

## A physical study on tidal currents in Mond and Helleh rivers in the Persian Gulf

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### Abstract

This research investigates distribution of physical properties in the estuaries of Helleh and Mond rivers. The study results and some important non-dimensional numbers showed that the estuaries of Helleh and Mond rivers are well-mixed or partially mixed in water column. So, the tidal currents have less role in mixing process relative to the rivers' discharge. In fall season, the amount of mixing in these rivers' estuaries show much more reduction and in spring season, the estuaries of these rivers are well mixed. The water flows in both estuaries are transitional which means not very turbulent and not very calm. The tidal currents in different seasons in the estuaries are calculated using available data in Bushehr coasts and turbulence energy equation for tidal mixing in the water column. The results show that the effect of tidal currents relative to density difference between river and sea is greater in Mond estuary than in the Helleh estuary. The average velocities of tidal currents were approximately determined 0.31 m/s and 0.35 m/s for Helleh and Mond rivers, respectively. The results indicated good consistency with the predicted values in other similar studies.

**Keywords:** Estuary; Mond River; Helleh River; Tidal Current; Persian Gulf.

### 1. Introduction

Estuary has two definitions: a) The part of a river where affected by tides, b) an area near

the mouth of a river, where the fresh water is mixed with saline seawater. Cameron and Pritchard defined the estuary as a semi-closed region, half of which is surrounded by water

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and has open paths to the open sea (Dyer, 1997). Water circulation and mixing processes in estuaries are due to the density difference, the interaction of fresh and salt water, and tides. Tides have two effects on water's movement of estuaries; first, it creates vertical mixing although the density stratification prevents this mixture, second, tides cause the strong vertical mixing, particularly, in estuaries that have a complex geometry (Barne and Green, 1972; Greenberg, 1983; Pond and Pickard, 2013).

In order to identify the estuaries, the physical data in the study area such as Estuary Number and other dimensionless numbers are calculated which can determine the most important parameters in the governing equations of water flow (Wright, 1974). Solving these equations can specify the tidal currents' velocity and their energy, and the stratification variations during different seasons in a year (Greenberg, 1983; Naji, 1998). Different types of physical studies and investigations were conducted about the estuaries in Iran such as the study of mixture at the mouth of Arvand and Bahmanshir rivers,

and the study of turbulent mixing in the Khor Musa (Pingree *et al.*, 1974). This research will investigate and recognize the physical characteristics of Mond and Helleh rivers' estuary in Bushehr province (Figure 1).

## 2. Materials and methods

There are different patterns for studying estuaries, which mainly are developed by effective parameters and dimensionless numbers. The effective parameters in estuaries are the rate of river flow that made the floating and stratification, and tidal currents caused mixing in water because of friction. Due to tidal estuaries, the water is ascending and descending, and the volume of water entering in estuary, between the lowest ebb and highest flow is called Tidal Prism. Tidal Prism of estuary is equal to its tidal range multiplied by its average surface area (Project report, 1999). When the proportion of river flow in a tidal period to the tidal prism, is equal to 1 or greater than 1, the estuary is considered fully stratified,

