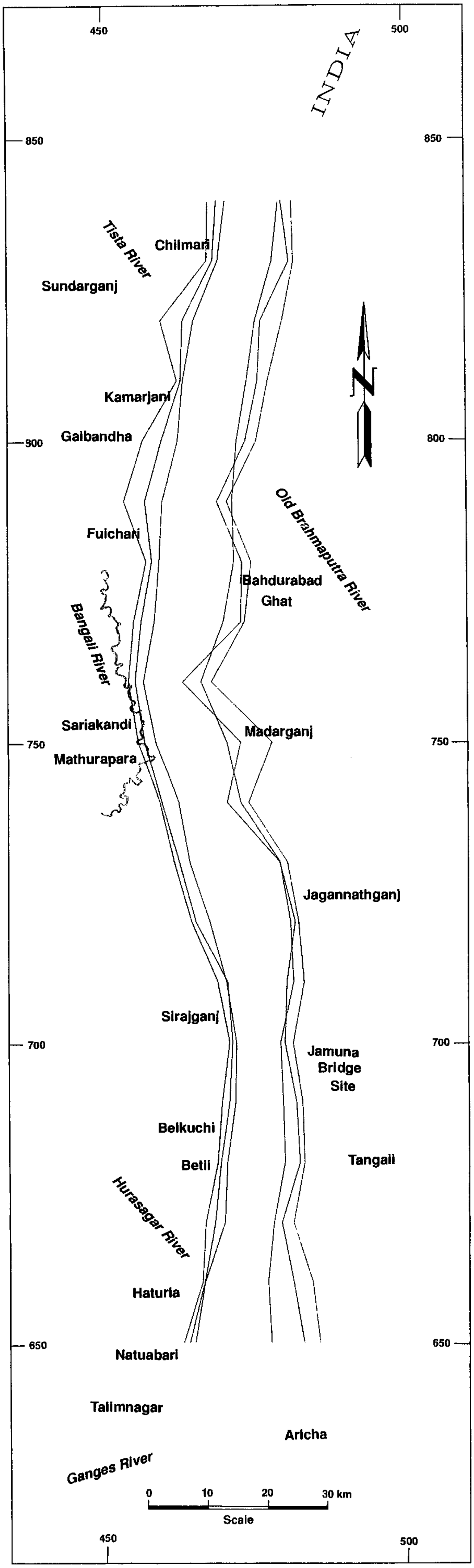
Halcrow/DHI/EPC/DIG

November 1992

Plate 11

Predicted Jamuna Bankline in the Year 2011

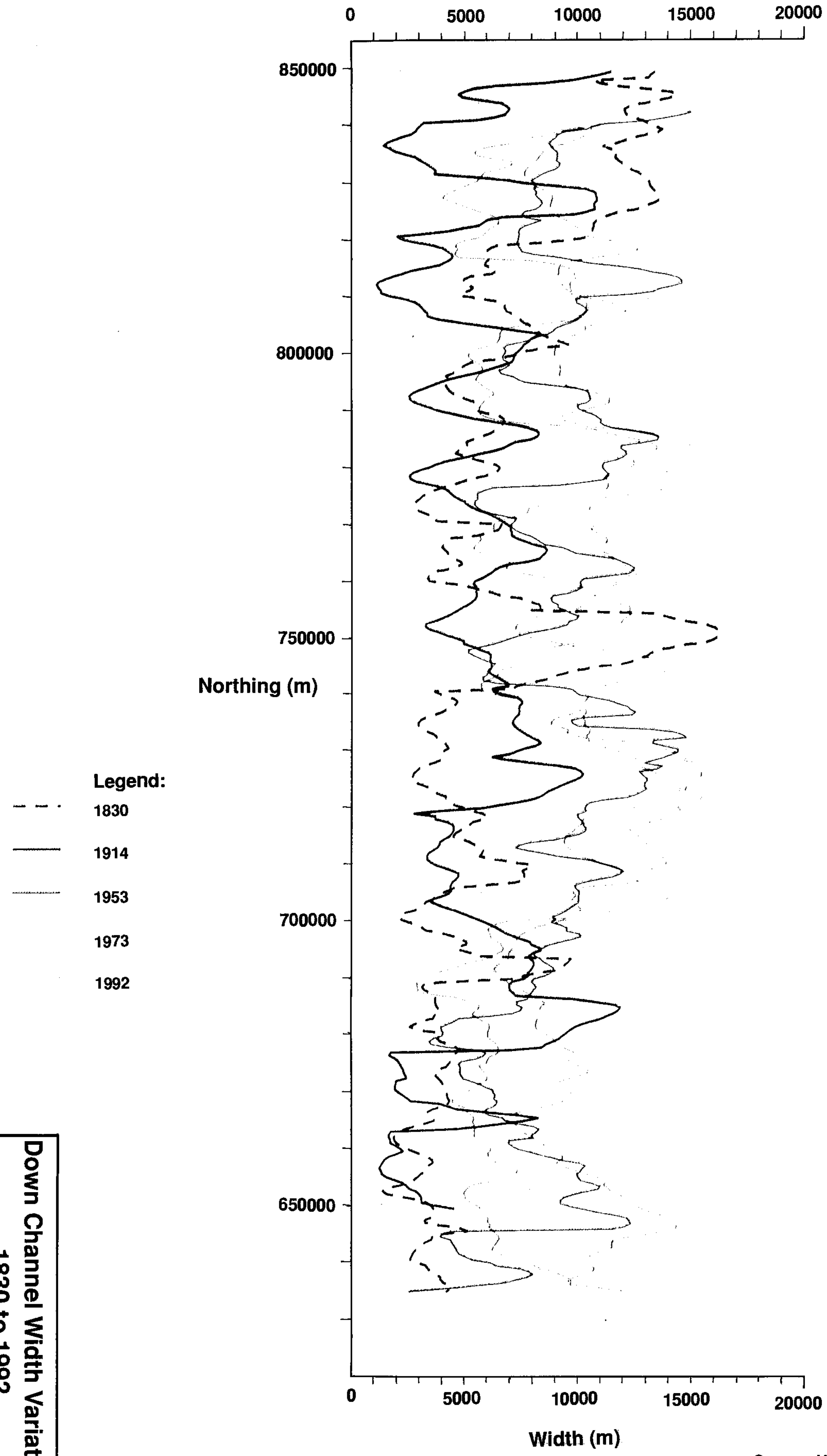
Halcrow/DHI/EPC/DIG | November 1992 | Plate 13



Legend:

- 1992 Bankline
- Predicted Bankline 50% Confidence Limit
- Predicted Bankline 5% Confidence Limit

Source: USAID/ISPAN FAP-19



Down Channel Width Variation 1830 to 1992

Halcrow/DHI/EPC/DIG

November 1992

Plate 16

Source: USAID/ISPAN FAP-19

163

164

APPENDICES

HALCROW

APPENDIX A

BANK RETREAT

APPENDIX A

BANK RETREAT

Reach 1: Northing 845000 to 780000

Island A, Inter-island a-b and Island B; Reaches 1 and 2 as used for Braiding Index; equivalent to Reaches 2,3,4 and 5 from the FAP-19/FAP-16 study

Proportion of zero erosion:
25.4 percent on average

Period	Percent
73-76	38.9
76-78	19.9
78-80	35.1
80-84	13.7
84-87	13.0
87-90	6.1
90-92	51.2

For the total period:

Exceedance percent	Rate m/y
5	500
10	400
50	150
90	70

Most severe period (highest median rate):	80-84	240 m/y
Most severe erosion (highest 5 percent exceedance):	84-87	650 m/y
Most mild period (lowest median rate):	90-92	100 m/y

All periods except 80-84 and 90-92 follow the mean for the period very closely

Reach 2: Northing 779500 to 757000

Inter-island b-c ; Part of Reach 3 as used for Braiding Index, equivalent to Reach 6 from the FAP-19/FAP-16 study

Proportion of zero erosion:
20.5 percent on average

Period	Percent
73-76	2.2
76-78	10.9
78-80	21.7
80-84	2.2
84-87	43.5
87-90	8.7
90-92	54.4

For the total period:

Exceedance percent	Rate m/y
5	420
10	330
50	140
90	70

162

Most severe period (highest median rate):	76-78	210 m/y
Most severe erosion (highest 5 percent exceedance):	76-78	500 m/y
Most mild period (lowest mediam rate):	90-92	110 m/y

All periods except 80-84 (high) and 90-92 (low) follow the mean for the period very closely

Very much less regular pattern than Reach 1. Very distinct tail off above 200 m/y. 76-78 and 80-84 stand out from the rest as periods of higher erosion rates.

