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Published online: 22 Sep 2019.

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Spatial and temporal analyses of salinity changes in Pulicat lagoon, a transitional ecosystem, during 1996–2015

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ABSTRACT

We investigated the salinity changes of Pulicat lagoon connected to the Bay of Bengal, during the period 1996–2015. Our objective was to drive useful perspectives on the annual, seasonal and sectoral trends of salinity changes using available datasets on salinity, precipitation, and sea-entrance closures. Annual mean salinities randomly correlated with the extent of rainfall. Highest dilution (89-91%) was observed for POE in 1997 and highest concentration in PRE was recorded in 1999 and 2005 (15.2–20.2%) with respect to mean salinity. Predominant changes were evident at the cross-over from dry season ("PRE"; February to September) to wet season ("POE"; October to January). Geostatistical models of PRE and POE salinities provided estimates to be 35.6 ± 4.1 ppt and 25.5 ± 12.9 ppt, respectively. Secondary salinization from run-off contributes to the increase in the salinities in the POE. Sectoral analyses of salinity deviations from mean revealed that the magnitude of desalination due to monsoonal dilution increased with distance from the sea under conditions of exclusivity to riverine influences (e.g. a decrease of ~12.41 ppt observed in 2015). Eastern sector experienced highest dilution in POE (100%; year 1997) as well as increase in PRE (22.9%; 1999). Lowest deviations in POE were observed in southern sector in POE (81.5%). The sensitivity of the various sectors to regime shifts from low magnitude salinity change decreases in the order: Western > Southern > Central > Eastern. Our results further emphasize the need for systematic monitoring of salinity distributions to understand ecosystem dynamics at multiple scales.

Introduction

The environmental histories of sensitive ecotones such as coastal lagoons are punctuated by high-impact events such as tsunamis, super-cyclones, large-scale floods or extreme drought and desiccation, and in response, they are known to show altered ecosystem states (e.g. Scheffer, Carpenter, Foley, Folke, & Walker, 2001). Among them, events of high monsoonal riverine discharges and high rates of precipitation can swiftly alter micro-habitats and niches in these ecosystems, due to the simultaneous loss of brackishness. More often, such reversals being seasonal and temporary go unnoticed; however, their impacts may be wider and progressive (e.g. Arimoro, Ikomi, Nwadukwe, Eruotor, & Edegbene, 2014; Blanco & Viloria, 2006). It has been recognized that desalination on variable temporal scales is a silent threat to shallow brackish water ecosystems, as it causes sudden salinity shifts that result in regime shifts (e.g. Jeppesen et al., 2007). Decreases in salinity are known to affect the survival rates of brackishwater biota, for example, prawns (e.g. Crisp, Partridge, Souza, Tweedley, & Moheimani, 2017) which significantly contribute to the economies of the coastal regions. Hence, it is important to study the intensities

of the change of salinities within seasons and over different regions of the coastal systems.

Trends in the changes of sectoral salinities within coastal lagoons have been successfully used to infer the distribution of the brackishwater flora and fauna such as macrophytes and ostracod valves, as well as in sediment cores for the development of proxies of past environmental conditions (e.g. Frenzel et al., 2005). Lagoon-specific salinity trends, including annual and seasonal variability and high salinity anomaly at the transitional boundaries, are very significant in the study of abrupt regime changes. In recent times, these have been highlighted as the key local-scale drivers of environmental changes with a direct implication to the regional climate change scenarios (e.g. Fichez et al., 2017). Thus, the study of the magnitudes of temporal and spatial salinity changes especially in the case of large coastal ecosystems, needs closer attention. It is not easy to estimate key ecosystem changes at short spatio-temporal scales for coastal systems (e.g. Schumann, Baudler, Glass, Dümcke, & Karsten, 2006).

From the perspective of coastal systems of Southeast India, monsoonal exchanges with low-saline waters of lagoons and influx from riverine estuaries have long been suspected as causes for the reduction of the long-

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term average salinity of the adjacent Bay of Bengal (BoB; e.g. Jensen, 2001; Santhanam & Natarajan, 2018; Vinayachandran, Jahfer, & Nanjundiah, 2015). Such lagoon ecosystems also exhibit high internal salinity variabilities between critical phases of shifts across the seasonal gradients. For example, Chilika lagoon, India's largest brackish water system along the east coast has been known to experience extreme monsoonal desalination (e.g. Gopikrishna, Sinha, & Kudale, 2014; Sarkar et al., 2012) and disturbances to tidal flux (Ghosh, Pattnaik, & Ballatore, 2006). Such changes have resulted in adverse ecosystem responses such as the decrease or loss of biodiversity, for example, the populations of the unique, indigenous Irrawaddy dolphins (e.g. Sinha, 2004). However, one of the major problems in the studying trends and changes of India's coastal lagoons is the non-availability of long-term time-series datasets covering all the key portions of the ecosystems, which are in active exchange with adjacent systems.

In the present study, we investigated salinity changes of Pulicat lagoon, a fragile coastal lagoon ecosystem connected to the BoB, over the period 1996–2015. The lagoon makes an interesting case for a natural microtidal ecosystem without extensive dredging or port activities during the period of investigation. A sudden diatom bloom was recorded in response to the 2015 extreme flood event signifying altered ecosystem states (Santhanam, Farooqui, & Karthikeyan, 2018). This has necessitated a quick appraisal of the impacts of desalination on the system status. The major points of discussion on the salinity variations within the Pulicat ecosystem till date have been based on two perspectives:

(1) The seasonal salinity of the lagoon as a whole (for, e.g. Nagaraju, Prasad, & Narasimharao, 1990 described it as a seasonally positive or negative "estuary" as a whole at a given time period).

(2) The approximate boundaries of salinity within the lagoon to study the multi-environmental characteristics, again confined to the specific period of investigation (e.g. Rao & Rao, 1974; Radhakrishnan, 1975; Raman, Kaliyamurthy, & Joseph, 1977).

