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Hydrodynamics, temperature/salinity variability and residence time in the Chilika lagoon during dry and wet period: Measurement and modeling

M.M. Mahanty [a,*], P.K. Mohanty [b], A.K. Pattnaik [c], U.S. Panda [d], S. Pradhan [c], R.N. Samal [c]

[a] National Institute of Ocean Technology, NIOT Campus, Pallikaranai, Chennai 600 100, Tamil Nadu, India
[b] Department of Marine Sciences, Berhampur University, Berhampur 760 007, India
[c] Chilika Development Authority, C-11, BJB Nagar, Bhubaneswar 751 014, India
[d] Integrated Coastal and Marine Area Management-Project Directorate, Ministry of Earth Sciences, Government of India, NIOT Campus, Chennai 600 100, India

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ABSTRACT

This paper investigated the hydrodynamics, spatio-temporal variability of temperature/salinity and the residence time of tracer concentrations in a largest brackish water coastal lagoon in Asia, namely the Chilika lagoon, India. An integrated approach combined the measurement and 2D hydrodynamic-advection/dispersion model is used to simulate circulation and temperature/salinity, and estimated the water residence time in lagoon under different forcing mechanisms, such as tide, wind and freshwater discharge during the dry and wet periods. Water circulation inside the lagoon is simulated when wind is included with the tide only forcing during dry period, and freshwater influx is included with the tide and wind forcing during wet period. Under the realistic forcing conditions, the computed temporal variability of water temperature and salinity are well correlated with the measurements in both the periods. The spatial variations of water temperature within the lagoon is influenced by the meteorological conditions, tide and freshwater influx as well as the shallowness of the lagoon, whereas the salinity is spatially controlled by the freshwater influx from the riverine system and seawater intrusion through the tidal inlets. The numerical model results show that in the Chilika lagoon tidal and river influx affect significantly the residence time spatially, and is site specific. The residence time varies from values of 4–5 days in the outer channel (OC) and 132 days at the northern sector (NS) in the main body of lagoon. The current study represents a first attempt to use a combined model approach, which is therefore, a useful tool to support the ecological implication of the lagoon ecosystem.

1. Introduction

Lagoons are important coastal habitats and recognized as highly productive ecosystems which support a rich biodiversity of aquatic plants and animals (Pérez-Ruzafa et al., 2011). They support a range of natural services that are extremely valuable to society including fisheries productivity, storm protection, tourism and others (Gönenc and Wolflin, 2005). The lagoon environment, as a complex system is mainly influenced by various physical, chemical and biological parameters (Ferrarin and Umgiesser, 2005). Concentrations of these parameters occur within in the coastal lagoons are generally dependent on hydrodynamics, salinity/temperature variability and residence time of water, in both seasonal and shorter time scale (Tsihrintzis et al., 2007).

Hydrodynamics in the coastal lagoons are primarily depends upon the variety of forcing mechanisms such as tide, wind and freshwater discharge, and response of these forcing functions separately in the lagoon (Antoranz et al., 2001; Vaz et al., 2005). The inlet configuration, lagoon orientation, and bottom topography determine the degree of flow characteristics in lagoons (Ferrarin et al., 2008; Umgiesser et al., 2014) and causes a time lag in the tidal peak, and asymmetry in the flow velocity (Lumborg and Windelin, 2003). Shallow lagoons are highly responsive to wind force because of the large surface area to depth ratio, and currents are quickly damped by bottom friction (Smith, 1994). Wind generated currents interact with the tides, by causing shear stresses that bring in residual circulations or eddies (Umgiesser et al., 2000). The seasonal variation of freshwater discharge into the lagoons has a reflective impact on the ecological viability by increasing the lagoon water level and opening of entrance channel,

* Corresponding author.
E-mail address: mmmahanty@gmail.com (M.M. Mahanty).

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which in turn, determine the distribution of water properties like salinity and temperature, as well as the distribution of other tracers (Liu et al., 2007; Rodrigues et al., 2012).

Salinity and temperature are plays the key environmental and ecological role within the lagoon, and influence the important parameters of the water in the lagoon (Cameron and Pritchard, 1963). Newton and Mudge (2003) demonstrated the variation of temperature and salinity characteristics in a shallow water of Ria Formosa (Portugal), both in winter and summer. Ghezzo et al. (2011) simulated the spatial and temporal variability of salinity in the lagoon of Venice using a two-dimensional (2D) hydrodynamic and dispersive model.

One of the important physical characteristic of lagoons is the water renewal rates that describe the lagoon's ability to renew the water contained within it (Takeoka, 1984; Kim and Park, 2012; Umgiesser, 2000). There are several concepts of renewal time scales such as residence time, age, flushing time, turnover time and transit time. Numerous researchers have suggested various ways of evaluating the water renewal time scales. Zimmerman (1976) described the movement of distinct particles for a spatially varying condition and determined that the residence time for each element was defined as the time for the element to reach the outlet. Takeoka (1984) defined that residence time (RT) at a given point in a lagoon is the period of time that measures the total time spent in the lagoon as the water parcel leaves and re-enters the control domain. Geyer (1997) assessed the water exchange processes between the lagoon and the sea, which is a complicated function of bathymetry, tide, wind and river discharge in different time scales. The concept of calculating the RT for lagoons is known as the *e*-folding time which corresponds to the time when the average concentration of contaminants in the lagoon is reduced to *1/e* of the initial concentration (Monsen, 2002). Juhland and Gierlevsen (2008) described that RT is equal to the time required to replace 50% of the tracer in the water body with new water entering through the boundaries of the area of interest. Gupta et al. (2008) described the RT in the Chilika lake using the ratio between the volume of the lake and total influx of water, and was estimated at 127 and 12.3 days during premonsoon and monsoon respectively. Malhadas et al. (2010) evaluated the RT of the water in the lagoon with respect to different forcing mechanisms using the numerical model simulations.

