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LIMNOLOGY OF THE ANNAPOLIS RIVER AND ESTUARY:
I. PHYSICAL AND CHEMICAL FEATURES

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Results of physical and chemical studies of the Annapolis River and Estuary during the summer of 1976 are presented. Since completion of the tidal dam at Annapolis Royal in 1960, the estuary has become highly stratified, with outflowing fresh water (<.2°/oo) overlying salt water of 16-24°/oo. A very narrow halocline and thermocline occurs at 4 to 5 m over most of the estuary. The salt wedge moves upstream during the summer months when river discharge is low, reaching > 25 km above the tidal dam. Owing to the lack of mixing, considerable oxygen deficits were recorded in the salt wedge. River discharge varied with rainfall with about 2 to 3 day delay. River waters were relatively high in chlorides, nitrates, and orthophosphates, and moderately well buffered. The consequences of installing a tidal power turbine in the causeway at Annapolis Royal are discussed.

Introduction

The province of Nova Scotia is, by any standards, both well watered and well drained. Precipitation falls in all months of the year and totals 100 to 150 cm. yr^{-1} in different parts of the province. The water collects, briefly, in more than 10,000 lakes and ponds, most of them situated on igneous rock in the southern half, and subsequently flows out to the Atlantic, the Gulf of St. Lawrence, or Bay of Fundy through a myriad of small and large streams. Most of the streams are short, flowing independently into common estuaries or directly into the sea along the more abrupt coastlines (Smith 1966).

Several of these river systems have, in the last half-century, been partially or completely impounded to produce hydroelectric power or control seasonal flooding of dykelands on the eastern estuaries. More than 60 reservoirs involving 16 river systems will be generating 355 MW when the Wreck Cove Project comes on stream this year. A number of major rivers, including the Shubenacadie, La Have, Annapolis, Margaree, Tusket, and Gaspereau, support important sport and commercial fishing activities based upon anadromous fish such as salmon (*Salmo salar*), striped bass (*Morone saxatilis*), shad (*Alosa sapidissima*), gaspereau (*A. pseudoharengus*), and smelt (*Osmerus mordax*) while many others are extensively fished for introduced trout (*Salmo gairdneri*). Last, but certainly not least, the rivers are also the recipients of the effluvia of our society: sewage, at best only partially treated, industrial wastes and the run-off from agricultural land and feed lots. It now seems probable that at least 1 river estuary will be used to generate electricity by manipulation of tidal water. It is surprising, in view of the manifold uses to which Nova Scotia's rivers have been put, that so little is known about their general limnological characteristics.

A recent study of striped bass spawning in the Annapolis River (Williams 1978) necessitated the accumulation of a substantial amount of background information on stratification, rates of flow, and physico-chemical properties of the river and its estuary. It seems appropriate at this time, when plans are under way to install a tidal power turbine in the causeway near Annapolis Royal, to review the information that has so far been obtained about this river. The present contribution summarises physical and chemical features, and provides a foundation for subsequent reports on fish distributions and benthic invertebrate populations.

Methods

Surface and bottom water samples were collected with a 2.1 l horizontal Van Dorn sampler at 4 locations (0.6, 16.7, 32.2, and 46.7 km upstream from the Annapolis causeway - Fig 1) in mid-May and at intervals of 2 to 9 days during June, July, and August 1976. Each sample was analysed for dissolved oxygen using the Alsterberg modification of Winkler's method (A.P.H.A. 1976). Total alkalinity, pH, chloride, sulphate, orthophosphate, nitrate-N, and turbidity were determined with a Hach DR-EL kit.

Vertical profiles of the river were obtained using a YS1 model 33 S-C-T meter. Salinity and temperature were recorded at each meter depth at 14 stations between Annapolis causeway (km 0) and km 20 on 10 May. Salinity profiles were again obtained at 17 stations between km 0 and km 30 on 2 July. Additional profiles were taken for specific short stretches of the river on other occasions. At Bloody Creek (km 25), a site of particular interest, profiles were taken at intervals of 1 to 10 days between 5 May and 2 July in order to study the oscillations of the salt wedge as influenced by tidal and precipitation patterns.

The Annapolis River System

The Annapolis River originates near Aylesford (Kings Co 45°02′N, 64°50′W) and flows southwestward through the Annapolis Valley for about 142 km before discharging into the Annapolis Basin near Annapolis Royal (Annapolis Co 44°45′N, 65°29′W). Decrease in elevation over that distance is a little more than 40 m, and with such gentle slope the river meanders extensively. The Valley ranges in width from 4 km at its western end to 9 km near Aylesford. It is flanked on the northern side by North Mountain, a basalt cuesta of the Triassic period, 5 to 8 km wide with crestline elevations of 183 to 244 m above MSL. The south face of North Mountain is a steep escarpment breached at intervals by the ravines of small streams tributary to the Annapolis River. Flow is usually intermittent in these short tributaries (Hickox 1962; MacDougall et al. 1969).

To the south the valley is bounded by the South Mountain Highlands, a somewhat older (Devonian) granite batholith. The slopes of South Mountain are well dissected by drainage streams that ultimately flow into the Annapolis River. However gradients are moderate, and the Highlands contain innumerable lakes and boggy depressions resulting from impeded drainage (MacDougall et al. 1969). Most of the streams are permanent, having measurable flow all year and follow winding or meandering channels (Fig 1). About two-thirds of the 2130 km^2 of the Annapolis watershed is within the South Mountain Highland (Trescott 1968).

About 50% of the soils in the valley are developed on glacial till, 30% on glacial-fluvial material, and the remainder on estuarine deposits and stream alluvium, with some areas of peat and muck. Riverside soils from Annapolis Royal to Paradise consist of poorly drained silty loam and silty clay loam, but upstream from Paradise the soils along the river are excessively drained sands and gravel. Soils on the lateral valley slopes are very thin and bedrock exposures abundant (MacDougall et al. 1969).

The natural vegetation of the Annapolis Valley is a forest of softwoods or mixed softwoods and hardwoods, but this has been greatly modified by human activity. Very little undisturbed forest remains (MacDougall et al. 1969). Marine aluvium deposits beside lower reaches of the Annapolis River and Annapolis Basin have never been forested. Many of these areas were reclaimed from salt marsh by erection of earth dykes.

In 1960 the Annapolis River Tidal Dam was constructed near Annapolis Royal. It consists of a rockfill causeway and a central section built of open concrete caissons, the latter containing 2 sluice gates used to control water levels and a permanently open 3 x 7 m fishway. Tidal amplitude on the basin side of the dam ranges from 7 to

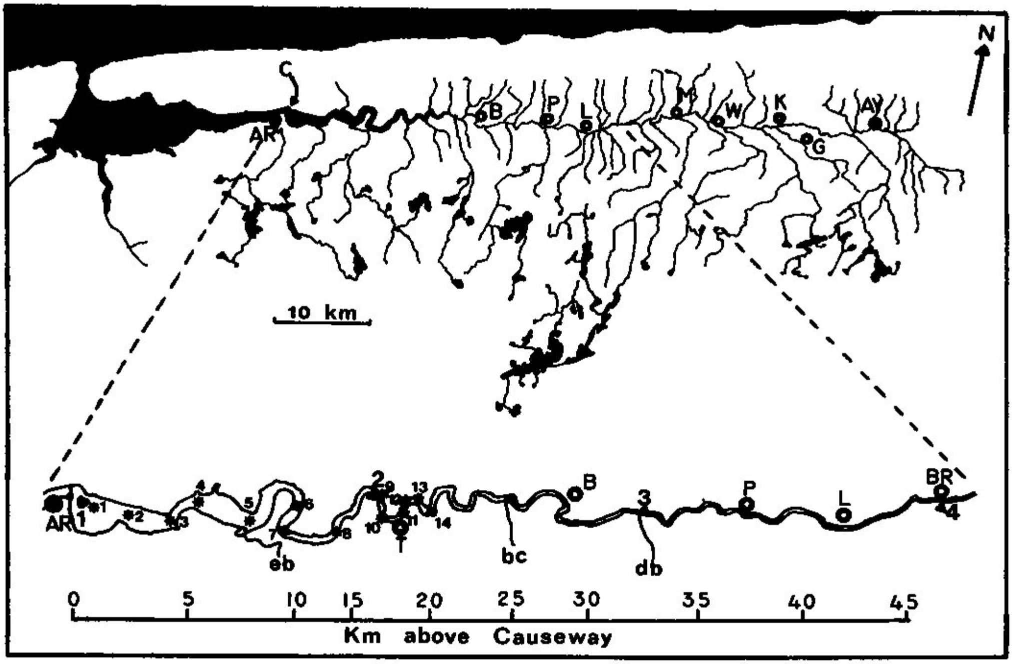

Fig 1. Upper: The Annapolis River System. Lower: Map of study area, slightly enlarged. AR - Annapolis Royal; AY - Aylesford; B - Bridgetown; BR - Brickton; C - Causeway; G - CFB Greenwood; K - Kingston; L - Lawrencetown; M - Middleton; P - Paradise; T - Tupperville; W - Wilmot; bc - Bloody Creek; db - Daniel's Brook; eb - Evans Brook.
▲ 1-4: Sample sites for water analyses;
* 1-14 Sites for 10 May salinity/temperature profiles.
Lower scale shows river distances above causeway for lower figure.

