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# Seasonal variation of oceanographic processes in Indus river estuary

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**सार** – सिंधु नदी के मुहाने में मौसम विज्ञान संबंधी, द्रवगतिकीय (हाइड्रोडायनामिक) तथा जल विज्ञान संबंधी चरों के स्थानिक और कालिक विविधताओं का अध्ययन करने के लिए क्षेत्र की जाँच की गई है। यह जाँच नमी वाले (नदी के सामान्य बहाव) बाढ़ (नदी के तीव्र बहाव) और शुष्क (नदी का शून्य बहाव) ऋतु में बाढ़ एवं बाढ़ के ज्वार के दौरान नदी की सतह तथा उसके नजदीक के तल के आँकड़ों के आधार पर की गई है। ये ज्वार दिन में एकाध बार आए जो लंबे ज्वार भाटे तथा बाढ़ के दौरान छोटे-छोटे ज्वार के साथ असममित पैटर्न दिखा रहे थे। हाइड्रोडायनामिक आँकड़ों से तीव्र मौसमी विभिन्नता का पता चला है, नमी वाली ऋतु के दौरान ज्वार के वेग अधिक देखे गए, शुष्क ऋतु के दौरान नदी की धारा के वेग में थोड़ा अंतर पाया गया। जबकि नमी वाले मौसम में ज्वार भाटा का काल बाढ़ के समय से अधिक लंबा रहा; हालांकि शुष्क मौसम के दौरान कोई महत्वपूर्ण अंतर नहीं देखा गया। इसके ठीक विपरीत बाढ़ की अवधि के दौरान पानी की धाराएँ नदी के तीव्र प्रवाह से काफी अधिक और एक ही दिशा में थीं। जलमार्ग में नमी और शुष्क मौसम के मुकाबले बाढ़ के मौसम में आविलता (Turbidity) का मान अधिक पाया गया। हालांकि जल मौसम विज्ञान संबंधी प्राचलों जैसे: तापमान एवं विगलित ऑक्सीजन से भी मौसमी तथा स्थानिक उतार-चढ़ाव का खुलासा हुआ है यद्यापि वे अनुमत सीमा के भीतर थे। जलमार्ग में लवणता का वितरण नदी के प्रवाह और ज्वार प्रसार से संबंधित था। शुष्क मौसम में उच्च लवणता के मान अभिलेखित किए गए, जिससे पता चला कि नदी के मुहाने में लवणता की विभिन्नता उत्तर अरब सागर से नमक के बलात प्रवेश के कारण होती है, जो नदी के प्रवाह के अनुरूप सिंधु नदी में नहीं है।

वर्तमान अध्ययन से पता चला है कि सिंधु नदी के मुहाने के जल-विज्ञान और द्रवगतिकीय अवस्थाओं में वास्तविक बदलाव सिंधु नदी के प्रवाह में भिन्नता की वजह से है, साथ ही साथ इस क्षेत्र में पवन गति एक अन्य महत्वपूर्ण वायुमंडलीय बल है जो दक्षिण-पश्चिमी मॉनसून के दौरान ज्वारीय बल को बढ़ाता है।

**ABSTRACT.** Field investigations were conducted to study spatial and temporal (seasonal) variations in meteorological, hydrodynamic and hydrological variables in Indus River Estuary. The investigations were undertaken during wet, (moderate fluvial discharge), flood (highest fluvial discharge) and dry (zero fluvial discharge) seasons to obtain surface and near bed data during flood and ebb tides. Tides were semidiurnal, showing an asymmetric pattern with longer ebb tides and shorter flood tides. The hydrodynamic data revealed strong seasonal variation, the ebb velocities were significantly higher than flood current velocities during wet season, whereas a slight difference was found in current velocities during dry season, while the ebb phase lasted longer than flood during wet season; however no significant difference was observed during dry season. On the other hand during flood period the water currents were substantially higher and unidirectional related to the strong river flow. Turbidity values were considerably higher during flood season, than wet and dry seasons along the channel. However hydrological parameters such as temperature and dissolved Oxygen also revealed seasonal and spatial fluctuations, though they were within permissible range. The salinity distribution along the channel was related to the incoming river flow and tidal propagation. Higher salinity values were recorded in dry season, suggested that salinity variation at Estuary was due to salt intrusion from the North Arabian Sea, related to the absent of fluvial discharge form Indus River.

Present study revealed substantial changes for hydrology and hydrodynamic conditions of the Indus River Estuary, related to the varying Indus River flow, as well as winds are another important atmospheric force in this region which enhanced the tidal forcing during southwest monsoon.

**Key words** – Estuarine, Hydrodynamic, Hydrology, Variation, River discharge.

## 1. Introduction

The estuary is where freshwater from natural water bodies especially rivers and streams reaches to the mouth of ocean and mixes with saline water (Cameron and Pritchard, 1963; Pritchard, 1967). The estuarine ecosystem has a pivotal role in productivity of earth ecosystem (Day *et al.*, 1989), also considered as nursery areas of commercially important species and number of other ecologically significant aquatic organisms (Kaiser *et al.*, 2005). Estuaries are highly dynamic with respect to physical and chemical processes along coastal zone. Meteorological and physical factors such as precipitation, winds, currents, tides are involved in creation of such a dynamic nature of system. Among various factors, the tidal cycle is responsible for fluctuation in important parameters of water, e.g., salinity, dissolved oxygen concentrations, temperature, turbidity and nutrient distribution. Hence the continuous research and monitoring of such processes is very important for protection, management and sustentation of these natural environments. Indus river estuary, one of the estuaries has been least studied on physical and chemical processes, it is located (24.15°, 67.66° - 23.98°, 67.4°) along North Arabian Sea. Indus delta is the sixth largest delta in the world, with a fan shaped structure built by huge amount of silt flowing down from the upland and mountains through Indus River, which covers a distance of about 2880 km to meet the North Arabian Sea (Abbasi, 2002). The current delta covers an area of about 600,000 hectares that is distributed in 17 major creeks and several minor creeks, mud flats and mangroves (Meynell and Qureshi, 1993). As shown in Fig. 1, the Indus River estuary is about 40 km long with a basin area of 36 km$^2$, comprising of 7 major tributaries, *i.e*., Rohro, Mutni, Wadh, Khund and Watho on left hand side, while Bhoori and Aado War on right-hand side. The main channel of Indus river estuary is called Khobar (Kalhoro *et al*., 2016), which creates a complex system of swamps, streams and mangroves forests.