However, until now, there has not been an attempt to derive the overall spatio-temporal trends or a quantification of the sectoral salinity changes. We hypothesize that given its multi-environmental nature, the salinity distribution of Pulicat would drastically vary across the seasons and in response to annual precipitation. Hence, we combined the above perspectives and used the available whole-lagoon datasets to provide deeper insights into the spatial salinity distribution in order to identify the salinity hotspots that drive these changes. In line with the above discussion, our main objective was to observe the annual, spatial and sectoral changes in the salinity of the lagoon in relation to the precipitation and seaward entrance statuses and to identify the regions within the ecosystem that are sensitive to regime shifts in response to sudden salinity changes.

Materials and methods

Study area

Pulicat is a transitional water ecosystem and the second largest after Chilika, on the east coast of India (Figure 1). It belongs to the hot sub-humid to semi-arid ecoregion with coastal alluvium soils. The lagoon is spread over ~450 km^2 with an average depth ~1 – 2 m. A bathymetric profile of the lagoon based on field measurements during 2015 is shown in Figure 1. It has been suggested that the lagoon has become shallower over the years (Sanjeevaraj, 2011).

On its eastern side, the system is connected to the Bay of Bengal through a narrow (~200 to 500 m) entrance located in the southern portion; the exchange of water between the lagoon and the sea primarily occurs here, except at times of total closure. A smaller entrance (~50–150 m) is located in the north devoid of a direct connection with the lagoon and the exchange through this is highly restricted. Thus, we do not consider this feature as a significant factor influencing the salinity dynamics. During the years of very low rainfall and high evaporation, it is common for the complete closures of both the entrances of the system. The effect of evaporation is particularly evident in the northern sectors, especially the eastern sector (Raman et al., 1977) which is devoid of a direct connection to sea or river. High rates of evaporation also increase the influence of secondary flow from the landward side on the hydrological characteristics of the lagoon waters.

On its western shore, two rivers – the Araniar (Figure 1; marked 'A') and the Kalangi (Figure 1; marked 'B') located in the south and north, respectively, bring in the freshwater during the monsoon season (October to December) with the absent or negligible flow in the dry seasons. The annual average flow of Kalangi at the zone of confluence with the lagoon is about 92 MCM while that of Araniar is about 100 MCM (Integrated Hydrological Data, 2015). Dilution from groundwater seepage is negligible, while seawater intrusion through the riverine backwaters has been reported widely (Jasmin & Mallikarjuna, 2015; Raju, Reddy, Muniratnam, Gossel, & Wycisk, 2013). The influx of the freshwater from these rivers, combined with the tidal influx of seawater from the Bay of Bengal, the large-scale monsoonal precipitation as well as influx from small streams such as Buckingham canal endows a multi-
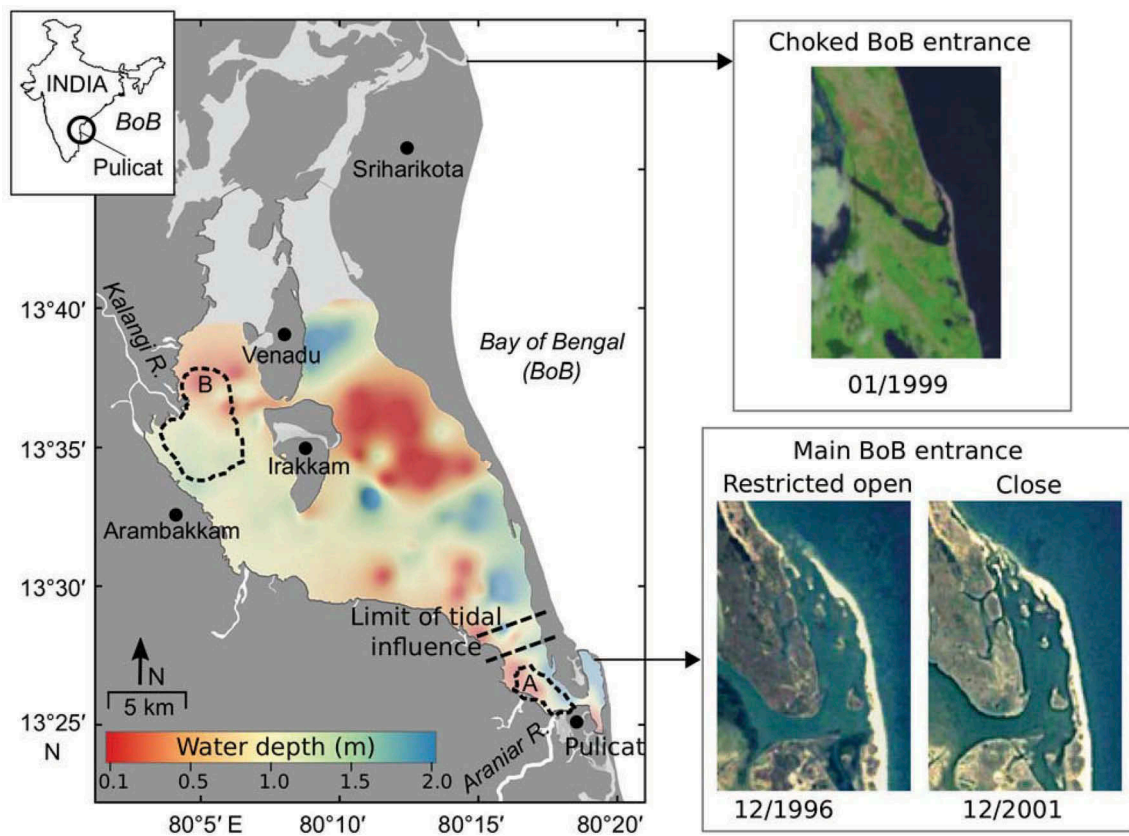
Figure 1. Location of Pulicat lagoon and its bathymetry. Red regions correspond to shallow regions and blues represent the deeper portions. Regions marked 'A' and 'B' correspond to the parts under the influence of rivers Araniar and Kalangi, respectively. The insets show images of the statuses of the southern ("Main BoB entrance"; connected to the sea) and northern ("Choked entrance"; restricted) entrances for selected periods. The gray-shaded northern-most portions are exposed areas of inaccessible marshes for which data is not available.

environment system with high internal salinity fluctuations (Rao and Rao 1975; Figure 2).