Reach 3: Northing 756500 to 706000

Islands C, D and E; Part of Reach 3 and Reach 4 as used for Braiding Index; equivalent to Reaches 7, 8 and 9 from the FAP-19/FAP-16 study

Proportion of zero erosion:
20.9 percent on average

Period	Percent
73-76	15.7
76-78	14.7
78-80	37.3
80-84	21.6
84-87	18.6
87-90	8.8
90-92	29.4

For the total period:

Exceedance percent	Rate m/y
5	420
10	330
50	150
90	70

Most severe period (highest median rate):	87-90	240 m/y
Most severe erosion (highest 5 percent exceedance):	90-92	550 m/y
Most mild period (lowest mediam rate):	80-84	110 m/y

All periods except 80-84 (low) follow the mean for the period very closely

Overall period pattern almost identical to Reach 2. Individual periods less irregular. 80-84 stand out from the rest as period of lower erosion rates.

Reach 4: Northing 705500 to 640000

Downstream of Island E; Reaches 5, 6 and 7 as used for Braiding Index; equivalent to Reaches 9 to 14 inclusive from the FAP-19/FAP-16 study

Proportion of zero erosion:
26.5 percent on average

Period	Percent
73-76	20.5
76-78	25.8
78-80	35.6
80-84	47.0
84-87	6.1
87-90	8.3
90-92	42.4

For the total period:

Exceedance percent	Rate m/y
5	370
10	300
50	120
90	60

Most severe period (highest median rate):	90-92	190 m/y
Most severe erosion (highest 5 percent exceedance):	90-92	570 m/y
Most mild period (lowest mediam rate):	80-84	100 m/y

All periods except 76-78 (fairly high) and 90-92 (high) follow the mean for the period very closely. Overall period pattern similar to other three reaches. Individual period patterns fairly regualr except for 90-92 which shows much higher rates in the 10 to 50 percent exceedance range.

Comparison of overall pattern for reaches 1 to 4

Reach 1 stands out as having higher rates in all exceedance categories by as much as 20 percent. The other three reaches follow very similar patterns with Reach 4 marginally lower than the other two.

Notable features:
Period 90-92: unusually high erosion rates in Reach 4 are attributed to the continuous stretch of erosion from south of Sirajganj down to Belkuchi. This is the most rapid erosion this reach has experienced since 1973. All the more notable because elsewhere the river is experiencing unusually low rates of bank erosion.

Probability of Duration of Erosion Rates

For the whole study area:

The average duration of all categories of erosion rate lie between 3 and 3.5 years, with the extremes (catastrophic and very slow) being closer to the 3 years.

The pattern for Catastrophic, very slow and rapid is very similar (very rapid is distorted by perhaps one or two special cases) with only 20 percent of cases lasting more than 4 years and less than 2.5 years. Thereafter about 5 percent last between 5 and 6 years and a neither catastrophic or very rapid ever last more than 8 years.

The normal category differ significantly only in that the 5 percent level is extended to almost 7 years, after which the curve tails off rapidly.

The slow category stands out distinctly from the others with 20 percent of cases lasting more than 6 years and the 5 percent level approaching 9 years.

In short: most of the time (80 percent) any state will not last more than 5 years, or 6 in the case of "slow", and the likelihood of it lasting more than 8 years is vry low. There is however little difference between the categories with the notable exception of "slow".

Reach by Reach

The pattern is very similar for all reaches. The "slow" category consistently shows the somewhat longer durations but this is particularly exagerated in Reach 4 and to a lesser degree in Reach 3.

APPENDIX B

BEND ANALYSIS

DRAFT FINAL REPORT - ANNEX 2

APPENDIX B

BEND ANALYSIS

Bends were selected from the 1 to 250000 satellite images of the Jamuna. These bends complied as far as possible with the following criteria.

1) The bend should not shift incrementally, but should only move by migrating laterally.

2) The bend should contain no confluences or bifurcations.

3) The bend should not change its width by more than a factor of three between consecutive images.

4) The width should be greater than 0.5 mm (equivalent to 125 metres) on the 1:250000 satellite images.

A total of 8 bends were selected: 3 on the right bank and 5 on the left bank. Their locations are shown in Figure B.1. Satellite images were available for 8 years between 1973 and 1992.

Bend A - Left Bank

Bend A shows a developing cutoff. In 1973 the bend is beginning to show signs of cutting off through the point bar. The ratio of the radius of curvature to the width (r_c/w) for the centure of the channel is very low. The cutoff progresses in 1976-1978. In 1980 the bend is left as a scar. The rate of erosion declines as the embayment is cutoff. The width of the bend decreases as the bend dies leading to increasing r_c/w and E/w ratios, which may be misleading.

