The Current Status of Density Stratification of Koggala Lagoon

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Abstract: *A field observation was conducted on 22nd November 2011 to estimate the present state of density stratification of Koggala lagoon. Vertical variation of salinity, water temperature and dissolved oxygen were measured with neap and ebb. The same measurements were taken from inflow streams. The observations indicate that main water body of the lagoon is salinity stratified despite the strong or partial mixing at the mouth. Particularly, strong saline stratification is prominent in the deep central part of the lagoon. Firstly, the current hydraulic state and then bulk parameter of Koggala lagoon is analysed. The relationship between the mixing state and the values of parameters of Koggala lagoon agree with Fisher's plot. The effects of modification of lagoon mouth are discussed based on these parameters. Temporal and spatial complexities of lagoon mouth affect transport and mixing of saline water and intrusion into the lagoon. In future, a modified bulk parameter will be needed for better understanding of stratification behaviour of the Koggala lagoon.*

Keywords: *Koggala lagoon, salinity, density stratification, lagoon mouth, estuary Richardson number.*

1. INTRODUCTION

Density stratification in coastal lagoons caused by saline water intrusion is one of the important factors determining various physical, chemical, and ecological processes occurred in the water body. The system of Lagoon is likely to consist of various elements such as catchment area, ocean conditions and lagoon mouth characteristics. The effects of these various factors surrounding a lagoon would influence mixing processes. Those various phenomena occurred in the lagoon affect social and economic activities around it. Conversely, various impacts by humans influence the coastal lagoon. Therefore, density stratification is an important issue to be considered for proper management of a lagoon.

Koggala lagoon is one of the forty-three coastal lagoons encircling the coastal belt of Sri Lanka. Extraction of substantial amount of sand from the sand bar at the mouth leads to a strong erosion. To prevent that a rock arm has been constructed causing lagoon mouth open all the time. The salinity level of this lagoon has increased due to large amount of seawater intrusion. These physico-chemical changes lead various problems such as socio-economical problems as well as natural ecosystem degradation in and around the lagoon. Thus, countermeasure for this issue is required. Previous studies have pointed out the importance of lagoon mouth morphology for restoration of lagoon environment (Priyadarshana et al. 2007, Gayana et al. 2009, 2010). By using hydrological parameters, an improved lagoon salinity level will be obtained by a new rubble mounde structure proposed by the authors. With the modifications it is expected that the ecosystem and the water quality of the lagoon would reverse to a more freshwater-oriented system. However, generally human impact will cause various unexpected effects on water bodies particularly complex systems like lagoons.

Amarasekara et al. (2011) reported that catches of the green chromide after groyne construction markedly decrease because of increase in salinity level. Some studies about past salinity condition of Koggala lagoon have been done (Suneetha and Chandana 2006, Priyadarshana et al. 2007) However, salinity stratification of Koggala lagoon has not been surveyed. Therefore the objective of this study is to estimate current states of density stratification of Koggala lagoon. This preliminary study would be useful for future research and management of Koggala lagoon as well as other coastal lagoons in Sri Lanka.

2. MATRERIALS AND METHODS

2.1. Study sites

Koggala lagoon is located on the southern coast of Sri Lanka (Fig. 1). Hydro-catchment at the lagoon outlet is about 55 km^2, of which about 15% is the lagoon area. It is estimated to have further 15% of paddy fields or low lying areas (Priyadarshana et al., 2007). The water depth ranges from 1.0 to 3.7 m (IWMI, 2006). The coastal lagoon is essentially fed by rain and a number of streams connected to it. Warabokka stream (Koggala-oya) enters the lagoon from the north-west. Kerena anicut was built combining both the streams named as Mudiyansege stream and Thithagalla stream. Heen stream contributes slightly to the water inflow. Apart from these three streams, Kahanda stream, Gurukanda stream, and Thelambu stream were contributors for inflow but presently these three are abandoned and have become marsh lands with almost zero water flow due to overgrown vegetation. The only outlet of the lagoon is Pol-oya located at the southeast corner; a narrow 300 m long canal connects the lagoon with the sea.

2.2. Field observations

Field observations to estimate present states of density stratification of Koggala lagoon were conducted (Table 1).