9 m. Prior to closure, the Annapolis River was tidal as far as the village of Paradise, but tidal range behind the dam is now usually controlled to ± 0.5 m (Jessop 1976). The dam eliminates need for the kilometers of running dykes formerly required to protect about 1740 ha of reclaimed marshland from tidal flooding.

Physical Features

A physical survey of the Annapolis estuary from the causeway to Bridgetown was done by Fisheries and Marine Service (Environment Canada) personnel in 1975 (Jessop 1976). The river upstream to Brickton was surveyed in 1976 as part of the present study.

The headpond above the dam is broad, 4.1 km in length by 0.7 to 1.6 km in width, and oriented about east-west. It is thus exposed to predominantly westerly winds that are funneled through the Annapolis Basin. Maximum depth encountered by Jessop in August 1975 was > 21 m about 1 km above the causeway. However, much of the headpond is 9 m in depth, the old river channel forming a relatively narrow trough that meanders for some 8 km above the dam to the southern side of the impounded area. The estuary narrows abruptly near Mochelle, widens to about 1 km at

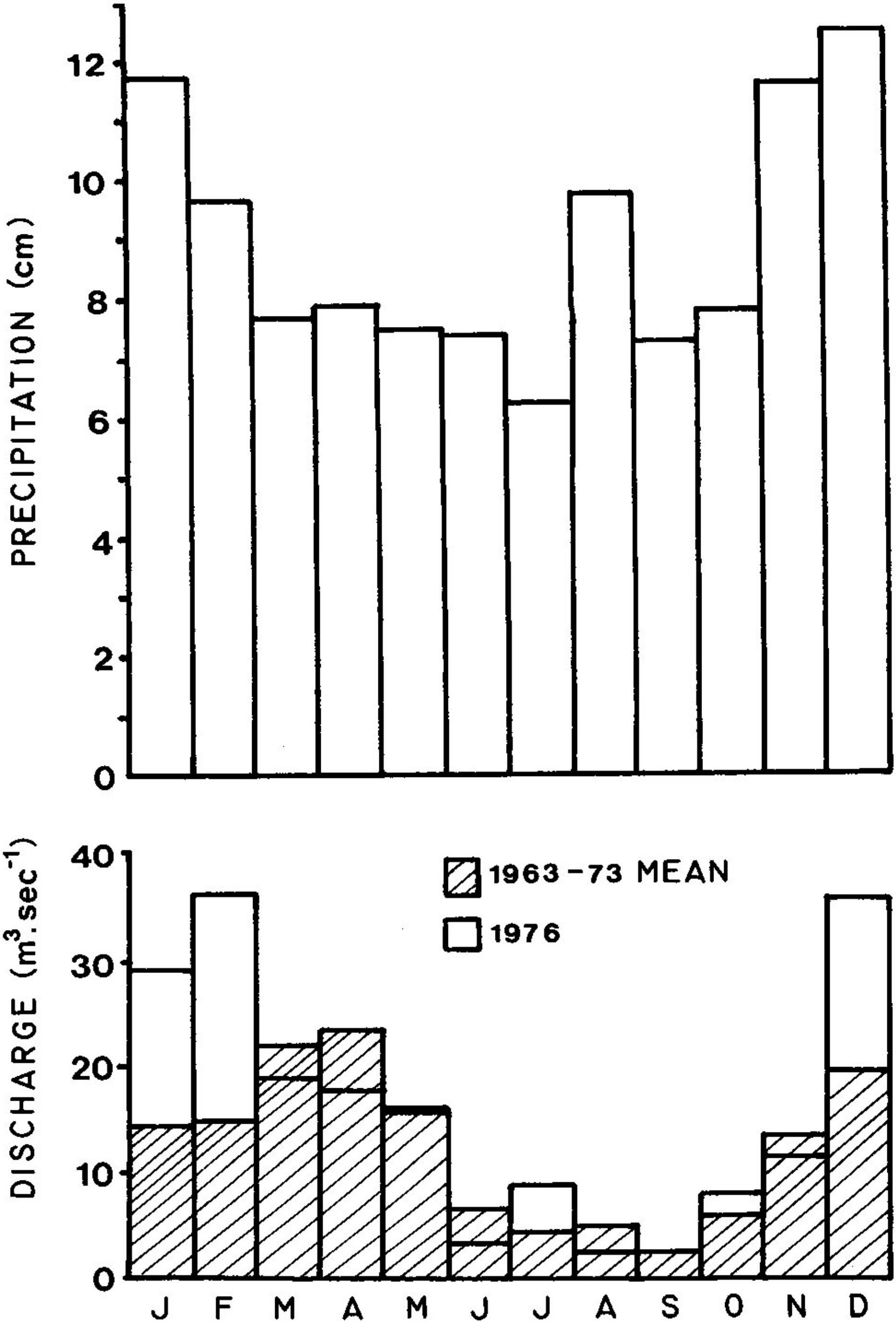

Fig 2. Total Monthly precipitation at CFB Greenwood, 1976, and monthly discharge of Annapolis River recorded at Wilmot.

Granville Centre, but then narrows again as it meanders around Pré Rond Marsh, where it is constrained between earthen dykes. Maximum depth at Pré Rond is 6 m. Depths diminish to 3 m between Tupperville (km 20) and Bridgetown (km 30), are generally < 2 m above km 30 and < 1 m above Lawrencetown (km 42).

Discharge of the Annapolis River has been recorded at Wilmot, about 80 km upstream from the causeway since 1963. The watershed monitored by this station is only 546 km^2 compared with the total of 2130 km^2 for the Annapolis system as a whole. The long term average monthly flow (1963-73) indicates a strongly seasonal pattern with maximum discharge in winter (Dec - Feb) and minima in mid to late summer (Fig 2).

This pattern corresponds fairly well with the long term average monthly precipitation as recorded for Greenwood 9 km away, except for the marked low in discharge during the summer. Obviously, much of the deficit is removed by direct evaporation, although some is used in mid-summer to replenish ground water supplies (MacDougall et al 1969). Total annual discharge at Wilmot in 1976 was 504 x $10^6 m^3$ (409,000 ac-ft) at a mean monthly rate of 15.9 m^3/sec (563 cfs). These values are considerably greater than the long term averages of 400 x $10^6 m^3$ (325,000 ac-ft) and 12.68 m^3/sec (448 cfs) respectively, and result primarily from unusually heavy winter snowfalls.

A comparison of the daily precipitation recorded at Greenwood with discharge at Wilmot for the period May to August 1976 indicates that the river responds with a 2 to 3 day delay (Fig 3). Surface water velocity measurements at 11 sites between Bloody Creek (km 25) and Lawrencetown (km 42) between June 10 and 19 indicated an average velocity of 0.32 m/sec (Williams 1978) corresponding to a daily distance travelled of > 27 km. These values were recorded at a period of low flow and thus indicate minimal response and conveyance time. Maximum velocity recorded during this study was 1.39 m/sec on 15 June, shortly after the very heavy rainfall of 12 June (Williams 1978).

Vertical profiles of temperature and salinity were taken at the 14 points between km 0 and km 20 on 10 May, 1976. At the station closest to the causeway (No. 1, Fig 1), a marked and progressive increase in salinity occurred as depths increased (Fig 4, 1). Surface waters were moderately fresh at 3°/oo, whereas near the bottom at 13.5 m salinity was 23 °/oo. A distinct halocline was not present in this area, although increases in salinity were greatest between 2 and 5 m, over which depth range temperatures also declined from c 11.5°C in upper waters to 10°C at 5 m.

At Station No. 2, however, in shallow water (7 m) about 2.5 km from the causeway, the water column was distinctly stratified. The top 2 m exhibited salinities of 1 to 2°/oo and temperatures of 12°C. This highly stratified structure was encountered as far upstream as km 8 (station 7) with narrow halocline and thermocline occurring at a depth of 4 to 5 m. Above km 10 the rapid shallowing of the estuary resulted in diminution of the lower saline layer until it was represented only by a narrow salt wedge lying on the bottom. This bottom layer was detected as far as Tupperville (km 18). Beyond this point on May 10 the river was uniformly fresh from surface to bottom and homothermal at 13°C.

