

## Salt intrusion study in Cochin estuary - using empirical models

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Intensive measurements of salt intrusion are taken at high and low waters during spring and neap tide for each month respectively from June 2007 to May 2008. Salt intrusion length at high water varied from 10 km in monsoon 2008 to more than 40 km in pre monsoon 2007. Salinity intrusion mostly depends on the fresh water discharge rather than spring-neap tidal oscillations. Stratification parameter of salinity varied with the distance along the estuary, tide and freshwater discharge indicating that the Cochin estuary experiences a transition from partially or well mixed estuary during post and pre monsoon to a strongly stratified estuary during the monsoon season. Instead of undergoing the entire process of data collection of all the parameters, for a prolonged period, which is quite expensive and time consuming, certain predictive models are preferred. A predictive model uses parameters which are measurable and quantifiable variables and determined through empirical relations. Four empirical models have been applied to the Cochin estuary in the present study to identify the most suitable model for predicting the salt intrusion length. Comparison of the obtained results indicate that the model of Van der Burgh (1972) is the most suitable empirical model for prediction of the salinity intrusion length in the Cochin estuary with the least RMS error of (6.1) and MAE of (4.8).

**[Keywords:** Salinity intrusion length, Empirical models, Tidal excursion, Salinity stratification]

### Introduction

Estuaries are among the most productive ecosystems on earth and more than 50% of the world population lives along the estuaries and coastlines<sup>1</sup>. Cochin Backwaters is a coastal plain and topographically a low lying area. It is characterized by its long axis running parallel to the Arabian coast and is separated from the sea by barrier spits interrupted by tidal passes at Azhikode and Cochin Harbor mouth.

Cochin estuary can be divided into three different zones based on the salinity contents. The first zone is completely saline and its salinity always is more than riverine water salinity. In the second zone, which coincides with the tidal excursion length, salinity varies periodically between freshwater and brackish water salinity. The third zone is always fresh and its salinity is the same as riverine water salinity. The major feature of the second zone may be its importance for water consumption, e.g. drinking<sup>2</sup>. The main purpose of the study is to (1) determine longitudinal distribution of salinity as function of directly measurable parameters such as geometry, fresh water flow and tide (2) select a suitable empirical model for Cochin backwaters for future salinity intrusion study (3) study seasonal salinity stratification parameter of the estuary.

### Methodology

#### *Field study*

A time series one year observation is carried along the Cochin backwaters in a speed boat starting from Munambam to Thanneermukkom. SeaBird portable CTD profiler (Seacat) is used and cast at all the stations for getting the salinity readings. Observation is carried out twice each month, both for spring and neap phase. For a perfect salinity intrusion study, it is essential to get bottom salinity values at least at 1km apart, but because of the extensive length of the estuary (72.5 km), it is very difficult to cast CTD at such regular intervals within the required time interval. The entire backwater from Munambam to Thanneermukkom is divided into 11 stations approximately 6-11.5 kms apart. Stations are (1) Munnabam, (2) Cherai Bridge, (3) Kadakkara, (4) Elamkunnappuzha, (5) Fort Kochi (Barmouth), (6) Thevara, (7) Aroor Bridge, (8) Panavally, (9) Vaikom, (10)Thanneermukkom north and (11) Thanneermukkom south, where the station Thanneermukkom south lies on the other side of the Thanneermukkom bund (Fig.1). Inlets at Azhikode and Fort Kochi are the openings, through which sea water enters the estuary during the flood tide and flushes out during the ebb tide. The cross sectional

area (m<sup>2</sup>) width (m) and mean depth (m) of the cochin backwaters from the munambam to thanneermukkom south is shown in Fig. 2. For the present study only

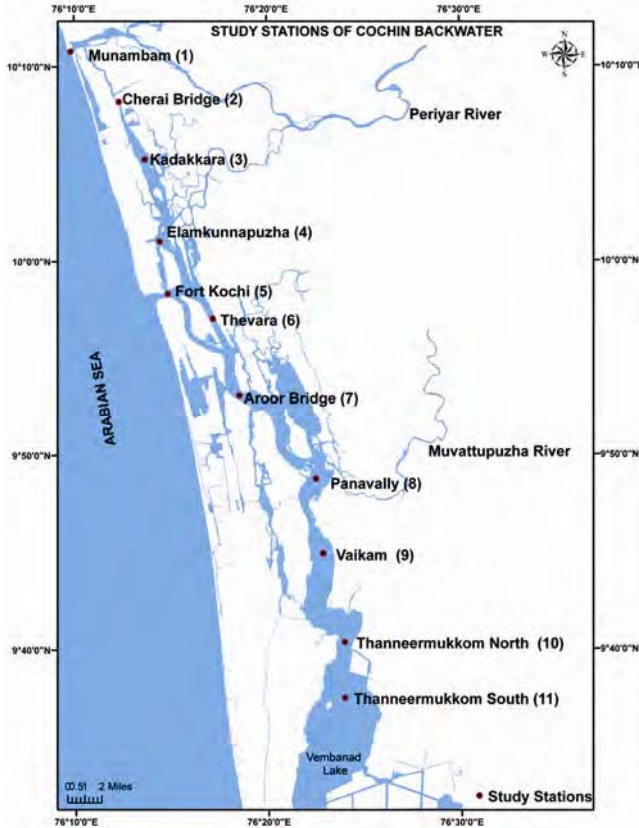


Fig. 1—Map of Cochin backwaters with 11 stations from Munambam to Thanneermukkom south with major rivers Periyar and Muvattupuzha draining into it.