Bend B - Left Bank

Bend B is a double bend in most years (there are two bend apexes). This may complicate the pattern on the bend somewhat. The bend is abandoned between 1978 and 1980, but is occupied again in 1990. The 1990 bend has reoccupied the former scar, but with a far smaller channel, leading to high values of r_c/w and E/w. In 1978 the bend is reduced to a single apex bend, which is reoccupied in 1990, and then divides into a double apex bend again in 1992. This suggests that the two bends develop separately. The southerly bend has a much higher rate of erosion than the other and in 1992 shows typical embayment development with a low vertical to horizontal movement ratio. The development may also be complicated by the fact that, especially in 1976 and 1978, the point bar is divided into chars which will affect the flow patterns significantly.

Bend C - Left Bank

Bend C also shows two phases of development. Initially C may be seen as a clear embayment. Lateral erosion occurs steadily until the bend cuts off after 1980. A new, much larger, bend has reoccupied the former scar by 1984. As this embayment develops, the rate of lateral erosion increases. BY 1992 the rate of erosion has begun to decline again, suggesting imminent cutoff. However, complications may occur due to chars causing flow diversions at the point bar and also at the upstream and of the outer bank in 1992.

Bend D - Right Bank

Bend D shows a large bend which cutoff to form a much smaller band, which again cuts off and dies. The cutoff of the large bend may be due mainly to the development of bends E and C as well as the loss in energy in the developing bend. The upstream limb of the bend gradually approaches the bank at a more extreme angle, enabling a cutoff to occur easily. However, the downstream limb of the cutoff remains sinuous and continues to develop forming a typical embayment before cutting off between 1990 and 1992. The embayment development of Bend D is complicated by the dramatic decrease in size the first cutoff, increasing the values of r_c/w and E/w.

Bend E - Left Bank

Bend E is fairly indistinct in 1973 and 1976, and thus has large r_c/w ratios. By 1978 a distinct bend has formed, which migrates laterally until 1984. Chars may cause disruptions in the flow pattern of the upstream reach of the bend in 1980, and a major confluence has opened up very close to the upstream limb in 1984. The bend has totally disappeared in 1990, presumably as a result of the 1987 and 1988 floods, which straightened many bends in the lower reaches of the Jamuna. The bend had a very low r_c/w ratio in 1984, which would have enabled a cutoff to occur easily.

Bend G - Left Bank

Bend G is a highly contorted bend, which almost doubles back on itself in 1992. It has a very low ratio of vertical to horizontal to vertical erosion, suggesting the formation of a well-defined embayment. The extreme amount of contortion found in 1992 would suggest that a cutoff is imminent. There appears to be no obvious reason why the bend is so contorted along its downstream limb. Before cutoff occurs, high rates of lateral erosion should be expected. These rates will be exacerbated by the presence of a confluence very close to the upstream limb of the bend. Chars also exist in the bend in 1992, indicating an imbalance in the energy transfer along the channel.

Bend H - Right Bank

Bend H shows the development of a very insignificant bend into a major, rapidly eroding bend. In 1980 the bend has many chars in the channel, which will affect the pattern on development. By 1984, however, the bend has grown in size and is cutting into the outer bank. A char is present in the centre of the bend, which will again affect its development. In 1990 and 1992, rapid erosion is occurring and increasing, suggesting a highly efficient channel. This bend is situation at Kazipur, which has suffered from rapid erosion problems in recent years.

Bend J - Right Bank

Bend J is the bend immediately before the confluence with the Ganges. The radius of curvature of the bend is generally very large, with correspondingly large widths. Much of the lateral migration which occurs takes place between 1973 and 1976. The rate slows markedly after this date. As the bend develops, chars in the channel become more numerous to compensate for the inefficiency of the bend. The bend development is curtailed, possibly by the floods in 1987 and 1988, which cause the bend to be cut off, similar to the cessation of bend E.

