J.Natl.Aquat.Resour.Res.Dev.Agency 36 (2000) 35-46
The National Aquatic Resources Research & Development Agency,
Crow Island, Mattakkuliya, Colombo-15, Sri Lanka.

Restricted Water Exchange in the Negombo Lagoon on the West Coast of Sri Lanka.

J.K. RAJAPAKSHA[1] & H.B. JAYASIRI[2]

1,2 *Oceanography Division, National Aquatic Resources, Research and Development Agency, Crow Island, Colombo 15.*

Abstract

KEY WORDS: TIDAL CHOKING; WATER EXCHANGE; RESIDENCE TIME; TROPICAL LAGOON.

Salinity, fresh water and sea level data from the Negombo lagoon with respect to oceanic sea level and salinity data were considered. The open ocean spring tidal range was 0.57 m, whereas the neap tidal range was 0.10 m. In lagoon, the corresponding spring tidal range was 0.13 m and neap tidal range is 0.05 m. The lagoon tide was strongly choked because of the restricted inlet channel, through which only a limited water exchange could take place over a tidal cycle.

Mean water exchange and the residence times for variable fresh water supplies were calculated. These calculations were based on fortnightly measurements of salinity and river discharges in 1993. During this year, salinity varied from 30-5 ‰ depending on the river inputs which were 20-225 m^3s^{-1}. Corresponding residence times varied from 11-2 days and the tide is dominated the exchange during low discharges of freshwater.

Introduction

The Negombo lagoon is a semienclosed shallow lagoon with a large freshwater supply and restricted water exchange with the ocean. It is considerably choked on tidal amplitudes because of its narrow inlet. Tidal choking is a reduction of tidal amplitudes by Bernoulli acceleration due to narrow inlet and also due to friction along a channel. Tidal range in semienclosed basins is usually low compared to oceanic tide. Reduction of the tidal amplitudes compared to the oceanic tide is referred to as choking (Glenne and Simensen, 1963; Stigebrandt, 1980). The magnitude of choking is mainly dependent on the inlet configuration (length, width, depth etc.) but is also associated with the available freshwater supply, size of the basin and spring-neap tidal ranges. This is related to the restriction of the water exchange.

Lagoon tidal range also depends on the surface area of the lagoon. Renewal of water in the lagoon is performed by tides and freshwater supply (Rydberg *et al.*, 1996). A knowledge on the exchange in any coastal water body is always essential for further calculation of behavior and fate of substances or biota (Michael, 1985).

Deepening of an inlet decrease choking by increasing the rate of water exchange, tidal range and moreover the saltwater intrusion into upstream. This in turn affects the water supply schemes for domestic, agricultural and industrial purposes. Development of water supply for the increasing demand for domestic purposes is not easy in the coastal areas. Over exploitation of river/ground water in the coastal areas on the other hand causes salt intrusion into the ground water aquifers, ultimately affecting the available water supply schemes and ground water resources, degrading agricultural lands.

The Study Area

Negombo lagoon is situated on the west coast of Sri Lanka, approximately 50 km north of Colombo at 7° 10'N and 79° 50'E (Fig.2). The lagoon is shallow and has a narrow inlet connecting it to the open ocean. The lagoon is surrounded by mangroves and mangrove associates. There is although one opening to the ocean the channel is divided into two towards the lagoon. The length of the main channel is 2 km, the average width is 150 m and the mean depth below mean sea level is 2 m. The lagoon is approximately 10 km long, 3.5 km wide and the mean depth is 1.2 m. The surface area is 31.5×10^6 m^2. The rivers Dandugam Oya and Ja-Ela are the main freshwater sources, both entering the lagoon from southern end (Fig.2). Drainage basin covers over 630 km^2. Lagoon experiences a strongly variable freshwater influx from rivers or irrigation systems.