Figure 1 shows the survey points on Koggala lagoon. Generally vertical density stratification of the lagoon differs depending not only on temporal conditions but also on spatial conditions. In addition, river-inflow and intrusion of saline water affects on the stratification through the lagoon mouth from sea. Considering such lagoon characteristics, survey points were decided as shown in Figure 1.Two main river-inflows were selected as observation sites; Warabokka and Heen streams. The density profiles were measured both longitudinally and vertically from Warabokka to the lagoon mouth through the lagoon water body. The same measurements were also taken in specific locations in the lagoon mouth area. Table 1 shows the detailed conditions of each survey point.

A water quality measuring equipment (multi probe) YSI Model 55 was used to obtain vertical profiles of temperature, salinity, and dissolved oxygen (DO) (approx. 0.5 m intervals).

Table 1 Outlines of survey points

Group	Stations	Distance [km]*1	Survey time	Depth [m]	z_s[m]*2
Ocean	O−1	−	16:10	−	−
	O−2	−	16:20	−	−
Mouth	M−1	0	15:40	1	−
	M−2	0.1	11:00	2.5	−
	M−3	0.35	11:15	1.5	1.2
	M−4	0.6	11:28	1.5	1.3
Lagoon	L−1	1.2	11:45	3.5	1.3
	L−2	1.7	12:15	1.5	0.9
	L−3	2.3	12:55	1.5	0.8
	L−3’	2.4	15:10	1.5	−
Inflow stream	W−1	−	17:30	2	−
	H−1	−	17:50	−	−
	K−1	−	18:10	−	−

*1 Distance from mouth end to upstream
*2 Transparency

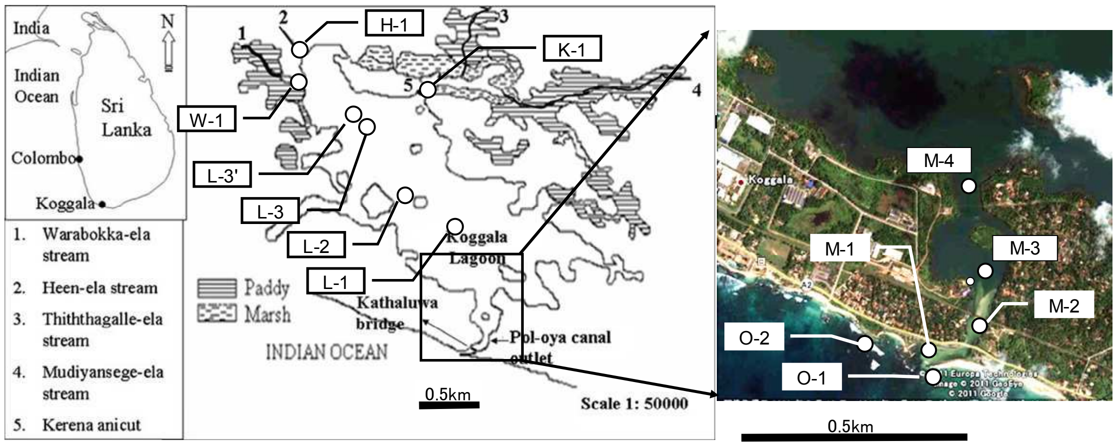

Figure 1 Koggala lagoon and survey points

Field observations were conducted on 22 November 2011. The lagoon receives fairly high rainfall from southwest monsoon from May to September. Although the survey was done on early northwest monsoon season (from October to February), it had already started raining before the survey day. Tidal condition of survey day was neap. The survey from the mouth area to the upstream station was done during 11 am to 5 pm period. Detailed time for each point is shown in Table 2.

3. RESULTS AND DISCUSSION

3.1. Density stratification of Koggala lagoon

In this section, the characteristics of density stratification and other related phenomena are described for each area.

3.1.1. Lagoon mouth area

Figure 2 shows the vertical profiles of each measured parameter of the mouth area. These measurements were made at the late flood tidal periods. The salinity level in the mouth area was low compared to that of the sea and it ranged from 10 to 20 ppt. Because the vertical nonuniformity increases at upstream and the lagoon mouth area is a transient zone which is influenced from strong mixing to partial mixing. Water temperature and DO exhibit similar vertical trends. M-4 station only shows the difference in results between the surface and the bottom. These results show that the bottom layer of M-4 remained without mixing for a certain period.