Calculations for Bend Analysis

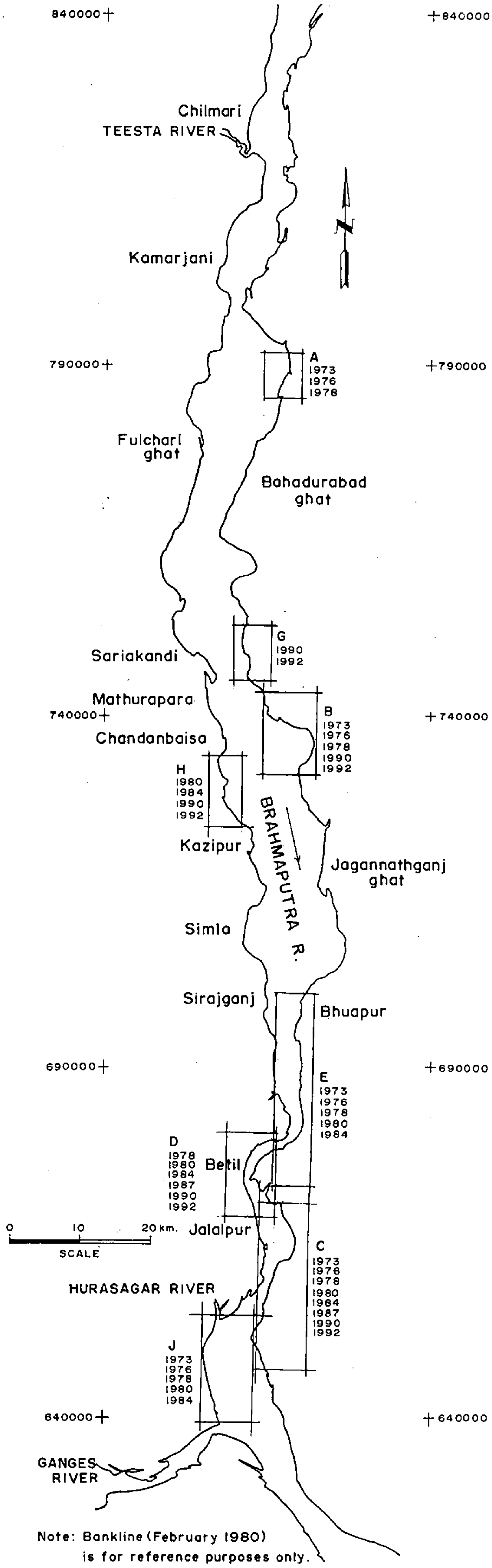
The bends were analysed using the ratios r_c/w and E/w, where r_c= radius of curvature of the bend (metres), E = the rate of embayment development (metres per year) and w = width of the bend (metres), r_c was measured by fitting a circle to the curvature of the bend. Both the outer bank curvature and the curvature of the centre of the bend were calculated to examine the different effects of the two curves. It was found that the use of the curvature of the centre of the bend was more significant when comparisons were made with other bend variables. The width was averaged from several points taken within the bend. The rate of erosion was taken as the difference between the maximum latitudinal extent of the bend between consecutive years. This gave a rate of change between, for example 1973 and 1976. Thus to obtain an average for a single year the following method was used:

Year 1 of bend development	= Average of year 1 and next year available (for example (1973 - 1976/3) = rate of erosion in 1973 (metres/year)).
Next available year =	Average of first 2 years taken and next two years (for example {[(1973 - 1976)/3] + [(1976 - 1978)/2]}/2 = rate of erosion in 1976 (metres/year)).
Last year taken =	Average of last year and second to last year taken (for example (1992 - 1990/2 = rate of erosion in 1992 (metres per year)).

This method of measuring the rate of erosion leads to problems when the bend development can only be measured over two satellite images, since the change in the rate of erosion cannot be measured. It was found that the relationship E/W and r_c was highly significant. A semi-log curve could be fitted to the graph with the maximum values of E/W occurring when r_c was approximately 2000 m. Thus as the bend tightens and the width increases, decreasing the value of r_c, the rate of erosion will increase dramatically.

Originally the rate of erosion was taken from the apex of the bend. However, this relied on the highly subjective placing of the apex, leading to misleading rates of erosion. It was also found that the apex of the bend could change dramatically without the bend actually migrating at all. It is hoped that the method used to measure the rate of erosion will give more accurate and consistent answers than the measurements from the apex.

It should also be noted that the satellite images all show low flow periods. They are not, therefore, representative of bend conditions at dominant discharge, when most bend development is thought to occur. A very small change in the angle of approach to the bend (as little as 10 degrees) may cause a shift in channel. A bend may, therefore, be severely altered during high flow events, as the increased discharge affects the patterns of flow. The values of r_c/w may also change considerably between low flow and dominant periods, thus negating the analysis. The angle of flow approach to the outer bank of the bend was plotted with the rate of erosion. Results were generally inconclusive. However, it was found that, discounting the broad scatter which occurred, the value of E/W generally increased with an increase in the angle of flow towards the bank. Similarly the value of r_c declined as the angle of flow towards the bank increased.



Halcrow/DHI/EPC/DIG

November 1992

Location of Bends for Evolution Study

Annex 2

Appendix B

Figure B.1

175