STUDY OF CURRENT FLOW PATTERNS IN THE ANNAPOLIS ESTUARY IN THE VICINITY OF FORT ANNE NATIONAL HISTORIC PARK

Final report to

Canadian Parks Service,
Environment Canada
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by

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EXECUTIVE SUMMARY

Recent erosion of the shoreline near Fort Anne National Historic Park has removed a protective band of saltmarsh that existed for decades, and exposed the foundations of fortress embankments to the action of wind-generated waves at times of high water. Examination of aerial photographs suggests that the marsh was intact during the 1940's and 1950's, but began to disappear during the 1960's and 1970's.

A study of water flow in the Annapolis Estuary adjacent to the Park during November and December 1992 revealed that patterns of flow are dominated during the flood tide and much of the later ebb tide by the outflow from the Annapolis Tidal Generating Station. Measurements of current velocities, salinity and temperature of water at a series of stations across the Estuary indicate that outflow from the Station tends to follow the north shore, and that inward-directed water movements on the flood are established first on the southern side of the Estuary. The data do not, however, support an initial hypothesis that erosion of the Fort Anne shore was caused by this lateral stratification. During the early ebb, before power generation starts at the station, the principal factor influencing water flow across the intertidal zone near the fort is the outflow from Allain River. As sea level falls, ebb velocities in Allain River increase, apparently because a constriction at the Highway 1 bridge restricts the rate of outflow of tidal water from the river. The study suggests that fine sediments are unable to settle on the intertidal zone near the fort as they do on most other areas of the Annapolis intertidal, because of the high shear stresses exerted on the sediment surface during the ebb tide.

It is concluded that factors affecting erosion on the shore are primarily local, and that construction of a comprehensive hydrodynamic model is probably not necessary in order to make sound choices regarding the design of protective works effective in the long term. It is recommended that a further local study of shear stress over the near foreshore be carried out to provide a basis for design of long-term protection, and that short-term protection against wave action be provided immediately.

INTRODUCTION

Evidence has been accumulating that the saltmarsh adjacent to Fort Anne National Historic Park is eroding so rapidly that the stability of the steep embankments on the Annapolis Estuary side of the fort is in doubt. Shoreline erosion is not a new problem at Fort Anne. Indeed, a review of historical documents held by the Canadian Parks Service indicates that engineers were frequently faced with the necessity for erosion protection of the seaward portions of the various forts that have occupied the site (Dunn 1992). Collapses of embankments were attributed to undermining by the sea, or direct erosion by waves, particularly at times of spring tides. However, the last major changes to the fortress that were aimed at shoreline protection appeared to have been those of the DeLabat Fort in the late 18th century. Although cribwork installed at that time on the Annapolis Estuary side was reported exposed on several occasions during the last two hundred years, no significant attempts appear to have been made to prevent erosion over that period.

In 1991 officials at Fort Anne became aware that retreat of the shoreline saltmarsh was revealing cribwork that had apparently not been exposed since it was installed in the mid-1700's. Surveying teams from the Nova Scotia College of Geographic Sciences were asked to investigate the rate of retreat of the marsh. Results from two surveys indicated that at several points along the Annapolis Estuary shoreline of the fort, the marsh had receded by as much as 2 metres between the fall of 1991 and the spring of 1992 (P. Hore - pers. comm.). A subsequent survey in the summer of 1992 confirmed that retreat of the marsh was very rapid, and that there was little saltmarsh left at the foot of the embankment and ravelin on the northwest corner of the fort. Wave action at high tide is now able to work directly against the base of the embankment.

Preliminary examination of aerial photographs taken between 1947 and 1977 suggested that the marsh had been consistently present during that period. The absence of noted erosional events, and indications that cribwork newly exposed in 1991/2 had not previously been weathered, also indicated that saltmarsh had probably been consistently present since the last major works in the late 18th century. Consequently, it was concluded that the present erosional process may be more severe than that occurring during the past two centuries, and that there is a strong likelihood that the seaward portions of the fort embankment could be undermined sufficiently for them to collapse in the near future.

In order to assess the prospects for and design of protective works, it is necessary to determine the proximal cause(s) of recent erosion. Over the last 40 years, significant man-made changes have occurred in the Annapolis Estuary. These include : enlargement of the

Lequille Hydro Electric Plant on Allain River (1968); construction of the Annapolis Causeway (1960); construction (1980-84) and operation (since 1985) of the Annapolis Tidal Generating Station. These major modifications to the patterns of flow in the Annapolis Estuary or Allain River were considered possible causes for accelerated erosion at Fort Anne. Smaller local changes include : collapse of the Annapolis Royal -- Granville Ferry bridge (associated with construction of the causeway); realignment of the Highway 1 bridge over Allain River; impoundments of large portions of marshland below Historic Gardens on Allain River; modifications to the shoreline for the Annapolis Royal Boardwalk; and deterioration of the historic Queen's Wharf. Unfortunately, no hydrodynamic model currently exists for the Annapolis Estuary that would permit hindcast assessment of the potential effects of each of these changes on erosional forces acting on the Fort Anne shorefront.

The Acadia Centre for Estuarine Research was asked by the Canadian Parks Service to conduct a drifter study of present patterns of water flow in the Annapolis Estuary in order to establish some critical information necessary for development of a hydrodynamic model. An initial study was carried out on 22 November 1992. Inclement weather on that date rendered the use of drogues ineffective, so the study was modified to obtain as much data as feasible on the direction and velocity of water flow during both ebb and flood tides, by use of a direct-reading directional current meter. Measurements were carried out during a flood tide on 1 December, and over the ebb tide on 9 December 1992.

Although it was beyond the scope of the contract, we also conducted a review of existing aerial photographs to assist in interpretation of the data obtained.

REVIEW OF AERIAL PHOTOGRAPHS

Copies of aerial photographs taken in the Annapolis Royal vicinity were obtained from several different sources. Most of these (1947, 1957, 1967, 1977, 1987) represent the decadal coverage of the province provided by Energy, Mines and Resources Canada. Because the time of flight is not determined by the state of the tide, some of these views were taken near high water, at which time the saltmarsh and intertidal zones were covered and their extent could not be determined. Only the 1947 image was obtained when the tide was very low, allowing a clear view of the saltmarsh near the fort. Two other views were obtained from the Canadian Parks Service : a photocopy of an oblique aerial photograph taken of Annapolis Royal in 1923, and a high resolution infrared image of the Annapolis Estuary taken in 1981. The second of these was apparently taken when the tide was down. Another aerial view taken in 1963 was obtained from P. Hore (College of Geographic Sciences). This appears to have been taken near mid-tide, as the well-developed saltmarsh is clearly visible.

The review (unpublished manuscript) shows that a number of changes in morphometry of the Annapolis Estuary and Allain River have taken place during the last four decades. Some of the photographs, especially that of 1963, give evidence of the extent of the saltmarsh on the Annapolis Estuary side of the fort. These collectively suggest that the major erosion took place sometime between the late 1960's and early 1980's, and therefore that the marsh had been substantially reduced prior to construction and opening of the Annapolis Tidal Generating Station. Textural changes in the intertidal sediments evident in the 1981 photograph suggest that the sediments have coarsened along the north side of the fort, as would be expected if erosive forces were greater here relative to other intertidal areas. It is also possible that the shoreline here has become steeper, since there are suggestions of a deeper channel between the rocky promontory and the adjacent intertidal zone below the fort. A close examination of the infra-red image obtained in 1981 reveals a line of red marks (presumably seaweed on solid substrates) extending from the tip of the fort across the intertidal zone toward the rocky subtidal point. This might indicate that in times past a structure has existed that would have limited the ebb flow of water issuing from Allain River over this portion of the intertidal.

Other changes that are potentially important influences on erosion are the deterioration of Queen's Wharf since the late-1950's, the realignment of the Highway 1 bridge and possible narrowing of Allain River at that point, and the construction of the Annapolis Causeway in 1960.

OBJECTIVES OF THE STUDY

The study was conducted to provide information on the dynamic relationships of the tidal water in the Annapolis Estuary and Allain River in the vicinity of Fort Anne. This information is needed for two reasons :

(1) to plan a more precise study that would provide a clearer insight into the oceanographic processes operating on the foreshore near Fort Anne; and

(2) to construct an appropriate hydrodynamic simulation model that would permit hindcast evaluation of the potential roles played by different changes in the system that might have contributed to the recent accelerated erosion of the saltmarsh fringing the fort.

Construction of the Annapolis Causeway in 1960 substantially reduced the volume of the tidal prism in the estuary below, and converted the upper estuary (above the causeway) into a stratified system with very small tides. Reduction of the tidal prism would have reduced tidal current velocities in the lower Estuary, but might also have caused changes in the patterns of flow that could redirect erosive forces onto areas that were previously less affected. The operation of the Annapolis Tidal Generating Station, which came on stream in 1985, was also considered as a potential factor, since observations of surface shear lines suggested that jetting of water during generation might be responsible for concentration of greater flood tide currents on the southern side of the estuary.

Smaller morphometric changes to the estuary might also be responsible for redirection of currents and/or waves along the fortress foreshore. Such changes include bridge construction on Allain River, deterioration of the Queen's Wharf, dyking of nearby marshlands, and shoreline protection works in the vicinity.

In addition to large and small morphometric modifications, there are dynamic changes that influence the stability of a depositional area of intertidal zone. These include an interruption of sediment supplied to the region, which might be caused by construction of a causeway, or impoundment of nearby marshlands which act variously as a sink and a source of fine sediment. In addition, there are natural changes in the dynamic action of the tides which occur both on short time scales, such as the fortnightly spring--neap cycle, and over longer periods, as in the 18.6-year nodal cycle. Although increases in tidal range may be small, they are associated with enhancement of current velocities and erosive forces that are non-linear functions of tidal range. It is notable that historic records indicate that major erosive events were associated with the highest spring tides (Dunn 1992).

FIELD METHODS

Because of the short daylengths at this time of the year, it was necessary to conduct studies of flood and ebb tide conditions on separate days in order to approximate a full tidal cycle. The initial attempt to determine current flow patterns using drogues was carried out on 22 November 1992, during the ebb tide. Sets of drogues were released at intervals along a transect northeast of Fort Anne, and their positions plotted by Loran C and sextant as they drifted seaward. Some of the drogues were designed to respond to near-surface flows, others to flows at depths of 1-2 m, on the assumption that flow directions might be different with depth. During the experiment, all drogues ended up drifting onto the southern side of the estuary along the Annapolis Royal and Fort Anne shorefront, but this was attributed to the strong northwest winds that prevailed throughout the day.