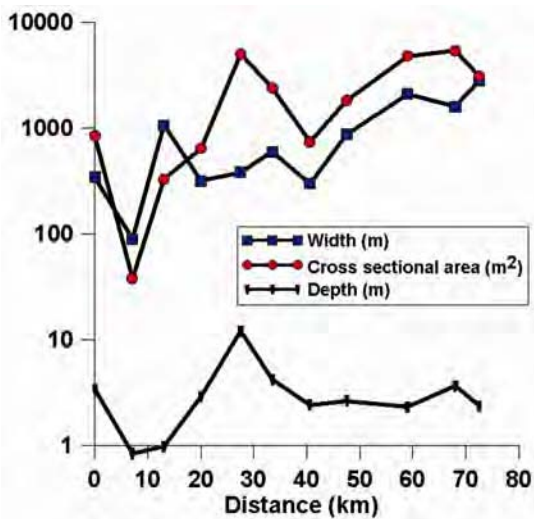


Fig. 2—Cross-sectional area (m<sup>2</sup>), width (m) and mean depth (m) of the Cochin backwaters from north to south (Azhikode to Munambam).

the southern arm of the estuary from Fort Kochi inlet to Thanneermukkom south is considered.

The longitudinal transects for salinity are taken at high waters during the spring phase and low waters at neap phase. GPS is used to obtain the exact location. Each cruise intended to start from the mouth, 1 hour before the high or low water slack and arrive in about one hour at the last station when the high or low water slack occurred but due to extensive length of the estuary and some unavoidable circumstances, the trip took about 4-5 hrs, as a result of which the values could not be obtained at the peak of the slack phase for few observations. This has resulted in few discrepancies between the observed and calculated values of salinity intrusion length. Readers are requested to overlook this lack of consistency between the observed and calculated values of salinity intrusion length in the models and only take into consideration the most coinciding model values.

The river discharge data for the year 2008-09, obtained from Central Water Commission, Thevara, uses the discharge data from the six stations namely, Neeleshwaram, Ramamangalam, Kidangoor, Thumpamon, Kalluoppara and Malakkara situated on the six rivers, namely Periyar, Muvatupuzha, Meenachil, Achankovil, Manimalla and Pampa respectively, emptying into the Cochin Backwaters and flowing out through the Cochin inlet into the Arabian sea. Periyar has the maximum contribution among all the rivers that discharge into the Cochin estuarine system with annual runoff (in MCM) of 5602, followed by Muvatupuzha, Pampa, Meenachil and Manimalla. Achankovil has the least annual runoff (in MCM) of 720 as recorded during the year 2008-09. Climate in Kerala is characterized by three distinct seasons: monsoon (June, July, August and September), post-monsoon (October, November, December, January) and pre-monsoon (February, March, April and May). Monsoon season is prone to the higher river discharge as compared to the post and pre-monsoon seasons (Fig. 3). The northerly connection, Azhikod, is at the mouth of the Periyar River. This connection takes care of half the discharge by the Periyar River, but has no real influence of tidal inflow. The inlet near Cochin discharges half of the discharge of the Periyar River and almost the whole discharge for the other five rivers, the Muvatupuzha, the Meenachil, the Manimalla, the Pampa and the Achankovil, who let out their water on the Vembanad lake<sup>3</sup>.

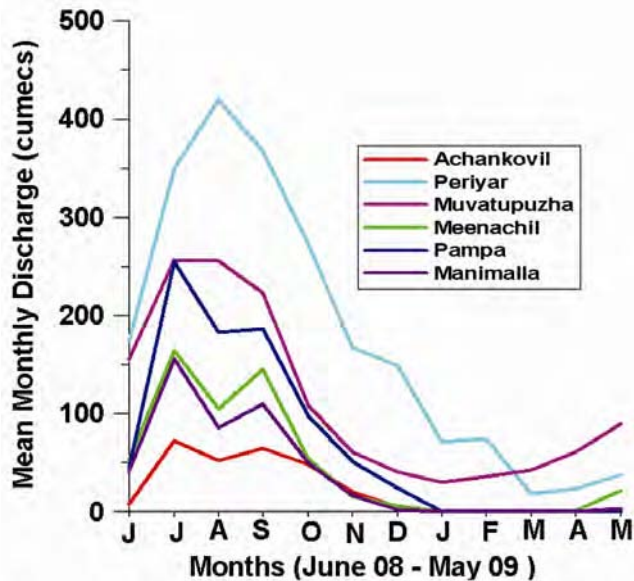


Fig. 3—Mean monthly discharge of the six major rivers draining into the Cochin backwaters.