Observations on salinities of the lagoon have been linked to different environmental parameters and the lagoonal biota over different periods, such as the populations of plankters (Kaliyamurthy, 1974, 1975); macrophytes (Radhakrishnan, 1975); foraminifera (Reddy & Reddy, 1994); mangroves (Farooqui & Vaz, 2000). Most reports describe the ecosystem statuses with respect to specific parameters such as methane gas evolution (Shalini, Ramesh, Purvaja, & Barnes, 2006), channel zone dynamics (Jayakumar, Steger, Chandra, & Seshadri, 2013) and nutrient distributions (e.g., Nagaraju et al., 1990; Purvaja, Ramesh, Shalini, & Rixen, 2008). Large-scale desalination of the lagoon seems to be a recurring phenomenon, albeit at different spatial and temporal scales. Winckworth (1931) first reported such an occurrence post the heavy precipitation of 1930. Similar events occurred in the aftermath of the 1984 Orissa super-cyclone (Sanjeevaraj, 2011) and also due to the 1996 cyclone (Padma & Periakali, 1999). A more recent 2015 event is comparable to these events and marks the most recent occurrence of desalination, when the lagoon experienced approximately 40% desalination due to the floods (Santhanam & Natarajan, 2018).

Considering the propensity of the system to undergo such sudden salinity drops, especially at the crossover between dry and wet seasons, it becomes essential to take a closer look at the causes and effects of the high internal salinity variations.

Salinity data

Surface water salinities of Pulicat lagoon were compiled from the available discrete datasets (see Table 1 for the list of sources) in the period 1996–2008. The period from PRE to POE corresponds to the critical period of salinity shifts for the lagoon from the dry season (March to September; including the buildup of salinity in the summer season) to the wet season (October to February). Considering the shallow water depth and the lack of stratification in field observations, we treated Pulicat as a 1-D shallow system and the values reported herein represent the salinity of the whole water column of the sites investigated. The locations of the datapoints of salinity observations used for the various years are given in Figure 2, which also shows their distribution throughout the lagoon system. It is important to note that the availability of whole-system datasets is quite limited for Pulicat. Hence, we have selected only such
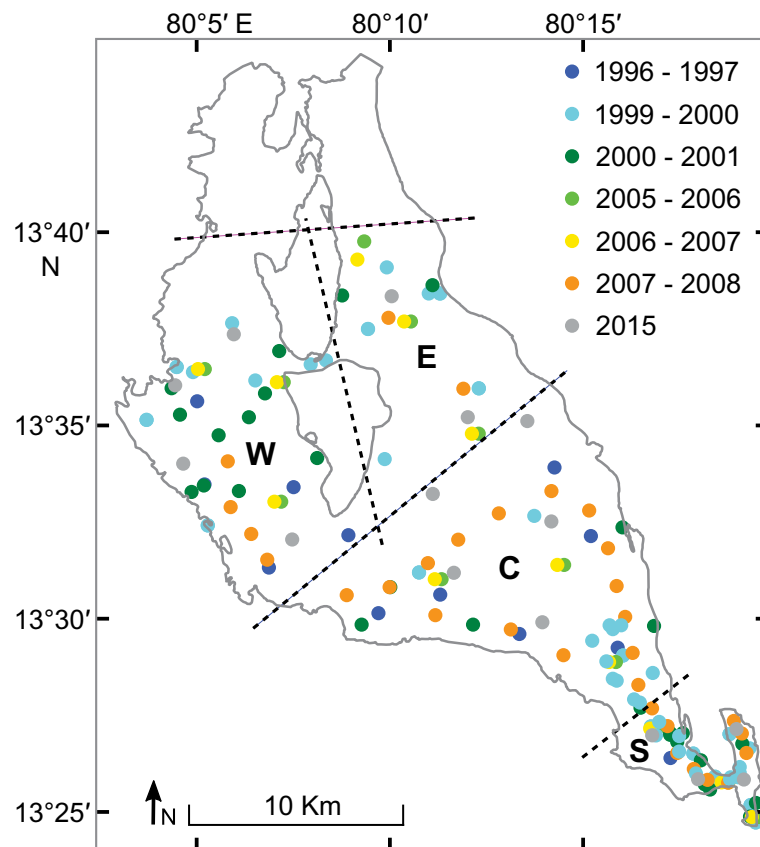
Figure 2. Locations of salinity data observations and sectoral classification of Pulicat lagoon, representing datasets used for the present investigation. 'S', 'C', 'W' and 'E' correspond to the Southern, Central, North-western and North-eastern portions of the lagoon derived considering the zonation described in Rao and Rao (1974), Radhakrishnan (1975) and Raman et al. (1977). The distribution of data points (colorized according to the year of observation) shows the density of observations used for the study.

Table 1. Datasets, their sources and the number of corresponding observations considered for the investigation.

