WATER BALANCE AND RENEWAL TIME OF REKAWA LAGOON, SRI LANKA; A RESTORATIVE APPROACH

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Abstract: Rekawa Lagoon is a chocked and shallow coastal water body located in the southern coast of Sri Lanka. It is relatively unusual in that the major freshwater input, Kirama-oya river connects through the constricted channel much closer to the inlet at seaward end. A causeway was constructed, around 700 m from the lagoon inlet to the inland, across the constricted channel with an effort to link a secluded Kapuhenwala village with the rest of the area which in turn greatly reduced the volume and speed of water entering and leaving the lagoon system. Construction of the causeway led to many environmental problems with poor flushing efficiency and hampering to and fro movement of the prawns in the lagoon. The aim of this study was to evaluate the present situation and propose alternative management scenarios for improvement of water flow and lagoon ecosystem. The implications of different development stages of the causeway were discussed in terms of field measurements supported by modeling to describe the water balance and the water renewal time. The alternative of modifying the existing causeway was proposed to increase the free water flow at the inlet that favors recruitment of juvenile shrimp species.

Keywords: Lagoon hydrology, Lagoon restoration; Shrimp fishery management

1 Introduction

Coastal lagoons are defined as shallow inland marine water bodies, usually oriented parallel to the coast, separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets (Phleger, 1969; Kjerfve and Magill, 1989). They are mainly important for fisheries and aquaculture in many areas of the world, since marine shrimp and fish species migrate towards the lagoons, which provide favorable conditions for feeding and shelter (Colombo, 1977). Many coastal lagoons have been affected over the decades by natural and mostly anthropogenic influences, including environmental degradation from hydrologic alterations (Tsihrintzis et al, 1996; Gunaratne et al, 2010b; Gunaratne et al, 2010c) and point and non-point sources of pollution (Miller et al., 1990). Physiochemical and biological parameters in a coastal lagoon may affect directly fish production and ecosystem dynamics (Corsi and Ardizzone, 1985) and these parameters are generally dependent on seawater circulation and water renewal time, in addition to inflowing freshwater and seawater quality (Tsihrintzis et al, 2007). Coastal lagoons are important for fisheries and extensive aquaculture, and contribute notably to the fishery economies in many countries. Sri Lankan coastline circles along about 1,585 km of sandy beaches, extensive lagoons, estuaries, mangroves, coastal marshes and dunes (Baldwin, 1991). In Sri Lanka many water bodies are usually named as lagoons that are really estuaries and Rekawa lagoon has been identified as a true lagoon (Baldwin, 1991).

The scope of this study is to present a comparative approach on hydrology and renewal time for different scenarios of inlet causeway changes, aiming at reaching better decisions with regards to lagoon restoration design and management actions for improvement of environmental conditions and shrimp fishery exploitation. Hydrology, including quantity, distribution and flow patterns, and quality of water, is possibly the most important factor affecting lagoon successful operation, management and/or restoration design. Several studies have been undertaken in this system over the last two decades (e.g.

Jayakody and Jayasinghe, 1992; Priyadarshana, 1998; Rathnaweera, 2005) but none investigates the changes in hydrology and flushing properties comprehensively. This study is performed through the analysis of recent meteorological, bathymetric, morphometric and tidal elevation data combined with mathematical models aiming at reaching better decisions with regard to design of the restoration interventions and management actions for improvement of environmental conditions and aquaculture.
The detail objectives of the work are 1) to determine the annual water balance of the lagoon; 2) to investigate the renewal time of the lagoon for different scenarios of inlet causeway changes; 3) to discuss the implications of the proposed scenario on the lagoon's shrimp fishery management. Annual water balance and renewal time were investigated for two or more scenarios of the lagoon and they are a) Before the construction of causeway or time period before year 1984 (Rekawa Scenario 1 - RS1); b) Existing situation or time period after year 2000 (Rekawa Scenario 2 – RS2) and c) Future scenario with respect to proposed box culvert introduction (Rekawa Scenario 3 – RS3)