#### Salinity intrusion

Estuaries are also considered as an especial ecosystem, due to the existence of tidal condition and brackish water. Multiple use of estuarine water indicates the importance of water quality of estuaries. Changes in water quality conditions have severe environmental impacts on the estuarine ecosystem<sup>4-5</sup>. Estuarine salinity is as an indicator of water quality for both, organism distribution and water consumptions criteria<sup>6-8</sup>. Salinity distribution in an estuary is affected by morphologic, bathymetric and hydrodynamic characteristics<sup>9-10</sup>. Savenije<sup>11</sup> conducted an extensive study on the salinity intrusion mechanism in the alluvial estuaries. He solved the advection-diffusion equation analytically to derive an empirical model to predict the salinity intrusion length. Most of natural estuaries have an exponentially varying width, depth and cross-sectional area<sup>11-14</sup>. But this is not so in case of Cochin estuary. Estuary is not a continuous unhindered flow channel, but has many islands scattered along main channel, causing a change in current direction and flow path (Fig.1).

Salinity intrusion length, is the length from the mouth to a point at which the salinity is approximately the same as riverine water salinity whereas tidal excursion length is the net horizontal distance traveled by a water particle from LWS to HWS or vice versa. It can be used to describe the movement of pollutants in estuaries during a tidal cycle<sup>15</sup>. Recent work of Savenije<sup>16</sup> implied that the

tidal excursion length is an important parameter, indicating the hydraulic and mixing mechanism of estuaries. He also showed that the tidal excursion length is used to estimate the dispersion coefficient and its longitudinal variation along an estuary. Tidal excursion length also can be used as a length scale in the modeling of sediment transport in estuaries<sup>17-19</sup>. schttelaars *et al.*<sup>20</sup> showed that morphodynamic equilibrium depends on the ratio of estuary width to the tidal excursion length. Savenije<sup>21</sup> showed that the product of the tidal excursion length and the cross-sectional area at the estuary mouth is a good approximation for the tidal prism. As estuaries are affected by both marine and riverine influences, their salinity and water quality depend strongly on the riverine discharge, tidal fluctuation, bottom roughness and the amount of salinity originated from the ocean<sup>22-24</sup>. Fresh water velocity decreases with increasing water depth and increases with increasing river discharge. Therefore, the salt water intrusion increases with increasing water depth while it decreases with increasing river discharge. Strength of gravitational circulation and therefore the salt intrusion increases with increasing driving density difference. Vertical mixing is a factor which limits salt intrusion. So, the salt intrusion decreases with increasing bed roughness, i.e. decreasing Chezy coefficient.

Salinity intrusion length varies periodically during a tidal cycle. Maximum and minimum salinity intrusion length occur in high water slack (HWS) and low water slack (LWS), respectively. Models of Van der Burgh<sup>25</sup>, Savenije<sup>16</sup> and Nguyen and Savenije<sup>26</sup> are based on real estuaries, whereas that of Fischer<sup>27</sup> is based on laboratory tests. Some researchers, such as Rigtter<sup>28</sup>, Fischer<sup>27</sup> and Van Os and Abraham<sup>29</sup>, used the intrusion length at low water slack  $L^{LWS}$ , others e.g. Van der Burgh (1972) and Savenije<sup>30</sup>, used the tidal average intrusion length  $L^{TA}$  (the averaged salinity measurement, carried out for a full tidal cycle) and Savenije<sup>11,16</sup> developed a method for HWS that predicts the salinity intrusion length, but in this study, we are considering the intrusion length at high and low water slack for spring and neap phase respectively. This is the maximum intrusion length occurring during a tidal cycle. The present study, deals with empirical work by Van der Burgh (1972), Fischer (1974), Savenije (1993, 2005) and Nguyen and Savenije (2006). Except Van der Burgh and Savenije all researchers based their analysis on laboratory tests and prototype measurements in

estuaries with constant cross section. Van der Burgh (1972) provided a tidal average model using limited field observations in real estuaries, including the Rotterdam Waterway, the Schelde and the Haringvliet. The equation is:

$$L^{TA} = 24\pi \frac{h_0}{K} F^{-0.5} N^{-0.5} \quad \dots (1)$$

where  $L^{TA}$  is the tidal averaged intrusion length,  $h_0$  is the tidal average depth,  $F$  is the Froude number ( $F = v_0 / (gh)^{1/2}$ ), and  $N$  is the Canter-Cremers estuary number, which is defined as the ratio of the freshwater entering the estuary during a tidal cycle ( $Q_f T$ ) to the flood volume of saltwater entering the estuary over a tidal cycle ( $Pt = A_0 E_0$ ). The flood volume can be very well approximated by the product of  $A_0$  and the tidal excursion  $E_0$  ( $E_0 = v_0 T / \pi$ ) at the estuary mouth Savenije (2005)  $K$  is the Van der Burgh coefficient, for which<sup>16</sup> developed an empirical predictive equation:

$$K = 0.2 * 10^{-3} \left(\frac{E}{H}\right)^{0.65} \left(\frac{E}{C^2}\right)^{0.39} (1 - \delta b)^{-2.0} \left(\frac{h}{a}\right)^{0.58} \left(\frac{E_0}{A_0}\right)^{0.14} \quad \dots (2)$$

