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Hydrodynamic Modelling of Puttalam Lagoon

M.M.M. Manas and K.P.P. Pathirana

Abstract: In the present study, a hydrodynamic model of Puttalam lagoon was set-up using DELFT 3D software. The simulations carried out to assess the present status of the lagoon show that the water level fluctuations gradually decrease by about 35% when propagating the tidal fluctuations at locations from Kalpitiya to Etalai basin whereas, the range of water level fluctuations decrease by about 65% at locations from Kalpitiya to Puttalam basin which is the lagoon head. The average velocity of flow in the lagoon is less than 0.3 m s^{-1} except at the Puttalam basin mouth where the cross section is small. In addition, the residence time varies between 40 days (downstream of Kalpitiya) to 100 days (Puttalam basin – at lagoon head) in the lagoon. The range of water level fluctuations in the lagoon is increased by about 0.2 m and 0.24 m due to Sea Level Rise (SLR) for the climate change scenarios of RCP 4.5 and RCP 8.5, respectively. In addition, the average velocity of flow is also increased due to SLR and, as a result, the residence time is reduced by 6% to 10% at various locations in the lagoon.

Keywords: Lagoon, Hydrodynamic modelling, Delft 3D, Residence time, Climate change, SLR.

1. Introduction

Inland coastal ocean-connected waters can be organized into six categories based on their geomorphological structure and they are estuary, coastal lagoon, fjord, bay, tidal river and strait [13]. Coastal lagoons are shallow water bodies along the coast, separated from the ocean by barriers such as barrier islands, spits, coral reefs and sand bank, and have only restricted connection with ocean through one or more inlets [13]. Lagoons play a vital role in supporting human wellbeing because of their immense resources and the life-supporting services they provide. They are much important in terms of both ecology, economic and social aspects.

Puttalam lagoon is an ecosystem with high productivity habitats for many species of fish, birds, plants and animals [15]. At the same time, many people living around the Puttalam lagoon depend on the lagoon resources for their sustenance [17]. Puttalam lagoon is very rich in natural resources, which includes fish, shellfish, coral reefs, sand dunes, mangroves, sea grass beds, salt marshes and beaches [17].

Fishing, trading fish products and agriculture are the main occupation of the people living near the Puttalam lagoon [17]. Other than their values on fisheries, it is an important place for aquaculture, salt extraction, electric power generation, transportation and many industrial activities [15]. Most People use Puttalam lagoon for recreation activities such as sailing, boating, fishing, swimming, and other water sports such as kite surfing, as well as for bird watching.

However, studies conducted at Puttalam lagoon ([10], [15], [17] and [19]) highlight that the productivity of this ecosystem has decreased due to many anthropogenic activities happening near the lagoon such as overfishing, destructive fishing techniques, marine debris, discharge of household sewage, aquaculture waste and agro chemicals. In addition, direct impacts on lagoon include destruction of habitats such as mangroves, coral reefs and forests. Lagoon water quality is severely affected by effluent discharge from shrimp farms, coal power plant water discharge, through solid waste pollution and over-exploitation of natural resources.

It is compulsory to protect the Puttalam lagoon system while receiving resources and services from the lagoon. Therefore, it is clear that water quality studies are extremely important for the lagoon. However, the first step to carry out these studies is to have a good understanding

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on hydrodynamic characteristics of the lagoon, numerical modelling techniques are valuable tools towards this understanding ([3], [11]). Application of these models to lagoon systems can help to assess the impacts of various management strategies, which include both structural and policy implementation plans [21].

The main objective of this study is to set-up a hydrodynamic model of Puttalam lagoon. In this study, a two-dimensional, depth averaged computational model was set-up using Delft3D software, to analyse hydrodynamic characteristics and residence time of Puttalam lagoon as at present condition. Furthermore, as impacts of Sea Level Rise (SLR) caused by climate change on hydrodynamic characteristics of Puttalam lagoon are poorly understood, this study also focuses on variation of hydrodynamic characteristics and residence time due to SLR.

