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RIVER SURVEY PROJECT

THE UNIVERSITY OF NOTTINGHAM

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Secondary currents and morphological evolution in a bifurcated channel

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Secondary Currents and Morphological Evolution in a Bifurcated Channel

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FAP24 & The University of Nottingham Joint Study 1994/95

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Summary

In studies of flow structures on single-thread meandering rivers, secondary currents have been shown to have a large influence on the morphological development of meander bends. Until this joint study between FAP 24 and the University of Nottingham, UK, there had been few similar studies carried out on the influence of secondary currents on large braided rivers such as the Brahmaputra River in Bangladesh. As a consequence of this lack of fieldwork, our understanding of braided river behaviour and the development of predictive tools have been impeded. This document reports on a series of field surveys to investigate the flow distributions around a braid bar in the Brahmaputra River near Bahadurabad. Results demonstrate linkages between large scale secondary current cells and the pattern of primary flow and the pathways of concentrated suspended sediment around the bar. Patterns observed along the flanks of the braid bar curved anabranch are similar to those observed in single-thread meandering channel bends. Patterns observed at the flow bifurcation upstream of the bar demonstrate how the secondary currents influence the development of the bifurcation through their effect on the near bed primary flow pattern and sediment transport. The results further demonstrate that an Acoustic Doppler Current Profiler is a powerful instrument, capable of investigating three-dimensional coherent flow structures in large rivers. A copy of all the data presented in this document is contained on a 3.5" diskette in ASCII text format attached to the back cover.

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Acronyms and abbreviations

ADCP	:	Acoustic Doppler Current Profiler
BWDB	:	Bangladesh Water Development Board
DGPS	:	Differential GPS (a high-accuracy satellite-based positioning system)
DHA ... DHE	:	(names of the survey vessels of the RSP)
FAP	:	Flood Action Plan
FAP24	:	FAP project 24 = The River Survey Project
GPS	:	Global Positioning System
PA	:	Project Advisor (of the RSP)
RSP	:	River Survey Project (= FAP 24)
RSPMU	:	River Survey Project Management Unit
UoN	:	University of Nottingham

1 Introduction

1.1 Context of the study

The River Survey Project

The River Survey Project was initiated on 9 June 1992. The project was executed by Flood Plan Coordination Organization (FPCO), presently merged with Water Resources Planning Organization (WARPO) under the Ministry of Water Resources (formerly the Ministry of Irrigation, Water Development and Flood Control). It was funded by the European Commission. The Consultant is DELFT-DHI Consortium in association with Osiris, Hydroland and Aprotech. Project supervision is undertaken by a Project Management Unit with participation by WARPO, a Project Adviser and a Resident Project Adviser.

The objectives of the project are (1) to establish the availability of detailed and accurate field data as part of the basis for the Flood Action Plan projects, and (2) to add to the basic data for any other planning, impact evaluation, and design activities within national water resources and river engineering activities.

The project consists of three categories of activities:

- a survey component, comprising a comprehensive field survey programme of river hydrology, sediment transport and morphology;
- a study component, comprising investigations of processes and effects within river hydrology, sediment transport and morphology; and
- a training component.

Background for the University of Nottingham/RSP joint study

In the ToR of the project a distinction is made between the study topics to be taken up under phase 1 and those for phase 2 of the project. In phase 1 the available data on river morphology and the historical water levels and discharges have been analyzed. And in phase 2 the programme of river studies had been undertaken to investigate key characteristics of the behaviour of the river systems. An inventory of possible study topics has been presented in Study Report 1, Selection of Study Topics for Phase 2, published in September 1993. The study of the flow and sediment distribution at bifurcations in braided channels and offtakes had received a high priority. In the list of study topics this study was described under topic 4.1. This study is intended to improve the understanding of factors which are important in determining the sediment transport distribution at bifurcations and, thereby, enable improved prediction of overall morphological trends. In the end of 1993, following the International Workshop on large alluvial rivers in Bangladesh, an agreement was reached to involve Prof. C. Thorne of the University of Nottingham in a joint study aimed at contributing to this improved understanding by investigating the influence of large scale, secondary flow structures.

This study is related to the study of sand bars, as reported in SPR-09 Bars and bedforms in Jamuna River. The University of Leeds was involved in that study. The bifurcation and confluence studied by the University of Nottingham is included in the study of the morphological developments in the left channel of the Jamuna river near Bahadurabad (SPR-24 Morphological developments at Bahadurabad). The study area was also part of the bathymetric surveys carried out by RSP (SPR_03 Bathymetric surveys).

Field data were collected by Mr Hans Høyer and staff from FAP-24 using the DHA vessel. Data processing was performed by a postgraduate research student at the University of Nottingham, Mr Roy Richardson, who is studying under the supervision of Prof. Thorne. Mr Richardson is funded by the Engineering and Physical Science Research Council, UK with sponsorship from Sir William Halcrow and Partners, UK. His research topic is concerned with the fluvial hydraulics of braided rivers. Hence, the joint study falls within the broader research topic of Mr Richardson. It is intended that he will use data from the FAP24-UoN joint study together with data from other reaches of large, alluvial rivers to form more general theories of flow and sediment transport in braided systems.

1.2 Objectives

The objectives of the joint study are to define the secondary flow pattern at a simple bifurcation-bar-confluence in a large braided river, examine the influence of changing stage on the secondary flow structure and relate the flow pattern to changes in channel morphology observed over a monsoon season.

1.3 Secondary currents, bend morphology and channel change in single thread meandering channels

Flow in alluvial rivers is strongly three-dimensional (Peters and Goldberg, 1989). Secondary currents are defined as currents which occur in the plane normal to the axis of the primary flow (Prandtl, 1952). They have been shown to be of two types: Stress-induced currents driven by non-uniform boundary shear stress distributions in straight channels; and skew-induced currents caused by skewing of cross-stream vorticity into a longstream direction when the flow is curved.

Three decades of research in meandering rivers has established that the pattern of primary isovels and pathways of bed material transport (both bed load and suspended load) are strongly affected by skew-induced secondary currents (Engelund, 1974; Hey and Thorne, 1975; Bathurst et al., 1977; Bridge, 1977; 1984; Dietrich et al., 1979; Bathurst et al., 1979; Thorne and Rais, 1984; Thorne et al., 1985; Odgaard and Berg, 1988; Markham and Thorne, 1992). Secondary currents occur at all flow stages in meander bends (Anthony, 1987) and at high flow they may also persist through the inflection point between meanders (Thorne and Hey, 1979). The influence of secondary currents on flow and sediment dynamics causes meander shifting through river bank erosion and bar sedimentation that leads to the planform evolution that is typical of meandering rivers (Friedkin, 1945; Thorne and Lewin, 1979; Lapointe and Carson, 1986; Thorne, 1991).

Up until the late 1970s it was thought that secondary flow at a bend consisted of a single, skew-induced cell carrying fast surface water towards the outer bank and slow, near bed water towards the inner bank (Engelund, 1974) (Fig. 1.1). However, direct measurements of secondary currents using electromagnetic current meters indicated that close to the eroding outer bank there was often a smaller cell of reverse rotation (Thorne and Hey, 1975; Bathurst et al. 1977, 1979) (Fig. 1.2). Further work in the late 1970s and early 1980s demonstrated that the skew-induced secondary cell does not extend to the inner bank (Dietrich et al., 1979, 1984; Thorne et al., 1985, Markham and Thorne, 1992). In fact, flow over the upper point bar is directed radially outwards throughout the whole water column (Fig. 1.2). This is the case because the outwards acting centrifugal force on the curved flow overcomes the inward pressure gradient force caused by the transverse water surface slope. Continuity is satisfied because the flow decelerates in the longstream direction and because the depth decreases due to shelving of the flow over the point bar (Dietrich, 1982).

In the papers cited above, geomorphologists and river engineers have shown how the pattern of secondary flow affects the distribution of primary velocity. Where the flow plunges, isovels are compressed leading to a steeper velocity gradient and intense near-bed shear stresses, while areas of upwelling show reduced primary velocity gradients and boundary stresses. Hence, secondary currents play a strong role in determining the distribution of scour and fill around the channel perimeter. This may be illustrated using two examples.

Close to the outer bank, the flow plunges where the skew-induced and outer bank cells converge at the surface. Hence, primary isovels are packed near the bed and bank shear stresses are high in this region, promoting toe scour and undercutting of the bank (Thorne and Lewin, 1979). This often leads to mass instability and bank collapse that produces rapid bankline retreat (Thorne, 1978; 1982; Thorne and Osman, 1988). Failure blocks fall to the lower bank and bank toe, but their residence time there is short due to the high velocities and shear stresses imposed by the flow. Hence, the basal clean-out phase is often very short. Once failed debris has been swept away, the flow again attacks the lower bank, again over-steepening it and generating further mass instability. In this way, the secondary and primary flows combine to produce aggressive and effective bank erosion capable of driving rapid and sustained bankline retreat.

Sediment transport in meander bends is also strongly influenced by the secondary flow pattern. On the upper, point bar platform bed material is transported laterally outwards, towards the point bar crest. Sedimentation on the platform consists mostly of fines and wash load deposited due to decreasing flow discharge and velocity in the longstream direction. Sediment sorting occurs on the sloping point bar face. The largest, heaviest particles roll downslope under gravity against the inwardly directed near-bed secondary current, while lighter particles are swept inwards against gravity (Fig. 1.3). At the junction of the skew-induced cell and the zone of outward flow, near-bed currents converge and there is upwelling. Here sediment ladened, near bed water is carried up into the body of the flow by upwelling secondary currents. Often, bed material transport (both bed load and suspended load) is concentrated in a ribbon running along the line of convergence of the main skew-induced cell and the zone of outward flow. The accumulation of sediment there leads to the building of a sharp ridge separating the upper, gently sloping point bar platform from the lower, steeper point bar face. This is significant, especially for the bed load component which cannot be neglected (Peters, 1993). Bed load is highly significant because it is responsible for driving morphological change through advance of the point bar crest (Dietrich,1982). In meandering rivers the point bar crest follows the zone of bed load convergence, which is skewed across the channel from the outer bank at the bend entrance, to the inner bank at the bend exit. This topographic feature itself induces further strong circulations that play important roles in sediment sorting by size fraction and determine sediment pathways through the bend (Dietrich et al., 1979; 1984; Dietrich and Whiting, 1989, Markham and Thorne, 1992) (Fig. 1.3).

Mathematical models of flow in bends initially emphasised the impacts of water and momentum transfers on the distribution of depth-averaged flow and bed topography (Engelund, 1974; Bridge 1977;

1984; Odgaard, 1986). More recently the importance of convective accelerations associated with topographic steering by the point bar in general and in particular radially directed outwards flow have led to revisions of models to better account for the actual patterns of secondary flow (Dietrich and Whiting, 1989; Smith and McLean, 1984). This illustrates that it is necessary to identify the factors involved in controlling morphology and driving morphological change through field studies before attempting to model flow and sedimentary phenomena numerically (Peters, 1993).

There is now overwhelming evidence that secondary currents significantly affect channel morphology in single-thread meandering rivers and that recognition of the pattern of secondary currents (both helical cells and lateral flows) are crucial to understanding, explaining and modelling flow and sediment processes in channel bendways.

1.4 Secondary currents and channel changes in the braided Jamuna River

There have been few field measurements of velocity fields around bars in braided rivers (Bridge and Gabel, 1992 is an exception, for a gravel-bed river) and to date there has been no systematic, field-based study of secondary currents in a large, sand-bed braided river due to lack of availability of suitable instrumentation and resources to mount the necessary field campaign. Those studies that have been carried out have tended to emphasize flow and morphological dynamics at confluences (see Bristow and Best, 1993 for a full review) with the link between converging flow at a confluence and subsequent divergence leading to bifurcation of the channel being relatively neglected. Consequently, rather little is known about flow in large braided rivers (Peters, 1977) and even less is known about any role secondary currents may play in confluence/difluence mechanics (Best and Bristow, 1993). Similarities between meandering and braided rivers do exist, however, (Thorne et al., 1993) suggesting that secondary currents could be in part responsible for significant morphological forms in braided rivers.

The joint study between the River Survey Project (FAP-24) and the University of Nottingham is intended to begin rectifying this gap in our knowledge by resolving at least some of the questions concerning the existence, patterns and morphological influence of secondary currents in braided rivers.

In a recent paper Ashworth and Ferguson (1992) suggested that a bifurcated channel could be viewed as consisting of back-to-back meander bends (Fig. 1.4), the left channel being a mirror image of the right. On this basis, they suggested that the secondary flow pattern would consist of twin skew-induced cells, diverging at the surface and converging at the bed (Fig. 1.4). The resulting circulation drives fast surface water outwards to the banks where it plunges, and bring slow, near bed water inwards, where it upwells at the channel centre.

While the analogy of a bifurcated channel in a braided river with back-to-back meanders has merit, examination of the results reported in the previous section on flow in meander bends of single-thread channels suggests that Ashworth and Ferguson's concept of secondary current cells possibly over-simplifies the situation found in nature.

A mirror image of the current understanding of secondary flow at a meander bend (Figure 1.2) would indicate that the likely pattern of secondary currents in a bifurcated channel might be similar to that shown in Figure 1.5. The salient features are:

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- Helical flow in the deep anabranch thalweg channels, with outwards flow driving fast surface water towards the outer, eroding banks and inwards flow bringing sediment ladened near bed flow towards the flank of braid bar;
- Outer bank cells generating flow convergence and plunging some distance out from the banks and promoting basal scour and undercutting of the banks around the bank toe; and
- Outwards flow over the upper part of the braid bar at the channel centre, concentrating bed material transport and deposition at the near-bed flow convergence/upwelling zone on the flank of the braid bar and promoting fines deposition on the bar top through reducing unit discharge over the bar in the downstream direction.

This hypothesis of secondary flow pattern is qualitatively consistent with the main morphological features of bifurcating channels and, if validated, establishment of the flow pattern could help our understanding of process-form linkages responsible for bed scour, bank erosion and bar sedimentation. Based on experience in single-thread rivers, qualitative understanding of flow patterns and the significance of secondary flow and convective acceleration terms in the equations of fluid motion are crucial prior to successful mathematical modelling of flow in bifurcating channels. Further, and perhaps most importantly, such an understanding could form the basis for intervention in channel evolution through the use of recurrent measures and Active Flood Plain Management in controlling, or at least influencing, flow patterns and channel migration.

It is known that the fundamental morphological unit of the braided river is the bifurcation-bar-confluence unit (Best and Bristow, 1993; Thorne et al., 1993). Hence, an investigation of secondary currents and braiding should cover this morphologic unit. On this basis, a field study programme should consist of cross-sections throughout a bifurcation-bar-confluence unit. A conceptual framework for field data collection is shown in Figure 1.6. In order to investigate process-form linkages and secondary flow patterns, it is desirable that measurements in a braided river be repeated at different flow stages during channel evolution.

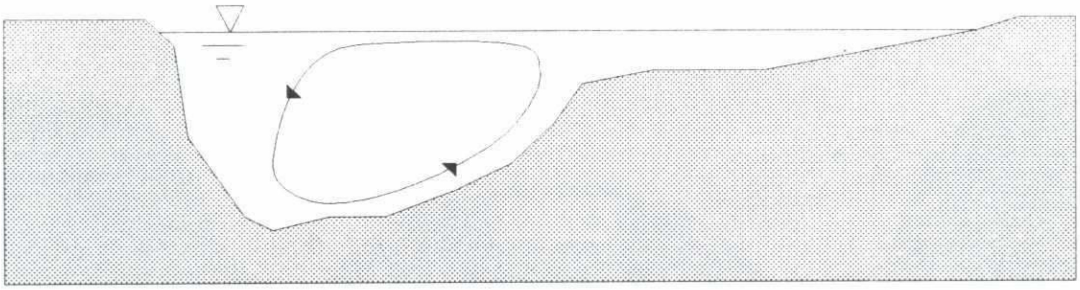

Figure 1.1: Single cell theory of bend flow in a meandering river

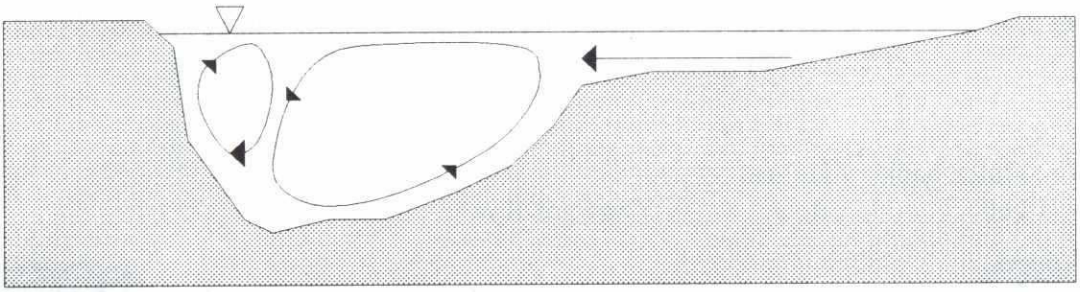

Figure 1.2: Current theory of bend flow with skew-induced and outer bank cells plus outwards flow at the inner bank

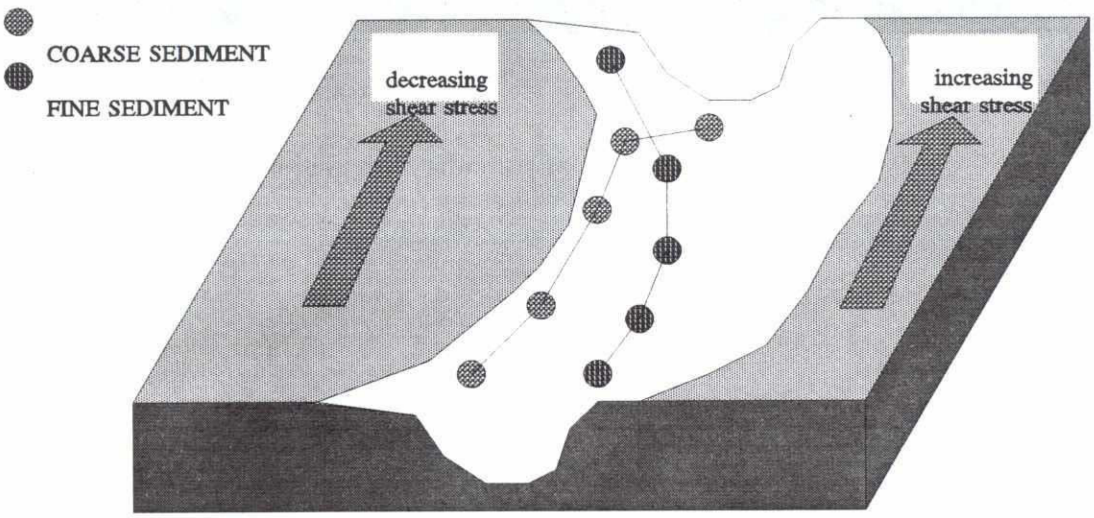

Figure 1.3: Effect of the point bar crest on flow pattern and sediment sorting in a meander bend (adapted from Dietrich, 1982).

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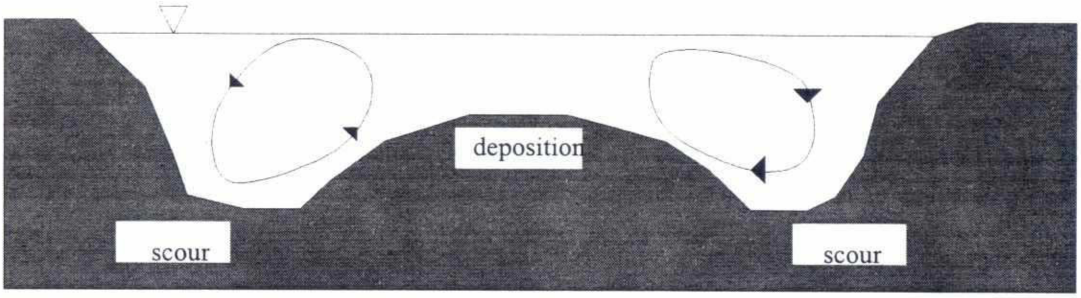

Figure 1.4: Concept of flow in a bifurcated channel as mirror image meanders (Ashworth et al., 1992)

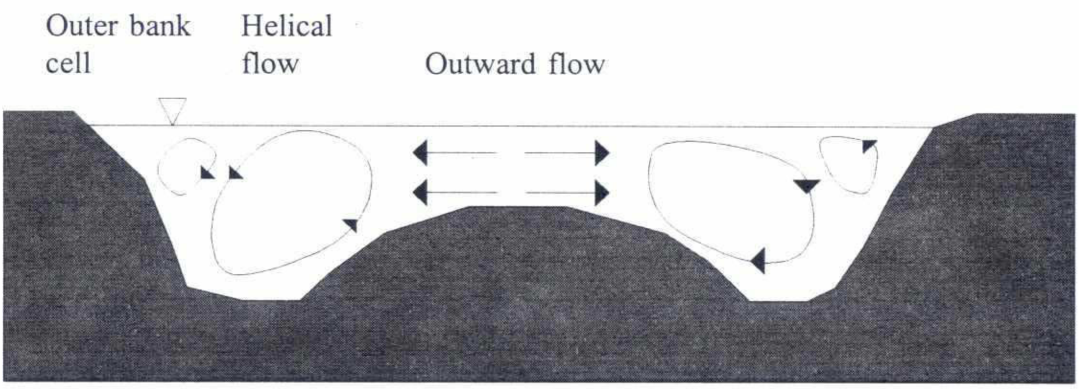

Figure 1.5: Hypothesis for the pattern of secondary circulation in a bifurcated channel.

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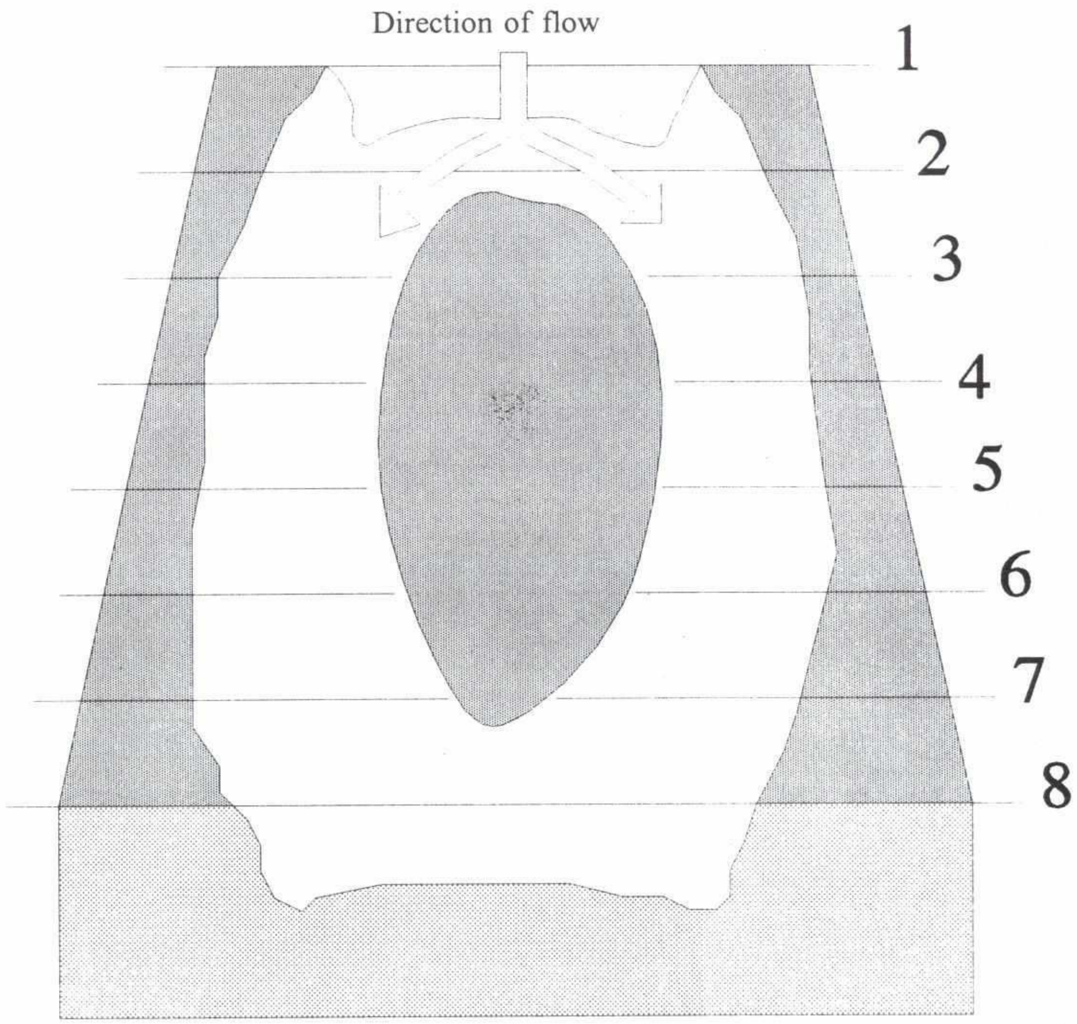

Figure 1.6: Conceptual framework for measurement sections in study of flow through a bifurcation-bar-confluence morphological unit in a braided river.

2 Site description and field methodology

2.1 Introduction

The concept of the field study outlined in chapter one (Fig. 1.6), called for a series of cross-sections to be established in a bifurcated channel, extending from upstream of the bifurcation (or difluence), through both sub-channels and ending downstream of the bar tail where the sub-channels again confluence. In May, 1994 a suitable study site was selected in the left bank anabranch of the Brahmaputra (Jamuna) River about 10 km south of Bahadurabad. The site chosen was around an asymmetrical divided flow reach about 4 km in length, with well defined sub-channels on either side. Sixteen transect lines were established extending from upstream, around and downstream of the bifurcated reach (Fig. 2.1).

2.2 Approach

Field measurements were made using the DHA vessel. ADCP, a high accuracy echo-sounder and differential GPS for position fixing were applied along selected transects in May, August, September and November, 1994. The dates of observations were chosen to correspond to the rising, peak, falling and low stages of the summer monsoon flow (Fig. 2.2). Transects extended as close as possible to the banks and were spaced at a distance of approximately 750 m in an attempt to eliminate gross changes in flow pattern between transects.

The draft of the DHA vessel meant that it was not possible to survey all sixteen transects on each measurement date. The Acoustic Doppler Current Profiler, Electromagnetic Flow meter, Echo-sounder and Differential Global Positioning System were all used on each occasion. Details of the operation of these instruments may be found in the relevant FAP-24 reports and documents and in order to keep this report to a manageable length they are not repeated here.

2.3 Summary

The data requirements for the FAP-24 / UoN joint study were successfully fulfilled in the field study programme. No significant deviations from the experimental design in the original proposal occurred and no major shortcomings in the pre-survey planning or survey techniques were revealed during the post survey processing and analysis of data.