Van der Burgh's coefficient  $K$  is a hydraulic characteristic of estuaries, which has a value between 0 and 1.  $E$  is the tidal excursion,  $H$  is the tidal range,  $C$  is the Chezy coefficient,  $\delta$  is the damping rate of the tidal range ( $\delta = (1/H) (\partial H / \partial x)$ ) and  $A_0$  is the cross-sectional area at the estuary mouth. The area convergence length ( $a$ ) and width convergence length ( $b$ ) are defined by exponential functions<sup>16</sup>:

$$A = A_0 \exp\left(-\frac{x}{a}\right) \quad \dots (3)$$

$$B = B_0 \exp\left(-\frac{x}{b}\right) \quad \dots (4)$$

where  $A$  and  $B$  are the cross-sectional area and width at a distance  $x$  (km) from the estuary mouth, respectively.  $A_0$  and  $B_0$  are the cross-sectional area and width at the estuary mouth ( $x=0$ ), respectively.

Savenije<sup>11,16,31</sup> developed a method for HWS that predicts the salinity along the estuary depending on the shape of the estuary, the tidal influence and the river discharge. The salt intrusion length,  $L$ , is defined by Savenije<sup>11</sup> (2005)

$$L^{HWS} = \ln\left(\frac{-D_0^{HWS} A_0}{K a Q_f} + 1\right) \quad \dots (5)$$

where  $L^{HWS}$  is the intrusion length at HWS (the maximum intrusion length during a tidal period),

$D_0^{HWS}$  is the dispersion coefficient at the estuary mouth at HWS.  $K$ ,  $a$  and  $A_0$  are (constants) hydraulic characteristics of the estuary and therefore are the same under any condition during the year, whereas  $D_0^{HWS}$  is time dependent, depending on both the river discharge and tidal range. The model has been applied to 17 different estuaries all over the world, particularly for HWS situations<sup>32</sup>. The dispersion coefficient,  $D_0^{HWS}$ , is expressed as follows:

$$D_0^{HWS} = 1400 \frac{h_0}{a} \sqrt{N_R} v_0 E_0 \quad \dots (6)$$

where  $h_0$  is the depth at the estuary mouth,  $a$  is the area convergence length,  $v_0$  is the velocity of  $M_2$  component,  $E_0$  is the tidal excursion at the estuary mouth and  $N_R$  is the Estuarine Richardson number. The Estuarine Richardson number  $N_R$ , (the ratio of the Canter- Cremers number  $N$  to the densimetric Froude number  $F_d$ ) is the dimensionless number that determines the balance between kinetic energy provided by the tide and potential energy provided by the river discharge through buoyancy of freshwater responsible for the mixing:

$$N_R = \frac{N}{F_d} = \frac{\Delta \rho g h_0 Q_f T}{\rho A_0 E_0 v_0^2} \quad \dots (7)$$

where  $\rho_f$  is density of water = 1000 kg/m<sup>3</sup> and  $\rho_s$  is density of sea water = 1025 kg/m<sup>3</sup> and  $\rho / \Delta \rho = 40$

Nguyen and Savenije (2006) further modified the dispersion coefficient,  $D_0^{HWS}$  in the<sup>16</sup> equation for partially- and well-mixed estuaries. The dispersion coefficient,  $D_0^{HWS}$ , was expressed as:

$$D_0^{HWS} = 1400 \frac{h^*}{b} \sqrt{N_R} v_0 E_0 \quad \dots (8)$$

where  $h^*$  is the average depth over the salt intrusion length and  $b$  is the width convergence length.<sup>27</sup> derived the formula for low water slack conditions as:

$$L^{LWS} = 17.7 \frac{h_0}{f^{0.433}} F_d^{-0.75} N^{-0.25} \quad \dots (9)$$

$L^{LWS}$  is the intrusion length at LWS,  $f$  is the Darcy-Weisbach friction factor ( $f = 8g/C^2$ ) and  $F_d$  is the densimetric Froude number

$$F_d = \frac{\rho v_0^2}{\Delta \rho g h_0} \quad \dots (10)$$

### Results and Discussions

Major differences between Van der Burgh (1972) and Fischer (1974) models are in the use of the

dimensionless numbers, namely  $F_d$ ,  $F$ ,  $K$  and  $f$ . Exponent of  $N$  is different for the two models, which is negative as the salt intrusion length diminishes with increased freshwater discharge. Darcy-Weisbach's coefficient, solely a function of flow roughness, is considered for the Fischer (1974) model. Van der Burgh coefficient ( $K$ ) is used in the models of Van der Burgh (1972) and Savenije (2005) and, which is a function of both the average tidal and freshwater flow characteristics. A time dependent (depending on both the river discharge and tidal range) dispersion coefficient ( $D_0^{HWS}$ ) near the estuary mouth is used in<sup>16</sup> and<sup>26</sup> models. All models described above are applied to the Cochin estuary to predict the salt intrusion length assuming a steady state. To examine the maximum salt intrusion length, the bottom salinity at high water has been used instead of the depth-averaged salinity. Variation in the salt intrusion is subsequently examined in response to freshwater input and tide.

