UNIVERSITY OF PORT ELIZABETH
ZOOLOGY DEPARTMENT
REPORT SERIES

STUDIES ON THE HYDRODYNAMICS AND SEDIMENTATION OF THE BUSHMANS RIVER ESTUARY, EASTERN CAPE COAST

by

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Report number 19. DECEMBER 1981

REPORT ON STUDIES OF THE HYDRODYNAMICS AND SEDIMENTATION OF THE BUSHMANS RIVER ESTUARY, EASTERN CAPE COAST

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DURATION OF PROJECT : 1.1.1980 - 31.12.1981

OBJECTIVES OF RESEARCH :

The objectives of this particular study were to investigate the sedimentological characteristics and the hydrodynamics of the Bushmans River estuary. Particular attention was given to the feasibility and consequences of the deepening (by means of dredging) of some channels in the lower reaches of the estuary. The effect of the road bridge on the hydrology and sedimentation have also been investigated.

INTRODUCTION :

This study was initiated in 1979 by the Department of Environment Affairs and funded during 1980 (R6000) and 1981 (R6000) by the CSIR (CSP). The request for dredging was made by the Bushmans-Kariega Trust and their full motivation is appended (Appendix I). The location of the Bushmans estuary is shown in Fig. 1.

The study was completed in October 1981 and a scientific article has been written which will be submitted to a scientific journal for publication. A copy of the manuscript is included (Appendix II).

The results, conclusions and recommendations are summarized in this short report. The reader is referred to Appendix II for more detailed information. A report dealing with the sedimentological characteristics of the Bushmans estuary has been completed by Reddering and Esterhuysen (1981).

The tidal dynamics of the Bushmans Estuary have been investigated in a short, scientific study design to provide a physical basis on which to evaluate the effects of possible dredging activities in the area (Uncles, Baird and Reddering, 1981).

A numerical model of the estuary was constructed which computed the tidal currents and tidal elevations of water level as functions of distance along the estuary. These computed data agreed well with the observations that were made. Therefore, it was considered that the model provided a reliable simulation of physical processes in the Bushmans Estuary, and could be used to investigate some of the processes which could not be observed experimentally in this short study.

Sediment distribution and dispersal patterns were determined from samples collected on a pre-determined sampling grid. The first fourteen sample lines are 250 m apart but the intervals were increased to 1000 m above the Ghio Bridge (see Fig. 2). Samples were collected by coring across the river bed at the surface as well as at a depth of 0,5 m into the substrate.

The following sections deal very briefly with the main features of water circulation in the region, as deduced from the model and verified by observations. The sediment transport paths produced by this circulation are then described, along with the possible effects of the proposed dredging, and the likely consequences which have resulted from the construction of the road bridge linking Port Alfred and Alexandria. It is important to emphasize that the problems associated with the evaluation of sedimentation rates are very difficult in a natural system like the Bushmans. Insufficient historical and contemporary data are available on channel topography, freshwater inputs and sand fluxes to make any other than qualitative assessments.

Water Circulation

The tidal regime in the coastal water adjacent to the Bushmans Estuary is mainly semidiurnal (high water roughly every 12½ hours), with a springs tidal range of about 1.5 m (the depth difference between high and low water). The tidal range decreases rapidly to about half its coastal value progressing into the estuary across the shallow, constricted tidal inlet (or mouth) (see Fig. 3). The range then decreases slowly towards the head of the estuary at Harvest Vale, some 33 km from the mouth. The tidal currents have their highest values of about 1 m s^{-1} at the tidal inlet during spring tides, and have low values (less than about 0.3 m s^{-1}) at distances greater than around 6 km from the tidal inlet.

An important consequence of the shallow, constricted tidal inlet is the effect it has on tidal propagation. Not only does it greatly reduce the tidal range and produce strong currents locally, but it also distorts these currents in such a way that flood tidal currents inside the estuary tend to exceed ebb tidal currents, but persist for a slightly shorter time. This influences the movement of sediment, for if sand is available at the tidal inlet, then it can be moved into the estuary as bed-load solely by the action of the periodic tidal currents. The up-estuary transport arises from the facts that only small increases in current speed are needed to produce large increases in sediment transport, and that flood currents exceed ebb currents. During freshwater spates the ebb currents can be very large as fresh water is discharged to sea, and the direction of sediment transport can be reversed.

Long-term (non tidal) circulation has not been investigated for the Bushmans. However, measurements of water density along the estuary indicate that density currents (up-estuary at the bed, down-estuary at the surface) will be very small. Localized, long-term circulations will occur at bends, around shoals and off promonotories and these will be very important to the local re-distribution of sediment.

Sediment distribution and transport

It was concluded from the sedimentological study (Reddering and Esterhuysen, 1981) that the sand bars extending from the inlet to about 3,5 km up-stream are of marine origin. This was determined from the mineralogy of the sediments, the roundness of the quartz grains, grain sizes and the sub-microscopic surface textures of the sand grains. The morphology of the sediment bodies which extended to 3,5 km up-stream indicates clearly that it has migrated up-estuary from the tidal inlet.

Sediment will move as bed-load into the estuary in response to asymmetric flood and ebb tidal currents. Some movement of sediment in suspension may also occur. Tidal stresses at the sea-bed (the frictional drag on the sediment) rapidly decrease up-estuary, so that whilst coarse marine sand will reach a position near the mouth where spring tide currents are unable to move it further as bed-load, finer material will be transported and deposited higher up-estuary. This distribution of marine sand sizes has been observed in the lower 3½ km of the estuary (see Uncles, et al., 1981).

The explanation for the presence of marine sand in the lower reaches of the estuary is thus that marine sand moves up and down channel as bed-load during flood and ebb tides, but has a nett up-channel transport due to positive residual stresses. Suspended sand in the coastal surf-zone is thus transported into the estuary by flood tides, where it settles out at positions which is dependent on the tidal current velocities.

The bed in the upper-reaches of the estuary (greater than 3½ km from the mouth) is covered with mud derived from freshwater discharges, and is probably carried in suspension during times of spate, being deposited to form a cohesive layer of sediment as the spate subsides. The low up-estuary tidal stresses are unable to transport the cohesive mud, whilst mud deposits near the mouth are resuspended and flushed from the estuary.

An attempt was made to estimate sand transport rates into the estuary using a widely accepted engineering formula (the Ackers and White sediment transport relationship). Results showed that the rate of transport is approximately 20 m³ per day, averaged over a spring-neap cycle. This is equivalent to an increase in mean sand depth of about 2 cm per year over a distance of 3½ km from the tidal inlet. The inflow of sediments can be balanced by flushing of sediment from the estuary during times of spate.

Effects of dredging

It has been proposed by the Bushmans-Kariega Trust that some existing channels be deepened by dredging (see Fig. 4, and Fig. 1 of Appendix I). The quantity of sand to be removed amounts to about 230 000 m³ in selected areas (see Fig. 4) at an estimated cost of approximately R650 000. For cost estimates, see Appendix II.

In a one dimensional model, the increase in estuarine volume can only be accommodated by increasing the cross sectional areas over the affected regions. The increase in volume and depth have been taken into account in the model, for all states of the tide. The effects of dredging on tidal elevations, current speeds and stresses are of most interest.

The model has been used to investigate the gross effects of possible dredging, subject to its limitations of being able to compute along-estuary variations only. In the newly dredged region, currents and tidal stresses will decrease owing to the fact that the increased area of estuarine cross-section carries very nearly the same volume of water per tidal cycle as the original area.

These smaller currents and tidal stresses in the newly dredged region will lead to increased sedimentation. However, the time required to fill-in dredged channels, based on the up-estuary rate of sediment transport in the Bushmans, is very many years. A much more important role to sediment in-fill of dredged channels is played by local redistribution of sediment in the vicinity of the channel, with no net changes in the total amount of sediment in the estuary. A typical local process might involve the slumping of sand into the newly dredged channel from adjacent banks which are not in equilibrium with respect to the modified tidal currents. Alternatively, a newly dredged channel, if sufficiently large, might reduce the currents in a neighbouring natural channel to such an extent that they are unable to transport slumped sediment, and thus fill-in.

Experience in United Kingdom estuaries is that dredging, once started, must be carried out on a continuous basis if rapid in-fill of either dredged or natural channels by such local processes is to be prevented (Dr M. Kendrick, Hydraulics Research Station, Wallingford, U.K., personal communication).

Reference to Fig. 4 shows that the deep channel meanders. Such meandering channels are common in rivers and small estuaries. They are generally unstable features, and a deep channel can migrate from one side of an estuary to the other during the course of time. One possible trigger for such migrations would be a freshwater spate curring open a new channel, which remains after the spate has subsided, and subsequent sedimentation of the original channel. Therefore, it is quite possible that what was once a deep channel close to one shore of the estuary might migrate to the other shore, entirely by natural causes. In the course of time it could return.

The areal extent of the inter-tidal shoreline will remain essentially the same and changes in tidal elevations will be negligible after dredging, and thus also the associated intertidal, benthic, biotic communities will be minimally affected. In the dredged areas, which are all sub-tidal, all benthic life will be eliminated but there is reason to believe that the faunal communities will re-establish themselves in a relatively short period of time, as shown by recent studies in the marine canals of the Kromme estuary (Baird, et al, 1981).

During dredging the suspended particle fraction in the water col~~l~~umn is considerabl~~e~~y increased. The higher turbidity will result in decreased light penetration with a resultant reduction in primary production of submerged plants such as Zostera, and of floating phytoplankton. This is especially so if dredging operations continue over extended periods of time. It is not possible to provide estimates of reduced primary produc= tion in the Bushmans estuary since these values are in any case not available. It has been shown, however, that primary production can be reduced by as much as 50% during dredging operations in the Ems Estuary, Netherlands (de Jonge, 1981).

Surely in our shallow estuaries, light is normally in Xcess.

A further ecological implication is that during dredging organic particles caught up in the sediments will be resuspended which could have a high biological oxygen demand. The dissolved oxygen in the water collum could then be depleted at a greater rate than under normal conditons, with an obvious adverse effect on the animals living in the water collumn.

can be est. from sediment composition.

Effects of the Road Bridge

The road bridge (Fig. 4) tends to "pin" the deep channel to the south bank. This may have reduced the mobility of the deep channel (as described above) to some extent, and may have hindered migration of the deep channel from the south shore to the Kenton-on-Sea shore. However, the present channels are very similar to those which existed when the early aerial photographs were taken. The bridge cannot, therefore, be held responsible for any long-term changes to the channel system, but may have contributed to its stability.

The road bridge will produce a local increase in sedimentation. Before the bridge was built, spring tides and freshwater spates were, apparently, able to overtop the "island" on which the central part of the bridge sits, and thus flush away fine sediment. With the central part of the bridge preventing this flushing, some localized build-up of fine material would be expected immediately up-stream and down-stream of the bridge. The mud banks on either side of the bridge have, in fact, increased from about 130 m in 1957 (the bridge was built during 1958) to the present 810 m, measured along the length axis of the estuary.

Spoil disp~~osition~~osal

Dredged material cannot be dumped in the flood plain or on existing mudbanks within the estuary. Spoil will have to transported to some site above the flood plain. If not, it will simply wash back into the estuary with the next rain or mild flood. This condition obviously has some financial implications which will add to the cost of dredging.

Conclusions

The tidal properties of the Bushmans Estuary result in an up-estuary transport of sand from the mouth. Because the tidal stresses rapidly decrease progressing into the estuary, this material is deposited within a few kilometers from the mouth. The rate of sedimentation is very small, and fresh-water spates are very important to the flushing of sediment from the estuary, and for its ultimate equilibrium. If widespread net sedimentation is occur=ring within the estuary (and no evidence exists for this) then it is most likely to be a consequence of reduced spate discharges due to damming.

Some idea of freshwater spates to balance marine deposition would help.

If dredging is undertaken then the new channels will probably either fill-in very rapidly with locally redistributed material, or be maintained at the expense of present natural channels. The former seems more likely, so that dredging will have to be undertaken on a continuous basis if channels are to be maintained. The effects of dredging on tidal elevations, shore=lines and shore ecosystems would be very slight.

The effects of the bridge on present conditions seem to be small. It has probably produced a local increase in sedimentation in its immediate vicinity, up and down-estuary of the central support, and increased scour in the deep channels. It is unlikely to have had any significant effect on overall rates of sedimentation in the estuary.

During this short study it has not been possible to measure sand fluxes directly. Such measurements are possible, but require specialized and ex=pensive equipment.

Recommendations

Since the process of shoaling of previously navigable channels appears to be a feature of many estuaries (eg. Kariega, Bushmans, Swartkops and Kromme estuaries) along the Eastern Cape Coast it can be expected that requests for dredging from local authorities will increase. This study on the Bushmans estuary was the first of its kind and it has outlined some of the natural forces operating in a shallow estuarine ecosystem. The need for proper management of such systems is evident especially if one considers the ever increasing utilization of these recreational areas by expanding resident and tourist populations.

I therefore strongly recommend the dredging of all or some areas in the Bushmans estuary (as shown in Fig. 4) on an experimental basis. The effects of dredging could then be closely monitored and the value of such an experiment would be to show

(a) the effects of dredging on the biota;

(b) the rate of recolonization by plants and animals, and

(c) the rate and nature, of sediment build-up.

The feasibility and consequences of dredging could then be properly assessed and applied to other estuaries if the necessary basic information are available.

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UNIVERSITY OF PORT ELIZABETH
12 JANUARY 1982

ENCLOSURES

APPENDIX I : Motivation for dredging, Bushmans-Kariega Trust

APPENDIX II : Manuscript on : Tidal dynamics of an estuary with a constricted inlet . . . . .

APPENDIX III : Costs estimates for dredging

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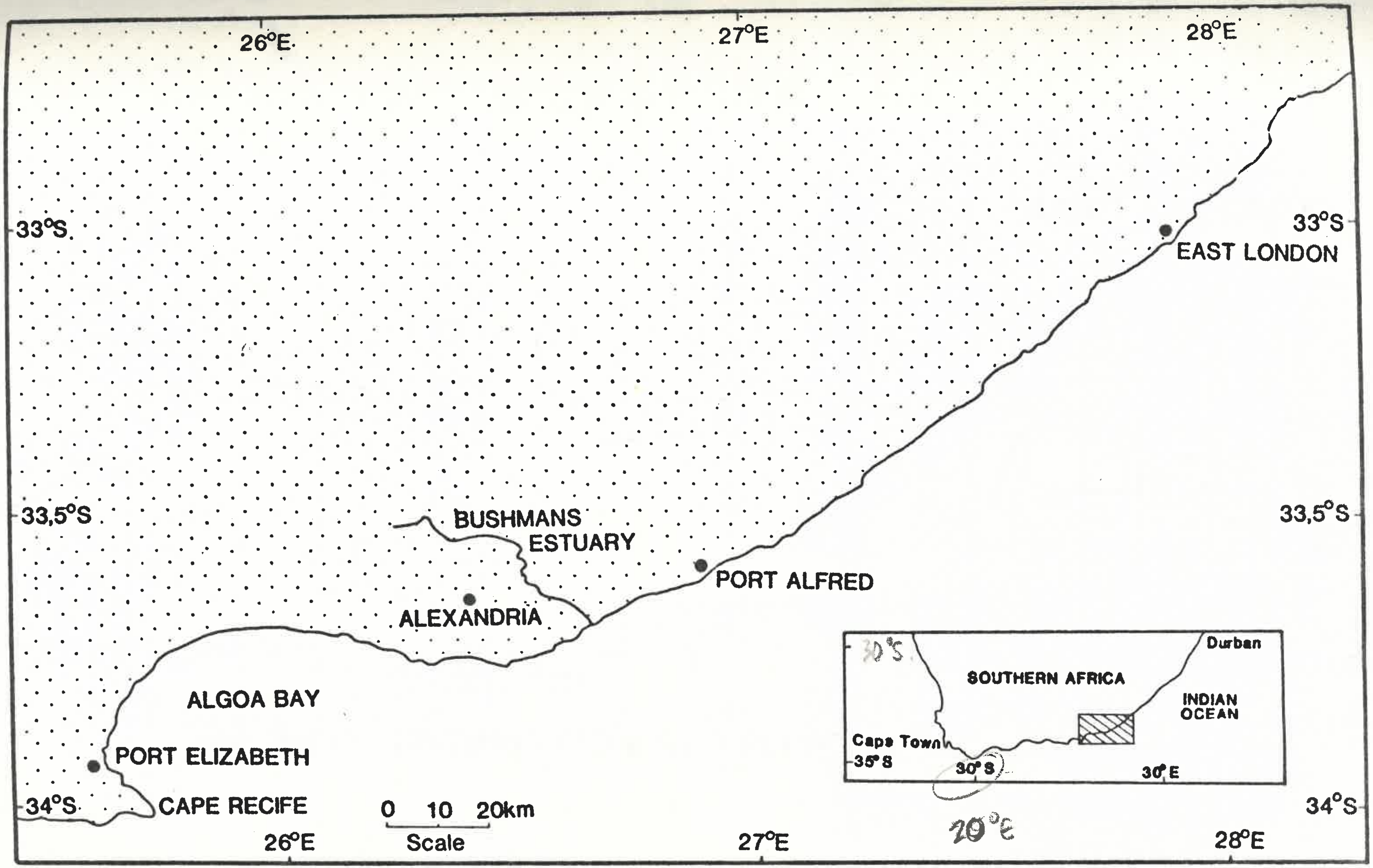
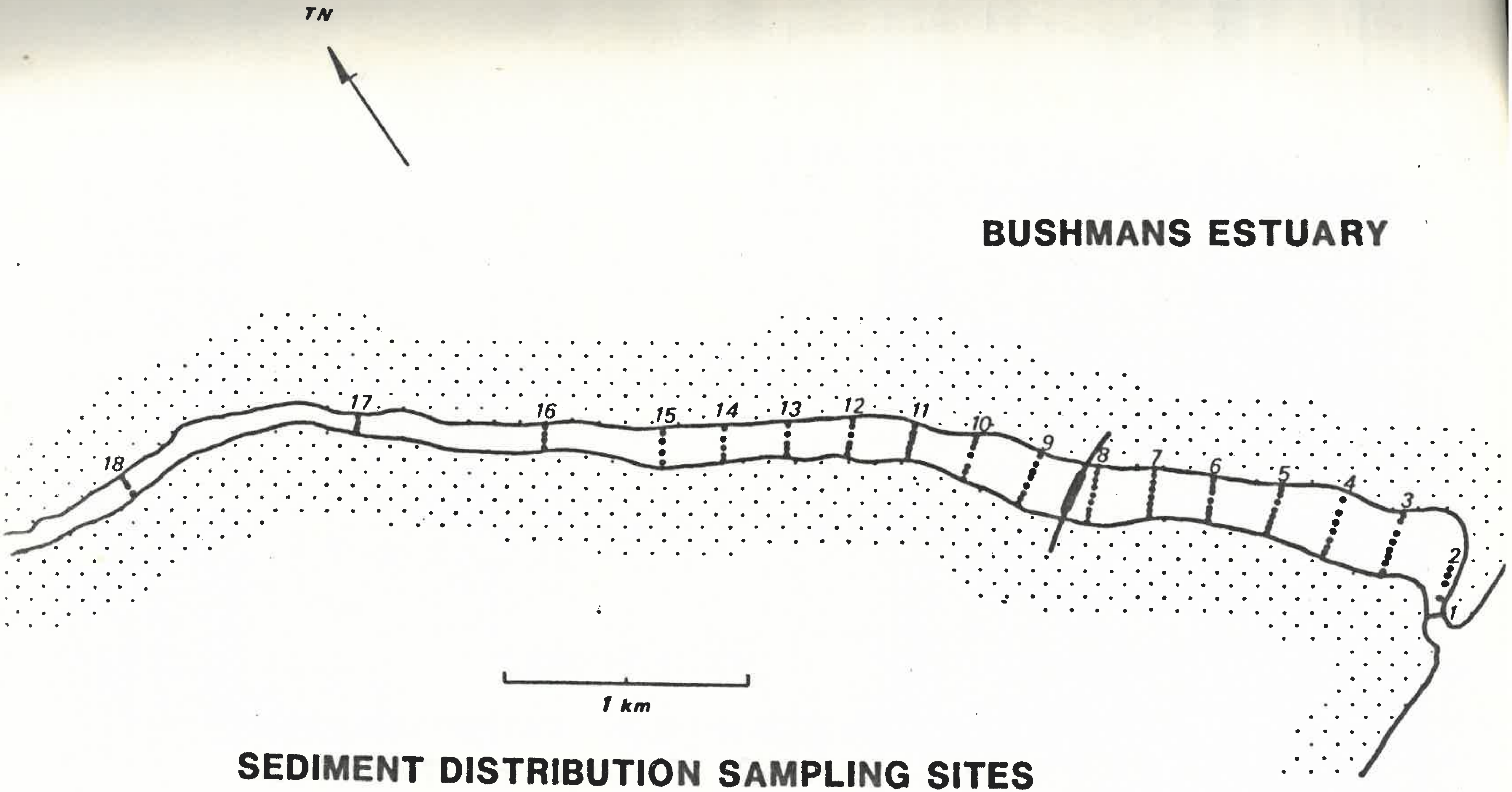