Between 10 May and 27 June salinity and temperature profiles were taken at intervals of 3 to 10 days at 8 locations between km 16 and km 32 (Daniel's Brook) in order to monitor the furthest extent of the salt wedge. These data are recorded in Williams (1978). Until 12 June the salt wedge was detected at km 22, but no further. On this date it extended at least to km 25, and on 15 June was up to Bridgetown (km 28). On 27 June it had reached km 29 but was not present at Daniel's Brook.

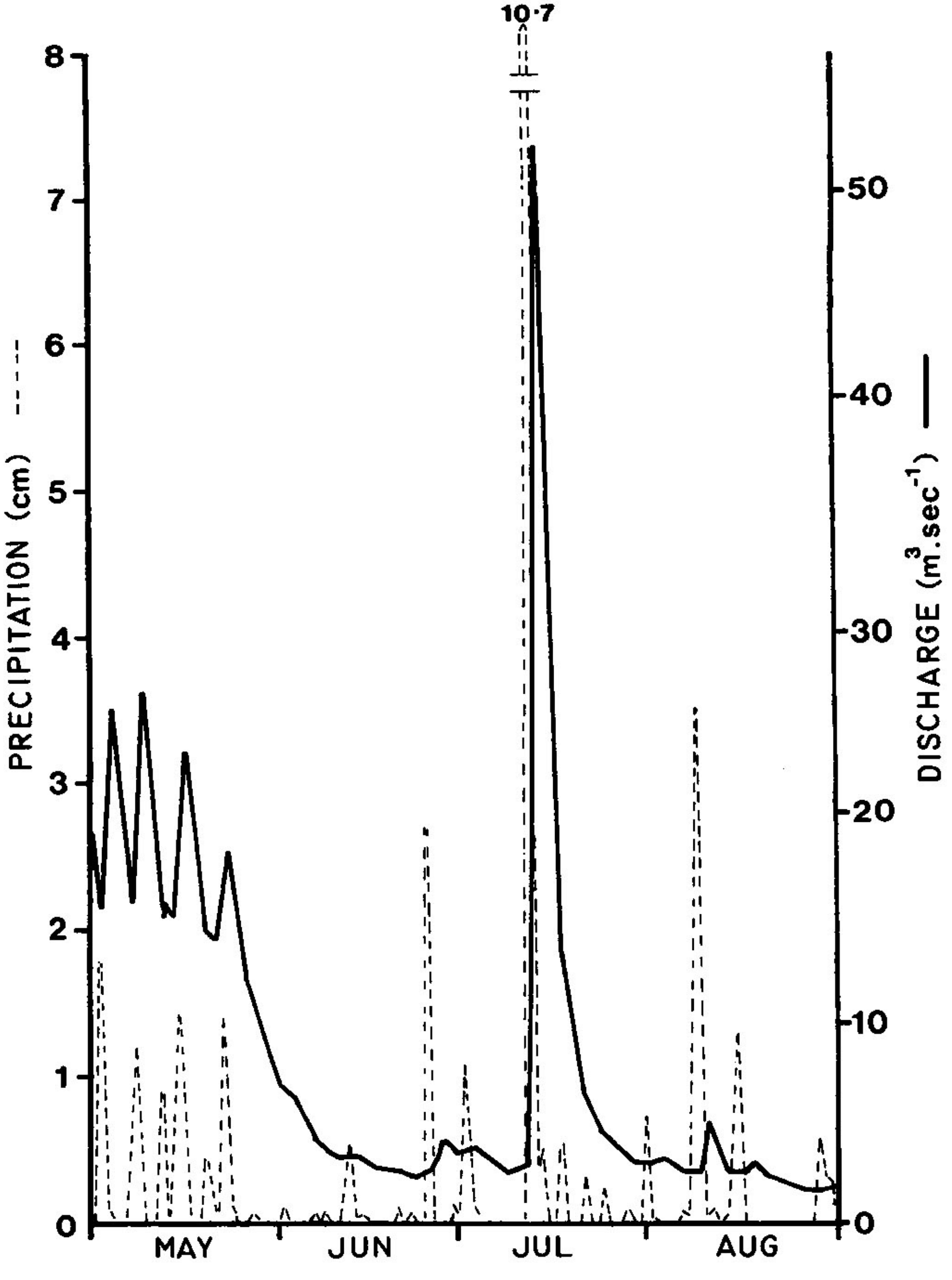

Fig 3. Daily precipitation at CFB Greenwood — and discharge of the Annapolis River at Wilmot — May-August 1976.

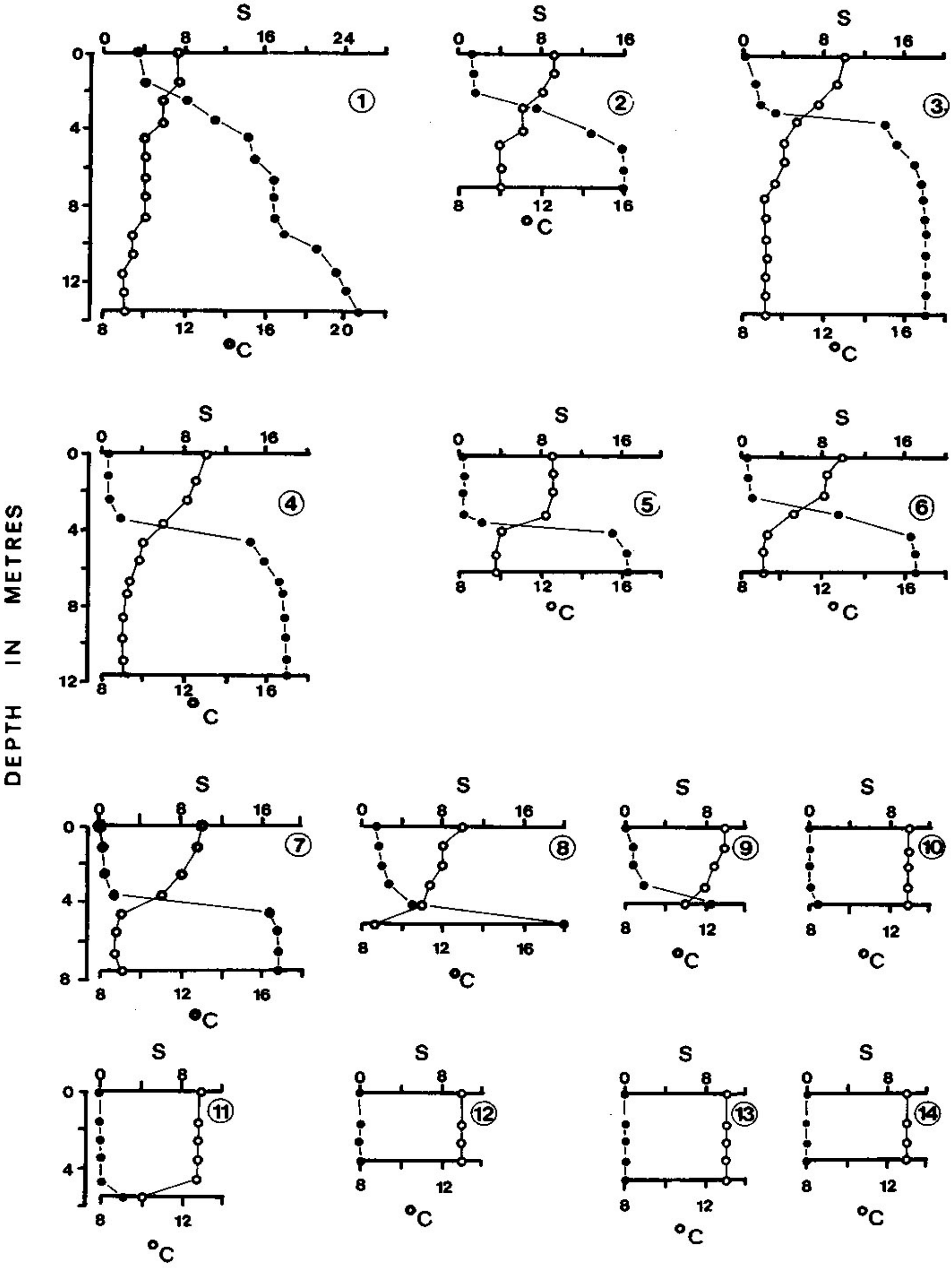

Fig 4. Salinity (S°/oo •—•) and temperature (°C, o—o) profiles of the Annapolis River, 10 May 1976. Sample station (1-14) locations in Fig 1.