Physically, the Indus River estuary can be categorized as the partially-mixed coastal plain estuary. The coastal climate is arid sub-tropical and is under the influence of biannual monsoonal cycle. The summer or South-West (SW) Monsoon covers the period from May to September and the winter or North-East (NE) monsoon from November to February. The SW and NE monsoons winds have significant influences on the physical and climatic scenario of the region (Banse, 1984). Wind speed during the SW Monsoons reaches up to 30 knots, which is more vigorous than the NE monsoon with the wind speed of 5-10 knots. The SW monsoon has capability to penetrate below the thermo-cline and affect the water movement while NE monsoon water movement is shallow (Majeed *et al*., 2010). Since Indus Delta is situated in a semi-arid climate zone with a quite low annual rainfall, the precipitation varies between 150-250 mm during the

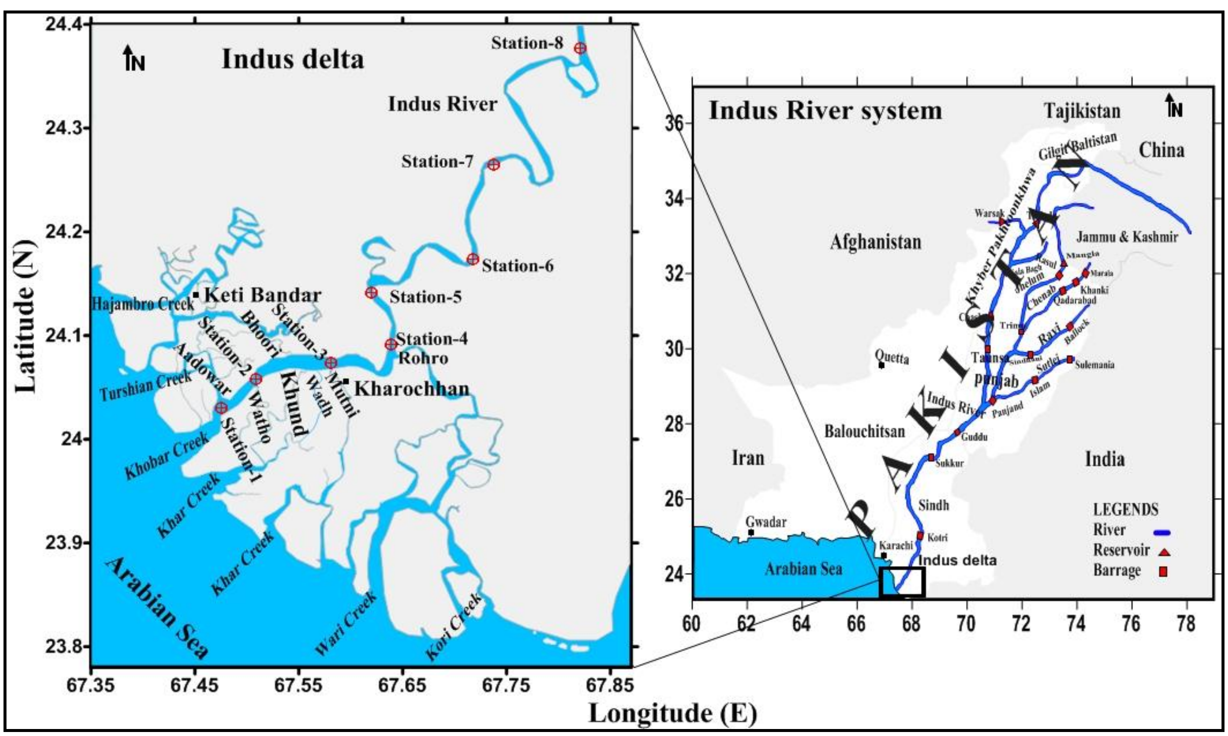



**Fig. 1.** Study area with the location of observational stations

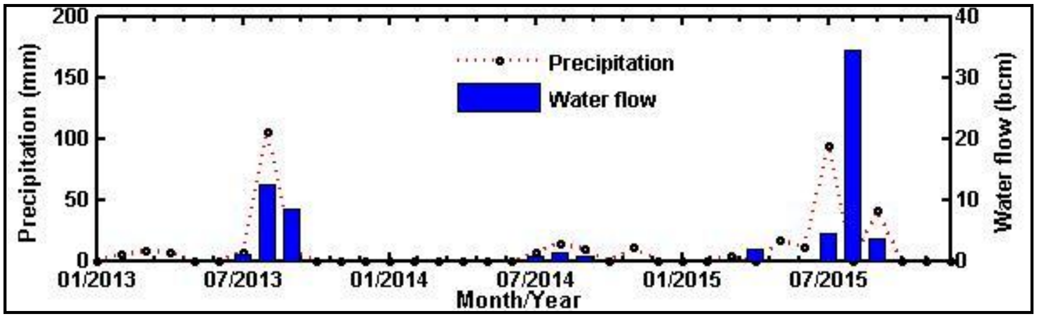


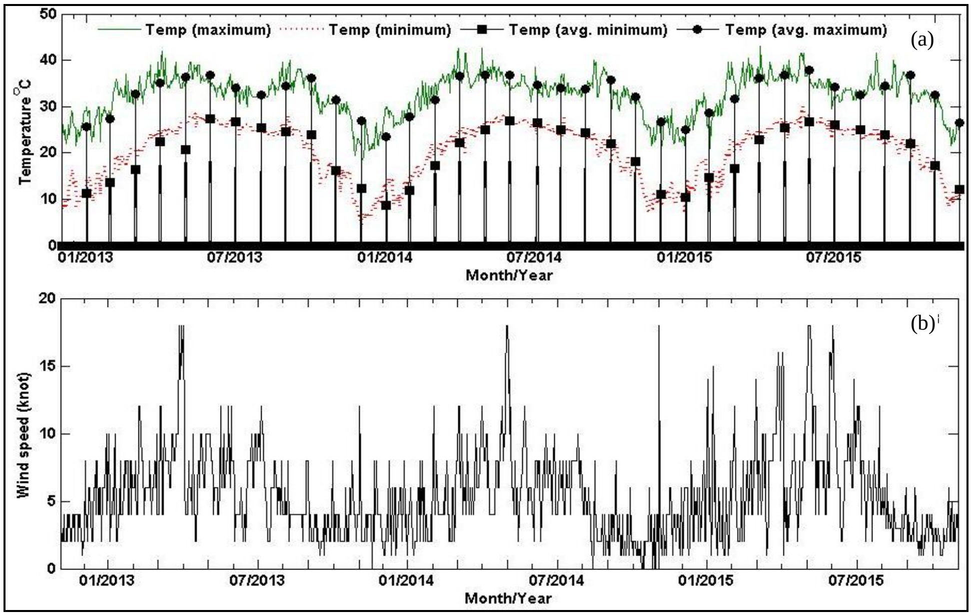

**Fig. 2.** Monthly precipitation in Indus deltaic region and river flow below Kotri barrage (2013-2015)

year. The average annual rainfall on the Sindh coast is 220 mm and the temperatures range between 23.8 and 28.7 degree Celsius (ADB & IUCN 2002).

