The determination of the net fluxes from a mangrove estuary system

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Abstract

The problem of determining the net exchange of properties between a mangrove estuary system and the adjacent ocean has been re-examined using an extensive data set from the Sungai Merbok, a short tidally-energetic estuary in Malaysia. Previous analysis of the data had indicated that the time-mean sectionally-averaged flow was not consistent with mass balance, apparently preventing meaningful estimation of net nutrient fluxes from the mangrove system. In this case the problem was aggravated by the lack of river gauge data and uncertainties introduced by the use of deflected-vane current meters to make the flow measurements.

In an alternative approach to the analysis, we have sought to put bounds on the net discharge and hence obtain limits for the nutrient output from the estuary. Tide gauge measurements have been used in conjunction with the section flow data to determine the hypsometry of the mangrove system and hence yield an unbiased estimate of tidal transport Q_t. A salt balance condition, appropriate to a mixed estuary is then applied to permit an estimate of Q_f the freshwater discharge. Q_f determined this way is found to be close to zero and certainly less than estimates for the period (mean ~$7m^3s^{-1}$) based on rainfall records and catchment area. The implication is that the combined effects of evaporation and transpiration are removing a large proportion of the freshwater entering the mangrove system from the rivers.

The very low net discharge means that the total nitrogen exchange is dominated by the covariance of Q_t with the sectionally averaged concentration N_t. The considerable variation in this latter term combined with the large amplitude of Q_t results in a high variability of the nitrate flux so that the estimate of the mean ($0.5\ gs^{-1}$) is subject to substantial sampling uncertainty (s.e. $= 12\ gs^{-1}$).

The application of the salt balance condition to flux studies in other estuarine systems is considered. Particular attention is drawn to the requirements of this approach to flux determination and especially the need for good timing control to allow the proper determination of the tidal diffusion flux of salt and other components.

Introduction

The determination of the residual fluxes of scalar properties through estuarine systems is a central requirement of many of the studies of land-sea interaction which are currently being planned or undertaken. The convincing measurement of these fluxes, however, frequently poses a difficult and challenging problem because of the complexity of the flow structure and property distributions in estuary systems. The difficulties are particularly severe in the, not uncommon, situation where tidal transports dominate over the residual movements and the latter has to be determined as the small difference of two large quantities.

Particular efforts have been made in recent years to use estuarine flux measurements to settle the important question of the net influence of mangrove systems on the adjacent ocean. The complex channel geometry of most mangrove systems makes it virtually impossible to monitor fluxes at the mangrove margin, but where the mangrove forest communicates with the sea only through a narrow estuarine channel, there is the possibility of monitoring the net effect of the mangrove system by a limited number of measurements on a well-instrumented estuary section. This attractive approach to an otherwise intractable problem has been developed, for example, by Ong et al. 1988 with a view to making definitive measurements of the exchange of nutrient elements and carbon.

In this paper we re-consider an extensive flow,salinity and nutrient data set from a mangrove-estuary system, identify some of the problems encountered in attempting net flux measurements of this kind and consider alternative methods of analysis which may contribute to a solution.

The mangrove-estuary system

The system with which we are concerned is that of the Sungai Merbok (fig. 1) which is situated in Kedah on the north-west side of the Malaysian peninsula (5° 40'N, 100° 23'W) about 20 km north of Penang. The physical charactersitics of the estuary have been described by Ong et al. (1991). The estuary, which is about 30 km long, is surrounded by an extensive area (~45 km^2) of luxuriant, highly productive mangrove forest. Freshwater input is not concentrated in a single river source but enters the estuary through a large number of tributaries, many of which flow through the mangrove forest. Average annual rainfall is about 2.1 m with maxima in September-October and in April. The complex inflow precludes accurate gauging of river discharge, but estimates, on the basis of the rainfall, suggest that the mean annual freshwater inflow is ~ 20 m^{3}s^{-1}.

No detailed bathymetry is available for the estuary but mid-channel depths vary from 15 m to 3 m with deeper holes where tributaries join the main channel. The tidal regime is mixed with a marked diurnal inequality and a large contrast in range between springs (maximum range ~2.5 m) and neaps (minimum ~0.4 m).

The Observations

In an effort to determine the net import/export of nutrients from the whole mangrove-estuary system, a series of intensive observations were made over a full springs-neaps cycle during the period June 2-18 1987. Measurements of current velocity, salinity, temperature and the concentrations of phosphate and total nitrogen (by the method of Koroleff 1983) were made at intervals of one lunar hour over 31 tidal cycles at four stations across a section in the lower estuary (fig 1). Currents were measured by simple vane current meters which determine the flow from the deflection of a weighted vane from the vertical (Kjerfve and Medeiros 1989). The flow data was supplemented by hourly measurements of the tidal elevation.

The processing of the resulting data base to obtain transports and sectionally-averaged properties has been described by Uncles, Ong and Gong(1990) who have utilised the results to characterise the development and breakdown of stratification in the estuary over the fortnightly cycle. Further interpretation of the this data set is described in Dyer,Ong and Gong(1992) who have undertaken an analysis of the processes contributing to the upstream salt flux in the estuary and identify a substantial imbalance between the total upstream flux of salt and downstream transport by the mean flow. Averaging over the full period of the observations the apparent discharge of salt exceeds upstream transport by a factor of more than 30.

The Problem

Underlying this lack of salt balance is a substantial imbalance of the mass flux as can be seen from averaging the sectional transport Q shown in fig.2a. The time mean of Q over 31 tidal cycles is 147 $m^3 s^{-1}$ which is an order of magnitude larger than the value based on rainfall estimates for the period (Uncles et al.1990). These transport estimates allow for the change in tidal elevation and so include the Stokes drift term. The equivalent downstream velocity, which is about 2.5 cm/s (see fig 3d of Dyer et al.(1992)) is small in relation to the tidal flows of up to 120 cm/s but clearly too large to allow resolution of the true residual which is equivalent to a few mm/s averaged over the cross-section.