This initial study showed that surface and deeper waters were not necessarily flowing in the same directions, even during the ebb tide. It was therefore considered necessary to obtain data on current velocity and direction, and determine how this varies during a tidal cycle, in order to understand the dynamic structure of the water in the estuary. The study was therefore redesigned.

On 1 December 1992, vertical profiles of current direction and velocity during a flood tide were obtained from two sets of transects, one east and one west of the Fort Anne foreshore, between 11.58 and 16.07 h. Each transect consisted of five sampling stations, (labelled F 1 - F 5 for the outer transect, and F 6 - F 10 for the inner transect), distributed across the estuary (see Figure 1). Each station was visited in turn, and current speed and direction recorded at each metre of depth from the surface to the bottom using an Endico Model 110 Direct-reading current meter. For each station vertical profiles of temperature and salinity were also obtained using an EMP 2000 Recording CTD (Conductivity--Temperature--Depth) meter. The measurements showed :

a) that the water was stratified, the top 2-4 m being of much lower salinity than deeper layers;

b) no evidence of lateral stratification resulting from salinity differences on the two sides of the Estuary, as had been hypothesised from previous observations of surface shear zones.

Position of each station was marked with a buoy, and fixed using Loran C, corrected for propagation errors. Predicted times of low and high water were 10.12 and 16.22 h, respectively. At the beginning of the study, the Annapolis Tidal Generating Station was

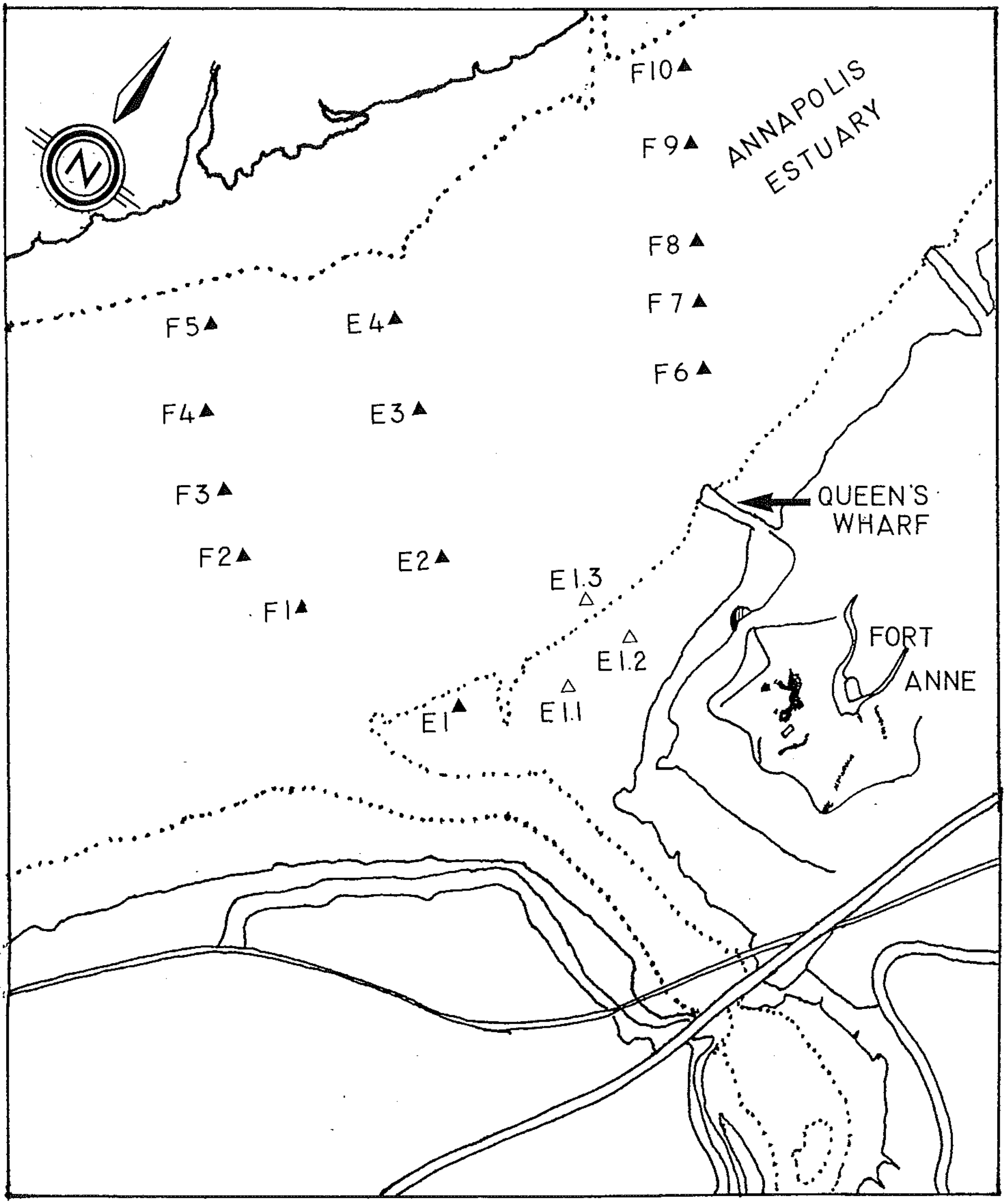

Figure 1. Stations occupied during a flood tide (F 1 - 10) on 1 December 1992 and an ebb tide (E 1 - 4 and E 1.1 - 1.3) on 9 December 1992.

operating, but with the rise in sea level on the flood, the station ceased generation at 12.55 h.

On 9 December the study was repeated during an ebb tide, from 12.00 to 15.27 h. In order to increase the frequency of sampling at each station, only one transect of four stations was visited repeatedly, together with three additional stations over the intertidal zone between the fort and the rocky outcropping at the junction of the Annapolis Estuary and Allain River channels. Positions of these stations are indicated in Figure 1 and recorded in Table 1. Predicted times of high and low water on this date were 10.35 and 16.53 h, respectively. Tidal power generation began at 14.15 h, and continued through the end of the study.

Table 1. Geographic Positions of Stations

Date	Transect	Stn. No.	Latitude	Longitude
Dec. 1	Outer	F 1	44°44.36'	65°31.60'
	"	F 2	44°44.36'	65°31.64'
	"	F 3	44°44.38'	65°31.68'
	"	F 4	44°44.41'	65°31.73'
	"	F 5	44°44.44'	65°31.78'
	Inner	F 6	44°44.62'	65°31.41'
	"	F 7	44°44.64'	65°31.45'
	"	F 8	44°44.66'	65°31.49'
	"	F 9	44°44.71'	65°31.55'
	"	F 10	44°44.74'	65°31.55'
Dec. 9	Middle	E 1	44°44.38'	65°31.43'
	"	E 2	44°44.45'	65°31.50'
	"	E 3	44°44.52'	65°31.57'
	"	E 4	44°44.56'	65°31.63'
	Extra	E 1.1	44°44.44'	65°31.38'
	"	E 1.2	44°44.47'	65°31.36'
	"	E 1.3	44°44.47'	65°31.40'

RESULTS

The salinity and temperature profiles for the two transects run on 1 December during a flooding tide are shown in Figures 2 and 3, and those for the transect run on 9 December during an ebbing tide are shown in Figure 4.

During the flood tide the water column at the outer transect (Stations F 1 - 5), located almost opposite the outflow of Allain River, remained stratified, with lower salinity water (22 - 28 ‰) from the Annapolis River remaining near the surface, and lying over a layer of sea water several metres thick (Figure 2). Salinity of the sea water was 30 - 31 ‰. Stratification was sharper on the south side of the estuary, where the surface layer was limited to about 5 - 6 m depth, and somewhat less so on the north side, where lowered salinities were recorded down to 8 m. These results indicate that outflow from the tidal generating station tends to favour the north shore of the Annapolis Estuary at this location. Similar results were evident at the more landward (inner) transect (Stations F 6 - 10 -- Figure 3). The general profiles on the two sides of the estuary were, however, similar at both transects, indicating that at these distances downstream of the causeway the jetting of water from the tidal power station does not induce a significant flow separation of the north and south sides as had been hypothesised. Nonetheless, the flow of less saline water through the tidal generating station is sufficiently strong, compared with tidal movements, that stratification persists in this portion of the estuary throughout the flood tide.

During the ebb tide study of 9 December, stratification of the water column was much less evident (Figure 4). Except right at the surface (0-2 m), salinities were generally in excess of 26 ‰ , and only a little less than the water below 4 - 6 m depth (about 30 ‰). It is possible that on this day the salinity of water issuing through the tidal generating station was higher than on 1 December, as would be the case if rainfall (or runoff) in the Annapolis watershed was less on 9 December than the week before.

During the course of the study on 9 December, three additional stations were examined in the shallow intertidal area near the fort. The stations were selected because of observations of a distinctive front extending from the east shore of Allain River across the Annapolis Estuary. The salinities on the west side of this front, more or less directly in the Allain River outflow, showed that the water in this outflow was vertically well mixed, whereas the two stations to the east of the front (over the Fort Anne intertidal zone) showed evidence of stratification, with surface waters being of lower salinity than deeper water (Figure 5). These values confirm the presence of two different water masses -- one in the river and one overlying the shallow intertidal -- and thus confirm the existence of flow