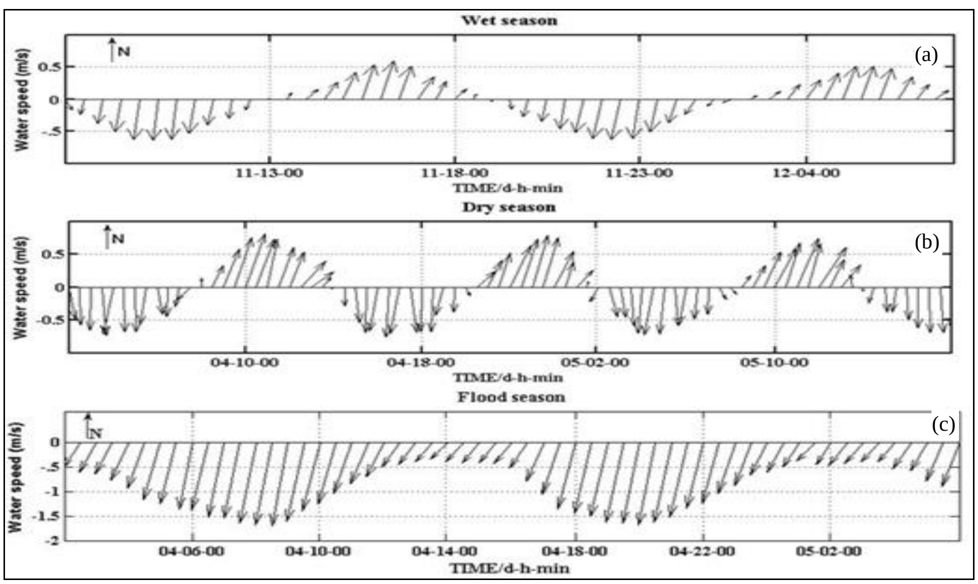
Seasonal variations are found in hydrographical and hydrodynamic characteristics of the Indus River estuary. According to Kravtsova *et al.* (2009), abrupt decrease in water and sediment runoff in the Indus River has significantly affected the hydrological processes in its estuary. The main cause of freshwater decline is due to the large-scale hydraulic engineering activities in the Indus River basin, runoff regulation and water withdrawal for irrigation and hydro-power plants. The major factor influencing the oceanographic processes of the Indus River estuary is the fluctuations in Indus River flow since the variations in fluvial discharge have a direct influence on salinity. Correspondingly, the regulation of estuarine biological production, sediment transport and water quality is impacted (Kasai *et al.*, 2010). However, the physical oceanographic aspects in the Indus delta creeks and coastal waters are poorly understood (Kidwai, 2004; Kravtsova *et al*., 2009) because of the shortage of detailed field observations. Therefore, present paper is the first study to investigate spatial and temporal variations of physical processes in Indus River estuary, which will be useful in the field of hydrology and coastal oceanography. In present study, we focus to analyze the effects of seasonal variation of Indus River discharge and meteorological conditions (wind and precipitation) on hydrodynamic (currents and tides) and hydrological variables (temperature, salinity, turbidity, dissolved oxygen), in a sub-tidal zone during dry, wet and flood seasons.

## 2. Methodology

Field data in Indus River Estuary (IRE) was collected by two approaches; one by in situ field surveys, while another by obtaining meteorological and hydrological data from PMD (Pakistan Meteorological Department) and Chief Engineer Kotri Barrage, Irrigation department Government of Sindh, respectively. Field surveys for the collection of oceanographic data were carried out during wet (July-September, 2014), flood (July-September, 2015) and dry (December, 2014 and January-March, 2015) seasons, respectively. The observations were carried out at every 8 km from the river mouth until 64 km upstream at the mid-channel. There were 8 stations observed along the IRE as shown in Fig. 1. Among these stations, the measurements at station-3 (20 km inside the river mouth) were conducted for 25 hours during wet (September, 2014) season, 41 hours during dry (March, 2015) season and 29 hours during the flood (September, 2015) period, respectively, including vertical profile of water temperature, salinity, dissolved oxygen, turbidity, water speed and direction. Meanwhile, the water levels, temperature and turbidity were recorded at station-3 for 40 days continuously on hourly basis and salinity was also recorded for 50 days at station-3 during wet and dry seasons. In addition 64 km longitudinal profiles of salinity was obtained at all 8 stations along the channel, while water samples collected after every 8 km at the surface and bottom inside the river during wet, dry and flood seasons. Water levels were recorded every 10 minutes for 40 days by using a pressure sensor based tidal gauge RBR Model No. 2050, fixed near fishermen floating jetty to the measuring profile. The continuous water temperature and turbidity were observed by RBR Model No.2050 and RBR Model XR-420, respectively. Currents were measured using a boat-mounted 1,200 kHz ADCP (Acoustic Doppler Current Profiler). However, 64 km longitudinal profile of salinity was obtained from water samples collected after every 8 km at the surface and bottom with a 5 L Niskin bottle inside the river. Water quality parameters of temperature, dissolved Oxygen and salinity were observed using a water quality meter (Hydrolab Model MS-5). Luminescence Dissolved Oxygen (LDO) optical dissolved Oxygen sensor of the water quality meter was calibrated with saturated air in synthetic seawater according the manual. Dissolved Oxygen was measured chemically through the Winkler method (Parsons, 1984). Salinity sensor of water quality meter was calibrated through standard saline water.




**Figs. 3 (a&b).** (a) Daily minimum and maximum temperature, monthly average minimum and maximum temperature (b) and daily maximum wind speed, from January 2013 to December 2015




**Figs. 4(a-c).** (a) Water currents mean velocities at station-3 during September 2014 (wet season) (b) March 2015 (dry Season) (c) and September 2015 (flood season)

## 3. Results

### 3.1. *Climate, winds and river flow*

The climate of Sindh Coast is arid sub-tropical under the influence of biannual monsoonal cycle. The summer or South-West (SW) Monsoon covers the period from May to September and the winter or North-East (NE) monsoon from November to February. The SW and NE monsoon winds have significant influences on the physical and climatic scenario of the region. A major factor influencing the oceanographic processes of the Indus coast is the discharge of the Indus River. Since Indus Delta is situated in a semi-arid climate zone with a quite low rainfall, therefore mangroves of Indus Delta are

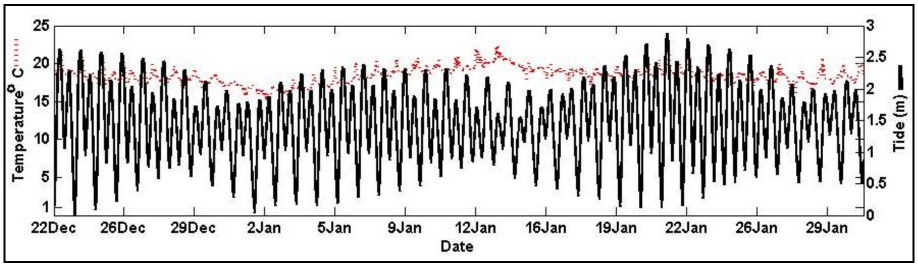
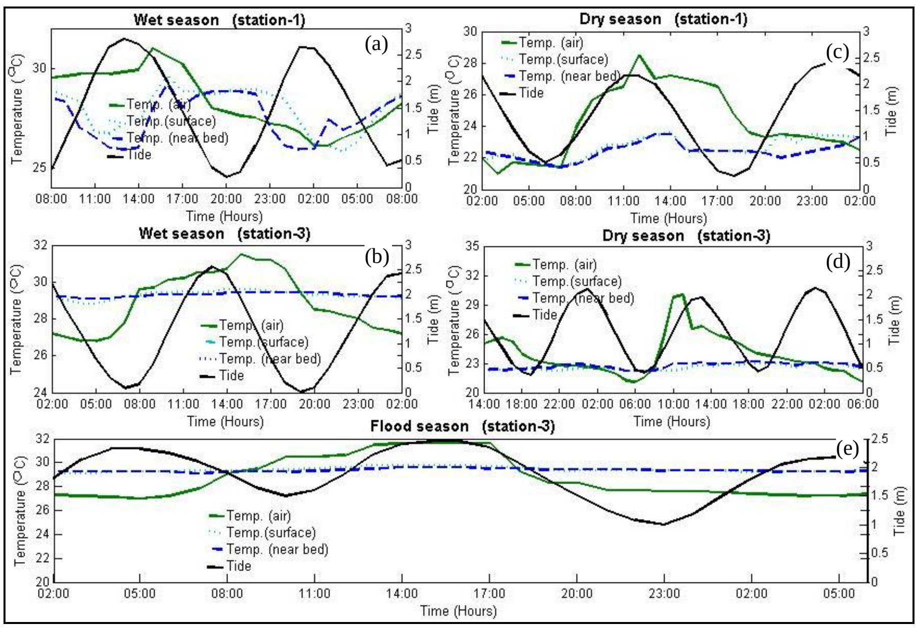