Theory

Water exchange

The water exchange in a lagoon can be determined by assuming conservation of salt and mass (volume). Assuming that the volume V is constant for longer time, conservation of salt can be written as,

$$V\frac{d(S_L)}{dt} = Q_o S_o - Q_L S_L \qquad 1$$

The volume conservation thus gives,

$$Q_L = Q_o + Q_f \qquad 2$$

Where, Q_f rate of fresh water input

$$Q_f = Q_r + (Q_p - Q_e)$$

$$Q_o = \frac{V\frac{d(S_L)}{dt} + Q_L S_L}{(S_o - S_L)} \qquad 3$$

The residence time T is determined from,

$$T = \frac{V}{Q_L} \qquad 4$$

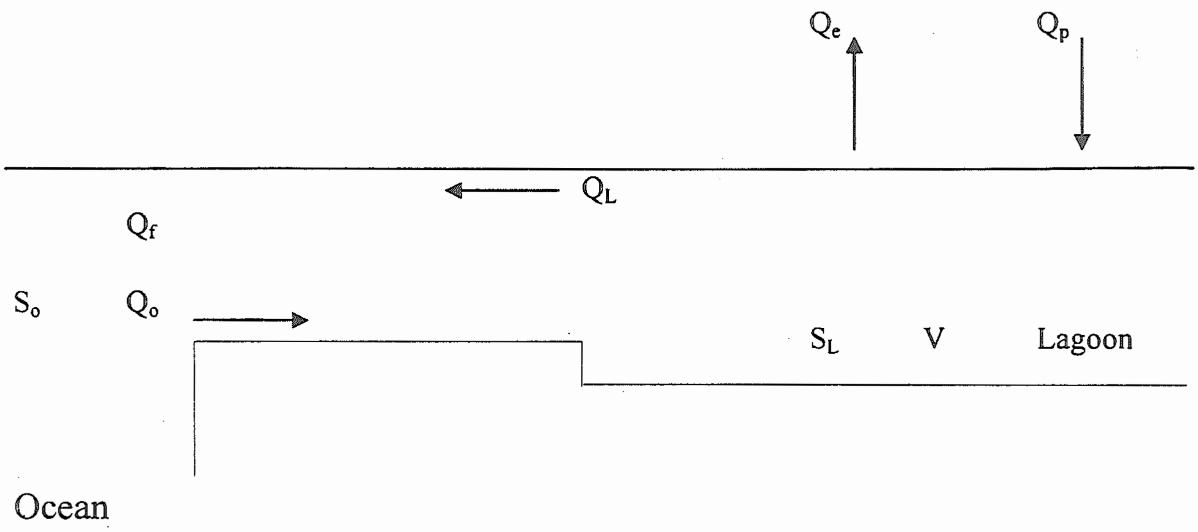

Fig.1: Schismatic diagram of a lagoon showing its water balance.

The terms, V-volume of the lagoon, Q_o- oceanic water inflow, Q_L-lagoon outflow, Q_e-evaporation, Q_p-precipitation, Q_r-river discharge, So and S_L are mean salinity of ocean and lagoon respectively. Q_L and Q_o are not tidal flows but the long-term exchange of water between the lagoon and the ocean.

Measurements & Methods

Salinity and current measurements were carried out twice per month from February to December 1993. Current measurements with pendulum current meters (Cederlof *et al* 1995) were carried out twice per month at the two rivers in order to estimate the river discharges into the lagoon. The volume fluxes were determined using computed lagoon sea level. Maximum, minimum and mean volume fluxes corresponding to the spring, neap and mean tide were computed. To determine the tide within the lagoon, and the flux through the inlet, simultaneous sea-level measurements were carried out at both sides of the inlet channel from 18th Dec. 1996 to 27th Feb. 97. Leveling of the gauges at stations T1, T2 (Fig.1) was done by assuming that the sea level is equal when the velocity is zero in between two tide gauges. The time for zero velocities, were determined by repeated observations around time for slack water using a current meter.