The management of lagoon ecosystems are not only requires in-situ measurements but also a widely used high sophisticated numerical hydrodynamic model. Numerical models are in distinct characteristics, with a variety of combination of tools for different spatial and temporal scales. However, they are basically simplification of real-world situations, and several challenges around the selection of model for a specific area, input data availability and for solving practical management problems. The recent application of process-based models for lagoon ecosystem has proven to be a good compromise between data availability and model complexity. When the models are properly calibrated and validated, they can be applied run scenarios under challenging conditions, and to test the impacts of various mitigation measures providing relevant information for water managers and policy makers (Grizzetti et al., 2010).

The numerical models have been classified based on their dimension(s) in which significantly affect the spatial variations of ecological parameters. A 3-D model is commonly used for deep and large water body, in which water parameters have significant gradient in the longitudinal, lateral and vertical dimensions, whereas 2-D model used in broad and well mixed lagoons with a vertically depth-averaged and strong coupling of surface wind and bottom friction stresses (Hayter et al., 1998).

In shallow water system, a depth integrated two-dimensional model is adequate to study the hydrodynamics and thus, residence time. Braunschweig et al. (2003) described the estimation of renewal time scales in Tagus estuary using a 2-D depth integrated model. Bilgili et al. (2005) computed the transport and ocean-estuary exchange processes in the Great Bay Estuarine system using a Lagrangian particle method embedded within a 2-D finite element code. Umgiesser and Cucco (2006) used a 2-D hydrodynamic model and calculated the RT in the Venice Lagoon; whereas Arega et al. (2008) estimated the average residence time in a tide-dominated East Scott Creek Estuary using a numerical modeling based on finite volume method. Patgaonkar et al. (2012) estimated the RT of pollutants in the Gulf of Kachchh using 2D Hydrodynamic particle analysis model. Yunliang and Jing (2015) estimated the RT in large river-lake system using a combination of hydrodynamic and transport model. Hence, using numerical model provides important benefits and enables a range of sensitivity analyses to understand the hydrodynamic of the lagoon system and the role of the various forcing.

The Chilika, largest brackish water lagoon in Asia (Mangla, 1989), encountered a combination of increased siltation and decreased salinity due to degradation of the drainage basin as well as partial closure of the outlet channel connecting to the sea (Samal, 2011), which causes the changing of the physical, chemical and biological processes. In consideration of these ecological parameters of the lagoon environment, an integrated approach is highly essential to understand the hydrodynamic, spatio-temporal variability of temperature/salinity, and the estimation of water RTs corresponding to the dry and wet periods, using field measurement, and a combined 2D hydrodynamic (HD) model with advection-dispersion (AD) transport model. Two studies which were made to understand the hydrodynamics of Chilika lagoon had their own limitations. The study by Jayaraman et al. (2007) was based on a simple depth-averaged 2D model having a coarse resolution (0.75kmx 0.75 km) with an approximation of a stair case boundary and two lateral boundary conditions. Although Panda et al. (2013) used the HD module of MIKE 21 with flexible mesh geometry, the model simulations were only for two inlet conditions during the flood period. Further, the validation of the model simulations was for a limited period of observations, and lacked in-situ time series measurements which are generally needed to validate the hydrodynamic model simulation. In this present study, attempts are made to fill the gaps in the previous study by considering a numerical MIKE21 HD model coupled with the AD transport module to validate the model simulations with field observations, and characterise the water circulation of the lagoon in response to different forcing mechanisms. The study also investigates the spatio-temporal variability of temperature/salinity, and water RT in the Chilika lagoon.

2. The study area

The Chilika, largest brackish water coastal lagoon (~1036 km^2) in Asia is situated on the east coast of India. It is separated from the sea by a sand bar of ~60 km in length, and a 24 km long channel termed as the outer channel, that runs parallel to the coast and is connected to the Bay of Bengal. The Chilika lagoon is considered as a 'Ramsar site', a status accorded by the International Convention on Environment held at Ramsar in Iran in 1971, due to its vast potential wealth of living and non-living resources and rich biodiversity. It is, therefore, important to survey and record the biodiversity and bio-resource profiles of Chilika, which has been supporting a population of more than 0.2 million people living in and around the Chilika lagoon. Owing to the ecological threats, the Chilika lagoon was added to the Montreux Record on 16 June 1993. Ecological changes in the Chilika lagoon have occurred rapidly over the last one and half decade. The lagoon environment was under serious threat due to the choking and silting