2. Study Area

Puttalam lagoon and Dutch bay along with Portugal bay form the brackish water body with a total surface area of approximately 32,700 ha [5] and located in the northwest part of Sri Lanka, between latitude 7°58′ N - 8°24′ N and longitude 79°43′E – 79°51′E (Figure 1) and it is considered as one of the largest lagoons in Sri Lanka.

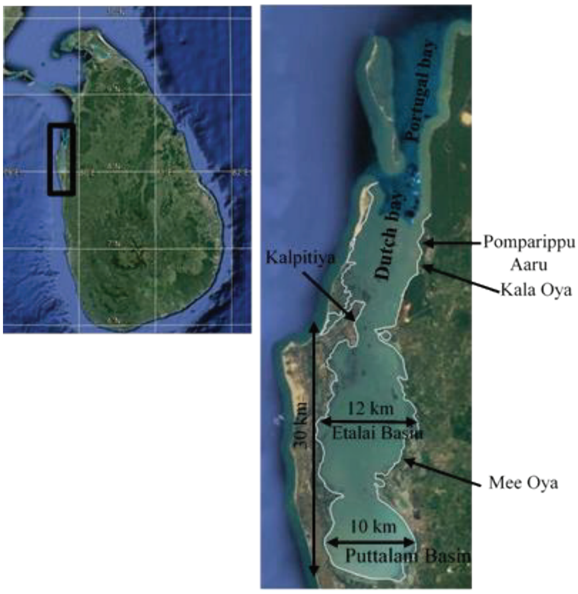

Figure 1 - Location of Puttalam Lagoon (left), Details of Puttalam Lagoon with Dimensions (Right) (Source: Google Earth)

Downstream of Puttalam lagoon connects to the ocean through Dutch bay and Portugal bay while its upstream connects to the Mundel lake through 16 km long Dutch canal [5]. The lagoon is surrounded by the mainland in the east and south and to the west by the narrow Kalpitiya peninsula. Puttalam lagoon has two basins, namely, Puttalam basin and Etalai basin having a maximum width of approximately 10 km and 12 km, respectively, and both basins together make a length of nearly 30 km.

In addition, Puttalam lagoon receives water from three river basins, namely, Kala Oya, Mee Oya, and the very small Pomparippu Aru (Figure 1). Catchment areas of these basins are 2772 km^2, 1516 km^2 and 44 km^2, respectively. The average discharges of Kala Oya and Mee Oya are estimated to be about 20 m^3/s and 8 m^3/s, respectively [23]. Bathymetry of Puttalam lagoon varies between 1 m – 2 m and deep depths are encountered in the channels, north of Kalpitiya (Figure 2). Puttalam lagoon is located in the dry zone of the country and it receives an average annual rainfall ranging between 1000 mm - 1100 mm and it is seasonal [10]. It has two dry seasons from January to March and July to September. The winds over Puttalam lagoon are monsoon dominated with the southwest monsoon blowing from June to September while the northeast monsoon blowing from December to March.

3. Methodology

3.1 Model Set-up

The computational domain of the model for Puttalam lagoon was developed with orthogonal boundary fitted structured curvilinear grid using Delft3D – RGFGRID tool in Cartesian coordinate system. It covers an area of 447 km^2. This system has 40,554 grid elements with each grid having a resolution of nearly 100 m x 100 m. The grid size used in this study was able to produce the model results which are in good agreement with the observed results.

Grids were refined so that they meet quality criteria given in Delft3D – RGFFRID [8] (Table 1), while ensuring computational accuracy and efficiency, where all grid properties were managed within the allowable limits as mentioned in the Delft3D grid generation guidelines [8]. Maximum and minimum values of grid properties used to set – up the model in this study and their allowable limits are summarized in Table 1.

These grids should be smooth in order to minimise errors in the finite difference approximations and should be orthogonal, which saves some computationally expensive transformation terms ([6] and [7]). The open boundary of the model was introduced sufficiently far away from the main lagoon area so that there is a buffer zone between the open boundary and the area of interest. This is to reduce or eliminate unduly influence from open boundary forces on the interested region. ([8] and [18]).