This bias in the residuals is of uncertain origin. It may be due, in part, to inadequate sampling across the section but a more likely source of bias is that the vane current meters used are not sufficiently accurate to determine such a small residual in the presence of dominant tidal flows and are liable to over-estimate the ebb flow. The latter may arise from enhanced drag,during the ebb, on the line suspending the vanes because of asymmetry in the ebb and flood current profiles. In any case, even with dense sampling by the best modern current meters, it is doubtful if the residual could be determined to sufficient accuracy to resolve the net discharge in the presence of a tidal flow which is more than two orders of magnitude larger.

Unfortunately, since there is no river gauging, we have no independent check on the net flow which we need to know to fair accuracy in order to estimate fluxes. Even if the main river inputs were gauged, the distributed lateral input from sheet flow through the mangroves, may make a substantial unmeasured contribution especially during periods of heavy rain. These circumstances, an unresolved residual in the presence of a dominating tidal flow and the lack of adequate river gauge data, are not unique to the Merbok and indeed are typical of the difficulties faced in trying to measure net transports in tidal estuaries in many parts of the world. In the next section, we attempt to develop a strategy for tackling these problems by making use of the tide gauge data and forcing a salt balance that we know exists from the salinity observations.

Enforcing mass and salt balance

We start by noting that the Merbok is a tidally energetic estuary in which the predominant mechanism for the upstream transport of salt is the tidal diffusion mechanism. According to Ong et al.(1991) estimates of the circulation parameters place the estuary close to the boundary between Hansen-Rattray types 1 and 2 where more than 95% of the upstream salt transport is due to tidal diffusion (also called tidal pumping) which is associated with the covariance of salinity and flow. Even at neap tides when the estuary tends to stratify, the gravitational circulation is still only a minor contributor to the upstream flux. This predominance of the tidal diffusion process is also indicated by the decomposition analysis of Dyer et al.(1992).

On this basis, we proceed to a simplified analysis of the transport by writing the sectionally averaged transport Q (positive seawards) and scalar concentration c as the sums of time mean and tidally oscillating components:

$$Q=Q_f+Q_t\ ; \qquad C=\overline{C}+C_t \tag{1}$$

where Q_f is the freshwater discharge from the estuary.

The mean flux of the scalar across the section will be:

$$\begin{aligned}\overline{F_c} &= \overline{(Q_f+Q_t)\ (\overline{C}+C_t)} \\ &= Q_f\,\overline{C}+\overline{Q_t\,C_t}\end{aligned} \tag{2}$$

where the overbar denotes a time average and, by defintion,

$$\overline{Q_t}=\overline{C_t}=0 \tag{3}$$

For salt we would expect no net flux between times when the salinity of the estuary had not changed significantly i.e. equation (2) becomes:

$$\overline{F_s}=\rho Q_f\,\overline{S}+\rho\,\overline{Q_t\,S_t}=0 \tag{4}$$

In principle enforcing this balance permits the determination of Q_f if we can obtain a good estimate of the salinity-transport covariance.

In order to validate the flow measurements and obtain an improved, unbiased estimate of the sectional mean tidal transport, we have made use of the tide gauge record assuming that the level differences within the basin are negligible. The justification for this assumption comes from the fact that the time for wave propagation over the 30 km length of this estuary is short (~50 minutes) and the observation reported by Ong et al.(1991) that spring tide amplitude increased by only 0.15 m at a station near the tidal limit of the estuary relative to the mouth.

Given this assumption we can obtain the transport Q from the rate of change of level recorded by the tide gauge. Continuity of volume requires that:

$$A(\eta)\frac{d\eta}{dt} = Q_f - Q = -Q_t \qquad (5)$$

where $A(\eta)$ is the relation between water surface area and elevation referred to as the hypsometry. Without a full bathymetry this function is unknown but may be determined from equation (5) by a regression analysis of the transport data versus the observed $d\eta/dt$. For each 0.5 m interval of tidal level, A is found as the slope of the plot of Q against $d\eta/dt$; the result is not influenced by any bias in Q which appears only in the constant of the regression analysis.

<u>Results</u>

The application of this procedure is illustrated in fig. 3 which shows the analysis for one range of depths (η=2.0-2.5) and the composite hypsometry produced by the complete set of regressions. In all cases the fit was satisfactory with $R^2 \geq 0.9$. The resulting function $A(\eta)$, the hypsometry (fig 3b), shows the effective area of the estuary mangrove system varying between 10 km^2 at low water and 45 km^2 at times of the highest spring tides. The difference is somewhat less than the previously estimated total area of the mangrove (45 km^2) so that the ratio of apparent to real area is 0.78. The basal area of the trees themselves would account for only a small part (< 1%) of this difference with the mounds built by the lobster <u>Thalassina</u> <u>Anomala</u> possibly making a similar small contribution. The principal change in the effective area arises from the recent construction of extensive aquaculture ponds within the mangrove area. It is estimated that since the original survey some 7 km^2 (16%) have been utilised in this way.

The time series of Q_t formed from the product of $A(\eta)$ and $d\eta/dt$ will automatically have zero mean when averaged over a whole number of tidal cycle (period T) since:

$$\overline{Q_t} = \frac{1}{T}\int -A(\eta)\frac{d\eta}{dt}\,dt = -\frac{1}{T}\int A(\eta)\,d\eta = 0 \qquad (6)$$

The time series for Q_t calculated in this way (fig 2a) has been used with the sectionally-averaged salinity data (fig 2b) to compute the covariance $\rho Q_t s_t$ for two different periods to give the results displayed in table 1. Period 1 is the full duration of the data which was 31 semi-diurnal tidal cycles. Over this period, we can see from the sectionally-averaged salinity (fig. 2b) that there was practically no net change in the salinity of the estuary so we can apply a simple salt balance and deduce from equation 3 that the net freshwater discharge was close to zero with $Q_f=0.6\ m^3s^{-1}$. During this period of 15 days, the covariance $\rho Q_t S_t$ averaged over 25 hours (fig 4a) exhibits considerable variability (standard deviation ~182) which implies a standard error in Q_f of ~1.5 m^3s^{-1} (see table 1).