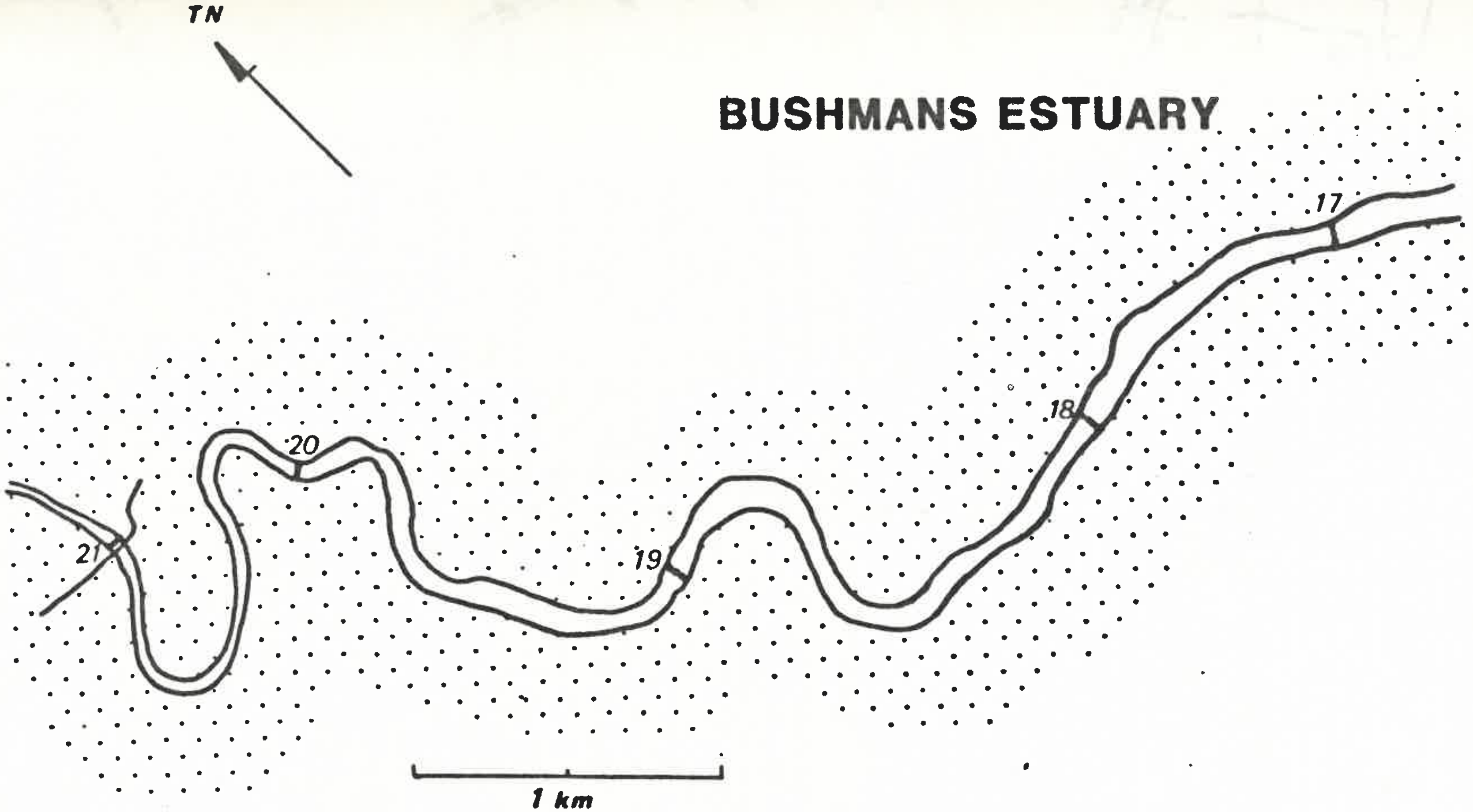
FIG. 1. LOCATION OF BUSHMANS RIVER ESTUARY, EASTERN CAPE.

BUSHMANS ESTUARY



SEDIMENT DISTRIBUTION SAMPLING SITES

Fig. 2


BUSHMANS ESTUARY

SEDIMENT DISTRIBUTION SAMPLING SITES

Fig. 2

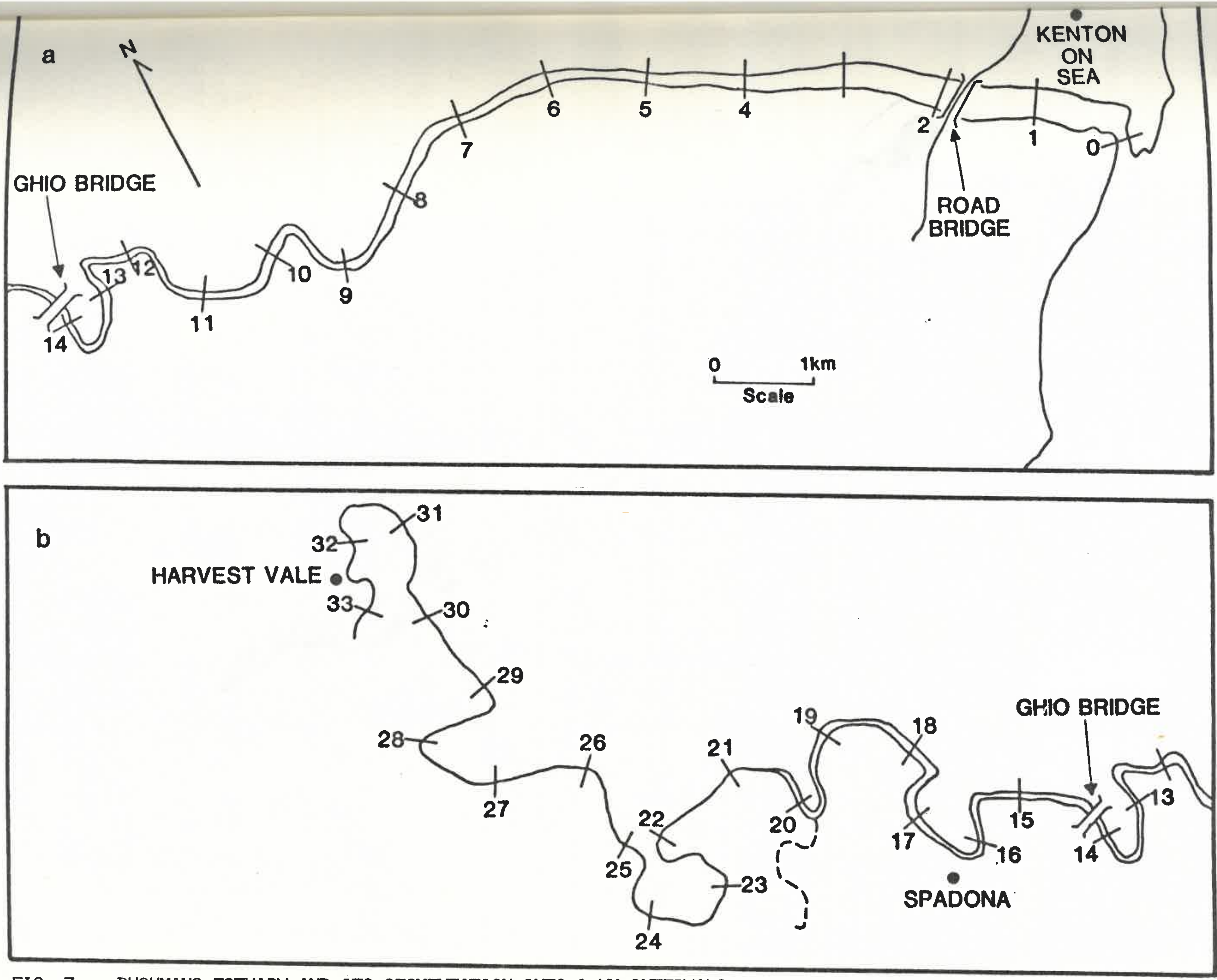


FIG. 3. BUSHMANS ESTUARY AND ITS SEGMENTATION INTO 1 KM INTERVALS.

(A) BETWEEN THE MOUTH AND GHIO BRIDGE

(B) BETWEEN GHIO BRIDGE AND HARVEST VALE.

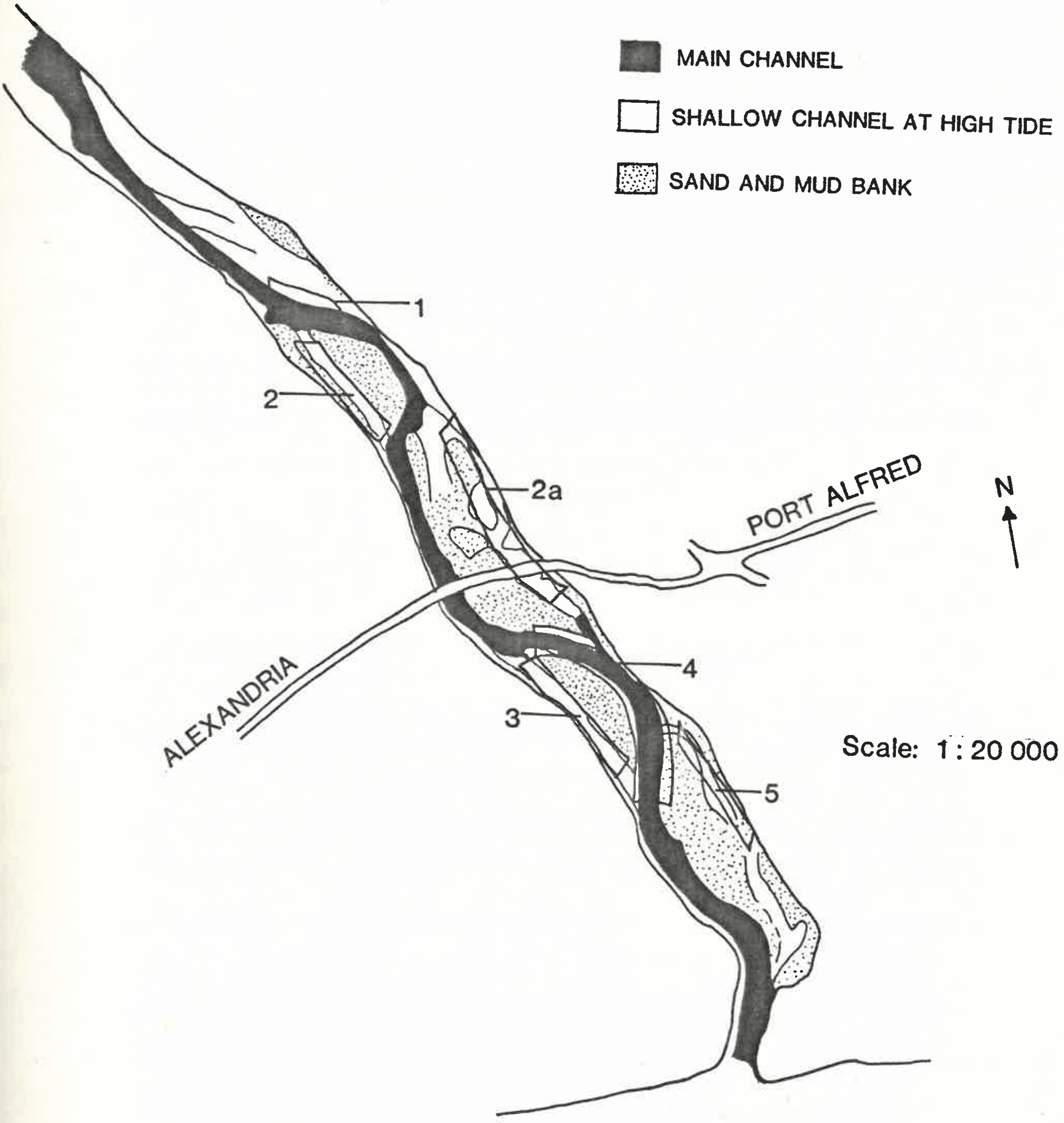


FIG. 4. PROPOSED AREAS FOR DREDGING: 1, 2, 2A, 3, 4 AND 5.

APPENDIX I

MUNICIPALITIES OF BOESMANSRIVIERMOND AND KENTON-ON-SEA AND BOESMANS KARIEGA TRUST:

MOTIVATION FOR DREDGING BUSHMANS RIVER ESTUARY

The Municipalities of Boesmansriviermond and Kenton-on-Sea as well as the Boesmans Kariega Trust have been in close contact with Prof. Baird and his team throughout their two year investigation of the siltation problems in the Bushmans River estuary.

As will be remembered this investigation was initiated at a meeting held at Boesmansriviermond on the 14th September, 1979, under the chairmanship of Dr Dries Visser and subsequently endorsed at a meeting held at the same venue on the 6th August, 1980 under the chairmanship of Dr D.H. Swart.

This report is now complete and is to be submitted to the office of the Prime Minister early in January, 1982. We, the local authorities and the B.K.T., are aware of the thoroughness of the report. However, we are also fully aware that no trained scientist or engineer could lay his head on the block and declare that dredging is the only and final answer to the problem which is growing worse with every tide. We fully agree!! BUT when the cost of the more permanent solutions (Training walls, sluice gates or changing the direction of the river mouth) are taken into account dredging is by far the cheapest in the short term. In any case dredging would have to be undertaken to reopen the channels of the estuary even if one of the more permanent solutions were decided on and it would remain an ongoing operation due to the drasticaly reduced scouring action of floods.

The municipalities and the Trust are, therefore, of the opinion that dredging should take place as a matter of urgency especially as it has now been established that the increase in the mean sand depth is in the region of 2cm per year over a distance of 3.5Km from the mouth and there are some areas where there are very few centimeters left.

According to the suppliers of the Mudcat Transportable Dredger, General Services Industries, the dredging operation can be done for R641,960 (based on cost per m^3). See attached letter R1.58 per m^3), including the capital outlay on the machine which could either be sold or used in other critical areas after the operation. (See attached documents).

The cost is minimal when compared with the valuation of the properties in the two Villages, namely:-

Boesmansriviermond (Present township	: 409 Erven)	R 6,753,610
Conservative Estimate Extension No 1 to be valued seperately in 1982	: 442 Erven	4,000,000
		R10,753,610
Kenton-on-Sea (Present township)		R14,628,970
Conservative Estimate Extension No 13 to be valued seperately in 1982	: 220 Erven	2,200,000
		R16,828,970

However, the rates income from the above valuations cannot cope with a dredging operation on top of the present anticipated expenditure on roads, water and sewerage schemes. It is, therefore, imperative that the State provide direct assistance to the local authorities for the preservation and maintenance of the Bushmans River estuary as a National environmental asset. The addresses on the attached Voters Roll fully proves the above statement. Kenton-on-Sea also have ratepayers from the whole of Southern Africa.

What the municipalities urgently require to be done is the following: (Here refer to the sketch map attached):

1. At point D1a to dredge the main channel to 50m wide by 3m deep at low tide.
2. At point D2 to dredge the main channel to 30m wide by 3m deep at low tide.
3. At point D1b to dredge a service channel 15m wide and 2m deep at low tide. (The original proposal was 20m wide there is therefore a reduction of 6,000 m^3 on this channel) (600m x 5m x 2m = 6,000m^3).
4. At point D3 to dredge a service channel 15m wide by 2m deep at low tide.
5. At point D4 to dredge a service channel 15m wide by 2m deep at low tide.
6. At point D1c to dredge a service channel 15m wide by 2m deep at low tide. (This proposal was omitted at the meeting of the 6th August, 1980 but it has become essential to the development of Kenton-on-Sea Extension No 13. Being approximately 1000m long it involves dredging an additional 25 to 30,000 m^3.