2 Methodology

2.1. Study site description

Rekawa is located in Hambantota District in the Southern Province of Sri Lanka and it is 200 km from Colombo to the south. It is a comparatively small coastal lagoon, having connected to the sea with a 3 km narrow inland waterway (Figure 1). Rekawa lagoon is shallow with a depth of averaging 1.4 meters and the widest point is approximately 2.5 km (Jayakody and Jayasinghe, 1992). The water surface area of the lagoon is 2.4 km^2 (Priyadarshana, 1998). Most parts of the lagoon are encircled with a mangrove belt. Winds and constant waves on the shoreline give rise to dispositional sand dunes along the coast. Such accumulation results in periodic closure of the lagoon mouth to the sea as very little sand is supplied by river deposits. Kirama-oya river (Tangalu-oya river) that enters the lagoon at the sea ward end of the inlet canal is the main freshwater supply (Figure 1). Apart from the main freshwater inflow, there are two small freshwater streams function only in rainy season and provide surface runoff from the suburb. The total hydro-catchment of the lagoon outlet is about 225 km^2 (Priyadarshana, 1998). Rekawa Lagoon is a unique natural resource and one of the most significant aquatic habitats in southern Sri Lanka. Shrimp fishery is highly seasonal and extends from October to April of the following year (fishermen information). The most abundant shrimp specie in Rekawa lagoon and commercially most important shrimp species is *Penaeus indicus* (White shrimp).

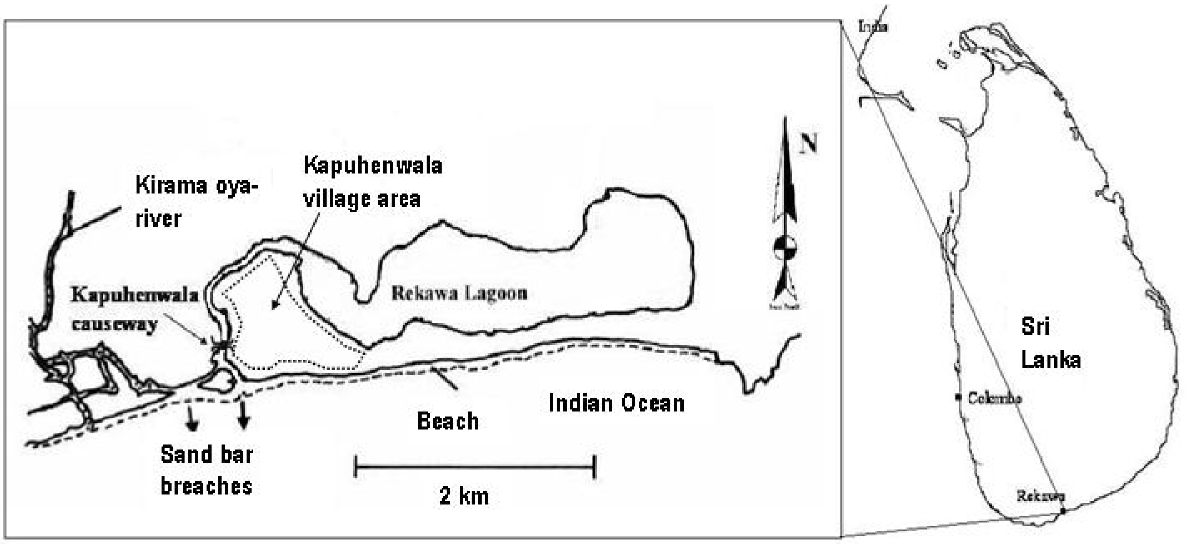

Figure 1: *Map of Rekawa Lagoon, Sri Lanka with the locations of major freshwater inflow (Kirama-oya river) and Kapuhewala causeway*