Period	Reference	Analysis for which the dataset is used	Number of observations	
			Premonsoon (PRE)	Postmonsoon (POE)
1996–1997	Padma and Periakali (1999)	Spatial, inter-annual and inter-sectoral analyses	12	12
1999–2000	Lagoons of India Report, ENVIS, (2001)	Spatial, inter-annual and inter-sectoral analyses	26	17
2000–2001	1. No Impact Zone studies, ICMAM Report, (2003)	Spatial, inter-annual and inter-sectoral analyses	20	20
	2. Ramesh et al. (2002)	Spatial analysis	8	0
2005–2006	Harini Santhanam, Ph.D thesis, Anna University, Chennai, India, (2009)	Spatial, inter-annual and inter-sectoral analyses	12	12
2006–2007	Harini Santhanam, Ph.D thesis, Anna University, Chennai, India, (2009)	Spatial, inter-annual and inter-sectoral analyses	12	12
2007–2008	Reddy et al. (2012)	Spatial, inter-annual and inter-sectoral analyses	30	30
2015	Direct field investigation, December 2015; Santhanam and Natarajan (2018)	Spatial analysis	0	15
	Total number of observations		*120*	*118*

datasets during the period of study (1996–2015), which could provide data covering all the sectors. The zonation of the lagoon, as described here, is also shown in Figure 2 for further clarity of the interpretation of the salinity distributions and multi-environmental characteristics.

The rationale behind selecting the different datasets for the current study is explained as follows. Datasets for 1996–1997, 1999–2000 and 2015 are coincident to high flood events as described in the literature (Padma & Periakali, 1999; No impact zone studies, 2003; Santhanam & Natarajan, 2018); we expected that these datasets could reflect high fluctuations in the salinities between premonsoon and post-monsoon periods, corresponding to low or no entrance closures. Data for 2000–2001 and 2007–2008 reflect the periods of lean monsoon (Ramesh et al., 2001; Reddy, Jayaraju, & Reddy, 2012). Such data could be useful to indicate the carry-over of salinities post the periods of low precipitation. Data for 2005–2006 and 2006–2007 (Santhanam Ph.

D. Thesis, 2009) reflect periods of post-tsunami sce-
nario with high rainfall, indicating lagoon exchanges
with the adjacent riverine and sea systems under
stable conditions and moderate entrance closure sce-
narios. Also, the datasets during the periods
2001–2008 would be useful to examine the influence
of secondary salinization of the lagoon under recent
periods of high anthropogenic impacts. We used the
salinity dataset for the POE season of 2015 to illus-
trate the salinity distributions of the lagoon for
a recent period under maximum deviation from the
normal mean (e.g. Santhanam & Natarajan, 2018).
This dataset is used as a standalone dataset for study-
ing the change in the spatial trends as a whole during
the period 1996–2015. We did not use this to study
the trends for successive seasons and years as PRE
dataset for 2015 was not available.

Spatial and statistical analysis of salinity

In order to derive the generalized spatial and tem-
poral trends in the salinity variations across the
lagoon, we created spatial salinity layers from
point salinity observations of each PRE and POE
periods. These layers were created with a grid size
of 100×100 m Geospatial models were obtained
using the bilinear/bicubic spline interpolation
method with Tykhonov regularization in GRASS
environment (Brovelli, Cannata, & Longoni, 2004).
The advantage of using this technique is that the
effect of outliers on the final distribution can be
avoided by ensuring the regularity of the surfaces,
minimizing the curvature in empty areas and
improving the reliability to the classification of
the salinity groups. Through this method, spatial
layers of salinity were generated for the PRE and
POE periods of the years: 1996–1997, 1999–2000,
2000–2001, 2005–2006, 2006–2007, 2007–2008 and
only the POE period of 2015.

The corresponding layers were overlaid through
geostatistical analysis to create mean and standard
deviation layers for PRE and POE periods. The
mean layer indicates the expected salinity value in
a given location while the standard deviation values
indicate the level of variations that have occurred
across the years. Further, we made statistical estima-
tions to represent relative variations between inter
and intra sectoral as well as across years.

We calculated two sets of deviations of mean sali-
nity values to denote intra-sectoral (Equation 1) and
inter-sectoral (Equation 2) changes for both the PRE
and POE seasons of each year. The computed varia-
tions are normalized in percentages.

$$A_i = INTER_{ijz} = (\bar{S}_{ijz} - \bar{S}_{iz}/\bar{S}_{iz}) * 100 \quad (1)$$

$$B_i = INTRA_{ijz} = (\bar{S}_{ijz} - \bar{S}_{jz}/\bar{S}_{jz}) * 100 \quad (2)$$

Where

$i \in \{years : 1996, 1997, 1999, 2001, 2005, 2006, 2007, 2008\}$
$j \in \{Sectors : South, Central, Western, Eastern\}$
$z \in \{Seasons : PRE, POE\}$
$INTER_{ijz}$ = Annual deviation of mean salinity of jth
sector in i^{th} year during z^{th} season denoted as 'A_i'
$INTRA_{ijz}$ = Sectoral deviation of mean salinity of
jth sector in i^{th} year during z^{th} season denoted as 'B_i'
$\overline{S_{ijz}}$ = Mean salinity of jth sector in i^{th} year during
z^{th} season
$\overline{S_{jz}}$ = Mean salinity of jth sector across all the years
during z^{th} season
$\overline{S_{iz}}$ = Mean salinity across all the sectors in i^{th} year
during z^{th} season

In both cases, the percent deviation represents the
extent of dilution (negative value) or concentration
(positive value) of salinity from the mean value in
consideration.

Precipitation and entrance closures

It is important to note that the North-East Monsoon
(NEM; October to December) is more dominant com-
pared to the South-West Monsoon (SWM; June to
September) in the south-east coastal region of India (e.g
Sreekala, Rao, & Rajeevan, 2012). We considered the
mean rainfall for both NEM and SWM for the period
under investigation corresponding to the POE and PRE
periods, respectively. We compiled rainfall data from
available sources as follows: http://hydro.imd.gov.in/;
http://www.indiawaterportal.org/met_data/; http://
www.indiawaterportal.org/articles/district-wise-monthly
-rainfall-data-list-raingauge-stations-india-meteorologi
cal-department. In the absence of data for PRE of 2015,
we consider the POE data as stand-alone. Nevertheless,
we were able to interpret the decadal trends using the
available datasets.