The total /3..

As previously stated the total cost of this operation based on the figures supplied by Mr Ellis of General Service Industries would be R642,960 (based on cost per m^3) of which R289,040 would be capital outlay on plant which could be easily transported by lowbed trailer to other critical areas such as the lagoons and lakes between Knysna and the Wilderness, the Zwartkops River or the Kariega River. This cost is exceedingly low for an experiment in the preservation of the National Environment. Experience gained on the Bushmans River would provide valuable scientific data relating to a problem which is common to all the rivers of the Republic which would also be of immense value for future operations. The local authorities and the Trust have limited capital reserves which they can call upon to assist such an operation up to a limit of about R50,000. However, they make these representations in the sure and certain faith that there will be a positive reaction from Government especially in view of the fact that we have it on record from the Director General of the office of the Prime Minister "that all the controlling authorities involved accept that the Bushmans River estuary will enjoy first priority where dredging must take place".

Signed: ....

MAYOR

....

TOWN CLERK

BOESMANSRIVIERMOND

....

MAYOR

....

TOWN CLERK

KENTON-ON-SEA

....

CHAIRMAN

....

SECRETARY

BOESMANS KARIEGA TRUST

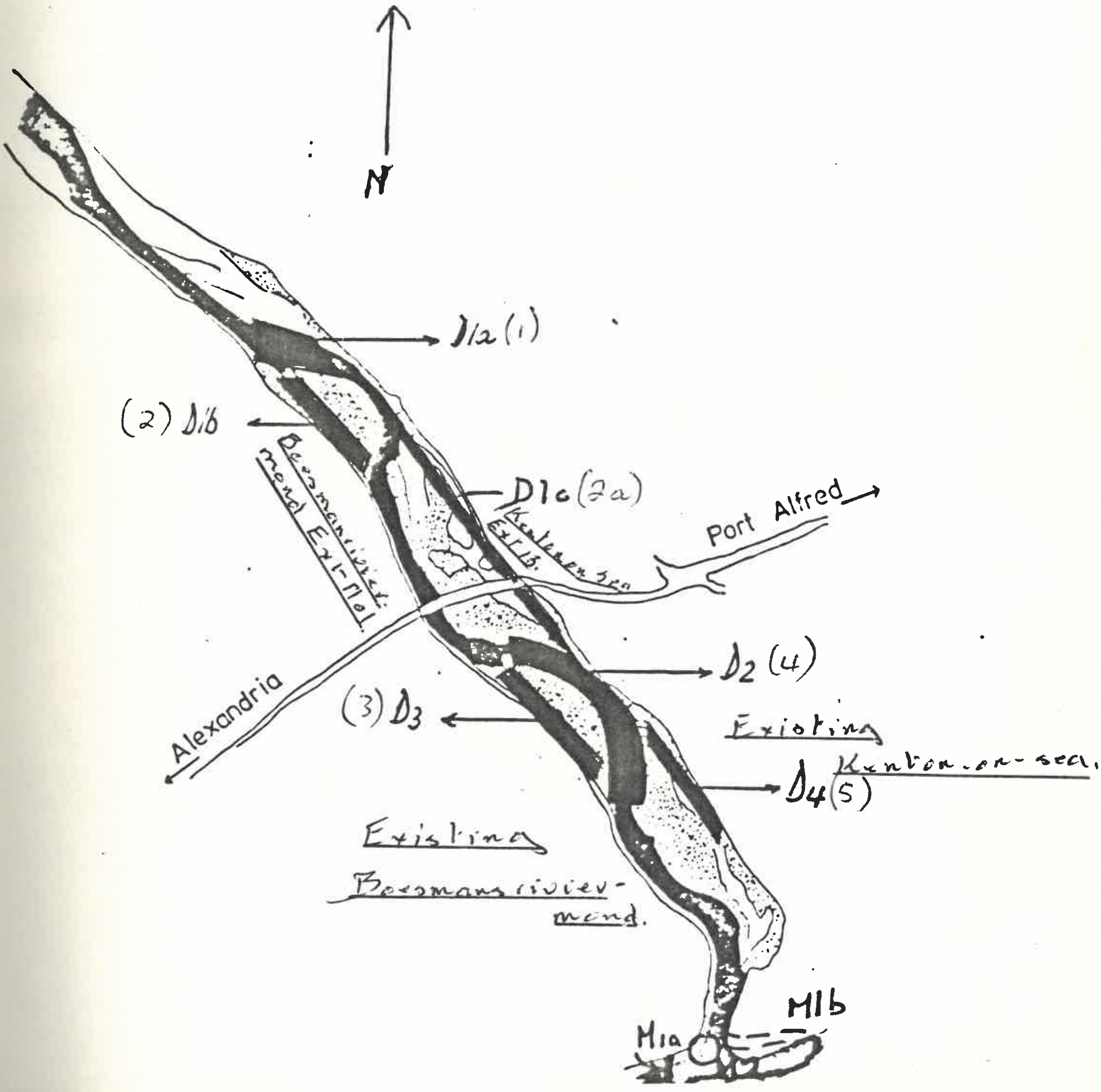
Fig 1: [illegible] (D1a+b, D2, D3 + D4)

Scale : 1 : 20 000

▆ main channel

☐ shallow channel at high tide

▨ sand and mud bank



APPENDIX II.

TIDAL DYNAMICS OF AN ESTUARY WITH A CONSTRICTED INLET, AND APPLICATION TO THE BUSHMANS ESTUARY, SOUTH AFRICA.

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(First draft)

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Keywords:

Bushmans Estuary;

South African coastline

Estuarine circulation;

Estuarine sedimentation.

Abstract

The tidal dynamics of a short, shallow hypothetical estuary having a constricted tidal inlet as are investigated. The bathymetry of the estuary approximates that of the Bushmans Estuary, South Africa. Overtides are generated at the inlet and propagated up-channel, where they lead to an asymmetry between flood and ebb tidal currents. The asymmetry produces an up-channel-directed residual frictional stress at the bed of the estuary. The residual tidal stresses, and maximum tidal stresses over a tidal cycle, are compared with observed data on sediment bed type in the Bushmans Estuary. The role of floods in flushing sediments from this estuary is described.

Introduction

Asymmetry between flood and ebb currents in an estuary influences the residual tidal stress at the bed of the estuary (McDowell and O'Connor 1977, Hunter 1979, Pingree and Griffiths 1979). In the Severn Estuary, U.K., a bifurcation point exists between seaward-directed, and up-estuary-directed residual tidal stresses due to M_2 and M_4 tidal interactions (Pingree and Griffiths 1979), and the mechanisms responsible for this feature have been investigated using a linearized, one-dimensional model of the overtides (Uncles, R.J. in press). In this model, non-linear generation of overtides is represented by source terms which describe interactions between tidal flow and changes in depth or breadth over a cross-section, frictional interaction between the tidal flow and Stokes drift, interaction between the tidal fluctuations in water depth and frictional retardation, and non-linear advection. The Severn is a long estuary (≃ 140 km) with a wide inlet (≃ 20 km) and a large tidal range (≃ 8 m on average). One of the aims of this paper is to establish whether similar, non-linear processes are important in short estuaries having constricted tidal inlets and lower tidal ranges. This may be considered a comparative study between estuaries of different morphological types, although it is particularly relevant to an understanding of tidal dynamics and sediment transport in South African estuaries. Many of these are short, shallow and possess constricted inlets because of the littoral long-shore drift of sand (Heydorn and Tinley 1980, Bruin 1978).

The tidal elevation, current and stress properties of a hypothetical estuary whose topography and physical characteristics approximate those of the Bushmans Estuary (Fig. 1) is investigated using a one-dimensional, hydrodynamical model. The Bushmans has the morphological properties of interest. It is also of practical importance in that concern has been expressed as to the likely consequences of possible dredging in the area. A sketch chart of the Bushmans estuary is shown in Figs. 2(a) and 2(b). It is segmented into 1 km intervals from $\chi = 0$ at the inlet to $\chi = 33$ km near Harvest Vale (χ being axial distance along the estuary). The Bushmans estuary has been surveyed over 15 unequally spaced cross-sections between the inlet and $\chi = 12$ km. Areas A, breadths, B, and effective depths, H, ($H = A/3$) were determined relative to a fixed datum level (MSL). These data have been used as the basis of the model's bathymetry (Fig. 3). Up-estuary of $\chi = 12$ km the cross-sections are assumed to be 'V' shaped. The depth to breadth ratio at $\chi = 12$ km is assumed to be constant further upstream while the breadth at MSL decreases linearly from its value at $\chi = 12$ km to 10 m at $\chi = 30$ km (close to the actual value in the Bushmans estuary). Up-estuary of $\chi = 30$ km the estuary's width and depth are constant.

Salinity and temperature data in the Bushmans on 24/3/1981 are shown as a function of distance along the estuary in Fig. 4. Also shown is the distribution of σ_t, which is defined by $\rho = \rho_o(1 + 10^{-3}\ \sigma_t)$, where ρ and ρ_o are the densities of estuarine and fresh water respectively. Salinity and density (σ_t) fall rapidly up-estuary of Ghio Bridge (at $\chi = 14$ km) in response to fresh water inputs, and gradients are also large near the inlet. Fresh water inputs to the Bushmans are monitored at a gauging station some considerable distance upstream from the estuary, and therefore underestimate the flow. However, these data indicate that the daily averaged inputs are generally much less than 1 $m^3\ s^{-1}$, but during floods the daily flows can rise to 60 $m^3\ s^{-1}$.

It is shown (Fig. 6) that currents and elevations computed by the model are in reasonable agreement with observations from the Bushmans estuary. Computed stresses can consequently be assumed to correspond to those in the real estuary, and are compared with sediment bed types and grain sizes. The effect of altering estuarine bathymetry on tidal properties is also briefly examined in the hope that such information may give an indication of the possible consequences of dredging in the area.

Basic equations

The equations of continuity and momentum are:

$$\partial \zeta / \partial t = -\frac{1}{B} \frac{\partial A u}{\partial x} \quad \ldots\ldots\ldots (1)$$

and

$$\partial u / \partial t = -\frac{u \partial u}{\partial x} - g \frac{\partial \zeta}{\partial x} - \frac{D u|u|}{H} \quad \ldots (2)$$

n which ζ , u , D and g denote surface elevation, cross-sectionally averaged velocity, drag coefficient and accelleration due to gravity respectively. Density gradients, axial momentum dispersion and meteorological effects in equation (2) are neglected owing to their insignificance to the semi-diurnal and quarter-diurnal tides. The stress on the sea bed (τ) is:

$$\tau = \rho D u|u| \quad \ldots\ldots\ldots\ldots\ldots (3)$$

The numerical solution of equations (1) and (2) has been described for the Severn Estuary (Uncles and Jordan 1980). Essentially the same methodology is used here, so that the procedure will not be reproduced. A space-step of 1.5 km is used in the numerical model, with A, u, D and H defined at x = 0, 1.5 km, 3.0 km, ..., 34.5 km, and B defined at x = -.075 km, 0.75 km, 2.25 km, ..., 33.75 km.

The drag coefficient, D, is maintained constant in time, and is derived from the Chezy coefficient, C, using $D = g/C^2$. An empirically dervied equation for C is given in McDowell and O'Connor (1977, p115), and leads to a value of $D = (6.2 \pm 0.5) \times 10^{-3}$, expressed as a mean and standard deviation for the estuary as a whole. Becuase the standard deviation is small, a spatially constant value of $D = 6.2 \times 10^{-3}$ is used.

Boundary conditions for the model are:

(i) $u(\chi = 34.5 \text{ km}) = 0$ (no flow at the head),
(ii) $(\chi = -0.75) = \zeta p$ (prescribed elevations in adjacent coastal sea) and
(iii) $\zeta(\chi) = 0 = u(\chi)$ at $t = 0$.

The condition of no flow at the mead means that only tidal effects are investigated. Except in the case of severe flooding, and very near the head, fresh water run-off will have a negligible effect on tides in the Bushmans estuary.

Observations in the Bushmans

Measurements of currents were made with simple, vane-orientating meters that determined speed only over a tidal cycle at four stations during 1/4/1980. Stations were occupied in the deep channel at $\chi = 0$, 1.0 km, 2.5 km and 4.6 km (see Fig. 5). Therefore, the assumption must be made that currents are either parallel or antiparallel to a fixed line at each station. Measurements were made at hourly intervals from the surface to the bed in steps of 0.5 m.

No attempt was made to determine either residual currents or vertical structures from these data. Instead, the data at each hour are averaged through the column to provide the depth-mean currents. The time-average of the depth-mean currents over a 12½ h period is then determined, and subtracted from the hourly values to provide a time-series for the depth-mean tidal current, $\tilde{u}$, where $\tilde{u} = u - \langle u \rangle$, and where $\langle . \rangle$ denotes an average over a tidal cycle.

Measurements of surface elevation, ζ, were made during 24/3/1981 using portable float-and-well tide gauges. These were situated near the deep channel at χ = 0.1 km, 1.7 km and 3.5 km (Fig. 5). As with the current meter data, a time-series for the tidal elevations, $\tilde{\zeta}$, is derived from $\tilde{\zeta} = \zeta - \langle \zeta \rangle$.

Fig. 6(a) shows the observed elevations, $\tilde{\zeta}$ (▲), and the computed curves over a tidal cycle on 24/3/1981. The tidal range at Port Elizabeth was 1.5 m (springs) during this period, and high water occurred at 1748h. Progressing up-estuary, the tidal range decreases, the times of high and low water (H.W. and L.W.) occur later, and the elevations become increasingly asymmetrical; the rise time (L.W. to H.W.) being significantly less than the fall time (H.W. to L.W.). This asymmetry is the result of overtide generation by the non-linear tidal dynamics (Uncles, R.J. in press).

The computed data in Figs. 6(a) and 6(b) were derived from the numerical model. Elevations at the seaward boundary, ζ_p (situated 0.75 km from the mouth in the adjacent sea area), were taken to be equal to those at Port Elizabeth, which is the nearest location for which tidal data are recorded (see Fig. 1). This is reasonable because the tidal ranges and times of H.W. at Port Elizabeth and East London are very similar (Annon 1981).

Computed and observed elevations in Fig. 6(a) are very close at χ = 1.7 km and 3.5 km (interpolating computed data). At χ = 0.1 km the agreement is less close, but this may be a result of the large gradient in elevation which occurs along the tidal inlet (see later), and associated errors in interpolating $\tilde{\zeta}$ to provide a value at χ = 0.1 km.

The comparison of computed and observed currents in Fig. 6(b) is also reasonably good. The computed currents tend to be smaller than observed values, but this is probably because the observations were made in the deep, fast channel, whereas the computed values are cross-sectionally averaged.

Comparison of computed and observed tidal properties indicate that the numerical model is capable of simulating the dynamics of the Bushmans estuary with reasonable accuracy (at least for the first four kilometers from the inlet) and it can therefore be assumed that results from the model are also applicable to the Bushmans estuary.

Model results for elevations and currents

Results are presented for the case where the model estuary is subjected to infinitely repeating spring tides. Fourier analysis is used to represent currents and elevations in the form:

$$u = \langle u \rangle + E_1 \cos(wt - e_1) + E_2 \cos(2wt - e_2) + \ldots$$

and

$$\zeta = \langle \zeta \rangle + C_1 \cos(wt - c_1) + C_2 \cos(2wt - c_2) + \ldots$$

The seaward boundary condition is:

$$\zeta_{\rho} = 0.2 + 0.8\cos(wt) + C_2\cos(2wt - c_2) \text{ in metres.}$$

The mean spring tidal range for Port Elizabeth is 1.6 m (Annon 1981) which gives $C_1 = 0.8$m. The mean water level at Port Elizabeth is 0.2 m above MSL (Zack 1980), so that $\langle \zeta \rangle = 0.2$. Data are presented for $C_2 = 0$, although solutions have also been obtained for $C_2 = 2.8$ cm and $c_2 = 020°$, which correspond to M_4+MS_4+S_4 at Port Elizabeth (Braun 1978), and which take into account the asymmetry in the spring elevations due to overtides. This value of C_2 is probably a large overestimate of the actual value in the sea area adjacent to the Bushmans estuary, and may be topographically induced overtides generated by flow around Cape Recife (Fig. 1). At East London, $C_2 = 0.7$ cm for spring tides.

The amplitudes of the semi-diurnal and quarter-diurnal spring tide elevations, $C_1(\chi)$ and $C_2(\chi)$ respectively, are drawn in Fig. 7(a). C_1 shows a rapid fall in magnitude across the tidal inlet decreasing from 80 cm in the adjacent coastal sea to 40 cm inside the inlet. Thus, one effect of a constricted inlet is to severly damp the tidal wave as it propagates into the estuary. The amplitude decreases along the estuary due to frictional damping associated with the shallow depths, (see Fig. 3). This dampening dominates over the tendency for the wave to increase in magnitude due to the up-estuary decreases in cross-sectional area, and associated funneling of water.

The amplitudes of the quarter-diurnal elevations, C_2, (Fig. 7(a)) maximize at the mouth because the semi-diurnal elevations and currents, and thus the non-linear generating mechanisms, are largest there.

Once generated, the overtide propagates into the estuary, where it is frictionally damped, and where it interacts with much smaller internally generated overtides (see appendix).

The solutions having C_2 = 2.8 cm at the seaward boundary are not significantly different from those shown in Fig. 7(a). This is a result of severe damping at the inlet, which greatly reduces the effect of the overtide in the adjacent sea, so that its amplitude becomes small compared with the overtide generated locally at the inlet.