2.2 Chronology of causeway development process

The Road Development Authority of Tangalle in1984 built a causeway called Kapuhenwela across the outlet canal; around 700 m from the lagoon mouth to the inland (Rathnaweera, 2005) (Fig.1). Water passes under the causeway through twenty three, 23 cm diameter pipes which greatly reduce the volume and speed of water entering and leaving the lagoon system. This causeway has prevented flushing of the lagoon by natural water flow, causing continues sedimentation in the lagoon. In 1999 a bridge of 6.2m in length was constructed in place of the part of the causeway in order to improve free water flow. After the Indian Ocean Tsunami in 2004, minor damage inflicted on the causeway and it was renovated and replaced with 8 cylindrical culverts with an average diameter of 79 cm in 2005. This modification remains to be changed until today in 2010(Fig. 2). Causeway itself and its modifications provoked concern over local resource users and environmentalists as the lagoon hydrology, salinity and there by the ecology showed drastic changes and variations. Figure 3 is a schematic representation of channel cross sections at the causeway before and after the construction of the causeway. Before the construction of causeway, effective channel cross section was $87m^2$ and it reduced upto $25m^2$ with the introduction of existing causeway structure with the bridge and it's a drop of 71% of effective channel cross section.

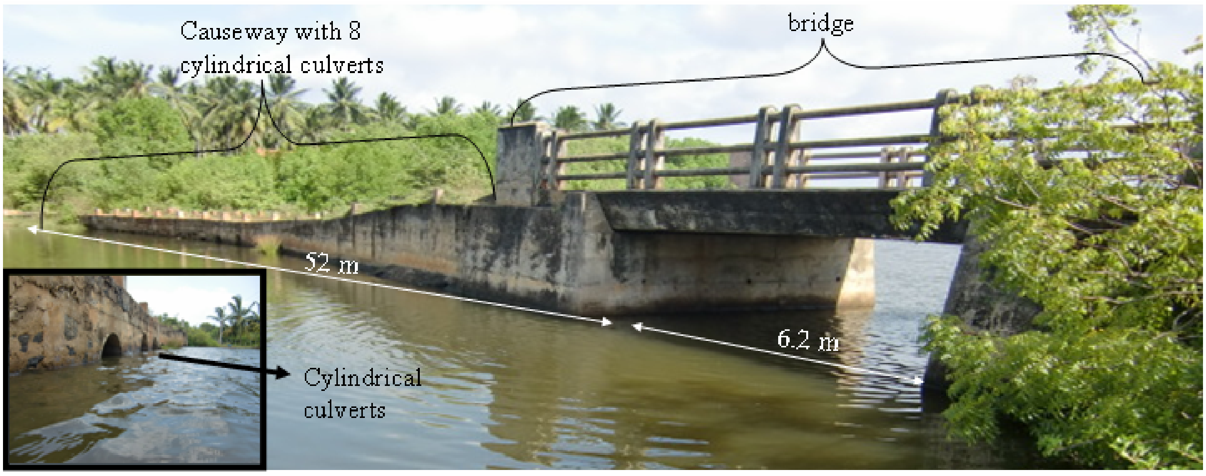

Fig. 2: *Existing situation of the causeway with 8 cylindrical culverts and the partial bridge at Kapuhenwala, Rekawa Lagoon*

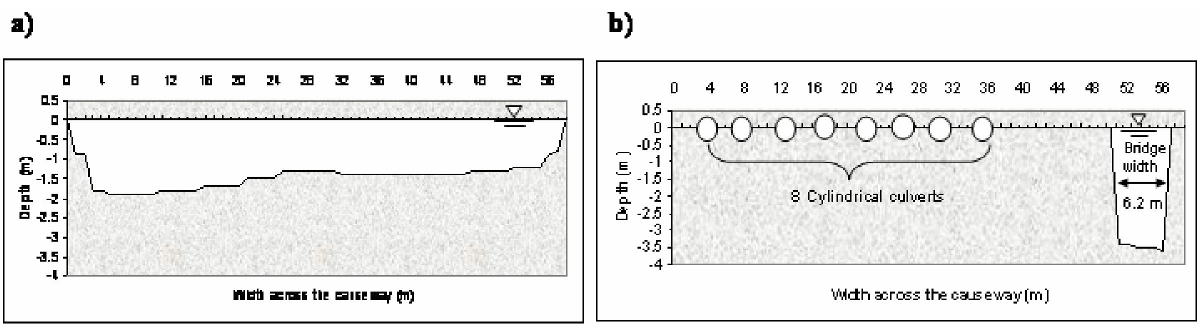

Figure 3: *Schematic representation of a) channel cross section at the causeway before the construction of causeway (Before 1984); b) channel cross section at the causeway after the construction of causeway and the bridge (After 2005)*

2.3 An Engineering solution

To improve the flushing efficiency it is essential to create a modification where ebb flow is dominant, which will also increase the amount of seawater entering the lagoon. An ideal engineering solution would be a complete bridge across the channel instead of the causeway with the partial bridge. This improves the free water flow which in turn increases the flushing efficiency which is poor in existing situation. Further, a complete bridge will have no adverse impacts on the adjoining banks or to the lagoon itself. However, though this option is technically highly feasible and capital costs are well-above the long term intended benefits.