**Fig. 5.** Tide and water temperature variations at station-3 (dry season)




**Figs. 6(a-e).** Hourly temperature variation at station-1 (a) wet (c) dry and station-3, during (b) wet, (d) dry and (e) flood, seasons

largely dependent upon the freshwater discharges from the Indus River. In our study, total annual river discharge and precipitation were observed in the wet season, extended from July to September, while the remaining months were associated with dry season in which river discharge was close to zero.

The hydrological runoff data obtained from the Executive Engineer Kotri Barrage, last barrage on the Indus River about 150 km away from coast, revealed a total discharge of 22.3, 2.58 and 44.55 BCM (billion cubic meter) for the year 2013, 2014 and 2015 respectively. Whereas 22.05, 2.519 and 42.41 BCM discharge was observed during (July-September) months of 2013, 2014 and 2015 respectively. Thus, river flow is irregular and limited to only 2-3 months throughout the year, as shown in Fig. 2.

In order to characterize seasonal variation in climatic parameters, the metrological data including minimum and maximum air temperature, precipitation, wind speed and direction was obtained from the nearby Meteorological automatic weather station Keti Bandar, located at a distance of 15 km from the study area, maintained by Pakistan Meteorological Department (PMD). Three-year's data suggested that average annual rainfall was 11.65, 3.31 and 13.74 mm during the year 2013, 2014 and 2015, respectively; however, maximum rainfall was observed during the months of July-September as shown in Fig. 2. The strongest winds, mainly from the southwest, were observed during the summer season with a maximal speeds up to 18 knots, while the moderate winds from the northeast were common during the winter season with a maximal speeds up to 10 knots as shown in Fig. 3(b). The daily minimum temperature varied between 6.5 to 28.5 ºC, while maximum temperature (19.5-42.5 ºC) was recorded from 2013 to 2015. Whereas monthly average minimum temperature varied from 8.7 to 27.45 ºC, while monthly average maximum temperature ranged 23.6 to 37.8 ºC, however maximum temperature was observed during summer as shown in Fig. 3(a). Whereas during the wet season (September, 2014) of study period minimum and

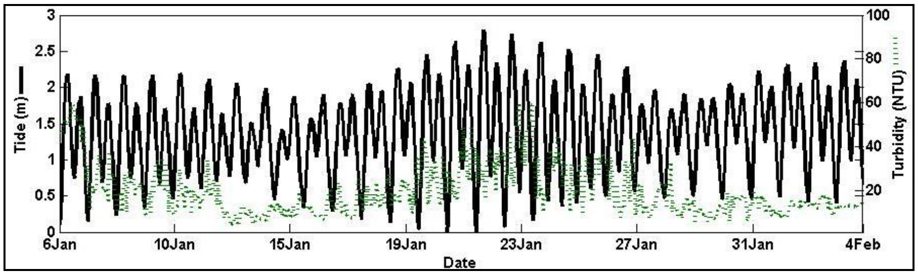
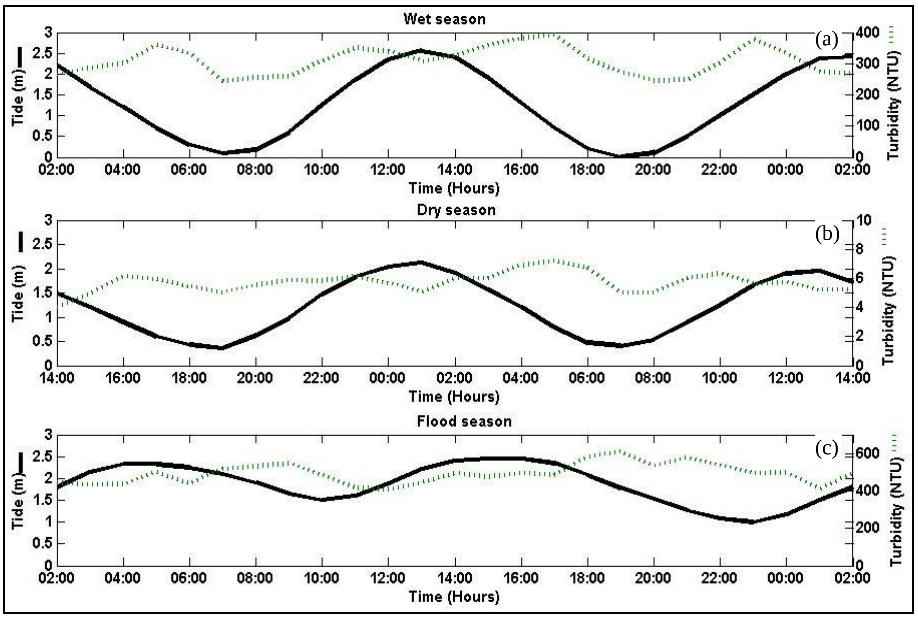



**Fig. 7.** Hourly tide and turbidity variations at station-3 (dry season)




**Figs. 8(a-c).** Hourly tidal and turbidity variations over a tidal cycle at station-3, during (a) wet, (b) dry and (c) flood, seasons

maximum temperature reached at 24.0 to 24.5 ºC and 33 to 34 ºC respectively, however, wind speed ranged between 2-8 knots. While during dry season (March, 2015), air temperature ranged 14-29 ºC, wind speed varied from 2 to 14 knots. Whereas during flood period (September, 2015) minimum and maximum temperature varied from 23 to 24 ºC and 32.5 to 33.5 ºC respectively, however, wind speed ranged between 2-6 knots. The wind direction was predominantly from the Southwest during the study period.

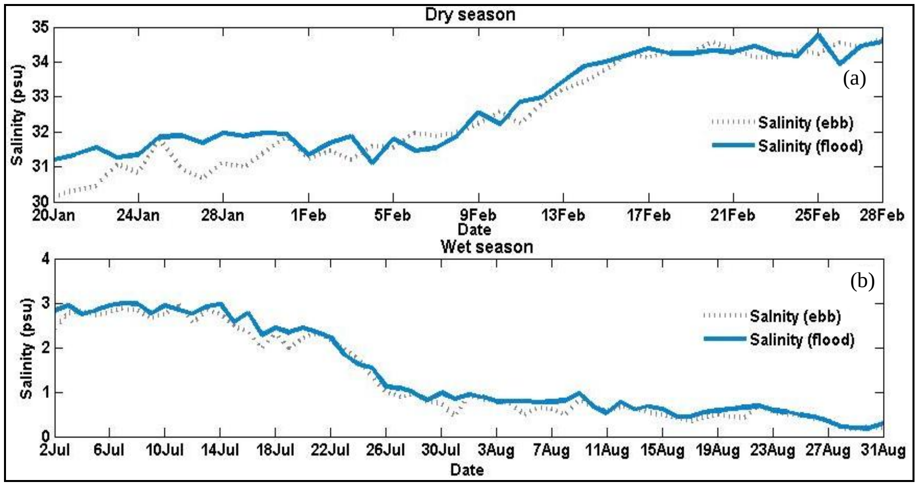
3.2. *Tides and water currents monitoring*

The tidal levels and near bed water temperature were continuously observed at station-3 for 40 days during dry season (December-January) as shown in Fig. 5. The maximum range of the spring tide was 2.79 m, while the neap tides less than 2.63 m. The tides were semi-diurnal in nature, but diurnal tidal asymmetric was found in all observations. These were categorized as Higher High Water (HHW), Lower High Water (LHW), Higher Low Water (HLW) and Lower Low Water (LLW).