The phases of the semi-diurnal and quarter-diurnal elevations, c_1 (χ) and c_2 (χ), are drawn in Fig. 7(b). Neither of these curves is significantly affected by using C_2 = 2.8 cm and c_2 = 020° at the seaward boundary. The phase of the semi-diurnal tide, c_1, shows that there is a smooth progression of H.W. from c_2 = 0° at the seaward boundary to c_2 = 150° at the head, a t ime difference of 150°/w ($\simeq$ 5 hours). The major gradient in phase occurs acorss the inlet, the phase at χ = 0.75 km being 30°($\simeq$ 1 hour) later than at the seaward boundary. The phases of the quarter-diurnal tide, c_2, also increase smoothly along the estuary, from $c_2 \simeq$ 0° at χ = 0.75 km to 250° at the head, a time difference of 230°/2w ($\simeq$ 4 hours).

The amplitudes of the semi-diurnal and quarter-diurnal currents at spring tides, $E_1(\chi)$ and $E_2(\chi)$, are drawn in Fig. 8(a). Solutions having C_2 = 2.8 cm at the seaward boundary are not significantly different from these. The hatched lines show E_1 and E_2 with modified bathymetry (see later).

E_1 is largest at the inlet. The rise in water level within the estuary depends on the flow through the constricted inlet because this flow is opposed by frictional forces which depend on the square of the speed. Large surface slopes will consequently be generated across the inlet in order to drive these friction-limited currents. The larger cross-sectional areas within the estuary convey the water with smaller currents. The quarter-diurnal currents, E_2, lie in the range 5 - 10 cm s^{-1}, and are also largest at the inlet. In general, E_2 follows the same trends as E_1, showing that the overtide is mainly generated at the inlet, and then propagates into the estuary.

Phases of the semi-diurnal and quarter-diurnal currents, $e_1(\chi)$ and $e_2(\chi)$, are drawn in Fig. 8(b). e_1 increases smoothly moving up-estuary, showing that the time of maximum flood for the semi-diurnal currents, e_1/w, occurs progressively later up-estuary. The phase difference between the semi-diurnal elevations and currents, Δ, where $\Delta = c_1 - e_1$, is a measure of how progressive the tidal wave is. For a standing wave $\Delta = 90°$, and for a progressive wave $\Delta = 0°$ or 270°, depending on the direction of propagation. Fig. 8(b) shows that Δ goes from 40° at the inlet to 90° near the head, so that the wave is generally partially progressive, but standing near the head. It is at its most progressive through the inlet. The partially progressive nature of the tide leads to a down-channel flowing residual current (Uncles, R.J. in press), $\langle u \rangle$, which is 17 cm s^{-1} at the inlet, 3 cm s^{-1} at $\chi = 1.5$ km and $\chi = 3.0$ km, and less than about 1 cm s^{-1} elsewhere.

The phases of the quarter-diurnal currents, e , show a smooth increase progressing up-channel (Fig. 8(b)). Nearest to and following time t = 0, the peak of the semi-diurnal flood current lags that of the quarter-diurnal current by a time $\varphi_e/2w$, where:

$$\varphi_e = 2e_1 - e_2. \quad \ldots\ldots\ldots\ldots\ldots(4)$$

$\varphi_e(\bullet)$ is drawn in Fig. 8(b). When $-90° < \varphi_e < 90°$ (which is satisfied by the model estuary) then the quarter-diurnal currents echance the semi-siurnal currents enhance the semi-diurnal flood currents, and reduce the ebb, so that flood currents exceed ebb currents, but are of shorter duration.

The overtides generated in this model estuary behave in a similar way to those in the Severn (Uncles, R.J. in press). The main differences are firstly the quarter-diurnal tide is generated at the inlet, rather than at the head and secondly the effect of quarter-diurnal oscillations in the adjacent sea on the estuary is small, because of their small amplitudes and further reduction by the inlet.

Results for tidal stress

Averaging equation (3) over a tidal cycle gives, in the approximation of cross-sectionally averaged flows, the residual stress on the bed of the estuary $\langle\tau\rangle$. Becuase the overtide and residual currents are much smaller than the semi-diurnal currents, $\langle\tau\rangle$ can be linearized to give ((Uncles, R.J. in press):

$$\langle\tau\rangle = \langle\tau\rangle' + \langle\tau\rangle''$$

where $\langle\tau\rangle'$ is the residual stress due to tidal flow, and $\langle\tau\rangle''$ is that due to residual flow, with:

$$\langle\tau\rangle' \simeq \rho D\langle u|\tilde{u}|\rangle \simeq (4/3\,\pi)\rho DE_1 . E_2 \cos\varphi_e \quad ....(5)$$

$$\langle\tau\rangle'' \simeq 2\rho D\langle|\tilde{u}|\rangle\langle u\rangle \simeq (4/\pi)\rho DE_1 . \langle u\rangle \quad .....(6)$$

and where φ_e is defined in equation (4).

In reality, the stress on the bed of the estuary is due to near-bottom tidal and residual currents. These are responsible for the movement of sediment as bed load. Cross-sectionally averaged tidal currents are higly correlated with the near-bottom tidal currents, and may be used to estimate stresses, $\langle\tau\rangle'$, with reasonable accuracy. However, cross-sectionally averaged residual cirrents, $\langle u\rangle$, are not necessarily an indication of the near-bottom residual currents, so that values of $\langle\tau\rangle''$ deduced from them may not be meaningful. $\langle\tau\rangle'$ appears to be particularly relevant to sediment movement (Hunter 1979, Pingree and Griffiths 1979), and this quantity is investigated here.

The direction of $\langle\tau\rangle'$ is determined by φ_e (equations (4) and (5). From Fig. 8(b) $\cos\varphi_e > 0$, so that $\langle\tau\rangle' > 0$. Therefore, $\langle\tau\rangle'$ is directed up-channel and actual values from the model for spring tides are drawn in Fig. 9(a). The effect of including C_2 = 2.8 cm at the seaward boundary is to increase $\langle\tau\rangle'$ by 10% at the inlet. Elsewhere it is insignificant. The dashed line (in Fig. 9b) defines $\langle\tau\rangle'$ with modified topography (see later). Provided the maximum tidal stresses, τ_{max}, are sufficiently strong to move sediment as bed load, then the up-channel directed residual stress will tend to move sediment from the inlet to the head in response to tidal currents. Maximum stresses, τ_{max}, are shown in Fig. 9(b) for spring tides, along with values for modified bathymetry. High values are restricted to within a few kilometres (x = 3.5) of the inlet.

Sedimentation

A sedimentological survey of the Bushmans estuary between the tidal inlet and the Ghio Bridge (χ = 0 to 14 km in Fig. 2(a) was undertaken during 23-25/3/81. The survey determined composition and distribution of sediments, as well as mean grain sizes (in ϕ units) for the sand component. ϕ may be defined as:

$$\phi = -\log_2 \quad \text{(grain diameter in mm)}$$

Several sites were sampled over each of 21 cross-sections.

The distribution of ϕ sizes is shown in Fig. 10(a), and the distribution of mud (a mixture of silt and clay of terrestrial origin) in Fig. 10(b). Up-channel of χ = 3.5 km the sediment is almost entirely mud, with a small component of fine sand of terrestrial origin (comprising mainly rock fragments). Down-channel of χ = 3.5 km the sediment is mainly quartz-rich with marine sand.

Grain size decreases from the inlet to the Ghio Bridge (Fig. 9b). ϕ- values are averaged over each sampling cross-section and then plotted against x. Assuming that the model estuary represents the Bushmans estuary, the initial decrease in grain size up-channel from the tidal inlet corresponds to the initial rapid fall in maximum stress, τ max (Fig. 9b). There follows a more scattered but slowly increasing trend for ϕ where the maximum stress falls more slowly. This region is terminated by a sharp rise in ϕ at still lower stresses, which marks the effective limit of marine sand intrusion at approximately $\chi \approx 3.5$ km.

One explanation of these distributions is that marine sand moves up and down-channel as bed load during flood and ebb, but has a net up-channel transport due to the positive residual stresses (Fig. 9(a). Tidal stresses rapidly decrease up-channel, so that whilst coarser sand will reach a postion near the inlet where maximum spring tide currents are unable to move it, finer material will be deposited further up-channel.

An alternative explanation is that suspended sand in the coastal surf zone is transported into the estuary on a flood tide, where it settles out at a position which depends on its fall velocity. The fall velocity of 2 ϕ quartz sand at a temperature of 22°C (see Fig. 4) is roughly 3 cm s^{-1}, and the maximum effective depth of the estuary is about 2 m (see Fig. 3). Even travelling at 80 cm s^{-1} (near the inlet) the sand will settle out within about 50 m in absence of vertical turbulence (Braun 1978). For 3 ϕ sand the drop-out distance is about 160 m. These distances are an order of magnitude smaller than those observed, and although they will increase with wave and tide-induced turbulence, it appears that sand transport within the estuary will largely be as bed-load.

Mud in the upper reaches are of fluvial origin. It is deposited from suspension and compacts as a cohesive deposit in time. The up-estuary tidal stresses as unable to transport the cohesive mud, whilst near the inlet mud is resuspended before compaction and flushed from the estuary.

The Ackers and White sediment transport relationship (Ackers & White 1973) has been used to quantify sand transport in estuaries. The relationships shows that almost all of the residual, up-estuary transport due to tidal asymmetry occurs during spring tides, and that the transport ceases up-estuary of χ = 4.5 km for 2.5 ϕ size sand. The observed distance is 3.5 km. Computed up-estuary transport of sand across the inlet due to tidal asymmetry amounts to 20 $m^3 day^{-1}$, averaged over a spring-neap cycle. This is equivalent to an increase in mean sand depth of about 2 cm $year^{-1}$ over a distance of 3.5 km from the mouth (the lenght of marine sand intrustion). The high rate of sedimentation is a consequence of strong tidal currents across the inlet, and their asymmetry. Tidally-induced residual currents ($\langle u \rangle = -17$ cm s^{-1} through the inlet at spring tides) have been ignored on the basis that only near bed currents of relevance to sediment movement and these cannot be computed from a one-dimensional model. If the tidally-induced residual current through the inlet were uniformly distributed across it in nature, then the residual transport of sand would be to the sea. Elsewhere in the estuary the sediment transport would remain up-channel, regardless of whether residual currents are taken into account or not.

The Ackers and White transport relationship (Ackers & White 1973) can be used to look at the role of floods in the flushing of sediment from the estuary. During floods the salinity will be reduced to a low level everywhere. The residual currents carrying run-off to the sea will be down-channel throughout the water column, with cross-sectionally averaged values being strongly correlated with near-bed currents.

The results indicate that a flood of 50 m^3 s^{-1} acting for one day would transport across the mouth 80 days build-up of unconsolidated sediment ($\pm$ 20 $m^3 day^{-1}$) due to tidal asymmetry. A flood of 60 m^3 s^{-1} acting for one day would remove 120 days build-up, and a flood of 90 m^3 s^{-1} would remove a year's build-up of sediment. Reasonably complete data on fresh water inputs (station P1M03) are available for years

1971-76. Assuming these are representative of the Bushmans river then one flood occurred during March 1976 which had a maximum daily averaged flow of 45 m^3 s^{-1}. No data are available on its duration, but if it maintained its strength for, say, 3 days, then 6 months build-up of sediment would have been removed. No floods occurred during 1971-73, nor 1974-75. Two floods occurred during 1973-74, with maximum daily averaged flows of 55 m^3 s^{-1} and 58 m^3 s^{-1} and assuming each of these lasted for three days, then roughly two years build-up of sediment due to tidal asymmetry would be transported seaward across the inlet.

These figures are crude estimates, but are the best that can be obtained with a one-dimensional model and available data. They do demonstrate the importance of floods to the removal of sediment from the Bushmans estuary. The ability of floods to transport sediment to sea across the inlet of the Bushmans estuary increases as roughly the square of the fresh water discharge, so that any reduction in flooding due to either climatological or man-induced changes can be expected to have a large effect on the rate of removal of sediment from the estuary.

Effects of modified bathymetry

It has been proposed that existing channels in the Bushmans estuary be deepended by dredging. The quantity of sand to be removed amounts to about 2 x $10^5 m^3$ in selected areas between χ = 3.0 km. In a one-dimensional model, this increase in estuarine volume can only be accommodated by in=creasing cross-sectional areas over the affected regions. Because each cross-section in the model occupies an axial length of 1.5 km, then an increase in volume of 2 x $10^5 m^3$ amounts to an increase in area of 133 m^2 at χ = 1.5 km if all the changes in volume are taken to occur between

χ = 0.75 km and 2.25 km. An increase in area of 133 m² at χ = 1.5 km for all states of the tide, and for unchanged widths, will take into account the increase in volume and depth associated with dredging. Such an approach is very rough, but it does give an indication of how sensitive the dynamics of the estuary are to changes in bathymetry.

The effects of dredging on tidal elevations, current speeds and stresses are of most interest (Figs. 7(a), 8(a), 9(a) and 9(b)). Changes in tidal elevations are negligible (Fig. 7(a)). The areal extent of mudflats and shoreline will consequently remain essentially the same, as will their associated biotic communities.

In the dredged areas subtidal benthic life will be eliminated but it is suspected that the faunal communities will establish themselves in time, as shown by recent studies in the marina canals of the Kromme estuary (Baird *et al* 1981).

The amplitudes of both semi-diurnal (E_1) and quarter-diurnal (E_3) currents are only significantly affected at χ = 1.5 km (Fig 8(a)) where the cross-section is increased to take dredging into account. The currents are reduced because the increased area is conveying essentially the same flow of water as was the case with unmodified bathymetry.

The residual stress remains up-channel due to tidal asymmetry but is reduced at χ = 1.5 km (Fig. 9(a)), elsewhere it is much the same as it was. The maximum tidal stress (Fig. 9(a)) is only affected significantly at χ = 1.5 km, where it is reduced to a level which is more characteristic of up-channel stresses ($\chi > 9$ km). This reduced stress is, according to the Ackers and White transport relationship (Ackers & White 1973), unable to move marine sand of the observed grain sizes as bed load. Therefore, it appears that sand will be transported into the modified region and deposited, rather than be transported further up-channel, thereby refilling the region with sand. The time-scale for re-filling is uncertain, but if all the sand transported across the inlet by tidal asymmetry (estimated to be 20 $m^3 day^{-1}$) were deposited in the dredged channels (of volume $2 \times 10^5 m^3$), and no flushing of sediment occurred, then a minimum time-scale for in-fill would be 10^4 days ($\sim$ 30 years). Sediment would be transported by both the flood and ebb flood tides. Effectively this means that sediments from adjacent channels would be deposited into the dredged section, enhancing the rate of in-fill.

It is stressed that the figures regarding rates of sedimentation (the only mechanism taken into account is tidal asymmetry) and rates of in-fill must be treated with extreme caution. They are only presented in this short study because of a complete absence of alternative data on which to base management decisions.

Discussion

This work shows that non-linear tidal processes are important in short, shallow estuaries having constricted inlets. The inlet plays a critical role in the development of these non-linearities and the generation of overtides. These in turn influence the patterns of sediment movement throughout the estuary.

The inlet severely damps the tidal fluctuations in water level as they propagate from the coastal sea into the estuary, and is also a region of intense tidal currents. These flow in response to the large differences in water level generated across the inlet. Both currents and elevations are largest at the inlet, and these, in conjunction with the shallow depths, generate overtides (in particular the quarter-diurnal tide) which propagate into the estuary. This is the reverse of what happens in an estuary like the Severn, where the main generation of overtides takes place near the shallow-head, and propagation is down-channel. The tidal dynamics and sediment movement in an estuary with a constricted inlet will clearly be sensitive to the geometry of the inlet.

The residual frictional stresses at the sea bed are the result of asymmetry between flood and ebb tidal currents, and near-bed residual currents. The asymmetry is produced by the presence of a quarter-diurnal tide, and is such that the residual stress is always directed up-channel. Near-bed tidally-induced residual flows cannot be determined from this work, and have been ignored.

Maximum tidal stresses during a tidal cycle (near peak flood or ebb) have largest values near the inlet, so that if sediment is able to move as bed load in response to these stresses, then coarser, marine-derived sand will be deposited near the inlet, and finer sand further up-channel (the residual motion occurs in the direction of residual stress). This is found to be the case for the Bushmans estuary.

Calculations of sediment transport across the inlet show that flushing of sediments from the estuary is sensitive to the strength of flood water discharges. If these flood discharges are reduced, by whatever means, then the subsequent trend appears to be one of increasing sedimentation.

Acknowledgements

We thank the Department of Environment Affairs, the University of Port Elizabeth and the CSIR for financial support. We also thank Dr Mary Kendrick and Dr Mike Thorne both of the Hydraulics Research Station, Wallingford, England and Mr Ken Russel and Mr W.A.M. Botes of the National Research Institute of Oceanology, Stellenbosch for their valuable suggestions. The assistance of the Director and staff of the Computer Centre of the University of Port Elizabeth is greatfully acknowledged.

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Appendix

In this section the importance of the inlet as a region of quarter-diurnal tidal generation is demonstrated. Equations describing the non-linear generation of quarter-diurnal tides are derived in Uncles (in press)

$$\frac{\partial \zeta_2}{\partial t} + \frac{1}{\langle B \rangle} \frac{\partial}{\partial x} \left\{ \langle A \rangle u_2 \right\} = f^{(0)}$$

and

$$\frac{\partial u_2}{\partial t} + g \frac{\partial \zeta_2}{\partial x} + \left(\frac{4 D E_1}{\pi \langle H \rangle} \right) u_2 = f^{(1)} + f^{(2)} + f^{(3)}$$

where $u_2 = E_2 \cos(2\omega t - e_2)$ and $\zeta_2 = C_2 \cos(2\omega t - c_2)$.

Full expressions for the quarter-diurnal source terms $f^{(0)}$ to $f^{(3)}$ need not be given here; to order of magnitude :

$$f^{(0)} \sim -\frac{\partial}{\partial x} \left(\tfrac{1}{2} C_1 E_1 \right)$$

$$f^{(1)} \sim -\frac{8 D E_1}{3 \pi \langle H \rangle} \cdot \langle \mu \rangle$$

$$f^{(2)} \sim \frac{8 D E_1}{3 \pi \langle H \rangle} \cdot \frac{C_1 E_1}{2 \langle H \rangle}$$

and

$$f^{(3)} \sim -\frac{1}{4} \frac{\partial}{\partial x} \left(E_1^2 \right)$$

The depth at the inlet is smaller than in any other seaward section of the estuary (see Fig. 3). Also, the amplitudes of elevations and currents, C_1 and E_1, as well as their gradients ($\partial/\partial x$) are much larger at the inlet than elsewhere (see Figs. 7(a) and 8(a). It follows immediately that $f^{(0)}$ to $f^{(3)}$ achieve their maximum values at the mouth, which is, therefore, the main source of quarter-diurnal tidal generation.