3.1.2. Koggala Lagoon

Figure 3 shows the vertical profiles of some parameters measured in Koggala lagoon. For comparison, the measured values at the upstream end of the mouth area (M-4) and the representative inflow stream (W-1) are also shown. The vertical profile of salinity shows similar trend for each point. Salinity level of the surface was about 10 ppt. For all points below 1m depth, halocline was confirmed. At the centre area of the deep layer, a high salinity bottom layer exists. Water temperature and DO exhibit similar trend. Below 1m depth high water temperature and relatively low DO concentration were confirmed. This means that deep layer water parcels remain without strong mixing with surface layer for a certain period.

The salinity level of the lagoon surface is similar to that of the inflow stream except for the stream surface. Brackish water from some streams through out the year would be the main source of lagoon surface water parcels.

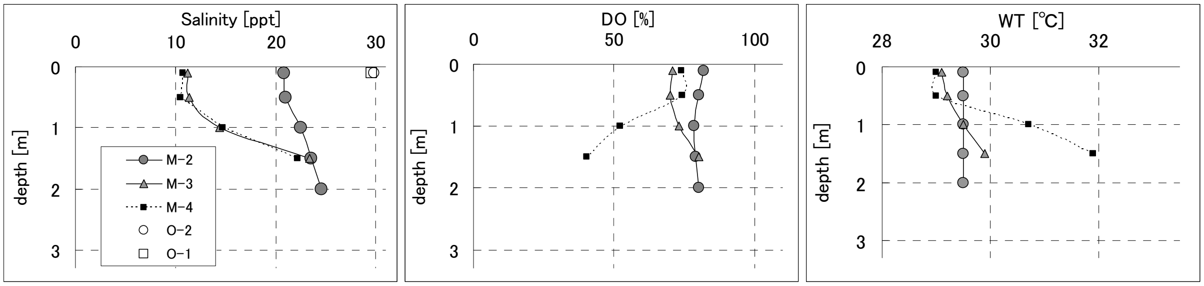

Figure 2 Vertical profiles of each measured parameter in the lagoon mouth area. The symbols in each legends mean survey stations (see Table 1).

3.1.3. Inflow streams

As shown in Figure 4, the inflow streams exhibit stratification of salinity and water temperature. The range of surface salinity was 0.8〜4.4ppt depending on each stream. On the other hand, below the surface depth, the same salinity level was measured for each measured station in the streams. The brackish water supply from inflow streams corresponds to the effects of permanently open-mouth to Koggala lagoon as reported by Priyadarshana et al. (2007). The important point is salinity stratification of inflow streams. Raining before this survey is to be the reason to have fresh water layer in the stream. However, the low level of salinity in the surface water body which is less than 10 ppt was not found in the lagoon. This means probably that surface low salinity water of inflow stream would be mixed as surface plumes by any mixing factor such as shear stress by wind. However, there are no detailed evidences for such explanation. This is also one of future problems unresolved.

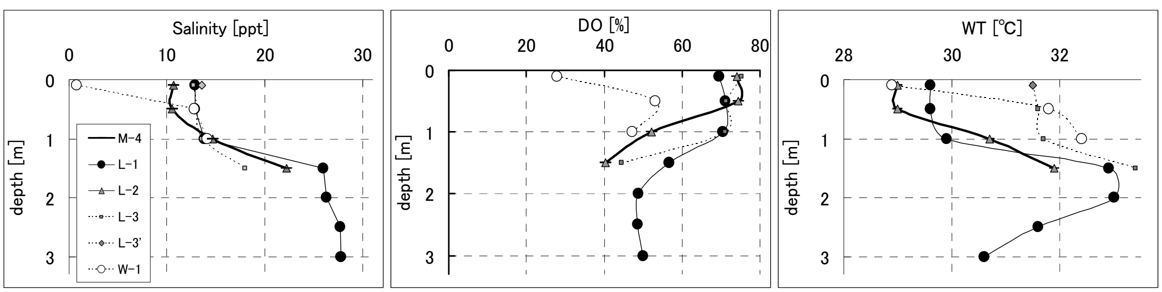

Figure 3 Vertical profiles of each parameter of Koggala lagoon.