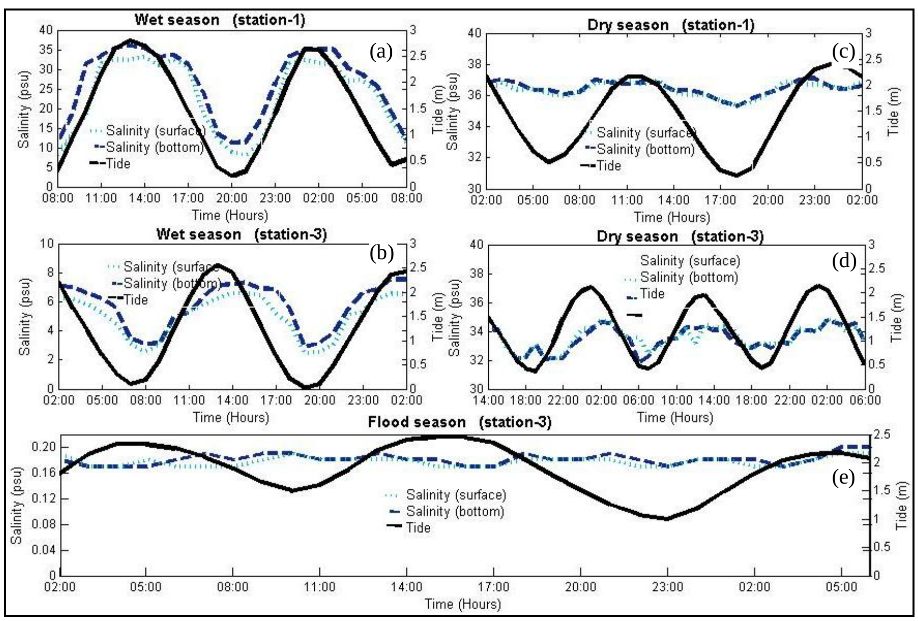
Hydrodynamic data showed a strong seasonal variation in water circulation. During dry season when river discharge was near to zero, the maximum current intensities were 0.72 m $s^{-1}$ and 0.75 m $s^{-1}$ during flood and ebb phases, respectively, as shown in Fig. 4(b). However during wet season, when water discharge was about 300.65 $m^3s^{-1}$ the maximum current velocities were 0.62 m $s^{-1}$ at the ebb and 0.58 m $s^{-1}$ at the flood phase, while ebb phase lasted longer than flood phase as shown in Fig. 4(a). On the other hand during flood period, the water currents were substantially higher as a consequence of strong River discharge below the Kotri barrage, that was about 1500 $m^3s^{-1}$, the ebb currents were dominant and uni-directional due to fluvial discharge, hence the flood velocities were absent as shown in Fig. 4(c). The minimum and maximum ebbing velocities were 0.42 and 1.64 m $s^{-1}$ respectively during the survey period.

3.3. *Temperature*

The results of seawater temperature revealed that the sea water temperature varied from 15.03 to 22.30 ºC



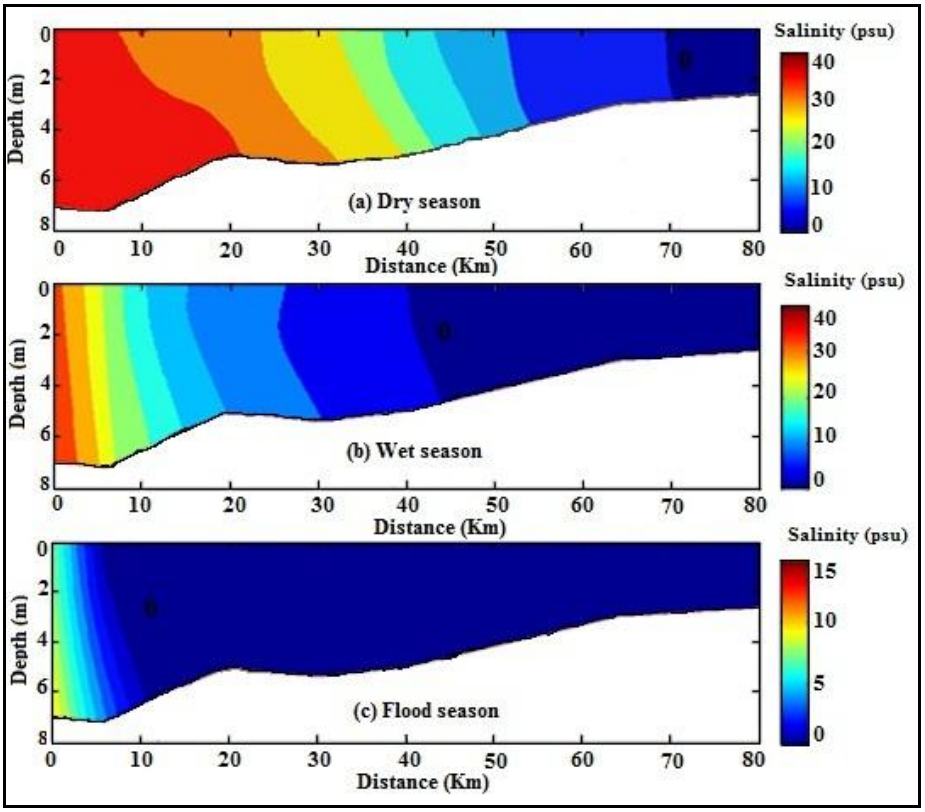

**Figs. 9(a&b).** Daily water salinity variations during ebb and flood tide at station-3, during (a) dry and (b) wet, seasons




**Figs. 10(a-e).** Hourly water salinity variation at station-1 (a) wet, (c) dry and station-3 (b) wet, (d) dry and (e) flood, season

during dry season. The seawater temperature was slightly higher during the peak high tide, while spring-neap variability was not significant (Fig. 5). Station wise temperature data showed that during the wet season at station-1, air temperature varied from 26.10 to 31.0 ºC, while the surface water temperature ranged from 25.80 to 28.80 ºC and near bottom temperature varied from 25.90 to 29.20 ºC [Fig. 6(a)].