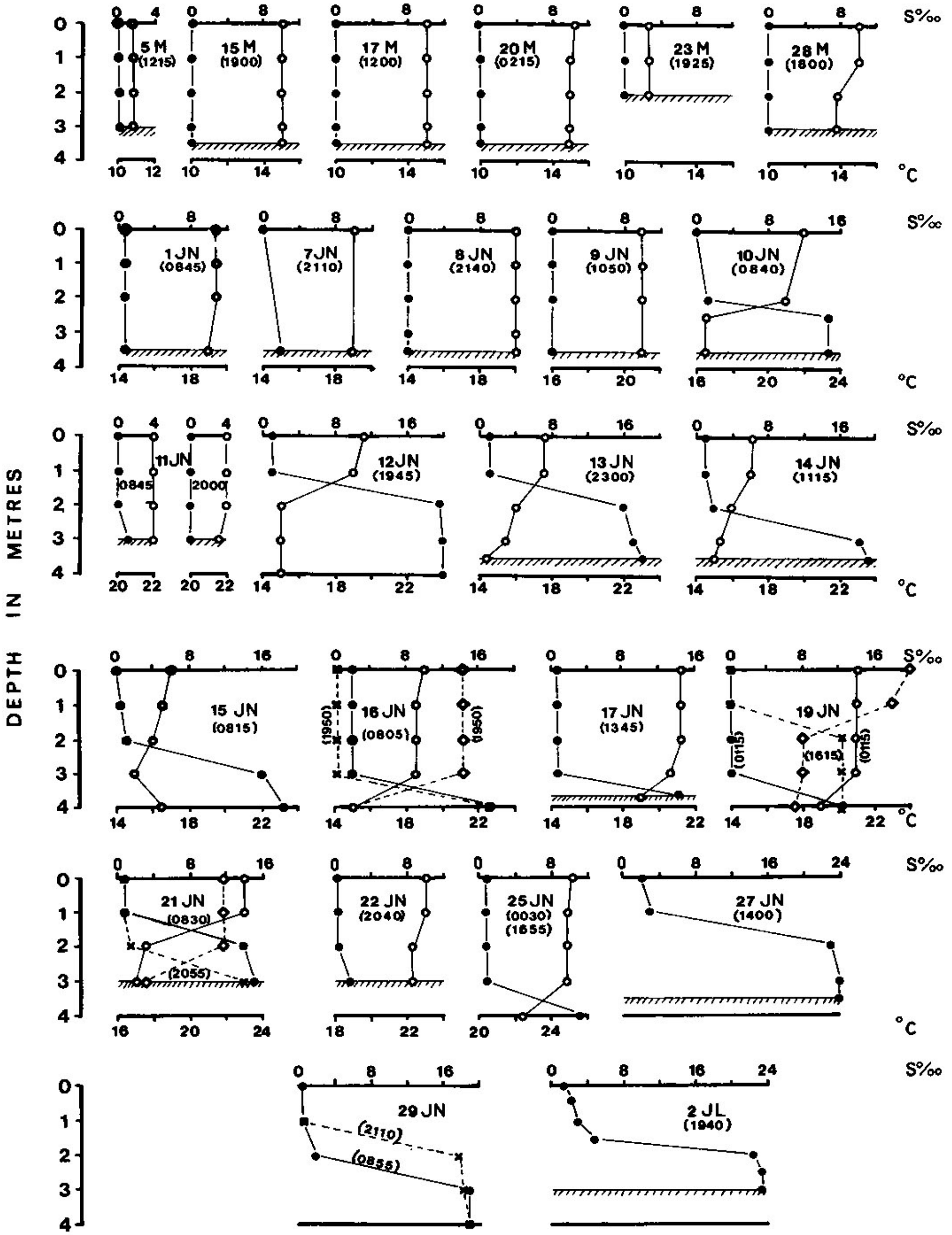

Fig 5. Salinity (S°/oo, ●—● x—x) and temperature (°C o—o,◊···◊) profiles at Bloody Creek (km 25) during May (M), June (JN) and July (JL), 1976. Sample times (in h) given in parentheses. Recorded depth varied according to state of tide, river flow, and precise sample point.

The results indicated a progressive upstream movement of the salt wedge as water levels declined. However, on 22 June, during an extended period of low flow (< 3 m^3/sec at Wilmot from 15 June), the salt wedge could not be detected at Bloody Creek (km 25) although it had been there a few days previously. It was apparent that tidal movements also influenced the uppermost extent of the salt. By 2 July the salt wedge had reached Daniel's Brook. It was not detected above this point at any time.

In order to examine the influences of tidal movement and river discharge on salt intrusion, we recorded vertical distributions of salinity and temperature near Bloody Creek at frequent intervals from 5 May to 2 July. The results are given in Figure 5. The salt was first detected at this station on 10 June (0840 h), was absent on 11 June and returned on 12 June. It was absent again on 22 June, but present on all other days examined. The thickness of the salt wedge, however, varied markedly on 19 June, where samples were taken at times close to low and high tides. Most other sample intervals were multiples of 12 h and thus corresponded approximately to the same stage of tide.

Records of turbidity were obtained at frequent intervals at 4 locations between the causeway and Brickton (km 47). Turbidity in the river and in surface waters of the estuary was generally low (< 50 JTU). Saline waters, however, were usually more turbid as would be expected in tidal regions off the Bay of Fundy, although a sharp and consistent decrease in turbidity took place during mid-summer in bottom waters near the causeway (Fig 6).

Chemical Features

pH at the river stations (3 and 4) varied little during the study (Fig 7) from 6.2 to 6.6, and there was no significant difference between surface and bottom water. Below Tupperville (No. 2), however, while surface waters remained slightly acidic because of stratification, the lower saline water was circumneutral. Near the causeway (No. 1) pH values fluctuated around neutrality, occasionally with surface waters exhibiting slightly lower values. These instances probably indicate decreased mixing between riverine and estuarine water.

The dissolved oxygen (DO) values given in Figure 8 are at best only indicative of general patterns because samples were taken at varying times of day and tide, and solubility varies considerably both with temperature and salinity. At the 2 river stations, DO varied irregularly between 6 and 9 mg/l during most of the study, representing 70 to 100% saturation. There was no significant difference between surface and bottom concentrations. A general trend can be seen whereby 0_2 saturation was inversely related to river discharge: at periods of low flow (eg mid-June and early August) the water was always close to saturation, whereas in early June and mid-July when discharge was greater 0_2 saturation declined to 70-80%. Since temperature varied little during June to August (20-23°C at the times of measurement) these changes are reflected in the concentration values shown in Figure 8.

In the estuary, surface waters exhibited similar patterns of DO concentration to the river, whereas the underlying salt water generally showed much lower concentrations. Near the causeway DO remained close to saturation (94-105%) for the whole study period, both at the surface and near bottom. The lower concentrations in deeper water are thus entirely a function of temperature and salinity. At the Tupperville station, however, whereas the outflowing river water at the surface remained consistently close to saturation, the underlying salt water was frequently much undersaturated. This is undoubtedly due to the very stable chemical stratification in that part of the river, which prevented replenishment of oxygen withdrawn by biological processes. It is to be noted that the salt wedge reached as little as 44% saturation in mid-August. This degree of undersaturation, if persistent, would have considerable ecological significance.

Total alkalinity at the river stations was generally < 30 ppm except for a sharp in-