The full data set, however, includes a period when increased run-off combined with neap tides led to an episode of stratification when surface to bottom salinities were ~10 for about two days. During this time our assumption of negligible contribution from the gravitational circulation is less well justified, though probably still valid if the Hansen-Rattray model applies. As a check, we have made a separate estimate for the second half of the time series (period 2) when tidal mixing was strong and there was minimal vertical structure. In this case, the salt balance yields $Q_f=2.5\ m^3s^{-1}$ but it may not be valid to apply a strict salt balance as the salt content of the estuary may have increased slightly over the period. Correction for this would tend to reduce the Q_f estimate to near zero.

Net freshwater exchange for both periods, therefore, appears to be close to zero and certainly less then the volume flux of freshwater estimated on the basis of rainfall. According to Uncles et al.(1990), the mean input of freshwater from the catchment over the full period was ~ $7m^3s^{-1}$ with a peak value of 15 m^3s^{-1} measurements for the same period. (Uncles et al.1990).
As a further check on the above result, we have used the simpler procedure of forcing mass balance by removing the apparent mean flow from the measured flow data (fig 2a) and then re-computing the $\rho Q_t S_t$ covariance term. The resulting Q_f is again not significantly different from zero.

The implication is that the mangrove estuary system is losing, by the combined effects of evaporation and transpiration, an amount of water almost equivalent to the river input. A net loss of 1 cm of water per day by these processes, which is of the order of the evapo-transpiration rate measured by Miller(1972), would account for a net loss of 5 $m^3\ s^{-1}$ from the system.

Limits to the total nitrogen flux

In principle, we may now proceed to utilise the above deductions about the flow regime to make a best estimate of the net nutrient exchange between the mangrove system and the adjacent sea. We combine the tidal flow time series Q_t and our estimates of Q_f with the sectionally-averaged nitrate concentration in the form:

$$F_N = Q_f \overline{N} + \overline{Q_t N_t} \qquad (7)$$

For the full period of the observations, the Q_tN_t term averages out to yield a mean export of +0.3 gs^{-1} of total nitrogen while the Q_fN contributes +0.2 gs^{-1} (table 1). The resulting net export of 0.5gs^{-1} cannot, however, be seen as a good estimate of the long term mean because of the large variability in the covariance. The 25 hour averaged flux (fig 4b) exhibits large fluctuations which greatly exceed the contribution from the mean discharge. In consequence our value for the mean has a standard error of ~12gs^{-1} so that, as an estimate of the average flux,it is not significantly different from zero. If we average only for the the second half of the data set (period 2 in table 1) we find a net import of 15.4 g/s which, as is evident from fig 4b is offset by large export contribution during the first week of the observations.

Discussion

Although the Merbok observations were carefully planned and executed and have led to a number of interesting new insights into the way estuary system operates, it has to be acknowledged that they have not yet enabled us to give satisfactory answers to the questions about nutrient and carbon exchanges which they were designed to answer. Perhaps their greatest value lies in the fact that they highlight the many difficulties involved in trying to estimate fluxes in tidally dominated estuaries with distributed river inputs.

The salt balance condition utilised above offers one practical way of estimating the mean flow when no gauging data is available. In this case it has led to the interesting conclusion that most of the river discharge entering the Merbok estuary under low flow conditions is apparently exported by evapo-transpiration through the mangrove system and that net flow discharge from the estuary is small. This somewhat surprising result, which seems unavoidable if our basic assumption about the mechanism of salt transport is valid, prompts the speculation that the mangrove demand for freshwater is regulated to take maximum advantage of the supply while avoiding the creation of hyper-saline conditions. To cast further light on this question there is an obvious need for measurements of mangrove transpiration under conditions of varying salinity. At present, with the exception of the results of Miller quoted above and Andrews et al. (1984), there is a dearth of mangrove transpiration estimates in the literature.

In order to usefully apply the salt balance method to other situations, it is important to note the requirements necessary for its application. The simple salt condition (equation 4) is based on the predominance of the tidal diffusion term in the upstream transport of salt. This is well justified for the Merbok in terms of estimates of the Hansen-Rattray parameters (Ong et al. 1991) and the analysis of flux contributions by Dyer et al.(1992) but our simplified analysis will not apply when vertical and/or horizontal shear make a significant contribution to the upstream salt flux.

To a first approximation, in a short estuary like the Merbok where the tidal response is essentially a standing wave, the salinity is in quadrature with the tidal transport and therefore in phase with the tidal displacement as has been demonstrated by Uncles et al.1990. It is the small departure from this standing wave phase relations which makes the covariance of Q and S non-zero and the accurate determination of their relative phase shift is critical in our approach. Numerical tests with artificial phase shifts emphasises the need for accurate coincidence of velocity and scalar measurements. A ten minute shift between the two measurements introduces an error in Q_f of 3.3 $m^3 s^{-1}$ in this case so the careful timing control (+/-3 minutes) applied in these measurements was fully justified.

The methods used to estimate the tidal flow from a tide gauge and the inferred hypsometry may also be of use in other situations. As well as revealing the hypsometry, which may be difficult to obtain directly, it serves as a method for validating the flow data with the independent tide gauge results. As noted above, its application requires that surface slopes within the estuary are small, an assumption which is generally only valid for estuaries which are short in relation to the tidal wavelength.

Perhaps the most serious and intractable problem we have encountered in attempting to deduce fluxes in the Merbok system, is associated with the large variability of the system. The amplitude of the tidal transport (~ 3000 m^3s^{-1}) is more than two orders of magnitude greater than the estimated river input. Combined with the considerable variations observed in nitrate levels, this leads to high variability in the daily-mean total nitrogen flux and limits our ability to determine a useful average as in the present case where our conclusion is a near-zero net flux but with wide error bounds.

Finally we should note that the problems encountered in attempting to estimate the fluxes of properties across a single section point to the extreme difficulty of making convincing flux divergence measurements which would be needed in order to characterise the role of estuary as a source or sink for a particular property.