Figure captions

Fig. 1. Location of Bushmans estuary, Eastern Cape Province, South Africa.

Fig. 2. Bushmans estuary and its segmentation into 1 km intervals.

(a) Between the mouth and Ghio Bridge.

(b) Between Ghio Bridge and Harvest Vale.

Fig. 3. Areas, A (o), widths, B (●) and effective depths, H (△), of the model estuary as functions of χ. Water levels at MSC.

Fig. 4. Salinity (S), temperature (T) and σ_t along the estuary during 24/3/81. Using this distribution of σ_t it is possible to show that density currents are negligible down-channel of Ghio Bridge (χ = 14 km).

Fig. 5. Locations of current meter stations (●) and tide gauge stations (▲) in Bushmans estuary. The deep channel is drawn in.

Fig. 6. Observed (▲, ●) and computed elevations and currents in the Bushmans estuary. (a) Elevations, ▲, (b) Currents, ● .

Fig. 7. Semi-diurnal and quarter-diurnal spring tide elevations in the model estuary as functions of χ.

(a) Amplitudes C_1 and C_2; the solutions with modified topography are also shown (—•—).

(b) Phases c_1 and c_2.

Fig. 8. Semi-diurnal and quarter-diurnal spring tide currents in the model estuary as functions of χ.

(a) Amplitudes, E_1 and E_2; the solutions with modified topography are also shown (—•—).

(b) Phases e_1 and e_2; variables Δ(△) and φ_e(•) are also shown (see text).

Fig. 9. Frictional stresses on the bed of the model estuary as functions of χ; solutions with modified topography are also shown (- ● -).

(a) Residual (mean) stress due to tidal asymmetry.

(b) Maximum tidal stress and cross-sectionally averaged sand grain size, ϕ, in the Bushmans estuary.

Fig. 10. Maps of

(a) mean grain size on surface

(b) percentage component of surface mud by mass in the Bushmans estuary.

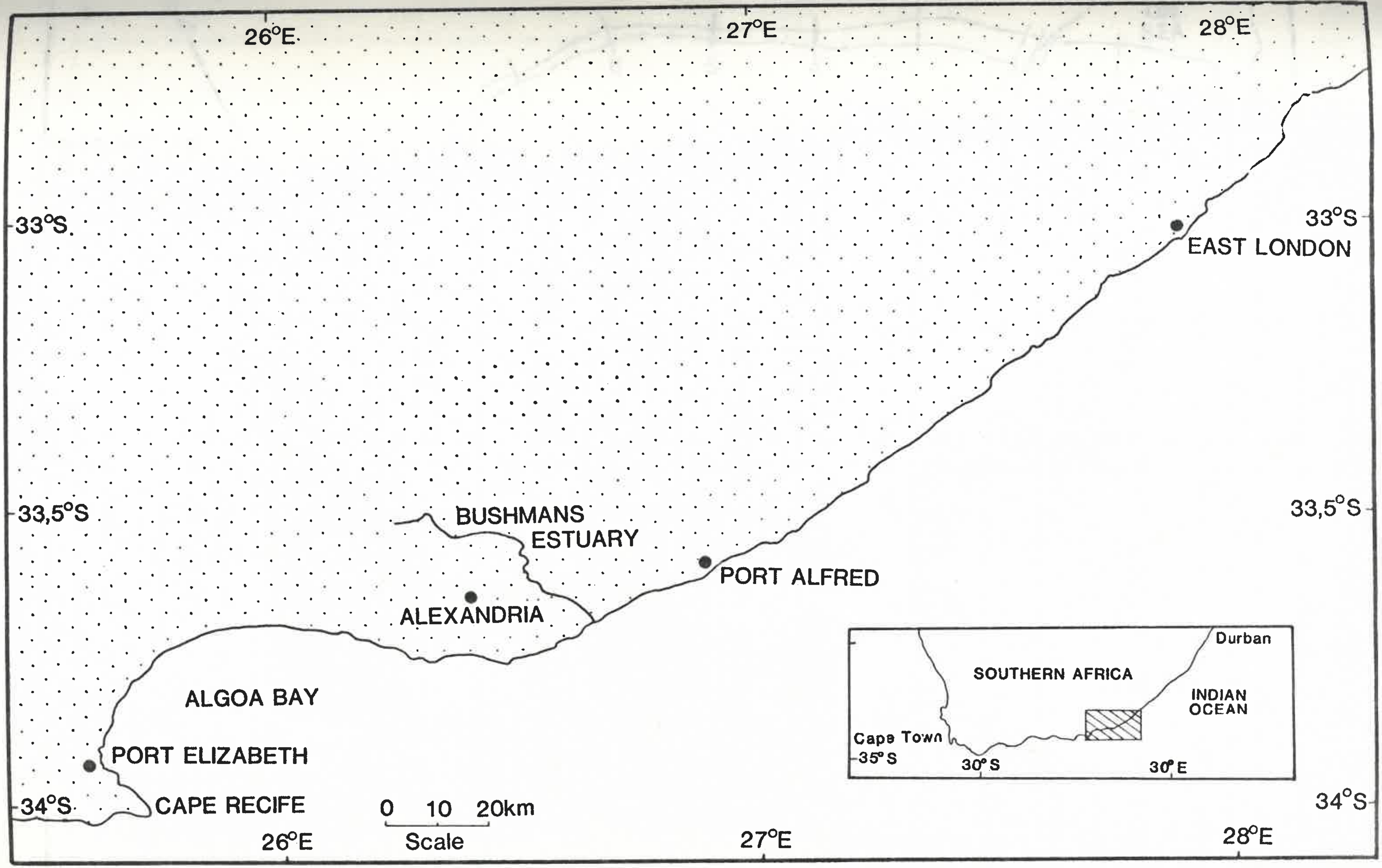
26°E
27°E
28°E
33°S
33,5°S
34°S
EAST LONDON
BUSHMANS
ESTUARY
PORT ALFRED
ALEXANDRIA
ALGOA BAY
PORT ELIZABETH
CAPE RECIFE
0 10 20km
Scale
Durban
SOUTHERN AFRICA
INDIAN
OCEAN
Cape Town
35°S
30°S
30°E

FIG. 1.

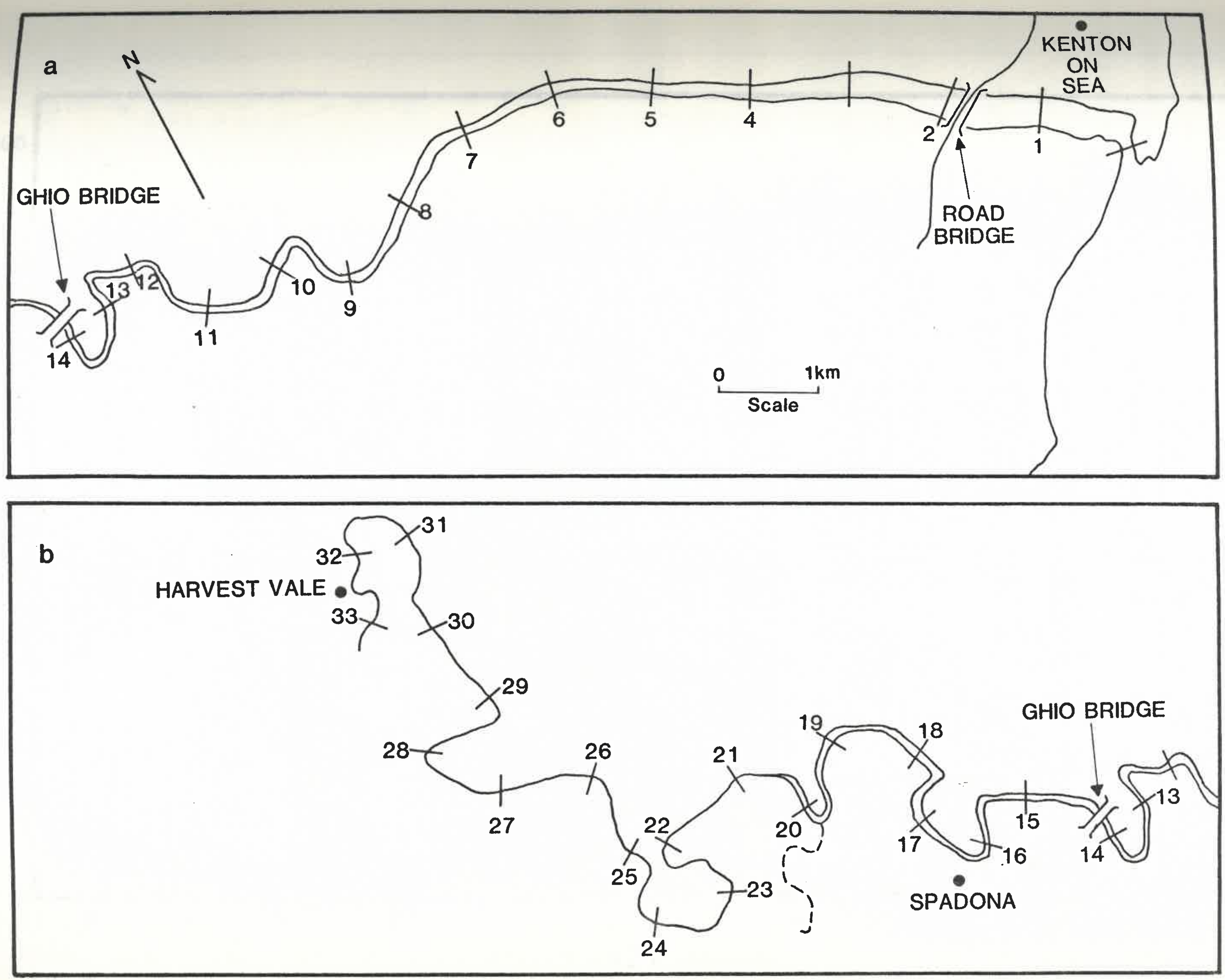
a
N
KENTON
ON
SEA
ROAD
BRIDGE
GHIO BRIDGE
1
2
4
5
6
7
8
9
10
11
12
13
14
0
1km
Scale
b
HARVEST VALE
SPADONA
GHIO BRIDGE
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33

FIG. 2.

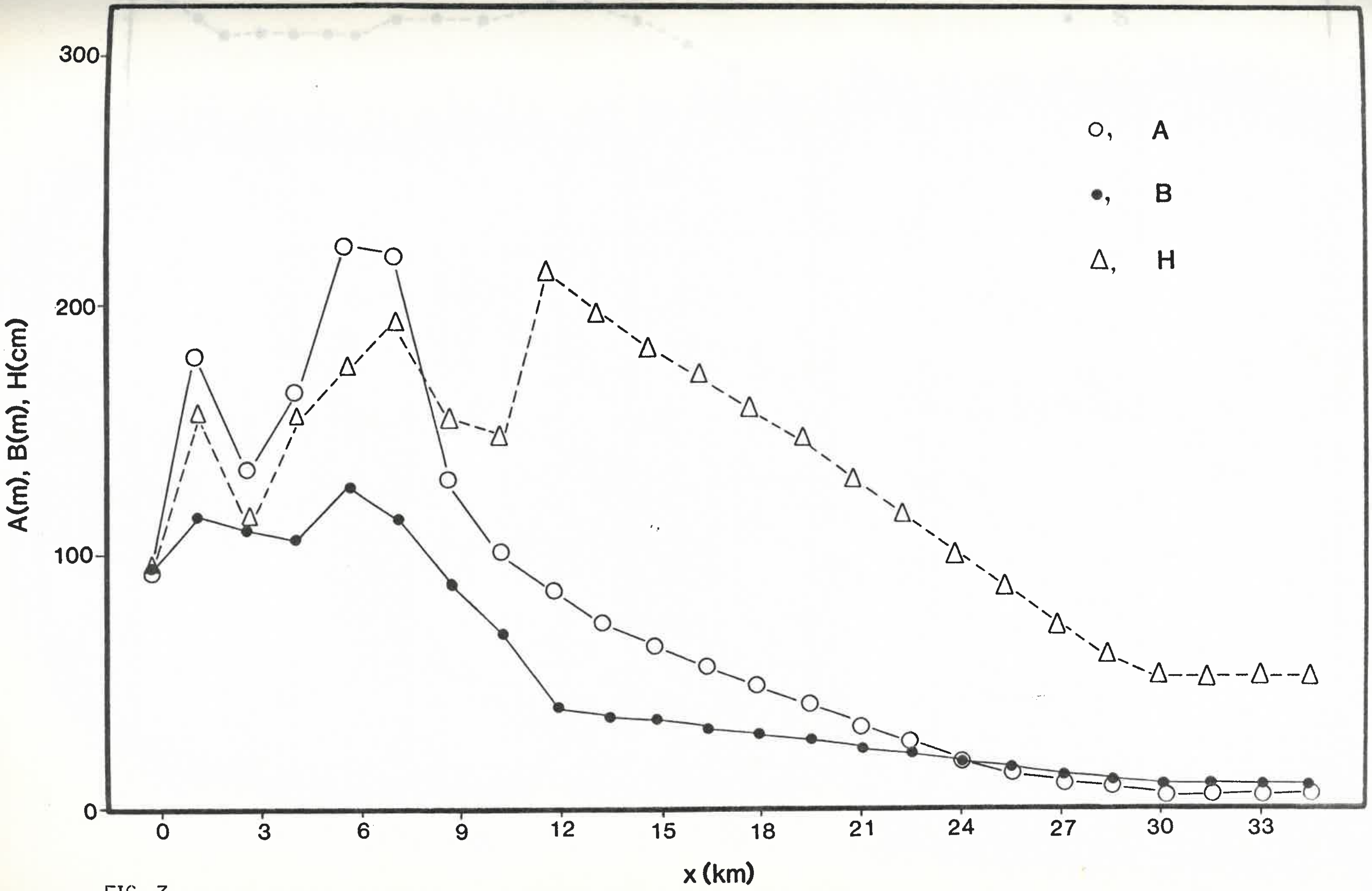

FIG. 3.

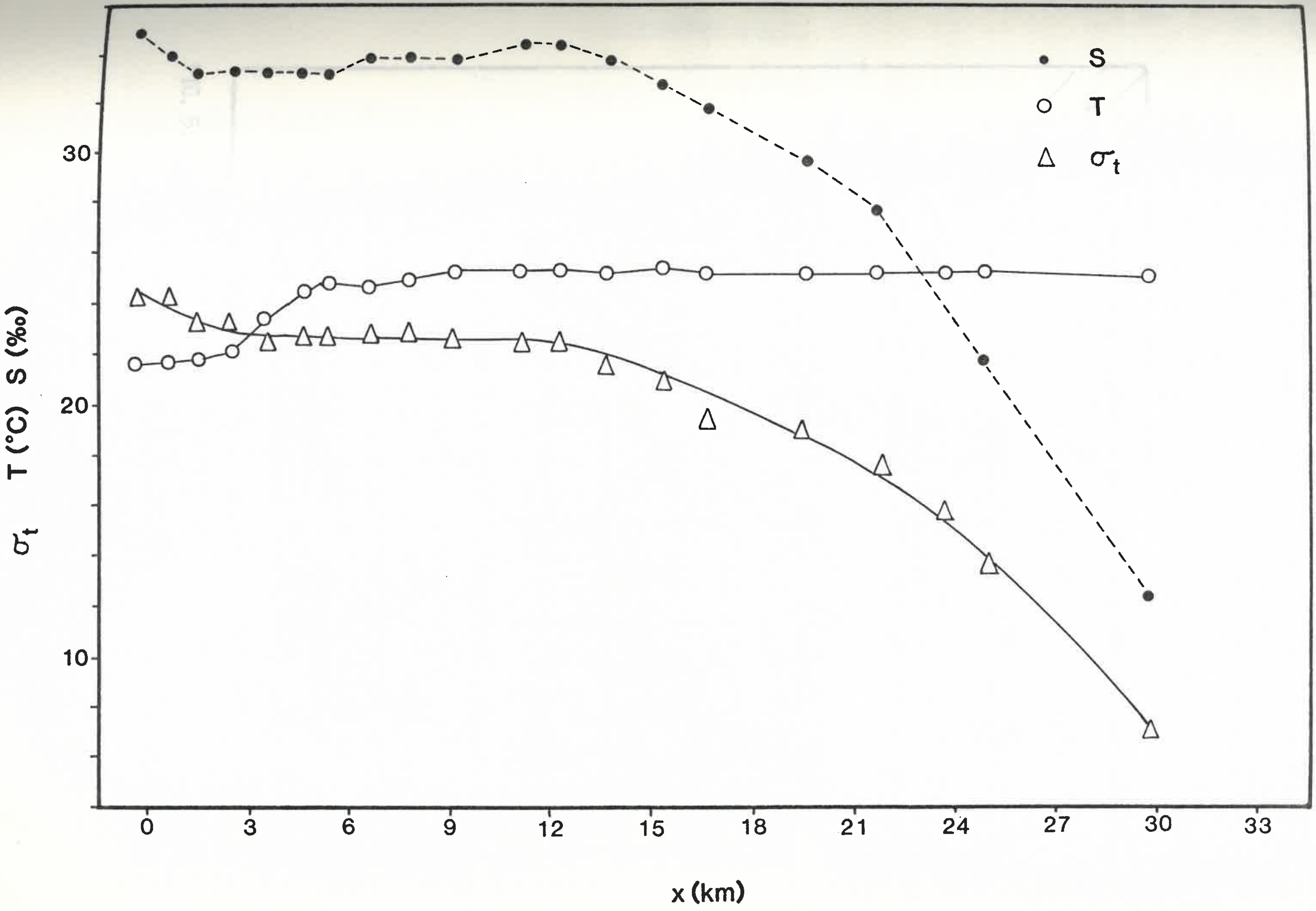

FIG. 4.

