Applicability of Salinity Stratification Estimation by New Bulk Model for Two Choked Coastal Lagoons in Sri Lanka

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Abstract: Two coastal lagoons in Sri Lanka, Koggala and Rekawa were studied to examine the applicability of a new bulk model to estimate relative stratification of choked lagoons. Two lagoons selected for the study represent two subcategories of choked coastal lagoons; permanently open choked coastal lagoons (POCCLs) and intermittently open and closed choked coastal lagoons (IOCCCLs). Application results for Koggala Lagoon demonstrate that δS/S estimation capability of the new bulk model is superior to Fischer’s model, suggesting that the new bulk model would be suitable to apply for POCCLs. On the other hand, when the model was applied to Rekawa Lagoon, it demonstrated poor δS/S estimation capability compared to the POCCL case. This might have caused due to the variation in the time scale required for the IOCCCLs to reach the quasi equivalent state related to mixing process as the quasi equivalent state assumption is trivial in RL derivation.

Keywords: Coastal lagoons, salinity stratification, Estuarine Richardson Number, wind induced mixing, Lagoon Richardson Number, Quasi-equivalent state

1. INTRODUCTION

Sustainable use of coastal lagoons in Sri Lanka is becoming essential as the lagoon environments are being rapidly and indiscriminately exploited by anthropogenic activities over the recent decade (IUCN, 2006). A comprehensive knowledge on the various aspects of coastal lagoons, including their physical process is a prerequisite for their sustainable use while preserving their naturalness. One such important physical process is the vertical mixing/stratification process and the level of stratification of coastal lagoons due to saline water intrusion. These can be crucial in determining the changes on the inherent nature of coastal lagoons as the vertical fluxes of water properties such as dissolved oxygen and nutrient elements depend on them (Simpson et al, 1990).

Simple bulk models could be useful for estimating the degree of stratification of coastal lagoons as they can be easily applied with minimum field requirements, unlike numerical models. These models become more useful in situations where there are no proper systems to monitor large number of hydrologic/riverine parameters on a regular basis, such as what is commonly experienced in coastal lagoons in Sri Lanka. Despite the controversies over the identification of coastal lagoons from estuaries, the number of coastal lagoons situated along the entire coast of Sri Lanka is estimated to
Coastal lagoons have been considered as a class of estuaries in many estuary classification schemes (Pritchard 1955; Hansen and Rattray, 1966) as they share the common characteristics such as having one or many restricted connections to the ocean and both of which the water circulation is driven by tides, river discharge, wind stress and heat balance. Yet, there is a considerable difference among the two types with respect to their geomorphologies which cause the two types to respond unequally. The typical planner view of a coastal plain estuary could be approximated by a funnel shape where the width of the estuary gradually decreases towards the upstream. On the other hand, typical planner view of a coastal lagoon would be a larger idealized rectangular or elliptic shape representing the main water body which connects with relatively smaller idealized rectangular shapes representing the lagoon mouth channels. However, this study focuses only on choked coastal lagoons which are one of the coastal lagoon types defined by Kjerfve (1989). According to Kjerfve, choked coastal lagoons are usually characterized by a long and narrow entrance channel where the ratio of the entrance channel cross section to surface area of the lagoon is small. Additionally, the long residence times, wind forcing and domination by the hydrologic/riverine cycles are some of the other characteristics of choked coastal lagoons (Kjerfve, 1989).

This paper aims on examining the applicability of a new bulk model (Perera et al, 2015) to estimate the relative stratification (δS/S) of choked coastal lagoons in Sri Lanka. The new bulk model used in this study is a modified version of Fisher’s model (Fischer, 1972) which was originally developed to estimate the relative stratification of estuaries. In this new version of the model, one of the bulk parameters included in Fisher’s model, the Estuarine Richardson Number (ReE) was replaced by a new bulk parameter, the Lagoon Richardson Number (RL) which is a theoretical enhancement of ReE. The significant difference between these two parameters ReE and RL is the inclusion of wind induced mixing energy in RL as such it would characterize the mixing process of choked coastal lagoons more ideally than ReE which was originally derived to characterize the mixing process of estuaries.