Table 1 - Grid Properties of Puttalam Lagoon Model

Grid property	Allowable limit	Puttalam lagoon model	
		Min	Max
Orthogonality	< 0.04 (in the area of interest) Up to 0.05 – 0.10 (In other areas)	0	0.002
Aspect ratio	0.5 – 2	1.000	1.231
Smoothness	< 1.1 – 1.4	1.000	1.097
Grid resolution (m)	-	98.27	110.70
Number of grid elements	40,000 – 60,000	40,501	

In Table 1, orthogonality is the Cosine value of the angle between an edge and the line between the circumcentres of the enclosing elements of that edge, aspect ratio is the ratio of cell dimensions in x and y directions, resolution is the square root of grid element area and smoothness is the ratio of length of adjacent grid elements [8].

Bathymetry of the system was updated using Delft3D – QUICKIN tool. Measured bathymetry data obtained from Lanka Hydraulic Institute (LHI) was used in this model by assigning these values at grid cell corners. Grid cell averaging method was used to interpolate the bathymetry data since the available bathymetry data was inadequate for accurate model simulations [9]. As the entire Puttalam lagoon is very shallow except only at the lagoon entrance area, it was decided to use 2D depth averaged version of Delft3D model by setting the model domain to have only one layer. This is a fair approximation used in many studies reported in literature [21].

The bathymetry map of Puttalam lagoon prepared using Delft 3D – QUICKIN is shown in Figure 2.

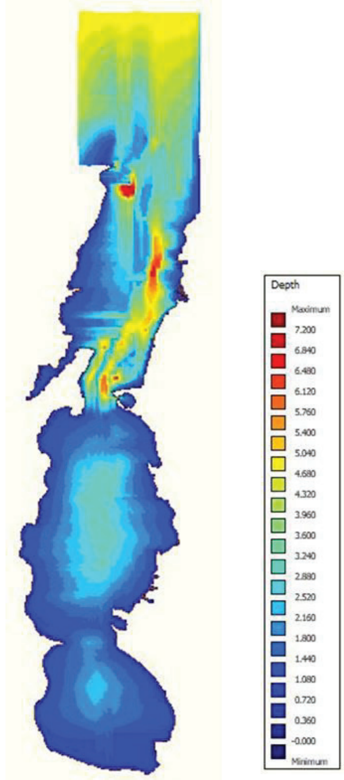

Figure 2 - Bathymetry of Puttalam Lagoon

Land boundary of the model was prepared using 1: 50000-scale map obtained from North-western Provincial Survey Department, Puttalam. Delft3D – RGFGRID was used to plot this land boundary. In addition, Google Earth and Global mapper 18 software were also used in preparation of the land boundary. Land and offshore boundaries of the model area with the locations of river outfalls are shown in Figure 3. The model was forced by tides, river discharges and wind applied at different boundaries of the model. The tidal fluctuations generated using tidal constituents at Kalpitiya (Table 2) which were collected from Admiralty Tide Tables, Vol. 3 – Indian Ocean and South China Sea, UK hydrographic Office were used as the offshore boundary condition. River discharges from Mee Oya and Kala Oya were assigned as constant flow rates of 8 m^3s^{-1} and 20 m^3s^{-1}, respectively [23], at river outfalls shown in Figure 3. Spatially uniform wind forcing was also applied over the entire lagoon water surface having a constant speed of 4 m s^{-1}. As initial condition of the model, salinity values of water at the head of the lagoon, downstream boundary of the model and river outfall locations were set at 36 ppt, 34 ppt and 0 ppt, respectively [1].