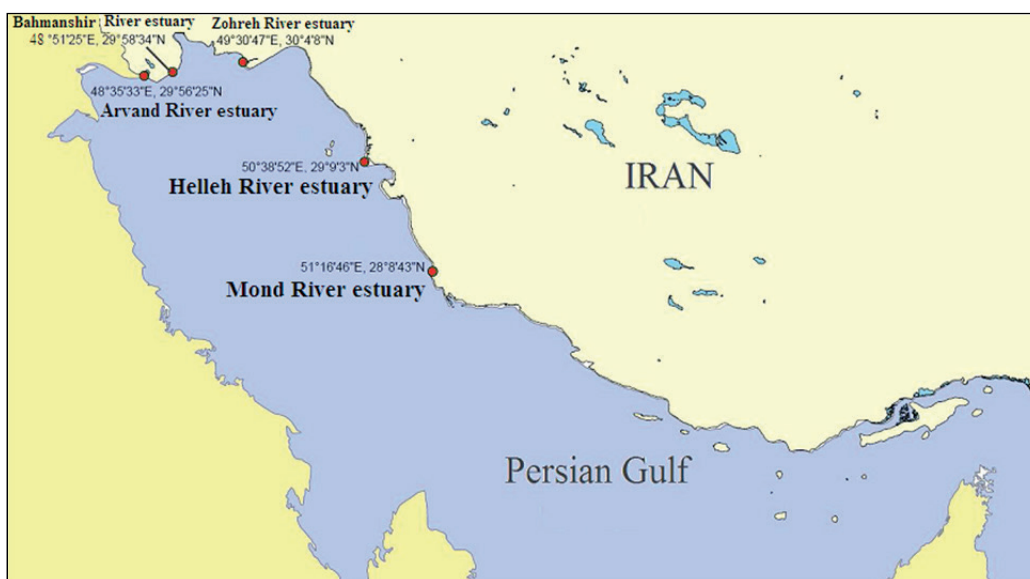


Figure 1. The location of Helleh and Mond rivers

when the proportion is about 0.25, the estuary is almost mixed, and when it is less than 0.1, the estuary is well mixed. The estuary number is as follow (Dyer, 1997; Project report, 1999):

$$Ne = \frac{PF_r^2}{TR} \quad (1)$$

which, P is the volume of tidal prism, T is the tide period, R is the river discharge, and  $F_r$  is Froud number which is calculated as follow:

$$F_r = \frac{U_f}{\sqrt{gh(\frac{\Delta\rho}{\rho})}} \quad (2)$$

which,  $U_f = \frac{R}{A}$  is the ratio of river flow (R) to the cross-section area of the estuary (A),  $\Delta\rho$  is the difference of sea water density ( $\rho$ ) and the density of water intake in the river, and h is the depth of water in the area. The estuary number is the ratio of river flow discharge to the tidal flow discharge. If  $Ne > 0.1$ , the estuary is fully mixed, and if  $Ne < 0.1$ , the estuary is completely stratified.

Using the data in Table 1, the estuary numbers of both Helleh and Mond rivers were calculated (Pugh, 1987; Project report, 1999) which is available in Table 2. Reynolds number compares the importance of viscosity and inertia forces in a stream, and it is calculated as follow:

$$Re = \frac{U_f D}{\nu}$$

which, D is water depth,  $U_f$  is average velocity, and  $\nu$  is the coefficient of kinematic viscosity. To determine the type of current in estuaries of Helleh and Mond rivers, the Reynolds number were calculated with available information. The Reynolds number values were 7778.3 and 13172.7 in spring, and 10373.73 and 9818.6 in summer, that all are larger than the 10 order and because  $2000 < Re < 10^5$ , so the current is in

transition status from laminar to turbulent flow. Furthermore, Froud number ( $Fr$ ) was obtained for Mond and Helleh estuary respectively, 1.018 and 1.016. Because the Froud number defined as the ratio of the inertia force to the gravity force, so, the both forces have the same role in equations of motion. The amount of energy needed for mixing in stratified water column is calculated by the difference between potential energy before and after mixing process. According to the Simpson and Hunter in 1974 and the difference between potential energy in mixing layer and stratified layer is obtained by the following equation (Mann and Lazier, 2005):

$$\Delta PE = \frac{1}{2} gh_1 h_2 \Delta\rho \quad (3)$$

which,  $h_1$  is the depth of surface layer of estuary and  $h_2$  is the depth layer, and  $\Delta\rho$  is density difference between the two layers. Turbulence energy needed for maintaining the mixing conditions in the water column is created by friction between tidal currents and the bed at the mouth of the estuary (Azadbakt, 1997). According to the Lodero Greenberg (1986), the amount of energy made by tidal currents is as follow (Greenberg, 1983):

$$D_t = \rho C_D (U^2 + V^2)^{3/2} \quad (4)$$

which,  $D_t$  is the kinetic energy from tidal currents,  $U$  and  $V$  are the horizontal components of tidal currents on the horizontal direction (average values during a tidal period),  $\rho$  is average density of water, and  $C_D$  is drag coefficient which is equal to 0.0027.