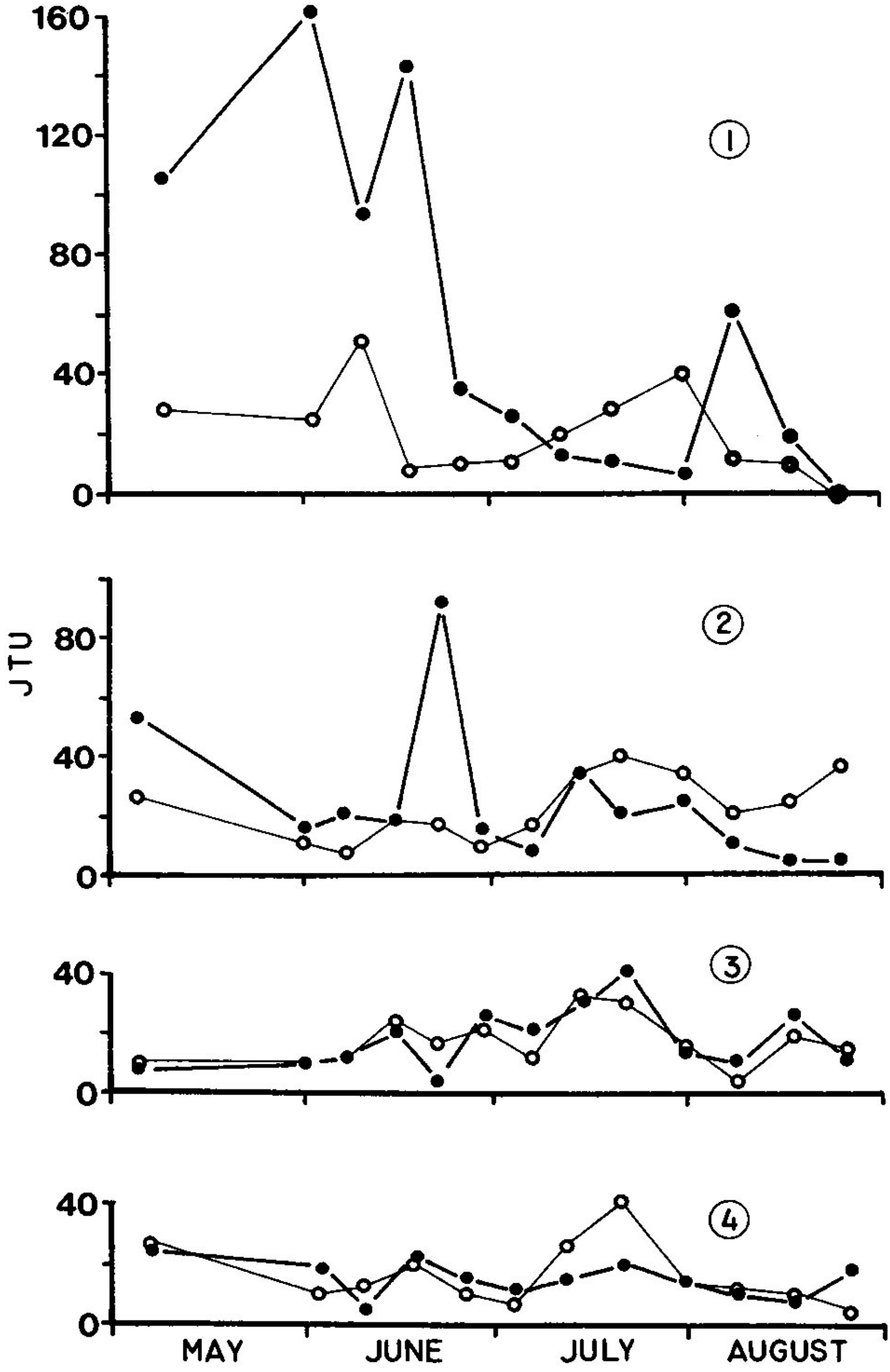

Fig 6. Turbidity (Jackson Turbidity Units—JTU) at Stations 1-4, May-August 1976 (• — • bottom sample; o—o surface sample). Sample stations (1-4) in Fig 1.

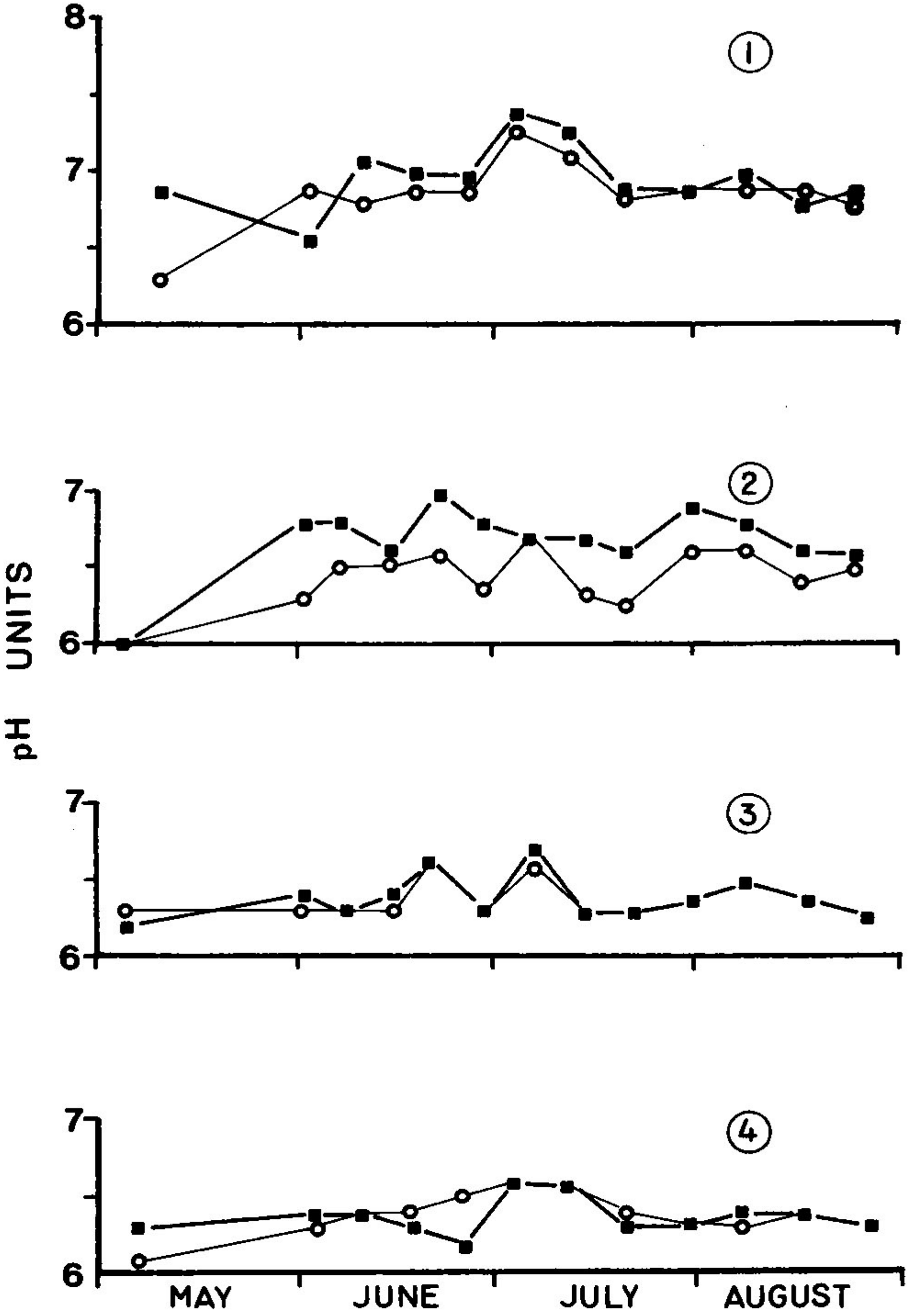

Fig 7. pH at stations 1-4, May-August 1976. (■ — ■ bottom sample; o—o surface sample).