Results

The spring tidal range in the ocean is approximately 0.70 m and the neap range is 0.10 m. The flood and ebb duration are between 6.0-6.3 hr. in the sea as well as in the lagoon (Table 1). This indicates that the freshwater supply was minimal during the sea level observations made in 1997. During spring, Q_{food} was 185 m^3s^{-1} and Q_{ebb} was 180 m^3s^{-1}, which indicates slightly longer ebb periods. Spring tidal range of the lagoon was 0.13 m and the neap range was 0.05 m. It may look surprising that the time lag between corresponding high/ low waters from ocean to lagoon is 2.5 hrs although the length of the channel is only 2 km and the mean depth was 2 m. The mean lagoon sea-level is slightly higher than that of the oceanic.

The choking coefficients for the semi-diurnal components were between 0.2-0.3 (strongly choked) while those for the diurnal were 0.5-0.7. The inlet channel acted as a low pass filter, more effective in damping the high frequencies. The mean oceanic tidal range was 0.372 m while the lagoon mean tidal range was 0.095 m, thus the choking coefficient for the mean range was 0.25. The choking coefficient for the spring tidal range was 0.22 while 0.43 for the neap range.

The mean salinity of the lagoon is inversely related to the monsoon rains with variations between 30-5 ‰ (Fig4b). The evaporation rates were always lower than the river input rates. Otherwise hypersaline conditions could be expected as a result of inverse estuarine circulation. The river discharge varied from 15-225 m^3s^{-1} of which 72% from Dandugam Oya and 28% from Ja-Ela. The maximum salinity (25-30 ‰) appeared at the end of the dry seasons in February-March and in August. These maxim dropped within few weeks after the rain started. Salinity response to the river discharge (Fig.4f) shows a non-linearity. It is due to different flow regimes for high and low river discharges. Relatively high salinity 30-15 ‰ exists with discharge of 20-100 m^3s^{-1}. Saltwater intrusion along the river bottoms may exceed 15 km at very low discharge (< 20 m^3s^{-1}) but there is no intrusion during high river discharge. There is a tendency for stratification during low salinity periods when the horizontal gradient increases. The average surface salinity is very close to linear with an average salinity gradient of about 1.5km^{-1} within the lagoon. The river runoff provides sufficient kinetic energy for a mixing at the head of the lagoon.

The influx Qo ranges from 20-55 m^3s^{-1} and the outflow Q_L from 40-210 m^3s^{-1} while the mean flood and ebb varies from 60-200 m^3s^{-1} (see Table 1, data from 1997). The exchange is dominated by the fresh-water during high freshwater inputs and by tides during low fresh-water inputs. The outflow Q_L vary almost linearly with the freshwater input, Q_f (Fig.4d) and the least square fit to a straight line gives the relation $Q_L = 1.2 \times Q_f + 22$. The residence time T of lagoon V/Q_L decreases with increasing freshwater input. After calculating the net volume fluxes between the lagoon and ocean, Q_L and Q_o we found that there is an even better correlation between river discharge and residence time $\acute{T} = V/Q_L$ (Fig.4e). For Low River discharge the salinity is high and the exchange is dominated by the tide.

The results were fitted to an exponential curve (Fig.4e). The dotted line shows the residence times driven by freshwater input only if there is no tide. Both tides and freshwater input influence the residence time. At very low mean flow (20 m^3s^{-1}) the residence time was more than 10 days while under the highest mean flow Q_f = 160 m^3s^{-1} the residence time appeared to be about 2 days (Fig.4e).