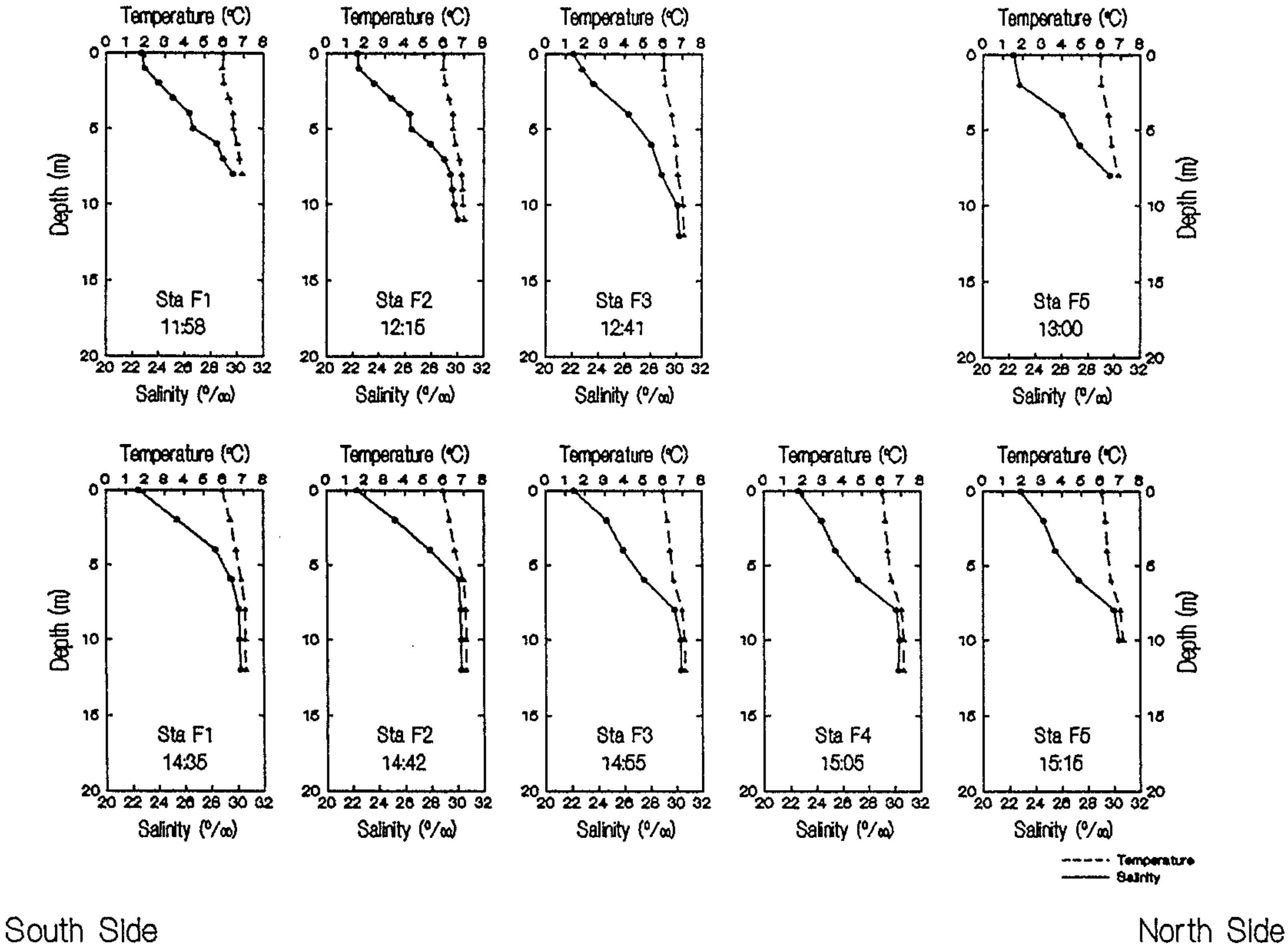

Figure 2. Vertical profiles of salinity and temperature at stations of the outer transect during a flood tide, 1 December 1992. Time of sampling is indicated below the station number. The tidal power station ceased generating at 12.55 h.

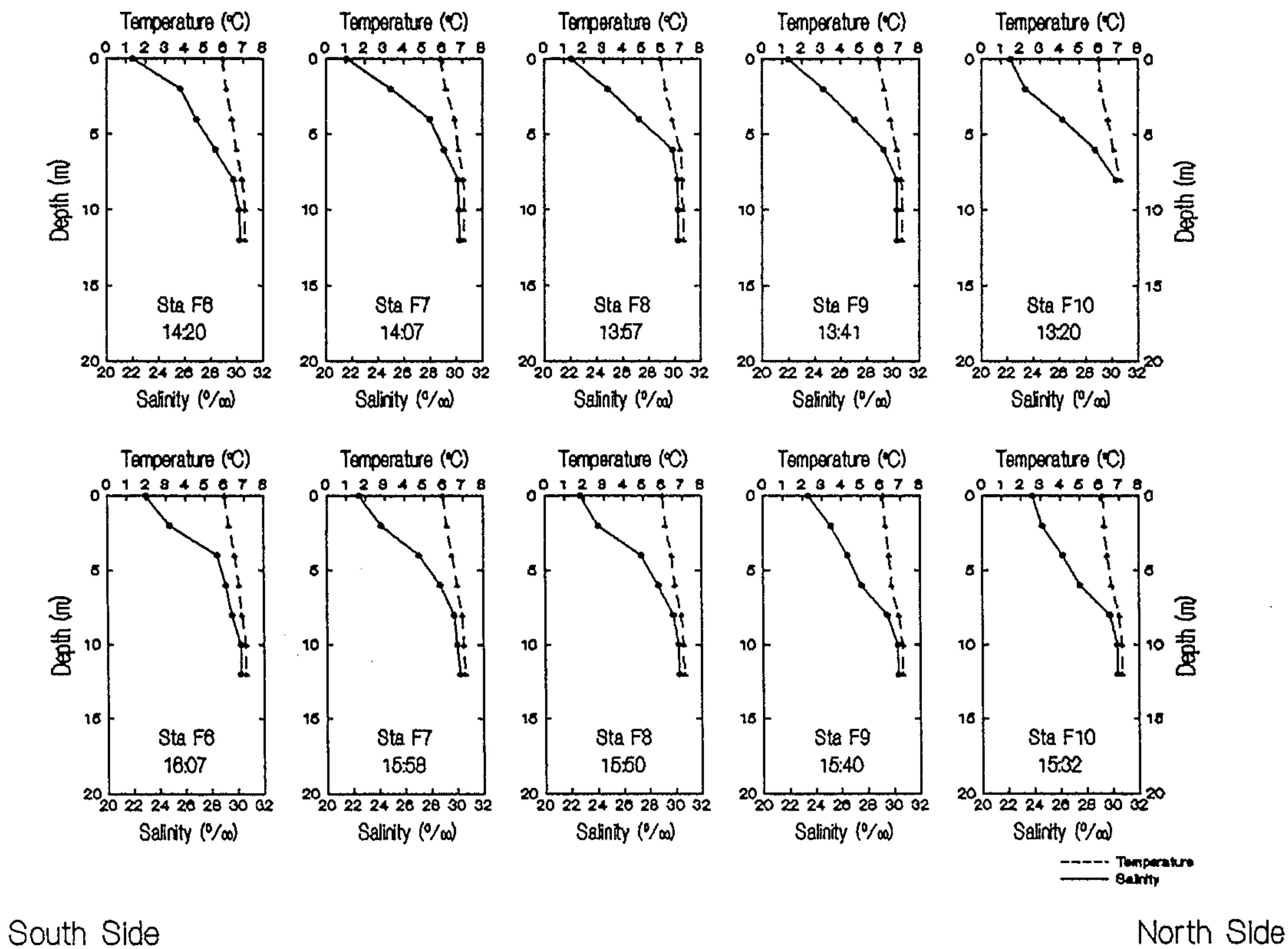

Figure 3. Vertical profiles of salinity and temperature at stations of the inner transect during a flood tide, 1 December 1992. Time of sampling is indicated below the station number. The tidal power station ceased generating at 12.55 h.

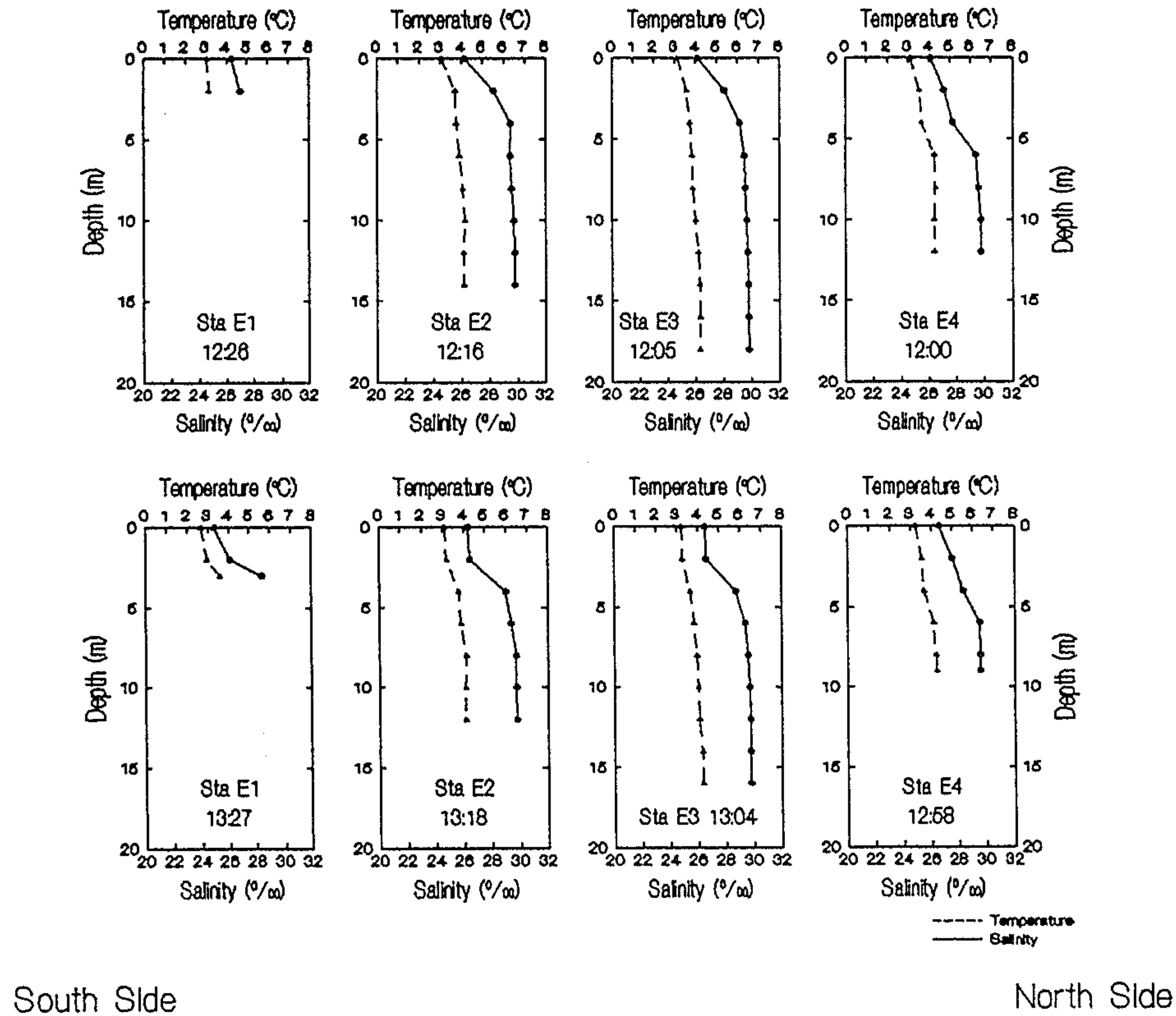

Figure 4 A. Vertical profiles of salinity and temperature at stations of the transect during the early ebb tide, 9 December 1992. Time of sampling is indicated below the station number.