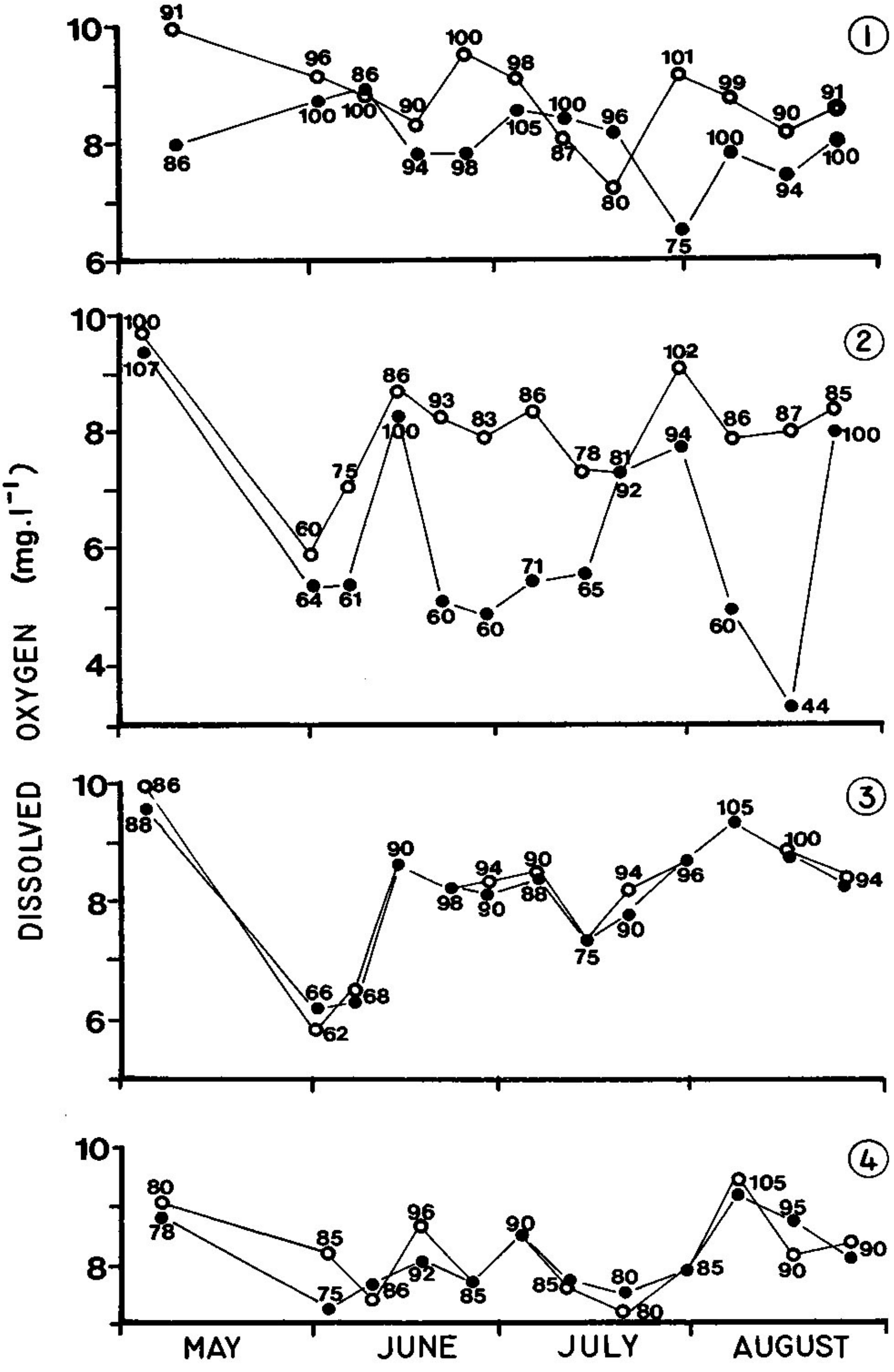

Fig 8. Dissolved oxygen at stations 1-4, May-August 1976. Numbers beside data points represent % oxygen saturation of water calculated from measured temperature and salinity (Symbols as Fig 6.).

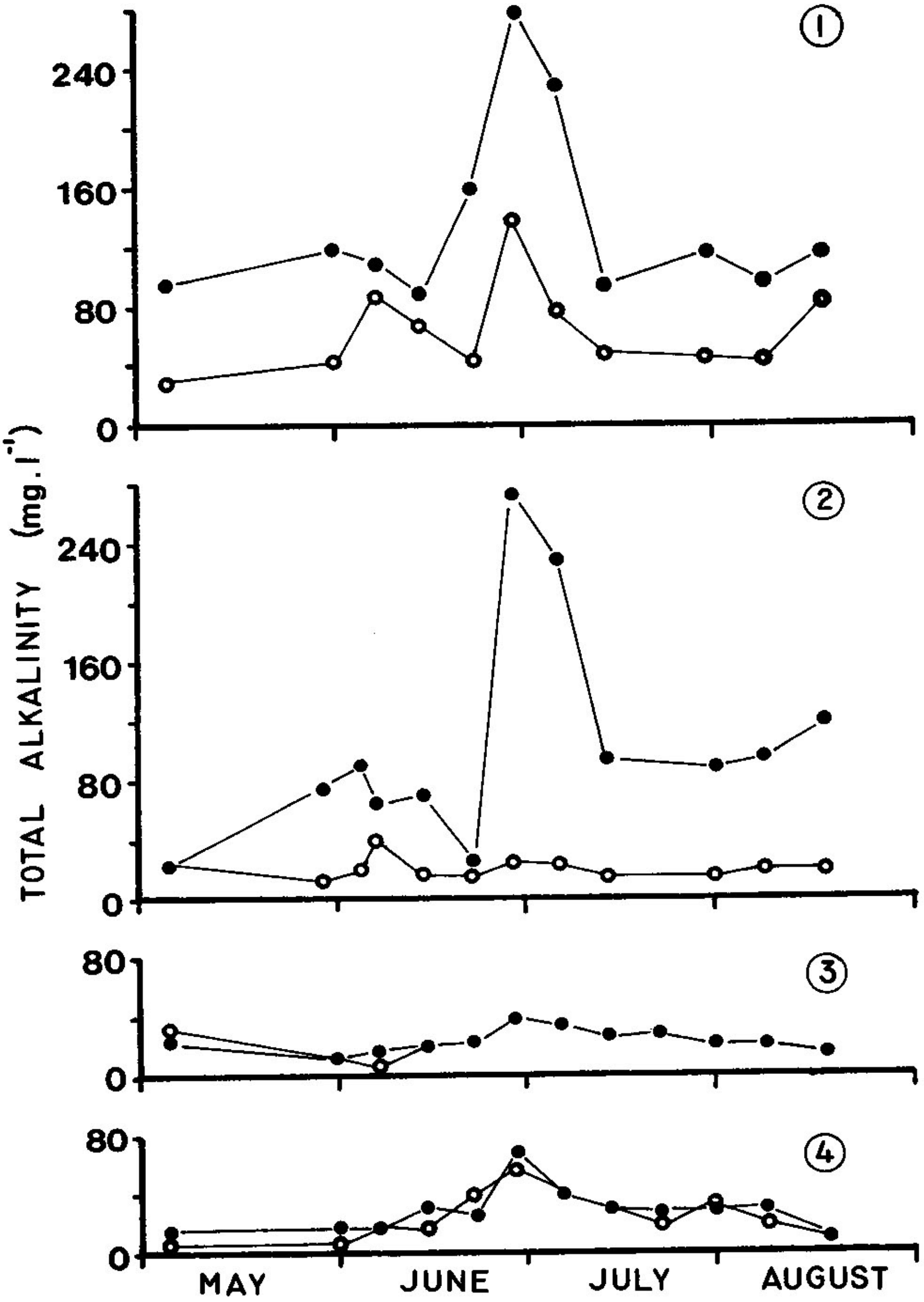

Fig 9. Total alkalinity (mg.1^{-1} CaCO$_3$) at stations 1-4, May-August 1976. (Symbols as Fig 6.)

crease at the end of June (Figure 9). This rise appeared after a relatively long period of low flow, but cannot be unequivocally related to it. In the estuary, the strong rise in alkalinity in lower waters was coincident with the persistent and extremely stable stratification resulting from the decrease in river output.

Chloride concentrations in bottom water near the causeway varied little (Fig 10) as would be expected, since this water was derived almost solely from tidal water outside the causeway. Surface waters fluctuated between 2500 and 18,000 ppm in a manner suggesting a varying degree of turbulent mixing. At station 2, below Tupperville, chloride concentration increased as the salt wedge moved upstream and showed a further tendency to increase as river levels declined toward the end of the summer. The 2 river stations present patterns that are not conformable with each other. Chloride concentrations were moderately high all summer for a river flowing largely off granite. Perhaps this suggests that some of the chloride in solution is anthropogenic.

Nitrate-N (Fig 11) and orthophosphate (Fig 12) concentrations were high and fluctuated irregularly during the study. Both were undoubtedly influenced greatly by agricultural practices. Sulfate concentrations in the river remained fairly constant except for sharp peaks toward the end of the June dry period (Fig 13). The pattern is only slightly reminiscent of that for chloride. In the estuary, surface water at both stations exhibited consistent increases during the June and August periods of low river flow, and at Tupperville the deeper water showed a steady increase in sulfate consistent with that of chloride. The enigmatic behavior of sulfate concentration near to the causeway is notable.

Discussion

With impoundment by the tidal dam in 1960, the Annapolis Estuary was transformed from a vertically homogeneous type of estuary with 10 m tides similar to others around the Bay of Fundy, into a highly stratified salt wedge estuary with 1 m tides. Usually a salt wedge estuary occurs when river flow is high compared with tidal flow (Perkins 1974). However, in the present instance the tidal energy in the Annapolis Basin is largely dissipated against the causeway, only surface waters entering the estuary through the sluice gates and fishway. In a sense, therefore, the Annapolis is a parody of a fjord, in which deep water in the estuary is impounded by the high sill at the mouth (Barnes 1974).

As in a fjord, restriction of inflow and outflow to surface waters results in little mixing of river and estuary water (Dyer 1972). Our results indicate that near the causeway turbulence produces some mixing such that salinity increases steadily with depth, and no halocline is present. Much of the inflowing saline water immediately descends beneath surface water because of its greater density. It would appear, to judge from the fairly high salinities recorded by Jessop (1976) and ourselves and the relatively low turbidity of deeper water, that residual or eddy currents generated by turbulence at the surface do not penetrate to the bottom.

Farther from the causeway, but within the headpond, the water was found to be highly stratified with a halocline exhibiting changes of 13 to 14°/oo over 0.5 m. Such stratification is extremely stable. There is clearly little exchange taking place between the outflowing river water and the underlying salt water. As a result, there is some danger of stagnation of the lower water, and this is indicated by the oxygen saturation deficits encountered. Stratification is probably broken down periodically by wind or rain storms acting directly on the headpond. A prolonged period of hot weather, however, or an increase in oxygen demand resulting from increased organic loading of the river might well result in complete oxygen depletion of bottom waters in the estuary, an event with serious consequences for fish populations in the headpond or spawning in the lower river.