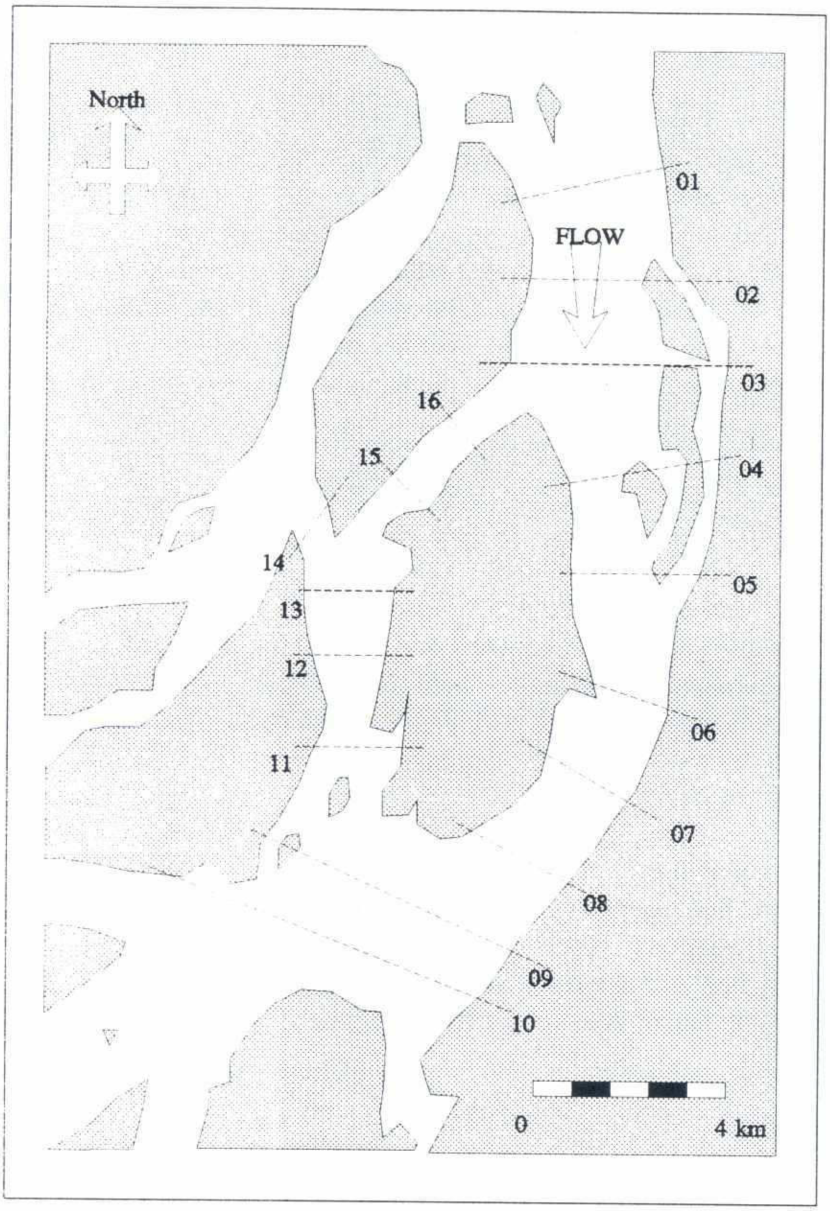

Figure 2.1: Study site showing position of survey lines

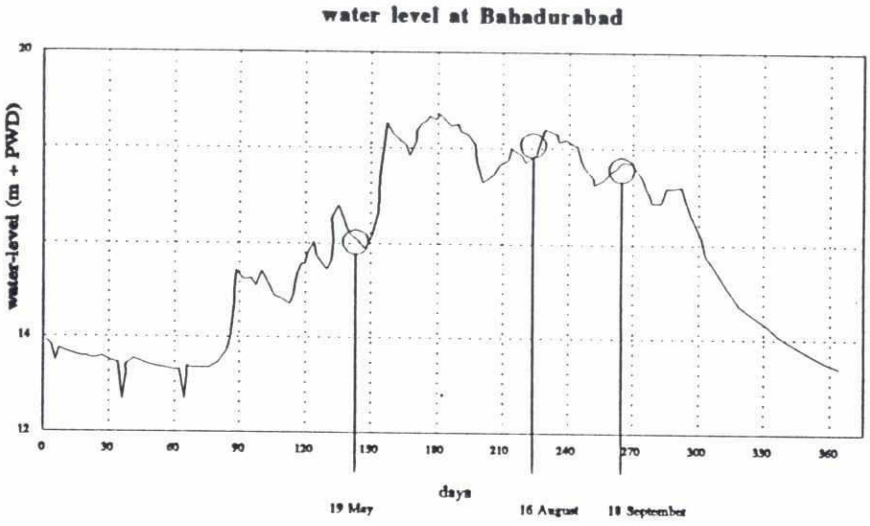

Figure 2.2: Monsoon hydrograph for 1994 with study dates marked

3 Longterm channel evolution: 1973-94

3.1 Context

Short-term field measurements of flow velocities, sediment dynamics and channel changes in an alluvial river must be interpreted within the context of longer-term historical channel changes. Unless this is done it is impossible to assess the relation of observed processes and morphological change to sustained trends of channel formation and evolution. Natural channels are seldom stable and channel evolution, although it may be progressive, rarely occurs at a steady or uniform rate. Hence, although short-term measurements may be indicative of sustained trends, they may equally involve entirely different rates, directions and patterns of change (see for example Thorne and Lewin, 1979).

Similarly, field measurements are limited in spatial extent by the time and resources available. The study site selected in this project covered a single bifurcation-bar-confluence morphological unit, but flow patterns and channel changes within that unit cannot be fully understood in isolation. Events in the channels upstream and, to a lesser extent, downstream of the study reach need to be considered.

In this study it was possible to address these issues of time and space scales using remotely sensed data supplied by FAP-19. Enlargements of satellite images covering the study reach and the channel upstream and downstream were used to document wider scale channel evolution historically for the period 1973-94. The images are presented in Figure 3.1(a-i). The years used in the images represent occasions when an image was available with the water stage close to that in all the other images. Hence, pattern differences between images may be attributed to morphological changes rather than differences in water levels.

3.2 Historical evolution in the Brahmaputre River around the study reach

In the satellite images the white crosses represent fixed points that may be used to cross-reference the channel patterns on different dates. This is essential because the highly dynamic nature of the Brahmaputra means that the channel pattern and position changes radically over the study period. In fact the planform in 1994 at first sight appears almost unrecognisable compared to that in 1973. Despite this, careful inspection reveals that there is some order and progression in channel change and that there are features of the planform pattern that have a distinct scale, are repetitive and persist throughout the study period.

Previous planform studies have shown that the Brahmaputra River often displays two major anabranches running down the right (west) and left (east) banks of the braid belt (Coleman, 1969; Bristow, 1987; Thorne et al., 1993). This is the case in the study reach, with the study site being located in the left bank anabranch, and the main channels are therefore referred to as the left and right anabranches (Note that since the banks are defined looking downstream, the left bank appears on the right of the images in Fig. 3.1). These anabranches tend to meet to form nodes in the braided pattern at about 30km intervals, with large islands between the nodes that separate the two anabranches by up to 10km (Fig. 3.2) (Coleman, 1969; Thorne et al., 1993). The reach covered by the satellite images extends from the northern tip of Island B, through the node b-c, to the upstream tip of Island C.

In 1973 the great majority of the flow followed the left bank anabranch and the right bank anabranch is barely discernible in the satellite image (Fig. 3.1a). The left bank anabranch was predominantly meandering at this time with a sinuous channel orientated from northeast to southwest and wide point bars with multiple chute channels crossing them. The meander wavelength in the left anabranch was around 15km and there is a meander crossing due west of Bahadurabad. The meander just upstream is west bank concave, but a symmetrical embayment in the left bank opposite indicates that in the past a symmetrical but east bank concave meander has existed here. The resulting channel planform is funnel shaped. The study site was at this time part of the left flood plain, due west of node b-c, which at this time was a narrow, very well defined junction between the right and left bank anabranches. The channel at the b-c node is next to the right bank because of the orientation of approaching flow in the dominant left bank anabranch and the development of a large point bar at the left bank.

In 1976 the majority of the flow is still following the left bank anabranch although the right bank anabranch is a little larger. The left bank anabranch has divided to form a braided pattern by a multiple chute channel cut-off of the bend just south of the offtake of the Old Brahmaputra. Downstream from the cut-off the left bank anabranch is more sinuous than it was in 1973, and the meander wavelength has shortened to around 12 km. The meander crossing west of Bahadurabad still exists. Point bars at the inside of the bends have chute channels which provide pathways for the rapid development of braiding. (Note: Development of braiding by enlargement of chute channels across point bars has been described by Ashmore (1991) and is widely recognised as a process in the transition of a single-thread to a braided channel in gravel-bed rivers. It is interesting to note that it also appears to occur in this sand-bed river.) The node at b-c is very well defined next to the right bank, due to the orientation of the approach flow and growth of the large point bar in the left bank anabranch.

In 1978 flow remains dominantly down the left bank anabranch, and multiple meander bend cut-offs through chute channel enlargement have produced a strongly braided pattern. Creation of multiple channels and braid bars has resulted in widening of the left bank anabranch, mostly through erosion Island B. There is an indistinct node-island pattern in the left bank anabranch, with nodes spaced at about 8km and corresponding to former meander crossings in the sinuous channel of 1976. For example, the former crossing west of Bahadurabad has become a node in the left anabranch braid pattern, giving the channel an hour glass shape. The major node at b-c remains well defined and adjacent to the right bank, but the channel is beginning to widen to accommodate downstream migration of bar tails from the braided left bank anabranch.

In 1980 flow is still predominantly following the left bank anabranch, although the right bank anabranch is continuing its slow growth. The braided pattern established in 1978 has changed little and vegetation has colonised both Island B and the smaller braid bars in the left anabranch. The node west of Bahadurabad is still present. The channel at node b-c has continued to widen and the large point bar at the left bank is starting to be dissected by multiple chute channels.

In 1984 the trends apparent in 1980 have produced significant changes to the overall pattern. The left bank anabranch is still dominant, but the right bank anabranch is noticeably larger. The braided pattern of the left bank anabranch is still present, with the node west of Bahadurabad clearly defined. The major node b-c formerly at the right bank has widened enormously through enlargement of chute channels in the point bar opposite.

In 1987 the right bank anabranch has grown to rival the left bank anabranch in size. Island B is now more clearly defined and abandonment of some sub-channels in the shrinking left bank anabranch has led to enlargement of Island B by the incorporation of bars at the downstream end of the island. The node west of Bahadurabad is less well defined. The major node b-c is hardly recognisable due to

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downstream growth of the tail of Island B (which prevents the anabranches confluencing) and intense braiding in both the left and right bank anabranches on either side of the island.

In 1990 the left and right bank anabranches are of approximately equal size. Both display low sinuosity, transition patterns, with elements of both braiding and meandering. However, the direction of change is opposite in the two anabranches. The right bank anabranch is gaining stream power and, as a result, is changing from a single-thread to a multi-thread channel. The left bank anabranch is losing stream power and is in transition from a braided to a meandering pattern. The node near Bahadurabad has shifted downstream and is well defined. It represents the narrow point in the hour glass shape of the left anabranch, separating wide meander/braid bar embayments immediately upstream and downstream. Intense braiding in both anabranches continues at node b-c where the width is only 20% less than at the widest point of the reach containing Island B.

In 1992 the anabranches are still in transitionary patterns between meandering and braiding. The left and right bank anabranch meander wavelengths are about 12 and 16 km, respectively, that is similar to the wavelengths in 1973. In the left anabranch, the node southwest of Bahadurabad is in the process of reverting to a meander crossing, as it was in 1973. The meander just upstream is west bank concave (again as it was in 1973), with a symmetrical embayment in the left bank opposite. In fact the configuration of the left bank anabranch is not dissimilar to that in 1973/6, except that the overall orientation of the channel has veered from northeast-southwest to north-south. The channel at the b-c node is narrowing due to abandonment of outer braid channels as symmetry of anabranch bends generates convergence at the downstream tail of Island B.

In 1994 both anabranches have predominantly meandering patterns, but with multiple chute channels across point bars that offer abundant opportunities for braiding. In the left anabranch the crossing southwest of Bahadurabad is present but a major chute cut-off of the bend upstream has occurred. This results in a re-orientation of the flow through the crossing/node as it approaches the study site. It is interesting to compare the left bank anabranch pattern in 1994 to that in 1984 and 1987: the configuration around Bahadurabad and the study site shows similarities. The major b-c node is still poorly defined due to outlying sub-channels, although convergence of the left and right anabranches in almost symmetrical meanders is starting to re-establish a narrow point.

3.3 Summary of significant historical developments around the study site

The 20 year history of channel evolution in the reaches containing Island B and Node b-c has important implications for the interpretation of measurements made in this study. Some of the most significant points are:

- Division of the flow between the left and right anabranches is variable. When flow is predominantly in one anabranch that channel braids and the lesser channel meanders. When it is equally divided both channels have channels in the braided/meandering transition.

- In the 1970s the left bank anabranch evolved from predominantly meandering to braided because it carried the majority of the flow in the Jamuna. In the 1980s the left channel flow diminished and the channel reverted to a meandering form with wide point bars and multiple chutes.

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- The present pattern of the left anabranch around the study site displays an hour glass shape, with wide embayments separated by a relatively narrow neck (or node) southwest of Bahadurabad. The historical narrative given here shows that this is a very persistent morphology. It has formed due to widening of the channel upstream and downstream of the node due to bank erosion around growing braid bars and at the outer banks of meander bends. Throughout the 20 years of record the flow in the left bank anabranch has crossed at the node on a heading between southeast and southwest.

- The study site can be identified on the 1994 image as part of a heavily dissected point bar (evident in 1992) in the left anabranch. The point bar is crossed by multiple chute channels, one of which constitutes the right channel in the study area separating the study bar from the rest of the point bar.

- The major chute cut-off of the meander upstream of the Bahadurabad node between 1992 and 1994 resulted in a realignment of flow at the node from southeast to almost due south. This has major implications for the study site because it promotes dissection of the point bar at the study site by enlargement of chute channels.

- Viewed in this historical context, it is understandable that the left channel at the study bar should grow while the right channel should diminish. There is in fact a historical precedent for this pattern of change. In the images for 1976 and 1978 it can be seen that re-alignment of the flow at the crossing west of Bahadurabad from southeast (1976) to southwest (1978) leads to dissection of the point bar between the yellow crosses and rapid growth of chute channels.

- It must be concluded that the key to understanding morphological change at the study site lies in identifying changes of flow orientation at the node/crossing upstream.

- Flow orientation at the node/crossing depends meander/braid bar growth and periodic chute cut-offs in the embayment upstream. These changes are, in turn, driven by cyclical planform evolution in the left anabranch coupled with channel changes due to switching of dominance in carrying flow in the Jamuna between the left and right anabranches.

- Morphological development at the study site is driven by changes at much larger space and time-scales. There is some order and periodicity to these changes and the resulting morphological developments may be described qualitatively and explained retrospectively. However, in detail changes are strongly stochastic so that they cannot at present be modelled numerically or predicted accurately.

Figure 3.1 (a) Satellite images for the study reach in 1973, Scale 1:120 000, images supplied by FAP 19.

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Figure 3.1 (b) Satellite images for the study reach in 1976, Scale 1:120 000, images supplied by FAP 19.

Figure 3.1 (c) Satellite images for the study reach in 1978, Scale 1:120 000, images supplied by FAP 19.

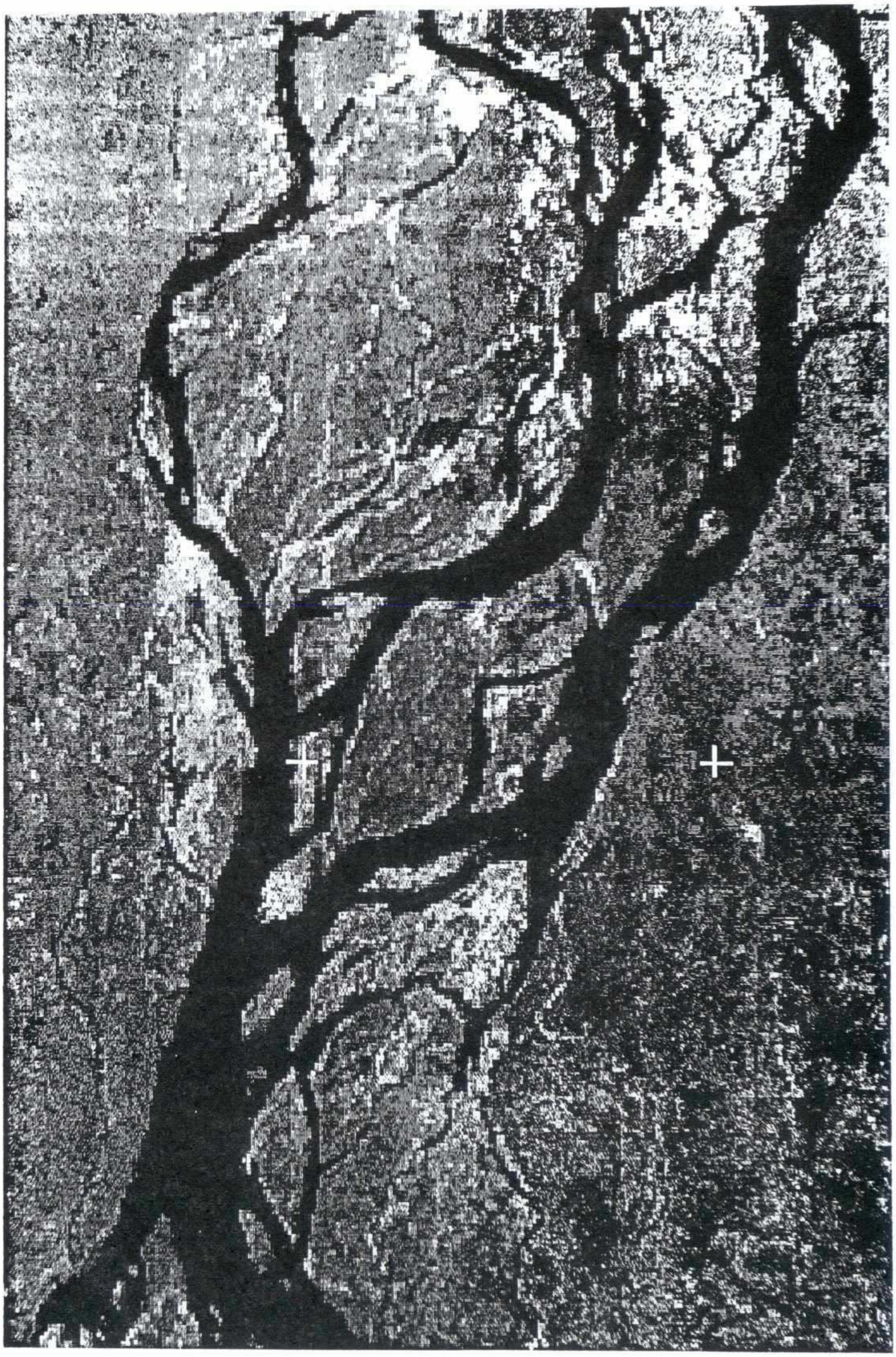

Figure 3.1 (d) Satellite images for the study reach in 1980, Scale 1:120 000, images supplied by FAP 19.

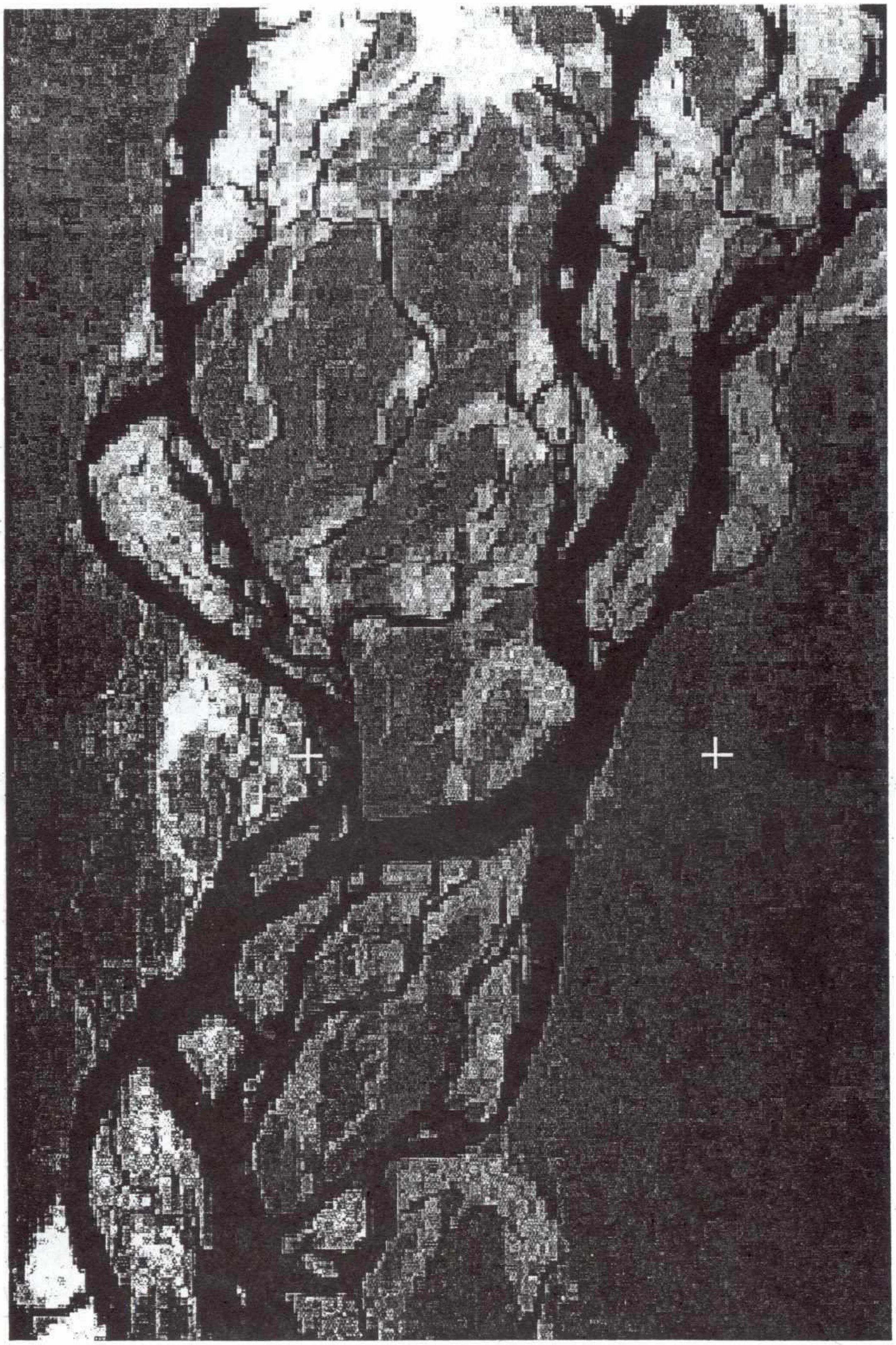

Figure 3.1 (e) Satellite images for the study reach in 1984, Scale 1:120 000, images supplied by FAP 19.

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Figure 3.1 (f) Satellite images for the study reach in 1987, Scale 1:120 000, images supplied by FAP 19.

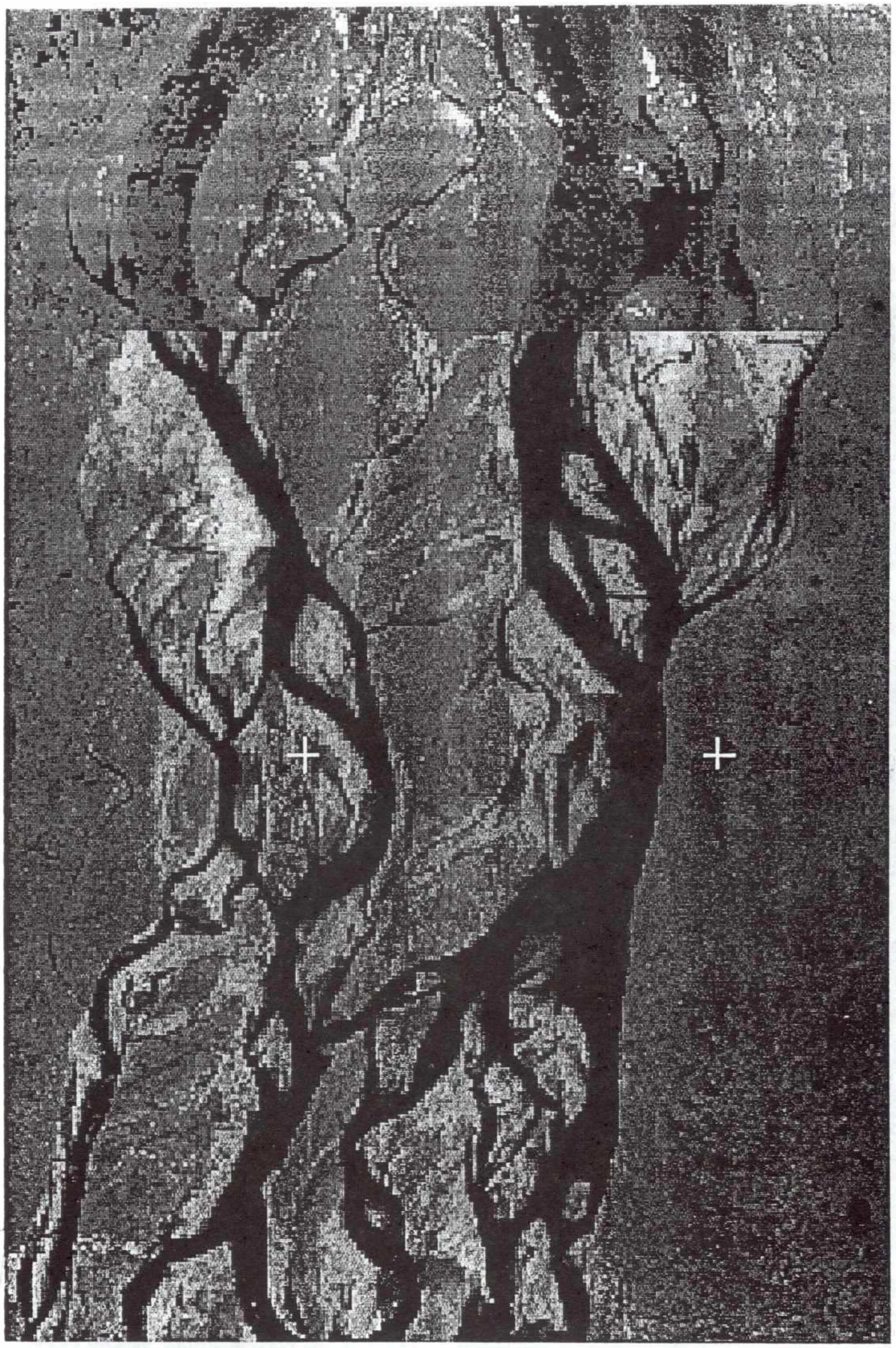

Figure 3.1 (g) Satellite images for the study reach in 1990, Scale 1:120 000, images supplied by FAP 19.

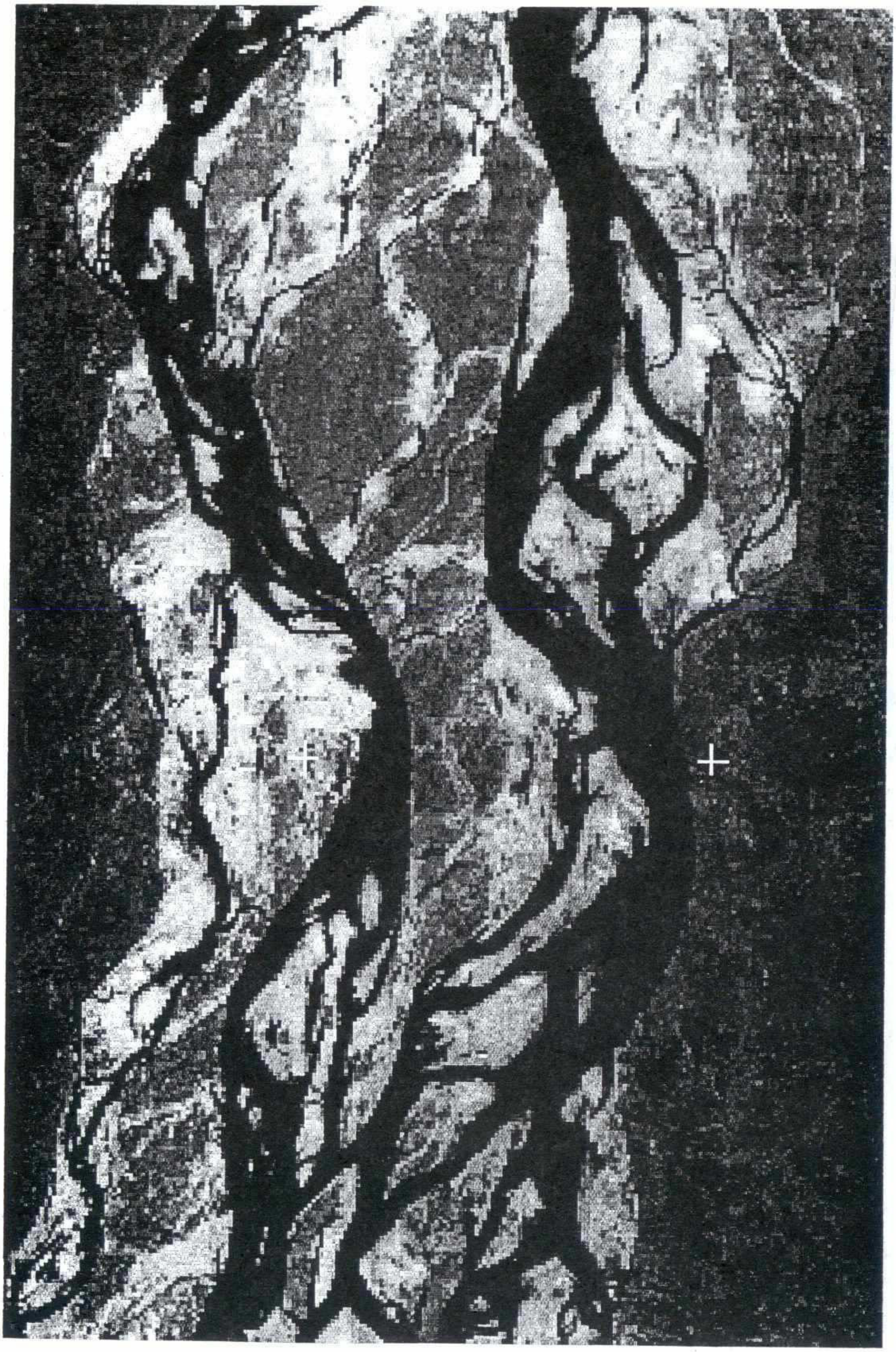

Figure 3.1 (h) Satellite images for the study reach in 1992, Scale 1:120 000, images supplied by FAP 19.