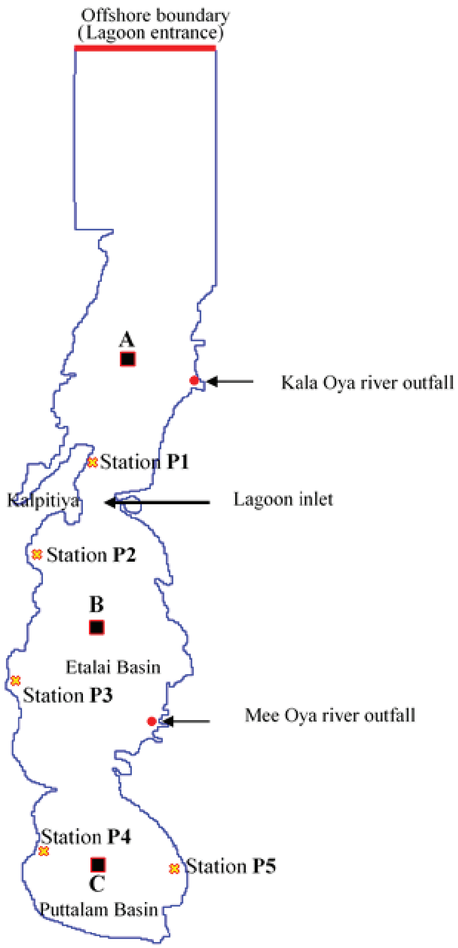

Figure 3 - Map of Puttalam Lagoon Showing Boundary Conditions, Gauging Stations and Locations Selected for the Comparison of Water Level Fluctuations

Table 2 - Tidal Constituents at Kalpitiya

Tidal constituents	Phase angle (^{0})	Amplitude (m)
M_2	97	0.12
S_2	147	0.08
K_1	71	0.06
O_1	91	0.03

3.2 Model Calibration

The model was calibrated using the water level fluctuations at stations P – 1, P – 3, and P – 5 (Figure 3) and velocity variation at location P – 1 obtained from a previous study [22]. Comparison between the measured water levels and model predicted water levels at stations P – 1, P – 3, and P – 5 are given in Figures 4, 5 and 6, respectively. It is worth noting that the measured water level variations collected from previous literature are given with respect to Mean Lower Low Water level and the model predicted water level variations are with respect to the MSL. Therefore, datum of model predicted water level variations were adjusted just to compare measured water levels and model predicted water levels, as shown in Figures 4, 5 and 6, respectively, for stations P - 1, P - 3 and P - 5. In addition, measured longitudinal velocity component at station P- 1 has also been compared with the model predicted longitudinal velocity component as shown in Figure 7.

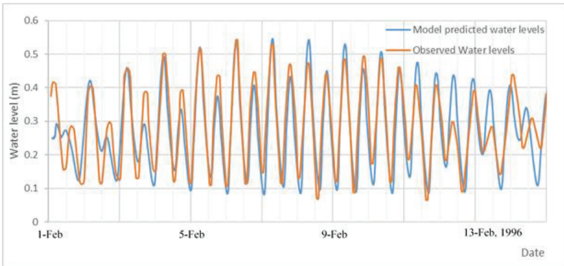

Figure 4 - Comparison of Observed [22] and Model Predicted Water Levels at Station P – 1

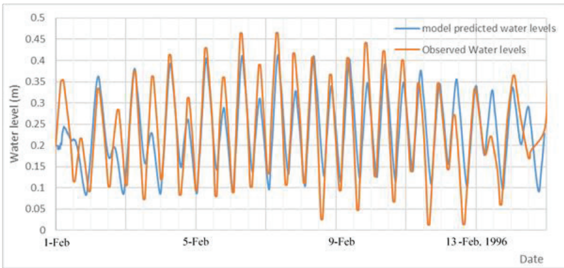

Figure 5 - Comparison of Observed [22] and Model Predicted Water Levels at Station P – 3

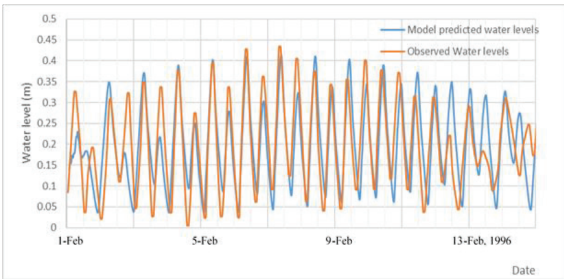

Figure 6 - Comparison of Observed [22] and Model Predicted Water Levels at Station P – 5