Although the whole energy is not used for mixing in the water column, calibration of this theory showed that only a fraction of this energy equivalent with  $\varepsilon_i \approx 2.6 \times 10^{-3}$  is used to change the water column layering. So, the

energy needed for keeping the mixed water is obtained by the following equation (Greenberg, 1983; Loder and Greenberg, 1986):

$$\varepsilon_i D_i = gh\alpha \frac{\Delta Q}{2C} \quad (5)$$

In this study,  $D_i$  were calculated using the values of  $h_1$ ,  $h_2$  and  $\Delta\theta$  in Equation (3) and Equation (5), then with the Equation (4), horizontal

components of tidal currents velocity and also the total velocity of current ( $\sqrt{U^2 + V^2}$ ) were determined. Moreover, using these relations and available information, the velocity of tidal flow in estuaries of Helleh and Mond rivers were estimated during different seasons (Table 3). Ficher defined the Estuarine Richardson Number as a rate of achieved potential energy

Table 1. The calculated physical characteristics in both Helleh and Mond rivers for different seasons of the year

Season	River name	Width of estuary (m)	Mean discharge ( m <sup>3</sup> /s)	Water temperature (°C)	Water temperature (°C)	Density (kg/m <sup>3</sup> )	Depth (m)
Spring	Helleh	54	8.346	30.5	24.5	999.11	0.23
				37	26	1000.02	0.56
				31.4	23.4	1000.69	0.70
	Mond	65	7.82	36.5	26	1000.47	0.27
				38	28.4	999.93	0.47
			30	23.4	1002.87	0.60	
Summer	Helleh	20.3	1.67	36	29.5	998.04	0.24
				36	32	999.81	0.36
				33	31.8	999.52	0.43
	Mond	78	4.46	38.5	33.8	999.63	0.42
				35	30.7	999.16	0.53
			33	31	1001.29	0.91	
Autumn	Helleh	38	3.30	17	19.8	1001.53	0.30
				21.5	19.5	1001.35	0.40
				18	19.5	1002.11	0.42
	Mond	43	8.62	22.5	21	1002.10	0.44
				24	22.6	1000.81	0.58
			23	22.4	1000.48	0.93	
Winter	Helleh	46.3	19.31	18.5	16.2	1000.68	0.45
				19	16.1	1000.16	0.51
				18	16.7	999.82	0.80
	Mond	120.3	61.58	21.1	17.3	999.57	0.78
				25.5	16.5	999.63	0.86
			22.1	16.9	999.56	0.94	

by water intake of river to the mixing power of tidal flow [13] as follow:

$$Ri_e = \frac{\Delta\rho}{\rho} \frac{gU_f}{bU_t^3} \quad (6)$$

which,  $b$  is width of estuary,  $U_t$  is the velocity of tidal current,  $\Delta\rho$  is the density difference of sea water ( $\rho$ ) and input water of river,  $U_f = \frac{R}{A}$  which is defined earlier. If  $Ri_e > 0.8$ , the estuary is strongly layered, for  $0.8 > Ri_e > 0.08$  is relatively mixed, and for  $Ri_e < 0.08$  is fully mixed (Naji, 1998).

Using the velocity of tidal current in Table 3 and the information from Environmental Protection Agency of Bushehr (1999), Estuarine Richardson Number in different seasons of a year was calculated (Table 2). Pingree *et al.* (1974) represented the loss of turbulent energy caused by tidal current by the Equation (7):

$$\epsilon = 2.5 \times 10 u^3/h \quad (7)$$

which,  $u$  is the average of tidal current,  $h$  is the depth of water in meter, and  $\epsilon$  is the loss of the turbulence energy caused by tidal current due to bed friction and the unit is w/kg. According to Officer's theory in 1976, solving the governing equations in the estuary with partial mixing condition, considering the river discharge and regardless of tidal currents, the vertical distribution of velocity with depth of  $z$  is presented as follows (Officer, 1976):

$$u(z) = 3Q/2h [1 - (z/h)^2] \quad (8)$$

which,  $Q$  is the average of river discharge, and  $h$  is the water depth in meters.

### 3. Discussion

As mentioned earlier, estuary number represents the ratio of velocity of river flow to velocity of tidal currents. Values of estuary number at the Helleh and Mond rivers (Table 2)

Table 2. The estuary number and Richardson number during different seasons in Helleh and Mond rivers

Quantity name	River's name	Season			
		Spring	Summer	Autumn	Winter
Estuary number	Helleh	0.179	0.277	0.287	0.416
	Mond	0.238	0.31	0.19	0.189
Richardson number	Helleh	0.019	0.176	0.083	0.2
	Mond	0.017	0.0081	0.14	0.018

Table 3. Mean velocity of tidal currents in estuaries of Helleh and Mond rivers during different seasons

River's name	Season			
	Spring	Summer	Autumn	Winter
Helleh	0.42	0.26	0.26	0.28
Mond	0.40	0.33	0.23	0.41

are more than 0.1 that means there is complete mixing in the estuaries. The velocity of Helleh River flow in the winter and Mond River in the spring are more than tidal flow, because, the river discharge mainly increase relative to the other season of the year. Estuary number for the Helleh River is almost more than 1 in the Mond River; therefore, the effects of river flow relative to the effects of tidal currents in the estuary of the Helleh River are more than the Mond River.