In the present study, since the stations selected for the study are more than 1 km apart, hence to measure the exact distance from the inlet at which salinity becomes approximately 1, the field data is extrapolated. The parameters needed to predict the salt intrusion length using these empirical models are freshwater inputs into the estuary at various times during the year, tidal information and the bathymetry along the estuary. Van der Burgh's coefficient  $K$  is another parameter used to describe the nature of salt transport mechanisms (both tide driven and density-driven dispersion) in estuaries<sup>32,33</sup>. If  $K$  is small ( $<0.3$ ), then tide-driven mixing is dominant in transporting salt. If  $K$  approaches 1 ( $>0.8$ ), gravitational circulation is dominant in transporting salt. If  $0.3 < K < 0.8$ , both tide-driven and density-driven mixing contribute to transporting salt. The value of the coefficient  $K$  calculated from the field data for the Cochin estuary using Eq. (2) is found to be 0.26, hence the up-estuary salt transport is entirely dominated by tide-driven mixing near the mouth. But according to Shaha<sup>33</sup> spatially varying Van der Burgh's coefficient  $K$ , determined from the estuarine parameter  $v$  with the assumption of an exponential function, is physically appealing as the spatially varying  $K$  can describe the spatially different tide-driven and density-driven mixing contributions along the estuary compared with a single  $K$  value. This describes the mixing processes reasonably well near the mouth, in the central regimes and near the toe of the salt intrusion curve in an estuary.

Darcy-Weisbach friction factor  $f$ , is calculated using equation ( $f = 8g/C^2$ ) and the value is 0.008, where  $C$  is Chezy coefficient. Based on the bed friction coefficient reported by Eldho<sup>34</sup>, Chezy coefficient is imposed as  $101 \text{ m}^{1/2}/\text{s}$ . Salinity intrusion lengths are calculated using  $h = 13.9 \text{ m}$ ,  $h^* = 3.42 \text{ m}$ ,  $A_0 = 5603.6 \text{ m}^2$ ,  $T = 12.42 \text{ hrs}$ . Convergence lengths of the cross-sectional area ( $a$ ) and width ( $b$ ) are  $75448.1 \text{ m}$  and  $24905.9 \text{ m}$  respectively calculated using Eq. (3) & (4). Mean freshwater discharge on the date of the field observation is used in this study. As the observed intrusion length was determined under a high water slack for the spring phase and low water slack for the neap phase situation in this study, hence the tidal excursion  $E$ , is added to the LWS model of and half the tidal excursion ( $E/2$ ) added to the TA model of Van der Burgh to obtain the high water slack intrusion length. Similarly  $E$  is subtracted from the HWS model of Fischer (1974), Savenije (1993, 2005) and half the tidal excursion ( $E/2$ ) was subtracted from the TA model of Van der Burgh to obtain the low water slack salt intrusion length.

Salinity intrusion along Cochin estuary is hindered by the Thanneermukkom bund constructed at about 40 km from Cochin harbor. The bund restricts the free flow of water into the Vembanad Lake and hence maintaining the lake as a fresh water zone. The bund remains closed from mid November to May, when the river discharge from the 4 rivers namely Pampa, Achankovil, Meenachil and Manimala is the almost nil. During monsoon, the bund opens allowing the rivers to empty into the estuary. Hence, the field observations beyond the bund during the dry season could not be taken but a high saline value of 15.1, during the month of March, at the bund indicates that salinity intrusion during dry season extends beyond the 40 km, from Cochin inlet into the Vembanad Lake.

High river discharges occurred during the spring tide of monsoon, when the tidal range is 0.86 - 0.70 m. The other seasons were susceptible to lower river discharges; when tidal range is as low as 0.08 m. Maximum calculated intrusion length from Van der burgh model is 114.37 km and occurred for a low river discharge of  $26.65 \text{ m}^3/\text{s}$  and tidal range of 0.58 m, during spring tide on 11 March 2009, while the minimum of 15.6 km, occurred at high river discharge of  $1203.55 \text{ m}^3/\text{s}$  and tidal range of 0.16 m during neap tide on 25 July 2008. This shows that salinity intrusion lengths were more of a function of river discharge throughout the year since the observed

as well as the calculated results of Van der Burge models show great correlation between river discharge and salinity intrusion length (Table 1). Two counteracting effects determine the effect of tidal amplitude. Large tidal amplitude at the mouth of the estuary is associated with strong tidal currents and hence strong turbulent mixing and weak stratification. Stronger the turbulent mixing, weaker the salt intrusion and thus salt intrusion tends to become smaller with increasing tidal amplitude, in particular when the estuary is stratified. Large tidal amplitude at the mouth of the estuary is further associated with large tidal excursion paths. Larger the tidal excursion path, the larger the salt intrusion at high water slack. So, the salt intrusion is larger with increasing tidal amplitude, in particular when the estuary is mixed. Hence which of the above counteracting mechanisms prevails, varies with the stratification, influenced by the strength of tide<sup>35</sup>. In the present scenario, stratification is stronger during the monsoon and weaker or well mixed during the pre monsoon, hence in spite of large tidal amplitude, salt intrusion is maximum during pre monsoon and least during the monsoon season.