Figure 3.1 (i) Satellite images for the study reach in 1994, Scale 1:120 000, images supplied by FAP 19.

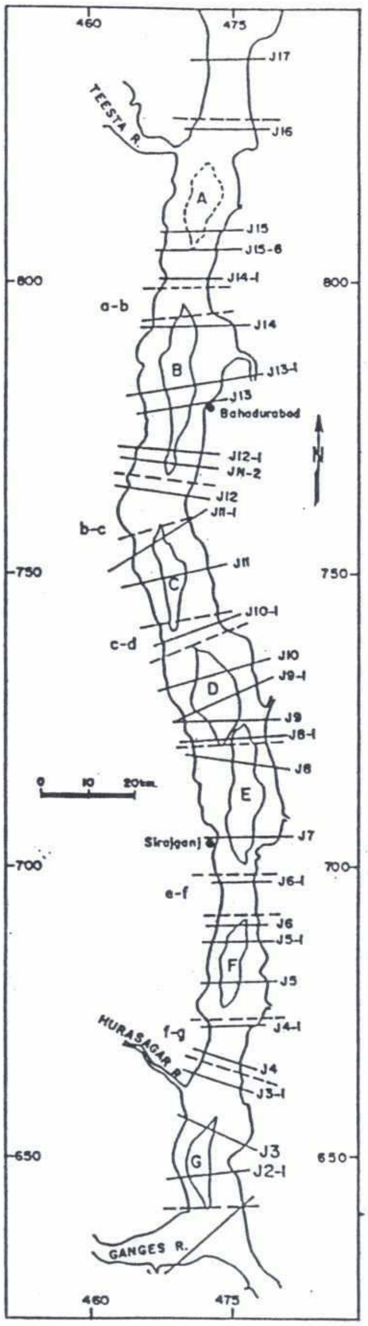

Figure 3.2: Locations of islands and nodes in the braided pattern of the Brahmaputra (Jamuna) River (from Thorne et al., 1993). The study reach shown in Fig. 3.1 extends from the upstream tip of Island B through node b-c to the upstream tip of Island C. The study site is in the left bank anabranch just south of Bahadurabad.

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4 Patterns of primary velocity, secondary velocity, backscatter intensity and cross-sectional change

4.1 Survey Summary

The following table summaries the transect lines survey on each survey date. Due to draft of the DHA vessel causing navigational problems, not all of the transect lines were surveyed on each date.

	Survey dates		
Transect number	May	August	September
01	X	X	√
02	√	√	√
03	√	√	√
04	√	√	√
05	√	√	√
06	√	√	√
07	√	√	√
08	√	√	√
09	√	√	√
10	X	√	√
11	X	X	√
12	X	√	√
13	X	√	√
14	X	√	X
15	X	√	√
16	X	√	X

Table 4.1: Survey summary

4.2 Primary and secondary velocity, and backscatter intensity plots

The plots of primary velocity, secondary velocity and backscatter intensity shown in Figure 4.1 are organised in order of transect line number. Each transect line has, depending on the survey summary above, a plot of results from (a) May, (b) August and (c) September.

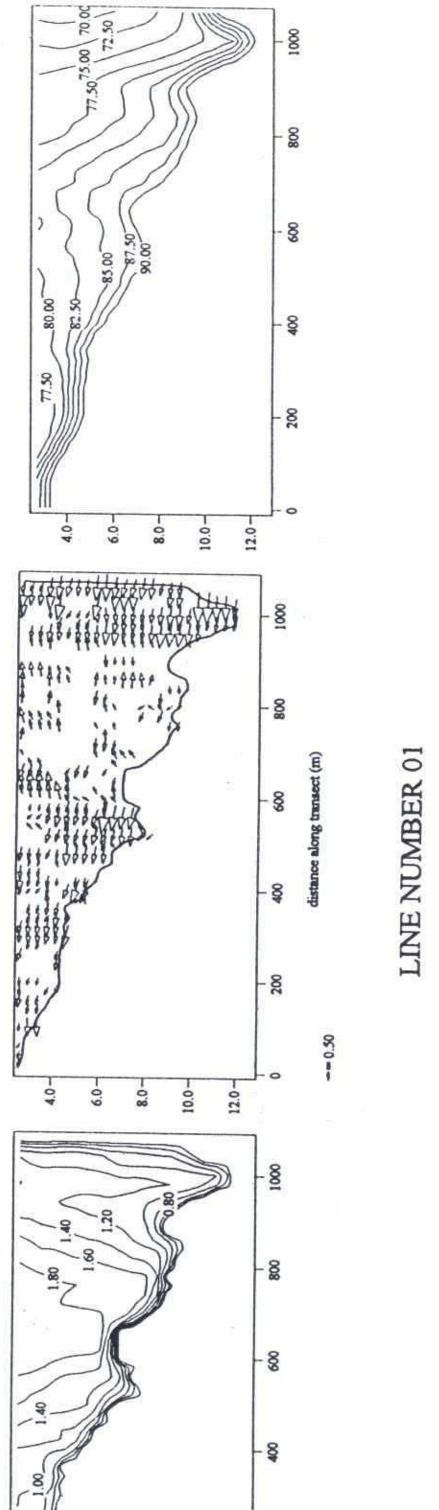

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 01).

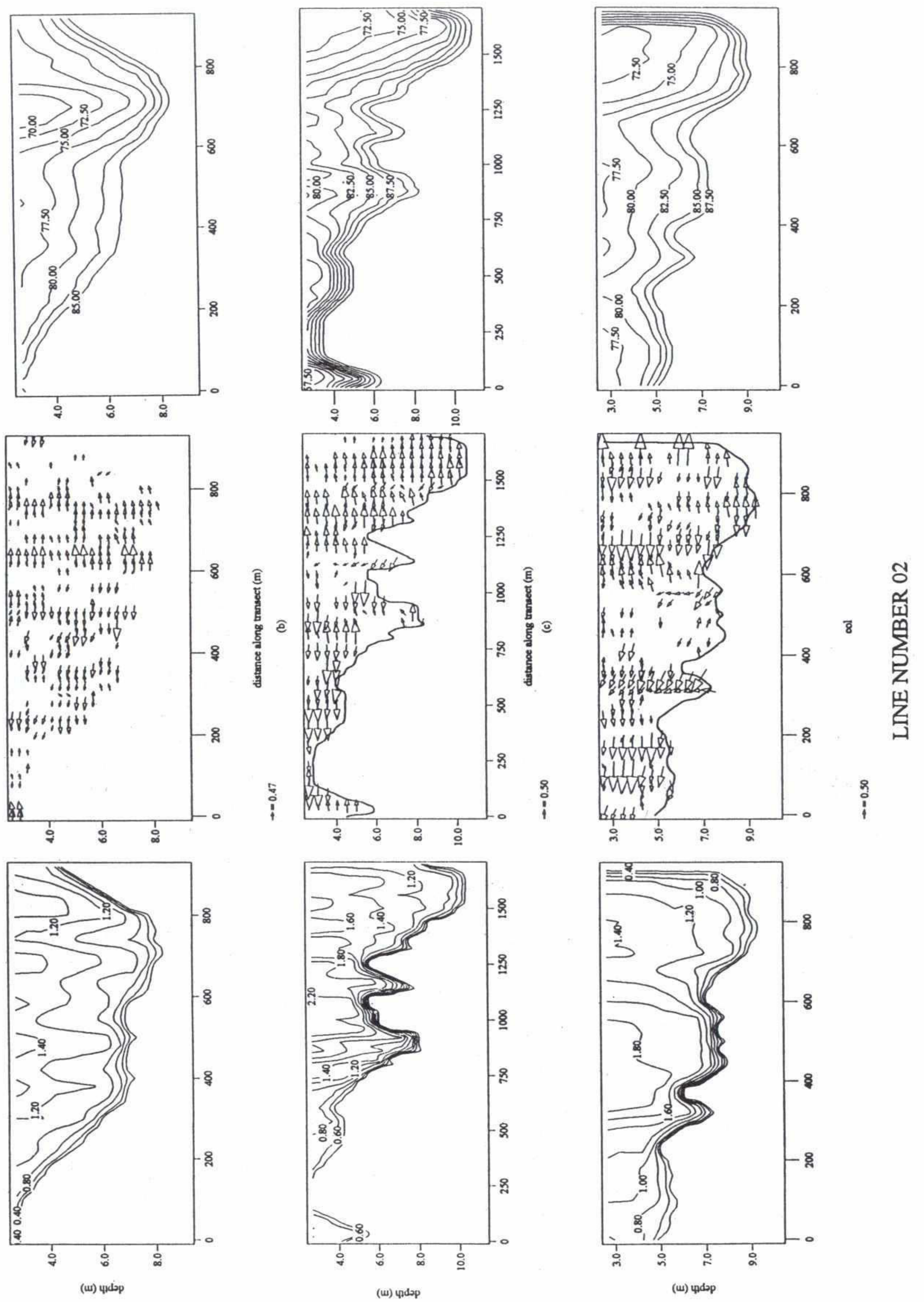

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 02).

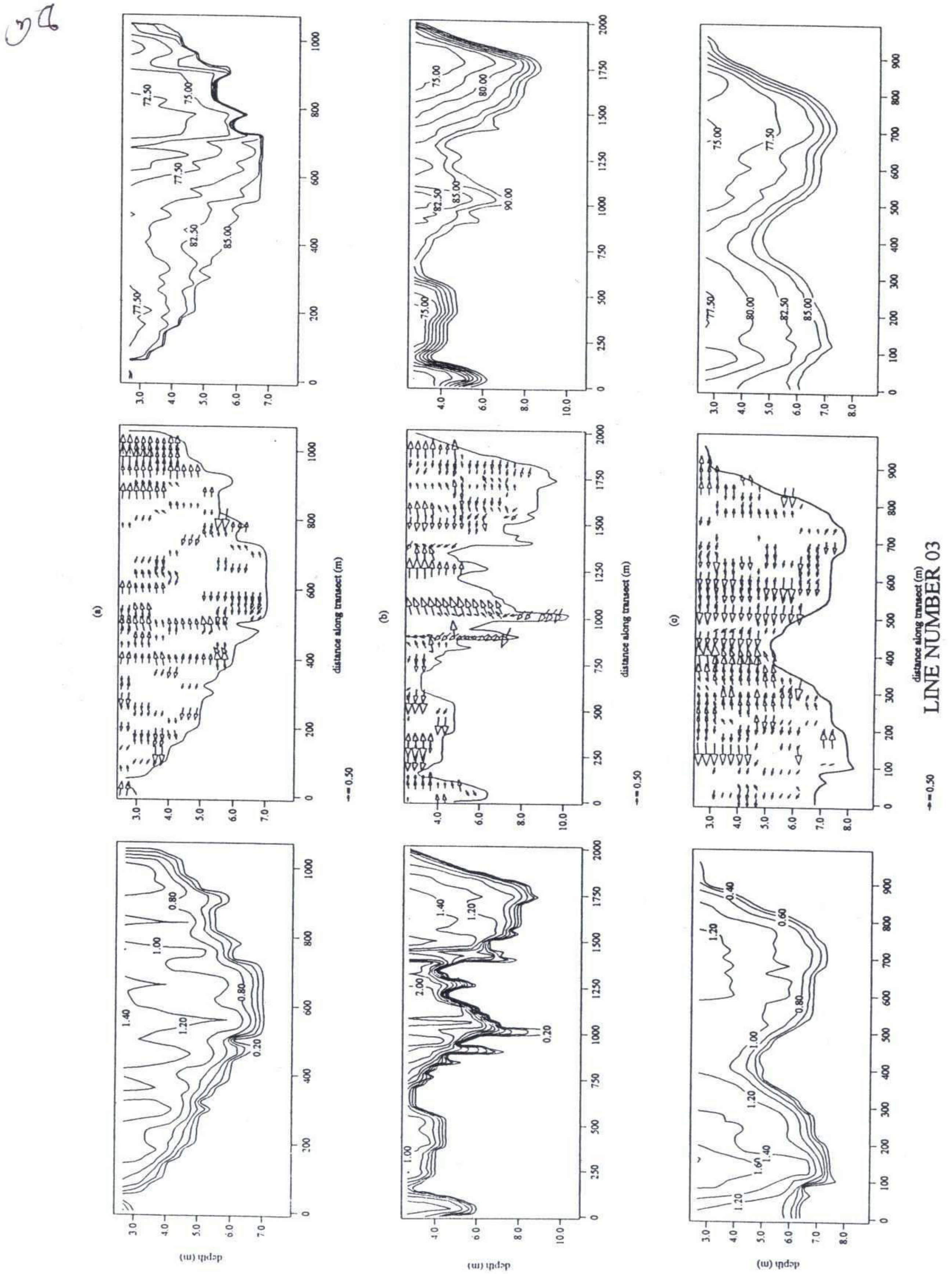

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 03).

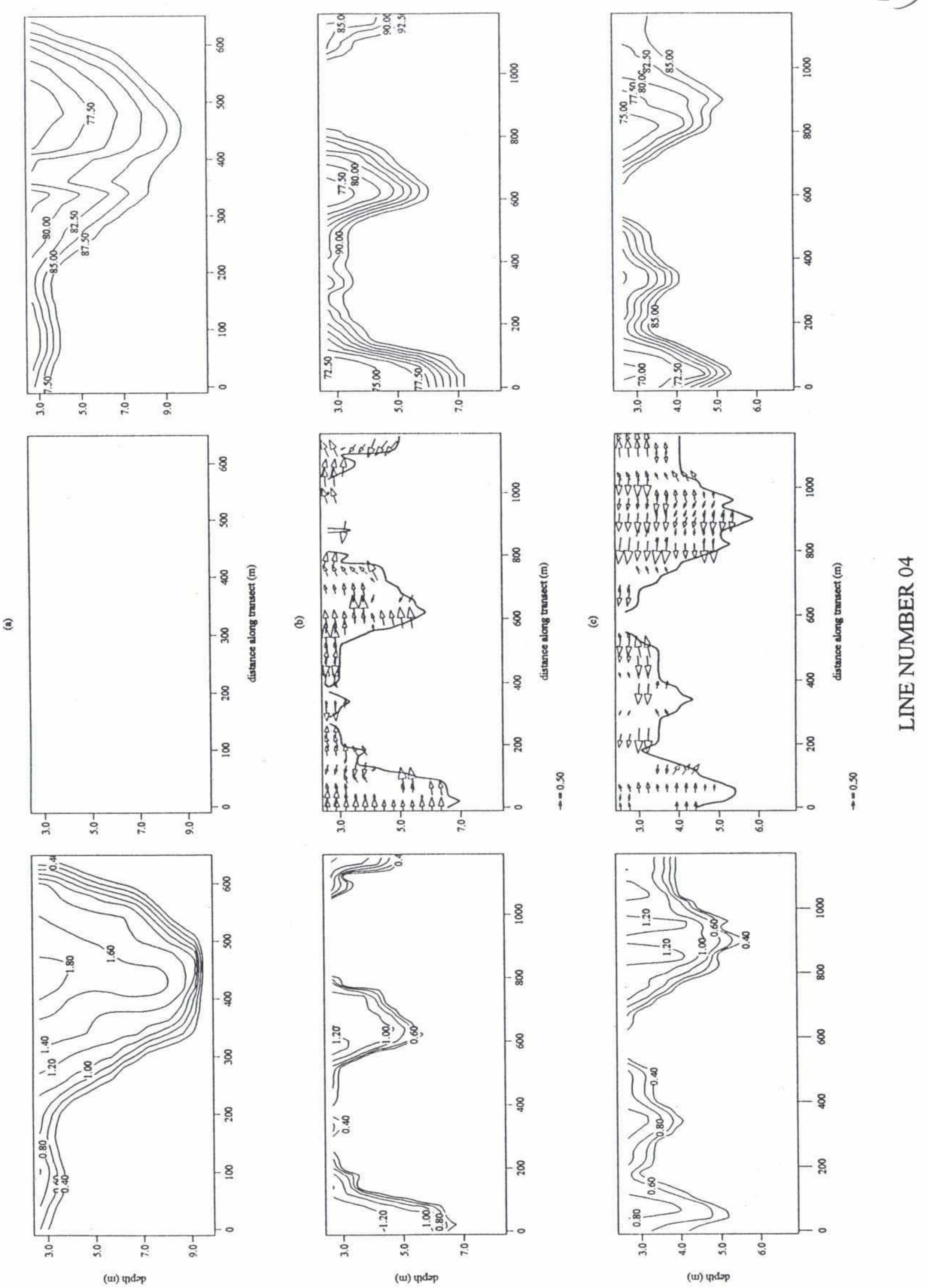

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 04).

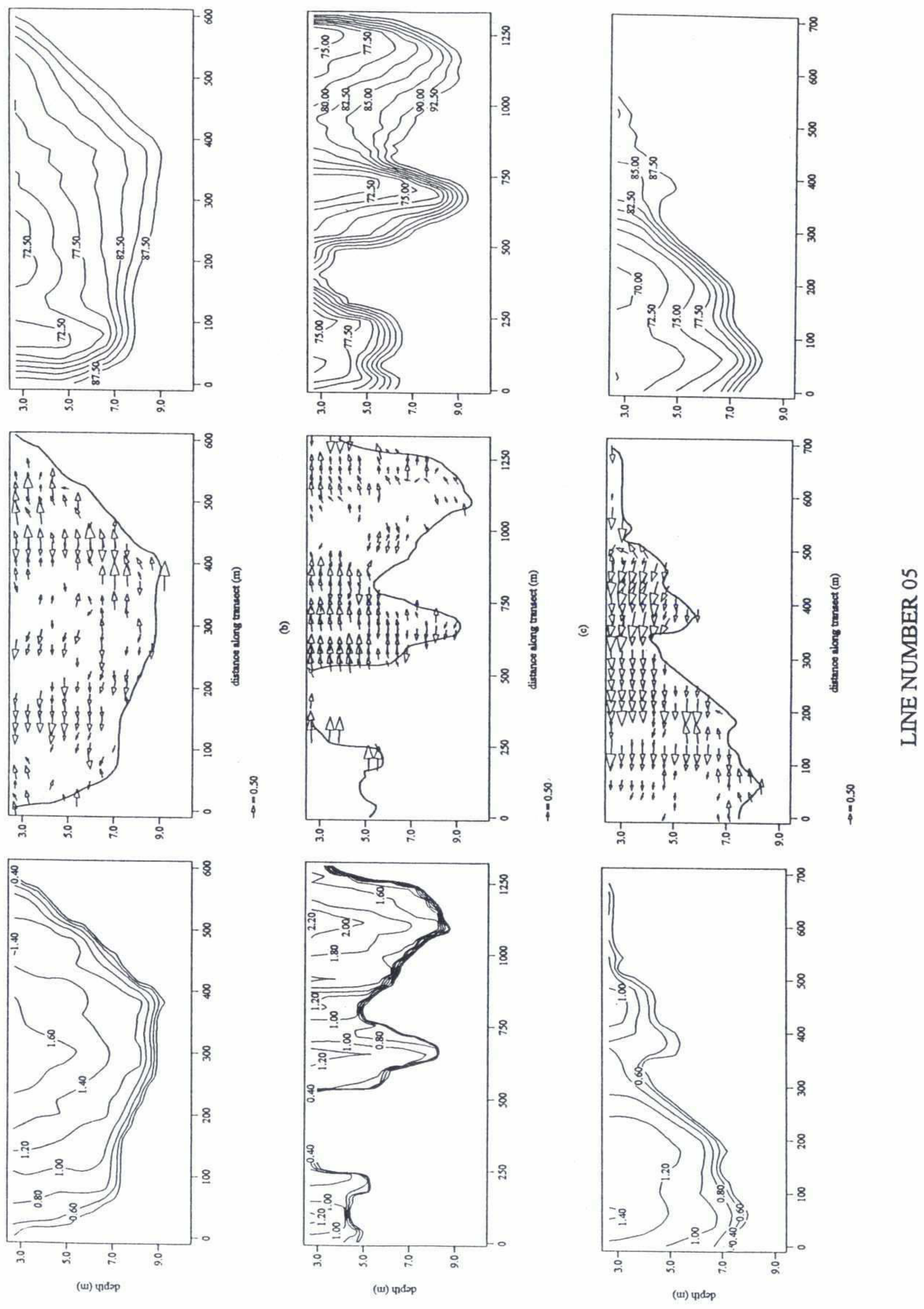

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 05).

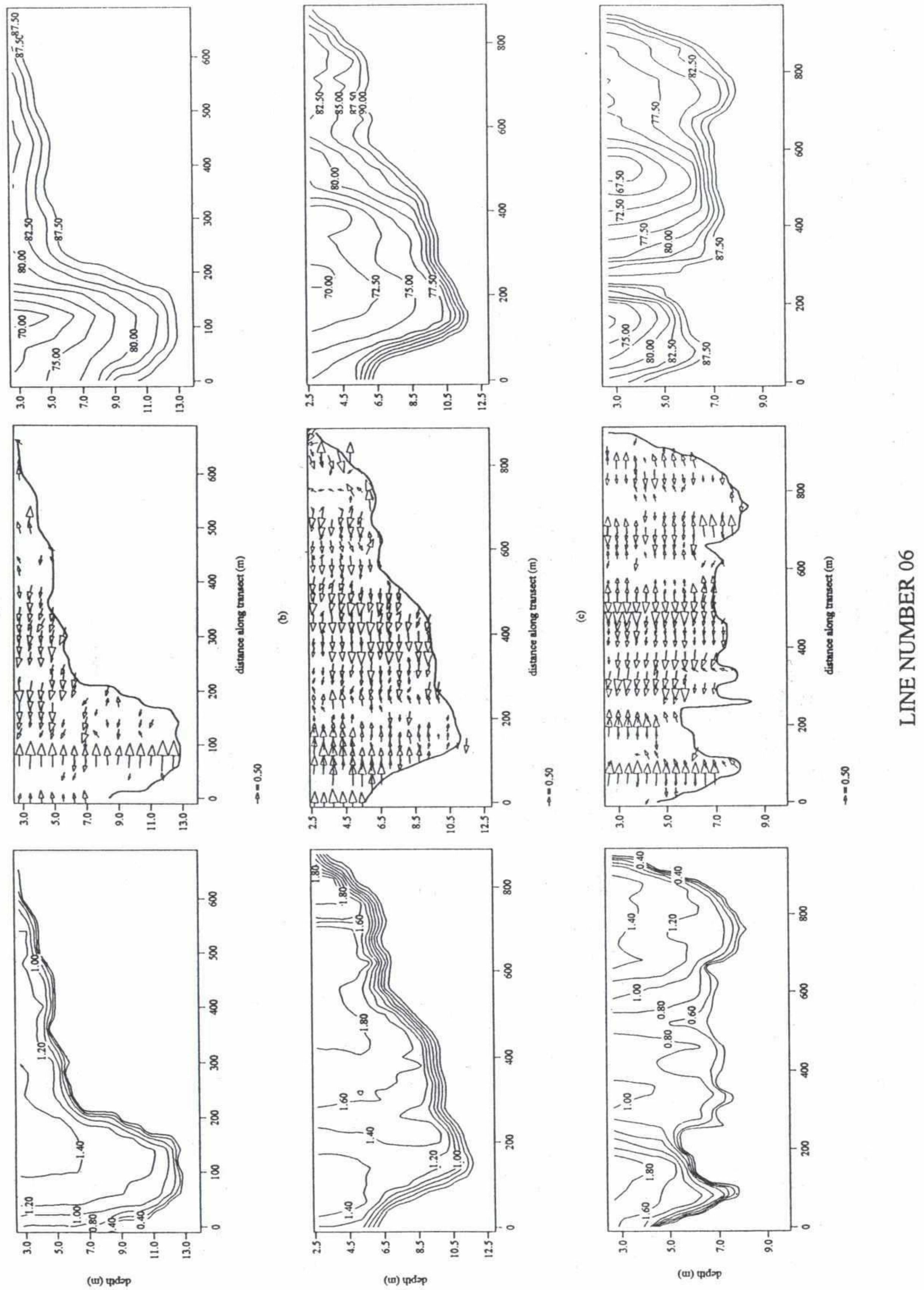

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 06).

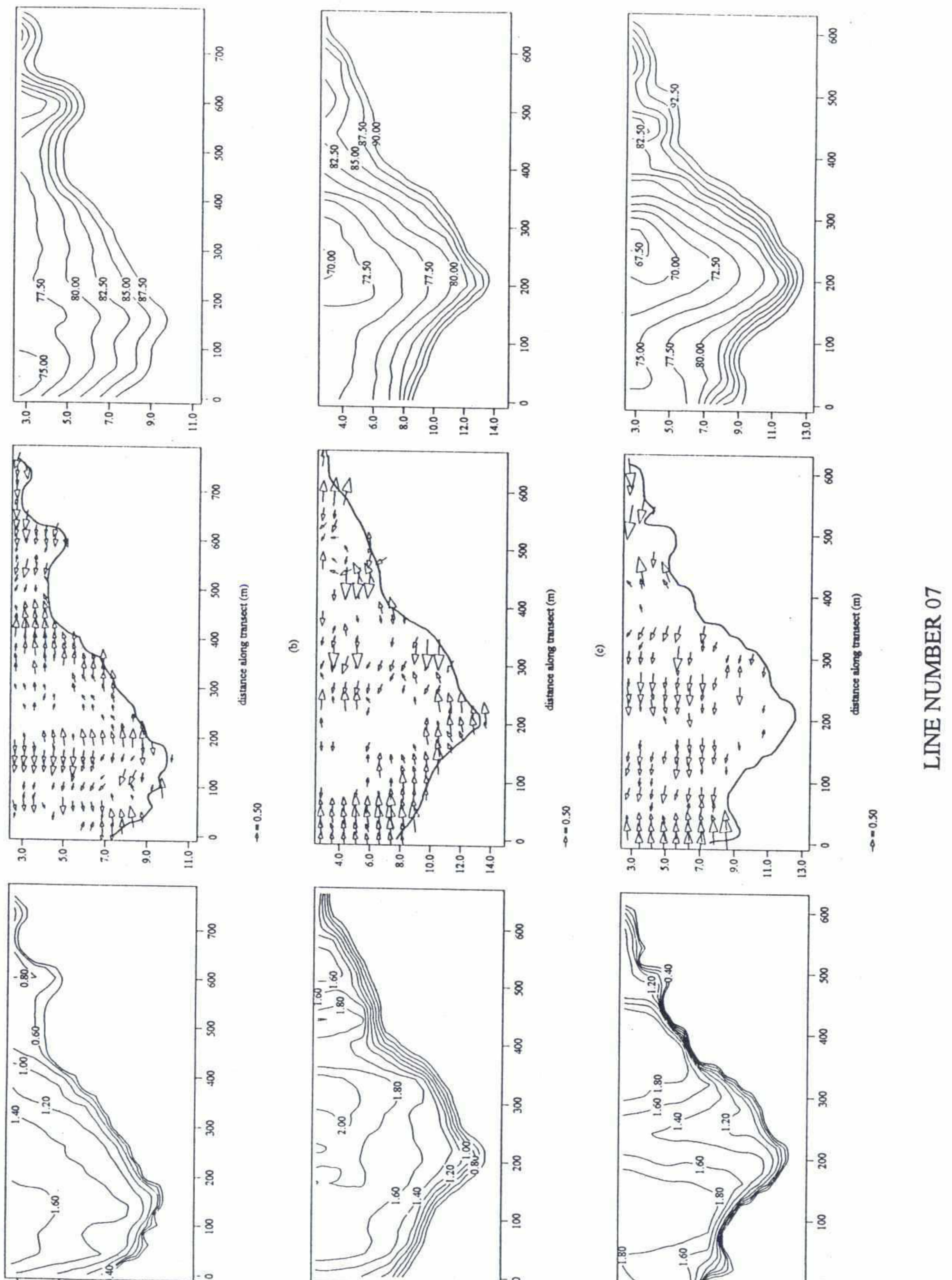

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 07).