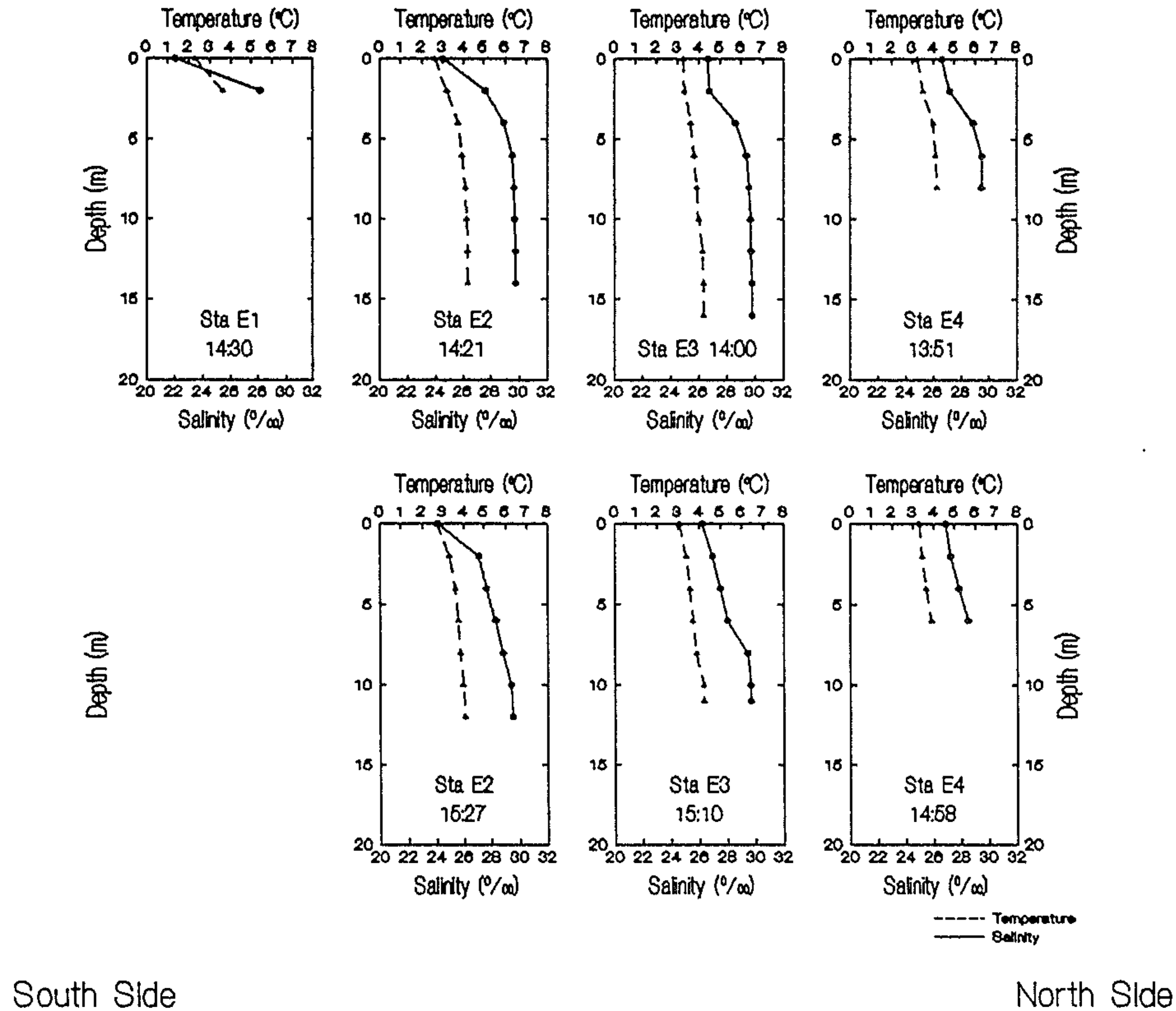

Figure 4 B. Vertical profiles of salinity and temperature at stations of the transect during the late ebb tide, 9 December 1992. Time of sampling is indicated below the station number. The tidal power station started generating at 14.20 h.

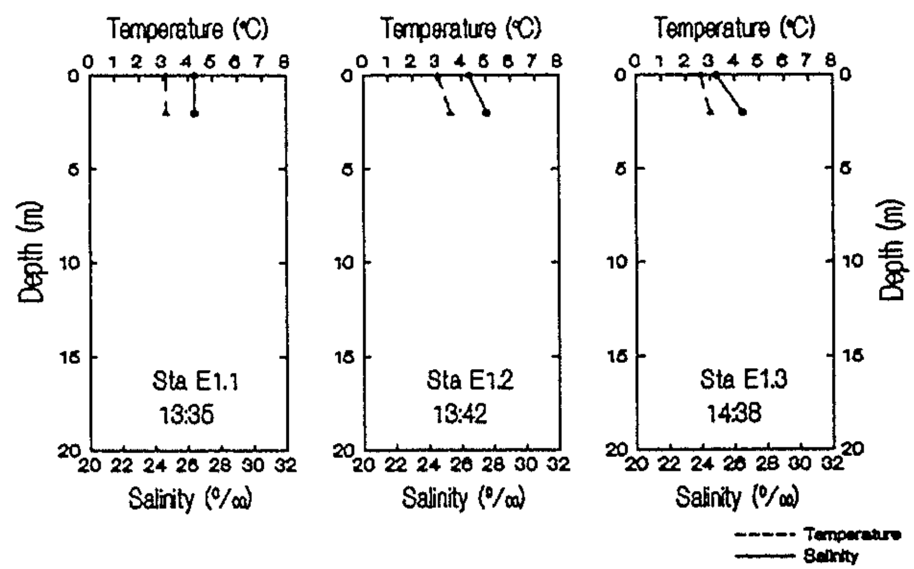

Figure 5. Vertical profiles of salinity and temperature at stations E 1.1 - 1.3 on the Fort Anne intertidal zone during the late ebb tide, 9 December 1992. Time of sampling is indicated below the station number. The tidal power station started generating at 14.20 h.

separation between Allain River and that over the tidal flat. However, the salinity and temperature differences are modest.

Results of the salinity and temperature measurements clearly indicate that the tidal generating station exerts a limited effect on lateral distribution of water masses in the Annapolis Estuary at the level of Fort Anne. Although there is vertical stratification during the flood tide, with lighter discharge water overlying the denser incoming seawater, this has only a modest effect in constraining flooding waters to the south shore. It therefore offers no explanation for recent erosion at Fort Anne.

Calculations of the density of the water (as sigma-t) confirm the tendency of outflow from the tidal generating station to favour the north shore of the estuary during the flooding tide. These results are plotted in Figure 6. On 9 December during the ebb tide, however, the less dense water is to be found on the south shore of the estuary rather than the north shore, although the density differences are really too small on this date to be of any consequence (Figure 7).

Profiles of current velocity and direction were obtained over the flooding tide on 1 December at two transects, one north of Allain River (stations F 1 - 5), and one north of Fort Anne (stations F 6 - 10). Measurements at each station were approximately 10 to 20 minutes apart because of differences in depth at each station, and the time needed to travel between stations. Results are presented in Figure 8. Although this was a flooding tide, flow at the surface and to depths of 3 - 5 m was downstream at all stations during the first sets of measurements, as a result of discharge from the Annapolis Tidal Generating Station. Generation stopped at approximately 12.55, but seaward flows were still evident for at least another hour. Maximum velocities at the surface were approximately 0.5 $m.sec^{-1}$ (1 kt). Since the fort is about one mile below the Annapolis Causeway, water released from the station requires approximately one hour to move down as far as Fort Anne. During later measurements (after 1400 h), surface waters moved in various directions, sometimes directly upstream and sometimes toward the north shore, at velocities of 0.2 - 0.3 $m.sec^{-1}$.

Below the 3 - 5 m surface layer, the flooding tide moved upstream, generally in line with the main channel of the estuary, at velocities of less than 0.3 $m.sec^{-1}$. Flows were somewhat stronger on the south side and, (at stations F 1 - F 3), directed toward the Allain River. At the inner transect, the flood tide is more conspicuous near the southern shore (stations F 6 - F 8), at velocities about 0.25 $m.sec^{-1}$ (0.5 kt). By the end of these series of measurements, about 3 h after the end of generation and one hour before the predicted time of high water, currents at all depths were <0.3 $m.sec^{-1}$ and directed upstream toward the causeway.