Longitudinal salinity profile for each month shows that a salinity of 1 reaches as far as Vaikom (30 km from Cochin inlet) during monsoon while a salinity as high as 15 is observed at Thanneermukkom near the bund during the pre monsoon season and would have penetrated the Vembanad lake making the

water brackish in the absence of the bund, making it unsuitable for irrigation. The study signifies the availability of fresh water in the Cochin estuary during different seasons.

The four models used to study salt intrusion in the Cochin estuary gave the following results. Fischer (1974) over estimated the salt intrusion length during both spring and neap tide, were salinity intrusion length exceeded the estuary length (Fig.4b and 4d). Savenije (2005) and Nguyen and Savenije (2006) predicted the salt intrusion length moderately well with some variations from the actual value (Fig.4c) but Fischer (1974) predicted the salt intrusion length quite adequately (Fig.4a). by Van der Burgh model (1972) Hence model can be considered as the most appropriate model to study salt intrusion length in Cochin estuary. Statistical analysis is also performed as a quantitative measure to study how good the empirical model results fitted the observed data, to evaluate the performance of each model and to select a model most suitable. To evaluate the error, in the model results, root-mean-square (RMS) and mean absolute error (MAE) are used to study their performance (Table 2). The results shows that root mean square error and mean absolute error showed a lower error value for the by Van der Burgh model (1972) both for the spring and neap phase compared to the other models. This proves that the Van der burgh model shows more consistency in results among all the models used.

Table 1—River discharge, tidal ranges and observed salt intrusion length and salt intrusion length calculated using van der Burgh model during 2008-09 for different seasons for both spring and neap phase.

Season	Month (June2008 May09)	Spring tide				Neap tide			
		River discharge (m <sup>3</sup> s <sup>-1</sup> )	Tidal range (m)	Salt intrusion length observed (km)	Van der Burgh intrusion length(km)	River discharge (m <sup>3</sup> s <sup>-1</sup> )	Tidal range (m)	Salt intrusion length observed (km)	Van der Burgh intrusion length (km)
Monsoon	June	466.68	0.86	29	29.3	492.99	0.2	16	25.8
	July	1279.9	0.88	13	18.9	1203.55	0.16	10	15.6
	August	1133.94	0.84	13	19.66	360.88	0.2	19	30.09
	September	705.18	0.70	12	23.9	294.58	0.3	19	35.1
	October	335.44	0.60	31.5	33.2	878.27	0.08	19	19.6
Post-monsoon	November	225.26	0.24	37	39.4	168.23	0.52	38	42.8
	December	90.98	0.18	>40	61.53	109.07	0.7	40	53.2
	January	90.79	0.34	>40	62.27	35.22	0.78	>40	94.75
Pre-monsoon	February	70.88	0.42	>40	70.35	88.7	0.72	>40	59.5
	March	26.65	0.58	>40	114.37	46.74	0.56	>40	83.8
	April	88.73	0.70	>40	63.8	62.91	0.7	>40	80.6
	May	88.34	1.14	>40	66.1	106.11	0.56	>40	55.3