2. MATERIALS AND METHODS

2.1. Sites Description

Two coastal lagoons, Koggala Lagoon and Rekawa Lagoon (Figure 1), which are located along the southern coast of Sri Lanka, were selected for the case studies. These two lagoons were selected to represent two different subcategories of choked coastal lagoons, permanently open choked coastal lagoons (POCCLs) and intermittently open and closed choked coastal lagoons (IOCCCLs). Above two subcategories were formed based on the different natures of lagoon mouth conditions as the two names suggest. Out of the two lagoons Koggala Lagoon represents POCCLs while Rekawa Lagoon represents IOCCCLs.
2.1.1. Koggala Lagoon

Koggala Lagoon (5°58' 6" 20' N and 80°17' 80°22' E) is situated about 130 km south from the country's trade capital, Colombo. Prior to 1995, Koggala Lagoon was an IOCCCL with a freshwater ecosystem. Recent anthropogenic activities such as unplanned sand removal and structural intervention at the lagoon mouth area turned Koggala Lagoon to a POCCL, consequently shifting its ecosystem towards more saline conditions. This transformation has generated various environmental and socio-economic problems (Priyadarshana et al, 2007). Having a waterway area of 7.27 km², Koggala Lagoon is approximately 4.8 km long and 2 km wide. The hydro-catchment area of Koggala Lagoon is approximately 55 km² consisting mainly of homesteads and cultivated fields of paddy, coconut, tea, rubber and other plantations (Priyadarshana et al, 2007). The depth of the lagoon ranges from 1.0 to 3.7 m and it can vary according to seasonal changes in rainfall. Koggala Lagoon usually experiences a mean annual rainfall of between 2,000 and 2,500 mm (IUCN, 2006). Although it receives freshwater influx from several streams, more than 88% of the stream water is received to the lagoon through Warabokka stream. Lagoon’s main water body is enclosed with 14 islets and the largest one is located in the south east corner of the lagoon. Lagoon mouth channel that connects the lagoon with the sea is located at the south east corner. Two bridges that was built as a part of the Colombo-Matara main road and rail track lie across the lagoon mouth channel of which the approximate width closer to rail track bridge is about 100 m.

2.1.2. Rekawa Lagoon

Rekawa Lagoon (5°58'N and 80°47'E) is situated about 200 km south from the country’s trade capital, Colombo. The hydro-catchment area of Rekawa Lagoon is approximately 225 km² consisting of a large tract of paddy fields, mangrove and scrub forest and homestead (Rekawa special area management coordinating committee, 1996). Lagoon’s surface extends up to approximately 1 km in width at the widest point and about 3.3 km in length along the shoreline, claiming to a surface area of 2.38 km² (Priyadarshana & Aseada, 2006). Kirama oya stream which connects with the lagoon mouth channel 0.7 km from the sea has been the main inflow tributary of the lagoon, especially during the mouth closed phase of the lagoon. Additionally, the lagoon receives freshwater from another inflow tributary which connects at downstream end of the lagoon’s main water body from the landward side and operates mostly in rainy season. This significant positioning of inflow tributaries together with relatively deep 2 km long meandering lagoon mouth channel makes Rekawa Lagoon a unique coastal water body. Although Rekawa Lagoon claims to a relatively larger catchment area, the numerous irrigation structures constructed along the inflow tributaries of Rekawa Lagoon has been significantly reducing the freshwater flow into the lagoon (Rekawa special area management coordinating committee, 1996). Rekawa Lagoon mouth is periodically closed, especially in dry season, as the winds and constant waves on the shoreline give rise to dispositional sand dunes along the coast and occasionally opened in rainy season naturally or artificially by local community to prevent flooding when higher amount of rainfall is received to the catchment area. The water depth of the lagoon can vary depending on the seasonal variations in rainfall as well as the open or close state of the lagoon mouth. Kapuhenwala causeway constructed across the lagoon mouth channel in 1984 has been drastically altering the natural rhythm of the lagoon as it impedes the water circulation of the lagoon (Rekawa special area management coordinating committee, 1996).

2.2. Field Observations

Field observations were conducted to investigate salinity stratification characteristics of the two lagoons during the time period starting from November 2011 to February 2013 under different seasonal, tidal and mouth conditions (Table 1).

Vertical profiles of salinity, dissolved oxygen, water temperature and flow velocity were measured with 0.5 m vertical intervals at several points covering all the key parts of the lagoons, lagoon mouths, main water bodies and main inflow tributaries. However in this study, the data collected at the selected main representative survey point of the central parts of the lagoons are presented. The selected survey point to represent the central part of Koggala Lagoon was L-1 while it was L-2 for all the cases of Rekawa Lagoon, except for the case named R21May12DC where the data collected at L-3 point was
used (see Table 1). A water quality measuring equipment (multi probe) YSI Model 55 and KENEK VP 100 flow meter were used to measure the water quality parameters and flow velocity, respectively.