To identify the entrance statuses, we used field
investigation reports (Coulthard, 2008; IOM report,
2003; Nagarjuna, Kumar, Kalarani, & Reddy, 2010;
Reddy et al., 2012) as well as selected satellite ima-
geries from the Landsat 1–5 MSS imageries with
a spatial resolution of 30 m and ETM+ (NASA
Landsat Program, 2013; 20 scenes) licensed for free
use by USGS and NASA, as well as Google Earth
imageries from 1996 to 2015.

Results

The results of the study are briefly described here.
Figure 3 shows the annual trends (A_i) and Figures 4
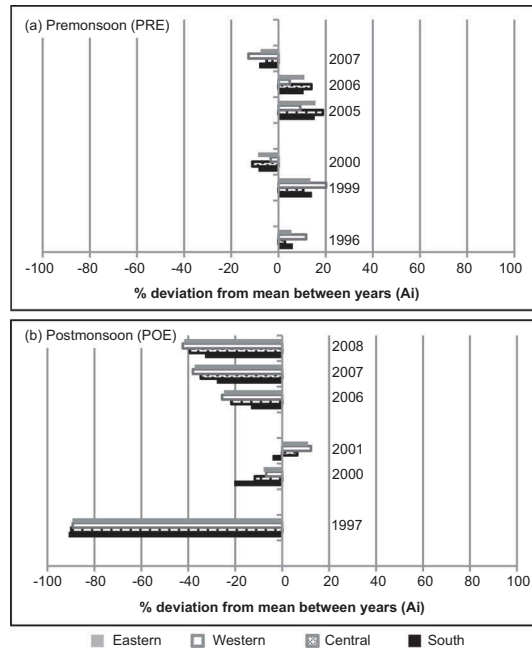and 5 illustrate the spatial trends and percent

Figure 3. Annual mean salinities of Pulicat lagoon during the period 1996–2015. Figure 3(a, b) shows the percent annual deviation (A_i) from the mean annual salinity over the four sectors for PRE and for POE seasons, respectively. '+' indicate the increase in the system salinity between the subsequent periods; '-' indicates the decrease.
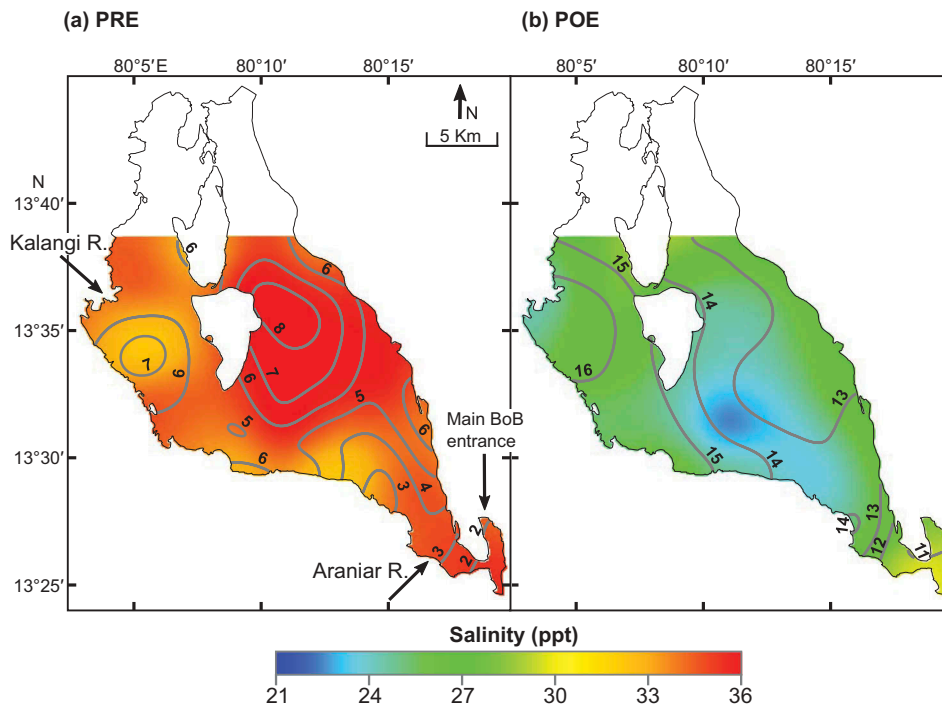

Figure 4. Long-term spatial distributions of the mean surface water salinities of Pulicat in pre-monsoon (PRE) and post-monsoon (POE) periods. Salinity distributions are color coded and the contours represent the respective standard deviations (S.D.) for PRE and POE. Figure 4a and 4b show the spatial variations across the lagoon during PRE and POE, respectively, by overlaying individual spatial distributions for the years to derive the mean distributions and S.D.

deviation of the surface salinities (B_i). Table 2 shows the mean salinities for annual and sectors of Pulicat lagoon. Figure 6 shows the net rainfall for NEM and SWM as well as the entrance statuses during the period of investigation.