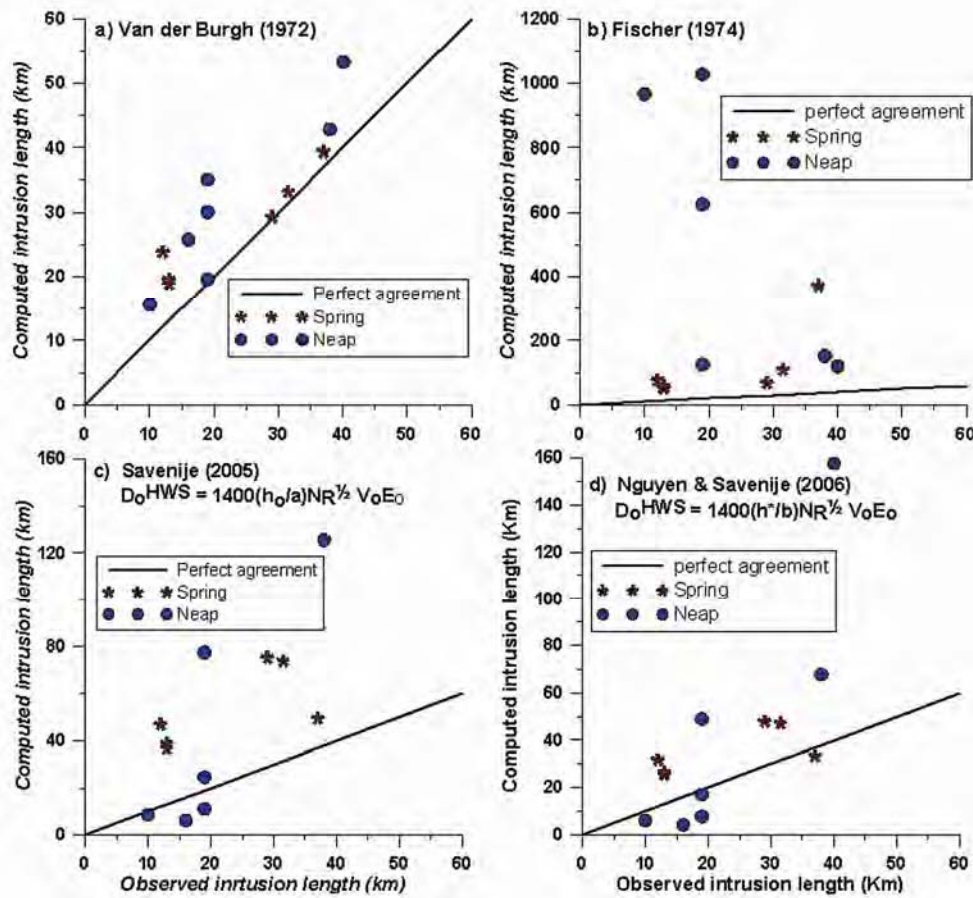


Fig. 4—Comparison of results of various empirical models: a) Van der Burgh (1972), b) Fischer (1974), c) Savenije (2005) and d) Nguyen and Savenije (2006) for salt intrusion lengths measured at high water slack during spring and low water slack during neap tides in the Cochin estuary.

Table 2—Root mean square and mean average error values for Van der Burgh, Fischer, Savenije and Nguyen and Savenije models for both spring and neap tides in the Cochin estuary.

Models	RMS (Km)		MAE (Km)	
	Spring	Neap	Spring	Neap
Van der burgh (1972)	6.18	10.05	4.81	8.74
Fischer (1974)	145.9	622.7	100.2	478.26
Savenije (2005)	33.02	43.35	30.93	28.45
Nguyen& Savenije (2006)	15.05	47.66	14.06	29.44

*Salinity stratification*

Estuary stratification is caused by the density difference between seawater and fresh river water. Kinetic energy supplied by tidal flow reduces the stratification and potential energy supplied by the river discharge enhances stratification. Based on hydrodynamics, estuaries are classified as sharply stratified, partially stratified and well mixed. Sharply stratified estuaries exhibit little mixing between the salt wedge and freshwater flow and tidal action is not

sufficient to mix the separate layers. Well mixed estuaries do not exhibit significant vertical density variations and tidal flow is normally greater than freshwater flow. Partially stratified estuaries are intermediate between sharply stratified and well mixed estuaries and exhibit significant vertical density gradient but the gradients are less sharp than in highly stratified estuaries<sup>36</sup>. Hansen and Rattray<sup>37</sup> developed a stratification parameter ( $\partial S / \langle S \rangle$ ), defined as the ratio of the salinity difference between surface

and bottom ( $\partial S$ ) divided by the depth averaged salinity  $\langle S \rangle$ , to characterize estuaries. Prandle<sup>38</sup> showed that  $(\partial S / \langle S \rangle) = 4S_t^{-0.55}$ , where  $S_t$  is the stratification number ( $S_t = (0.85 kv_o^3 L) / (\Delta\rho/\rho)gh^2u_m$ ),  $k$  is the friction coefficient,  $L$  is the salt intrusion length,  $v_o^3$  is the amplitude of the tidal currents,  $h$  is the water depth and  $u_m$  is the depths mean current. This means that if  $\partial S / \langle S \rangle < 0.15$ , then the estuary is well mixed and if  $\partial S / \langle S \rangle > 0.32$ , it is stratified. In the present study, the stratification parameter is calculated for all stations using data surveyed for each season in the Cochin estuary.

During monsoon period, heavy rainfall results in High River discharge which eventually reach the estuary mouth at Fort Kochi. Stratification often develops and results in conditions with less dense river water at surface and high dense seawater at the bottom layers. From June to about early October the surface salinity values were almost zero. However, the bottom values were comparatively high, resulting in well-defined vertical salinity stratification, from Fort Kochi inlet to Panavally (stations 5 to 8). Thus a strong halocline could be inferred during the monsoon. This halocline loses its vertical stratification while proceeding to the head of the estuary, and is much weaker beyond Panavally, wherein a fresh water condition prevails, from top to bottom. Figure 5 shows higher stratification values ( $>0.32$ ) for all the four months of monsoon except for June when the river discharge was low ( $466.68 \text{ m}^3\text{s}^{-1}$ ).