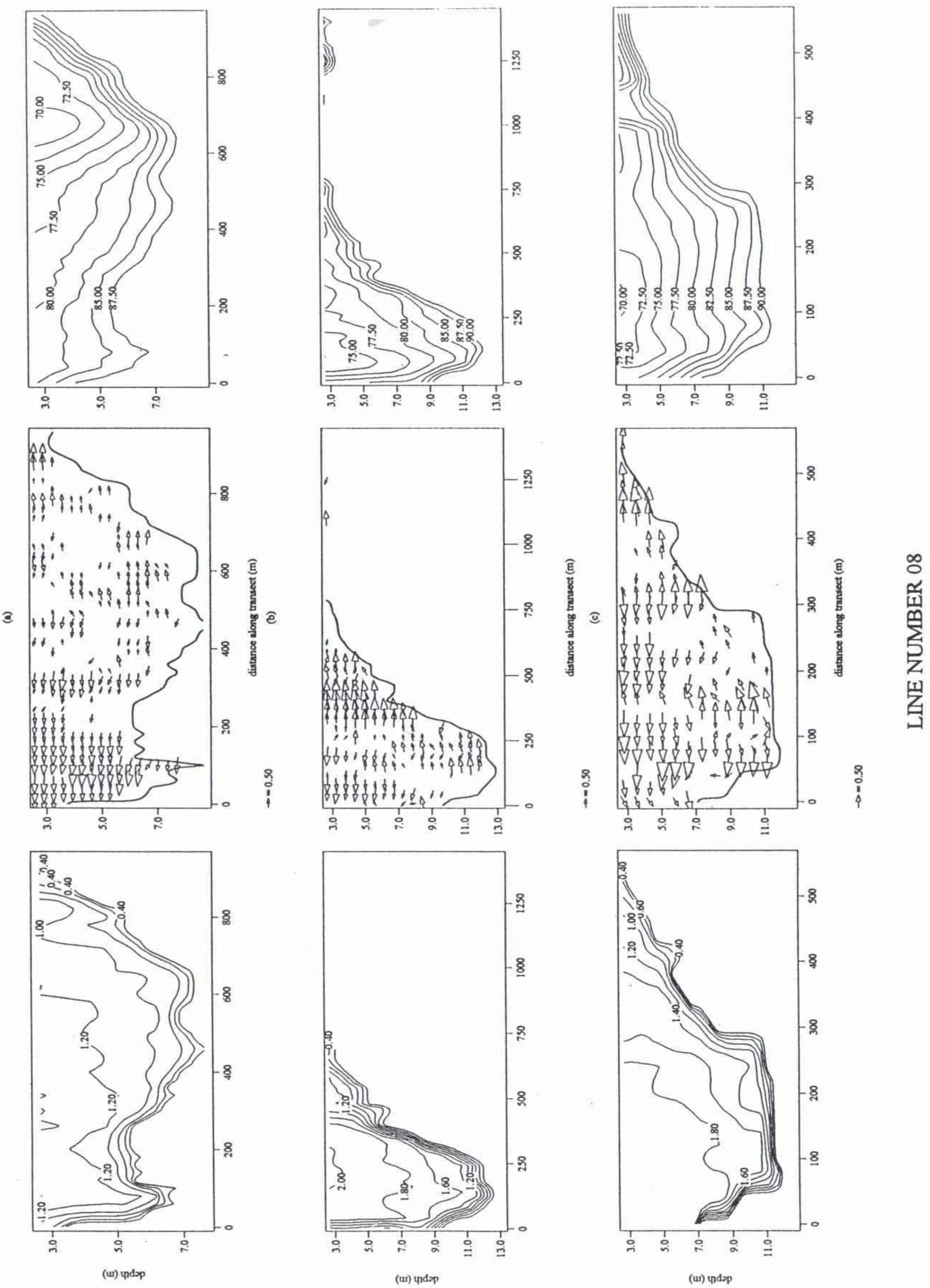

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 08).

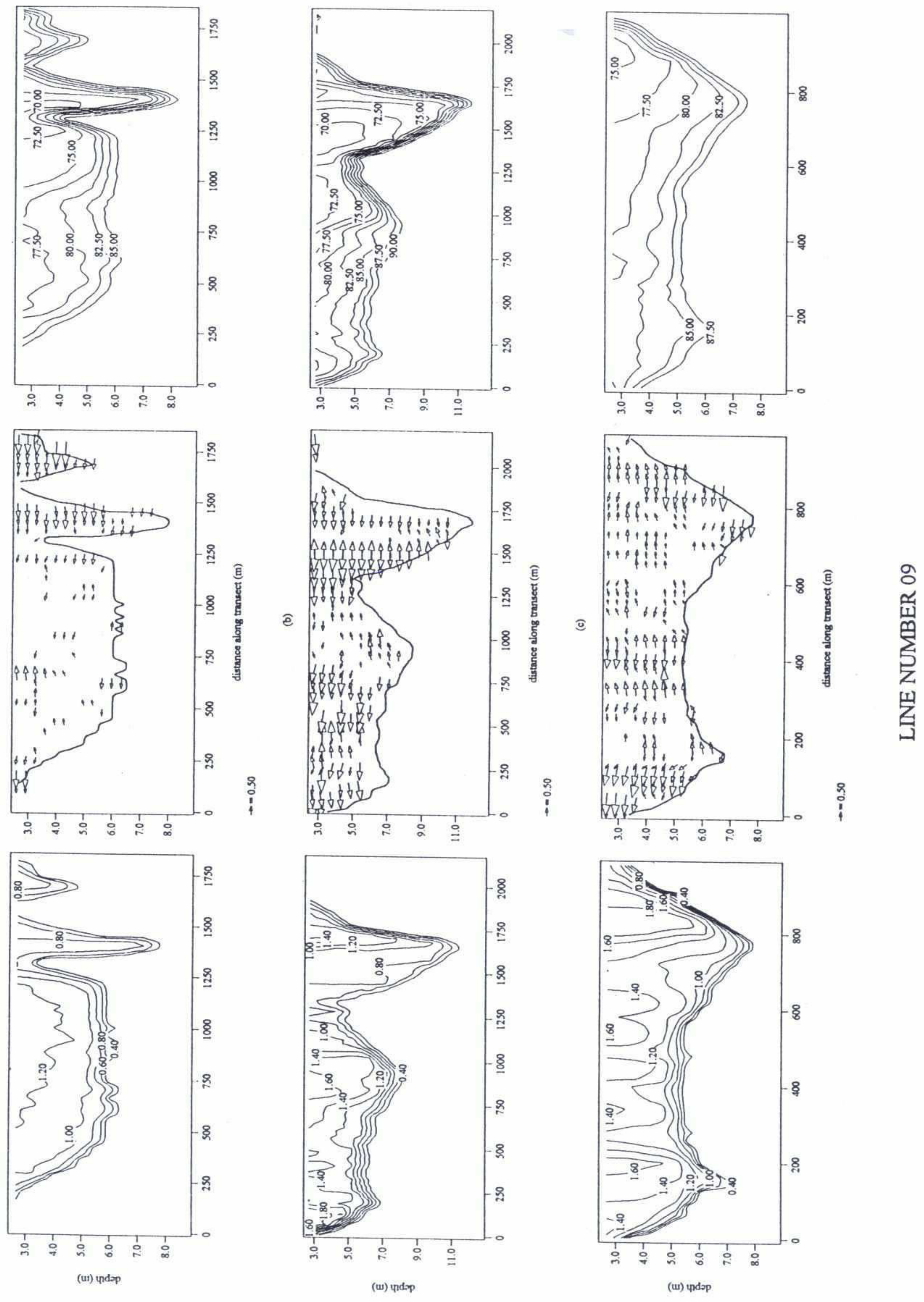

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 09).

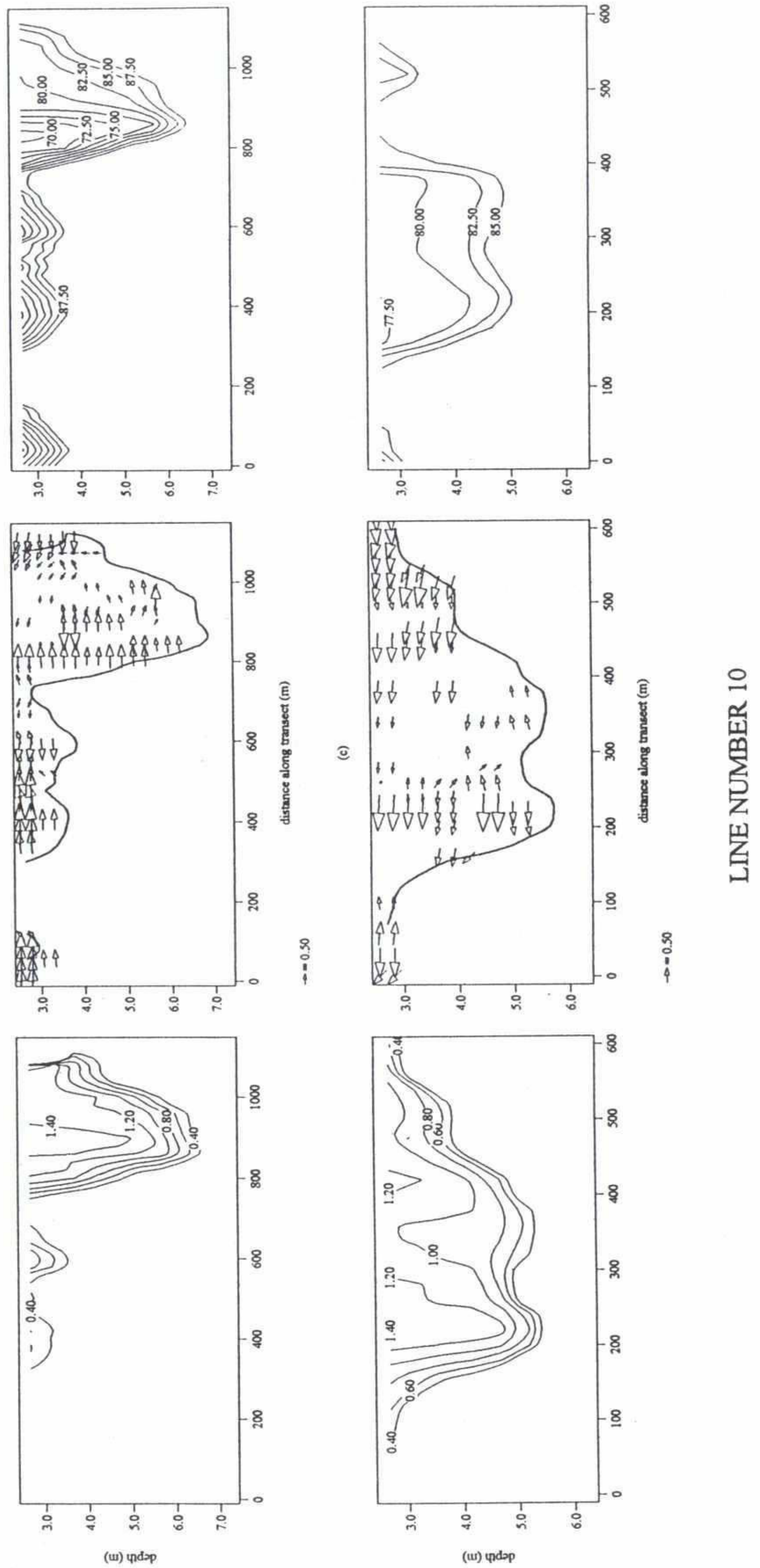

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 10).

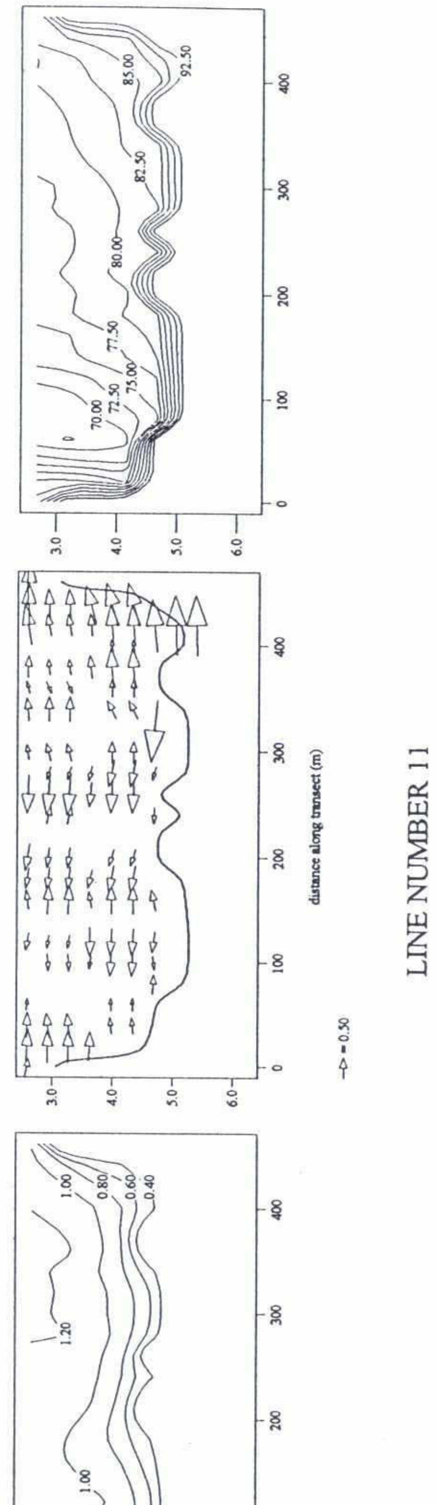

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 11).

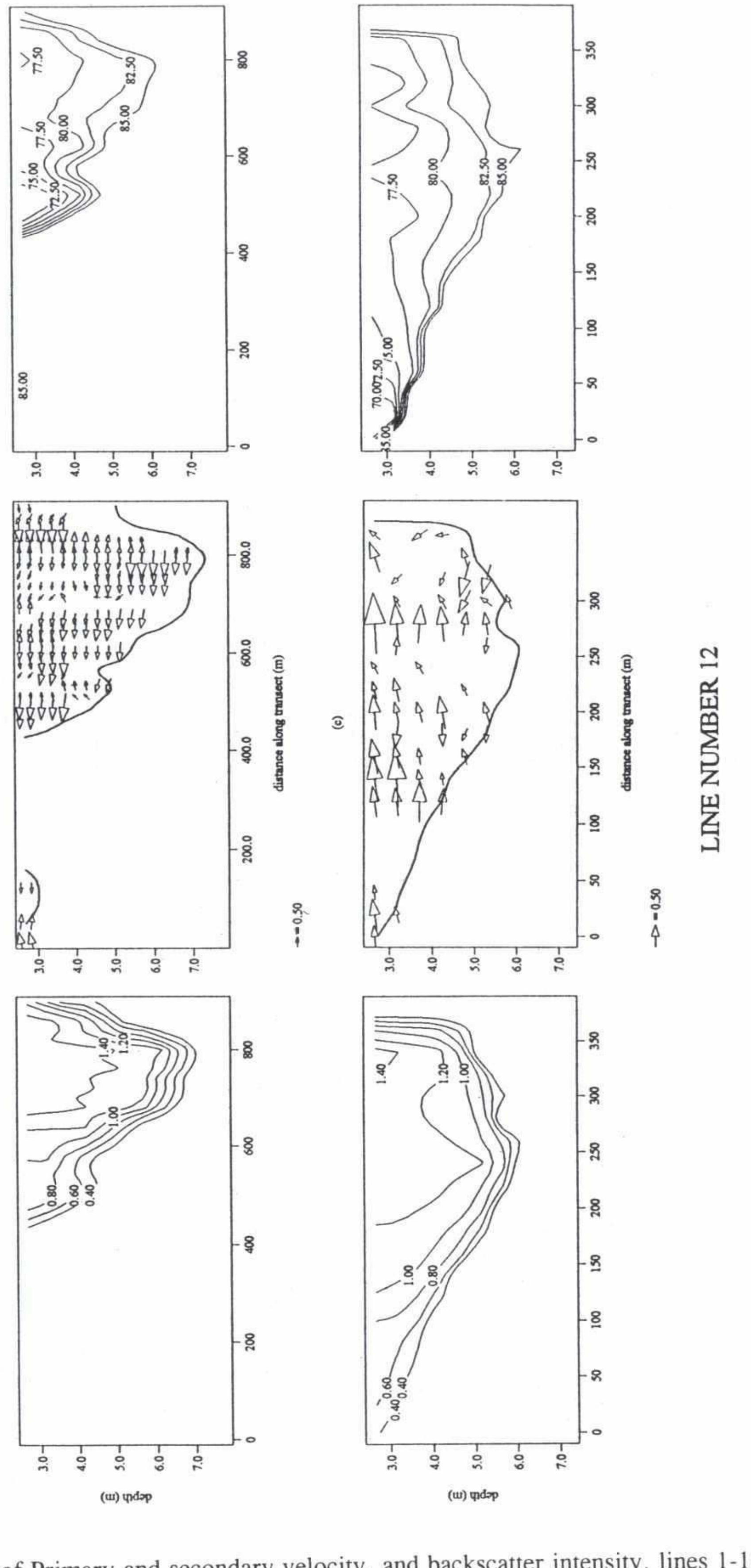

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 12).

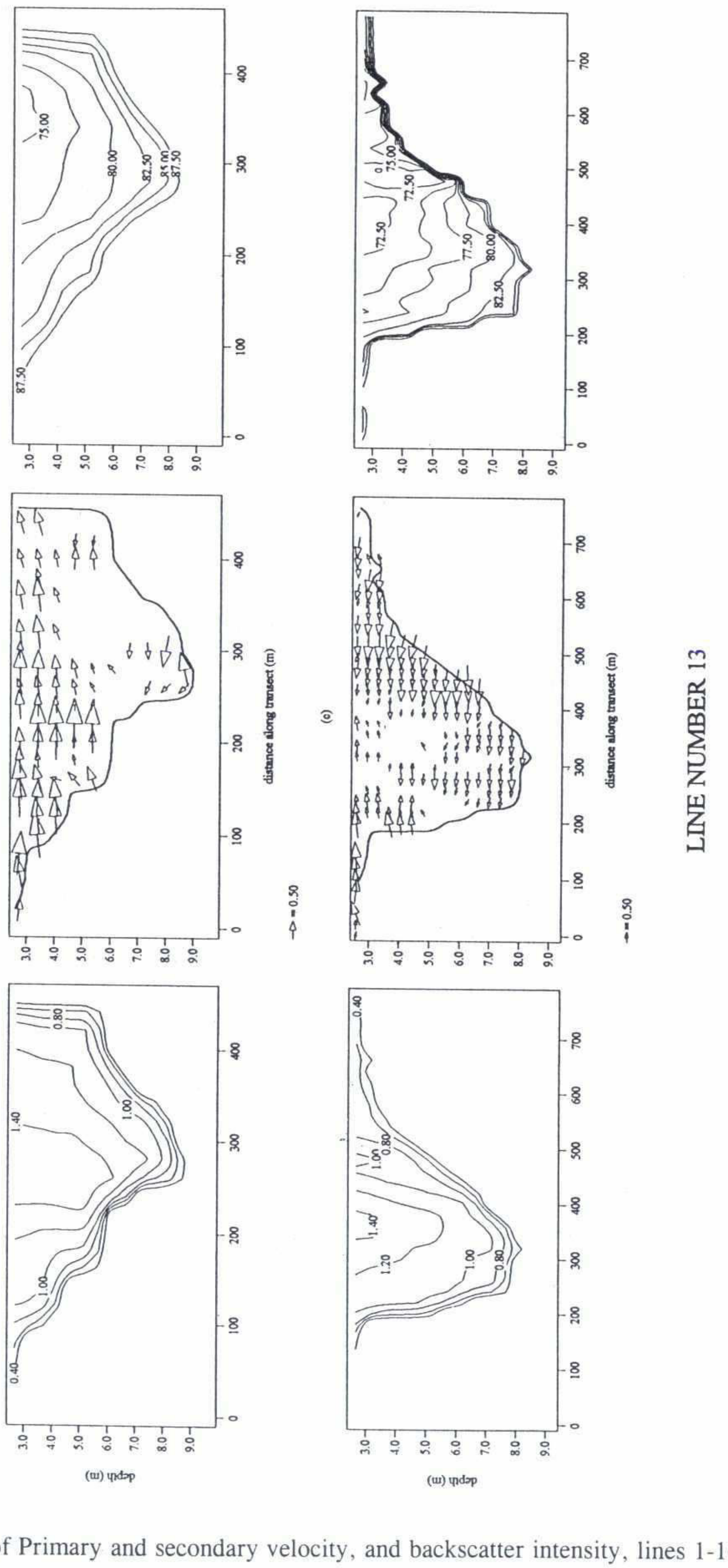

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 13).

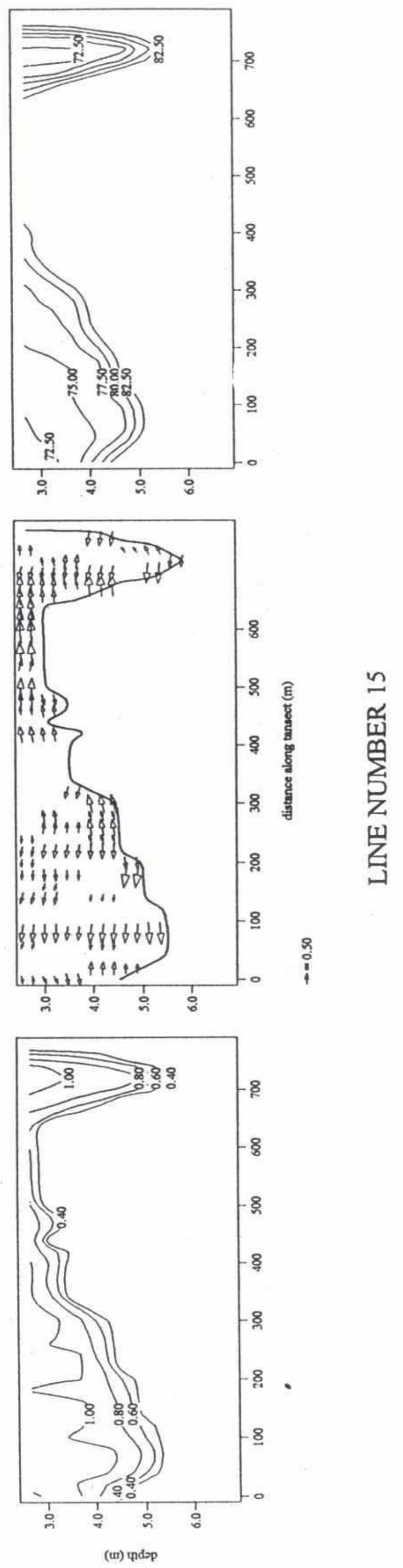

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 15).

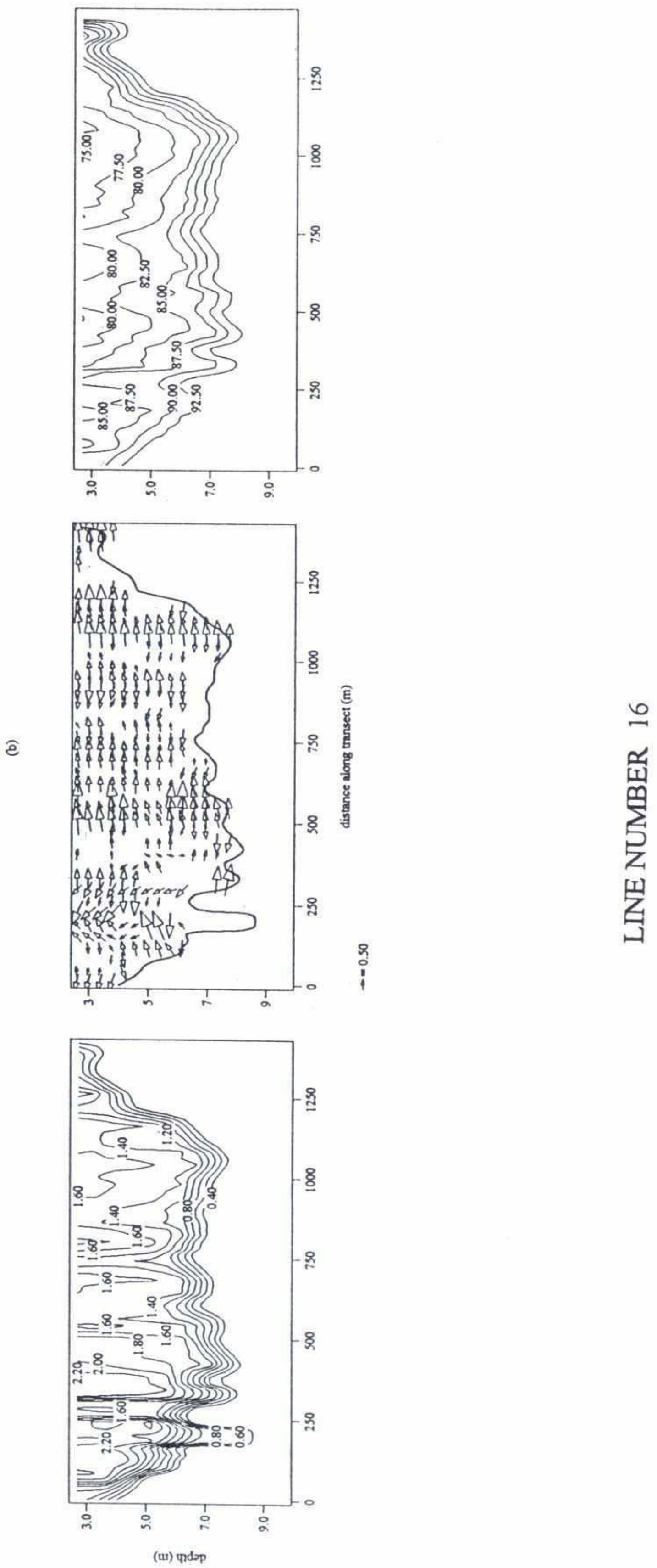

Figure 4.1: Plots of Primary and secondary velocity, and backscatter intensity, lines 1-16, May to September (Line number 16).

Figure 4.2: Bed level change plots, lines 2-13, (a) May to August, (b) August to September and (c) May to September.