Therefore, a relatively 'soft' solution is proposed in this report which is based on the concept of expanding the existing culvert cross sections. Box culverts would be introduced instead of existing cylindrical culverts.

An engineering solution was proposed with a redesign of existing causeway structure with more room for freeware flow introducing box culverts (Fig. 4). With the modification, effective channel cross section is expanded introducing 10 box culverts, each with 2m X 2m cross sectional dimensions.

The effectiveness of the solution was determined after the comprehensive study of the water balance and renewal time.

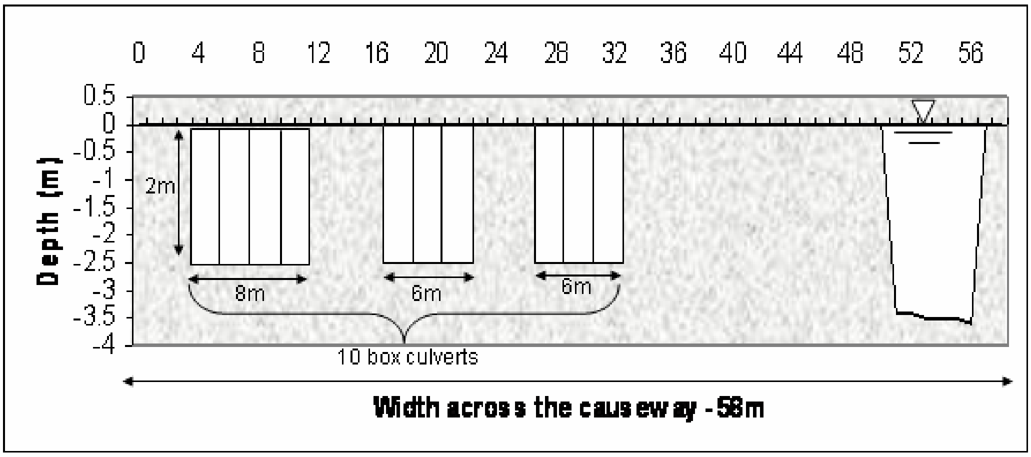

Figure 4: *Schematic representation of proposed modifications to the causeway with 10 box culverts each of 2mx2m replacing existing 8 cylindrical culverts. Box culverts are placed 0.5m below of the causeway top surface.*

2.4 Water Balance

The net water balance contributors for Rekawa lagoon for two scenarios (RS1 and RS2) were analyzed, in order to investigate the order of magnitude of the hydrologic processes responsible for maintaining steady-state conditions. This methodology has also been described by LOICZ Biogeochemical Modeling Guidelines (Gordon et al., 1996) for the application of simple budget models in coastal water bodies. These budget models are generally defined as mass balance calculations of specific variables (water, salt, sediment, carbon, nitrogen, phosphorus, etc.) for a defined geographical area and time period. Thus, the net water balance can be written as:

$$\frac{\Delta V}{\Delta t} = Q_P + Q_E + Q_G + Q_R + Q_O \qquad (1)$$

where V is the lagoon water volume (m^3), Q_P is mean monthly precipitation rate (m^{3}s^{-1}), calculated as the sum of products of daily rainfall depths times the lagoon surface area, Q_E is mean monthly evaporation rate (m^{3}s^{-1}), computed as the sum of the products of daily evaporation depth times the lagoon surface area. Mean monthly precipitation and evaporation data for past 10 years at Bataatha and Angunakolapelessa stations respectively were used for calculations (DOMSL, 2010). Q_G represents the groundwater inflow into the lagoon, which should be at least an order of magnitude lower than the other parameters, thus it can be ignored, since no measured data were available. However, inclusion of real data would probably slightly modify the water balance. The term Q_R represents the surface runoff discharge rate (m^{3}s^{-1}) from the surrounding drainage basin. Q_R was calculated using simple tidal prism considerations and salinity data. For a lagoon basin with constant salinity over time, the amount of salt entering and leaving the basin within a tidal cycle must be zero. If V_R is the volume of fresh water entering each lagoon basin from the drainage basin and V_P the volume of saline water entering (during flood) or leaving (during ebb) the lagoon basin through its mouth, according to tidal phase, then salt balance requires:

$$\frac{V_R}{2} S_R - \left(\frac{V_R}{2} + V_P\right) S_L + \frac{V_R}{2} S_R + \left(V_P - \frac{V_R}{2}\right) S_O = 0 \qquad (2)$$

where S_R, S_L and S_O the salinity at the river, the lagoon and the coastal sea water, respectively. Salinity data were obtained from filed study in May to Sep 2010 and from existing literature. Since monthly salinity values are available for each lagoon and V_P can be estimated from the lagoon area and mean tidal range. Mean tidal range in the sea, 0.34m was adapted from Gunaratne (2010a) and mean tidal range in the lagoon for RS1, RS2 and RS3 scenarios were computed using repletion factors as explained by Kjerfve and Magill (1989). Equation (2) can be used to quantify V_R, which represents the monthly average volume of fresh water entering each lagoon basin. The magnitude of the monthly Q_R -term was calculated as $Q_R = V_R T^{-1}$, where T the duration of a tidal cycle. These monthly Q_R values were used to calculate the mean monthly freshwater discharge flowing into the lagoon. The term Q_O represents the residual water exchange between the inflow of saline coastal water and the outflow of lagoon brackish water on tidal, meteorological and longer time scales. On the assumption that the lagoon volume remains constant within the period of observation, Q_O was estimated from Equation (1). Over the period of study (Δt = one month), there are no indications that the mean water level changed; thus, the term dV/dt can safely be assumed equal to zero.

2.5 Water renewal time

Water renewal time or flushing time for a lagoon is defined by Officer (1980) as the mean time a particle of a conservative substance spends in a given volume. Salt and fresh water are usually considered conservative substances in estuarine hydrodynamics. In quantifying the flushing of Rekawa lagoon, the concept of flushing half-life ($T_{50\%}$ hours) was adapted as the optimum measure of flushing time. Flushing half-life defines as the time that it takes to replace half of the lagoon water volume and this definition is based on a rather restrictive assumption, i.e. it is assumed that complete mixing occurs rapidly compared to flushing half time (Knoppers et al. 1991). Assuming first order kinetics, if V denotes the volume of water in the lagoon, t time, and k a rate constant, it is expressed

$$\frac{dV}{dt} = -kV \qquad (3)$$

(Pritchard, 1961) which can be integrated from t = 0 when the lagoon volume was V_0, to a new time, $T_{50\%}$, when the total water volume is the same but only 50% of the original water parcels remain inside the lagoon, or when $V_{new}/V_0 = 0.50$. It follows that

$$T_{50\%} = 0.69/k \qquad (4)$$

where k is a rate constant calculated as the average fraction of lagoon water volume replaced each second by the sum of the water fluxes. Hence,

$$k = \frac{\left[Q_R + Q_P + Q_G + Q_O + |Q_T|\right]}{V} \qquad (5)$$

The term Q_T represents the tidal flushing rate ($m^3 s^{-1}$); hence the absolute value sign was used. Since in both lagoon systems predominant tidal constituent is the semi-diurnal tide, Q_T, was expressed as the prism entering the lagoon system per tidal cycle, although in reality this transport occurs only during half a tidal cycle. Q_T was calculated by:

$$Q_T = \pm \frac{A_W \times \Delta h}{T} \qquad (6)$$

where Δh is the mean tidal range and A_W is the waterway area of the lagoon. A_W does not change appreciably between high and low tides because of the small tidal ranges, but are often appreciably different seasonally as a result of the runoff conditions. A_W was adapted from existing literature. T is the period of the semi-diurnal tide (T = 12.42 hr = 44714 s).