After the monsoon, there is an increase in salinity both at the surface and at the bottom, with the maximum occurring during December-May. During

post and pre monsoon, the fresh water inflow decreases gradually, leading to an increase in the surface salinity. During post-monsoon, river discharge gradually diminishes and tidal influence gains momentum as the estuarine conditions change to a partially mixed type, weakening stratification. This is mainly a transitional period. However the months of October and November shows some stratification characteristics, this is because the fresh water efflux has not ceased completely and bund being still open contributes fresh water discharge of the 4 rivers from the south and Muvatupuzha near Panavally. Sea water starts to dominate by December, stratification being less apparent at the mouth, the season merging into the homogeneous conditions of the pre monsoon. But stratification occurred in December in the stations away from the mouth since salinity incursion was not strong enough to completely mask the effect of fresh water flow. During the pre-monsoon, the river discharge is minimum and seawater influence is maximum upstream, the estuary is well-mixed and homogeneity exists in the water column. Salinity values go as high as 34 and no appreciable difference occurs between high tide and low tide. Salinity steadily advances and registers the maximum value for the season of 34 at barmouth and 15 at Thannermukkam (Figure.5). Table 3 shows the varying surface bottom salinity and also the stratification parameter for fort Kochi (barmouth) seasonally. Generally higher values of stratification parameters are found during monsoon months. The highest value (1.87) of stratification parameter is found in July and the lowest (0.031) in April, 2008-09.

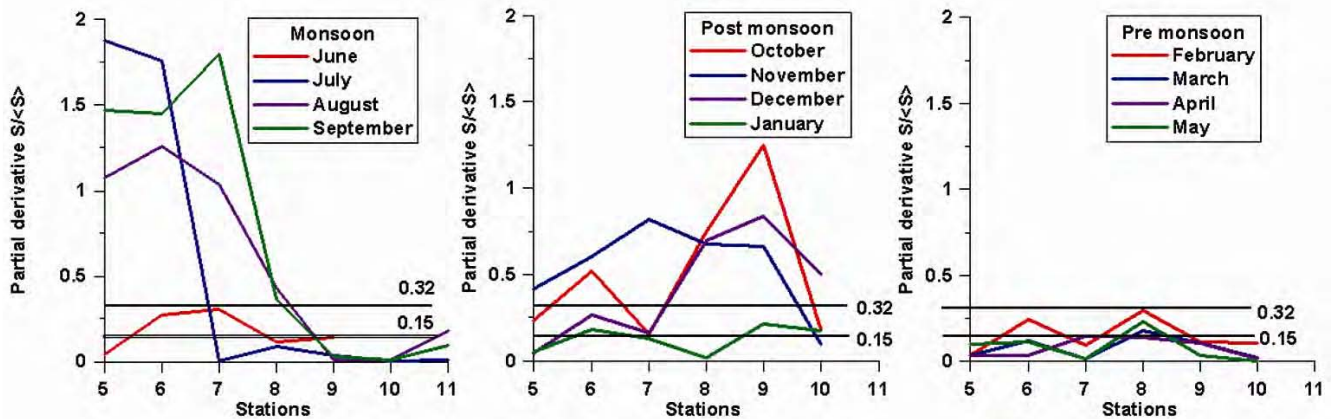


Fig. 5—Salinity stratification plot for each season with  $\partial S / \langle S \rangle < 0.15$  indicating well mixed,  $0.15 < \partial S / \langle S \rangle < 0.32$  as partially mixed and  $\partial S / \langle S \rangle > 0.32$  as stratified estuary condition.



Table 3—Surface and bottom salinity and stratification parameters at Cochin inlet

Months (2008-09)	Surface salinity	Bottom salinity	$\delta S / \langle S \rangle$
June	33.0263	34.4516	0.041
July	1.9628	31.5513	1.876
August	2.431	27.7574	1.076
September	3.1282	32.5841	1.471
October	26.3821	33.9952	0.237
November	19.8989	31.75	0.416
December	29.2661	30.5443	0.042
January	31.3437	32.9572	0.051
February	30.8466	31.8513	0.033
March	32.4522	33.5677	0.033
April	32.267	33.3106	0.031
May	30.9312	34.2009	0.097

### Conclusion

The value of Van der Burgh's coefficient, K, calculated from the field data is 0.26 and hence indicates that the up-estuary salt transport is entirely dominated by tide-driven mixing near the mouth. Darcy-Weisbach friction factor f is calculated and the value is 0.008 for the Cochin estuary. Longitudinal salinity profile shows great correlation between river discharge, tidal amplitude and salinity intrusion length. Salt intrusion length is the least when river discharge during monsoon is maximum while during post and pre monsoon, the fresh water inflow decreases leading to an increase in surface salinity and salt intrusion length. Salinity intrusion in the Cochin estuary is studied using four empirical models and the results are compared with the observed data. By comparison of the obtained results from the empirical model and field data, it is found that the model of by Van der Burgh (1972) gives the most accurate results for predicting the salinity intrusion in the Cochin estuary.

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