Whereas, temperature values were higher at station-3, air temperature varied from 26.80 to 31.50 ºC, surface water temperature ranged from 28.80 to 29.60 ºC and near bottom temperature remained stable ranging between 29.10 - 29.40 ºC [Fig. 6(b)]. However during the flood period temperature values were higher, air temperature varied from 27.0 to 31.60 ºC, surface water temperature ranged from 29.10 to 29.80 ºC, while near bed temperature varied from 29.10 to 29.60 ºC [Fig. 6(e)]. On the other hand, during dry season, temperature was lower than wet season, at station-1 the air temperature ranged from 21.0 to 28.5 ºC, while the surface and near bed water temperature varied from 21.4 to 23.6 and 21.4 to 23.5 ºC respectively [Fig. 6(c)]. However at station-3, air temperature ranged between (21.10-30.0) ºC, while the surface water temperature and near bed temperature were ranged from 22.2 to 23.0 ºC and 22.2 to 23.20 ºC respectively [Fig. 6(d)].




**Figs. 11(a-c).** Longitudinal distribution of salinity along IRE during (a) March, 2015 (dry season) (b) September, 2014 (wet season) and (c) September, 2015 (flood period)

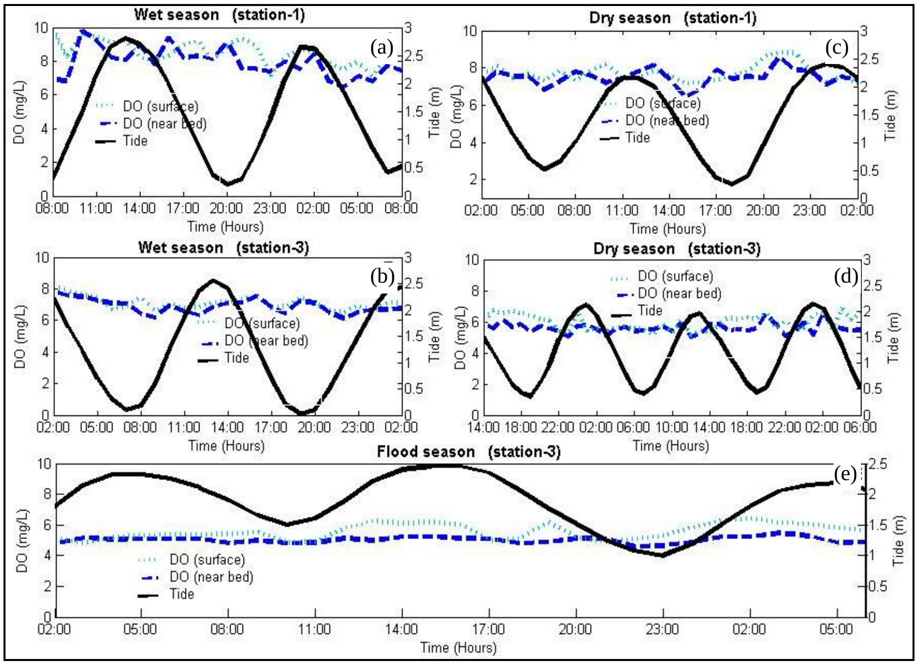
3.4. *Turbidity monitoring*

The tidal levels and turbidity were continuously recorded at station-3 from January, 2015 to February, 2015 during dry season (Fig. 7). The turbidity values varied from 4.14 to 60.14 NTU (Nephelometric Turbidity Unit), during the dry season (January-February, 2015) at station-3. Time series data of turbidity suggested that turbidity was higher during mid ebb and mid flood, when water current velocities were higher. As the spring/neap variation was significant, turbidity was higher during spring than neap tide.

The season wise turbidity values at station-3 revealed that, turbidity ranged from 243 to 392 NTU during the wet season (September, 2014) [Fig. 8(a)], while it varied from 4.02 to 7.24 NTU during dry season [Fig. 8(b)]. However, the strong fluvial runoff was dominant during flood period (September 2015), hence turbidity values were substantially higher varied from 410.33 to 612.50 NTU during survey period as shown in Fig. 8(c).

3.5. *Salinity distribution*

During the wet (July-August) and dry (January-February) seasons water salinity was continuously observed at station-3. The time series data revealed that salinity ranged from 0.17 to 3.0 PSU (practical salinity unit) during wet season, hence a decreasing pattern was observed from July to onward [Fig. 9(b)]. On the other hand during dry season, salinity varied from 30.12 to 34.65 PSU, thus an increasing trend was indicated from January to onward [Fig. 9(a)]. During the wet season, lunar hourly profile of salinity at station-1 (near the mouth) revealed that salinity varied from 7.95 to 33.04 PSU at ebb and 11.22 to 36.12 PSU at flood phase [Fig. 10(a)]. The salinity was higher during two high tides, while lower at ebb tides. However, a slight variation from surface to bottom was observed during both tidal phases. Whereas at the station-3, salinity ranged from 2.46 to 6.57 at the surface and 2.88 to 7.53 PSU at the bottom, respectively [Fig. 10(b)]. The salinity was strongly influenced by the river runoff, hence flood-ebb variation was not significant.




**Figs. 12(a-e).** Hourly dissolved oxygen variation at station-1 (a) wet, (c) dry and station-3, (b) wet, (d) dry and (e) flood seasons

However, during the flood period, the river flow was dominant, hence salinity near the mouth was almost absent and the flood-ebb variation was insignificant, in which salinity ranged from 0.17 to 0.20 PSU at station-3 [Fig. 10(e)].

On the other hand during the dry season, when the river discharge was near to zero, salinity ranged from 35.31 to 37 PSU at the surface and 35.32 to 37.10 PSU close to the bed respectively, at station-1 (near the mouth) as shown in Fig. 10(c). The same trend was observed at station-3, the salinity varied from 31.80 to 34.64 at surface and 32.08 to 34.8 PSU near to bed [Fig. 10(d)].

The station wise variation of salinity was recorded during wet, flood and dry periods. During the wet season mean salinity varied from 0 to 26.28 PSU, the maximum (26.28 PSU) and minimum (0.21 PSU) salinity was observed at station-1 and 7 respectively. While salinity was absent at station-8, about 64 km upstream as shown in Fig. 11(b). Whereas during the flood period, the salinity was controlled by strong flood water discharged from river Indus, hence salinity was considerably lower in the mouth where the sea water was greatly diluted by the freshwater. The salinity varied from 0 to 5.22 PSU, the minimum salinity (0.148 PSU) and maximum (5.22 PSU) were recorded at station-1 and station-5 respectively. While salinity was absent at stations (6, 7 and 8) as shown in Fig. 11(c). On the other hand during dry season, river discharge was negligible, hence salt water penetrated a longer distance to upstream, the station wise mean values of salinity were 36.48, 34.16, 33.50, 33.33, 28.71, 21.35, 10.34 and 4.92 PSU at station-1, 2, 3, 4, 5, 6, 7 and 8 respectively. The minimum value was observed at station-8 about 64 km upstream, while maximum salinity was recorded at station-1 (near the mouth) as shown in Fig. 11(a).

### 3.6. *Dissolved Oxygen (DO)*

In the present study, DO values varied from 7.10 to 9.92 mg/L at station-1 [Fig. 12(a)], while at station-3, DO values were slightly lower than station-1, ranged from 6.52 to 8.14 mg/L [Fig. 12(b)] during wet season. Whereas during dry, season, DO values ranged from 7.14 to 8.82 mg/L at station-1 [Fig. 12(c)], while DO values were slightly lower at station-3, ranged from 5.12 to 6.86 mg/L as shown in Fig. 12(d). However, during flood season DO values were substantially lower varied from 4.80 to 6.40 mg/L [Fig. 12(e)].