Annual trends

We observe that although the overall trends in deviations appear similar, the magnitude of salinity concentration varies in PRE and POE seasons over the years (Figure 3; Table 2). The value of A_i varies
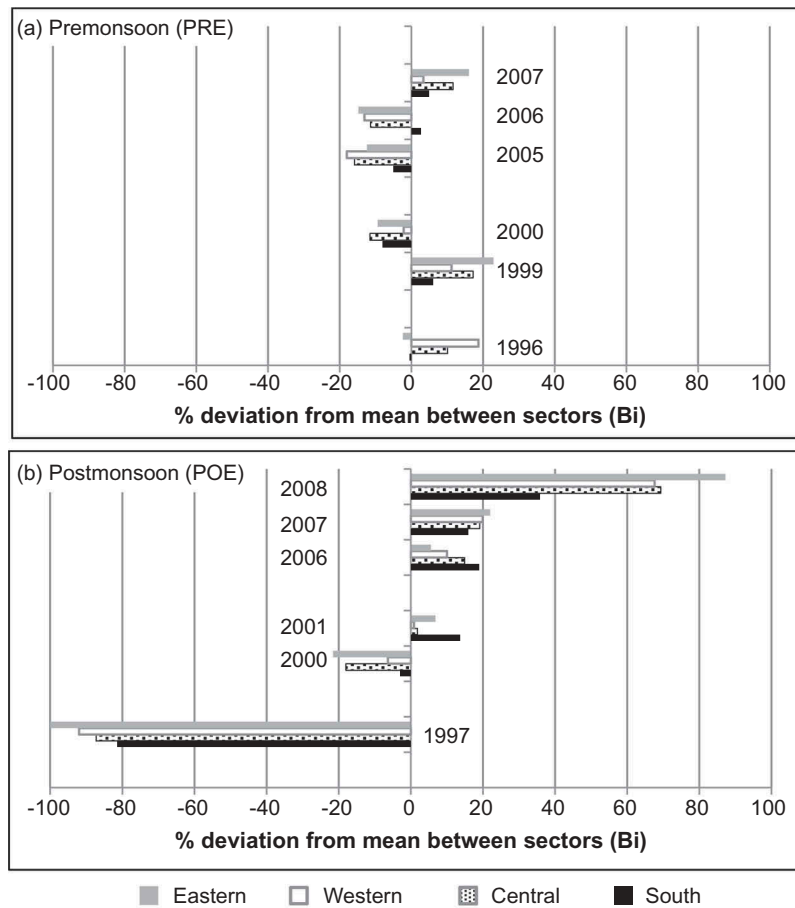
Figure 5. Sector-wise mean salinities of Pulicat lagoon during the period 1996–2015. Figure 5(a,b) show the percent deviation (B_i) from the mean sector-wise salinity over the four sectors for PRE and for POE, respectively. '+' indicate the increase in the system salinity between the subsequent periods; '-' indicates the decrease.

Table 2. Mean salinities calculated from the annual and sector-wise datasets of Pulicat lagoon for successive premonsoon and postmonsoon seasons.

PREMONSOON SALINITY in ppt (PRE)					POSTMONSOON SALINITY in ppt (POE)				
Year	South	Central	Western	Eastern	Year	South	Central	Western	Eastern
1996	35.50	40.56	40.20	35.00	1996	-	-	-	-
1997	-	-	-	-	1997	5.20	3.24	1.92	0.00
1999	37.88	43.17	37.67	44.07	1999	-	-	-	-
2000	32.82	32.58	33.14	32.50	2000	27.23	20.79	22.51	19.08
2001	-	-	-	-	2001	31.93	25.82	24.25	25.97
2005	33.89	30.98	27.76	31.40	2005	-	-	-	-
2006	36.67	32.63	29.43	30.57	2006	33.41	29.14	26.46	25.67
2007	37.47	41.11	35.00	41.62	2007	32.57	30.20	28.83	29.67
2008					2008	38.16	42.93	40.30	45.53
Mean	**35.70**	**36.84**	**33.87**	**35.86**	Mean	**28.08**	**25.35**	**24.05**	**24.32**
	Overall PRE mean			35.57		*Overall POE mean*			24.45

within a maximum range of −12.7 and +20.2% across the sectors for PRE season. For the POE season, the values range between −90.8 and +12.2% across the sectors. Successive PRE seasons across the years illustrate different degrees of dilution or increase in salinities. In contrast, dilution is predominantly evident from successive POE seasons over the years. For the year 1997, low positive A_i values for PRE (<12%) indicating an increase and high negative A_i (>89%) for POE season illustrating dilution are consistent across all four the sectors. High A_i values for PRE are observed in the years 1999 (+20.2%) and 2005 (+18.8%) in the western and central sectors, respectively. Across the years, increase in salinity was the maximum for PRE of 1999 (range of A_i across sectors is +10.5% to 20.2%). Further, the salinity increase in POE of 2001 is a singular occurrence in all sectors (range: +6.5–12.2%) with the exception of the south, where, a low A_i value of −3.9% is observed.
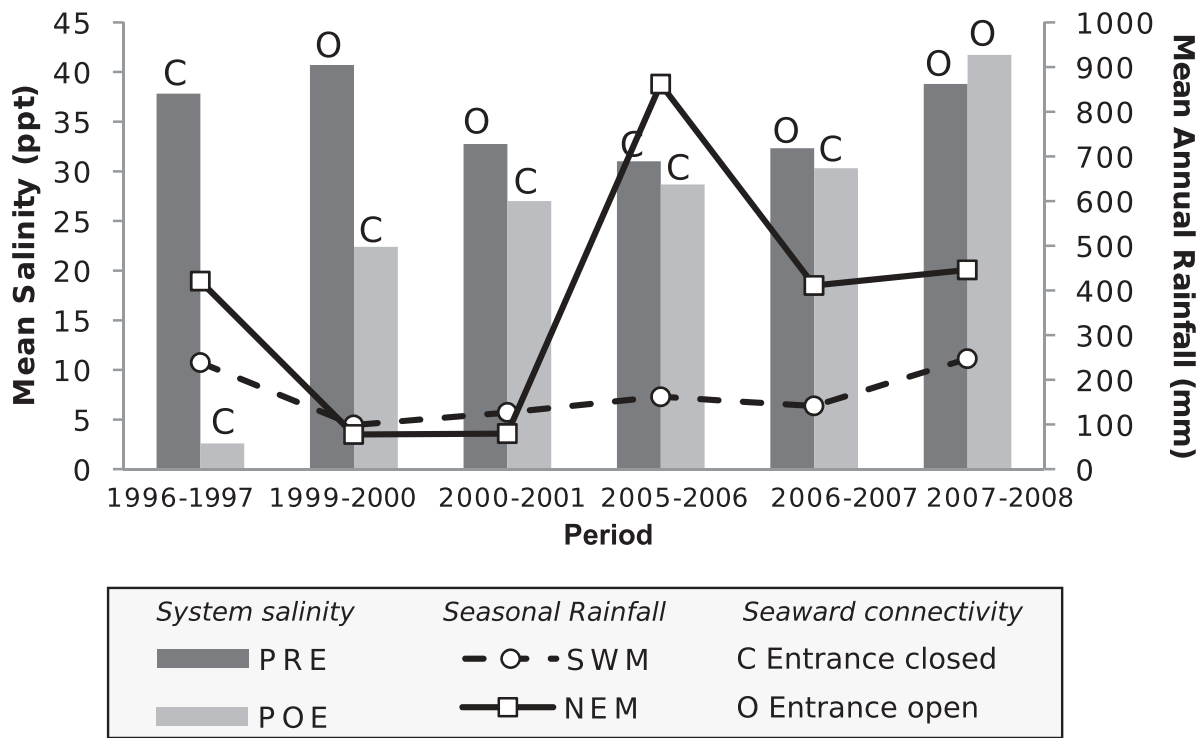
Figure 6. Plots of mean salinity (primary axis) and rainfall (secondary axis) for the pre-monsoon (PRE) and post-monsoon (POE) periods during 1996 − 2008 for the South-west monsoon (SWM; May to September) and North-east Monsoon (NEM;October to December) seasons (Sources: http://hydro.imd.gov.in/; http://www.indiawaterportal.org) are shown. Data for 2015 are not included here. The statuses of connectivity to the sea (BoB) via the southern main entrance are marked as 'C' = closed; 'O' = open, visually interpreted using imageries from Google Earth and field reports (Coulthard, 2008; Nagarjuna et al., 2010; Reddy et al., 2012) without any band transformations or geospatial analyses.