Table 1 Survey timing and conditions with corresponding survey case names

<table>
<thead>
<tr>
<th>Lagoon</th>
<th>Season</th>
<th>Mouth</th>
<th>Timing</th>
<th>Case Name</th>
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<td>Koggala</td>
<td>Rainy</td>
<td>Open</td>
<td>22Nov2011</td>
<td>K22Nov11RO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open</td>
<td>30Nov2012</td>
<td>K30Nov12RO</td>
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<tr>
<td></td>
<td></td>
<td>Open</td>
<td>15Sep2012</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Open</td>
<td>15Oct2012</td>
<td>K15Oct12RO</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>Open</td>
<td>16Mar2012</td>
<td>K16Mar12DO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open</td>
<td>14Feb2013</td>
<td>K14Feb13DO</td>
</tr>
<tr>
<td>Rekawa</td>
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<td>Open</td>
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<td>R21Oct12RO</td>
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<td>Close</td>
<td>17Mar2012</td>
<td>R17Mar12DC</td>
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<tr>
<td></td>
<td></td>
<td>Close</td>
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<td>R21May12DC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Close</td>
<td>27Jan2013</td>
<td>R27Jan13DC</td>
</tr>
</tbody>
</table>

2.3. Application of the New Bulk Model

Fischer’s model uses two bulk parameters which characterize a typical estuary to estimate its relative stratification ($\delta S/S$; the ratio of surface and bottom salinity difference to mean salinity of the considered cross section). Those two bulk parameters are $R_E$ and the Densimetric Froude Number ($F_m$) (Hansen & Rattray, 1966) which were defined as:

$$R_E = \frac{\Delta \rho / \rho}{U_t^3}$$

(1)

$$F_m = \frac{Q / \rho g d}{U_t^3}$$

(2)

where $\Delta \rho$ is the density difference between river inflow ($\rho_i$) and sea water ($\rho_s$), $g$ is the acceleration of gravity, $Q_i$ is freshwater inflow rate, $U_t$ is the r.m.s tidal velocity, $b$ is the width and $d$ is the depth of the estuary. Here, $R_E$ specifically characterizes the balance between the two energy contributions for the mixing/stratification process of estuaries (the potential energy input by the tributaries and the kinetic energy input by the tide during a tidal period) while $F_m$ determines the magnitude of the vertical circulation (Fischer, 1972). Considering the differences in the energy contributions for mixing process of estuaries and coastal lagoons, Perera et al (2015) replaced $R_E$ from a new bulk parameter, $R_L$, and used it with $F_m$ to estimate $\delta S/S$ for POCCL. In addition to the two energies considered in $R_E$, the energy input by the wind force is also constituted in $R_L$ as expressed in the following equation.

$$R_L = \frac{\Delta \rho Q a_{ls}}{\rho_w \rho_s (b_M d_M) U_t^3 + 4C_D b_m \rho_w \rho_s (b_L d_L) U_t^3}$$

(3)

where $Q$ is the inflow rate of the stream water along with the surface runoff from the catchment area of the lagoon, $C_D$ is the drag coefficient, $\rho_w$ is the density of water at the mean temperature of the lagoon, $\rho_s$ is the air density, $U_L$ is the wind speed at 10 m above the water surface. $b_M$, $d_M$, $b_L$ and $d_L$ are the mean width and mean depth of the lagoon mouth and lagoon, respectively. Additionally, $d_{ls}$ is the theoretical effective surface depth of the lagoon which is calculated using 99% of the flushing time of the lagoon ($T_f$), lagoon surface area ($A_L$) and $Q_i$, according to the following equation;

$$d_{ls} = (Q T_f / A_L)$$

(4)

The new bulk model with the two bulk parameters $R_L$ and $F_m$ is applied to Koggala and Rekawa Lagoons in order to examine its applicability to choked coastal lagoons with two different lagoon mouth characteristics. The monthly mean inflow rate from the stream and catchment of Koggala Lagoon was
used as $Q_i$ for calculating the bulk parameters included in the model. When calculating $Q$ values a linear relationship was assumed with the monthly precipitation (Gunaratne et al, 2010a) (Figure 2.) Similarly, the mean monthly inflow rate from the tributaries were used as $Q_i$ for Rekawa Lagoon which were calculated assuming a linear relationship with monthly precipitation and mean monthly surface runoff rates estimated by Gunaratne et al (2010b). The water densities corresponding to each survey were calculated according to McCutcheon et al (1993) by using observed salinity and temperature data. Furthermore, the entrance width and the mean depth of the lagoon mouth channels were used as parameters $b_M$ and $d_M$, respectively. Moreover, $1.3 \times 10^{-3}$ was used as the value of $C_D$ which is recommended by Fischer et al (1979) for most of the engineering calculations of the same kind. The corresponding mean monthly inflow rate of the tributaries was divided by the mean cross section of Kirama oya river to calculate the $U_t$ values for mouth closed phase of Rekawa Lagoon. This calculation should be reasonable since Kirama oya stream acts as the main inflow tributary during the dry season while the functioning of other tributaries cease due to lack of rainfall. Additionally, it may be reasonable to not consider Kirama oya stream as an inflow tributary during the mouth open phase as it connects with the lagoon mouth channel at the downstream end, much closer to lagoon mouth. The wind speed data required for the calculation of $R_{IL}$ for Koggala and Rekawa lagoons were collected from Galle and Hambantota Meteorological stations, respectively.