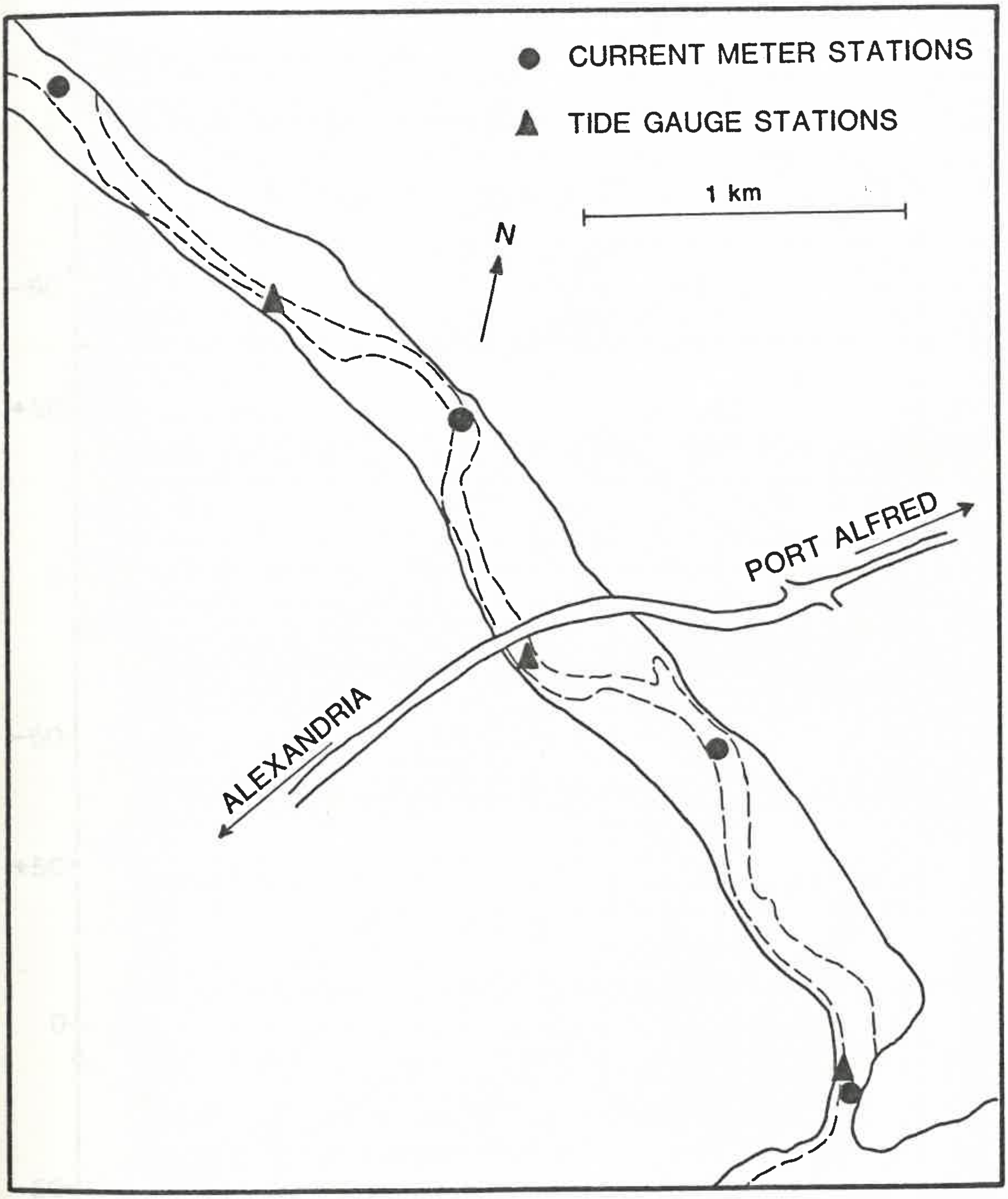
● CURRENT METER STATIONS
▲ TIDE GAUGE STATIONS
1 km
N
PORT ALFRED
ALEXANDRIA

FIG. 5.

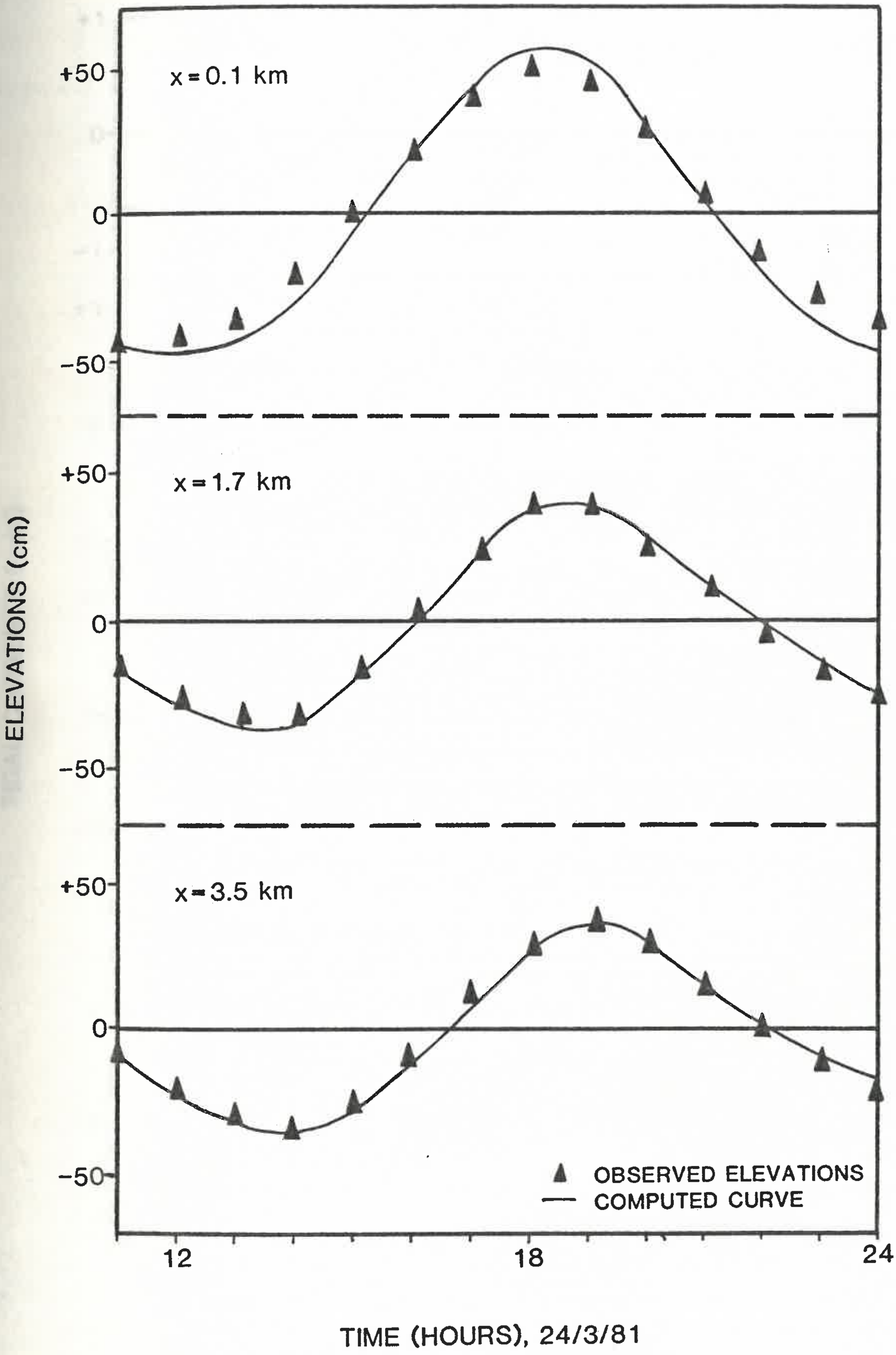
x = 0.1 km
x = 1.7 km
x = 3.5 km
+50
0
-50
ELEVATIONS (cm)
12
18
24
TIME (HOURS), 24/3/81
OBSERVED ELEVATIONS
COMPUTED CURVE

FIG. 6A

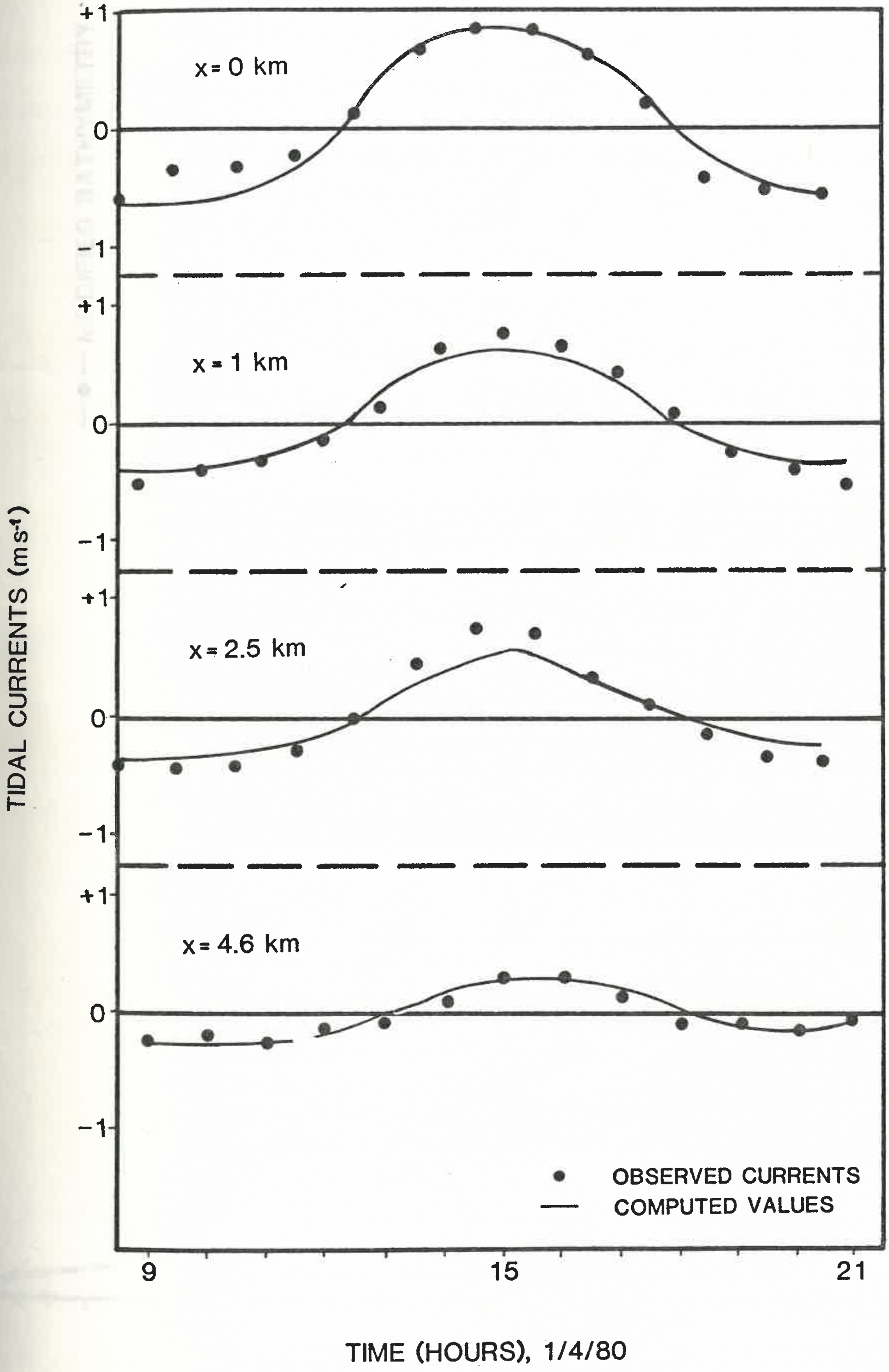
TIDAL CURRENTS (ms-1)
+1
0
-1
x= 0 km
x = 1 km
x= 2.5 km
x= 4.6 km
OBSERVED CURRENTS
COMPUTED VALUES
9
15
21
TIME (HOURS), 1/4/80

FIG. 6B

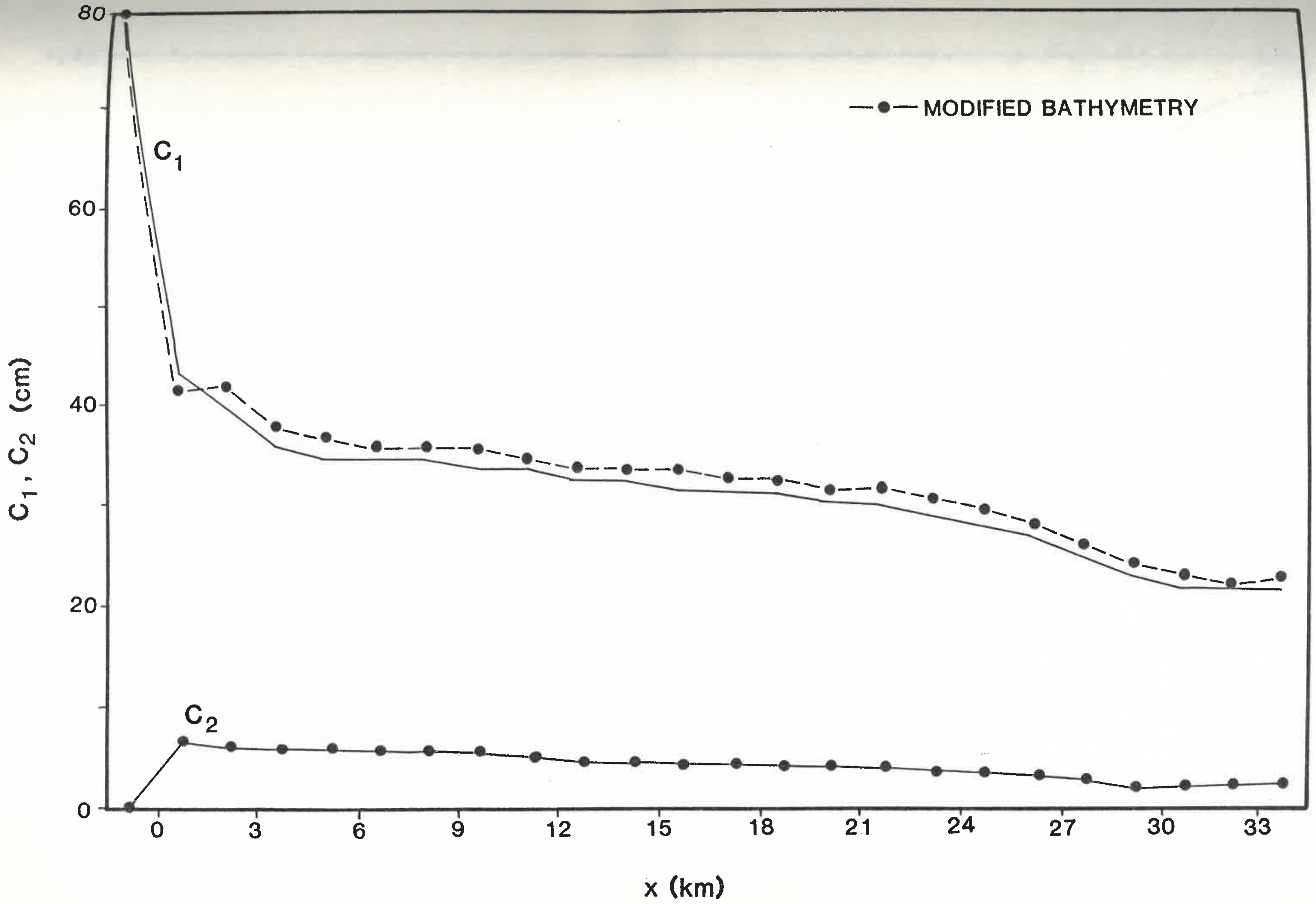
—●— MODIFIED BATHYMETRY
C_1
C_2
80
60
40
20
0
C_1, C_2 (cm)
0
3
6
9
12
15
18
21
24
27
30
33
x (km)

FIG. 7A.

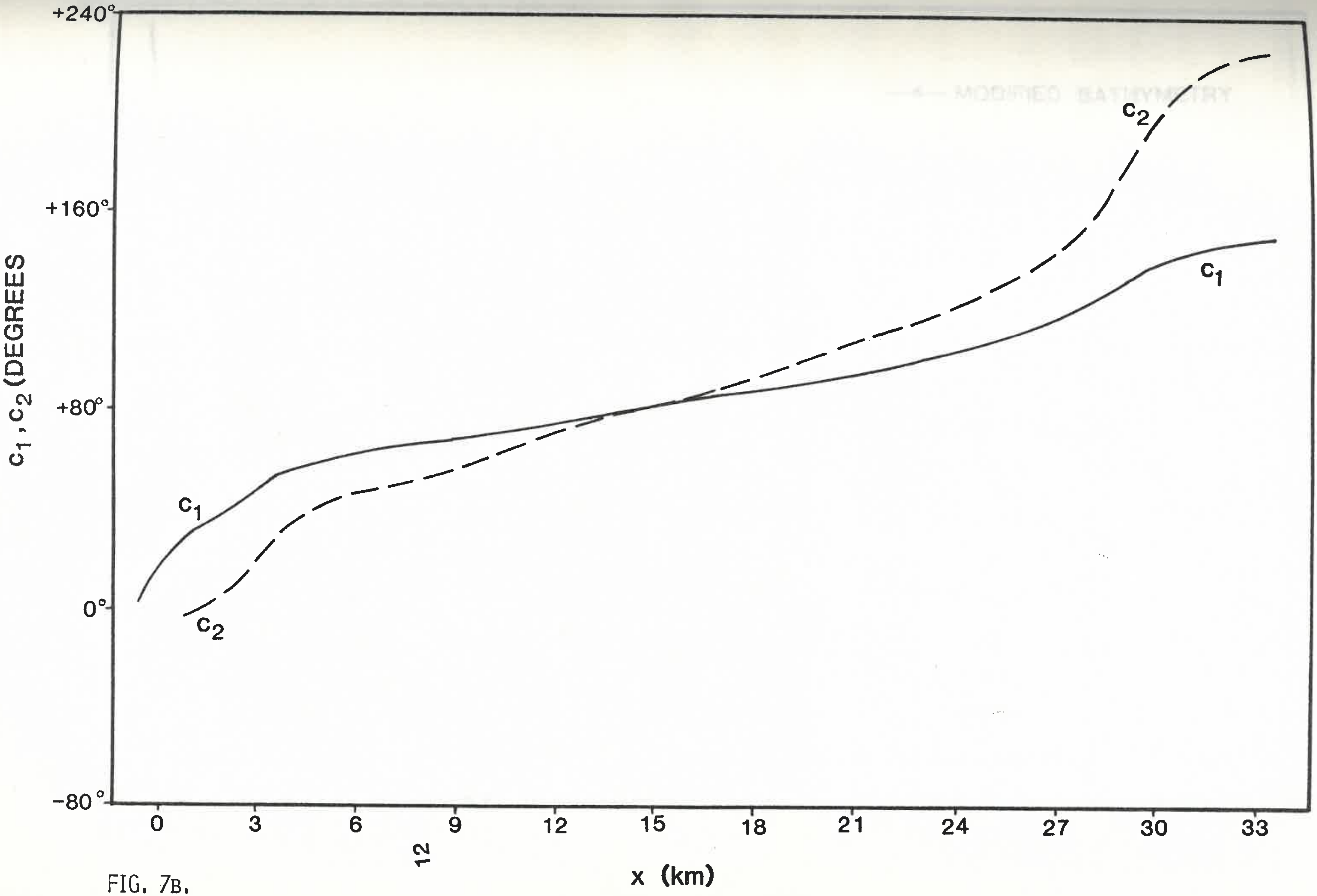
+240°
+160°
+80°
0°
−80°
c_1, c_2 (DEGREES
c_1
c_2
c_1
c_2
0
3
6
9
12
15
18
21
24
27
30
33
x (km)

FIG. 7B.