With impoundment the head of the tide, which was previously near Paradise

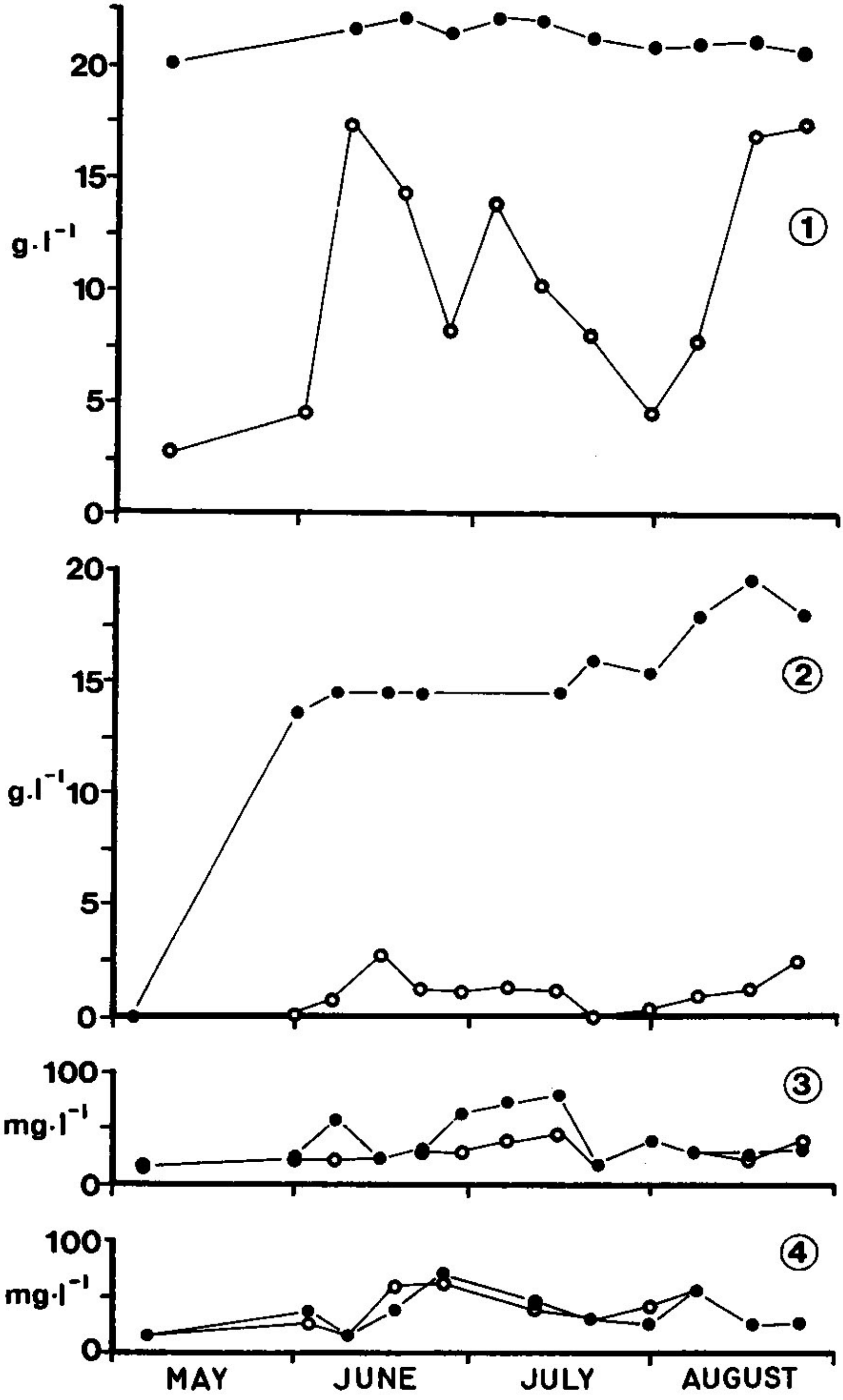

Fig 10. Chloride concentrations at stations 1-4, May-August 1976. Symbols as Fig. 6. Note difference of scale between estuary (1,2) and river (3,4) stations.

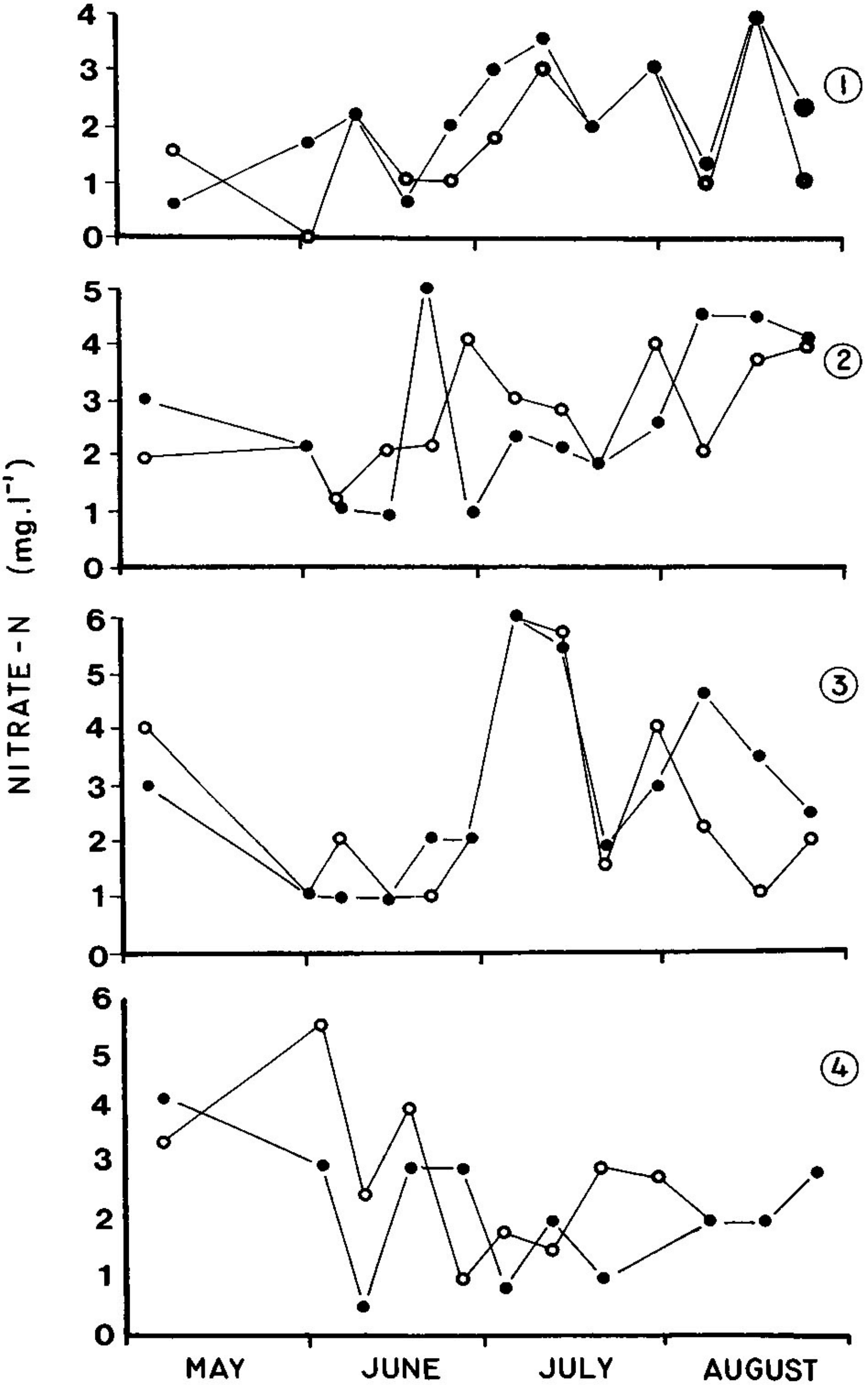

Fig 11. Nitrate—N at stations 1-4, May-August 1976. (Symbols as Fig 6.)