Acknowledgements

The 31-tidal cycle data set was obtained under a project funded by the International Development Research Centre of Canada (Mangrove Malaysia: Centre File 3-P-82-0192) with infrastructural support from the Universiti Sains Malaysia (USM). We would like to thank Dr B.Davy and his staff at IRDC Asia Regional Centre in Singapore for their excellent support. We also thank Drs Wong Chee Hoong and Zubir Hj Din as co-principal investigators as well as the 60 laboratory staff and students who cheerfully assisted in the arduous field and laboratory work. This project is also funded by the Government of Malaysia through its "Intensification of Research Priority Areas" Research and Development Project under the Sixth Malaysia Plan. A USM-British Council CICHE Grant enabled one of us (JHS) to participate in this phase of the project.

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Figure Captions

1. The Sungai Merbok mangrove estuary system. The inset at bottom right shows a down estuary view of the bathymetry on the measurement cross-section along with the location of the stations 1-4.

2. Time series of integrated transport and properties derived from measurements at four stations on the control section (see fig 1):

(a) Volume transports in $m^3 s^{-1}$, directly observed total transport Q (dotted) and tidal transport Q_t derived from equation 5
(b) Salinity averaged over the section
(c) Total nitrogen in gm^{-3} averaged over the section

3. Hypsometry derived by regression:

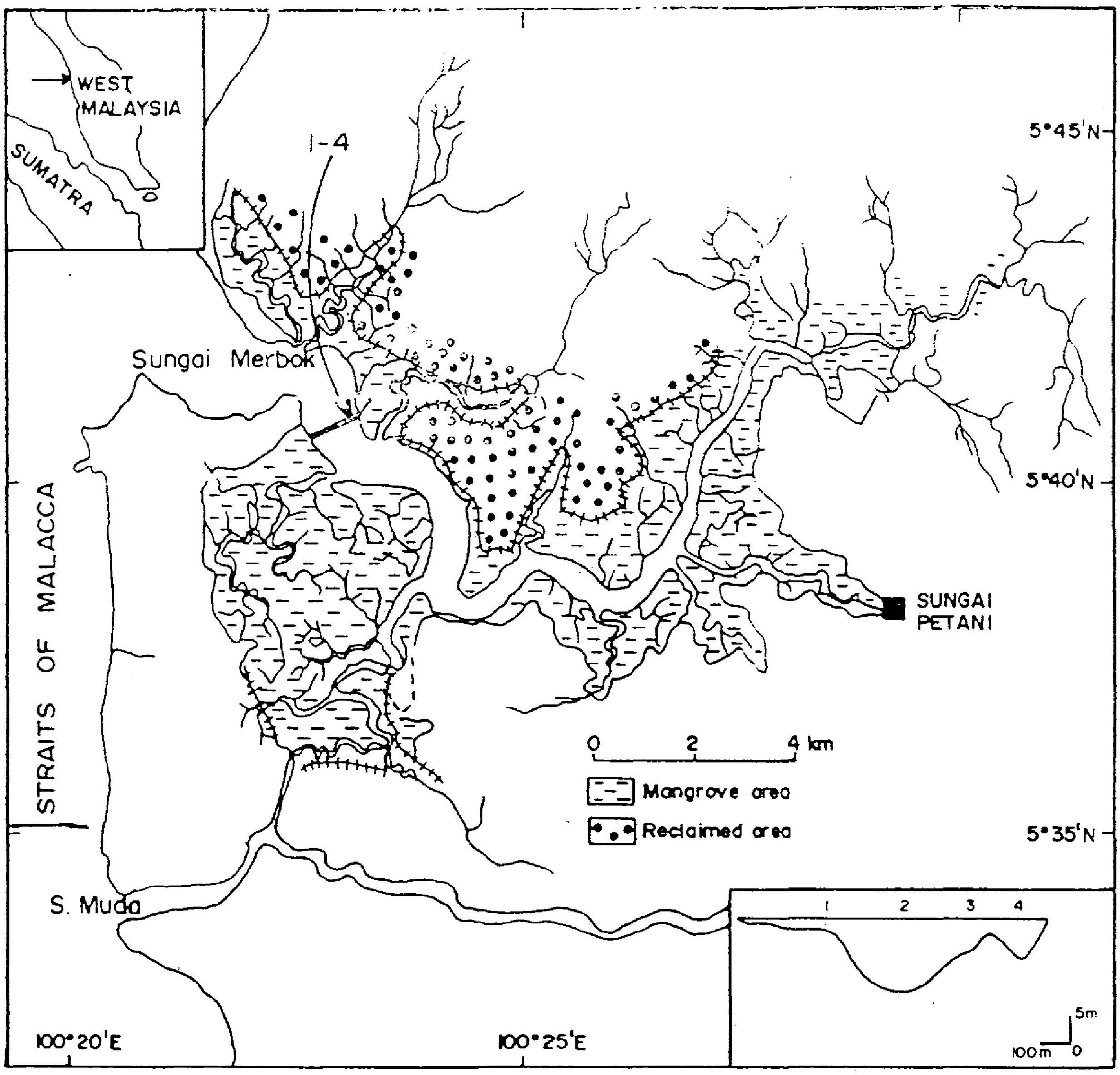
(a) plot of Q versus $d\eta/dt$ for depth range $2.0 < \eta < 2.5$ m
$R_2=0.93$; Area=slope = 30.9 km^2

(b) composite plot of regression slope A=surface area in km^2 versus elevation η.