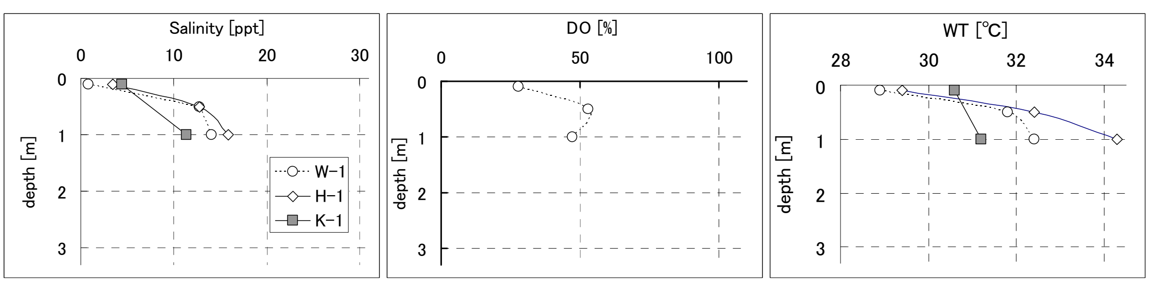

Figure 4 Observation results of inflow stream

3.2. The current states of mixing conditions and related phenomena of Koggala lagoon

Based on the field observation results described above, the characteristics of hydraulic and related phenomena in Koggala lagoon can be estimated as follows (Figure 5).

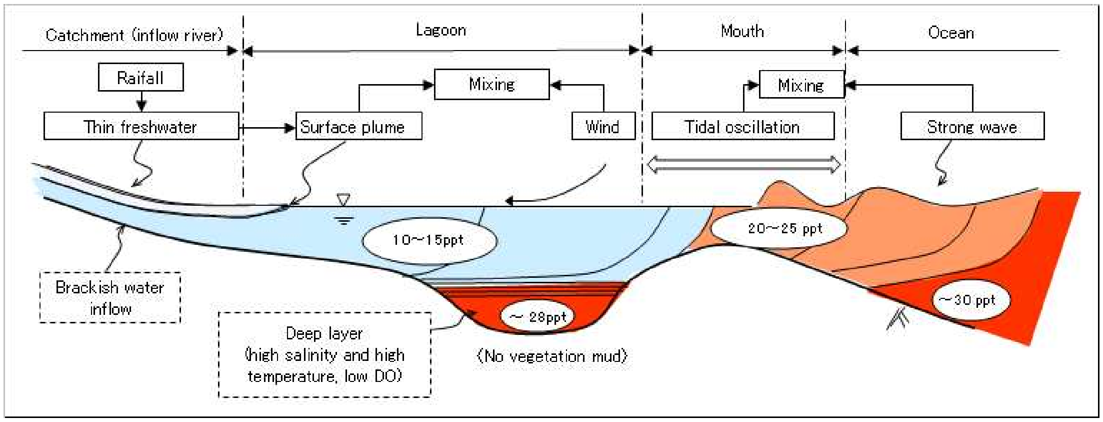

Figure 5 Synoptic representation of density stratification and related phenomena of Koggala lagoon of neap and high water. Lines in water bodies represent isohalines. Values in circles are salinity level.

Firstly in the lagoon mouth area, high saline brackish water parcels longitudinally oscillate as strong mixing state. However, in the upstream area of the mouth, mixing state transits to partial mixing. High salinity in deep water exists in the centre area of the lagoon. Because the survey was done at neap tidal condition, salinity level of this area is possibly higher than the level we measured in more strong tidal conditions such as in spring tide.

Secondly, internal water body of the lagoon consists of brackish surface layer with half salinity level of sea and high salinity warm deep layer. The depth of surface layer is about 1m and halocline exists up to 1.5m depth. Below this depth, the deep layer exists. Water temperature of the deep layer is higher than that of sea water (~32℃). Considering that the transparency is higher than 1m, the deep layer suffers solar radiation. Thus, the water parcel remained for a certain period after entering from sea to the lagoon in the strong tide condition before the measurements were taken. Generally, high temperature makes saturation concentration of DO lower level. Moreover, DO consumption rate is high at high temperature. Therefore, the deep layer has the potential of making anoxic condition. Submerged plants grown in the lagoon bottom were disappeared after removal of sand bar (Priyadarshana et al. 2007). This condition will lead more rapid decrease in DO concentration.

Finally, thin surface freshwater parcels of inflow streams could not be measured in the lagoon and even in the upstream station (L-3'). This means that surface vertical or horizontal mixing by wind stress can not be neglected in Koggala lagoon.