![Figure 2 Monthly rainfall (Galle and Bata Ata-block2 rain gauge stations for Koggala and Rekawa Lagoons, Department of Meteorology, Sri Lanka) and monthly inflow rate from the stream and catchment of lagoons for the period from January, 2011 to February, 2013 with survey timing (Black color arrows; surveys conducted in rainy season, white colour arrows; surveys conducted in dry season).](image)

### RESULTS

#### 3.1 Koggala Lagoon (POCCL)

Figure 3 shows a comparison of the Fischer model and new bulk model application to Koggala Lagoon. Results demonstrate that $\delta S/S$ estimating capability is improved in the new bulk model application with the introduction of $R_{IL}$, particularly for dry season. However, the deviation of the observed and estimated $\delta S/S$ values in rainy season (Figure 3; black and corresponding gray colour
plots) are not significantly reduced because the energy supplied by the wind for the mixing process is not remarkably large compared to the energy supplied by the inflow stream during rainy season. On the other hand, the deviation of observed and estimated $\delta S/S$ values in dry season (Figure 3; white and corresponding grey color plots) are significantly reduced as the magnitude of potential energy supplied by inflow stream is remarkably reduced so that the effect of the energy supplied by wind stress becomes significant during dry season. Thus, it would be safer to infer that the new bulk model would provide good estimation results of relative stratification for POCCLs than Fisher’s model for both seasons according to this case study.

3.2. Rekawa Lagoon (IOCCCL)

Figure 5 shows a comparison of the application results of Fischer model and new bulk model to Rekawa Lagoon. Although the new bulk model shows better estimation in rainy season (mouth open condition) the deviation of observed and estimated $\delta S/S$ results in dry season (mouth closed condition) are almost similar to the results obtained by applying Fischer’s model. Additionally, the estimated relative stratification status corresponding to the survey case name R21May12DC is completely different for the two models where the Fisher’s model estimates stratified condition and the new bulk model estimates more mixed condition while the actual salinity profile indicates partially stratified condition (see Figure 4). This contrasting result together with the large deviation in observed and estimated $\delta S/S$ values under mouth closed condition indicates that it is not safer to use any of these models to estimate relative stratification of IOCCCLs, particularly during the mouth closed phase (dry season). Thus, the cause of this problem should be common to both models. Going back to the basic assumptions considered in deriving the bulk parameters used in both models, suggests that the assumption which is most likely to have cause this problem would be the quasi-equivalent state assumption which is trivial in the derivation of $R_{iL}$ as well as $R_{iE}$.

Quasi-equivalent state of a lagoon can be altered with respect to different time scales depending on the significant variations in the dominant forcing factors such as wind, rainfall and tide etc. According to Furusato et al (2013) the quasi-equivalent state of POCCLs related to its mixing state would last throughout a season (several months) without changing remarkably though it can be changed quite regularly for IOCCCLs depending on the timescale related to the opening and closing event duration of the lagoon mouth. Thus, POCCLs such as Koggala Lagoon are inherent with longer time scales of
quasi-equivalent states related to the mixing process due to permanently open nature of the lagoon mouth and would show better estimation results when new bulk model is applied. On the other hand, when the new bulk model is applied to IOCCCLs such as Rekawa Lagoon, the estimation capability of the model could vary depending on the situation whether the IOCCCL is in quasi-equivalent state or not.

4. CONCLUSION

The new bulk model with $R_{iL}$ which characterize the mixing/stratification process of coastal lagoons was applied to Koggala and Rekawa Lagoons in order to examine its applicability to choked coastal lagoons in Sri Lanka. The new model provides better estimation results than Fischer’s model for Koggala Lagoon suggesting that the new model would be suitable to apply for POCCLs. However, when it is applied to Rekawa Lagoon the improvement of the estimation capability is quite low compared with the previous case. One of the probable causes for this problem would be the difference in the time scales required for IOCCCLs to reach its quasi equivalent state as it a trivial assumption in the derivation of $R_{iL}$. Thus, $R_{iL}$ should be further enhanced in order to apply for IOCCCLs by including a parameter to represent the time scale. However, the validity of this explanation together with the effectiveness and applicability of the proposed model to IOCCCLs and POCCLs needs to be further verified by applying it to more choked coastal lagoons in the future.
5. ACKNOWLEDGMENTS

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6. REFERENCES


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