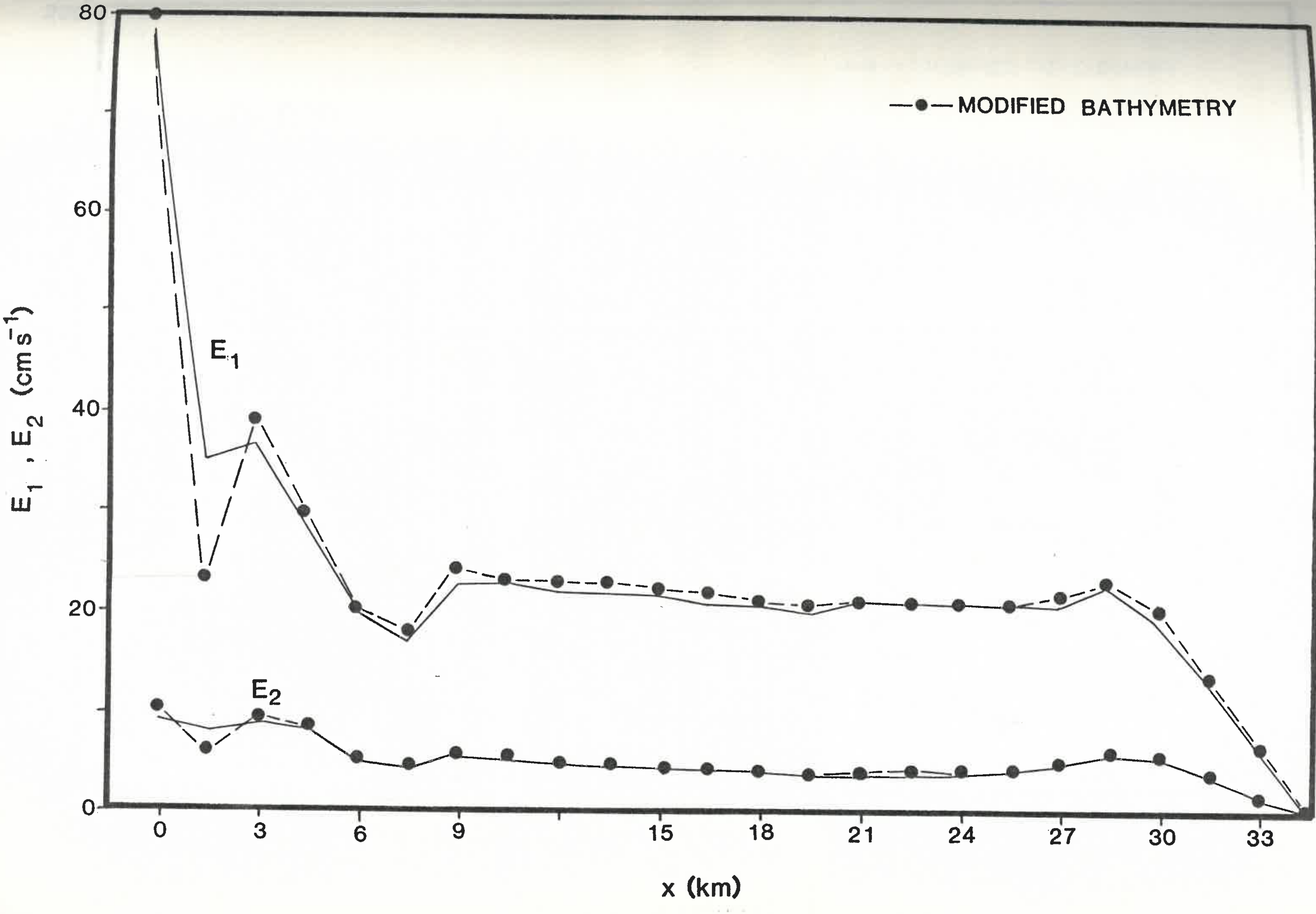
—●— MODIFIED BATHYMETRY
E_1
E_2
E_1 , E_2 (cm s^{-1})
80
60
40
20
0
0
3
6
9
15
18
21
24
27
30
33
x (km)

FIG. 8A.

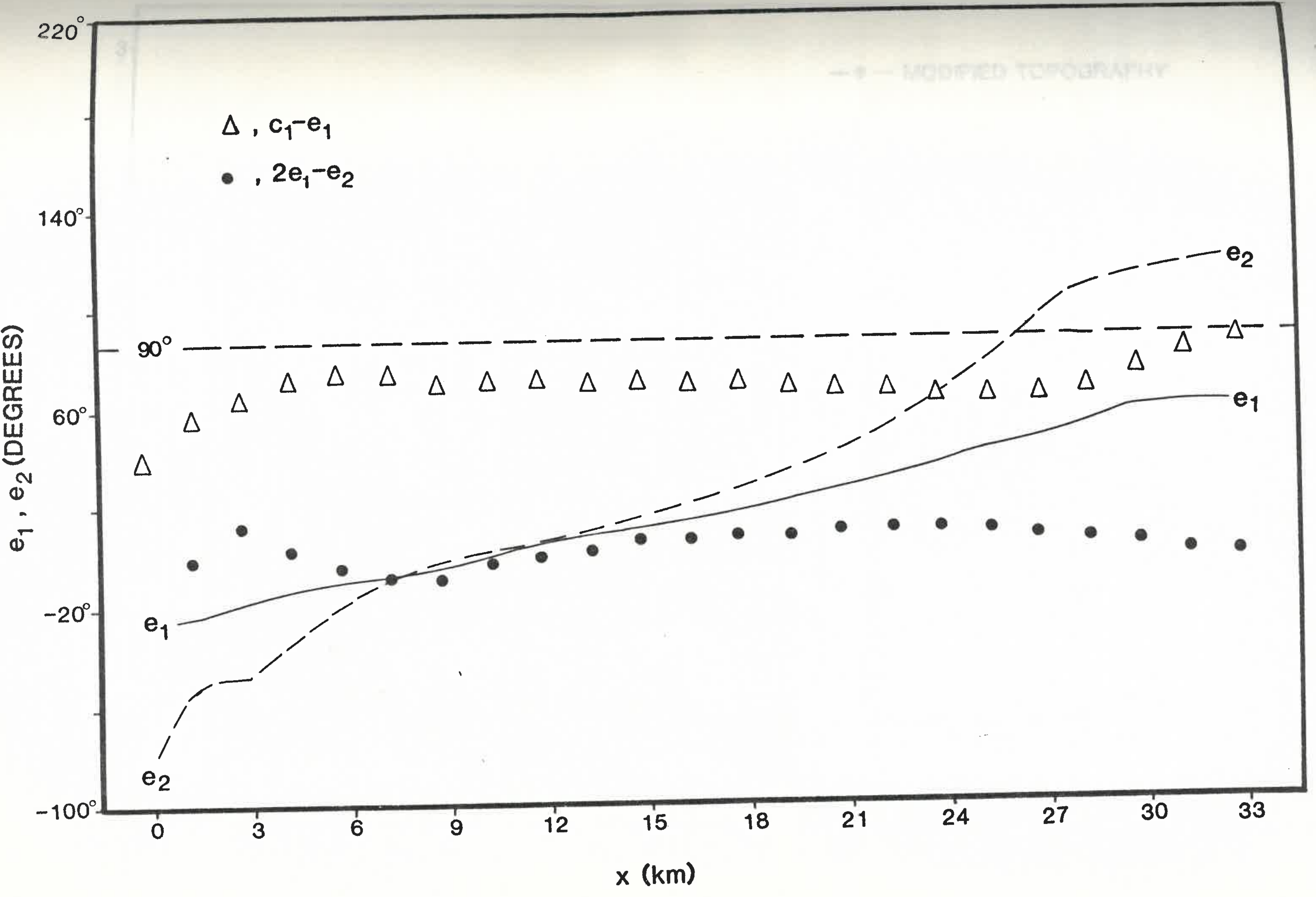
Δ , $c_1 - e_1$
● , $2e_1 - e_2$
220°
140°
90°
60°
-20°
-100°
e_1, e_2 (DEGREES)
e_1
e_2
e_1
e_2
0
3
6
9
12
15
18
21
24
27
30
33
x (km)

FIG. 8B

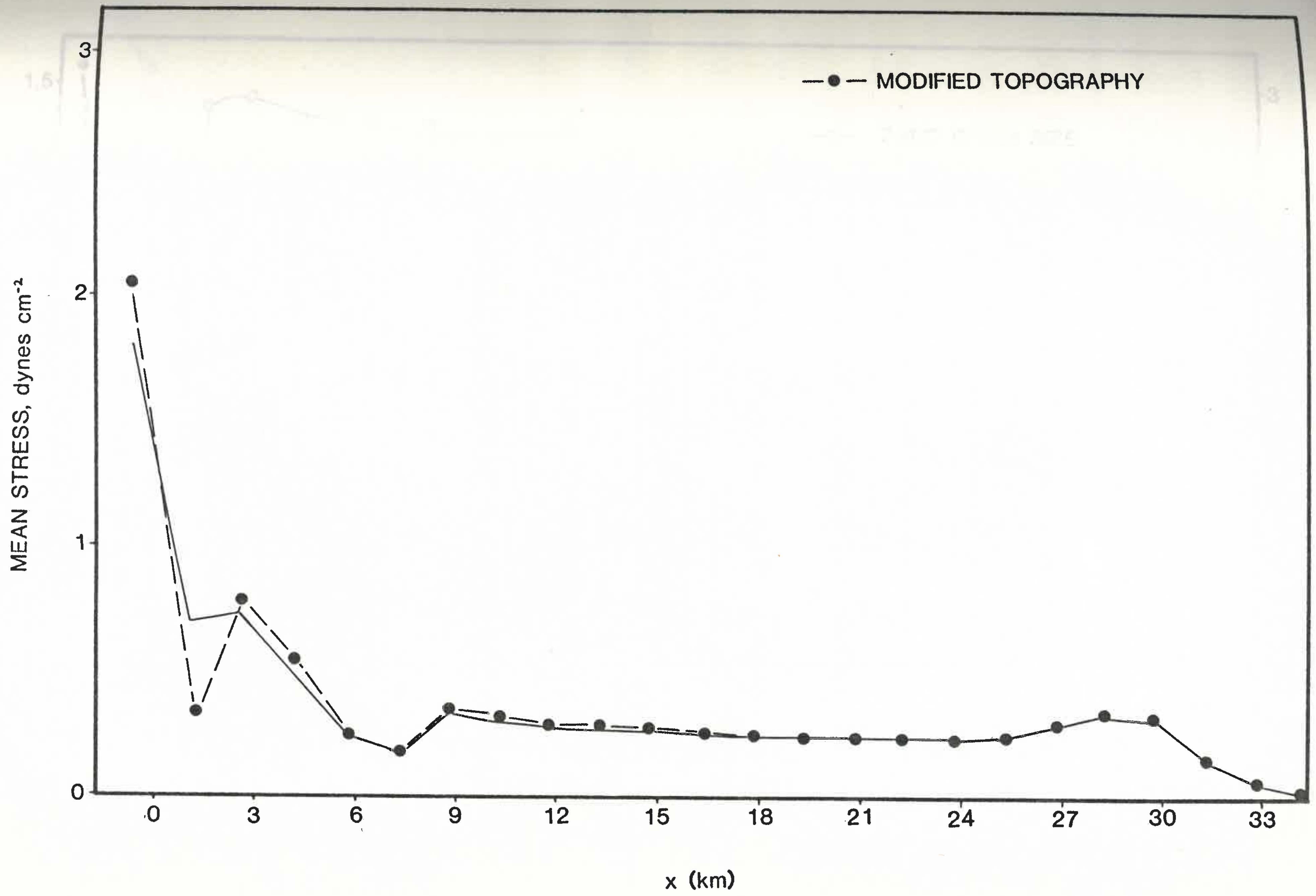
—●— MODIFIED TOPOGRAPHY
MEAN STRESS, dynes cm⁻²
0
1
2
3
0
3
6
9
12
15
18
21
24
27
30
33
x (km)

FIG. 9A.

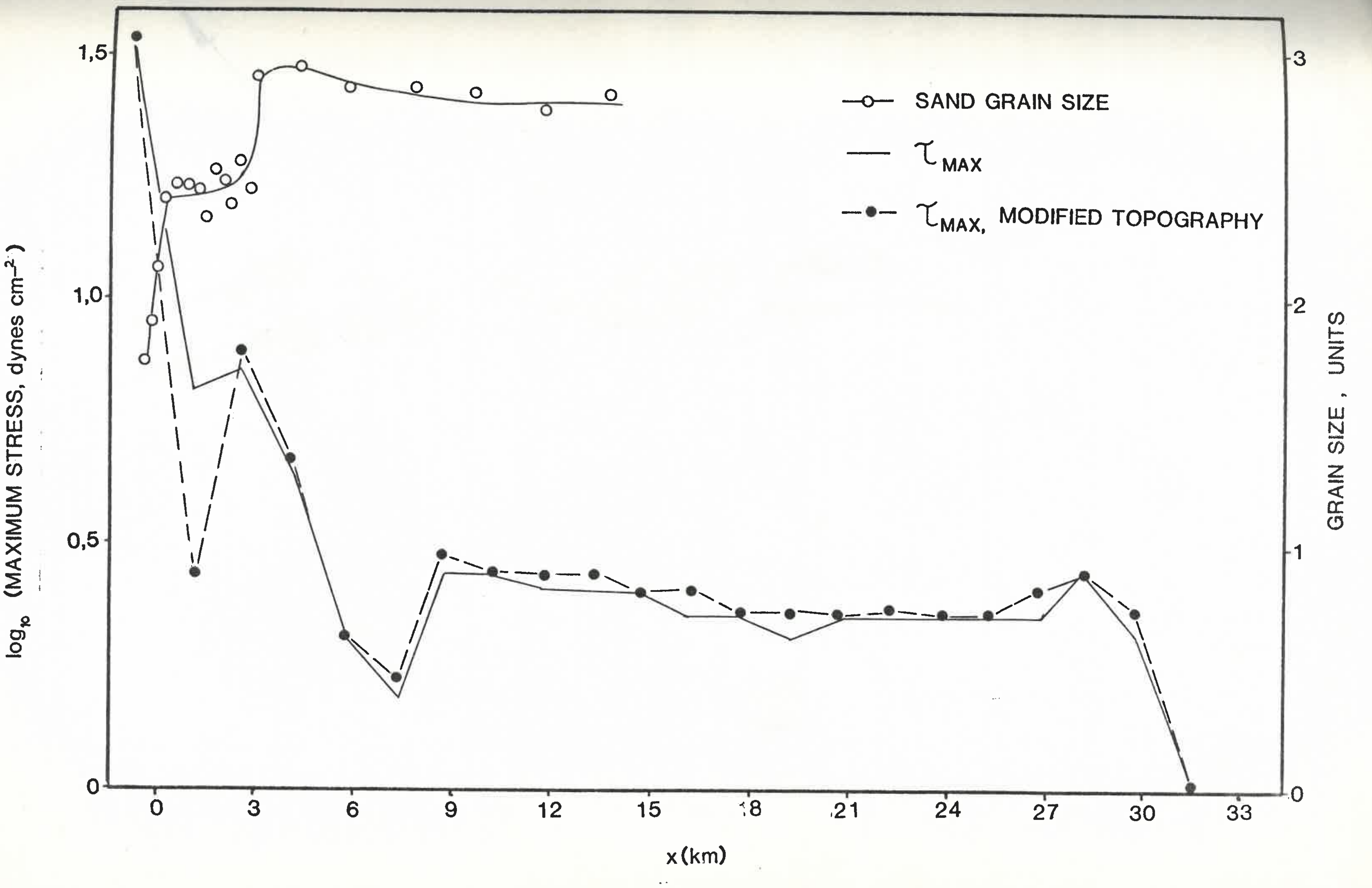
1,5
1,0
0,5
0
log₁₀ (MAXIMUM STRESS, dynes cm⁻²)
3
2
1
0
GRAIN SIZE , UNITS
SAND GRAIN SIZE
τ MAX
τ MAX, MODIFIED TOPOGRAPHY
0
3
6
9
12
15
18
21
24
27
30
33
x (km)

FIG. 9B.