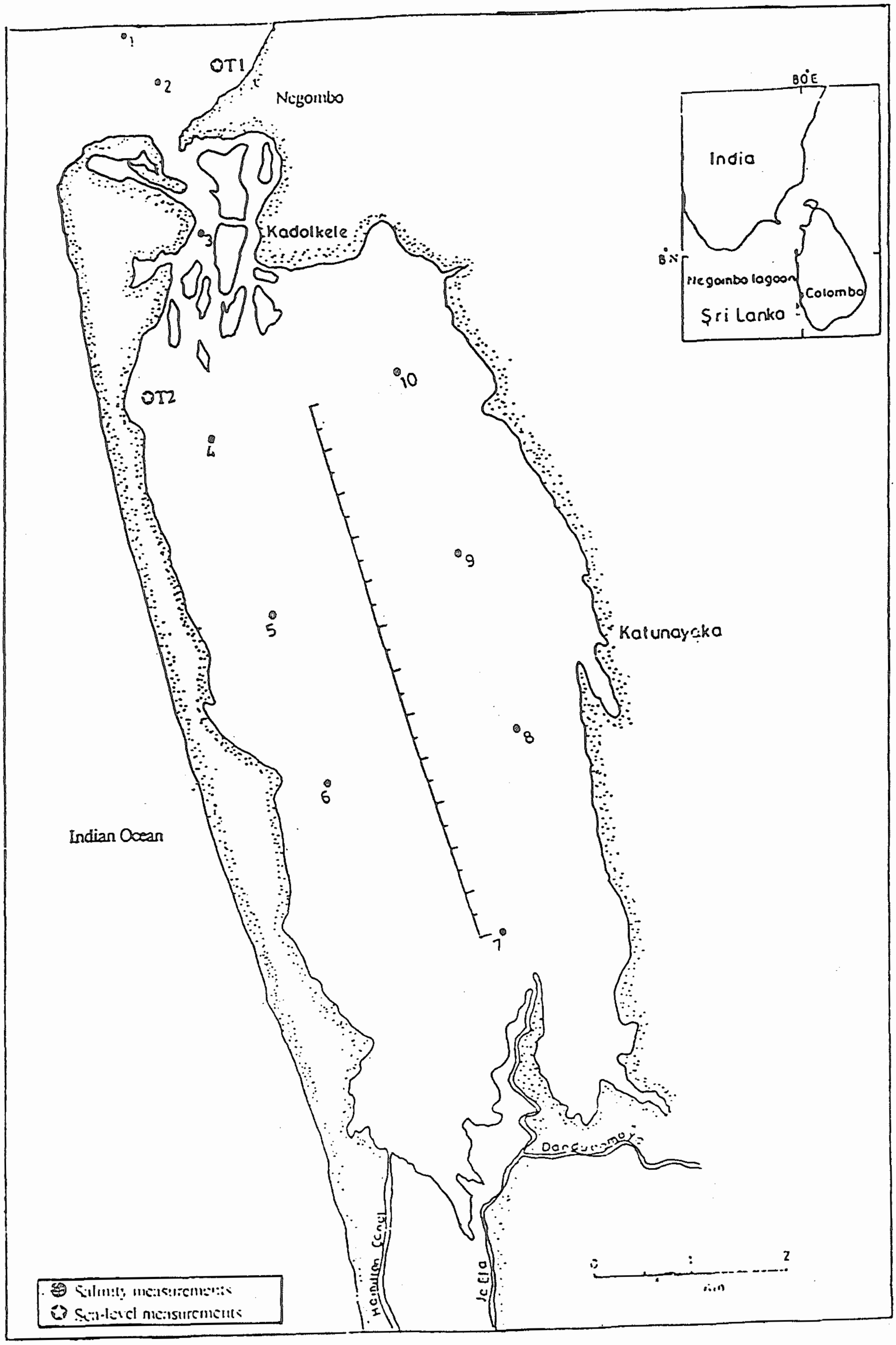

Fig.2: Negombo Lagoon showing its sampling locations for salinity and sea level measurements