## 4. Discussion

The hydrographic and hydrodynamic conditions in Indus river estuary showed strong seasonal variability. Three-years' meteorological record revealed that Indus delta is located in intense heat zone and under the influence of southwest monsoon, with dominant wind direction blowing from the south and precipitation being very low, hence Indus delta is largely dependent on Indus river discharge (Majeed *et al*., 2010; Khan *et al.*, 2002). The water flow record below the Kotri barrage revealed a strong variation in river flow discharge. In normal condition Indus delta received water during the months of July-September, Inam *et al.* (2007) also made the similar reports. Thus Indus delta remained dry throughout the year except two or three months of wet season or during the super flood years when glaciers melt up at the upper basin (Chandio *et al.*, 2011). Hence the seasonal variation of flow discharge from Indus River greatly affected the dynamic behaviour of estuary and resulted in salt water intrusion, especially in dry season.

The tidal levels recorded during the study showed an asymmetric pattern with longer ebb tides and shorter flood tides, however, tidal asymmetry was more significant during wet season, possibly influenced by river inflow during wet season. In normal conditions the local circulation was dominated by the tidal currents with predominantly northeastward flow during flood tide and southwestward flow during ebb tide on a semi-diurnal cycle of about 12 h and 15 min. During the wet season ebb currents speed was significantly higher than flood currents, while the flood currents were weaker overall, possibly river discharge contributed to faster ebb currents, same pattern was found by (Gomes *et al.*, 2013) in Caete' Estuary North Brazil. However during dry season ebb and flood currents were nearly equal and tidal asymmetry was not significant, probably related to the absent of fluvial discharge. On the other hand during super flood period, when the fluvial discharge was at its highest level, the velocity of ebb currents reached up to 1.64 m/s, as a consequence the flood currents were absent and ebb currents were dominant and unidirectional related to strong river flow. This is in agreement with (Godin, 1999) who reported that river discharge reduces the duration of the period of flood flow.

Salinity is one of the important factors which have great influence on the abundance and distribution of marine organisms and estuarine environment (Manikannan *et al.*, 2011). The time series observation of salinity at station-3 revealed that a strong seasonal variation was observed from dry season to wet season. The salinity was lower during the wet season influenced by river discharge and a decreasing pattern was observed from July to onward, while the salinity values were very high during the dry season because of the intrusion of seawater and an increasing trend of salinity was observed from January to onward.

In the present study the lunar hourly profile of salinity at station-1 (near the mouth) revealed that the salinity ranged from 7.95 to oceanic value (36.12 PSU). The lowest and highest values of salinity were highly associated with tides and river discharges. The same pattern was found by (Dixit *et al.*, 2013) in Mahandi river of India. Salinity values were lower at station-3 during wet season where salinity was strongly influenced by the river runoff, hence salinity was nearly absent during ebb tide and the flood-ebb and vertical variation was very small. On the other hand, during the flood season river flow was dominant at all stations (1-8) and suppressed the tides (Horrevoets *et al*., 2004), hence salinity was almost absent during ebb and flood tides.

However, during the dry season, coastal waters were dominant at station-1, hence salinity was substantially higher. The same pattern was observed at station-3, as a result of nearly no discharge of fresh water below Kotri Braarage during dry season. Similar reports were also given by previous researchers (Warsi, 1991; Kijine *et al*., 1992; Ahmad, 1993; Amjad *et al.*, 2003). However a small variation in salinity was found between station 1 and 3, which indicated a small discharge from agricultural lands or seepage.

The longitudinal measurements showed that salinity was highly impacted by river runoff during the wet season (moderate flow) and lower values of salinity were observed during wet and flood periods to upstream which was diluted by strong river runoff. On the other hand, during dry season salinity values varied from 4.91 to 36.48 PSU along the channel. The salinity was even observed at station-8, 64 km up stream, which indicated a strong seawater intrusion due to due to the absence of river discharge and strong tidal pumping (Amjad *et al*., 2007; Guo and Valle-Levinson, 2007; Robinson *et al*., 2007).

Temperature data revealed that, high air temperature was recorded after noon, because maximum temperature usually occurs in the afternoon (Rasul *et al*., 2012). During wet season, surface and near bed variation was significant at station-1, possibly due to the large tidal fluctuation in the estuary near the mouth, with cold incoming seawater and warm outgoing freshwater. However the different from surface to bottom was absent at station-3 because the freshwater was dominant there. On the other hand during dry season surface to bottom difference in temperature was not significant, because fresh water in put was absent and shallowness nature of estuary. However, temperature revealed significant seasonal variation. The temperature values were significantly higher in the wet season in comparison with the dry season. This behavior was mainly attributed to the climatic zone which experienced the highest temperatures around June/September. Whereas, dissolved oxygen concentration observed at station-1 were slightly higher than station-3 during both seasons, which might be due to the mixing of fresh water with saline and this region was more dynamic, the similar results were found by (Saleem, *et al*., 2014) in Hajamro creek. However during flood season, DO values were lower which is possibly influenced by the high turbid water with increased temperature, similar to the Kakum and Nyan estuaries along southwestern coast of Ghana (Dzakpasu and Yankson, 2015).

Water turbidity values ranged from 243 to 392 (NTU) and 410.33 to 612.50 (NTU) during wet and flood seasons, respectively. Higher turbidity values during wet and flood season was mainly contributed by the input of sediment from Indus River. On the other hand turbidity values varied from 4.14 to 60.14 NTU during dry season because of the reduction of freshwater and sediment from river and high values of salinity.

## 5. Conclusions

The field investigation from this study suggested that oceanographic processes of Indus River Estuary, including currents, tides, temperature, salinity, turbidity, dissolved oxygen, are largely dependent on the seasonality of fluvial discharge, as well as monsoonal winds which are responsible to enhance the tidal influence in the region. The wet period is characterized by small variability on hydrographic properties (temperature, salinity, turbidity, dissolved oxygen), with relatively low salinity values, while hydrodynamic aspects (currents and tides) were significantly different during flood season with the dominance of river flow. On the other hand, water current data showed that the dynamics were mainly driven by coastal waters during dry season. The irregular river flow in the lower Indus has caused saltwater intrusion in the region. During the wet season it exhibited the weakly stratified characteristics at station-1 near the mouth, however it showed characteristics of salt wedge to the upstream during the dry season. When river flow was negligible, the salinity intrusion reached more than 64 km upstream and an increasing trend of saltwater intrusion was observed. Whereas, seawater intrusion into the river was restricted during flood period when river discharge was high.

Furthermore, for these conditions a more accurate evaluation should be achieved by using a three-dimensional model, because Indus Delta is characterized as a diverse, complicated and important estuarine system in Pakistan. There is a need for realistic estimate of onshore coastal inundation and sea water intrusion in Indus deltaic region to protect the estuarine ecosystem.

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**References**

Abbasi, A. G., 2002, "Restoration of Sindh's Primary Rights over River Indus", 18th Convention of SANA, Cherry Hill, New Jersey, July 4-7.