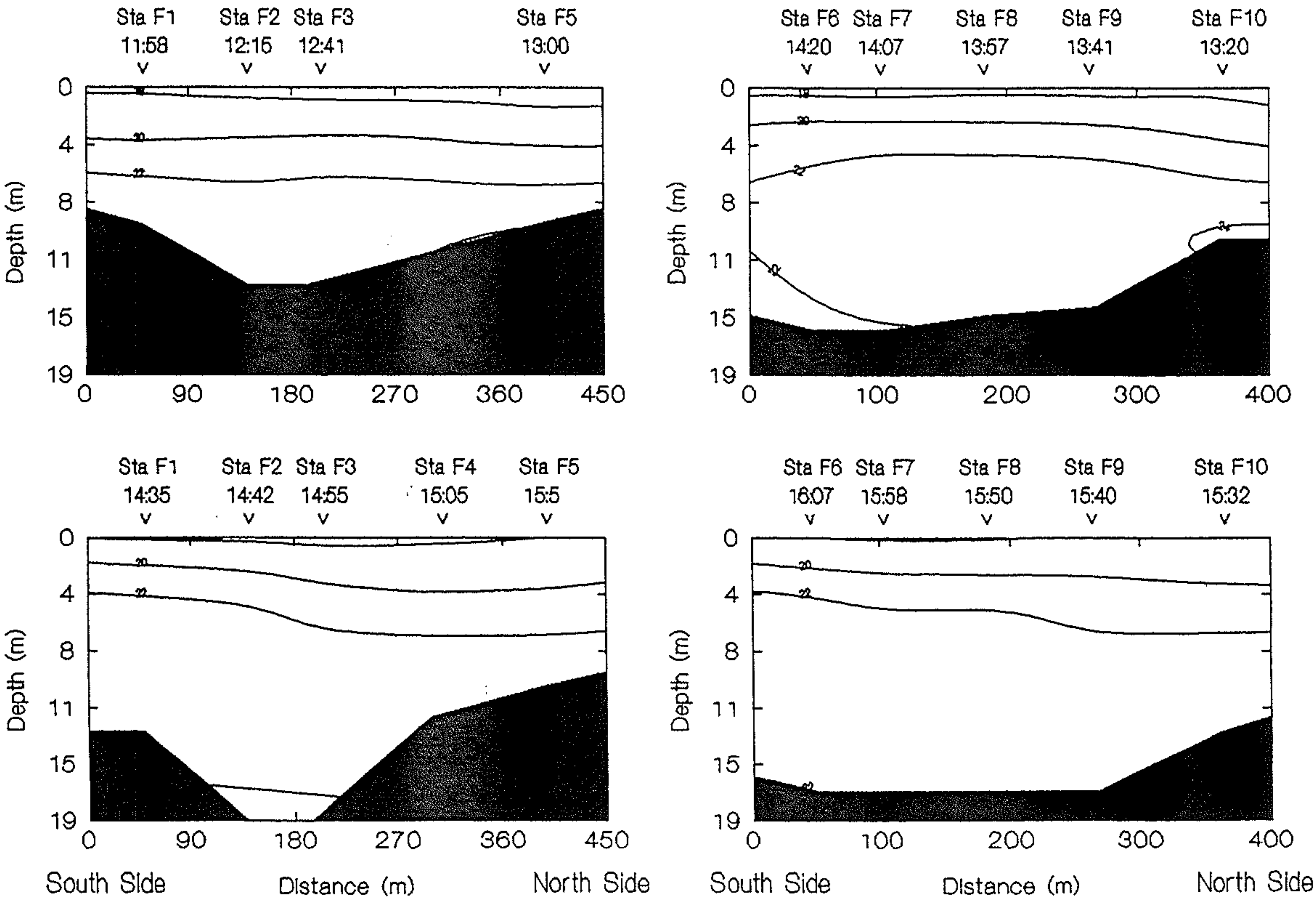

Figure 6. Density isopleths (as sigma-t values) calculated from salinity and temperature profiles during the flood tide, 1 December 1992. Station number and time of sampling are indicated above each panel.

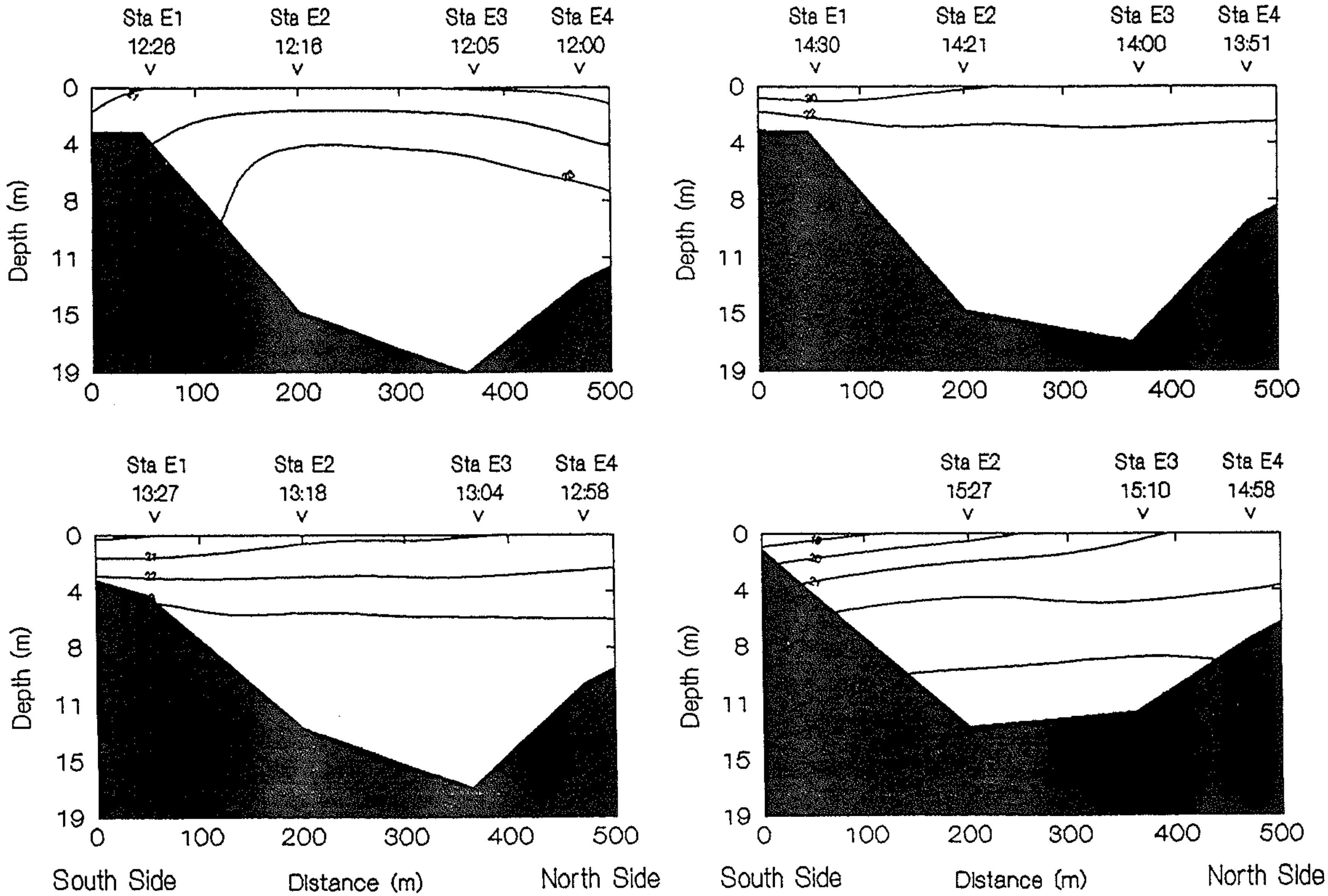

Figure 7. Density isopleths (as sigma-t values) calculated from salinity and temperature profiles during the ebb tide, 9 December 1992. Station number and time of sampling are indicated above each panel.

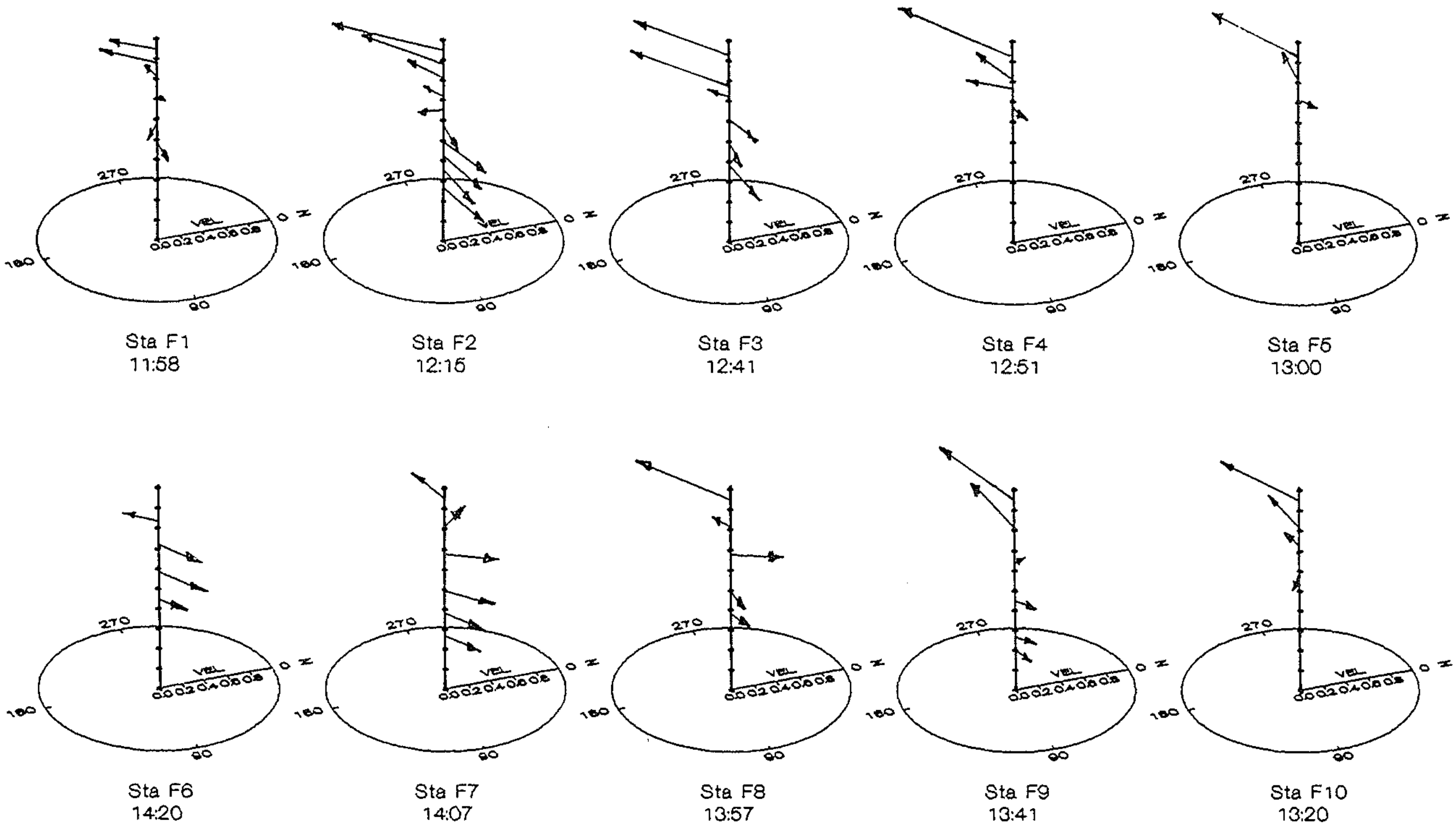

Figure 8 A. Profiles of current velocity and direction at stations occupied during the early flood tide, 1 December 1992. Depth is indicated on the vertical bar at 2 m intervals. Direction is shown by the orientation of arrows at each depth, in degrees relative to true north (N = 0). Velocity is represented by the length of arrows at each depth. Time of sampling is given beneath the station number. The tidal power station ceased generating at 12.55 h.

