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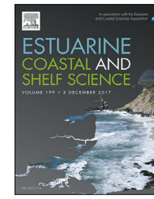

Field observations of hypersaline runoff through a shallow estuary

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A B S T R A C T

This study investigates a rare situation at the Mond River Estuary in the Persian Gulf, in which the classical estuarine density gradient coincides with hypersaline runoff entering from saline soils upstream of the estuary after severe precipitation. This builds a unique estuarine setting, where two salt water masses, one originating from the coastal ocean and the other being discharged from upstream confine a range of almost freshwater in the middle of estuary. This "freshwater lens estuary" (FLE) situation includes two saltwater sources with opposing senses of estuarine circulation. Therefore, the tidal damping by the strong river flood can occur, especially during neap tide when high Unsteadiness number (~0.04) signified ebb oriented condition which was induced by straining residual lateral circulation near the FLE mouth. Transition from well-mixed to weak strain induced periodic stratification regimes indicated the importance of the spring-neap tidal variations. Close to the mouth, a 13.66-day periodic tidal asymmetry from the triad K_1-O_1-M_2 (ebb-dominance during spring tide and flood-dominance in neap tide) was overcome by higher harmonics.

1. Introduction

Due to freshwater input, salinity decreases from the mouth of an estuary toward its head in a positive estuary. However, due to excess rate of evaporation in an inverse estuary, the salinity increases in the landward direction (Geyer, 2010). As a result of high evaporation rate, a salinity maximum zone (Valle-Levinson, 2010) or salt plug (Wolanski, 1986; Valle-Levinson, 2011) is likely to occur in a low-inflow estuary in which salinity is higher inside the salt plug than both its seaward and landward directions.

The freshwater lens estuary (FLE) which we describe here as a unique phenomenon, might occur when a hypersaline runoff from the watershed follows an almost freshwater river discharge with a time lag of few hours/days. Such a condition is likely to occur when a source of salinity exists in the watershed. This condition is met for the Mond River Estuary (see Fig. 1) in the northern coast of the Persian Gulf, and occurs occasionally during wet season in which precipitation over a saline soil area close to the river produces a rain-driven flood. This hypersaline water mass follows a freshwater river inflow and enters into the estuary. This condition has not been reported in the Mond Estuary so far.

In FLEs, longitudinal density gradient is in opposite of a salt plug system. The water density increases in both seaward and landward directions of the freshwater in the middle of a FLE whereas in the low-inflow estuary, the water density decreases from the salt plug to both seaward (similar to an inverse estuary), and landward (similar to a positive estuary) directions.

In a positive estuary, salinity increases during high tide and decreases in low tide (Hardisty, 2008). Since seawater and runoff driven hypersaline water are two salinity sources for FLEs, temporal variations of salinity, can be complex especially if the tidal blockage is occurred by the strong hypersaline river flood.

In fact, tidal variation from neap tide to spring period in many estuaries is sufficient to make a transition from stratified state to well-mixed condition. The change in fresh river discharge is another factor which can make the dynamics of the estuary more complex (Geyer and MacCready, 2014).

In a FLE, variations in the salinity of the river flood (hypersaline water following freshwater) make a unique condition. Such a regime has never been reported so far to the best of the authors' knowledge. This manuscript represents a brief report a set of measurements inside a shallow FLE which can be used for future