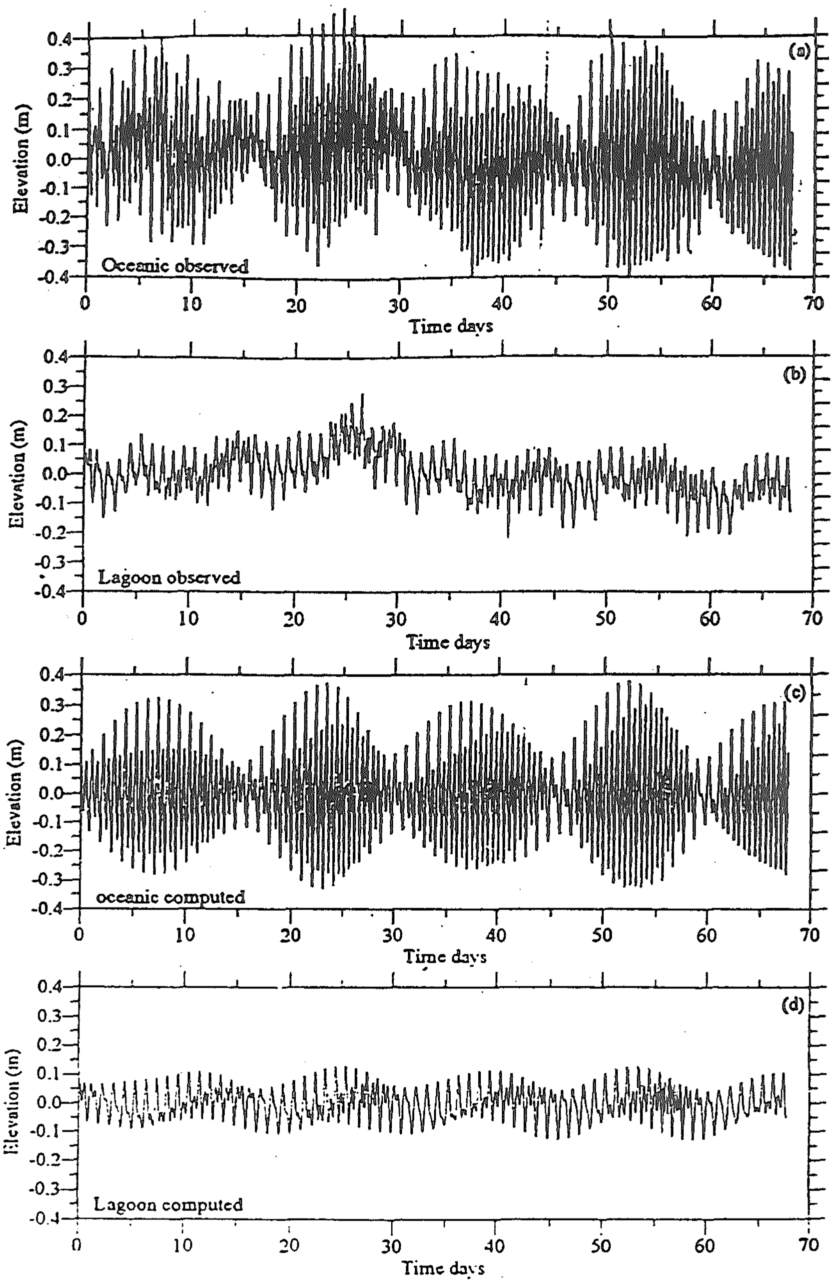

Fig.3: (a) Observed oceanic sea level (T1), (b) Observed lagoon sea level(T2), (c) Computed tide for the oceanic and (d) Computed tide for the lagoon after 14 harmonic constituents extracted, data from 18th December 1996-25th Feb 1997.