Flushing half-life was calculated for three scenarios of Rekawa lagoon; 1) Before the construction of causeway or time period before year 1984 (Rekawa Scenario 1 - RS1); 2) Existing situation or time period after year 2000 (Rekawa Scenario 2 – RS2) and 3) Future scenario with respect to proposed box culvert introduction (Rekawa Scenario 3 – RS3).

3 Results and discussion

3.1 Water Balance

Table 1 illustrates the summary of the estimated average monthly water budget contributors for Rekawa lagoon for RS1 and RS2 scenarios based on rainfall and evaporation data for past 10 years (from 2000 to 2010 Sep.). According to the Table 1 tidal net water discharge (Q_O) through out the year was negative and that means the total outflow runs towards the sea. February has the highest Q_O despite of low freshwater inflow due to increasing seawater inflow. December has the second highest Q_O and that is due to the increment of freshwater inflow. Comparatively Q_O for RS1 scenario is larger than Q_O for RS2 scenario due to the tidal chocking caused by the causeway. These water budget contributors are expressed in m^3s^{-1} with the sign convention that water gain is positive and water loss is negative.

Table 1: *Summary of the estimated average monthly water budget contributors for Rekawa lagoon fro RS1 and RS2 scenarios based on rainfall and evaporation data for past 10 years (from 2000 to 2010 Sep.)*

Month	Q_P (m^3s^{-1})	Q_E (m^3s^{-1})	Q_R-*RS1*(m^3s^{-1})	Q_O-*RS2*(m^3s^{-1})	Q_R-*RS2*(m^3s^{-1})	Q_O-*RS2*(m^3s^{-1})
Jan	0.075	-0.003	23.488	-23.559	9.430	-9.501
Feb	0.016	-0.004	24.675	-24.687	9.906	-9.918
Mar	0.085	-0.004	22.592	-22.673	9.070	-9.151
Apr	0.092	-0.004	22.196	-22.283	8.911	-8.999
May	0.065	-0.004	18.891	-18.951	7.584	-7.644
Jun	0.041	-0.004	18.777	-18.813	7.538	-7.575
Jul	0.032	-0.005	18.663	-18.690	7.493	-7.520
Aug	0.063	-0.005	15.807	-15.865	6.346	-6.404
Sep	0.093	-0.004	18.243	-18.332	7.324	-7.413
Oct	0.101	-0.004	18.421	-18.518	7.396	-7.493
Nov	0.139	-0.003	23.261	-23.397	9.339	-9.474
Dec	0.104	-0.003	24.032	-24.133	9.648	-9.749

Q_P - mean monthly precipitation rate; Q_E - mean monthly evaporation rate; Q_R –estimated monthly surface runoff discharge rate; Q_O – estimated monthly tidal net water discharge rate

Results on water balance suggest the causeway has prevented flushing of the lagoon by natural water flow, causing continuous sedimentation in the lagoon. Consequently, the invading mangrove encroachment takes it toll resulting in the loss of the water surface area. Priyadarshana (1998) found nearly 2.38km^2 of water surface in 1998 whereas the Hambantota District profile completed in 1983 indicated 3.30 km^2 of water surface area (Samaranayake, 1983). It proves to be of significant evidence on gradual shrinkage of the lagoon area due to sedimentation with mangrove encroachment.

3.2 Water Renewal time

Estimated mean monthly flushing half-life and tidal flushing rate for Rekawa lagoon for three scenarios RS1, RS2 and RS3 for past ten years (from 2000 to 2010 Sep.) are illustrated in Fig. 5.

For RS1 flushing half-life ranges from 15hours to 20hours while it ranges from 39hours to 50hours for RS2. For RS3 it fluctuates from 25hours to 29 hours. For RS1, RS2 and RS3 scenarios tidal flushing rates (Q_T) were 13.6m^3s^{-1}, 5.5m^3s^{-1} and 14.1m^3s^{-1} respectively. Results depict renewal time increase with decreasing tidal flushing rates while decreases with increasing tidal flushing rates. Proposed modifications to the causeway (RS3) have positively effected to improve the flushing efficiency with respect to existing scenario (RS2) while providing more openings for increment of seawater. Flushing half-life was presented in hours in order identify its variation noticeably with its minute magnitudes.