The decrease in the magnitude of dilution in POE is observed as we move from 1997 to 2008, as illustrated by a general decrease in the A_i values for all the four sectors. After a maximum decrease in the extent of dilution in 2001, a slight increase in dilution is observed from 2005 onwards as reflected in their A_i values (Figure 3(b)). The decrease in the magnitude of desalination in POE may be due to the increase in secondary salinization of the lagoon waters through run-offs from the rivers Araniar (South) and Kalangi (Western) and their streams.

Increase or dilution in salinity in POE does not relate well with the extent of rainfall post 2001 (Figure 6). For example, while moderate NEM rainfall in 1997 caused a higher magnitude of dilution, high NEM rainfall in 2006 did not incur a similar magnitude of dilution. However, the closure of the entrance has apparently played a major role in the increase in salinity in PRE of 2005 as well as low dilution in POE 2006. Similarly, the higher than average NEM rainfall in the years 2007 and 2008 alleviated the salinity increase only upto a certain extent. Even though the entrance remained open in 2007 and 2008, the salinity increase is apparently high during these years (Figure 6). With the exception of the years 1996–97 and 2015, we did not encounter dramatic drops in the values of the POE salinities and the general trend evident is that of the cumulative increase in carry-over salinity from the POE to PRE in successive years, making the lagoon more saltier than the preceding years.

Seasonal spatial distribution

Figure 4(a,b) show the overall spatial patterns of salinity variations (in the range of 21 −36 ppt) as observed from the spatial interpolation of the datasets over the period 1996–2015. The differences in the mean salinities are distinct between PRM and POE. It is important to consider the contours representing the standard deviation (S.D) across the lagoon. While the values of salinity variations are higher in PRE across the lagoon, their respective S.D is lesser. In contrast, lower values of salinities with higher S.Ds are observed in the case of POE suggesting a chaotic distribution over wide ranges of salinities.

In both PRE and POE, the southern sector remains the sector with lowest S.D. indicating a somewhat persistent salinity climate across the years among all sectors. A change of 1 ppt S.D is evident within about 10 km into the lagoon from the southern entrance and rapid succession of the 1, 2 and 3 ppt contours for PRE and 11, 12 and 13 ppt contours for POE are evident. This indicates the dynamic nature of the sector during POE and possible deviations to the extents of tidal influences at different years.

Maximum deviation contours of 8 ppt are observed in eastern sector during PRE and 16 ppt are observed in western sector for POE indicating the multi-environmental nature of the lagoon and its inter-sectoral differences in salinity distribution. In the central and the eastern sectors, high salinities are progressively developed during individual years based on the carry-over salinity from the previous POE period as reported in section 3.1. In the case of the southern sector, connectivity to the sea, even if restricted, endows it with a uniform sea-side salinity with less chances for dilution from Araniar river except during extreme events as the 2015 flood event. These observations again imply the multi-environmental responses to the mixing characteristics of the lagoon.

Sector-wise trends

Comparing the extent of deviation from the mean sectoral values (B_i), it is evident that it varies widely for the different sectors, once again illustrating the multi-environmental nature of the lagoon (Figure 5). Significant increases in salinity between PRE and POE are not uniform across all the sectors. The extent of dilution in the southern sector is generally less compared to the other sectors (Figure 5(a)), implying that the existence of uniform salinity conditions in the sector due to its connectivity with the sea. However, random trends are observed for the other sectors (Figure 5(a,b)). The western sector receiving freshwater through Kalangi and its tributaries responds differently to the freshwater influx across the years, which is explained as follows.

Dilution in the salinity seems to occur in the years where secondary salinization was not very significant (e.g. POE of 1997, PRE of 2005 and 2006). Contrastingly, an increase of salinity is observed corresponding to the increase in the secondary salinization through riverine inputs (e.g. 2007 and 2008). The same trend is observed across all the sectors at different magnitudes. Overall, the extent of dilution between successive PRE and POE is observed to be higher in the western sector compared to the other sectors. The maximum extent of dilution from PRE to POE occurred in 1997 at the eastern sector (~100% deviation from mean sectoral value). In contrast, the highest salinity increase is illustrated in the POE of 2008 (>80% deviation) corresponding to secondary salinization in the latter years. Hence, we consider that the nature of salinity changes in the southern and western sectors is different given their proximities with systems of exchanges. This again denotes the differential patterns of changes within different sectors of the lagoon which is an interesting observation showing different spatially constrained regions of the lagoon.