ADB and IUCN, 2002, "Regional Technical Assistance for Coastal and Marine Resources Management and Poverty Reduction in South Asia: Situation Analysis Report", RETA 5974-PAK, Asian Development Bank and International Union for Conservation of Nature.

Ahmad, N., 1993, "Water Resources of Pakistan", Lahore.

Amjad, A. S., Kasawani, I. and Kamaruzaman, J., 2007, "Degradation of Indus delta mangroves in Pakistan", *International Journal of Geology*, **3**, 1, 27-34.

Amjad, S., Rizvi, S. H. N. and Inam, A., 2003, "Impact of reduced river discharge on the mangroves ecosystem and socio-economy of the coastal zone of Indus delta", National Institute of Oceanography, ST. 47, Block-1, Clifton, Karachi, Pakistan, 1-14.

Banse, K., 1984, "Overview of hydrography and associated biological phenomenon of Arabian Sea off Pakistan", *Marine geology and oceanography of Arabian Sea and the coastal Pakistan*, Haq BU, Milliman J (eds). VNR/SAE Co. New York, 271-303.

Cameron, W. M. and Pritchard, D. W., 1963, "Estuaries", In M. N. Hill (ed), *The Sea*, **2**, John Wiley & Sons, New York, 306-324.

Chandio, N. H., Anwar, M. M. and Chandio, A. A., 2011, "Degradation of Indus Delta, removal of mangroves forestland; its causes. A case study of Indus River delta", *Sindh university Research journal* (Science Series), **43**, 1, 67-72.

Day, J. W., Hall, C. A. S. and Kemp, W. M., 1989, "Estuarine Ecology", p558.

Dixit, P. R., Kar, B., Chattopadhyay, P. and Panda, C. R., 2013, "Seasonal variation of the physicochemical properties of water Samples in Mahanadi Estuary, East Coast of India", *Journal of Environmental Protection*, **4**, 843-848, (http://www.scirp.org/journal/jep).

Dzakpasu, M. F. A. and Yankson, K., 2015, "Hydrographic Characteristics of Two Estuaries on the south western coast of Ghana", *New York Science Journal*, **8**, 4, 60-69.

Godin, G., 1999, "The propagation of tides up rivers with special considerations on the upper Saint Lawrence river", *Estuarine Coastal Shelf Sci.*, **48**, 307-324.

Gomes, V. J. C., Freitas, P. T. A. and Asp, N. E., 2013, "Dynamics and seasonality of the middle sector of a macrotidal estuary", In: Conley, D. C., Masselink, G., Russell, P. E. and O'Hare, T. J. (eds.), Proceedings 12th International Coastal Symposium (Plymouth, England), *Journal of Coastal Research*, Special Issue No. **65**, pp. 1140-1145.

Guo, X. Y. and Valle-Levinson, A., 2007, "Tidal effects on estuarine circulation and outflow plume in the Chesapeake Bay", *Continental Shelf Research*, **27**, 20-42.

Horrevoets, A. C., Savenije, H. H. G., Schuurman, J. N. and Graas, S., 2004, "The influence of river discharge on tidal damping in alluvial estuaries", *J. Hydrol*., **294**, 213-228.

Inam, A., Clift, P. D., Giosan, L, Tabrez A.L., Tahir, M., Rabbani, M.M. and Danish, M 2007, "The geographic, geological and oceanographic setting of the Indus river", *Large Rivers: Geomorphology and management*, edited by A. Gupta, John Wiley & Sons, Ltd. 333-346.

Kasai, A., Kurikawa, Y., Ueno, M., Robert, D. and Yamashita, Y., 2010, "Salt-wedge intrusion of seawater and its implication for phytoplankton dynamics in the Yura Estuary, Japan", *Estuarine, Coastal and Shelf Science*, **86**, 408-414.

Kaiser, M. J., Attrill, M. J., Jennings, S., Thomas, D. N., Barnes, D. K., Brierley, A. S., Polunin, N. V. C., Raffaelli, D. G. and Willians, P. J. le B., 2005, "Marine Ecology: Processes, systems and impacts", Oxford: Oxford University press, p557.

Kalhoro, N. A., He, Z., Xu, D., Faiz, M., Yafei, L. V., Sohoo, N. and Bhutto, A. H., 2016, "Vulnerability of the Indus River Delta of the North Arabian Sea, Pakistan", *Global NEST Journal*, **18**, 3, 599-610.

Khan, T. M. A., Razzak, D. A., Chaudry, Q. Z., Quadir, D. A., Kabir, A. and Sarker, M. A., 2002, "Sea level variations and geomorphological changes in the coastal belt of Pakistan", *Marine Geodesy*, **25**, 159-174.

Kidwai, S., 2004, "The Zooplankton from the Eutrophic and Oligotrophic (Coastal and deeper waters) Marine Environment of the North Arabian Sea with relation to the Monsoonal Regimes and a special reference to the Planktonic Larvae of commercially important species", *CEMB*, University of Karachi, Ph. D Thesis, 1-317.

Kijine, J. W., Jr, E. J. and Van der Velde, 1992, "Irrigation Management Implications of Indus Basin Climate Change - A Case Study", Lahore, IIMI.

Kravtsova, V. I., Mikhailov, V. N. and Efremova, N. A., 2009, "Variations of the hydrological regime, morphological structure and landscapers of the Indus River delta (Pakistan) under the effect of large-scale water management measures", *Water Resources*, **36**, 4, 365-379.

Majeed, S., Zaman, S. B., Ali, I. and Ahmed, S., 2010, "Situational analysis of Sindh coast-issues and 0ptions", *Managing natural resources for sustaining future agriculture*, **2**, 11, 1-23.

Manikannan, R., Asokan, S. and Ali, A. H. M. S., 2011, "Seasonal variations of physico-chemical properties of the Great Vedaranyam Swamp, Point Calimere Wildlife Sanctuary, South-east coast of India", *African Journal of Environmental Science and Technology*, **5**, 9, 673-681, http://www.academic journals.org/AJEST.

Meynell, P. and Qureshi, T., 1993, "Sustainable management of mangroves in the Indus Delta, Pakistan", In David, T. (ed) *Towards the Wise Use of Wetlands*, Ramsar Bureau, Gland.

Parsons, T. R., Maita, Y. and Lalli, C. M., 1984, "A manual of chemical and biological methods for seawater analysis", Pergamon Press: Oxford, UK. ISBN 0-08-030287-4.XIV, p173.

Pritchard, D. W., 1967, "What is an estuary: physical standpoint", In: G. H. Lauff (Editor), *Am. Assoc. Adv. Sci. Publ*., **83**, 3-5.

Rasul, G. A., Afzal, M. and Bukhari, S. A. A., 2012, "Climate change in Pakistan, Focused on Sindh Province", *Technical Report*, No. PMD-25/2012, 1-61.

Robinson, C., Li, L. and Barry, D. A., 2007, "Effect of tidal forcing on a subterranean estuary", *Advances in Water Resources*, **30**, 851-865.

Saleem, M., Aftab, J., Kahkashan S., Kalhoro, N. A. and Ahmed, W., 2014, "Diurnal variation of nutrients, water quality and plankton composition in the Hajamro creek (Indus Delta) during north east monsoon", *The Nucleus*, **51**, 1, 51-61.

Warsi, M., 1991, "Indus and Other River Basin of Pakistan, Stream Flow Records", *Case Study Report*, WAPDA.