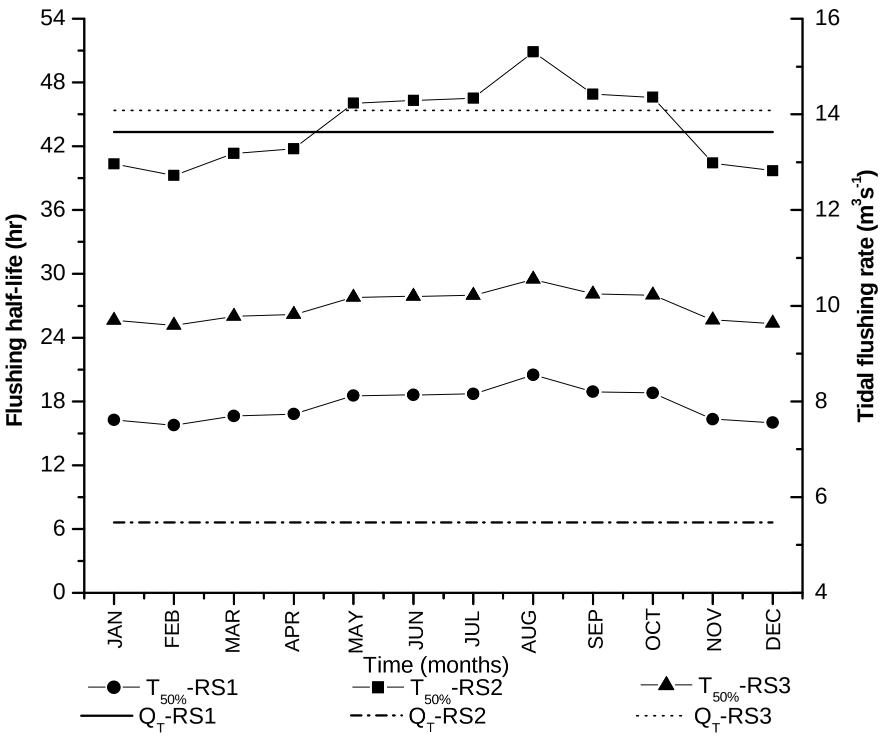

Figure 5: *Estimated mean monthly flushing half-life and estimated tidal flushing rate for Rekawa lagoon for three scenarios RS1, RS2 and RS3 for past ten years (from 2000 to 2010 Sep.)*

Reduction of total outflow and tidal flushing of the lagoon with the construction of the causeway indicates the impedance of free water flow due to causeway which in turn negatively affects on the shrimp growth because it needs around 8pH level and sandy bottom for better growth. Due to poor flushing and exchanging water, the pH level and salt contain of the lagoon water drop considerably, resulting in an unsuitable and unfriendly environment for the shrimp growth and production. Moreover, shrimps travel on the floor of the lagoon and since the water passing cylindrical culverts are placed on approximately 1m higher elevation than the lagoon floor, the shrimps do not go over it, as it becomes a barrier; it in turn stops the number of shrimps coming into the lagoon from sea.

4 Conclusions and management proposals

The comparative water budget and water renewal time have been studied in this paper for three scenarios (RS1,RS2 and RS3) of Rekawa lagoon, one of the most significant lagoonal system in Southern Sri Lanka. Results of water balance and flushing time reveal the impedance of free water flow due to causeway which in turn negatively affects on the recruitment of juvenile shrimp species. All the problems related to existing causeway were analyzed in redesigning the proposed causeway with box culverts. With the modification effective cross sectional area will be enhanced up to 74% from 28% in the existing situation which provides more allowance for free water flow. It is recommended that further dredging is required in either sides of the existing causeway as it still accumulated with some debris generated on last Tsunami disaster. Study can be concluded that the introduction of 10 box culverts will help to improve free water flow across the causeway there by it favors recruitment of juvenile shrimp species from the adjacent sea.

Water balance and water renewal time (Flushing half-life) can be used to support lagoon water resource planning and management. All the assessments can be a tool for restoration of Rekawa lagoon and can help the decision makers to take the correct decisions.

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