3.3. Bulk parameter analysis and estimation of future stratification states of Koggala lagoon

Salinity stratification occurred in coastal lagoons is influenced by various and complex factors. However, for engineering point of view, simple bulk parameters are useful for estimation of the effects of human intervention on natural phenomenon. In this section, classical bulk parameters related to estuary mixing are applied to the present states of Koggala lagoon. Using the parameters, the effects of lagoon mouth modification on future stratification was discussed.

1.1.1. Parameter description

Generally, salinity stratification of estuaries including coastal lagoons can be estimated by bulk parameters such as estuary Richardson number (R_{iE}) (Fisher 1972) and densimetric Froude number (F_m) (Hansen and Rattray 1966).

$$Ri_E = \frac{(\Delta\rho/\rho)\, g\,(Qf/b)}{U^3} \quad (1)$$

$$Fm = \frac{Qf/bd}{\sqrt{gd\,\Delta\rho/\rho}} \quad (2)$$

Where $\Delta\rho$ is the density difference between inflow freshwater and sea water, g is the acceleration of gravity, Qf is the discharge of fresh water into the estuary from tributaries, b is the width, U is the r.m.s. tidal velocity, d is the depth. Ri_E expresses the likelihood that a buoyant discharge mixes vertically in a river flow. If Ri_E is very small it is expected that the estuary to be well mixed. From observations of real estuaries, the transition from a well mixed to a strongly stratified estuary occurs in the range of $0.08 < Ri_E < 0.8$ (Fisher 1972). In addition to above relationship, large Fm makes δS (salinity difference between surface and bottom) increase.

3.3.1. Application of bulk parameters to Koggala lagoon

These parameters were estimated by using both field observation data and previous data on Koggala lagoon (Gunaratne et al. 2010, 2011). Table 2 shows these values. The values of bulk parameter are estimated as Ri_E 2.42, Fm 0.15 respectively. The values of $\delta S/S$, from both the observed and estimated data, were plotted according to original Fisher's diagram. As shown in Figure 6, the condition of present salinity stratification of Koggala lagoon agrees with the bulk parameter estimation. However, similar to the original diagram, there is a certain difference between the observed and estimated $\delta S/S$. These bulk parameters are concluded to be useful for roughly estimating the salinity stratification of Koggala lagoon from small number parameters.

Table 2 Values used for calculation of the Ri_E, Fm and $\delta S/S$

Parameters		Values	Unit	Description
Qf	Freshwater inflow discharge	9.478[*1]	m^3/s	Mean annual total stream water inflow
$\Delta\rho/\rho$	Density difference between inflow water from catchment and ocean	0.018	-	Estimated from observed salinity and water temperature obtained by this survey
b	Width of mouth	85[*2]	m	Existing lagoon mouth width
d	Maximum depth of mouth	1.0	m	Existing lagoon mouth topography
U	r. m. s. tidal velosity	0.2	m/s	Observed value at mouth end[*2]

[*1] Gunaratne et al. (2010) Table 3
[*2] Gunaratne et al. (2011b)

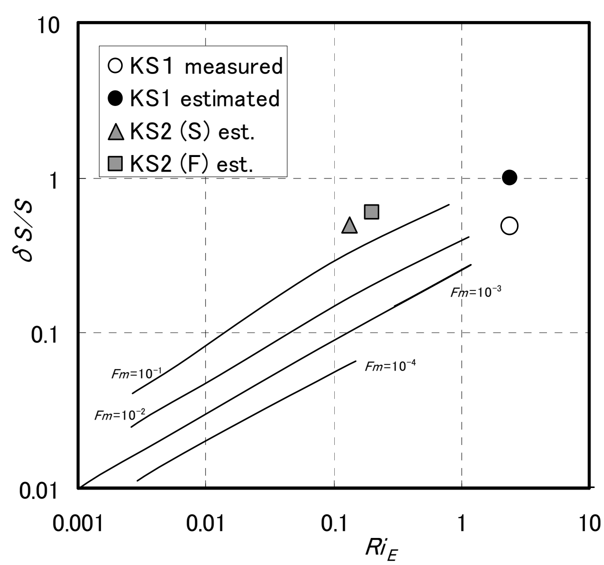

Figure 6 Present and future conditions of Koggala lagoon in Fisher diagram. ○, measured salinity difference;●, ▲ and ■, estimated value based on Ri_E and Fm