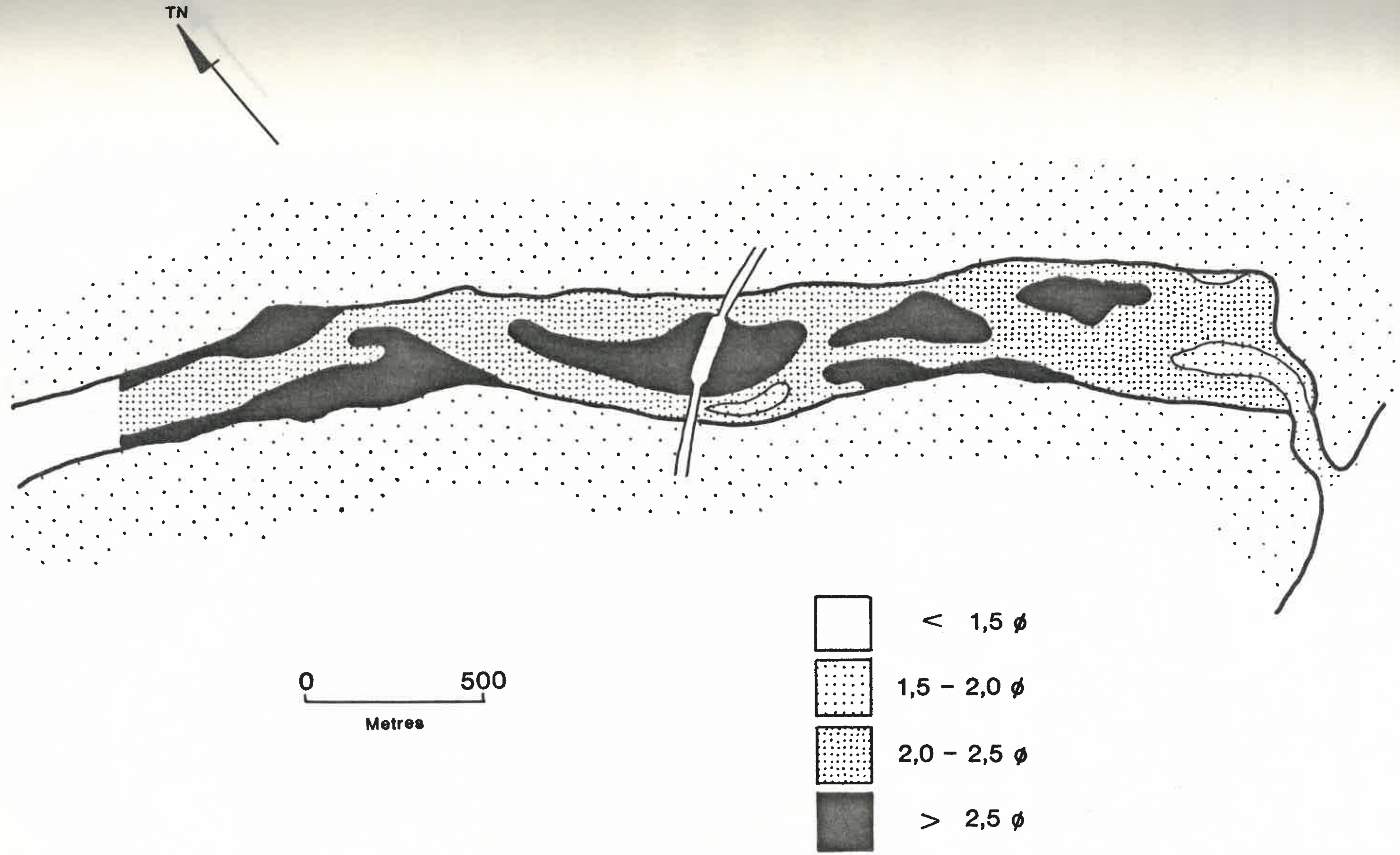

FIG. 10A.

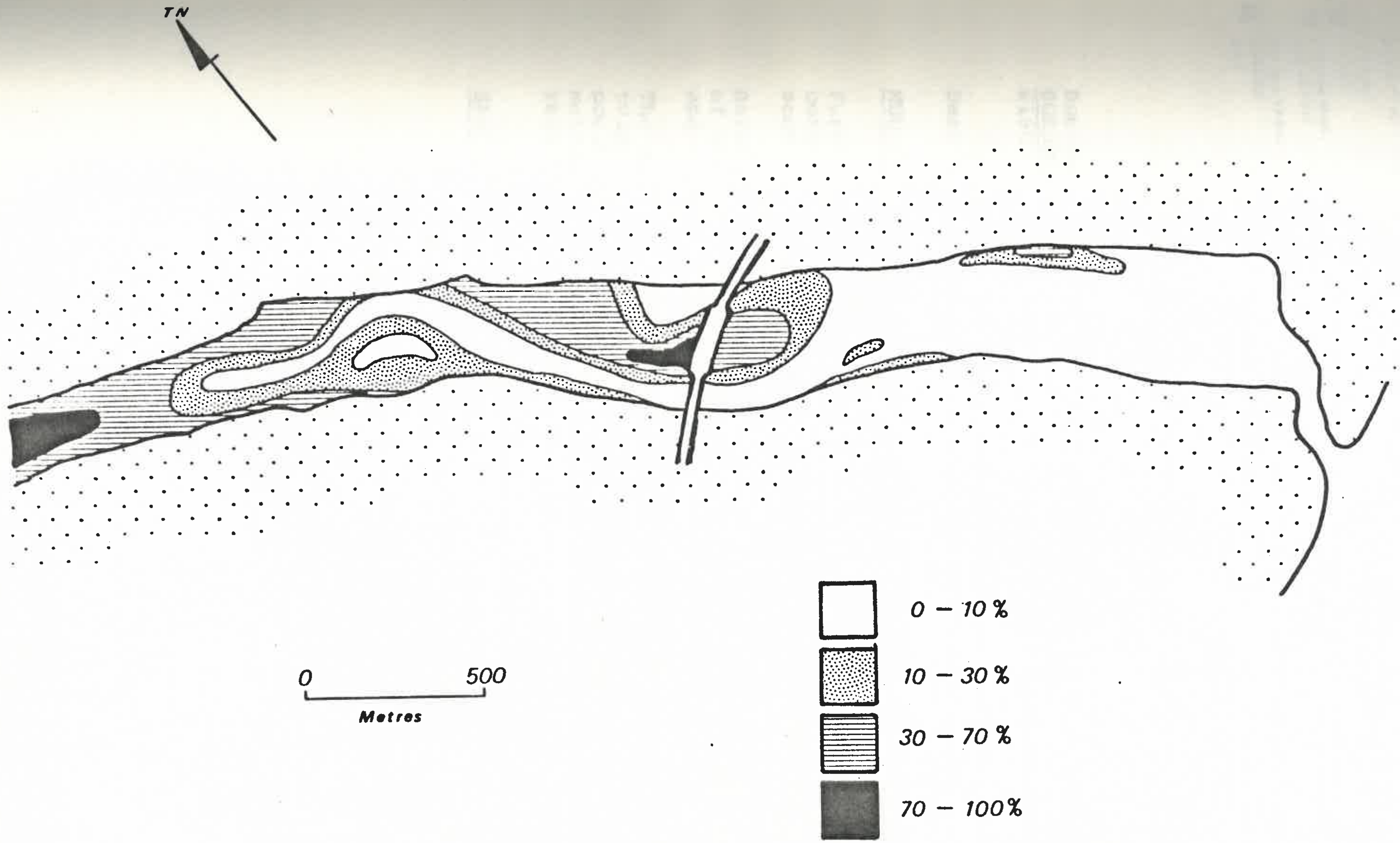

FIG. 10B.

APPENDIX III,

GENERAL SERVICES INDUSTRIALS (PTY) LTD.

GSI

ENGINEERS IN AIR POLLUTION CONTROL

DURBAN BRANCH
"Gebaire"
☎ 31-3562
208 Gale Street
Durban 4001
P.O. Box 18360
Dalbridge
4014

HEAD OFFICE
"Gebaire"
☎ 618-4170
8 3987 S.A.
c/r Barney & Raeb
Rds. Benrose
P.O. Box 7417
Johannesburg 200

Your Ref

Our Ref: MJE/MC162/CMT

TENDER

8 December 1981

Boesmanriviermond Municipality,
BOESMANRIVIERMOND
6190

Attention : Mr W.H.D. Deacon
Town Clerk

Dear Sirs,

MUD CAT DREDGER

Further to my visit, which I should like to thank you for my cordial reception, we have pleasure in confirming our telegram sent on the 30 November 1981.

Based on this visit, we are happy to recommend the suitability of the Mud Cat as a suitable machine for the removal of silts and sand with certain limitations.

The Mud Cat is able to work in conditions observed, and can tolerate a certain amount of wave action, but it is not an ocean going dredge. The pumping distance is limited to 930 metres with a lead of 54 metres, and additional distances would requiry a booster station.

SPECIFICATION

SCOPE

This specification covers the furnishing of a portable dredging unit.

MUNISIPALITEIT
BOESMANSRIVIERMO
15-12-1981
MUNICIPALITY

GENERAL

The unit would be the latest improved model in current production at the time of delivery; the standard production model offered to commercial firms, of new manufacture, including all parts, components, and accessory items.

Parts and components not specifically mentioned in this specification, but which are required to provide a complete unit shall be included as a part of the equipment to be furnished.

Equipment/2.....

Equipment furnished under this section shall be fabricated, assembled, erected, and placed in proper operating condition in full conformity with drawings, specifications, engineering data, instructions and recommendations of the equipment manufacturer unless exceptions are noted by the Engineer.

Stated requirements are minimum; equipment that exceeds these in quality, and/or size and capacity will be acceptable unless otherwise stated. Standard equipment that exceeds the requirements will become the Owner's new minimums.

The unit shall have components parts necessary to give maximum performance, service life and safety, and not merely meet minimum requirements of the specification.

WORKMANSHIP

In all matters of details, including those not specifically covered by these specifications, the work shall be professionally and skillfully accomplished in accordance withthe best trade customs and professional standards of work of like character and purpose, as generally recognized by trade standards.

SERVICE AND INSTALLATION CONDITIONS

The equipment furnished under this specification shall be suitable for marine service.

Four lifting lugs shall be provided for loading, off-loading and transferring the unit with a crane.

The unit shall be completely assembled and serviced at the designated location and ready for continuous service. Servicing shall include complete lubrication and cooling system.

FLOTATION

Flotation shall be provided by integrally welded hull constructed from a minimum of 12 gauge hot rolled steel with integral bulkheads and stiffeners, formed for rigidity and filled with polyurethane foam. An enclosed equipment compartment shall be located between two main pontoons and recessed below deck level to provide a low center of gravity and maximum stability.

CUTTER ASSEMBLY

The cutter assembly shall be a horizontal spiral auger type mounted on a hydraulically operated boom. Detachable, heat treated, cutter knives shall be mounted on auger flighting and boom attachment frame. A separate, hydraulically adjustable mudshield shall extend the full length of the cutter assembly unit.

The/3......

CUTTER ASSEMBLY - Continued

The hydraulically driven auger shall be capable of operating at variable rotational cutting speeds upto 100 RPM and shall be capable of producing minimum torque of 19 008 kg/cm.

The hydraulically operated boom shall be capable of moving the operating auger-cutter assembly from slightly above the water surface to the maximum working depth. The upper position is for periodic inspection and maintenance of the auger-cutter assembly only and is not an operating requirement.

ENGINE

The unit shall be equipped with a six cylinder, naturally aspirated, diesel engine. Minimum power rating shall be 175 BHP at 1 800 RPM. The engine shall be radiator cooled and fitted with a high degree chamber type silencer. The fuel system shall have a minimum fuel capacity of 8 400 litres.

Instrumentation and controls for monitoring and regulating engine performance shall be mounted in a consol, which shall be located directly in front of the operator when seated in the cab. Instrumentation shall include tachometer w/hour meter, oil pressure gauge, coolant temperature gauge and ammeter. Controls shall include emergency shutdown control, vernier speed adjustment control and starter switch. The speed control equipment shall include an engine mounted governor. An alarm system shall be engine mounted to indicate low oil pressure or high coolant temperature.

POWER TRAIN

Power from the engine shall be transmitted to the dredge pump through a heavy duty transmission with appropriate reduction gear.

DREDGE PUMP

The dredge pump shall be of the centrifugal, closed impellor type with a minimum rated capacity of 8 400 lit/min at 1 700 RPM against 95m of head (fresh water). A pump characteristic curve showing head capacity, efficiency, and brake horsepower curves for the specified speed shall be submitted with acceptance. The pump shall operate at a minimum of 70% efficiency at the rated capacity.

The pump wet-end parts shall be :-

> (Optional) Ni-hard abrasion-resistant alloy
> cast iron per ASTM A532 Class I Type A.

The pump shall have a 203 mm suction diameter and be capable of passing a 100 mm shpere.

Bearings/4.......

DREDGE PUMP - Continued

Bearings shall be enclosed in a housing and protected by rotating slingers affixed to the pump shaft. Gauges shall be provided to monitor the pump discharge pressure in psi and the suction vacuum in inches of mercury.

The pump shall have a flush type stuffing box and replaceable shaft sleeve. A service water pump shall be provided for lubricating and cooling and the packing material. A gauge shall be provided to monitor the service water pressure in psi.

HYDRAULIC SYSTEM

The hydraulic system shall consist of a multiple system designed to separately operate the auger-cutter assembly and an accessor circuit for operating the boom, mudshield and propelling winch. The hydraulic system(s) shall have a common fluid reservoir and filtering elements to protect the system(s) from contamination and foreign material. The system(s) shall be protected by relief valves set at the manufacturers recommended relief pressures. Each pump power system shall be powered directly off the main diesel engine. Gauges shall be provided for monitoring the system pressures.

PROPULSION SYSTEM

This unit shall be propelled by a treble sheave type hydraulic winch having a maximum traverse speed of 15.2 m/min forward and reverse. The unit shall be capable of cutting at speeds upto 3.6 m/min in both directions.

ELECTRICAL SYSTEM

The electrical system shall be a 12 volt 2-wire, full ground system. The system shall include a heavy duty alternator and 12-volt, Size 8D battery(s). These units shall be capable of providing electrical power for primary and accessory functions including engine starting, lighting, warning devices and appurtenances such as heater fan and automatic bilge pump.

CAB

The unit shall be fitted with a one-man all weather cab to permit continuous operation of the unit. The cab shall be of all metal construction and the interior shall be upholstered with a vinyl covered sound absorbing material. Windows shall be provided in the front, back and sides and shall be made of tempered safety glass. The cab shall include the following appurtenances :-

Operators/5..........

CAB - Continued

a. Operator's console containing all engine gauges, pump pressure and vacuum gauges, hydraulic pressure gauges, and operating levers, and shall be in full view of the operator when facing the auger-cutter assembly.

b. Cushioned seat with back support. Unit shall be vinyl covered foam rubber.

c. Work lights, navigation lights and accessory lights.

d. Hinged side window and door. The door shall be equipped with a locking handle.

The cab shall be able to be tilted in order to afford access to the components located beneath it in the bilge area. The tilting mechanism shall be hydraulically operated by means of a hand operated pump.

PROTECTIVE FINISH

All metal surfaces subject to corrosion shall be protected with a corrosion inhibitive primer and polyurethane finish coat. Decks and walkways shall have a non-slip abrasive coat.

SPARE PARTS

The manufacturers shall provide a quantity of spare parts for routine servicing and repairing minor equipment failures. Spare parts shall include as a minimum one set replacement cutter knives, auger bearings, fan belts, one set filter elements, pump packing material and replacement lamps for lighting equipment.

SAFETY EQUIPMENT

The following safety equipment shall be provided :-

a. Two (2) large adult size U.S. Coast Guard approved Type 111 life jackets.

b. Three (3) mounted U.S. Coast Guard Marine Type A, Size 11, CO_2 or dry chemical, 10 pound fire extinguishers.

WARRANTY

The manufacturer's standard warranty shall be given to the Owner at the time of delivery of the unit. The effective date of warranty shall be the date of delivery.

Training/6........

TRAINING SERVICES

Operating and maintenance training shall be available for personnel assigned to operate and maintain this equipment for a period of three days.

OPERATIONS MANUAL

The manufacturer shall furnish a minimum of two operating manuals. The operations manual shall contain complete operating and maintenance instruction, including lubrication guides and trouble shooting section. An electrical layout shall also be included.

PARTS BOOK

The manufacturer shall furnish a minimum of two parts books. The parts book shall be illustrated to show relationship of parts and to facilitate repairs. Parts lists shall have complete descriptions and/or manufacturers names.

PRICE SCHEDULE

Our price for a MC915 Mud Cat as described would be delivered to Boesmanriviermond, would be................................	R238 500-00

ACCESSORIES

Our price for accessories as listed in enclosed specification sheet, would be....	R50 540-00

GENERAL OPERATING AND OWNING COST

The estimated owning cost based on 10 000 hours and considering an interest of money of 16% and an insurance at 1.5% of the purchase price would be R52/hour.

OPERATION COST

On a general fuel consumption of 28 litres/hour and with regular maintainance and oil hydraulic changes, and filters the cost would be R27-80/hour.

Operation/7.......

OPERATION PERSONNEL

Should be based on Dredgemaster and two helpers this is variable depending on the grade of personnel used, but we would suggest a figure of R15/hour.

TOTAL OWNING

This gives a total owning/operating cost of R94/hour with a theoretical cost of R1-04/m^3. However a more realistically obtainable removal rate is 60 m^3/hour with a cost of R1-58/m^3.

EXCLUSIONS

Services and items not taken into account :-

1. Mid stream anchoring.
2. Service boat.
3. Support floats (normally 2x200 litre oil drums).

We trust that the foregoing is of interest and we are available for further discussions or to arrange a site visit to a working Mud Cat.

Assuring you of our best attention at all times.

Yours faithfully,
GENERAL SERVICES INDUSTRIALS (PTY) LTD

M. J. ELLIS
MARKETING MANAGER

ACCESSORY EQUIPMENT

80	PVC 8 mm wall thickness 200 mm diameter 6 metre long pipes.
40	'B' Clamps
40	'C' Clamps
1	150 mm diameter pump discharge hose rubber laminated 5 metres long.
1	Expansion section 150 to 200 mm diameter.
4	Terfor 4 ton griphoists
4	Tree slings
2	Cables 350 m roll 8 mm diameter.
2	Triangles.
1	Swivel cable Crosby S-1
1	Swivel cable Crosby S-2
1	Cable cutter.
24	Clamps - Crosby
5	Shackle anchor Crosby G-209
1	Rope polyethyelene
4	Danforths anchors.