4. 25 hour running mean values of:

(a) the covariance $\rho Q_t S_t$

(b) the covariance $Q_t N_t$



WEST
MALAYSIA
SUMATRA
1-4
Sungai Merbok
STRAITS OF MALACCA
5°45'N
5°40'N
5°35'N
SUNGAI
PETANI
0
2
4 km
Mangrove area
Reclaimed area
S. Muda
100°20'E
100°25'E
1
2
3
4
5m
100m
0

Fig 1

Table 1

	Period 1: 31 cycles		Period 2: 16 cycles		
	mean	s.e.	mean	s.e.	units
S	29.13		29.57		
$\rho Q_t S_t$	-17.3	46.1	-69.0	45.9	kgs^{-1}
Q_f	0.58	1.54	2.28	1.51	m^3s^{-1}
N	0.36		0.40		gm^{-3}
$Q_t N_t$	0.3	12.0	-16.3	13.5	gs^{-1}
$Q_f N$	o.20	0.57	0.91	0.60	gs^{-1}

Table 1 Summary of flux estimates

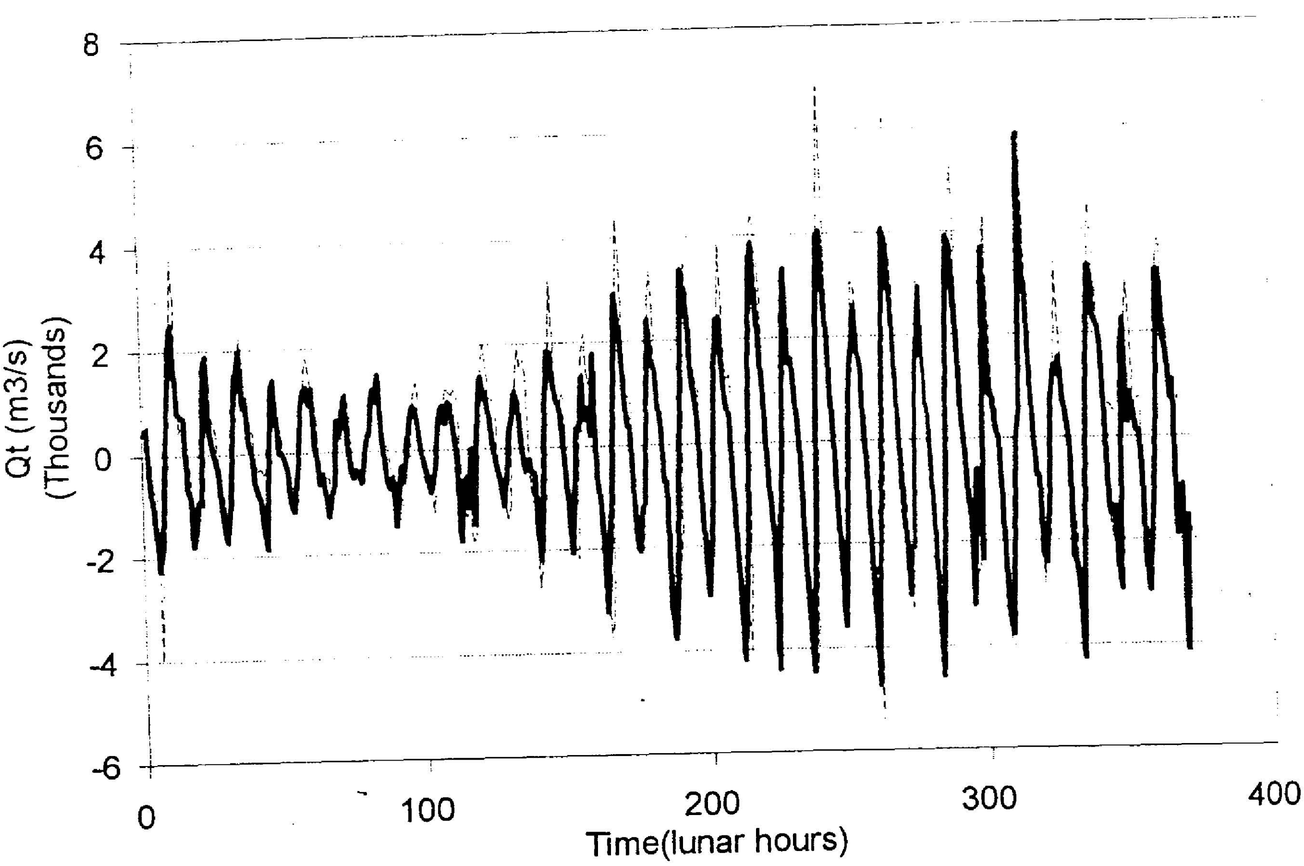
s is in practical salinity units(i.e. dimensionless)
s.e. =standard error determined from:

$$s.e. \cdot \frac{\sigma}{\sqrt{n}}$$

where σ =standard deviation and n = 16 = number of independent estimates of the 25 hour averaged covariance.

The total nitrogen flux estimate is in units of gs^{-1} of total nitrogen.