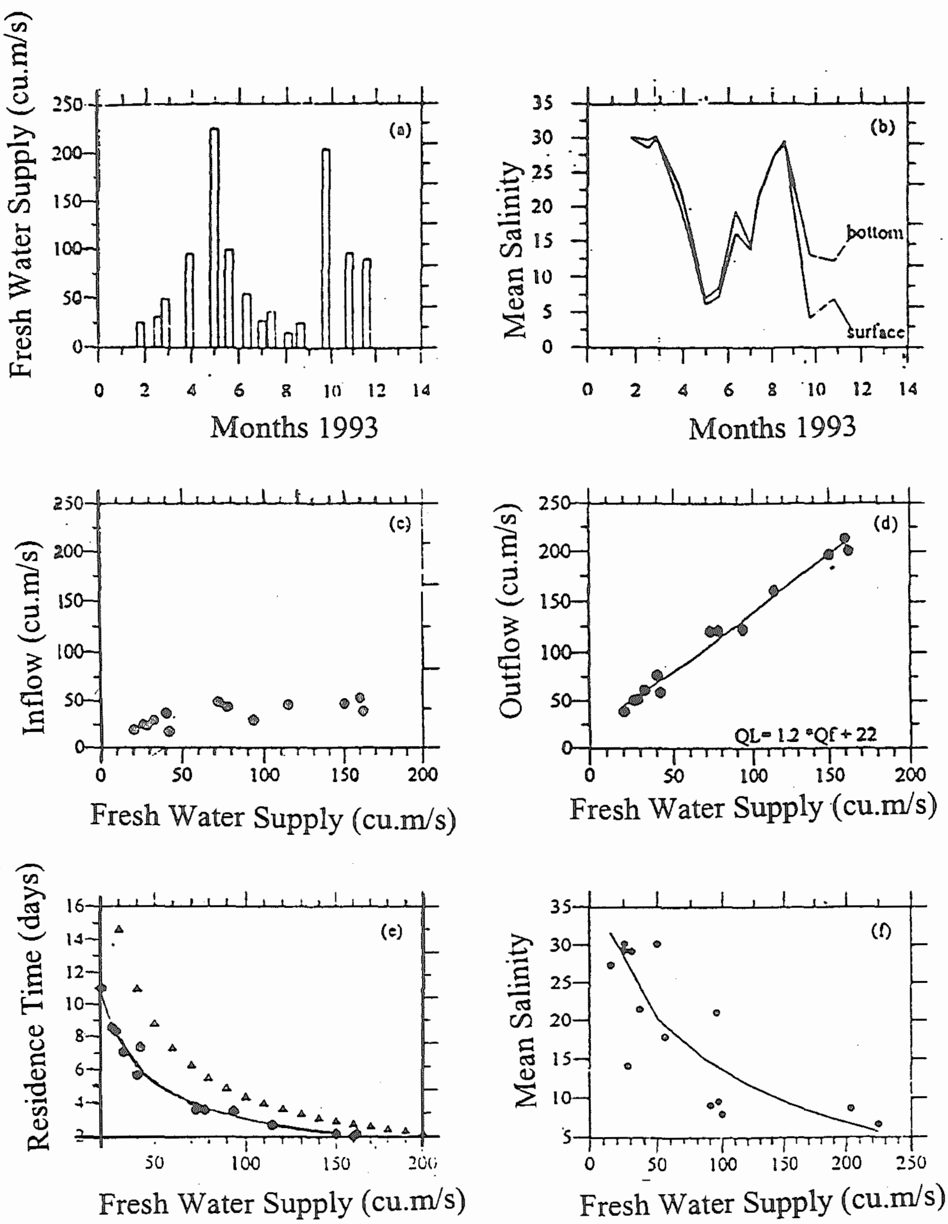

Fig.4: (a) Mean fresh water supply (b) Mean salinity 1993 (c) Inflow of oceanic water (d) Outflow of lagoon water (e) Residence times, the triangular symbols indicate that the residence time driven by fresh water supply only (f) Salinity responses to fresh water supply in to the lagoon

Discussion & Conclusions

Rydberg and Wickbom (1996) observed a choking coefficient of 0.12 at spring and 0.43 at neap although they had only 2-3 short periods of observations (2-5 day each). Thus the choking coefficient vary with the forcing tidal ranges implying that the lagoon experiences variable choking over a spring-neap cycle. On the other hand the lagoon tidal range does not vary as the oceanic tidal range because high choking for high tidal ranges and vise versa (Fig.3b).