Discussion

It is quite evident from the results of the present investigation that the sectoral changes are pronounced over short term (seasonal) and are influenced by the entrance closures. The magnitude of desalination due to monsoonal dilution increases with distance from the sea under conditions of exclusivity to riverine influences within the lagoon. The overall seasonal spatial distribution illustrates the long-term changes due to desalination events as seen in the years 1997 and 2015.

Increase in the secondary salinization from run-offs contributed by Araniar river and Pulicat back-water channels draining into the southern sector might be the reason for the increase in the salinity in POE post 1999. Similar trends in secondary salinization of aquatic ecosystems have been reported elsewhere (e.g. Nielsen, Brock, Rees, & Baldwin, 2003). This is probably due to massive land-use changes and agricultural practices in the periphery of the lagoon post 1999. It should be highlighted that the central sector is devoid of any connections to the riverine channels, although many small rainwater channels and streams may drain into this portion. Thus, it should be noted that any dilution in salinity would be facilitated through direct surface mixing with the rainwater. The presence of sandy shoals in this portion of the lagoon (Sanjeevaraj, 2011; Santhanam & Natarajan, 2018) contributes to the uneven mixing of the tidal water from the south, with the freshwater from the Western portion under the influence of river Kalangi and the hypersaline water from the stagnant eastern sector of the lagoon. Hence, the impact of secondary salinization is not easily visible in central sector as it was in the case of the southern sector. In the case of the eastern sector, the decrease in circulation and reach of the freshwater into the eastern sector causes an increase in salinity over the years with lower deviations across the years.

However, the differential roles of the sectors of the lagoon as mean "salinity drivers" for the lagoon become evident only in the POE. Central sector is observed to be highly saline in PRE and low to moderately saline in POE, while the Eastern sector illustrates high mean salinities in both PRE and POE. Hence, the transient Central sector can be a "driver" for the high mean salinity during PRE but equally facilitates lowering in salinity in the POE.

The overall trends of sectoral changes, B_i values and S.D. from spatial models, indicate that the short-term salinity shifts changes for the lagoon can be pronounced in the following order of the lagoonal sectors: Western>Central>Southern>Eastern. Thus, we contend that regime shifts due to sudden salinity changes may impact the western sector at a magnitude slightly greater than Southern, Central

and Eastern sectors. It is important to highlight that such regime shifts can be quite rapid and extensive which would flag close-range monitoring. For example, considerable shifts of the mean salinities from the ambient ranges of 20–34 ppt for the western sector could indicate acute high short-term changes to the stable salinity configuration.

The data from 2015 support this observation on a possible regime shift. The salinity dilution in the aftermath of the event was quantified to be approximately 40% (Santhanam & Natarajan, 2018) and concurrently, a high-magnitude diatom bloom comprising most exclusively of the *Biddulphia sp.* has recently been reported closer to the Kalangi influence zone in the Western sector and the Araniar influence zone in the Southern sector (Santhanam et al., 2018). Thus, the present study provides explanation for the observation of a strong relationship of dilution in salinity with observable regime shifts favoring the growth of selective species of biota in the lagoon. Low magnitude impacts, on the other hand, can be anticipated, if the significant deviations from the mean ranges of salinities occur in the southern, central and eastern sectors, respectively, from 31 to 36 ppt, 27 to 37 ppt, and 30 to 37 ppt, especially at biologically sensitive times.

Conclusions

Our investigations illustrated the salinity changes of Pulicat lagoon for the period 1996–2015 across the river-lagoon-sea continuum. The present study highlighted the important trends in annual and seasonal differences in mean salinities and discussed the carry-over salinity from POE to the successive PRE over the shorter periods. It has emerged that the differences in carry-over salinities evolve in reaction to the differential scales of precipitation, entrance dynamics and sectoral exchanges, which in turn determine the long-term trends.

Short-term variabilities would assume importance to Pulicat with its major shrimp and fish landings on the eastern coast of India. These results form the basis for further investigations of the increase of anthropogenic activities in the lagoon near the southern sector (where the Pulicat fish landing center operates) that cause higher secondary salinization through the riverine run-off of Araniar and Kalangi rivers, and consequently, contributing to a higher magnitude of POE salinity changes. The major conclusions from the study are listed below:

(1) Magnitude of dilution decreases as we move toward the latter years, despite high rainfall: e.g. In 2005, 2006.
(2) Closure of bar mouth did not significantly affect salinity decrease in POE in the successive years, suggesting that Pulicat is an intermittently open and closed system.

(3) Western sector always illustrates the higher amount of desalination and the magnitude of desalination of Southern sector close to the sea becomes critical in deciding the extent of export of low-saline waters to the Bay of Bengal.
(4) Secondary salinization from run-off clearly suppresses the dilution effect of precipitation in the lagoon over the long-term leading to higher carry-over salinities between successive seasons.

In the absence of constructed hydraulic channels or periodic dredging operations at Pulicat, the natural processes of long-shore sedimentation and siltation control the entrance dynamics of the lagoon at large. It is interesting to speculate whether such intermittent entrance closures, leading to the increase in high mean salinities of the lagoon are, in fact, a smaller part of a larger feedback mechanism in operation that controls the magnitude of export of low-saline waters to the sea. It is not uncommon for coastal lagoons across eco-regions to develop such special structural and functional controls to achieve high productivity and carrying capacities. If that should be the case, then long-term changes in salinities can offer a clue to detect these self-regulatory operations in place. Our study supports the view that both long-term and short-term changes in salinities of lagoons are crucial markers to understand the regime shifts. In light of these results, it is mandatory to record seasonal observations of ecosystem salinities for evolving effective long-term management strategies for Pulicat lagoon.

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