Tidal Transport Qt



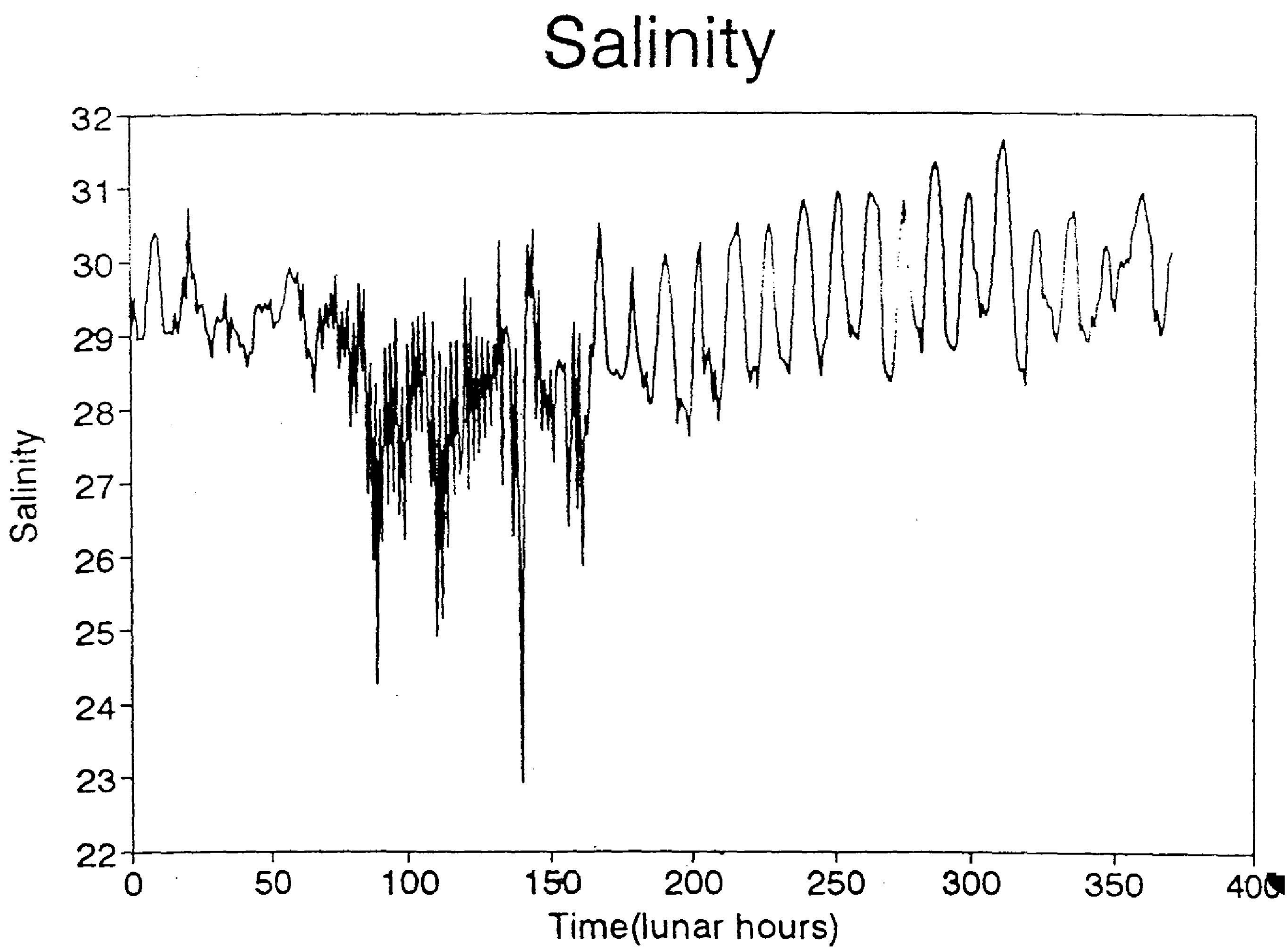

Salinity
32
31
30
29
28
27
26
25
24
23
22
0
50
100
150
200
250
300
350
400
Time(lunar hours)
Salinity

Fig 2?