Key:

Deposition

Erosion

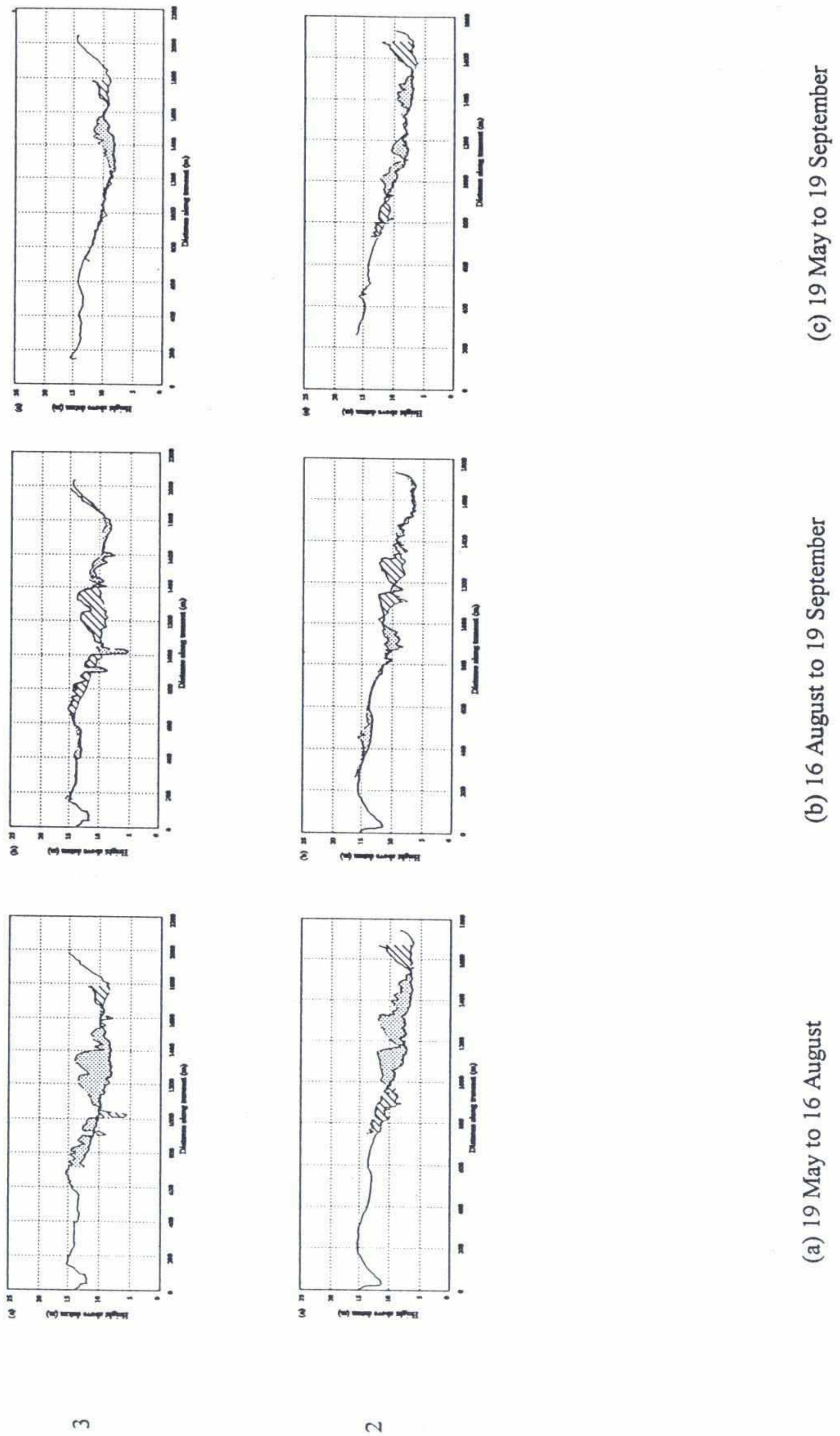

Figure 4.2: Bed level change plots, lines 2-13, (a) May to August, (b) August to September and (c) May to September.

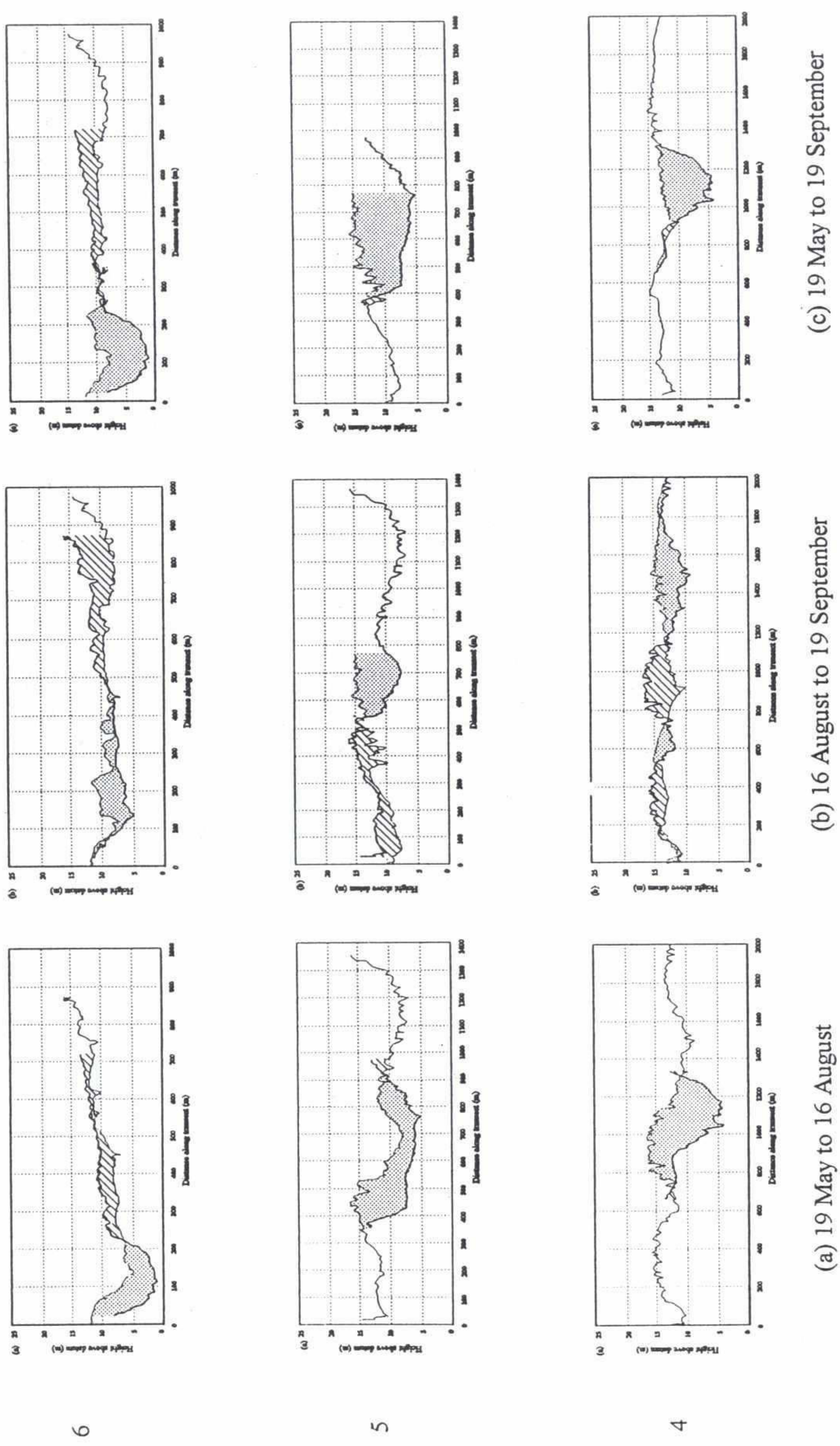

Figure 4.2: Bed level change plots, lines 2-13, (a) May to August, (b) August to September and (c) May to September.

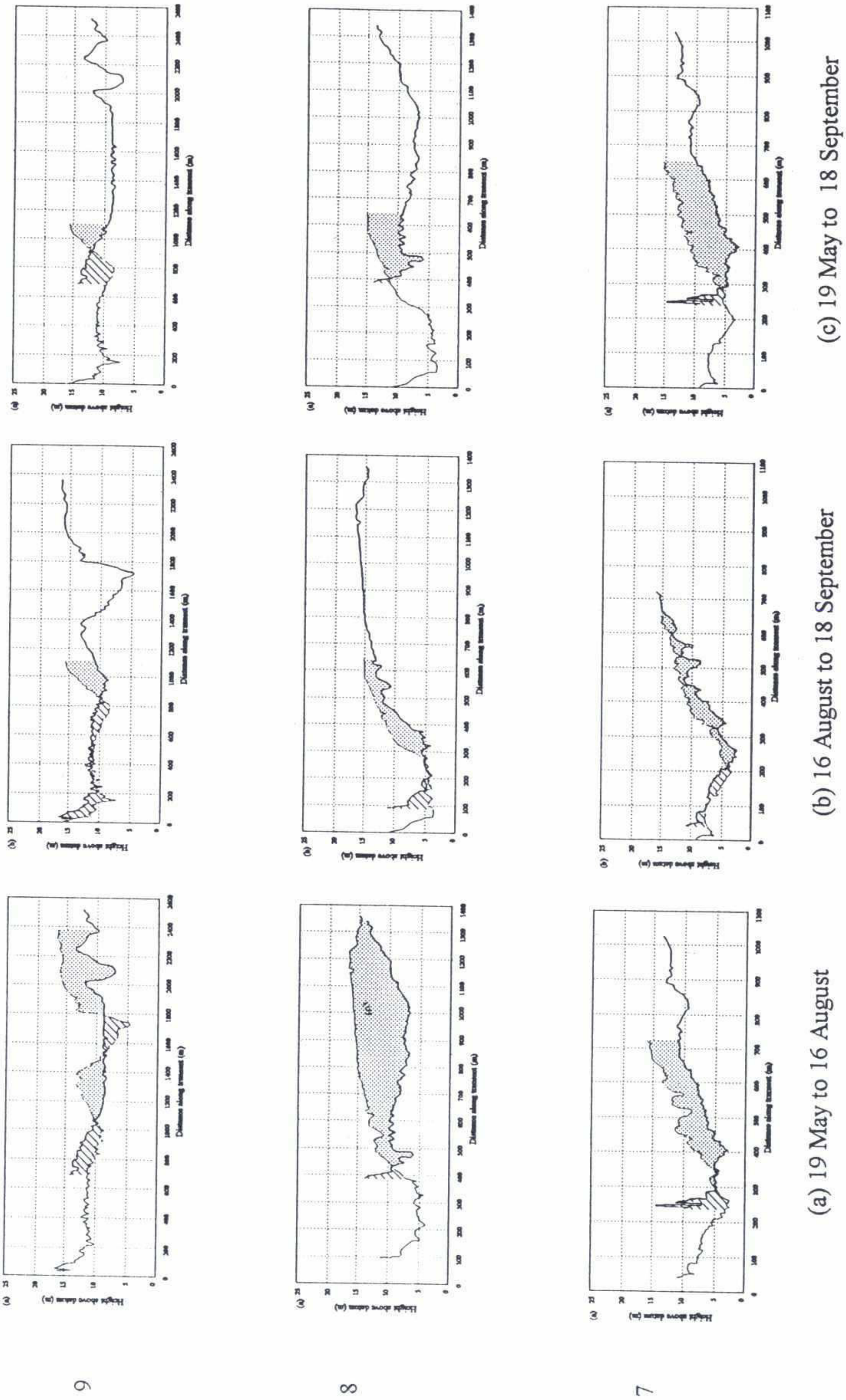

Figure 4.2: Bed level change plots, lines 2-13, (a) May to August, (b) August to September and (c) May to September.

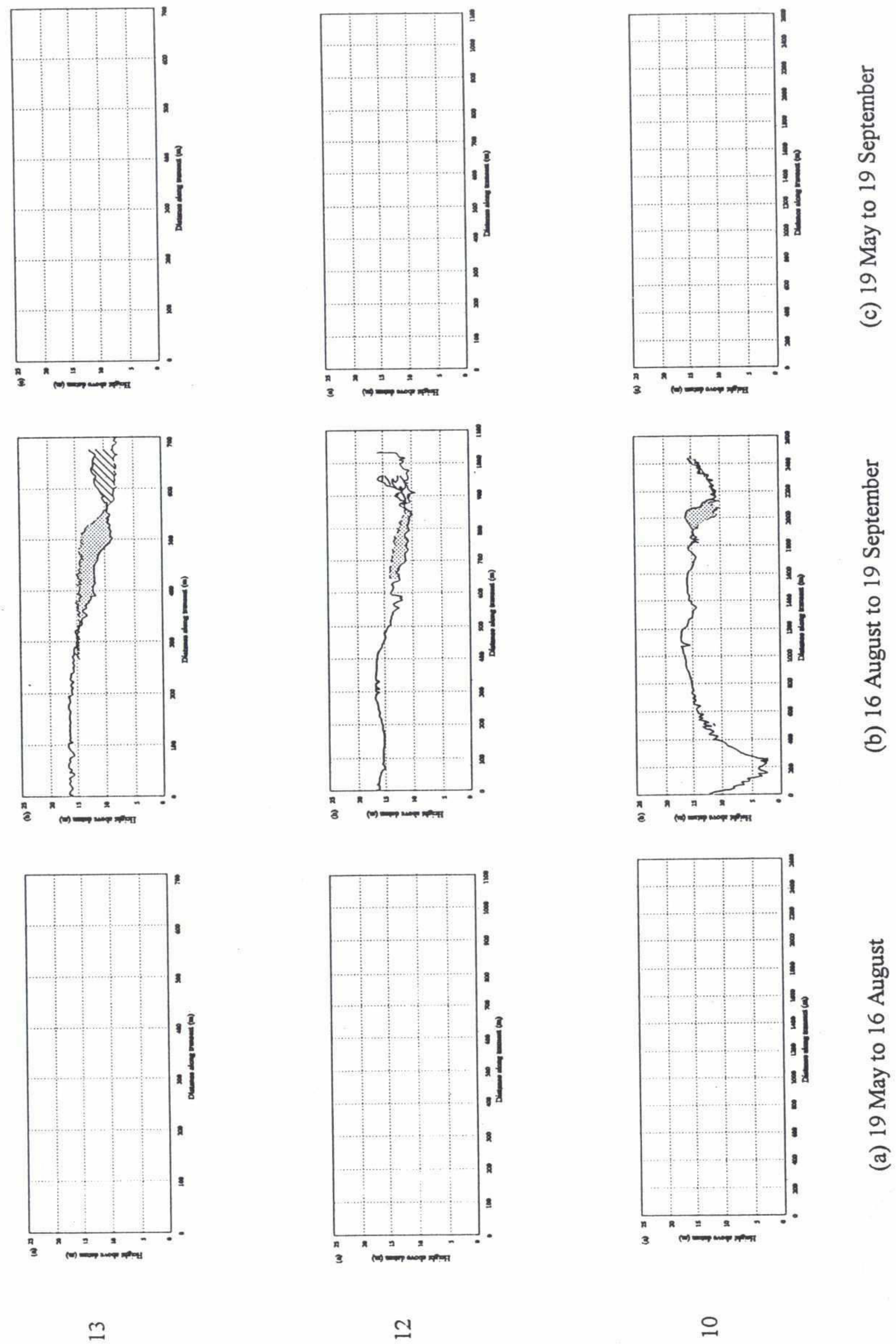

Figure 4.2: Bed level change plots, lines 2-13, (a) May to August, (b) August to September and (c) May to September.

5 Distribution of scour and fill during 1993-1994

5.1 Bathymetry maps for 1993-94

Detailed mapping of bathymetry throughout the study reach was performed as part of FAP-24 studies in November 1993 and November 1994 and the results were made available to the joint study (Figs. 5.1 and 5.2).

5.2 Bathymetric change map and distributions for 1993-94

Data supplied by FAP-24 were used by UoN to produce a map of change in bathymetry (Fig. 5.3). Positive values on Figure 5.3 relate to areas of erosion and negative values relate to areas of depostion.

5.3 Discussion of bathymetric changes 1993-94

Examination of the map for November 1993 shows the outline of the study site clearly. At the node upstream the channel is asymmetrical, with the thalweg close to the right bank as it approaches the bifurcated reach. This is consistent with the planform of the left anabranch at this time (see Fig. 3.1(i), satellite image for 1994) which shows a right bank concave curve in the channel between Bahadurabad and the study site.

At the nose of the study bar the bathymetry shows a scour hole in the left channel, just downstream of the nose of the bar. There is a pronounced bar to the east, in the outer part of the channel and then a small back channel along the left bank. All of these features are consistent with the satellite image in Figure 3.1(i). Hoewever, existence of a scour hole and bar in this configuration relative to the bifurcation are inconsistent with the hypothetical cross-sections outlined in chapter 1 and illustrated in Figure 1.5.

In the left channel the thalweg crosses to the left (outer) bank about one third of the way along the bifurcated reach. It follows the bank closely and then swings back towards the centre of the channel at the bar tail. This pattern is consistent with the hypothesis in chapter 1.

In the November 1993 map the right channel at the study site is much smaller than the left channel. The bed topography is broadly a mirror image of that in the left channel. The scour hole at the nose of the bar is offset towards the bar side of the channel. The thalweg crosses to the outer (concave) side of the right channel for the middle third of the length of the bar and then it crosses back to the inner bank at the bar tail.

Examination of the map for November 1994 reveals substantial evolution of the bed topography during the 1994 monsoon flow. The study bar is still easily recognisable, but its position and shape have changed in response to flow scour and deposition. Orderly spatial patterns of scour and fill can be identified in the change map (Fig. 5.3).

At the node upstream of the bifurcation the channel continues to be asymmetrical. The scour hole at the right bank has shifted downstream while maintaining its shape and approximate dimensions. This is consistent with downstream migration of the right bank concave curve which can be identified in the satellite image for 1995 (see Fig. 6.2).

The point of bifurcation appears to have shifted downstream although the pattern is complicated by a remnant of the former nose of the bar that persists in about the location of the point of bifurcation in November 1993.

The left channel has changed considerably during the 1994 monsoon. The scour hole close to the nose of the bar in November 1993 has shifted downstream and to the west, eroding deep into the north-eastern flank of the study bar. Expansion of the left channel due to this erosion has been accompanied by growth of a substantial medial (braid?) bar and scour along each flank of this bar by November 1994.

The thalweg in the left channel is by November 1994 divided around the growing bar, which occupies nearly the first half of the length of the left channel. In the downstream half of the left channel there is a single thalweg that crosses to the outer (left) bank and continues to migrate southeast, with the bankline. The inner half of the channel shows substantial sediment fill through accretion on the southeast flank of the bar.

The right channel enlarged considerably during 1994. The scour hole just downstream of the bifurcation has deepened and widened, cutting into the banks on both sides of the right channel. Along the middle third of its length, scour in the outside half of the right channel and fill in the inner half has led to increased channel cuvature and pronounced lateral growth of the study bar. In the last third of the right channel the thalweg continues to cross back to the inner bank. The pattern of scour and fill here is reversed, with accretion on the right (outer) margin and scour of the bar tail.

5.4 Summary of significant points

The morphological changes during the 1994 monsoon flow reveal that the morphology of the bifurcated channel evolved markedly in response to the imposed flow pattern. The configuration of the channel and the changes observed are not entirely consistent with the hypothetical morphology and flow patterns suggested in chapter 1. The salient features are:

- Existence of scour holes adjacent to the bar head in the channels on each side of the bar just downstream of the point of bifurcation;
- Downstream migration of the point of bifurcation and the associated scour holes leading to erosion of the bar head, northeast and northwest flanks of the bar;
- Expansion of the crossing bar in the left channel to become a substantial medial (braid?) bar;
- Scour in both left and right channels along the outer margins leading to widening through bankline retreat;
- Fill in both the left and right channels along the inner margins leading to accretion on the flanks of the bar and pronounced lateral growth;
- Scour at the inner margin of the last third of the left channel leading to erosion of the bar tail in this area.

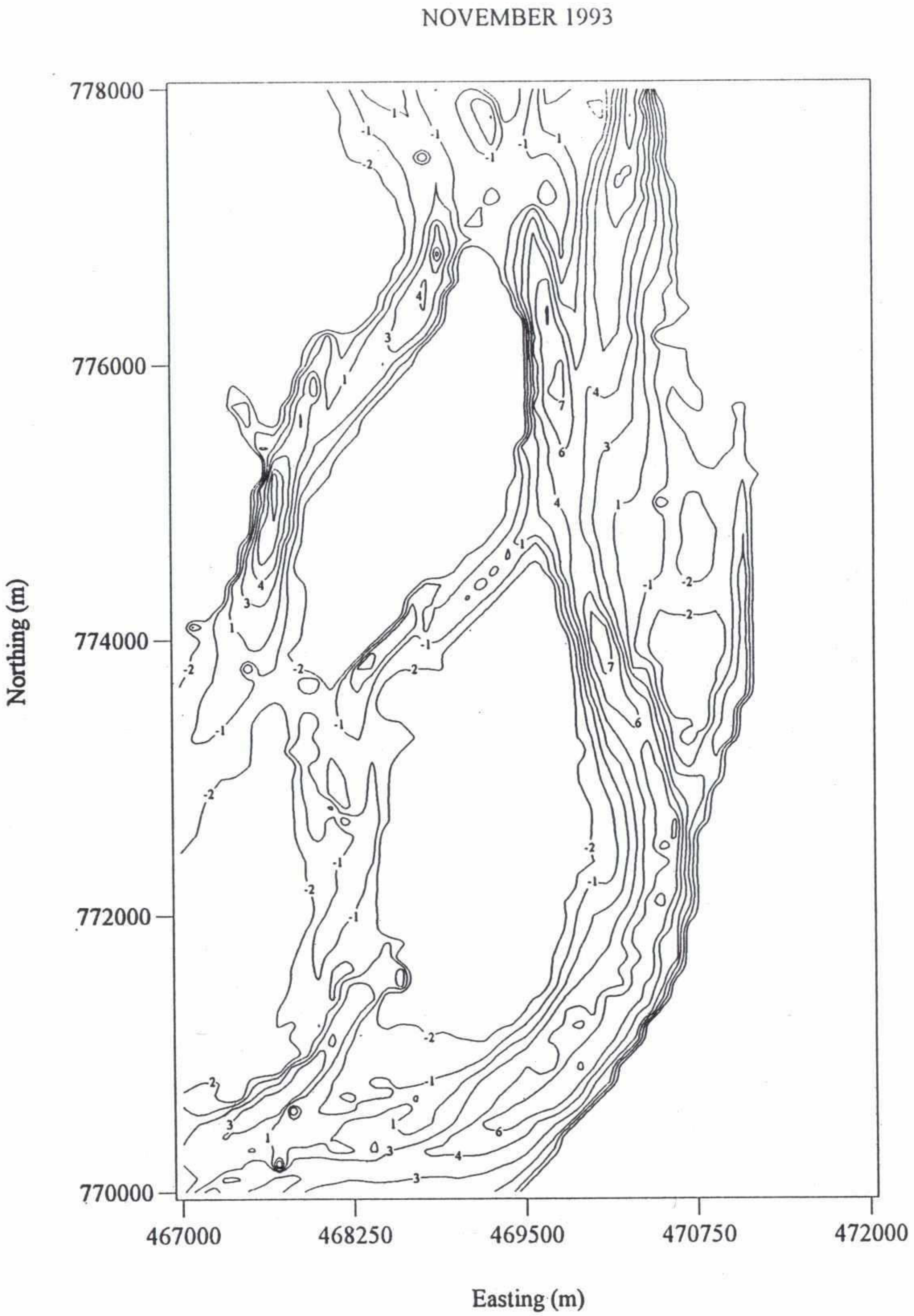

Figure 5.1 Bathymetry map of study reach in November 1993

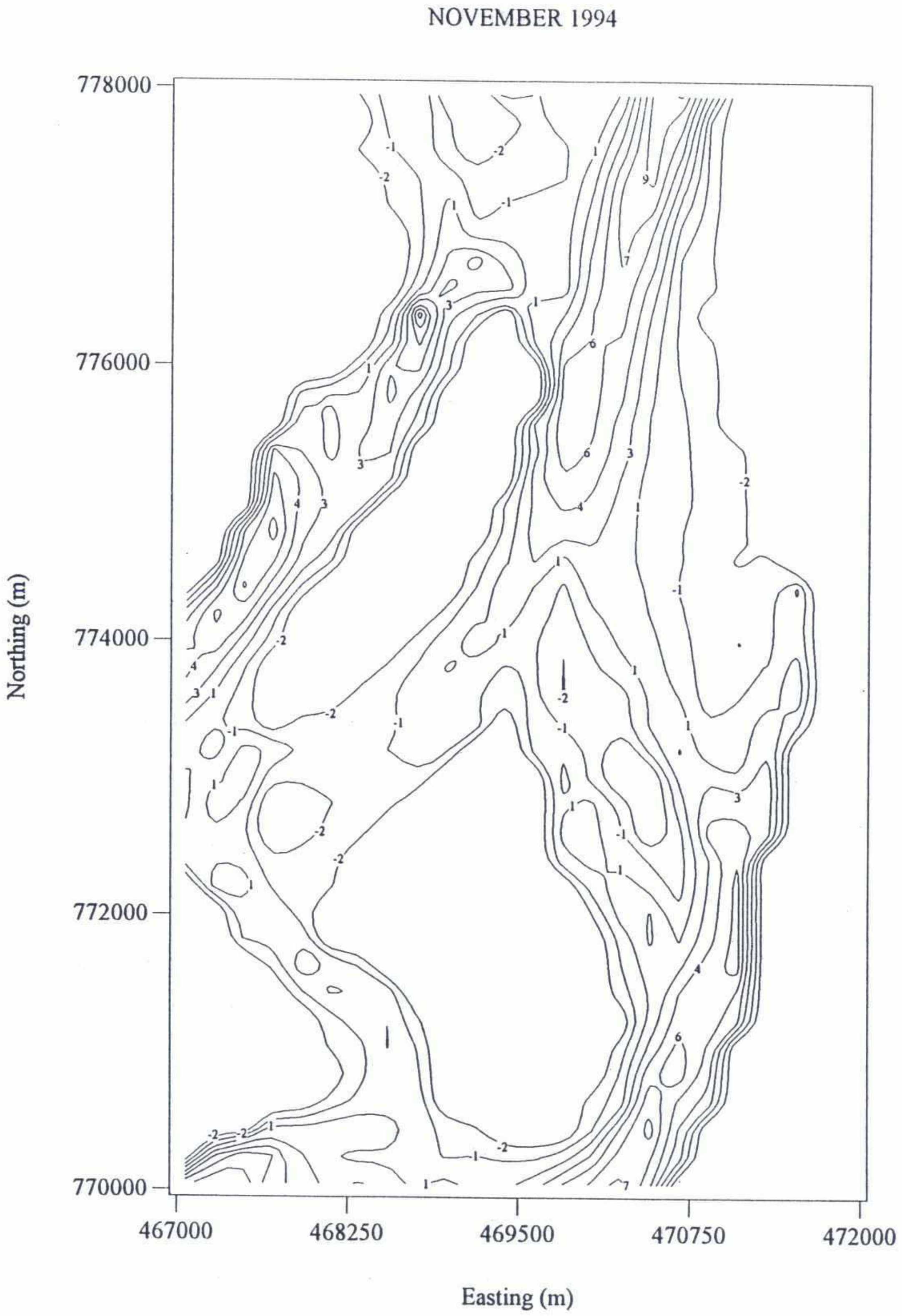

Figure 5.2 Bathymetry map of study reach in November 1994

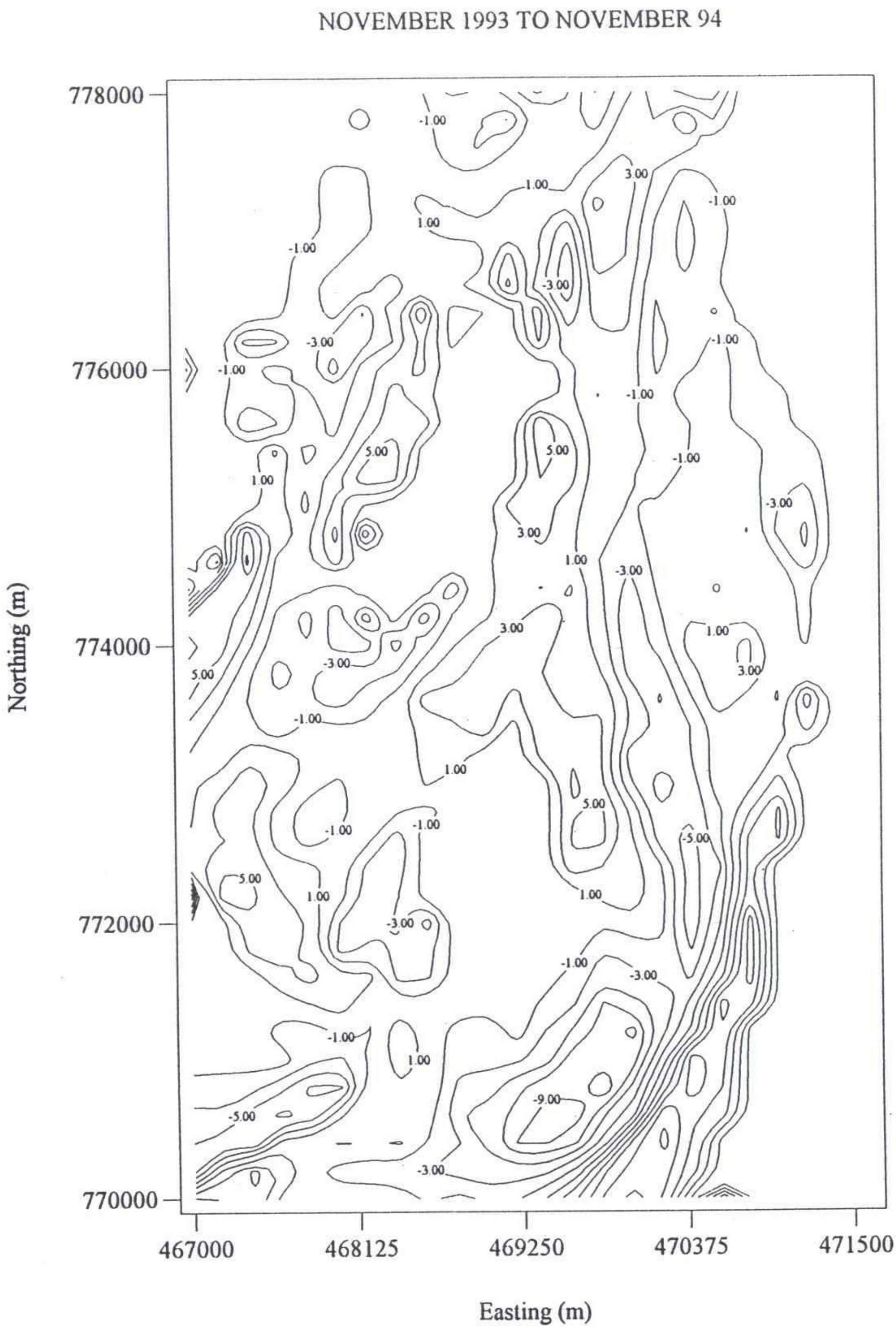

Figure 5.3 Map of change in bathymetry between November 1993 and November 1994

6 Bankline changes in the study area 1973-1995

6.1 Context

The banklines of the Brahmaputra/Jamuna River are highly mobile. Analysis of bankline movements based on historical maps and satellite images was performed in the Brahmaputra River Training Study (BRTS-FAP1) for the period 1953/6 to 1988. The results were summarised by Thorne et al. (1993). Table 6.1 presents summary data from Thorne et al.'s paper.