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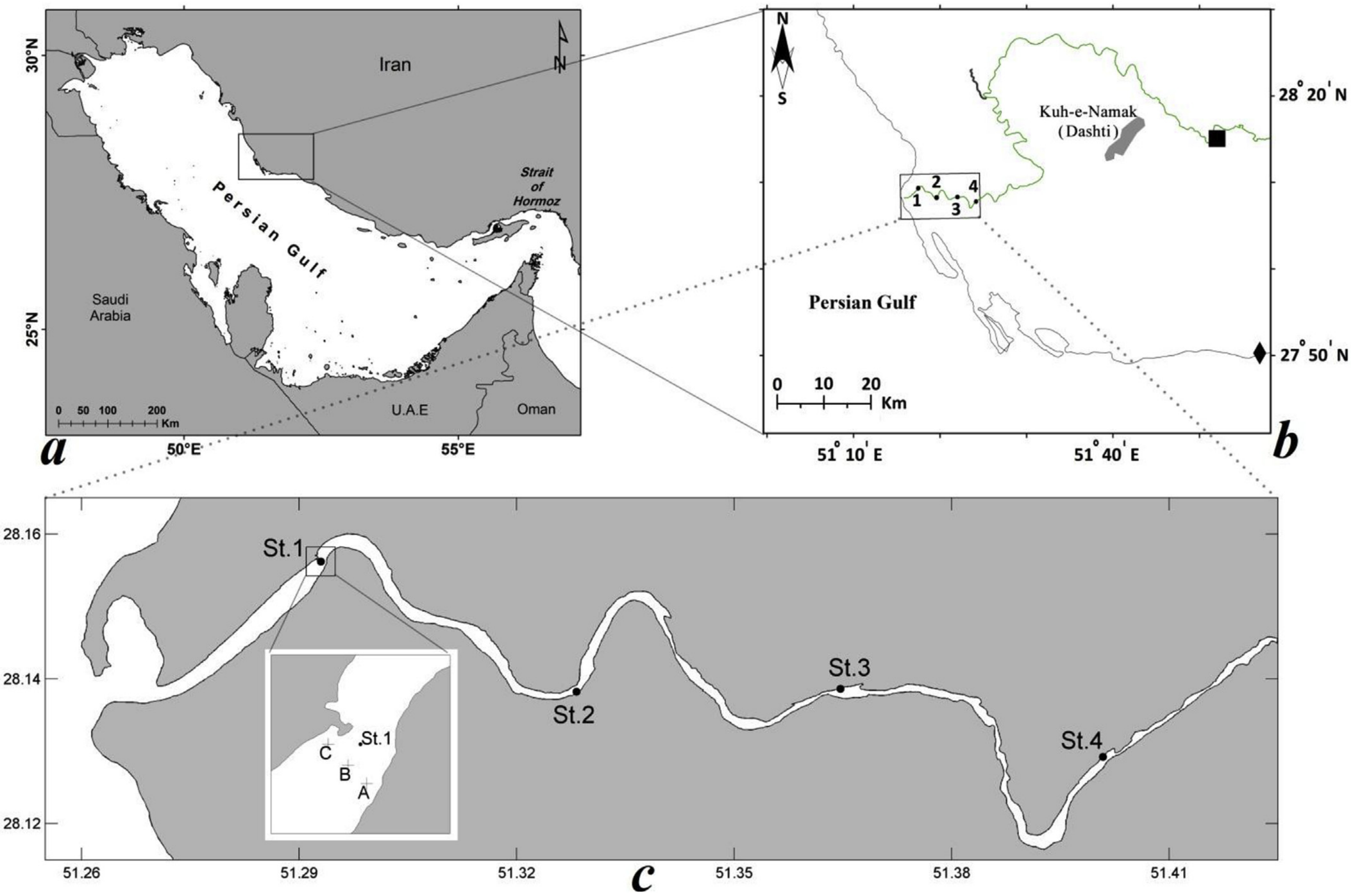

Fig. 1. **(a)** The location of the Mond River Estuary in the Persian Gulf; **(b)** the locations of 4 CTD-Current meter stations 1 to 4, Kuh-e-Namak (Dashti), Dayyer meteorological Station (Black Diamond) and the Qantareh rain and river discharge recorders (Black Square); **(c)** ADCP-CTD Stations of A, B, C close to St.1.

details study of the FLE hydrodynamics. The longitudinal variations of the salinity, temperature, velocity and tidal fluctuations are studied in a short, micro-tidal estuary with mixed mainly semi-diurnal regime during two periods of at least 25 h in spring and neap tides. The neap period includes a river flood with low-salinity water following by a hypersaline runoff, observed in the middle and upstream of the estuary respectively (strong FLE). The 25-h spring period coincides with a precipitation event which reinforces a positive condition in the downstream of the estuary and produces the appearance of FLE at the head (weak FLE).

Skewness parameter and the non-dimensional numbers of Simpson, Mixing and Unsteadiness as well as potential energy anomaly are used to analyze the data measurements and to describe the dynamics of this FLE. Since tidal transport is diminished at the up-estuary especially by the hypersaline runoff, these non-dimensional numbers are calculated in the positive system of down-estuary. Then, potential energy anomaly is applied to depict the role of tidal straining on mixing and stratification.

Tidal asymmetry in a semi-enclosed embayment with mixed mainly semidiurnal tide has not been studied considerably in comparison with estuaries with semidiurnal tide. Therefore, tidal asymmetry is also investigated through skewness parameter in the estuary mouth which has mixed mainly semidiurnal tidal regime.

The durations of increasing water level and falling water level are not the same in an estuary due to shallow water effects and/or interactions of astronomical tidal constituents. This process is denoted by duration asymmetry (Nidzieko and Ralston, 2012), and can be evaluated by the skewness parameter:

$$A = \frac{m_3}{m_2^{3/2}} \tag{1}$$

which is defined based on the i-th moment about mean value:

$$m_i = \frac{1}{J-1}\sum_{j=1}^{J}(n_j)^i \tag{2}$$

and J is the number of samples n_j. If $n = \frac{\partial \varepsilon}{\partial t}$ is used in Equation (2), the duration asymmetry in the rise and fall of water level (A^{ε_t}) can be determined. The negative/positive values for A^{ε_t} designate longer/shorter duration of rising water than falling in tidal cycle. Substituting $n = u$ in Equation (2) determines the asymmetry in tidal velocities (A^U). The negative/positive values for A^U show ebb/flood dominant conditions. The values of A^{ε_t} and A^U are identical for pure standing waves.

Tidal asymmetry might be resulted from interactions of astronomical tides and/or higher harmonics produced by nonlinearity effects into an estuary with mixed mainly semidiurnal tide (Hoitink et al., 2003; Nidzieko, 2010). In U.S. west coasts, when higher high water (HHW) precedes lower low water (LLW), the ebb dominant condition occurs (Friedrichs, 1995). This condition occurred during spring tide along the continental shelf of the U.S. west coast and A^{ε_t} was negative (Nidzieko, 2010).

The tidal constituents K_1 and O_1 produce the tropic-equatorial cycle of 13.66 days. The combination of these two diurnal tides