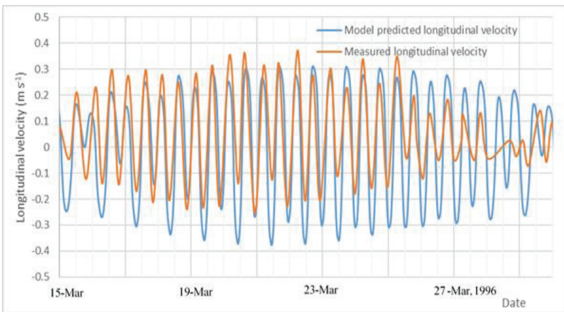

Figure 7 - Comparison of Observed [22] and Model Predicted Longitudinal Velocity at Station P - 1

Bottom roughness (Manning's coefficient), wind drag coefficient, horizontal eddy viscosity and horizontal eddy diffusivity were used as calibration parameters of the model and these values are 0.016, 0.0011, 1 m^2s^{-1} and 80 m^2s^{-1}, respectively. The Manning's coefficient selected for the calibration of the model in this study is comparable with many other similar studies ([2], [14], [16]) and the values reported in these studies vary between 0.015 and 0.025.

According to Figures 4 to 7, it can be noted that the model predictions are satisfactorily correlated with the measured values of water levels and longitudinal velocities, despite small deviations in amplitudes predicted by the model particularly during neap tides.

3.3 Model Verification

The calibrated model was validated by comparing the model predicted water levels at stations P – 2 and P – 4 (see Figure 3) with measured water levels at those stations as shown in Figures 8 and 9.

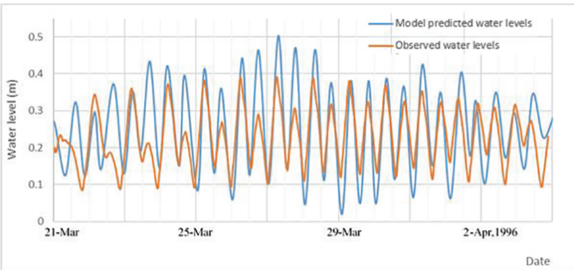

Figure 8 - Comparison of Observed [22] and Model Predicted Water Levels at Station P – 2

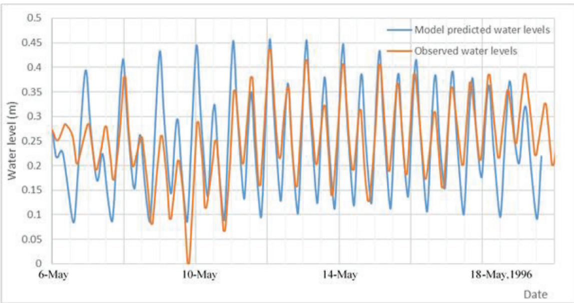

Figure 9 - Comparison of Observed [22] and Model Predicted Water Levels at Station P – 4

Figures 8 and 9 show that the model predictions are in good agreement with the measured water levels simulated during validation of the model. Model predictions follow the same trend as the measured water levels. However, small deviations in amplitudes between model predictions and measured values could be noted. The reason for these slight variations of the model predictions may be due to the bathymetry of the lagoon used in this study which was not the same as the one during the field measurement. The bathymetry assigned to this hydrodynamic model was from a recent bathymetry survey conducted in 2018, whereas the water level and velocity measurements were collected in 1996. During this time period bathymetry of the lagoon may have changed, which influenced the model results.