Examination of the table shows that the reach around the study site has historically experienced severe bank erosion. Around Island B both banks have retreated, but the rate for the left bank (65.6 m/y) is actually a little higher than that for the right bank (59.2 m/y), which is unusual for the Jamuna as a whole. However, considering the margin for error in this type of map-based record, it can be concluded that the banks essentially retreated symmetrically as Island B grew in width between the mid-1950s and 1988. Data for node b-c indicate a relatively more stable situation, with the channel widening and migrating westward through erosion of the right bank and accretion (at a slower rate) of the left bank.

The satellite images presented in Section 3 were used by FAP-19 to synthesise a map of cumulative bankline erosion for the period 1973-94 (Fig. 6.1). Examination of the map shows that bank erosion has occurred along all of the left bank, but that bank retreat is variable both space and time. At the scale of the study reach variations are not random but are closely related to the planform of the near-bank anabranches and particularly to flow deflection around growing point or braid bars. Discussion here concentrates on the left bank anabranch which is relevant to the study site.

6.2 History of bankline retreat 1973-94

Over the study period the left bankline follows a wavy line with three embayments in the study reach covered by the erosion map (Fig. 6.1). During the period 1973-94 the bankline retreats eastward while shifting its waveform downstream a little and increasing the amplitude of the embayments. The spacing of the embayments is 6 to 8 km, which coincides with the length of braid/point bars in major anabranches of the Jamuna (as noted by Thorne et al., 1993). It is also approximately half the meander wavelength of the left bank anabranch (see section 3). Hence, it may be concluded that geometrically the bank embayments are scaled on the same channel parameters as the other major planform features.

The rate of bank retreat is unsteady and non-uniform, but is organised spatially between embayments. The embayment, upstream of Bahadurabad, developed strongly between 1976 and 1990. Comparison with the satellite images for this period (Figs 3.1b to g) shows that the embayment already existed prior to 1973, but was located behind a wide point bar in the meandering left bank anabranch. Bank erosion was initiated in 1976 when a chute channel behind the point bar was re-occupied and enlarged. During 1976 to 1978 the bank eroded because the chute channel enlarged to become the left sub-channel of the braided left bank anabranch. Between 1978 and 1984 bank erosion continued as the sub-channel shifted eastward through concave bank erosion alongside a growing braid bar. But by 1984 the sub-channel had abandoned the embayment through a chute cut-off across the braid bar. In 1987 the left sub-channel re-occupied the embayment with bank erosion causing downstream migration of the embayment. By 1990 the left bank anabranch had changed to a predominantly meandering planform, and flow in the embayment diminished. Consequently, enlargement of the embayment through bank erosion ceased, although it did continue to migrate downstream between 1990 and 1992. By 1994 the embayment was completely abandoned.

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The embayment downstream of Bahadurabad is larger and has developed more strongly during the study period. It also existed prior to 1973, and eroded rapidly between then and 1976 due to concave bank erosion matched by point bar development in a meander bend of the left bank anabranch. In 1978 this bend had cut-off and erosion practically ceased between then and 1980. Between 1980 and 1984 erosion started again due to braid bar growth in the braided left bank anabranch, with the locus of bank retreat shifted downstream by about 4 km because of downstream shifting of the pattern node west of Bahadurabad (see section 3). The period 1984 to 1987 was one of rapid bank retreat as the braided left bank anabranch migrated eastward. Retreat continued at about this rate in 1987-1992, with the locus shifting about 4 km upstream due to development of a left bank concave meander in the left bank anabranch. The study bar is part of the point bar complex opposite this embayment and in 1994 represented the apex of the point bar. On this basis growth of this bar is seen to be responsible for the rapid left bank retreat and embayment growth between 1990 and 1994.

The third embayment is located near node b-c in the pattern of the Jamuna. Examination of the erosion map shows a large, lenticular patch of retreat in 1973-1976 which is not due to bank erosion but to the conversion of an attached char into an island char by enlargement of a back channel. In fact, there was very little bank erosion in this nodal reach prior to 1987. At this time the extensive point bar in front of the left bank was dissected by enlargement of pre-existing chute channels, leading to rapid widening between 1987 and 1992. After 1992 abandonment of marginal chute channels has resulted in reduced bank erosion in this embayment.

6.3 Bankline changes 1994-1995

A spring 1995 satellite image for the study reach was made available to the joint study by FAP-24 (Fig. 6.2).

The image shows that the left anabranch upstream of Bahadurabad is migrating slowly eastward, starting to re-occupy the left bank embayment in that reach. As a result flow alignment at the crossing southwest of Bahadurabad continues to rotate towards the southwest.

At the study reach erosion in the left bank embayment has continued, with the locus of erosion in the downstream third of the embayment, opposite the area of maximum accretion on the point bar complex opposite. This has led to downstream migration of the embayment with little eastward growth of the feature. The study bar is the apex component of the dissected point bar in this embayment. The embayment now directs flow exiting the left channel at the study site into a northwesterly direction against the regional flow direction in the Jamuna, which is southwards. This situation is probably not sustainable for very long and a chute cut-off of the left bank embayment through one or more of the chute channels crossing the point bar complex may well be imminent.

Downstream at node b-c inward turning of the major left and right bank anabranches in almost symmetrical meanders leads to abandonment of marginal anabranch channels adjacent to the banks. This continues to promote narrowing, particularly at the left bank.

6.4 Summary of significant historical developments around the study site

The history of bankline retreat in the study reach has some important implications for interpretation of the flow measurements and morphological changes observed at the study site. Some of the more significant points are:

- bankline retreat has taken place along the entire length of the left bank in the study reach. Its distribution in time and space is not random but is closely related to the planform pattern of the left bank anabranch;

- the bankline follows a wavy line with embayments separated by promontories spaced at about 6 to 8km apart. This corresponds to the length of both the average meander arc and braid bar unit in the left bank anabranch;

- embayments form due to concave bank erosion at the outside of meander bends and along the flanks of growing braid bars in the left bank anabranch;

- promontories are not necessarily erosion resistant hard points in the bank but may occur at nodes in the channel pattern;

- embayments are abandoned by chute cut-offs of a meander bend and sub-channel flanking a braid bar when curvature becomes too great, but they are usually re-occupied and re-activated as sites of bank erosion sometime later.

- The strong curvature and orientation of flow exiting the left bank embayment containing the study bar suggests that a chute cut-off is imminent. On this basis enlargement of chute channels such as the right channel in the bifurcated study reach is expected to continue.

			Average erosion rate	
Reach	Period	Length (km)	Right bank (m/yr)	Left bank (m/yr)
Island A	1953-89	31.0	58.2	-18.8*
Node A/B	1953-89	5.5	-10.6	1.73
Island B	1953-89	25.0	59.2	65.6
Node B/C	1953-89	9.5	22.6	-8.36
Island C	1953-89	16.0	94.0	-16.6
Node C/D	1953-89	5.0	86.7	106.9
Island D	1953-89	18.0	165.0	-11.1
Island E	1953-89	18.0	151.4	73.0
Node E/F	1953-89	20.5	9.4	-36.7
Island F	1953-89	18.0	198.5	-34.2
Node F/G	1953-89	11.5	109.0	-98.1
Averages:				
Island reaches		21.0	111.6	10.2
Node		10.4	39.2	-47.8
Study reach		178.0	90.4	-6.7

* Negative erosion rates indicate bank accretion

Table 6.1 Bank erosion rates in the Jamuna River 1953/6 to 1988. Island and nodal reaches are shown in Fig. 3.2 (adapted from Thorne et al., 1993)

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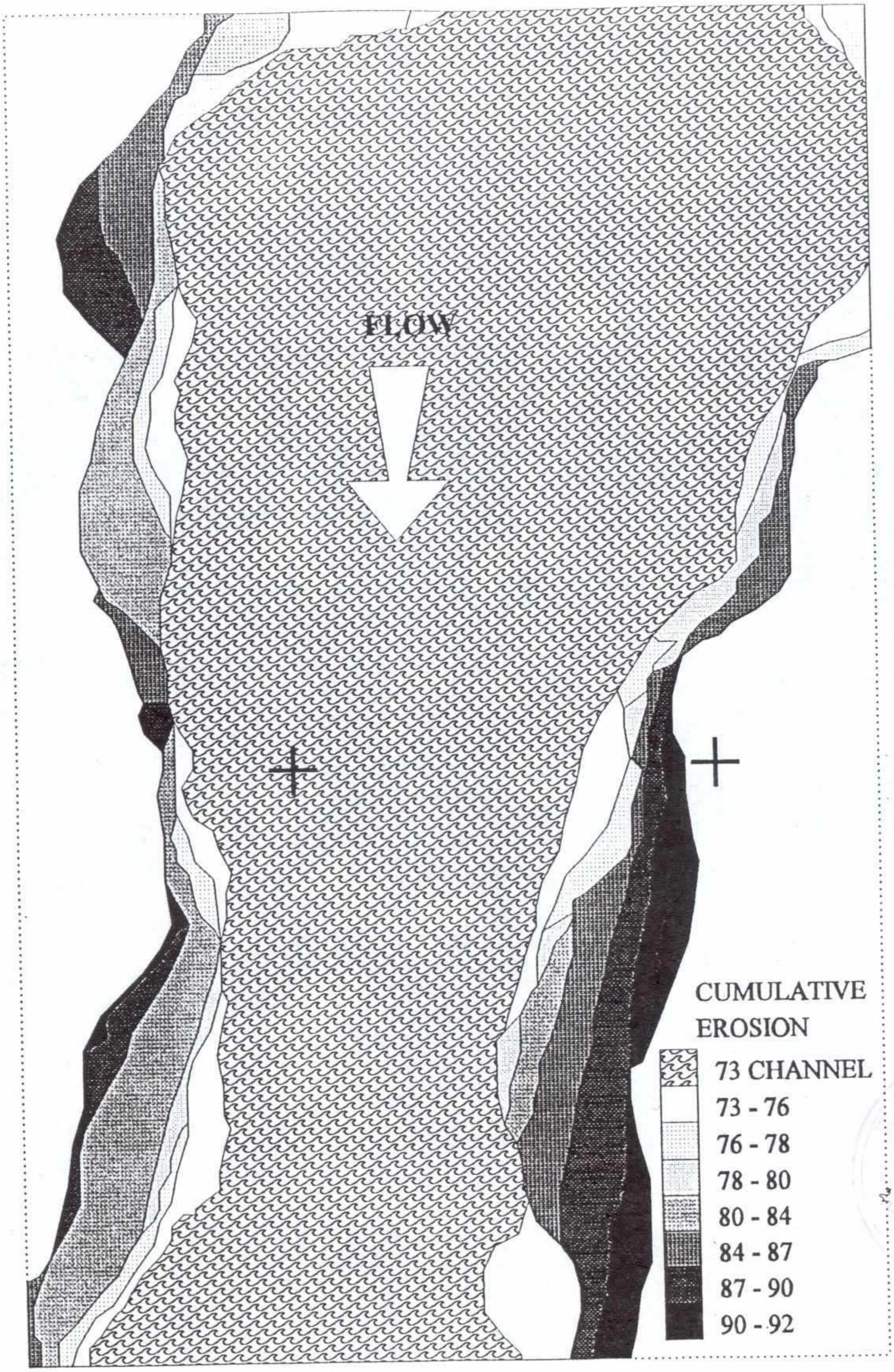

Figure 6.1 Cumulative bankline erosion in the study reach between 1973 and 1992. The black crosses may be used for reference : they coincide with the cross hairs in Figure 3.1. Figure produced and supplied by, FAP 19.

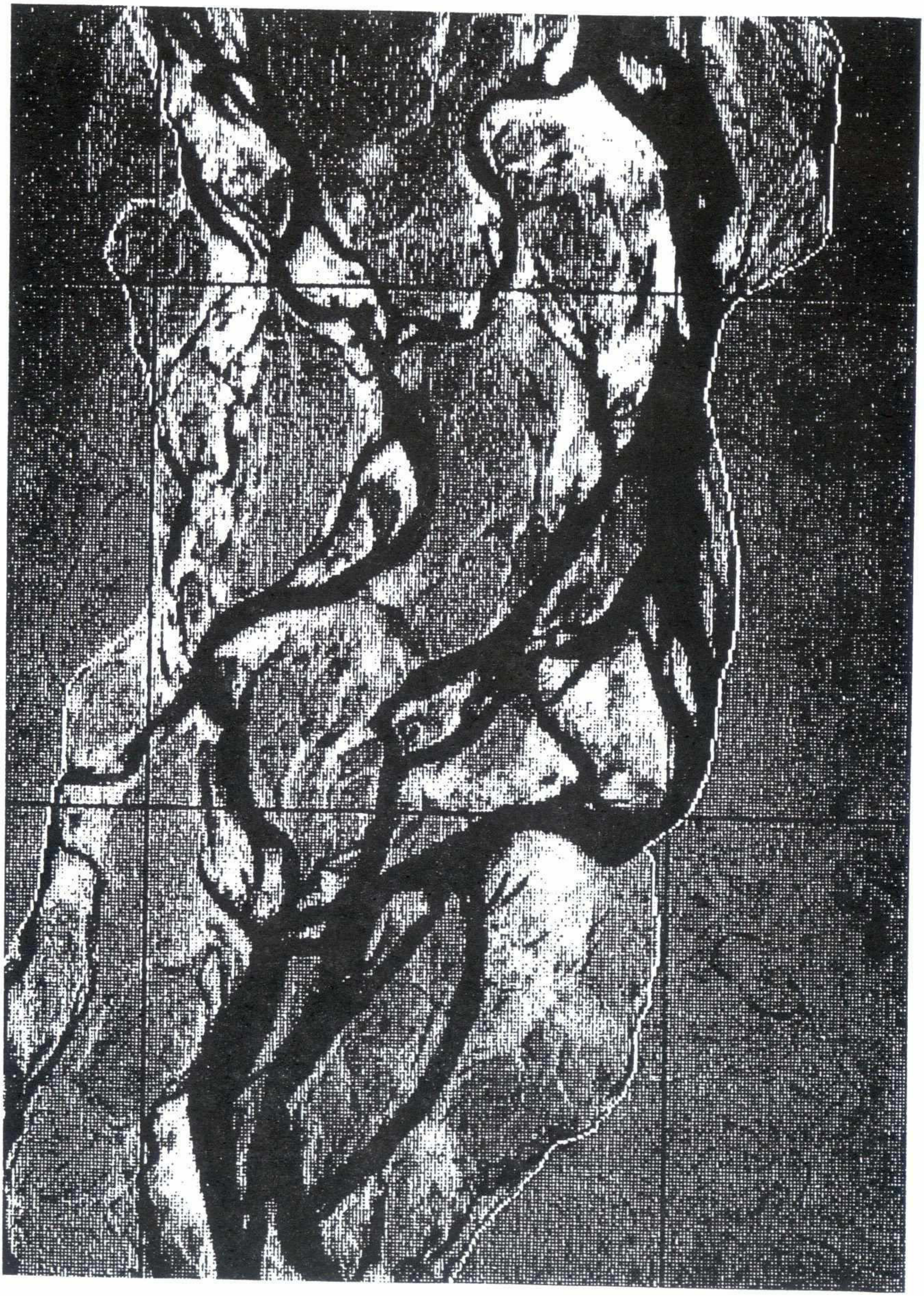

Figure 6.2 Satellite image for the study reach in spring 1995

7 Interpretation of results

7.1 Introduction

The field measurements using the ADCP and GPS instruments were processed using software supplied for use in all FAP-24 studies by DHI. This resulted in a large dataset giving eastings and northings of each measurement profile and velocity vectors (magnitude, horizontal angle and vertical angle) and backscatter intensity for a number of measurement bins in each profile. The complete dataset defining the velocity fields in the bifurcated channel may be found in ASCII files on the diskette within the back cover.

The velocity data were then resolved into primary and secondary components in order to determine the patterns of primary isovels and secondary currents. The method by which the primary flow direction and secondary plane were determined is described with examples in Appendix A.

The complete results for all measured sections are displayed in chapter 4. In this chapter summary diagrams presenting overviews of the results are presented to support interpretation of the flow patterns and their relation to sediment concentrations inferred from the backscatter plots.

In the field a two-component electromagnetic current meter was used to measure velocities in the top 2.6 m of the flow, which could not be measured using the ADCP. These results are not processed in the DHI software if they lie outside of certain quality control parameters.

7.2 Interpretation method

Interpretation rests on qualitative interpretation and sound geomorphological insight on behalf of the study team because the secondary current pattern is not always easily derived from the raw results and cannot usually be simply transcribed from the secondary velocity results alone.

The interpretation was performed by inspecting the primary isovels, secondary velocities, backscatter plots and cross-sectional geometry of the channel and then synthesising a likely picture of the secondary current pattern for each transect. The patterns for each section were also compared to those for transects immediately upstream and downstream to check for consistency.

For example, the results for Section 13 in the August survey are shown in Figure 7.1. This is a data set where the secondary current pattern is clearly displayed in the distribution of secondary velocity arrows. Little supporting evidence is required from the primary isovel and backscatter plots to conclude that the secondary pattern consists of outward directed secondary flow at the shelving left bank and strong helical flow in the thalweg. However, this clarity in the directions of the secondary arrows is relatively rare. Supporting evidence does actually exist in the primary isovels. Applying the rules established in studies of single-thread rivers that were outlined in chapter 1, upwelling should be associated with upwards bulging of isovels, while downwelling causes compression of isovels: this association may be identified in Figure 7.1. Similarly, upwelling is associated with high sediment concentrations in the body of the flow, while downwelling brings sediment free water down closer to the channel perimeter. This association is also discernible in Figure 7.1.

On the basis of the existence of these associations, the patterns of primary isovels at transects were used to assist the study team in inferring secondary current patterns where the pattern could not be defined from the secondary vector arrows alone, or where data were for any reason unavailable. The technique is quite straight forward in practice. For example, Figure 7.2 shows primary velocities for

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section 4 in May. Even without any secondary velocity arrows, it is possible to infer the secondary circulation from the cross-sectional shape, distortion of primary isovels and distribution of backscatter (sediment concentration).

It should be borne in mind that at present the uppermost 2.6 m of the water column are excluded from interpretation due to the poor quality of em-flowmeter measurements. With further work these data may be able to be taken into consideration and the interpretation modified according to the results.

7.3 Interpreted distributions of secondary flow: May 1994

The interpreted distributions of secondary flow are shown on cross-sections represented schematically in Figure 7.3, together with the distributions of near-surface velocity and areas of low and high backscatter intensity.

In May measurements were confined to the left channel by the draught of the DHA vessel. The results indicate that upstream of the bifurcation in the channel the flow is already hydraulically divided as there are two distinct streams of flow, each with its own maximum velocity filament. At section 2 the line of flow split, at the profile of minimum depth-averaged velocity between the two maximum velocity filaments, shows heavy sediment concentration, upwelling and converging secondary currents. At both sections 2 and 3 flow to the left of the line of flow split is helicoidal, with clockwise rotation. This is consistent with the curved flow exiting the nodal reach southwest of Bahadurabad and with the cross-sectional asymmetry of the section.

At section 4 the cross-section is strongly asymmetrical, with deep scour and a steep bank next to bar and bar and shelving bank at the outer flood plain bank. No secondary velocities are currently available for this section due to technical problems, but inference based on the isovels and backscatter suggests secondary flow off the top of the bar at the left bank and counter-clockwise helical flow in the thalweg. These results are mirror images of those expected from the hypothetical cross-section in Figure 1.5.

Section 5 has a symmetrical cross-section with no evidence of secondary cells. The shape and lack of strong helical flow are similar to results from crossings between meander bends of single-thread rivers.

Section 6 has a strongly asymmetrical shape, with deep scour at the steep left bank a very steep bar face at the channel centre and a low angle, shelving right bank. The maximum velocity is close to the channel centreline. There is counter-clockwise helical flow in the thalweg with secondary flow outwards over the upper bar top at the right bank and some evidence of a small outer bank cell at the left bank. Sediment is concentrated at the zone of near-bed convergence where the bar face meets the bar top while sediment free water plunges at the junction of the helical and outerbank cells.

Section 7 displays a similar pattern to Section 6, although the asymmetry in the channel is less pronounced and the maximum velocity filament is very close to the left (outer) bank.

At Section 8 the cross-section shows a double thalweg, divided by a mid-channel bar. The main thalweg is against the right (bar) bank and there is a wide bar left of the channel centreline. Helical flow has a clockwise rotation in the main thalweg, with erosion to the right bank. Flow is outwards over the medial bar towards the left bank, promoting high sediment concentration where secondary currents coverage.

Section 9 is very wide and shallow. Deeps at the far right end are cut by flow exiting the right channel. There is evidence of a two cell secondary pattern with bed convergence and upwelling close to the channel centreline.

The overall pattern that emerges for the May measurements is more complicated than that envisaged in the hypothesis in chapter 1. It appears that immediately after splitting into a bifurcated flow, curvature induces a strong, clockwise helical cell which produces deep scour next to the bar at Section 4. At Section 5 the flow crosses to the left and strong helical flow is together with outwards flow over the upper bar is induced at Sections 6 and 7. Here the sections do support the hypothesis in chapter 1, Figure 1.5. The flow crosses again by Section 8, which has clock-wise helical flow attacking the right (bar) bank.

It can be concluded that the left channel contains not one curved flow in May, but 3, with 2 crossings in between.

7.4 Interpreted distributions of secondary flow: August 1994

Approaching the bifurcation a line of flow split can be identified. Secondaries converge near the bed and upwell along the splitting line. Flow in the approach channel has a clockwise helical cell due to flow curvature in the right bank concave bend southwest of Bahadurabad.

In August the major features of flow in the left channel are present, but the pattern has shifted downstream. Hence, Section 4 is less asymmetrical and widening associated with downstream migration of the bar head, coupled with erosion of the flank of the bar, has widened the channel. A medial bar is growing where near bed currents converge at the channel centre.

Section 5 has also widened. The right channel is dominant, with strong clock-wise helical flow attacking the right bank and sweeping sediment onto the medial bar. Section 5 was a crossing in May, but is developing into an asymmetrical, bend-like section.

Section 6 is much more symmetrical than it was in May and no strong secondary currents can be inferred. It is gaining the appearance of a crossing section.

Section 7 is now strongly asymmetrical, with strong counter-clockwise helical flow in the thalweg and evidence of an outer bank cell.

Section 8 is also asymmetrical and it displays a strong counter-clockwise secondary cell and outwards flow over the bar top at the inner bank.

The helical cell appears to persist downstream at Section 9, close to the left bank. There is evidence of multiple cells in the wide shallow left channel at section 9.

It is concluded that the pattern identified in the left channel in May persists in August, but is shifted downstream by about one section.

In the right channel at Section 16 the pattern is confused, but at Sections 13 and 12 there is support for the hypothesis presented in Figure 1.5.

At Sections 10 and 9 the sense of helical flow is reversed from the predicted in the hypothesis with plunging flow attacking the left (inner) bank.

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It is concluded that results for the right channel are broadly similar to those for the left channel. No sections were taken in the upstream half of the channel, but in the downstream half two reaches of curved flow and strong helical circulation were identified. At the widest point on the bar flow attacks the outer bank and concentrates sediment at the inner bank. At the bar tail this pattern is reversed, with the bag being eroded.

7.5 Interpreted distributions of secondary flow: September 1994

Helical flow is found at Section 1 due to flow curvature in the right bank concave bend there. This persists weakly downstream to Section 2 and 3. The physical bifurcation of the channel has migrated downstream, but the hydraulic split can still be found analytically at Sections 1, 2 and 3 using the method described in Appendix B.

At Sections 4 and 5 there is a problem in interpreting the results because information does not extend far enough to the right in these wide shallow sections. Available results indicate continued widening, growth of the medial bar and attack of the outer banks due to curved flow and strong helical circulation in both thalweg channels.

Section 6 has completely lost the asymmetry displayed in May and now has multiple secondary cells and velocity filaments, in the form expected for a crossing.

Section 7 is also changing from a bend apex-like to a crossing-like geometry with no strong helical flow. However, helical flow and asymmetry at Section 8 remain strong and Section 9 displays near-bed convergence, upwelling at the channel centre and medial bar growth in a similar pattern to that in May.

The results for September follow logically from those for May and August. They are consistent with morphological changes driven by the flow patterns that result in increased amplitude of curved flow segments and their downstream migration through time.

In the right channel the flow patterns at Sections 13 and 12 are similar to those in August. The situation at 12 is slightly complicated by flow entering the right channel from another anabranch to the west.