Water exchange in Negombo lagoon was estimated using freshwater supply and salinity measurements during 1993. There were no reliable freshwater discharge data of the rivers and therefore, occasional observations with pendulum current meters were made. The measurements as such are reliable but these were not sufficient to consider as representative data to calculate weekly or monthly averages of freshwater input to the system. Still, there is a remarkably good correlation between salinity and freshwater discharge (Fig.4f). Freshwater in this case was a passive tracer, implying that for a doubling of the freshwater input, the freshwater content also doubles. A different effect could be observed when the freshwater supply is high. A two layer estuarine gravitational circulation becomes gradually dominated at the inlet (or, if the wind is weak within the lagoon). The relationship of lagoon salinity with freshwater supply then takes another form, which varies due to the type of mixing (c.f. Stigebrandt 1980; Rydberg 1981). The inflow of oceanic water to the lagoon Q_o, was found to be almost independent of freshwater supply, ($Q_o \approx 50$ m^{3}s^{-1}) except at low discharge. But still the net flow is rather high compared to the average tidal flow, which is 180 m^{3}s^{-1} during spring and 60 m^{3}s^{-1} during neap. The residence time T attained values between 2-11 days with the lowest values when the river inputs were above 200 m^{3}s^{-1}, while the highest T appeared at low inputs. Rydberg and Wickbom (1996) estimated the exchange to be 4 days at a discharge of 110 m^{3}s^{-1}, and to be 2 weeks at minimum discharge (20 m^{3}s^{-1}) and neap tide. At the average rate of freshwater input (78 m^{3}s^{-1}) the residence time was 5.5 days. Large differences in the residence time T was due to different exchange mechanisms where the tide dominates at low freshwater discharge. Freshwater content of the lagoon does not increase linearly with river input since the river input increases the magnitude of the density driven exchange carrying freshwater out of the lagoon (Fig.4f).

This study has confirmed the earlier observations by Rydberg and Wickbom (1996) with respect to water exchange, mean choking coefficient, drag coefficient and phase lag. Moreover present study indicates a clear fortnightly tide within the lagoon with variable phase lags in relation to the oceanic tide. Salt and water budget for the Negombo lagoon was well defined with respect to earlier observations.

Table 1: Flood and ebb duration / volume flux and channel velocity (u) using observed and computed tide from 18th Dec. 96 to 25th Feb. 1997.

		From observed sea level				From computed tide			
		Flood hrs.		Ebb hrs		Flood hrs.		Ebb hrs	
Ocean		6.05		6.13		6.31		6.11	
Lagoon		6.08		6.16		6.11		6.31	
Time lag between Lagoon & ocean		ocean - lagoon 2.51 hrs				ocean - lagoon 2.45 hrs			
Range m	η_m m	**Flood** $m^3 s^{-1}$	**u** $m s^{-1}$	**Ebb** $m^3 s^{-1}$	**u** $m s^{-1}$	**Flood** $m^3 s^{-1}$	**u** $m s^{-1}$	**Ebb** $m^3 s^{-1}$	**u** $m s^{-1}$
Spring 0.128	0.351	184.2	0.70	181.8	0.69	183.3	0.70	177.5	0.67
Neap 0.044	0.073	63.3	0.29	62.5	0.29	63.0	0.29	61.0	0.28
Mean 0.095	0.233	136.7	0.56	135.0	0.55	136.0	0.56	131.7	0.54

Table 2: Fresh water input, water exchange and residence time in Negombo lagoon during 1993.