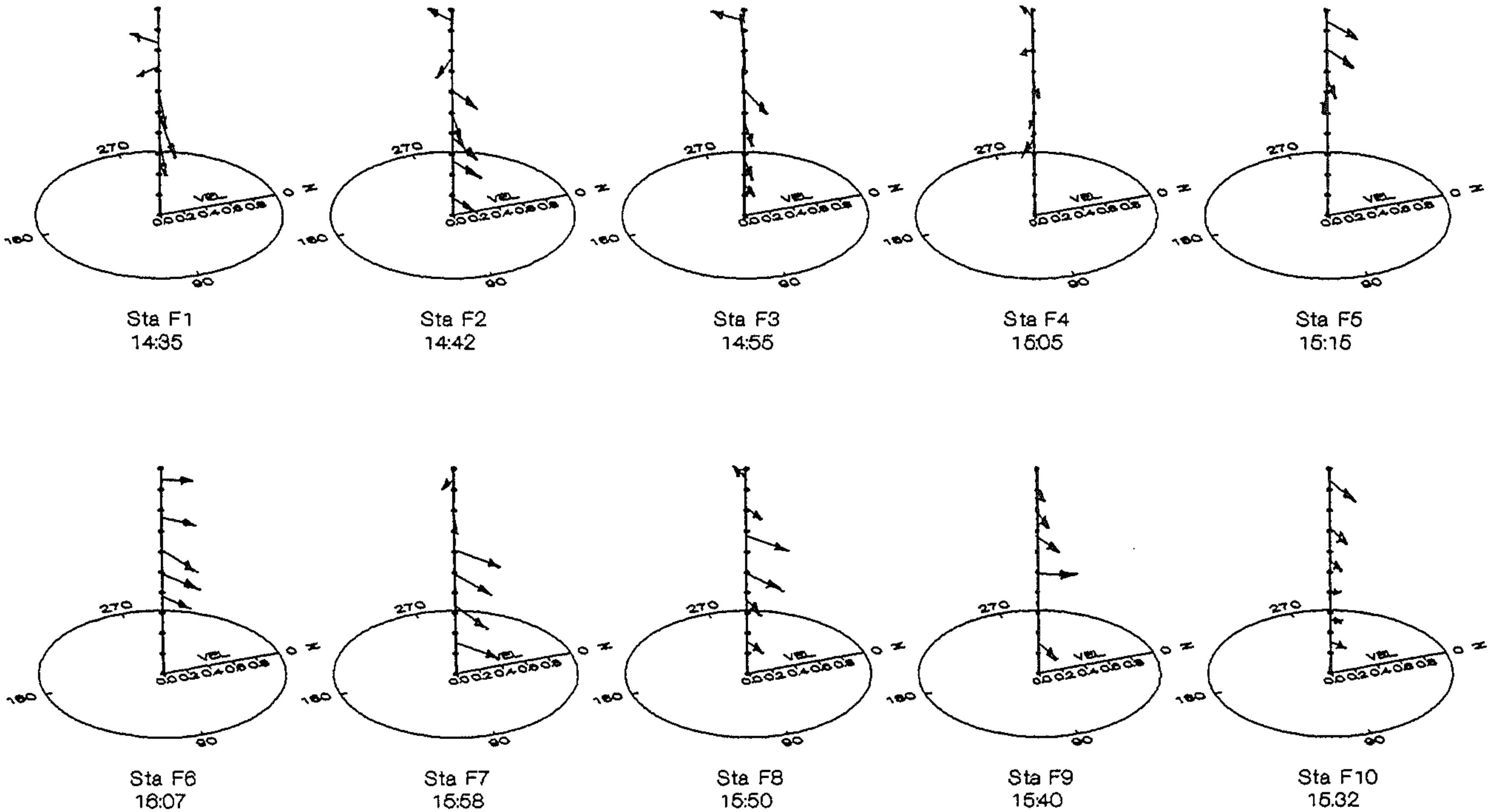

Figure 8 B. Profiles of current velocity and direction at stations occupied during the late flood tide, 1 December 1992. Depth is indicated on the vertical bar at 2 m intervals. Direction is shown by the orientation of arrows at each depth, in degrees relative to true north (N = 0). Velocity is represented by the length of arrows at each depth. Time of sampling is given beneath the station number.

On 9 December corresponding measurements were made at a single transect of four stations (E 1 - 4) across the estuary opposite Fort Anne (Figure 9). The southernmost station was located near the edge of the intertidal zone, and hence in relatively shallow water. The other three stations were in deeper portions of the estuary. Four sets of profiles were obtained, starting approximately 1 h after the predicted time of high water, at which stage the tidal power station was not operating. During the first transit, currents at all four stations were very small (mostly < 0.2 $m.sec^{-1}$), and oriented in various directions. On the south side of the estuary, a weak seaward flow was evident at the surface. On the north shore, however, deeper waters were consistently oriented upstream, even though the ebb flow should have commenced. During the second transit (12.58 to 13.27 h), water flow on both sides of the estuary was generally seaward, but at station E 3, water at intermediate depths of 4 - 8 m was still quite strongly oriented upstream. This inward flow was also evident at this station during the next transit, which took place almost an hour later. At all other stations and depths, however, there was a fairly well developed ebb flow down the estuary, at rates of 0.2 to 0.4 $m.sec^{-1}$. Flows accelerated with time as the influence of the tidal power station became more prominent following its opening at 14.20 h. (Lack of water prevented a fourth profile being made at station E 1.)

At about mid-tide, three stations were occupied over the intertidal zone west of Fort Anne. Results are shown in Figure 10. At station E 1.1, the direction of flow was to the north, (i.e., almost against the ebb flow in the estuary), whereas at the other two stations (E 1.2 and E 1.3) it was mostly directed onshore toward the fort itself. All flows were weak (<0.2 $m.sec^{-1}$). The difference between E 1.1 and the other two stations is related to an apparent front observable at the surface, that extended across the Annapolis Estuary from the east shore of Allain River; station E 1.1 was to the west of this front, whereas the other two were on the east side of it.

Observations made during the study indicate that the position of this front systematically changes as the ebb flow develops out of the Annapolis. When first seen, at 13.27 h, it extended northwestward from the point near the fort, across the Annapolis Estuary, between stations E 1 and E 2. Winds at this time were northerly and brisk -- about 10 kt. An hour and a half later (14.58 h), the same front had rotated in a counterclockwise direction, so that its southerly end was below the fort, and the northerly end trended towards the west. It continued to rotate until, by 15.30, it was oriented directly downstream along the axis of the estuary. Successive positions of this front are shown in Figure 11.

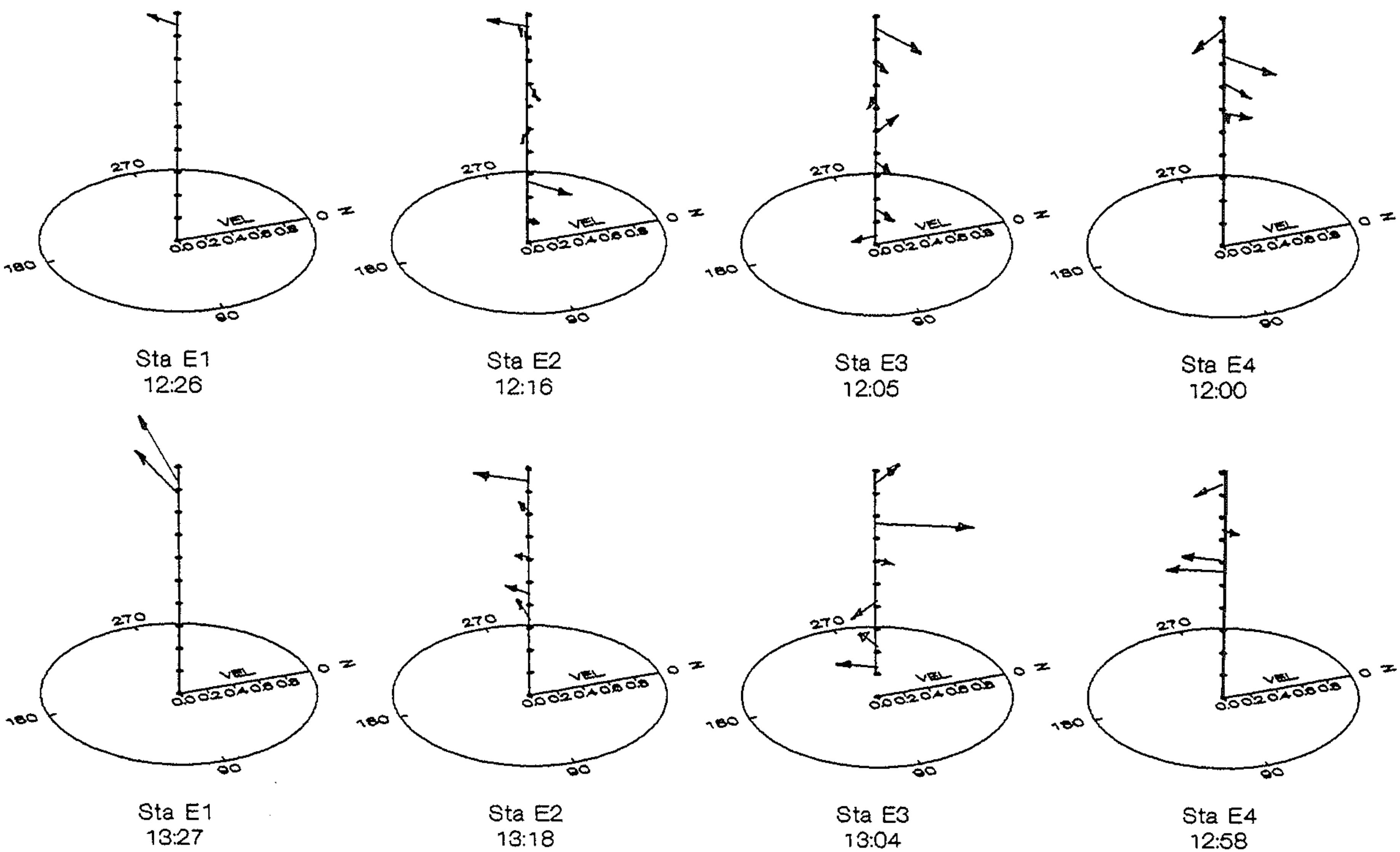

Figure 9 A. Profiles of current velocity and direction at stations occupied during the early ebb tide, 9 December 1992. Depth is indicated on the vertical bar at 2 m intervals. Direction is shown by the orientation of arrows at each depth, in degrees relative to true north (N = 0). Velocity is represented by the length of arrows at each depth. Time of sampling is given beneath the station number.