Total Nitrogen

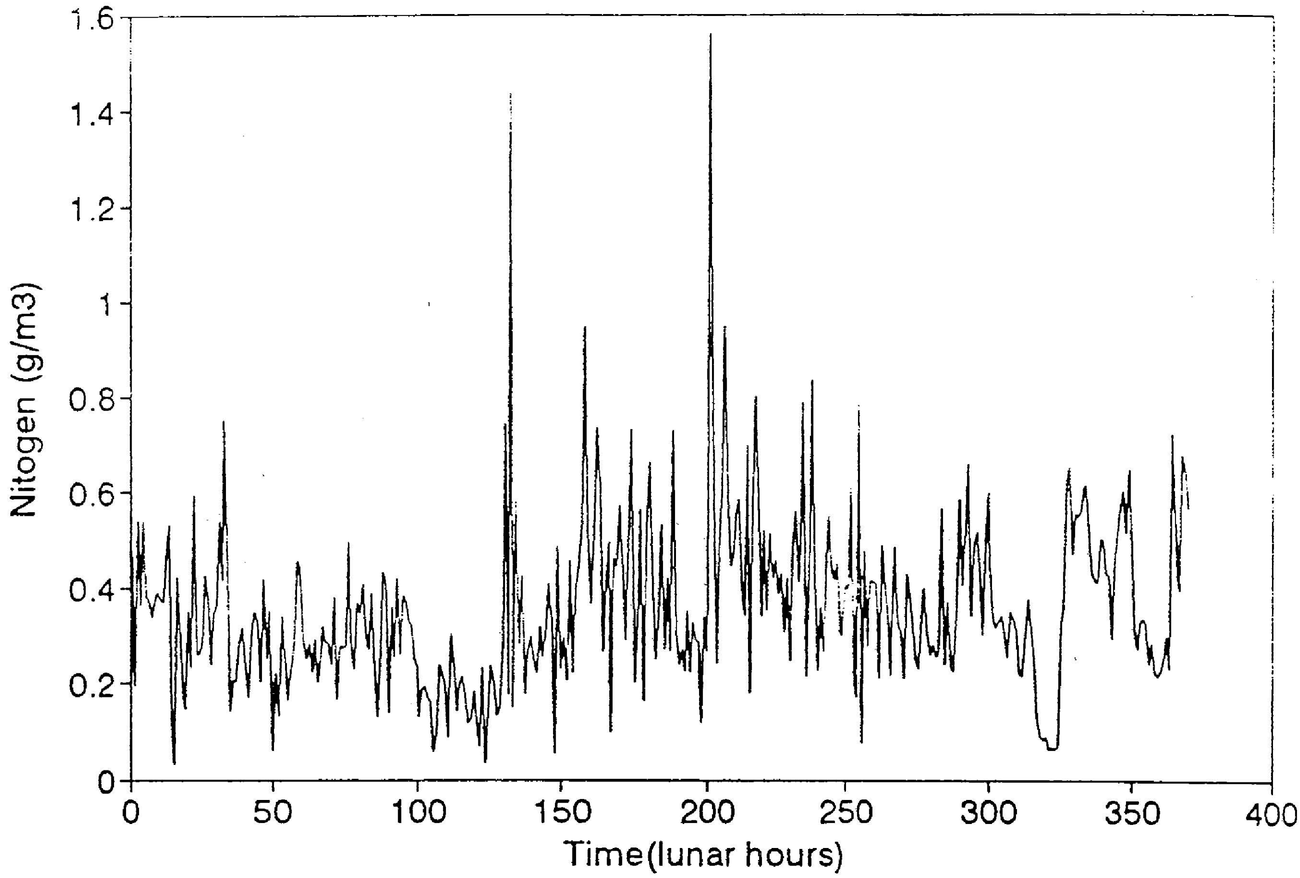


Fig 2(c

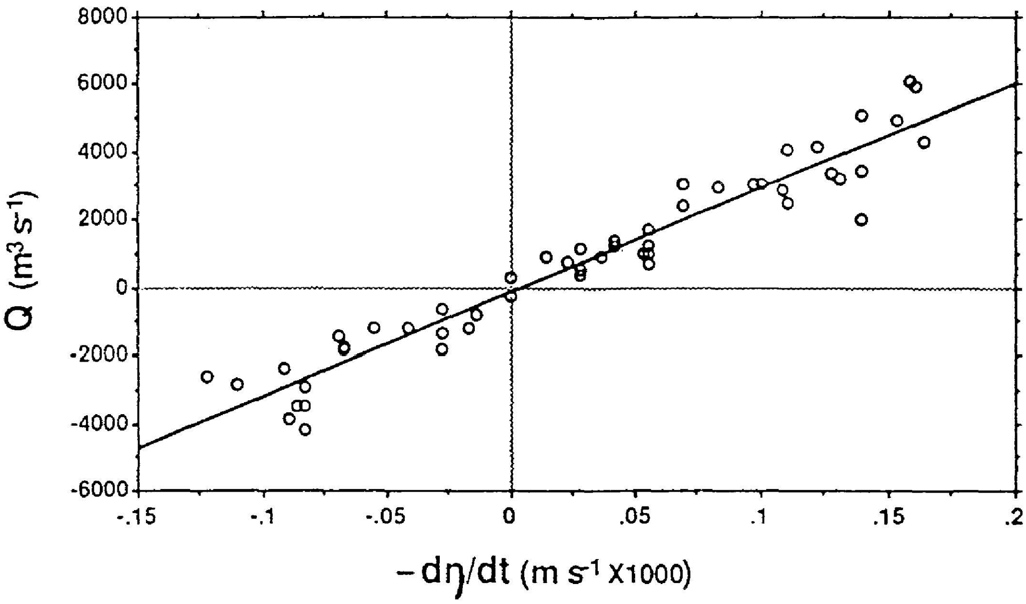

8000
6000
4000
2000
0
-2000
-4000
-6000
Q (m^3 s^{-1})
-.15
-.1
-.05
0
.05
.1
.15
.2
$-d\eta/dt$ (m s^{-1} X1000)

Fig 3(a)