Helical flow persists at Section 11 (not covered in May or August), but the core of maximum velocity now crosses at Section 10, where before there was a clockwise helix.

Results for the right channel in September are broadly in agreement with those for the left channel. They indicate perseverance of the patterns identified in August, but with downstream migration of the patterns and associated cross-sectional morphologies.

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7.6 Impact of flow entering from side channels

The DHA vessel was limited by its draught from entering small sub-channels and side channels at certain water levels. The flow entering or leaving the system from these smaller channels may well have significant affects on the flow patterns at relevant cross-sections. In order to quantify this situation maps have been drawn of discharge continuity and are shown in Figure 7.4. Quantities shown in red are actual measured discharges calculated using the DHI software, whereas quantities shown in blue are estimated using continuity.

In May 1994 it would be expected that measurements made at cross-sections 6, in the left anabranch channel, would be affected by the small sub-channel converging with the main channel just upstream of section 6. Examination of the secondary velocity plot for section 6 in May, reveals that thereis indeed an area of outward flow close to the outer bank associated with this sub-channel. This result explains in part why the pattern expected for at a bend apex cross-section, in particular at the outer bank, can not be identified.

In August, the results at cross-section 13, in the right anabranch channel, are clearly affected by the leakage across the boundary with the larger anabranch channel to the west. It can be seen in Figure 7.4(b) that approximately 27% of the discharge entering this region 'leaks' across the channel boundaries. This pattern is the reverse to the situation found in May, where water was actually flowing into the channel from the larger anabranch to the west, which perhaps corresponds to the change in dominance of the two anabranch channels around the study bar. At the bifurcation upstream of the bar, the right anabranch channel carried approximately 8% of the total discharge entering the region in May, compared with 29% in August and 30% in September.

In September, a significant sub-channel in the left anabranch was not surveyed due to the problems associated with the DHA draft. This sub-channel clearly has implications for the interpretations of results from the left anabranch. These results demonstrate the importance of studying bathymetry surveys together with analysing continuity maps in the interpretation of results on large braided rivers of this nature.

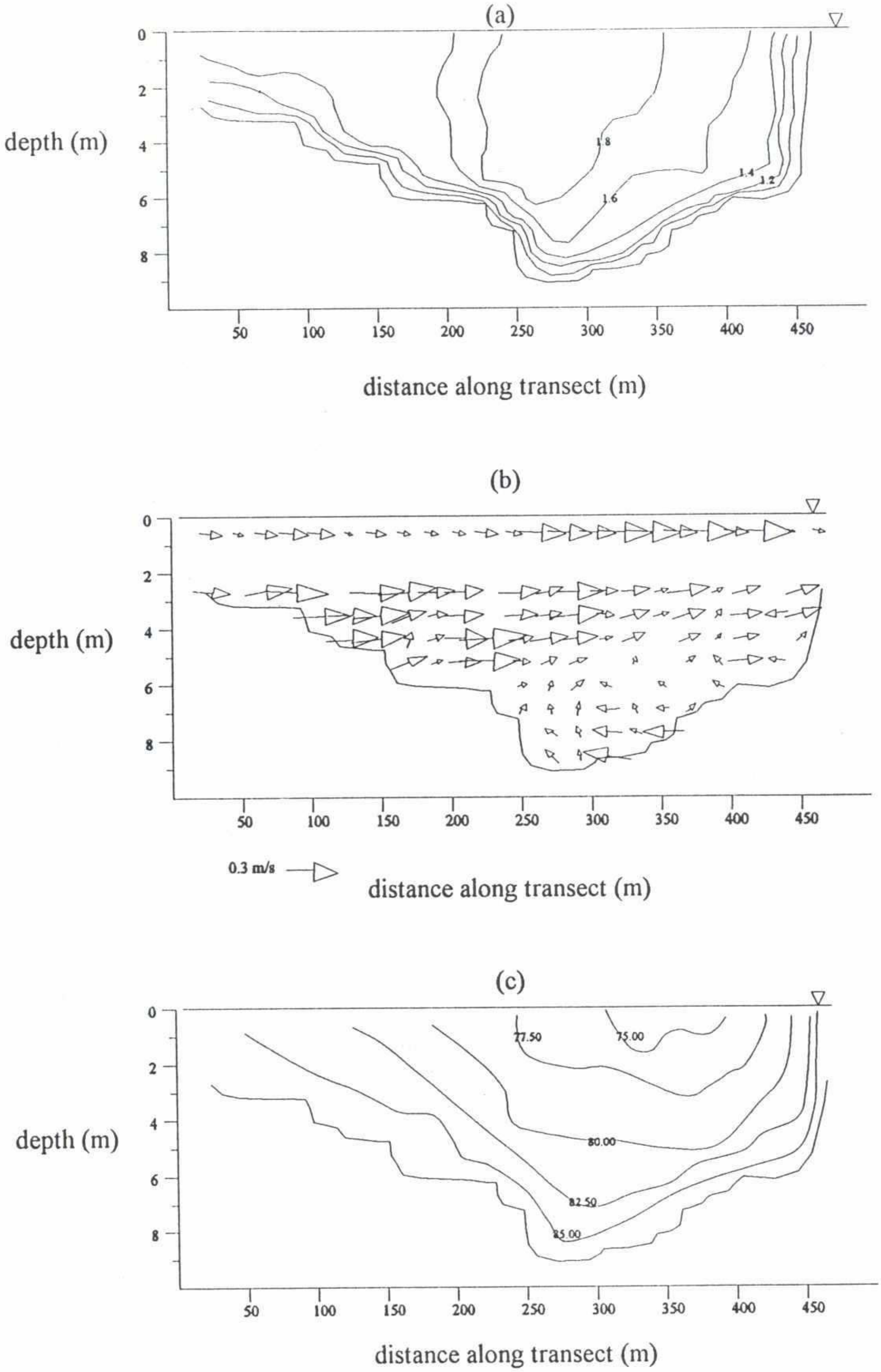
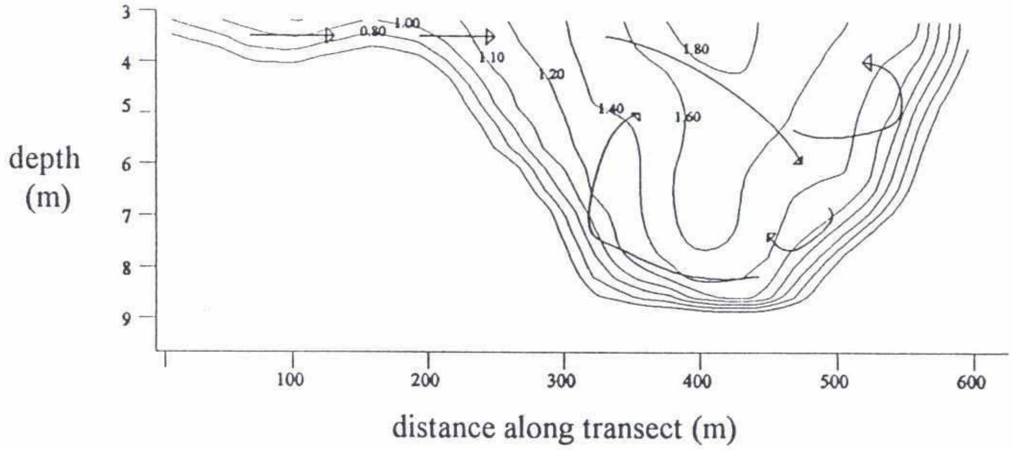


Figure 7.1 Primary isovels, secondary velocities and backscatter for section 13 in August

(a)



(b)

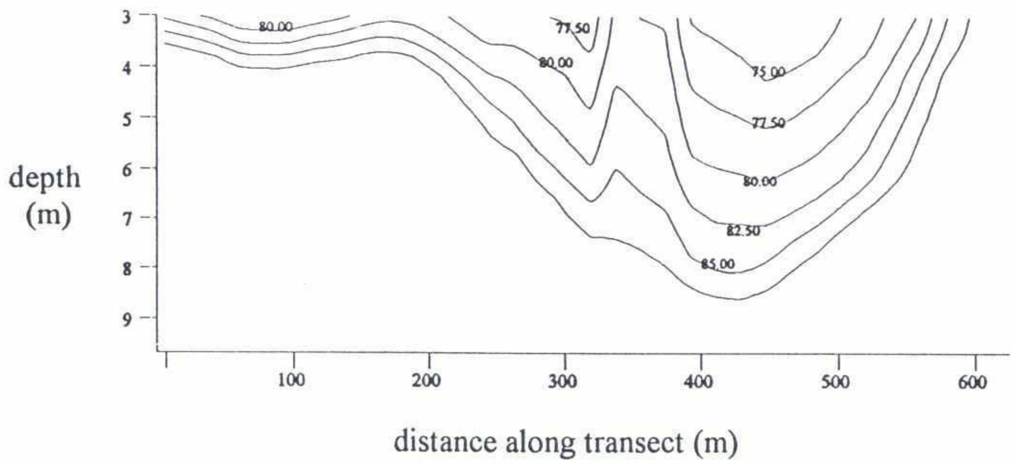


Figure 7.2 (a) Primary isovels (m/s) and backscatter (db) for section 4 in May. Note shape of channel (compared to Figure 1.2), distortion of isovels and lines of constant backscatter used to infer secondary current pattern.

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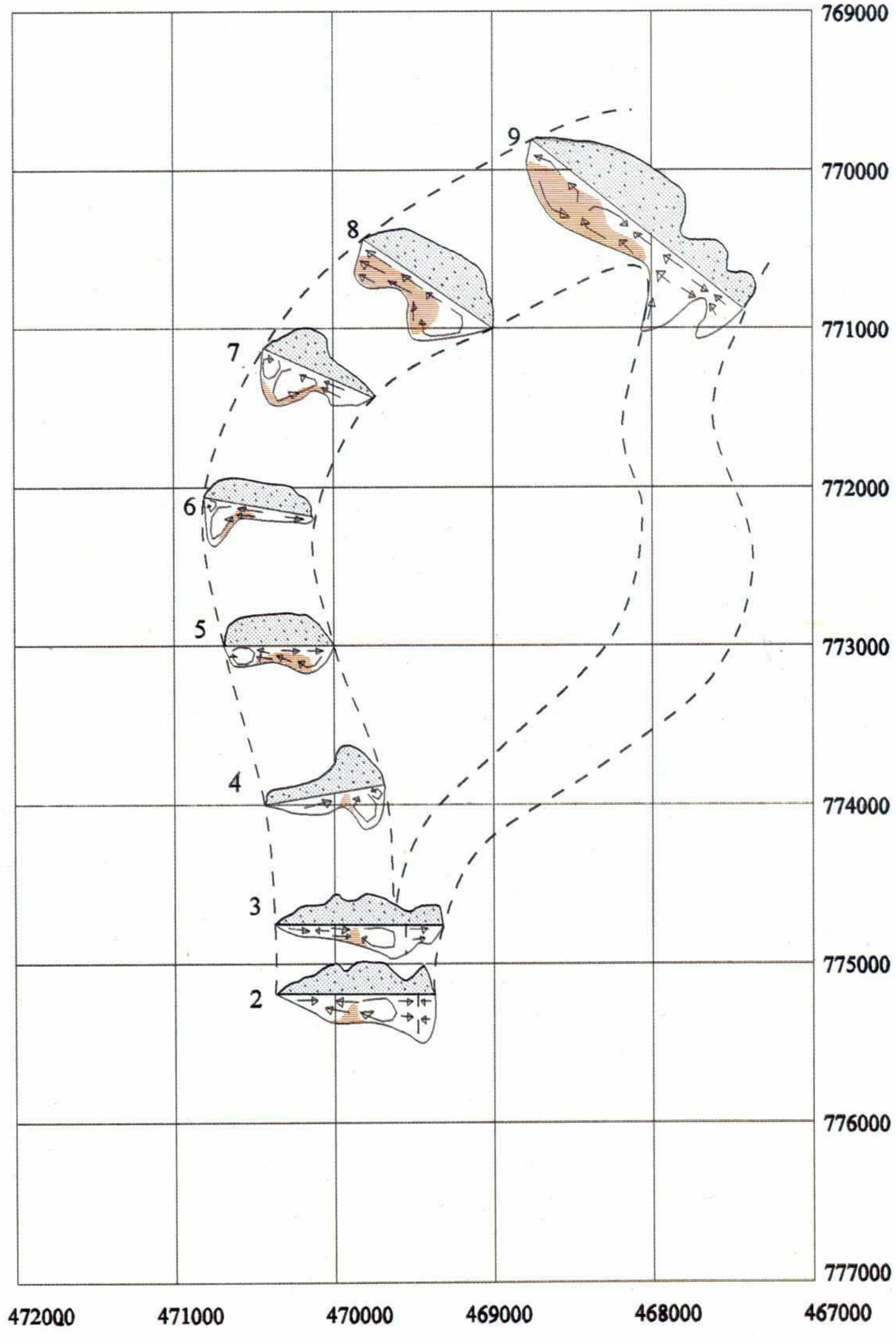

Figure 7.3(a) Near surface velocities and inferred secondary currents in May

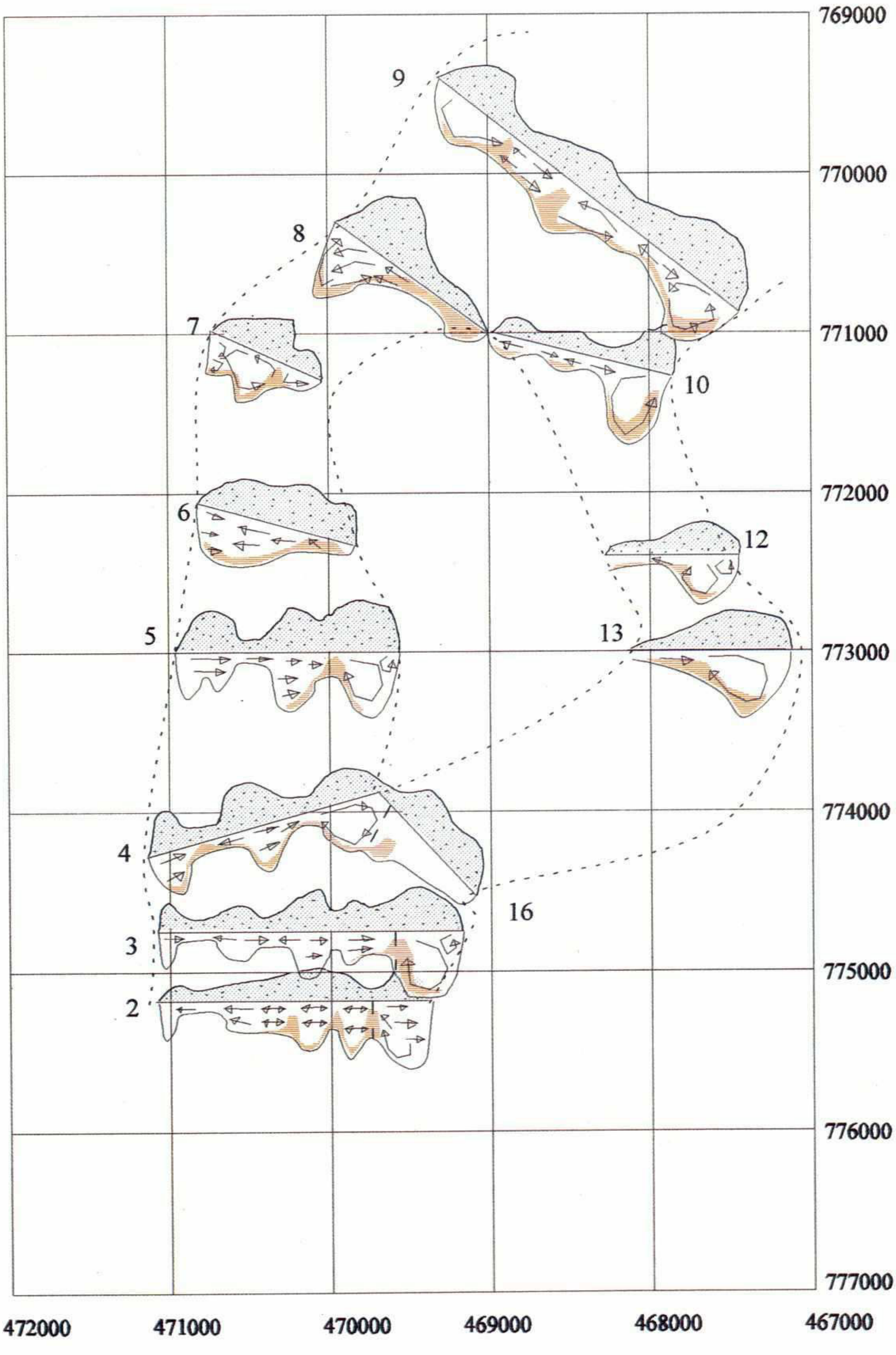

Figure 7.3(b) Near surface velocities and inferred secondary currents in August

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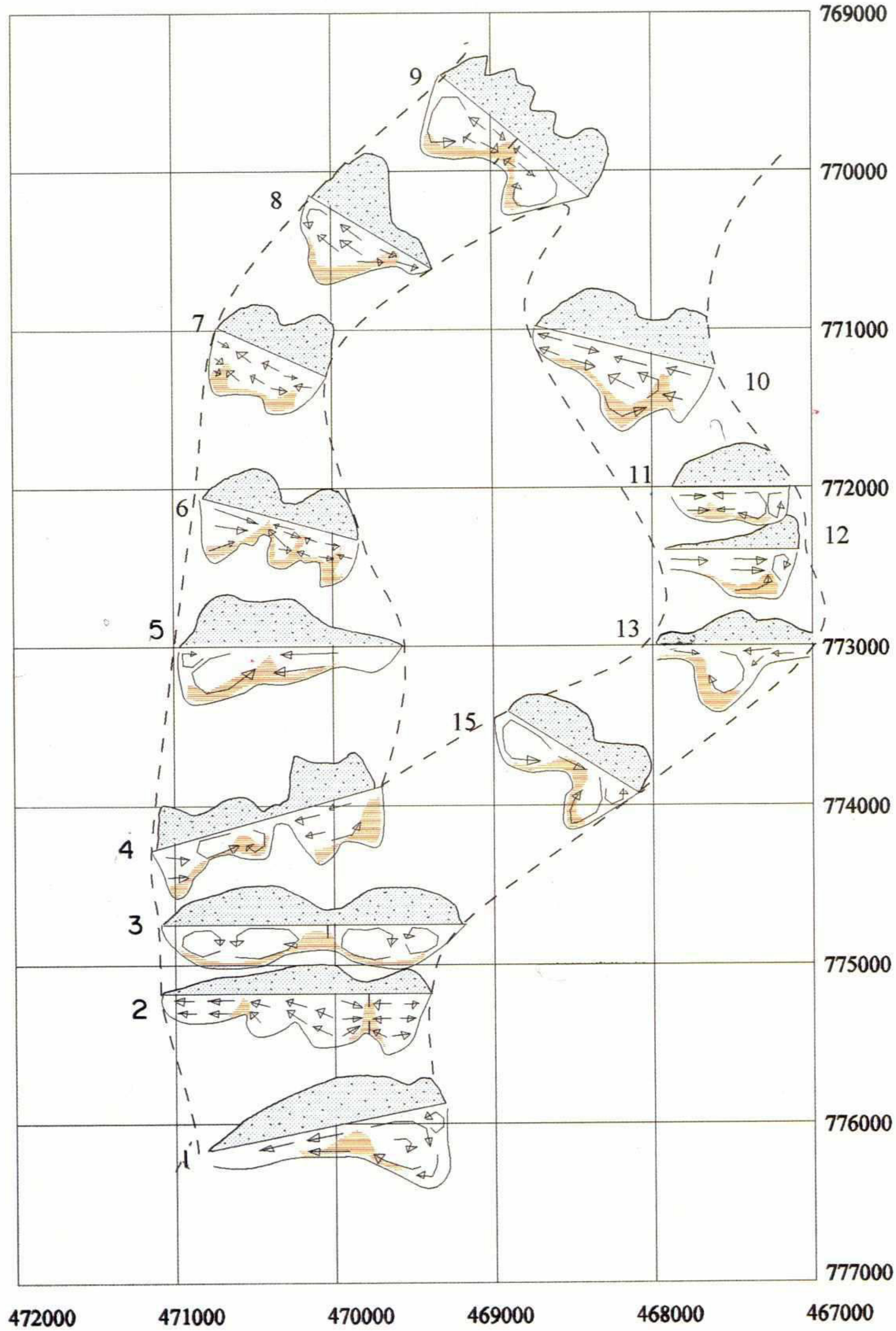

Figure 7.3(c) Near surface velocities and inferred secondary currents in September

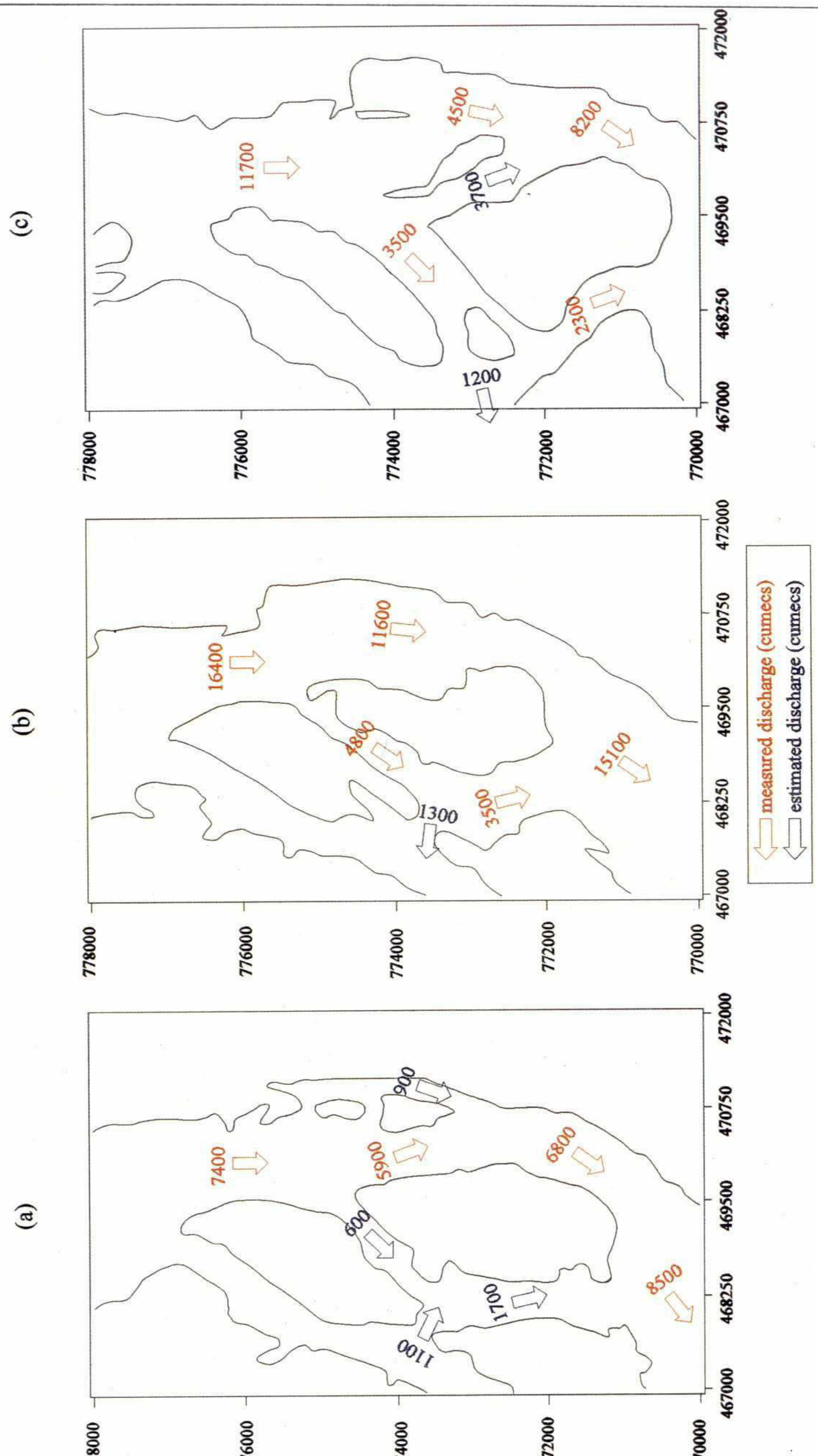

Figure 7.4 Discharge continuity maps for study area in; (a) May, (b) August and (c) September 1994

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8. Conclusions and Recommendations

8.1 Conclusions

The data collected in the joint FAP24-UoN study indicate that the pattern of secondary currents in a bifurcating channel is more complex than the hypothesis put forward in chapter 1.

It is suggested that curvature of the flow at the point of hydraulic division of the two streams of water induces helical flow that is clockwise in the left channel and counter-clockwise in the right channel. Scour produces asymmetry in the divided channels with deep scour adjacent to the flanks of the bar nose and bar building in the outer half of the channels.

The main flow crosses to the outer banks about one third of the way along the bifurcated reach. At the crossings the channel is almost symmetrical, possibly with a medial bar, and secondary currents are weak. There may be bed convergent flows and, possibly the medial bar may itself develop to split the flow and become a new braid bar.

Along the middle third of the divided reach strong helical flow exists, with a counter-clockwise rotation in the left channel and clockwise rotation in the right channel. The flow scours the bed in the outer half of the channel and attacks the outer bank through flow erosion and toe scour. At the inner bank flow is directed outwards over the entire flow depth. Near-bed convergence and upwelling on the flanks of the bar drives lateral growth of the bar through advance of the bar crest and sedimentation on the upper bar platform. Flow patterns, bed topography and morphological changes in this middle reach correspond to the hypothesised system described in chapter 1 and shown in Figure 1.5.

Approximately two thirds of the way along the bifurcated reach the main flow crosses the channel again. Crossing sections are characterised by symmetrical geometries and weak secondary currents.

Downstream of the crossing curvature of the flow as it approaches the flanks of the bar induces circulation that is clockwise in the left channel and counter-clockwise in the right channel. The effect is to draw the flows in the sub-channels into near parallel courses approaching the point of convergence and to carve ridges trailing from the tail of the bar.

Through time the entire flow pattern tends to shift downstream, eroding the nose and upstream third of the bar, increasing both channel and bar width in the middle third and shifting downstream the bar tail and confluence zone.

It should be noted that these results were observed in one particular bifurcated channel flowing around a large, mature bar feature in the Jamuna River. While the site was selected to be typical of bar features in that river, there is no reason to suppose at this time that the results are general.

Bar features in the Jamuna are known to exist in a hierarchy (see Coleman, 1969, Bristow, 1987, Thorne et al., 1993). The largest bar features are the islands that divide anastomosed reaches of the Jamuna and are scaled on the width of the entire braid belt. The smallest are dune bedforms scaled on the local depth and intensity of sediment transport. The bar selected was of intermediate size and is believed to scale on the width of the anabranch containing it (Bristow, 1987). As identified in the account of longer term development of the study reach, it is in fact a component of a much larger, point bar-like feature which is crossed by multiple chute channels. Viewed in this context, it is not a simple unit braid bar. Measurements around smaller unit bars, such as that studied in the FAP24-University of Leeds project, would therefore be expected to produce different results. Both studies are valid and yield valuable insights into flow and sediment processes in braided rivers, but they are studying quite different morphological features.

The possibility that the nose of the bar actually migrated upstream rather than downstream was raised in discussion. Examination of the bathymetric change map (Fig. 5.3) clearly shows erosion in the area of the original bar tip. This supports the hypothesis that the bar migrated downstream during the syudy period. The area of deposition shown in the November 1994 bathymetry charts appears to be a new mid-channel bar formed during the August to November period.

The results and conclusions presented here represent flow patterns, channel evolution and bar development for a bifurcated reach which is longer than the characteristic crossing spacing in the channels on either side. As such they indicate late-stage processes, in a divided reach rather than those associated with bar genesis and/or early growth.