Periods from	to	Net fresh water flux (Q_f) m^3s^{-1}	Net oceanic water inflow (Q_f) m^3s^{-1}	Net lagoon water outflow (Q_f) m^3s^{-1}	Residence time *T* days
23.02.93	07.03.93	28.31	24.10	52.40	8.35
17.03.93	07.03.93	40.43	36.89	77.31	5.66
27.03.93	07.04.93	72.75	48.68	121.43	3.60
27.04.93	09.05.93	160.10	53.10	213.10	2.05
29.05.93	06.06.93	162.10	39.42	201.50	2.17
16.06.93	09.07.93	77.62	44.01	121.63	3.59
09.07.93	08.07.93	41.91	17.49	59.40	7.37
28.07.93	09.08.93	32.59	29.38	61.96	7.60
09.08.93	30.08.93	26.26	24.85	51.10	8.56
30.08.93	15.09.93	20.45	19.30	39.74	11.01
15.09.93	09.10.93	114.40	46.50	160.86	2.72
19.10.93	20.11.93	150.00	47.37	197.34	2.23
20.11.93	03.12.93	93.50	30.13	123.62	3.54

Acknowledgments

This study was financially supported by the Swedish Agency for Research Cooperation (SAREC) with developing countries through which the regional program was initiated. In this connection I wish to thank Dr. Lars Rydberg, Ulf Cedrlof and O. Lindon.

References

ARULANANTHAN, K., RYDBERG, L., CEDERLÖF, U. & WIJERATNE, E.M.S. (1995) Water Exchange in a Hypersaline Tropical Estuary, the Puttalam Lagoon, Sri Lanka. *Royal Swedish Academy of Sciences vol.24, pp438-443.*

AWAJI, T., NORIHISA IMASATO & H. KUNISHI (1980) Tidal exchange through a straight: a numerical experiment using a simple model basin. *Journal of Physical Oceanography vol.10, pp. 1499-1508.*

CEDERLÖF, U., RODHE, J., RYDBERG, L. & SEHLSTEDT, P. I. (1996) Performance study of the Haamer gelatin pendulum current meter. *Journal of Sea Research vol. 35,pp.55-61.*

GLENNE, B. & SIMENSEN (1963) Tidal current choking in the landlocked fjord of Nordåsvatnet. *Sarsia vol.11,pp.43-73.*

HILL, A.E. (1994) Fortnightly tides in a lagoon with variable choking. *Estuarine, Coastal and Shelf science vol.38,pp 423-434.*

KJERFVE, B. (1991) *Tidal choking in a coastal lagoon.* Edited by Bruce B. Parker by John Wiley & Sons, Inc.169-180.

LE BLOND, P.H. (1979) Forced Fortnightly tides in shallow rivers. *Atmosphere-Ocean* vol.*17,pp. 253-264.*

MCCLIMANS, T.A. (1978) On the energetics of tidal inlets to landlocked fjords. *Marine Science vol. 4(2), pp.121-137.*

MICHAEL, E. Q. PILSON (1985) On the residence time of water in Narragansett bay. *Estuaries vol.8,pp. 2-14.*

NED, P. SMITH. (1979) Tidal dynamics and low-frequency exchange in the Aransas Pass, Texas. *Estuaries vol.2, pp218-227.*

ROBINSON, I. S. (1983) A tidal residence model of the fleet-an English tidal lagoon. *Estuarine, Coastal and Shelf science vol.16,pp. 699-688.*

RYDBERG, L., WICKBOM, L. (1996) Tidal choking and bed friction in Negombo Lagoon, Sri Lanka. *Estuaries vol.19, pp.540-547.*

STIGEBRANDT, A. (1980) Some aspect of tidal interaction with fjord constriction. *Estuarine and Coastal Marine Science vol.11, pp151-166.*

STIGEBRANDT, A. (1980) Barotropic and baroclinic response of a semi-enclosed basin to barotropic forcing from the sea. *Fjord Oceanography (ed. by H.J. Freeland, D.M. Farmer and C.D.Levings), Plenum.pp. 151-164.*

STIGEBRANDT, A. & MOLVAER, J. (1988) On the water exchange of Framvaren. *Marine chemistry. vol. 23,pp 219-228.*