4. Model Simulations

4.1 Present Status of the Lagoon

The validated model was used to simulate the hydrodynamic characteristics of the lagoon as at present conditions. Water level fluctuations and longitudinal velocities extracted from the model at three locations A, B, C and also at the lagoon entrance (see Figure 3) during spring and neap tides were analysed in order to quantify the damping effect of hydrodynamic parameters within the lagoon. In addition, phase differences between these points were also assessed.

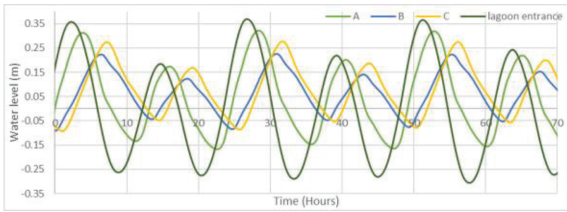

Figure 10 - Comparison of Water Level Fluctuations at Locations A, B, C and Lagoon Entrance

Figure 10 shows that the range of water level fluctuations decrease when propagating the tidal effect from lagoon entrance to location "A" and these fluctuations further decrease when reaching location "B". This may be due to the damping effect caused by the lagoon bed due to shallow water depths and water loses its energy when propagating tidal fluctuations from the lagoon mouth to interior of the lagoon. However, the range of water level fluctuations is somewhat higher at location "C" compared to that of at location "B". This could be due to the superimposition of incident and reflected tidal oscillations in the lagoon head. It is also important to note that, as the lagoon is little wider at location "B" compared to location "C", the incident wave energy also spreads laterally over a wider area, thus reducing the water level fluctuations at location "B" compared to location "C".

When propagating the tidal fluctuations from location "A" to location "B", the model predicts a reduction of water level fluctuations from 0.51 m to 0.33 m, giving a reduction of 35%, whereas, range of water level fluctuation reduces by 65% when water propagates from location "A'' to location "C".

In addition, water level variations and circulation patterns over the entire lagoon at different times of a tidal cycle were obtained and analysed for both spring and neap tides. The four time instances considered in a tidal cycle for the above analysis are,

a) High tide at lagoon entrance (P)
b) Nearly 3 hours after high tide at lagoon entrance (Q)
c) Low tide at lagoon entrance (R)
d) Nearly 3 hours after low tide at lagoon entrance (S)

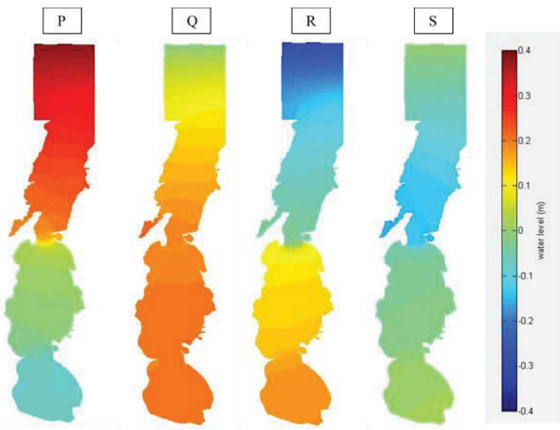

Figure 11 - Spatial Distribution of Water Levels Over Entire Lagoon at Time Instances P, Q, R and S, Respectively During a Tidal Cycle

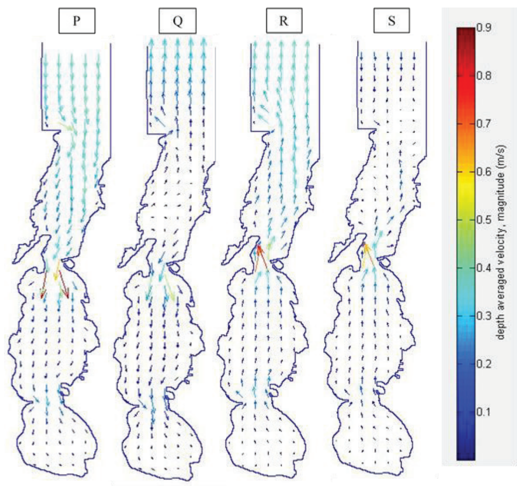

Figure 12 - Velocity Distribution Over Entire Lagoon at Time Instances P, Q, R and S, Respectively During a Tidal Cycle

Hereafter, these time instances will be referred as P, Q, R and S, respectively. The model results of water level variations and circulation patterns are given in Figure 11 and Figure 12, respectively.