8.2 Recommendations

Based on experience gained in the joint study and the comments of the Project adviser the following recommendations are made:

- The DHA vessel was limited by its draught from entering small sub-channels and side channels. Flow entering the main channels from side channels could have significant impacts on flow patterns. In future studies, it would be desirable to make measurements in smaller channels using smaller boats. With regard to the records in hand, an attempt has been made to estimate cross flows using discharge continuity maps (Fig. 7.4) and bathymetric charts.

- In a report issued in June 1994 the PA examines in detail the near bed sediment load in the study reach using measurements made in May 1994. The results of the PA's study should be cross-referenced in relation to the findings of this study in the overall FAP 24 report.

- The relationship between measured secondary velocities and turbulence should be examined further. The measurements reported here were made for only six seconds and this is not long enough to average out turbulent velocity fluctuations. Measurements were repeated and averaged, however. Further field studies should be undertaken to test if increasing the duration of readings produced more coherent secondary flow patterns. Evidence to support the hypothesis that longer measurement durations would lead to a clear pictures of coherent flow structures is presented in appendix B, where ADCP results taken from a special survey carried out at cross-section 5 in May 1994 are examined.

- The potential for correcting em-flowmeter data should be examined.

- Considering the problems encountered with the em-flowmeter data, efforts should be made to try and increase the percentage coverage of the ADCP. Work carried out recently by the UoN in North American used a similar RDI instruments ADCP with a different setup configuration. Figure 8.1 shows a plot of percentage coverage for the two systems. Clearly for the water depths encountered in this study (Table 8.1) the system employed on board the DHA vessel performs less well. Further work should be carried out to investigate altering the present setup.

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Survey	Average ensemble depth (m)	% coverage DHA	% coverage U.S.A
May	6.89	66.5	82.6
August	6.95	66.7	82.7
September	6.89	66.5	82.6

Table 8.1

The authors feel that most of the issues raised above did not fall under the scope of this study, as outlined in our original proposal. However, they will be addressed in the doctoral thesis of Mr.Richardson which will be made available to FAP 24.

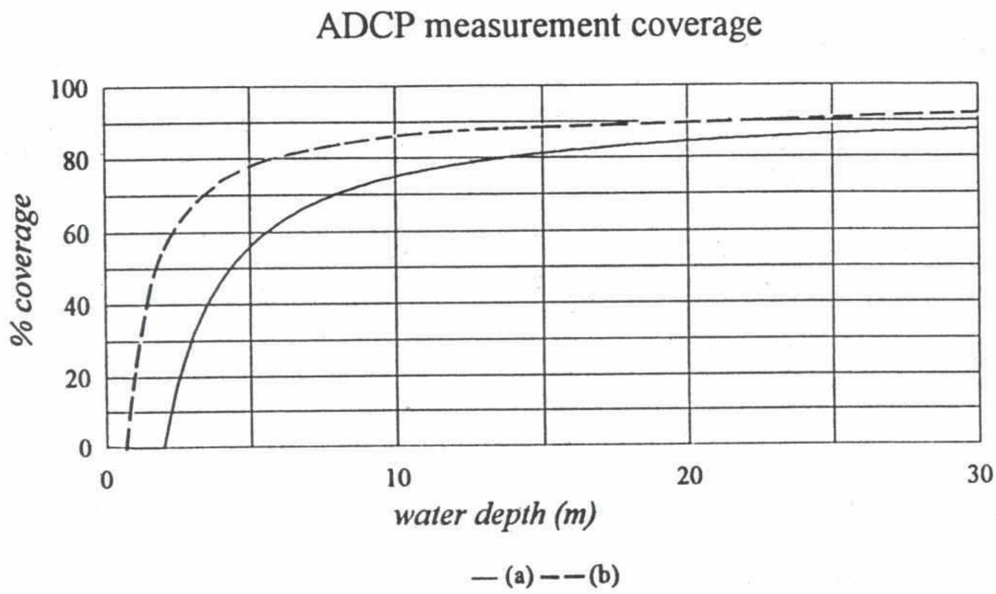

Figure 8.1 ADCP measurement coverage for; (a) ADCP depth = 0.95m, blank distance after transmit = 1.0m and (b) ADCP depth = 0.3m, blank distance after transmit = 0.5m. System (a) used on board DHA vessel, system (b) used during studies in North America.

8.3 Acknowledgements

The work reported here benefitted from the efforts of all the FAP-24 team and the UoN team express their sincere thanks to everyone involved.

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APPENDIX A

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APPENDIX A

1. Introduction

In the majority of field surveys it is necessary to apply corrections to the measured velocity distributions once they have been collected, the real orientation of the flow field is rarely known before the measurements have been made.

As outlined in S McLelland, P Ashworth and J Best, 'Velocity correction methods in open channels: descriptions, critique and recommendations', FAP 24 working paper, there are several widely used methods for correcting measurements in open channels in order to gain a clearer understanding of the actual flow distributions. However, as stated in the working paper, none of these methods are ideally suited to velocity measurements made on large braided rivers such as the Brahmaputra.

Therefore, in order to achieve the objectives of the FAP 24 / UoN joint study, namely to define the secondary flow pattern around a simple braid bar in the Brahmaputra, it is necessary to derive a new technique to correct velocity measurements without the shortcomings of previous methods. Any velocity correction method employed should be designed to fulfill the aims of a particular study. The FAP 24 / UoN study is interested in secondary flow patterns from a qualitative perspective and not in order to quantify terms in force-balance relationships. Therefore, the method outlined below has been designed with these objectives in mind.

2. Definitions

The measured components of flow velocity are referred to as a measured horizontal velocity magnitude (V_H) and direction (φ), and vertical velocity (U_Y), whilst the corrected flow components are referred to as primary (U_P), secondary (U_S) and normal (U_N).

In order to simplify the problem, the measured vertical velocity is assumed to be equal to the normal velocity, i.e. the flow is parallel to the water surface over the whole flow depth. Two methods of velocity correction can be applied to the vertical velocities, either a derivation of Dietrich's continuity method or the Markham and Thorne plane of no net flow method. Due to the covergae of ADCP measurements during this study, i.e. the missing near surface and near bed velocities, neither of these two methods can be successfully applied to the data. Figure 5 shows a plot of percentage coverage by the ADCP against flow depth. For the flow depths encountered during this study (typically 0-15m), the coverage of the ADCP measurements lie below 80 %. In fact for the average ensemble depth in May of 6.9m, the ADCP covers 66.5% of the flow. This compares with 66.7% in August and 66.5% in September.

3. Velocity correction in a multi-threaded cross-section

Braided rivers are characterised by a multi-threaded planform. In any one cross-section in a braided channel there may be several thalwegs present, separated by various bed features. Due to the roughness of the channel boundary, you would expect to find that each of these thalwegs contains a core of local maximum velocity which will act as a semi-independent stream. It is proposed that each of these streams of water will have their own primary and hence secondary orthogonal velocity directions. Therefore any technique for correcting velocity measurements in a braided channel should be able to define separate secondary flow planes for each stream of water in a multi-threaded channel cross-section.

In order to achieve this goal a secondary flow function was derived to search for secondary flow, measuring secondary activity for various alignments of the flow within the river channel. The proposed secondary flow function measures helical rotation for various cross-sectional alignments and highlights peaks at certain orientations. However, this method is not exclusive to helical and can with the correct interpretation, as is shown in Chapter 4, measure lateral secondary flow due to topographic steering or longstream continuity effects. The major advantages of this method over those outlined in McLelland et al. are:

- The technique allows more than one primary and secondary flow planes to be defined in any given cross-section.
- The technique uses measured velocity data only, therefore, it does not introduce uncertainty in the correction applied due to extrapolation of data to the channel boundary.
- It does not require consecutive downstream bank to bank surveys in order to monitor continuity within the measurements.
- Primary and secondary planes are orientated on the flow not on the channel boundaries, which can be misleading in a rivers such as the Brahmaputra with a very high width to depth ratio.

4. Secondary flow function

The secondary flow function for a given flow orientation (α) is defined as follows:

$$\Sigma \frac{U_S}{|U_S|}.(y - Y).W \qquad (1)$$

where:

U_S	=	$V_H \cdot \cos(\varphi - \alpha)$
α	=	flow orientation
y	=	depth of measurement bin
Y	=	ensemble mid-depth
W	=	ensemble width

this function is summed for all the measurements bins within a given ensemble. The absolute value of this summation is then summed again for all the ensembles with a cross-section. A plot is then made of the total summation against all possible flow orientations, i.e. 0 to 180° from North.

For a simple channel with only one core of maximum velocity the above function will show a peak at a certain value of α (fig. 1). This α value represents the orientation of the flow which best exhibits helical rotation. All the measured velocity components can now be corrected using this new flow alignment and plots of secondary and primary velocities can be drawn (Fig. 2).

However, in multi-stream cross-sections, such as a flow bifurcation, more than one peak in the secondary flow function may be present (Fig. 3a). Each of these peaks will represent a value of α for which one or more of the streams are exhibiting maximum helical rotation. A plot of the secondary flow function at the peak values of α against ensemble no. (Fig. 3b & c) then can be used to determine which peaks in the secondary flow function correspond to which streams in the channel. The channel can be sub-divided using the method proposed of locating the position of minimum depth averaged velocity between cores of maximum velocity. Each stream of water can be given an independent orientation and semi-independent plots of secondary and primary velocities and be drawn (Fig. 4).

5. Summary

The major shortcomings of the previous methods of velocity correction derived for single thread channels, such as those used in Bathurst et al., (1977), Dietrich and Smith (1983), and Markham and Thorne (1992) can now be overcome for a multi-threaded braided channel such as the Brahmaputra River.

Previous plots of secondary flow patterns at bifurcations and confluences such as those reported in Bridge and Gabel (1992), showed purely diverging/converging flow or did not allow for lateral flows. Using this technique of flow correction, an independent primary and secondary plane can be assigned to each stream of water in a river bifurcation or confluence enabling any helical cells with each flow to be visualised.

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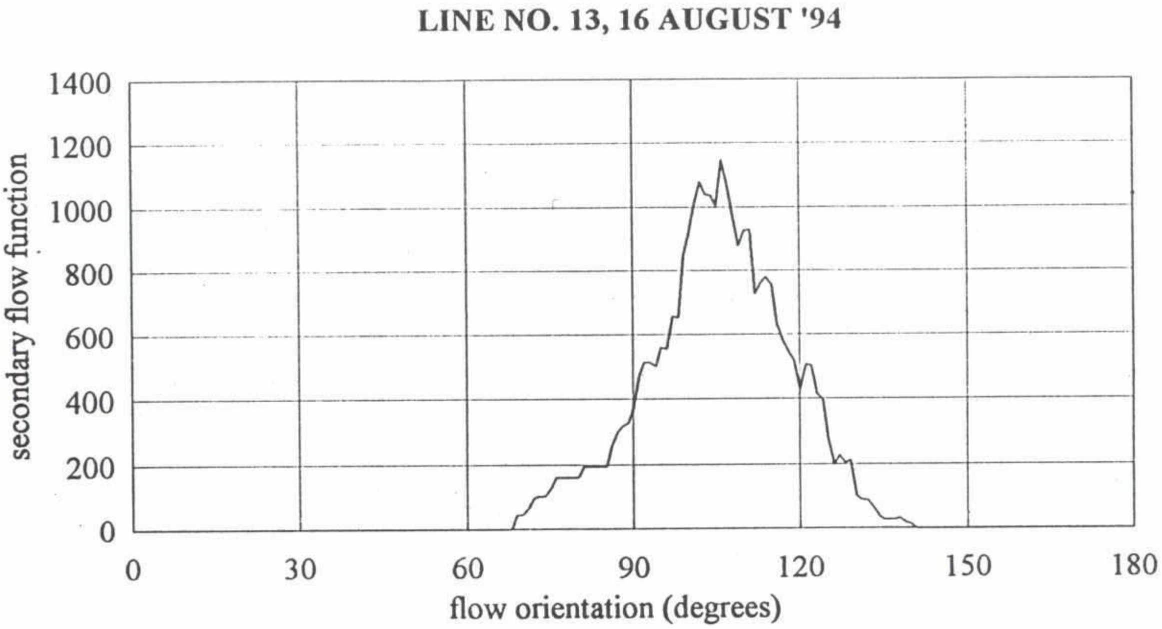


Figure 1 Secondary flow function for line no. 13 (August). Note: peak value of secondary flow function at a flow orientation of 106° from North.

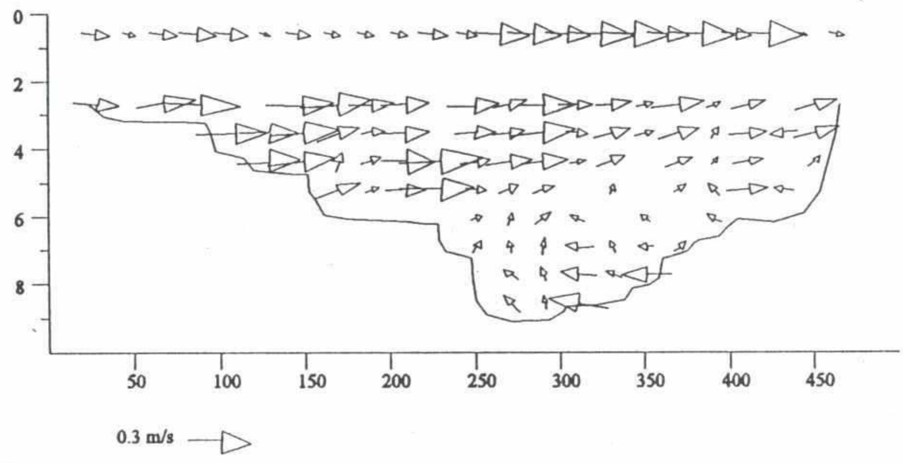


Figure 2 Secondary currents for line no. 13 (August) plotted at an orientation of 106° from North

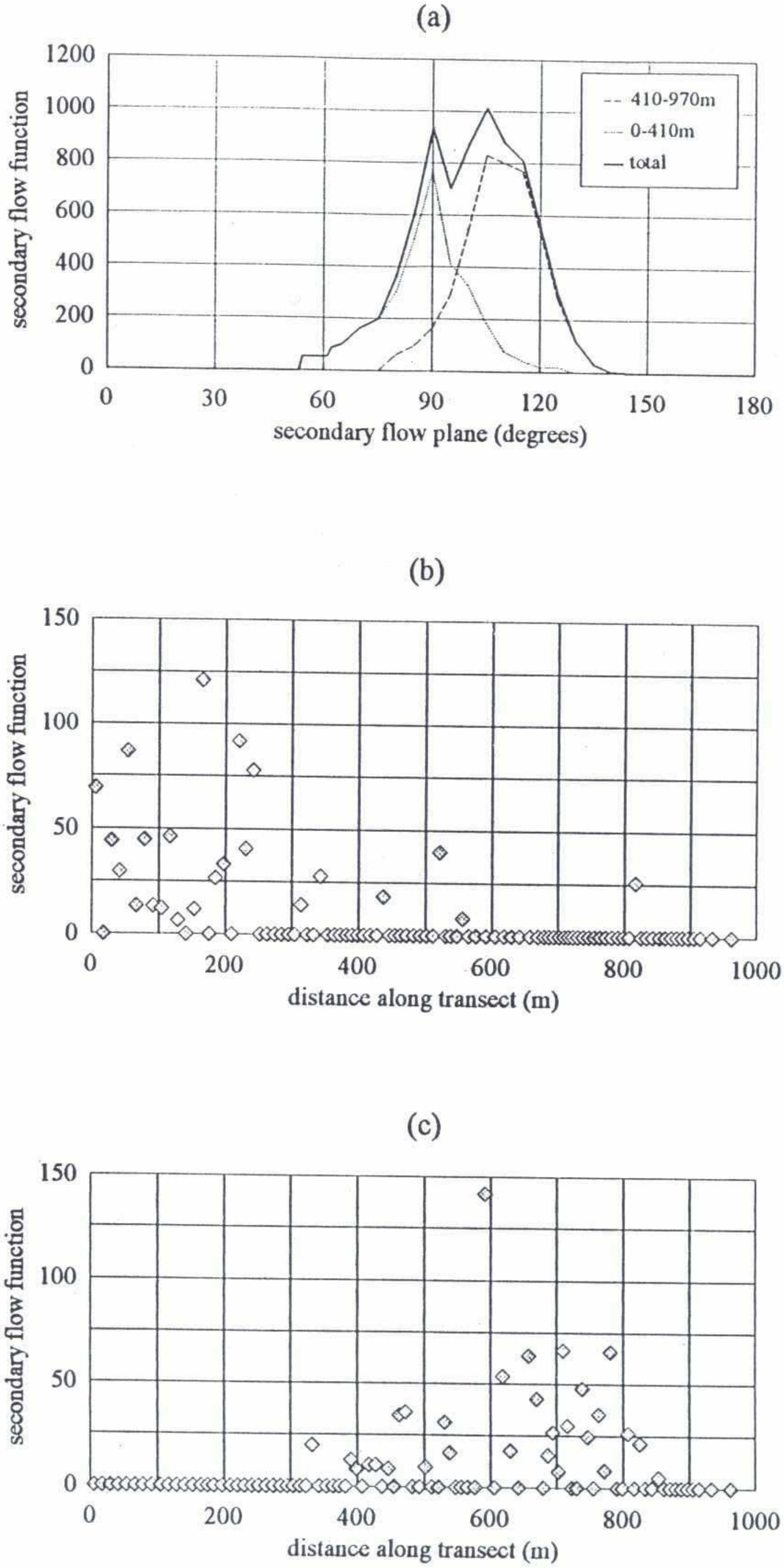
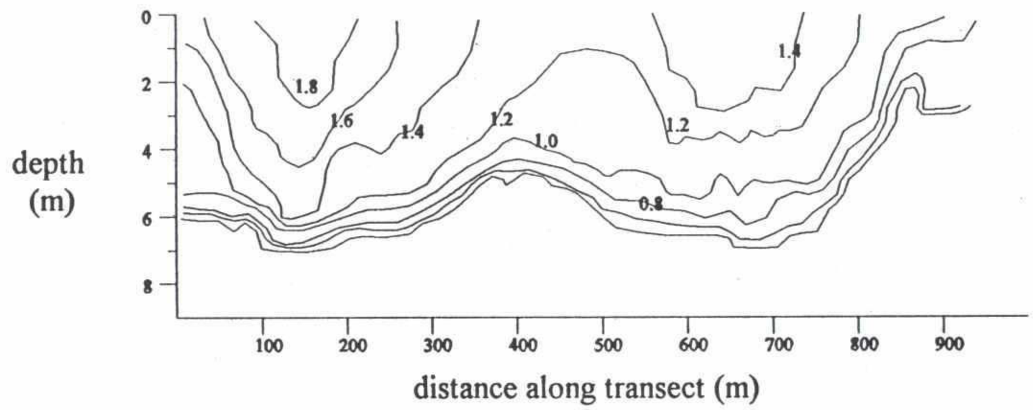


Figure 3 Secondary flow function for line no. 3 (September). (a) secondary flow function on the flow plane, (b) secondary flow function 0-410 m, (c) secondary flow function 410-970 m.

(a)



(b)

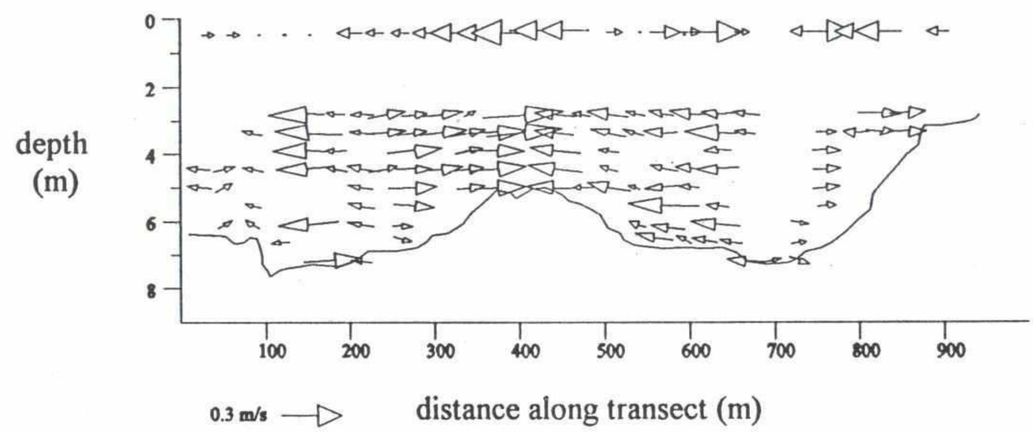


Figure 4 (a) primary (b) secondary velocity plots for line no. 3 (September). 0-410 m plotted on a flow orientation of 88°, 410-970 m plotted on a flow orientation of 114°.

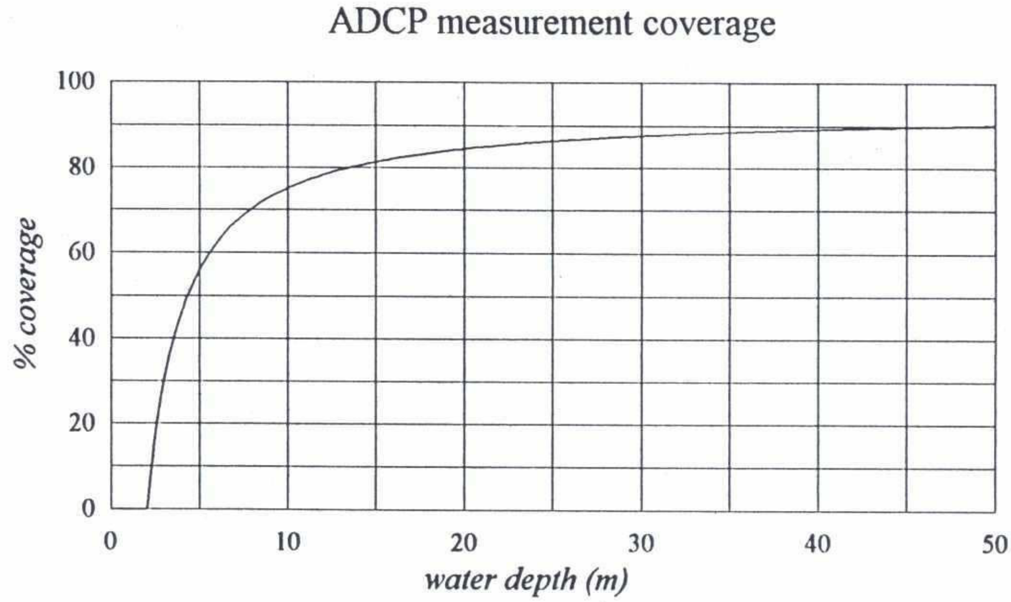


Figure 5 ADCP measurement coverage for configuration used on board DHA vessel during study

APPENDIX B

Appendix B

1. Introduction

A special survey was organised on the 28th and 29th May 1994 by the project Advisor and the survey team at cross section no. 5. The main objective of this special survey was to test the Delft-Bottle sampler purchased by FPCO, on the recommendation of the Project Advisor. The Delft-Bottle was employed together with the other flow and sediment transport equipment on board the DHA vessel including the ADCP, to confirm or deny the existence of a significant near-bed material load, which is suggested to be morphologically important.

The ADCP data collected during this special survey allowed the opportunity to examine the extent to which longer measuring periods in a fixed position altered the observed flow patterns.

2. ADCP measurements

During sediment sampling the ADCP recorded velocity profile data at a fixed position averaging the data every 50s over 1-2 hours. This was repeated during the survey at 4 profile positions along the cross section.

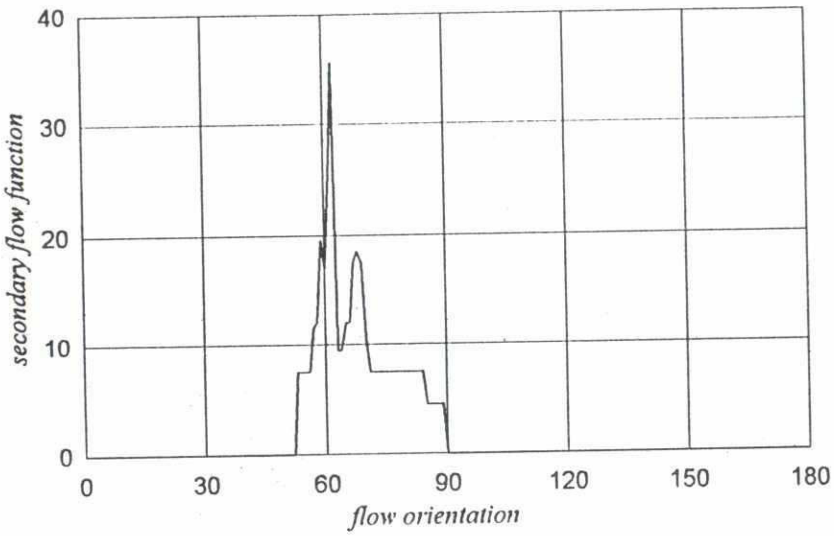
The standard method used throuhout this report for orientating ADCP measurings was applied to the profile data and the results are shown in Figure 1. The plot of secondary velocity vectors (Fig 2.b) clearly displays helical rotation in the main portion of the channel. The direction of rotation and nature of the secondary flow pattern onserved here closely resemble the inferred pattern of secondary flow for cross section 5, in May (Figure 7.3(a), main report).

3. Discussion

The observations presented here demonstrate that the longer averaging periods used in the special survey helped to clarify the secondary flow pattern at this site. This result would seem to suggest that the present 6s averaging period combined with present speed of transect crossing may not be sufficient in order to observe clearly the coherent flow patterns. This is not to say that the present survey technique and data do not give an indication of the flow patterns and clearly at some cross sections reported in the main body of the report, such as cross section 13 in August, little would be gained from a longer averaging period.

The use of profile data as opposed to transect data for measuring flow patterns along a given cross section has obvious disadvantages in terms of time and resources. An alternate therefore, may be a longer averaging period for the transect measurements combined with a slower transect crosssing. Further special studies into the effect of altering the measuring periods both in terms of ensemble averaging periods and transect crossing times on the observations of coherent flow patterns is needed.

(a)



(b)

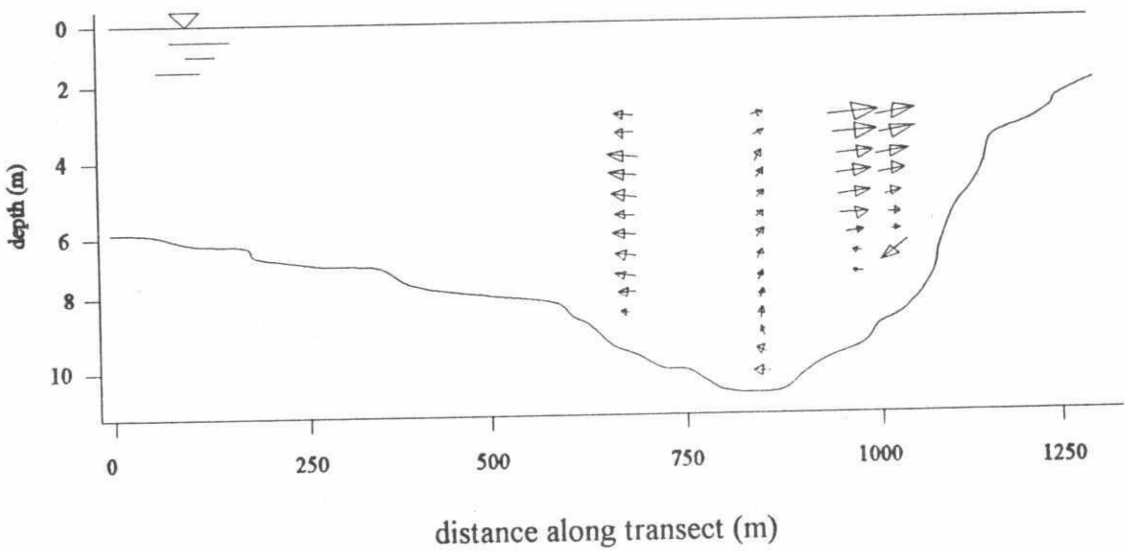


Figure 1 (a) Secondary flow funcion and (b) secondary velocity vectors for special survey, May 1994