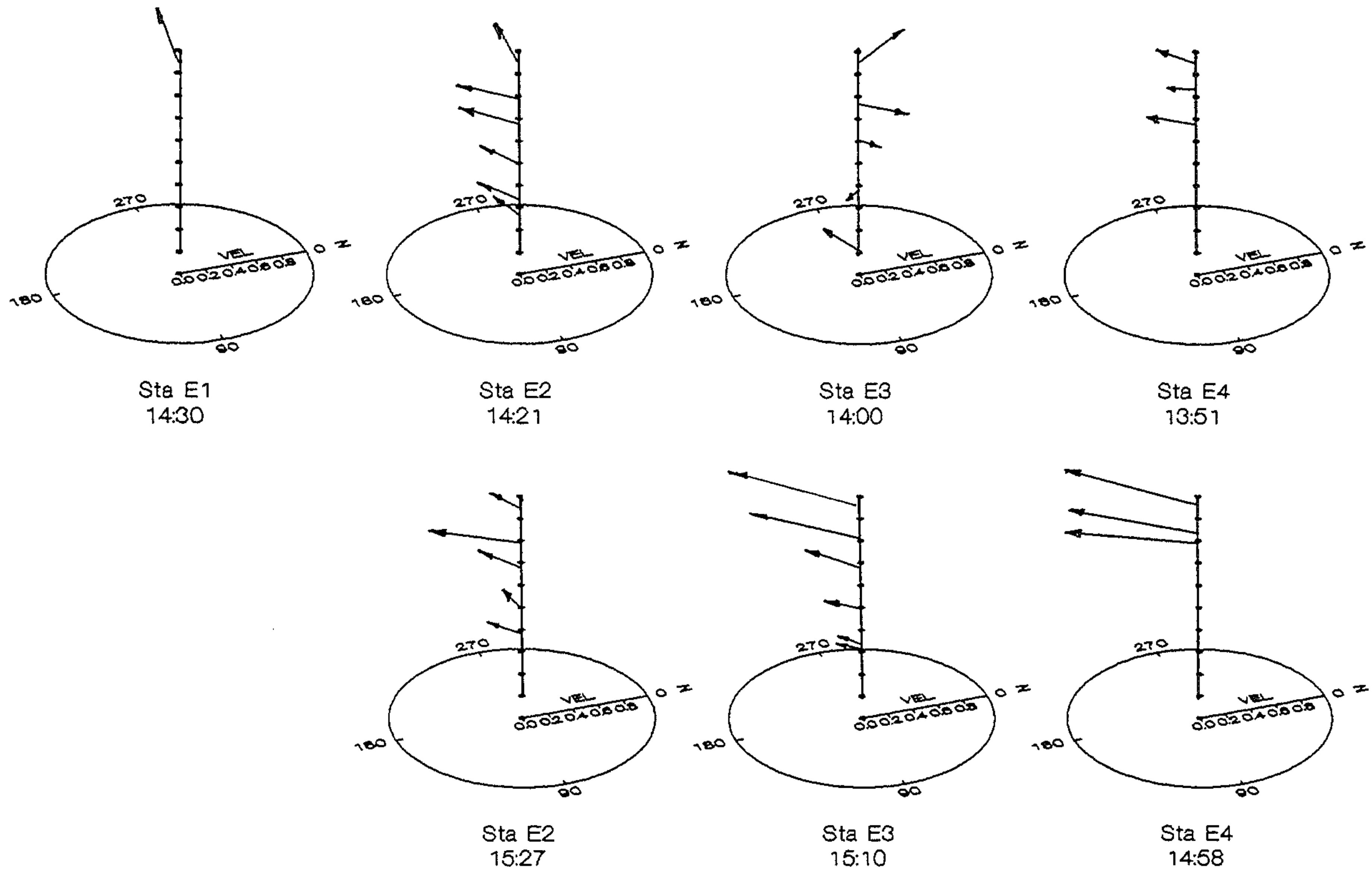

Figure 9 B. Profiles of current velocity and direction at stations occupied during the late ebb tide, 9 December 1992. Depth is indicated on the vertical bar at 2 m intervals. Direction is shown by the orientation of arrows at each depth, in degrees relative to true north (N = 0). Velocity is represented by the length of arrows at each depth. Time of sampling is given beneath the station number. The tidal power station started generating at 14.20 h.

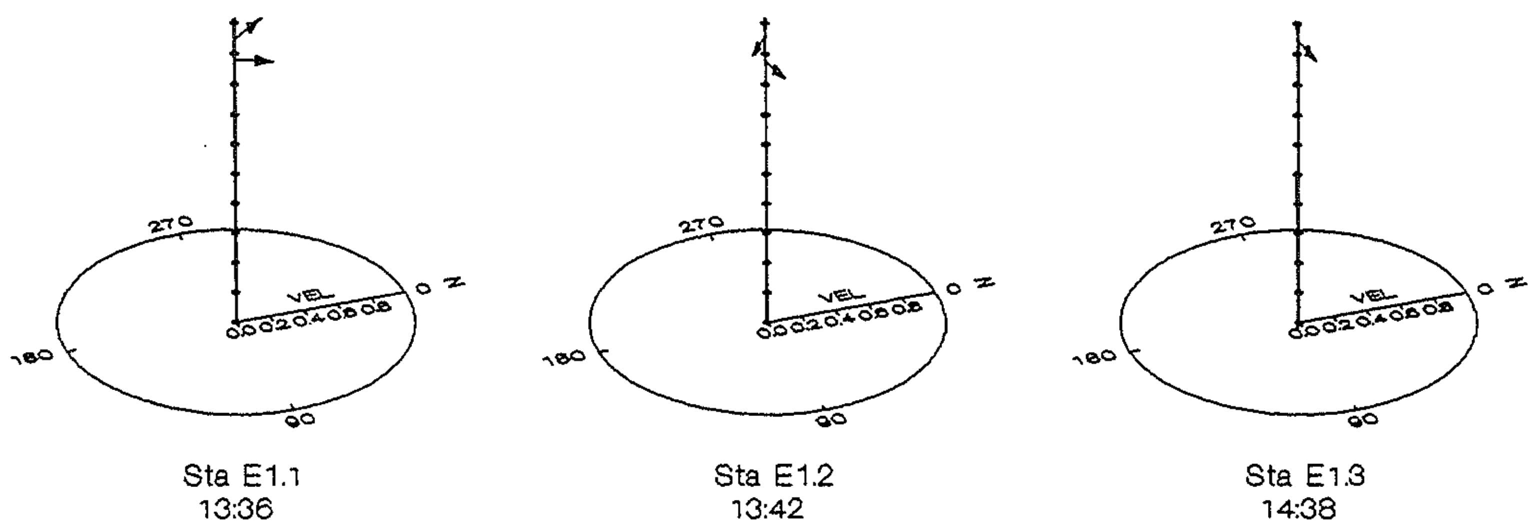

Figure 10. Profiles of current velocity and direction at stations on the Fort Anne intertidal zone during the late ebb tide, 9 December 1992. Depth is indicated on the vertical bar at 2 m intervals. Direction is shown by the orientation of arrows at each depth, in degrees relative to true north (N = 0). Velocity is represented by the length of arrows at each depth. Time of sampling is given beneath the station number. The tidal power station started generating at 14.20 h.

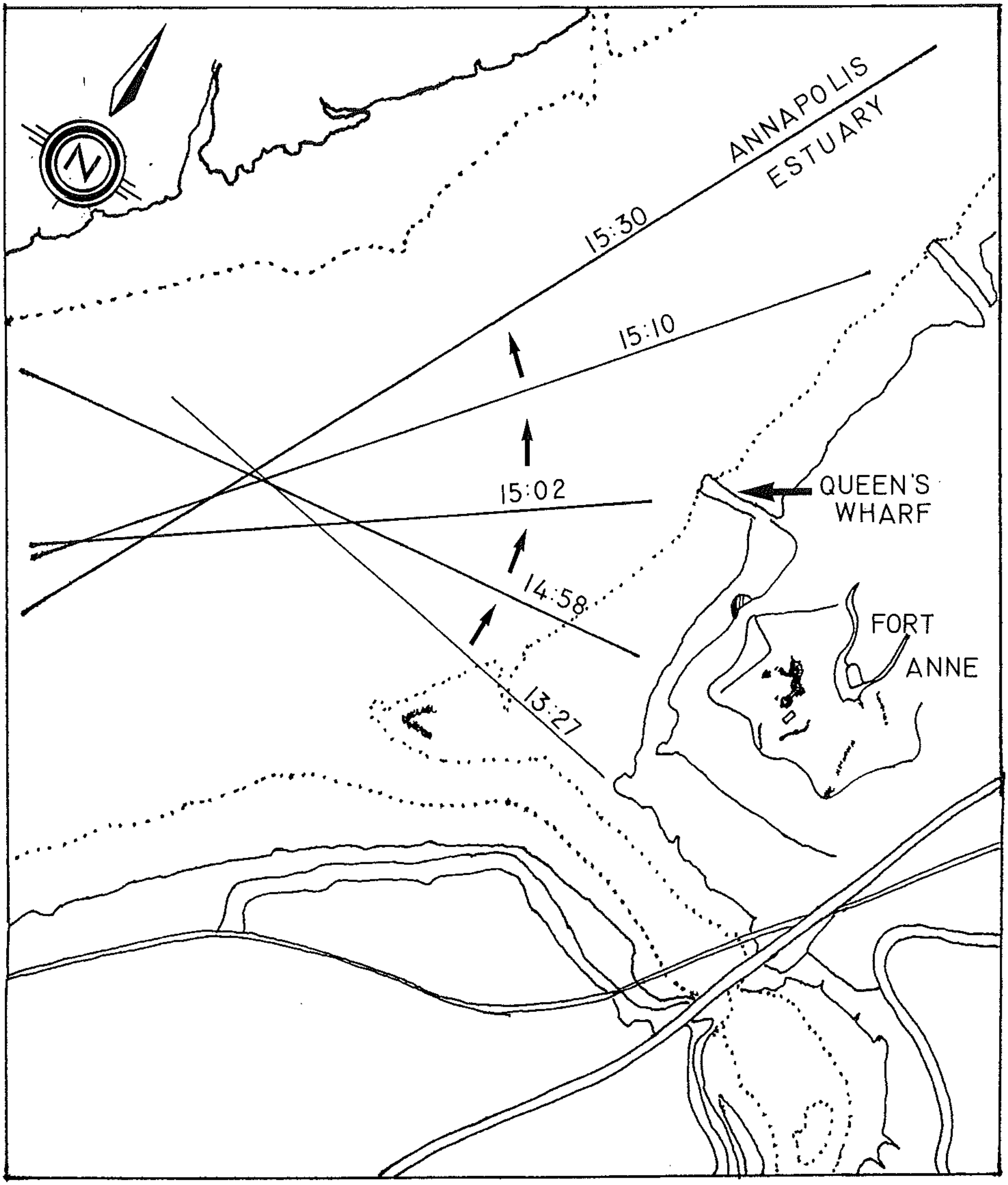

Figure 11. Positions of front observed during ebb tide, 9 December 1992.