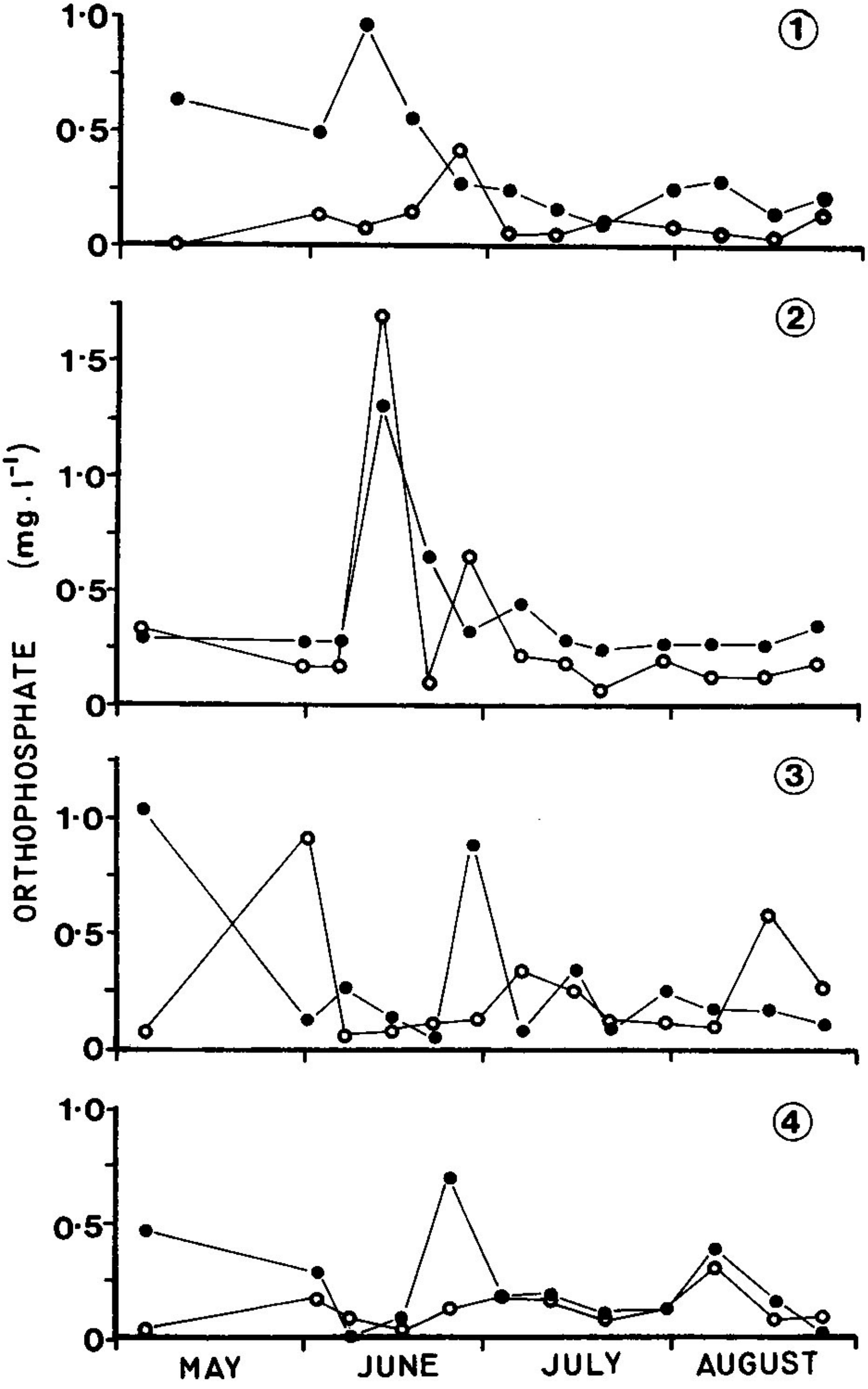

Fig 12. Orthophosphate concentrations at stations 1-4, May-August 1976 (Symbols as Fig 6.)

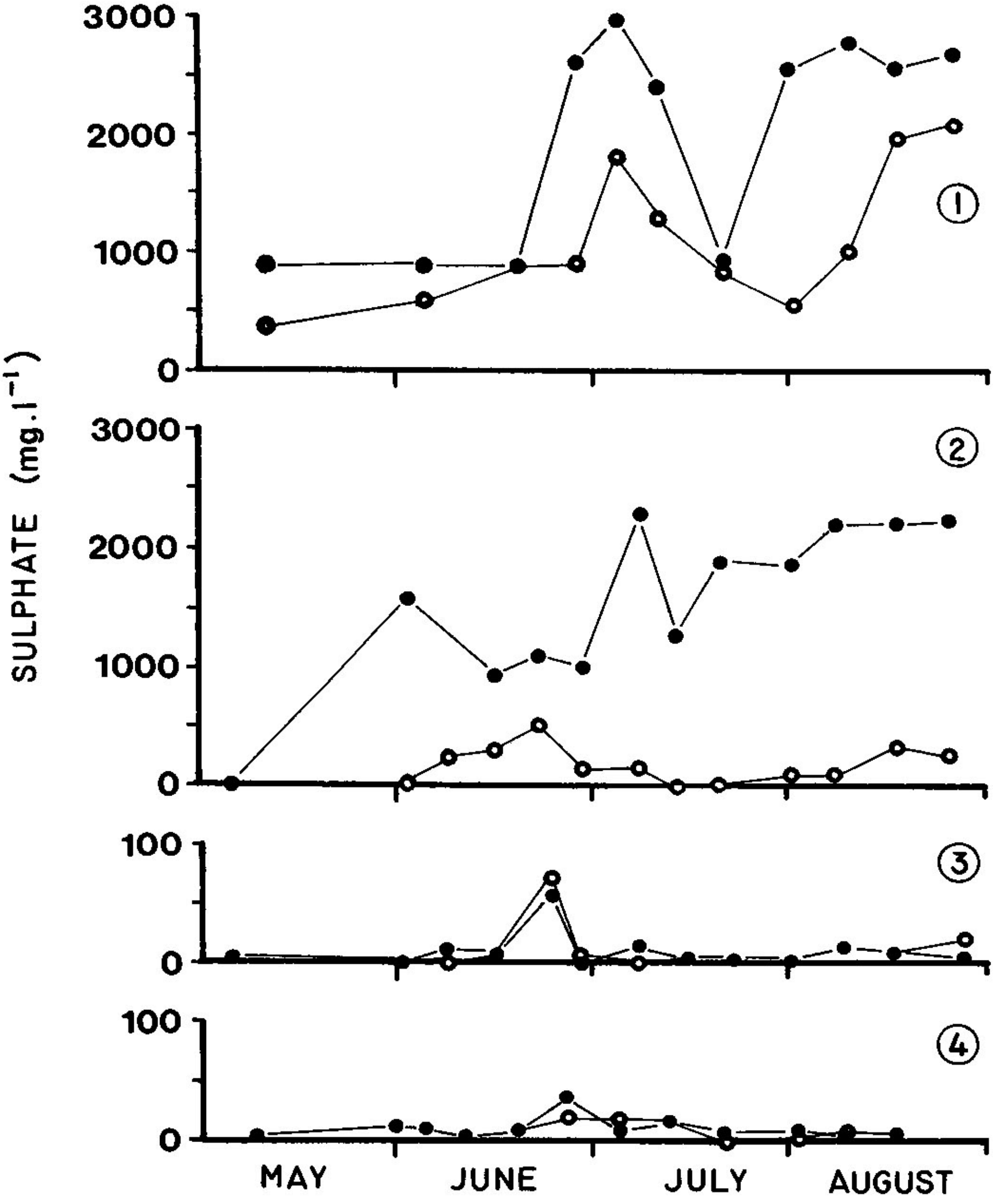

Fig 13. Sulfate concentrations at stations 1-4, May-August 1976 (Symbols as Fig 6.)

(MacDougall et al 1969), appears now to be located near Bridgetown, about 30 km above the causeway. The tip of the salt wedge oscillates some distance as a result of tidal flow, manipulation of headpond and river levels, and of intermittent water release from Paradise Reservoir into Daniel's Brook.

The river is chemically unexceptional, although our results suggest rather high levels of inorganic phosphorus and nitrate. These nutrients undoubtedly contribute to the productivity of the estuary. Although productivity of the estuary has not been studied, we noted a diverse and abundant plankton, and have documented a diverse and abundant ichthyofauna. A high productivity in the headpond is to be expected from the retention of nutrients derived from river input and dykeland drainage, and the relative clarity of the water.

The foregoing account, gleaned from our own study and those of Jessop (1976) and Jessop and Doubleday (1976) provides a basis for preliminary consideration of the effects to be expected from installation of a tidal power turbine in the Annapolis causeway. Since the turbine would withdraw water at some depth, the first consequence would be a tendency to diminish the impoundment of lower waters and allow release of these to the Annapolis Basin. Furthermore, turbulence associated with turbine operation and inflow through the sluice gates would probably help to prevent stratification over much of the headpond and decrease the danger of stagnation of bottom waters. Greater manipulation of water levels might also increase the degree of mixing between riverine and estuarine water and the generation of eddy currents throughout the headpond.

As a consequence of greater mixing and recirculation of nutrients, it is likely that primary production in the headpond would increase, although greater turbidity might restrict the photic zone.

These suggestions are clearly speculative, being based upon a study of limited scope. It is to be hoped that a more thorough investigation into the physical structure and productivity of the estuary be carried out before the Annapolis River is manipulated once again.

Acknowledgments

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