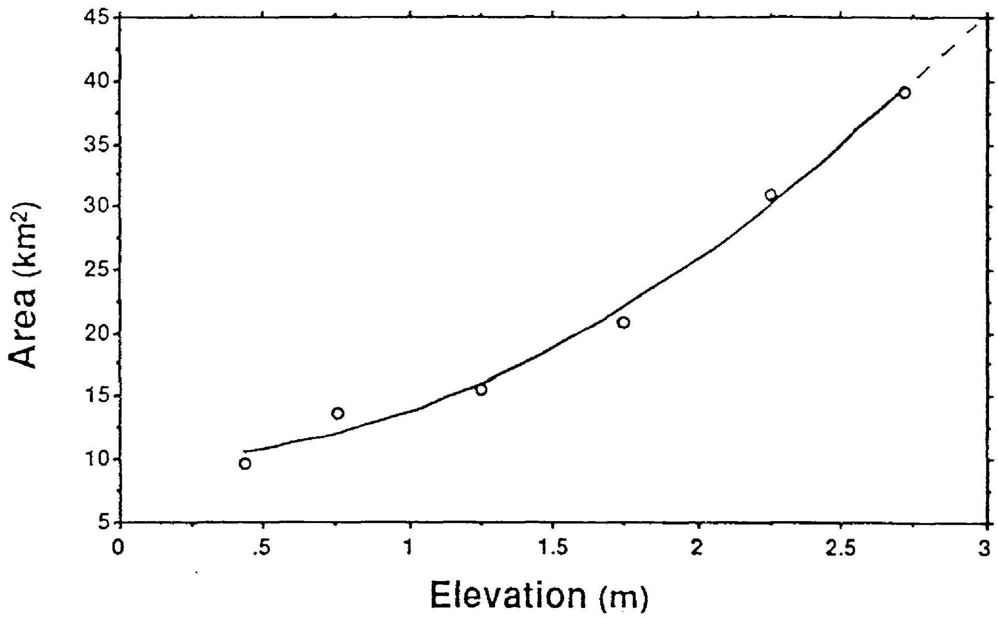


Fig 3(b

Salt Flux from $\overline{QtSt}$

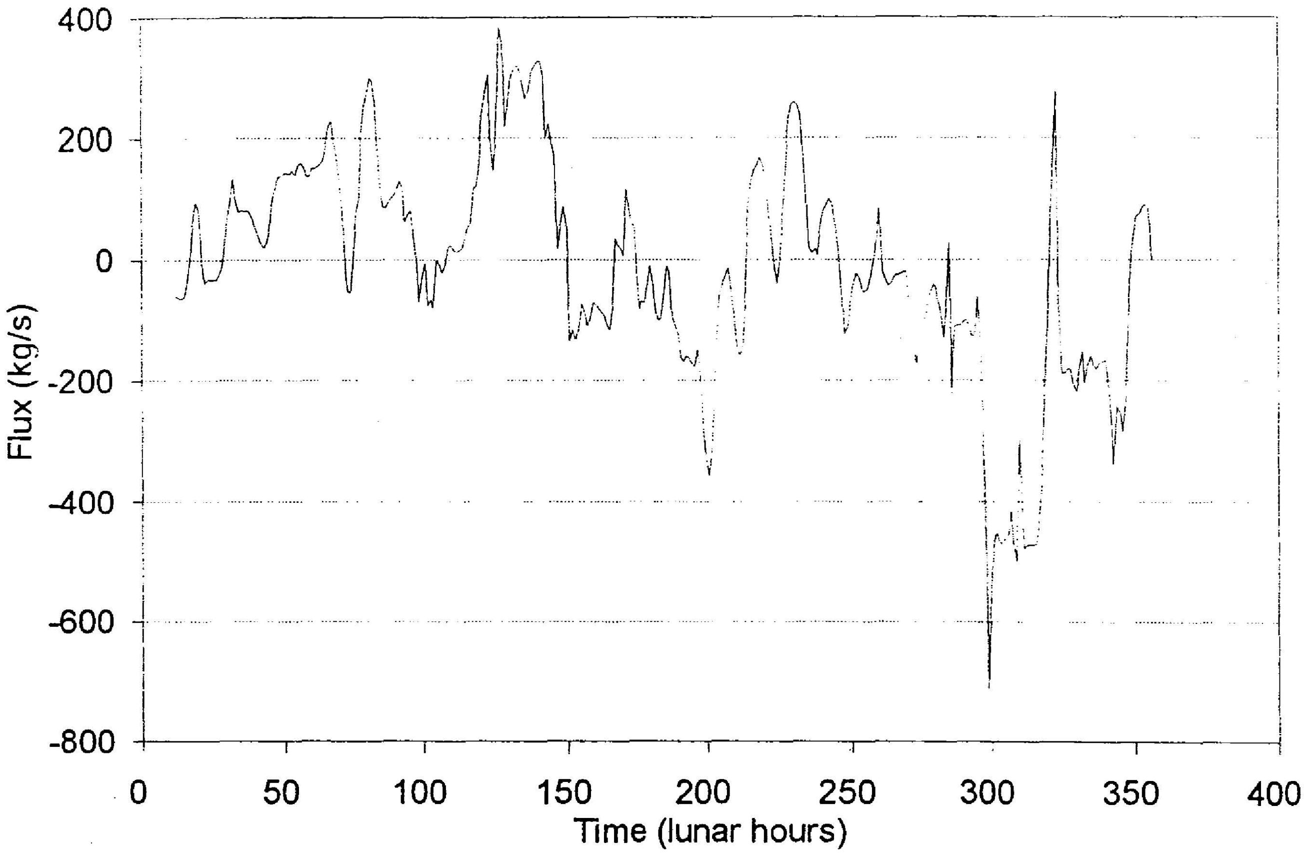


Fig 4(a)

Total Nitrogen Flux from $\overline{QtNt}$

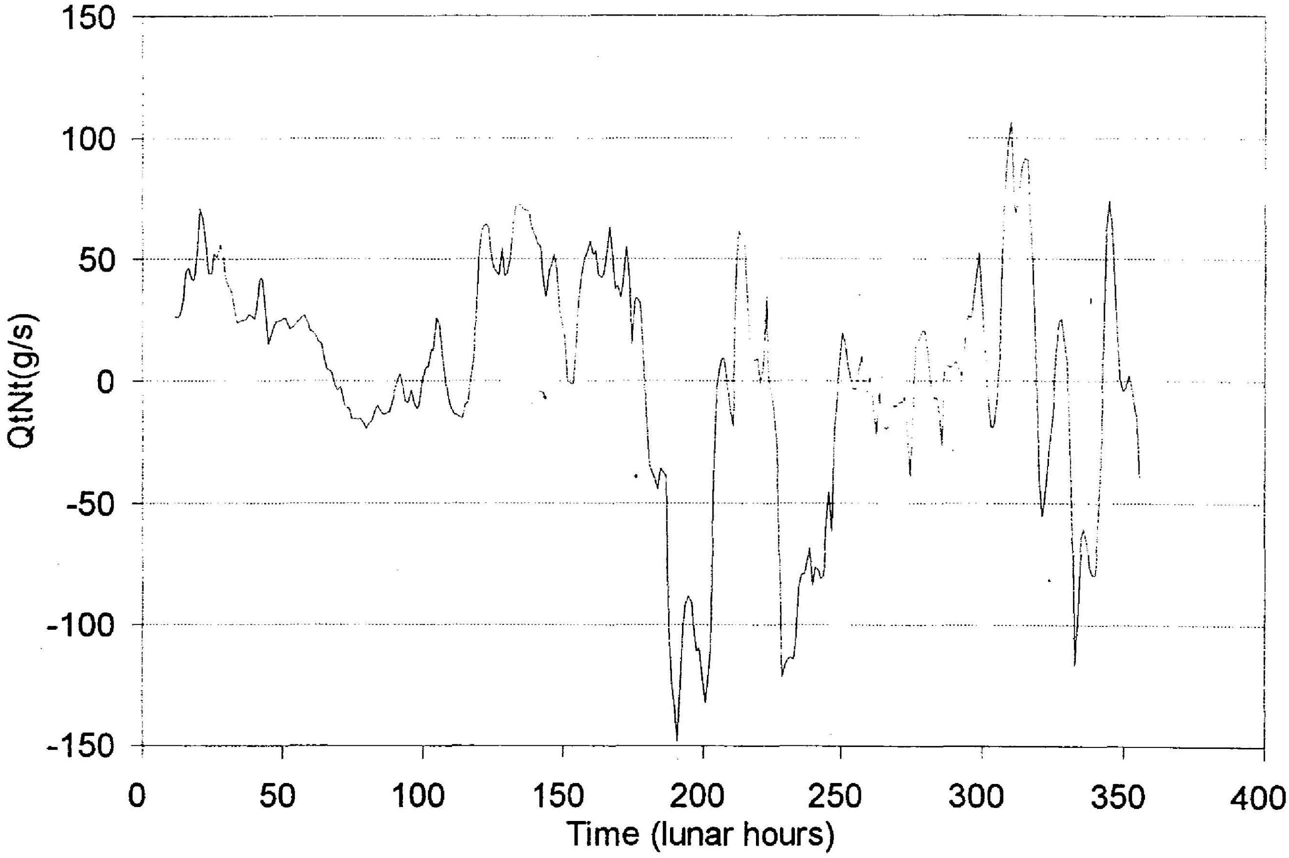


Fig 4(b)