Residence times at various locations of the lagoon were evaluated using the model. In the present situation, spatial variation of residence times within the lagoon was estimated according to Jouon [12] and Qin [18]. In this method, the average residence time at a given location within a lagoon is described as the time taken to dilute the initial concentration of a constituent of 1 kg/m^3 released at this location to a concentration of about 0.37 kg/m^3 (1/e). The residence times at diffident locations in Puttalam lagoon were estimated and the results are presented Figure 13.

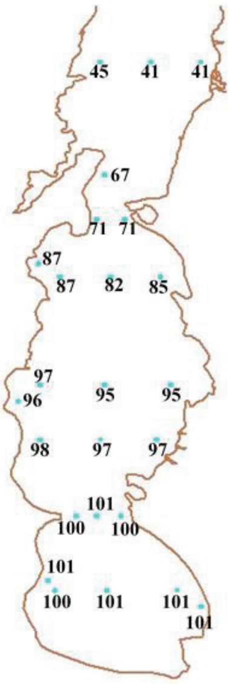

Figure 13 - Spatial Variation of Residence Time in Days

4.2 Model Simulations for Expected Maximum SLR

In this study, the validated model was used to simulate hydrodynamic characteristics of Puttalam lagoon due to the expected SLR. RCP 4.5 is the scenario which is most likely to happen in future [4]. However, since these are long term impacts and usually take many years to experience the proposed sea level rise, it might also be appropriate to consider the worst case scenario, that is RCP 8.5. In this study, SLR of 0.71 m and 0.98 m were considered for the simulation of RCP 4.5 and RCP 8.5, respectively.

Figure 14 shows that, there is no such big differences observed in the range of water level fluctuations at location "A" where water depths are high and the water level variation at location "A" follows the rhythm of the open ocean. However, it is clear from Figure 15 and Figure 16, that the range of water level fluctuations have increased significantly compared to present status of the lagoon, at locations "B" and "C" which are located in the Etalai and Puttalam basins, respectively, where the water depths are relatively shallow.