The integrity of this surface front, despite somewhat windy conditions, indicates that flow velocities on each side are different : i.e., this front represents a shear line. Current velocities at stations E 3 and E 4, representing the northern side of the estuary, were considerably greater than those on the south side, as indicated at E 2. On the southern shore, a band of relatively still water about 50 m wide was observed, indicating that disharge from the turbine does not always control water movements along the Annapolis and fort shoreline. Thus, when the power station is generating, outflow occurs predominantly along the northern side of the estuary, and because the water on the southern side is not moving so rapidly, a persistent shear line is present in between these two flows. This is clearly the explanation for its presence, but it does not represent such a major difference in flows that it could be responsible for the enhanced erosion occurring at Fort Anne.

INTERPRETATION

This study has shown that water movements in the Annapolis Estuary in the vicinity of Fort Anne are complicated and highly variable. Salinity and temperature measurements indicate that water discharging through the Annapolis Tidal Generating Station tends to remain at the surface, as a layer 2 - 5 m deep, overlying the denser seawater. The degree of stratification is probably variable, depending upon the amount of freshwater flowing down the Annapolis River above the causeway. Velocities of this surface water are higher than movements attributable to either flood or ebb flows.

During the flood tide, the seaward discharge current persists at the location of Fort Anne until more than an hour after the station has ceased generation. The outward flow at the surface tends to favour the northern side of the estuary, and the incoming tidal flow develops along the bottom, with some tendency toward the southern shore. Maximum velocities along the south shore are not particularly high at any time, and diminish as high tide is approached.

On the ebb tide, the seaward flow starts in the vicinity of Allain River well before the ebb develops in the rest of the estuary. In fact, upstream flows are present at certain intermediate depths in the central part of the Annapolis Estuary as much as 3 - 4 hours after high water. This may indicate the presence of a progressive wave in the main estuary, a result of which is that reversal of flow lags behind the reversal of the changes in relative water level.

It appears that the flow out of Allain River is the dominant movement during the early ebb tide. As sea level falls, the slope of the water surface in Allain River increases because of the restriction to flow represented by the highway bridge, and relatively high velocities develop. Because the water jets out of Allain River at much greater rate than water is moving in the Annapolis itself, a surface shear line develops that is oriented across the estuary, and actually cuts across the intertidal zone beside Fort Anne. This shear line is clearly evident in a 1977 aerial photograph, which indicates that these conditions have been present for a long period of time. As the sea level continues to fall, the velocity of the outflow from Allain River increases, but the decreasing depth of water at the mouth of the river means that the rocky outcropping off the western point of the fort eventually begins to play a role in determining flow direction.

The situation changes, however, after the tidal power station begins to operate. The discharge current does not appear in the vicinity of Fort Anne until about one hour after the wicket gates are opened, and thus 4-5 hours after the predicted time of high water. This discharge current tends to favour the north shore, and may at this time be accompanied by a weak landward flow along the south shore. As the discharge current increases in velocity, and the continually falling sea level induces flow out of the whole estuary, the Allain River outflow also begins to turn downstream. As a consequence, the prominent shear line rotates until it comes to lie in mid-stream, where it represents a boundary between the more rapidly moving discharge flow along the north shore, and the lesser flows of the south side. Although insufficient measurements are available over the intertidal zone beside the fort during the ebb tide, the integrity of the shear line suggests that some of the water discharging from Allain River may now be flowing over this shallow area towards Queen's Wharf. Although flows are probably quite small, such a movement of water could potentially result in transportation of fine sediments from the Fort Anne shore into the Annapolis Estuary on the northeasterly side of the promontory. Several times it has been observed that a band of turbid water exists along the fortress shore. This effect is apparent in the 1987 aerial photograph and in the most recent aerial photograph taken in August 1992. This particular image shows that a band of highly turbid water occurs between Queen's Wharf and the Allain River, and seems to suggest that the sediment is moved into Allain River at the end of the flood tide. The 1992 photograph indicates resuspension of sediments only along the Fort Anne shoreline, and nowhere else in the nearby estuary.

Eventually, the falling water levels mean that the outflow from Allain River becomes entirely constrained within the normal channel and directed seaward.

Observations of the front between the water flowing out of Allain River and that moving away from the intertidal zone near the fort indicate that the geometry of this tributary at its junction with the Estuary results in some separation of flows. A further study needs to be conducted with more concentration upon events occurring in the immediate vicinity of the fort, in order to determine the direction of flow across this portion of the intertidal on both flooding and ebbing tides.

CONCLUSIONS AND RECOMMENDATIONS

(1) Examination of a number of aerial photographs has indicated that shoreline erosion adjacent to Fort Anne has been continuing for at least two or three decades. Much of the saltmarsh along the Annapolis Estuary shore had disappeared by 1981, and there are indications in a 1981 photograph that the intertidal zone beside the fort has a very different texture from other intertidal zones in the vicinity. The sediment here seems distinctly more coarse, reflecting greater shear stress on the bottom at this point compared with other intertidal areas nearby. It is possible that the slope of the shore has increased because of the erosive removal of the muds that were present there during the 1940's. If that is the case, the saltmarsh above might have been rendered much less stable. Present indications are that the principal agent of erosion now is wave action, driven by the wind.

(2) Our study of the Annapolis Estuary shows that when the Annapolis tidal generating plant is operating, it dominates flows in the estuary at the level of Fort Anne. Discharge water tends to remain at the surface, so that the water is at least partly stratified. The discharge also tends to follow the north shore, although during mid-flood and late ebb, surface water flows seaward across the whole estuary. Flood tide currents tend to develop first in bottom water, and toward the south side, but the velocities are not sufficently high to cause significant erosion along the south shore. About one hour after the plant stops generating, the flood tide develops across the whole estuary, and inward-directed currents persist well into the ebb.

(3) The dominant influence during the early part of the ebb is the discharge from Allain River. Observations made during this study confirm that a significant jet of water develops as sea level falls, apparently as a result of the constriction at the Highway 1 bridge. The behaviour of a shear line created by the Allain River flow suggests that there may be significant flow across the Fort Anne intertidal zone during early parts of the ebb. Data are presently insufficient to determine if such flows are strong enough to explain the loss of fine sediments from this region.

(4) At this time there is no clear indicator of a single factor that is primarily responsible for the recent process of erosion, except that of wind-driven waves. Because most of the saltmarsh has gone, even small wavelets are capable of washing out the fine sediments that form the basis of the remaining marsh and that have been used to construct the fortress embankments. It is apparent that present conditions do not permit any eroded sediment to remain and accumulate on the intertidal zone below. This in turn indicates that water flow across the intertidal zone beside Fort Anne is at times quite strong.

(5) Several local changes may have contributed to the overall increase in susceptibility of this marsh and shoreline to erosion. The flows out of Allain River are especially strong and dominant, and this seems to be due to the constriction at the highway bridge. The deterioration of Queen's Wharf may have opened the Fort Anne shoreline to slightly stronger flows along the Estuary, although our measurements do not suggest that these flows could be responsible for significant erosion of intertidal sediments.

(6) It seems probable now that the loss of the Fort Anne marsh is the result of a long-term change in local dynamics, probably related to construction of the Annapolis Causeway in 1960. However, it must be remembered that single episodic events may be effective in triggering or accelerating processes that have long time frames. Such an event could have been the 1976 Groundhog Day storm.

Our analysis of data gained from this study, and other information obtained mostly through examination of aerial photographs, leads to the following recommendations:

(1) The process of erosion seems to be ongoing, and will shortly result in severe damage to some of the external structures of Fort Anne. It is necessary that protection against wave action be provided in the short term for the most vulnerable portions of the embankment. This should be installed soon.

(2) Because the ultimate cause of the erosion is still unclear, it is unwise to commit to expensive long-term protective works at this time, since the most appropriate design would be difficult to choose. We recommend that some further examination of the problem be undertaken as outlined below.

(3) On the basis of our study of the main estuary, we conclude that development of a large scale hydrodynamic model would not be appropriate. The forces acting on this portion of the shore seem to be limited to the immediate area, and are probably the result of changes to the estuary, especially the Annapolis Causeway. A cogent hypothesis that now presents itself is that the outflow of Allain River, modified as it has been by constructional activities of the last several decades, may be a continuing source of stress on that intertidal area that has resulted in removal of the fine sediment. In order to assess this possibility, a short term intensive study of current velocities on the intertidal zone itself between the fort and the rocky promontory should be carried out. An outline of this study is presented in the Appendix. This study would provide an indication both of the probability that these

ebb currents are contributing stress factors, and if so, suggest remedial measures that might be taken to reduce their effect in the long term.

(4) If the proposed measurements confirm the hypothesis that outflow from the Allain River across the Fort Anne foreshore during the early ebb is preventing deposition of fine sediments, then several long-term solutions present themselves. The objectives of protective structures should be :

a) to protect the upper shore against wave erosion in the immediate future;

b) to diminish erosive forces that presently work on the intertidal zone, especially during the ebb tide;

c) to encourage the accumulation of fine sediment in this area; and

d) to attempt to rebuild the saltmarsh at the top of the intertidal zone.

It may be that rebuilding of Queen's Wharf, and replacement of whatever structure originally extended from the northwest tip of the fort to the rocky point (visible in the 1981 photograph), might be sufficient to decrease erosion on this shore in the long-term.

REFERENCE

Dunn, B. 1992. A preliminary look at the history of erosion at Fort Anne. Internal Publication, Atlantic Regional Office, Canadian Parks Service. 32 p.

APPENDIX: Current Flow Patterns on the Fort Anne Foreshore

Objectives

1. To obtain detailed measurements of current velocity and direction at two points on the Annapolis Estuary intertidal zone near Fort Anne.

2. To obtain measurements of suspended sediment concentrations during the late flood and early ebb tides on the Fort Anne foreshore.

3. To confirm the hypothesis that strongest flows of water across the Fort Anne foreshore are associated with outflow from Allain River during the first hours of the ebb tide, and that these are sufficient to remove any sediment resuspended from the shoreline during inundation by the tide.

Methods

1. Two INTEROCEAN S4 recording current meters will be installed at points on the intertidal zone adjacent to Fort Anne for two tidal cycles.

2. Periodic water samples will be taken during inundation of the intertidal zone to assess the extent of and time frame of sediment resuspension.

3. Profiles of salinty, temperature and suspended sediment concentration will be obtained during inundation of the tidal zone at stations in Allain River and on the Fort Anne foreshore.