3.3.2. Problems of applying Fisher's model to a choked coastal lagoon

Fisher's model is directed to wide range estuaries including different types of water body such as river mouth, coastal lagoon and fjord. Additionally, there are three types for coastal lagoon such as choked, restricted and leaky lagoon (Kjerfve & Magill 1989). Hume et al. (2007) reported that many factors such as climate, oceanic, riverine, and catchment property determine the physical and biological characteristics of estuaries. Particularly, for a choked lagoon, the topology of lagoon mouth is complex. Intermittent mouth closing will have any effect on the stratification. Such temporal and spatial complexities of lagoon mouth will affect transport and mixing of saline intrusion. In future, a modified bulk parameter including such coastal lagoon characteristics will be needed. Particularly, mixing in the mouth region should be investigated because of the importance for stratification occurred in chocked lagoon, such as Koggala lagoon.

3.3.3. Future viewpoint of research on Koggala lagoon for proper management

Gunaratne et al. (2011b) stated the possibility of improving salinity condition of Koggala lagoon by modifying the lagoon mouth (see scenario KS2 in Gunaratne et al. 2011b). Table 3 shows the anticipated hydrodynamic changes by improving the lagoon mouth (Gunaratne et al. 2011b). In the table, we added the calculated bulk parameters related to density stratification. For the calculation, two future conditions are assumed. One is only mouth modification (KS2(S)). The other is that inflow stream water quality becomes freshwater (KS2(F)). Figure 6 also shows the estimated *δS/S* from these parameters although the validation of applicability of the model to Koggala lagoon is not sufficient. There is a potential for remaining any stratified condition of Koggala lagoon (Figure 7).

Table 3 Comparison between hydrodymanic and mixing parameters of Koggala lagoon between the Scenarios[*0]

Parameters	KS1	KS2 (S)	KS2 (F)
B	85m[*1]	20m[*1]	
Fs[*2]	0.68[*1]	0.54[*1]	
$T_{50\%}$[*3] [h]	9 – 37 [*1]	12 – 72 [*1]	
EF[*4]	17 [*1]	40.77 [*1]	
Salinity of inflow stream [ppt]	12	12	1
R_{iE}	2.42	0.13	0.20
F_m	0.15	0.62	0.50

[*1] Gunaratne et al. (2011b)
[*2] Salting factor (Chubarenko et al. 2005)
[*3] Flushing half time (Gunaratne et al. (2011b)
[*4] Evacuation factor (Haines et al. 2006)
[*5] Salinity level of inflow for estimating inflow density, ρ

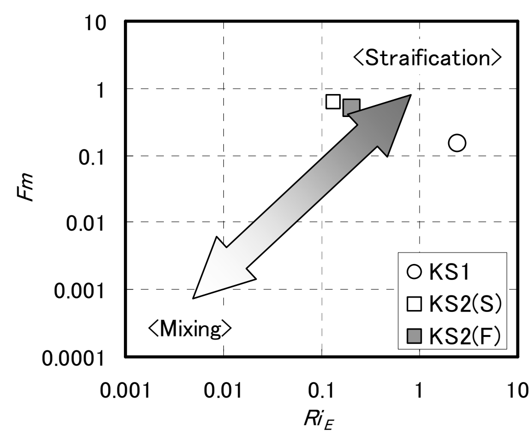

Figure 7 Bulk parameters of present and future of Koggala lagoon

Needless to say, returning the salinity level to past condition is important. However, in these processes, various unexpected phenomenon would occur. Becker et al. (2009) reported that fish-kill by anoxic conditions occurred by closed mouth in temperate coastal lagoon. As shown in Figure 5, one of the physio-chemical characteristics of Koggala lagoon is “high saline and high temperature bottom layer”. Generally, high water temperature leads low DO level because of low saturated DO concentration. Thus, if the decrease in exchange between the deep layer and oxic water parcels such as in surface layer or saline intrusion from sea occur, DO level will immediately become anoxic condition. It is not immediately evident whether such phenomenon occurs or not in the future. However, for proper future management of Koggala lagoon, the research focusing on density stratification will be needed. Furthermore, the knowledge about the relationship between the conditions of lagoon mouth and internal processes of lagoons likely density stratification will be needed for sustainable development of coastal areas in Sri Lanka.

4. ACKNOWLEDGMENTS

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