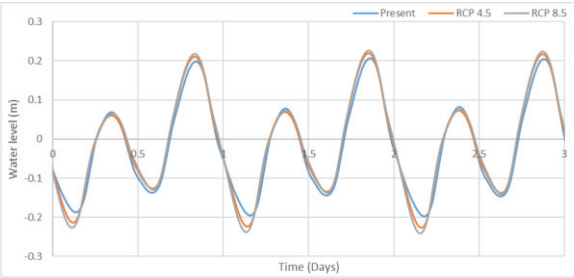

Figure 14 - Comparison of Water Level Fluctuations at Location A

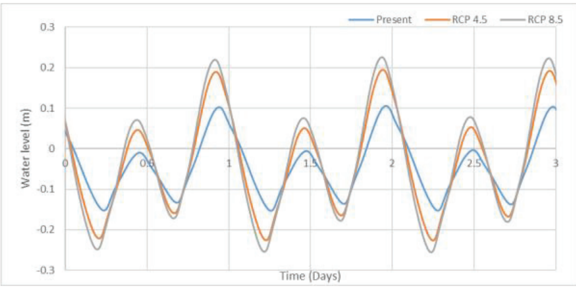

Figure 15 - Comparison of Water Level Fluctuations at Location B

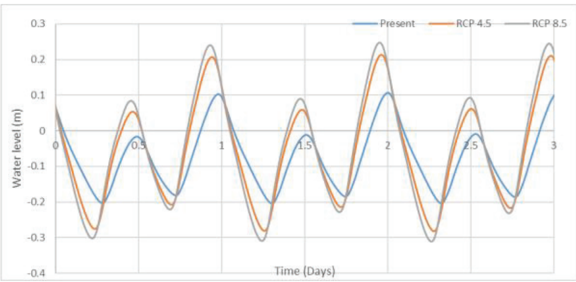

Figure 16 - Comparison of Water Level Fluctuations at Location C

The above simulations also indicate that the sea level rise (SLR) for the climate change scenario RCP 4.5, increases the range of water level fluctuations by about 0.2 m at locations "B" and "C" in the lagoon. Therefore, it can be noticed that due to climate change scenario of RCP 4.5, the water level fluctuations at locations "B" and "C" are increased by about 60% compared to present water level fluctuations. Likewise, SLR climate change scenario RCP 8.5 increases the range of water level fluctuations by 0.24 m at locations "B" and "C" in the lagoon. It can be stated that due to climate change scenario of RCP 8.5, the water level fluctuations at locations "B" and "C" are increased by about 67% compared to present water level fluctuations. There is also a small phase difference occuring compared to present status of the lagoon due to the SLR.

Figure 17 shows the residence time at various locations in the lagoon for climate change scenarios of RCP 4.5 (left) and RCP 8.5 (right). Figure 17 (left) shows that the residence time is reduced by about 7.5%, 9.5% and 8%, respectively, at locations Kalpitiya, Etalai and Puttalam, due to the SLR climate change scenario of RCP 4.5 compared to the residence time at present status of the lagoon (see Figure 14). Likewise, Figure 17 (right) shows that the residence time is reduced by about 10%, 8.5% and 6%, respectively, at locations Kalpitiya, Etalai and Puttalam, due to the SLR climate change scenarios of RCP 8.5 compared to the residence time at present status of the lagoon (see Figure 13). Similar results have been obtained by Ranjbar [20] in his recent study.

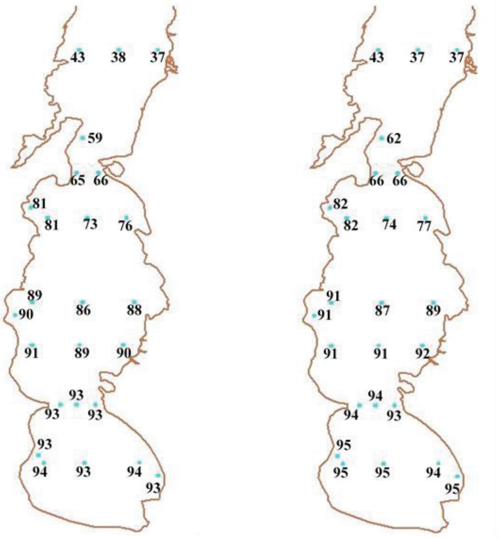

Figure 17 - Spatial Variation of Residence Time in Days for SLR RCP 4.5 (Left) and RCP 8.5 (Right)

5. Conclusions

In this study, a two-dimensional, depth averaged computational model was set-up using Delft3D, to analyse hydrodynamic characteristics of Puttalam lagoon. This model was calibrated and validated using water levels and velocity measurements obtained from previous studies. The simulations carried out to assess the present status of the lagoon reveal that the range of water level fluctuations gradually reduce by about 35% when propagating the tidal fluctuations from Kalpitiya to Etalai whereas the range of water level fluctuations reduces by about 65% when propagating the tidal fluctuations from Kalpitiya to Puttalam. In addition, residence time at various locations in the lagoon appears to vary between 40 days to 100 days at the present status of the lagoon. The residence time is about 40 days at downstream of Kalpitiya where the water circulation is relatively high while it is nearly 100 days at lagoon head region where the water circulation is very poor.

The results of the model simulations carried out to study the effect of SLR on lagoon hydrodynamics show that the range of water level fluctuations in the lagoon is increased by about 0.2 m and 0.24 m due to SLR for the climate change scenarios of RCP 4.5 and RCP 8.5, respectively. In addition, the average velocity of flow is also increased due to SLR and, as a result, the residence time is reduced by 6% to 10% at various locations in the lagoon.

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