Estuarine Richardson Number is the ratio of potential energy created by input water to the power of mixing due to tidal current. Table 3 shows that the Estuarine Richardson Number is less than 0.8 during all seasons of a year. Therefore, in the estuaries of these rivers, partial or complete mixing exists in water column. As a result, in the formation of turbulence and mixing in the water column, the tidal current plays a greater role than the density difference between the river and the sea. In estuaries of Helleh and Mond rivers, there is a complete mixing during the spring, and partial mixing in other seasons, because Estuarine Richardson Number is more than 0.08 and less than 0.8. The stratification effect in the rivers' estuary, which is subject of the study, is very small and unstable, and density changes with depth cannot dominate on velocity changes with depth. In addition, in estuary of these rivers, the maximum mixing in water column occurs during the winter for Mond River and in the spring for Helleh River confirmed by the high values of calculated velocity of tidal currents in Table 2, and the low values of Estuarine Richardson Number in Table 3. Values of Estuarine Richardson Number for Helleh River are more than the Mond River during all seasons except of autumn. This means

that the effect of tidal currents relative to density difference between the river and sea at the estuary of Mond River is greater than in Helleh River. Figure 2 and Figure 3 indicate the relationship between estuary number and estuarine Richardson number for Helleh and Mond rivers. The correlation between these two numbers for the estuary of Helleh River is positive. Since the changes of estuary number is reverse of the estuarine Richardson's number, the positive correlation shows the lower effect of river discharge of Helleh relative to density difference of the river and water of Persian Gulf.

Proceeding of tidal currents in an estuary is affected by changes of estuary's width and depth, bed friction, and river discharge. Decreasing in estuary depth is caused increasing in tidal current amplitude and decreasing in wavelength. To invest this status in estuaries of both rivers which are subject of the study, using the available information and given equations, the velocity of currents during different seasons of the year were calculated (Table 3). Then, the velocity changes of tidal currents were drawn and represented in Figure 4.

The maximum flow velocity, in the estuary of the Helleh River during the spring is 0.42 m/s and in the estuary of the Mond River, during the winter is 0.41 m/s. Almost, the status of tidal flow of two rivers in spring and autumn is in reverse. In spring, the water in estuary of both rivers was completely mixed, whereas, in autumn, the water column is partially decreased and the average tidal velocity in the river estuary of the Mond is more than it in the Helleh. In winter, with increasing the Helleh river discharge and decreasing the velocity of tidal currents, the effects of river flows were dominated to tidal currents, thus,

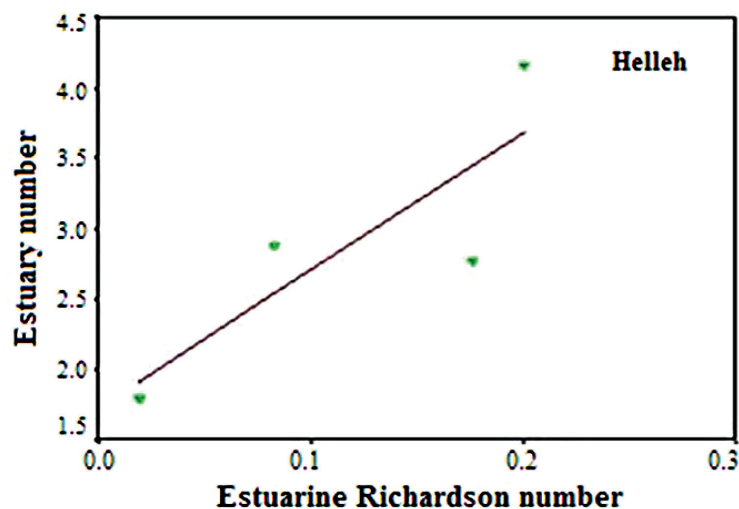


Figure 2. The relationship between estuary number and estuarine Richardson number for Helleh

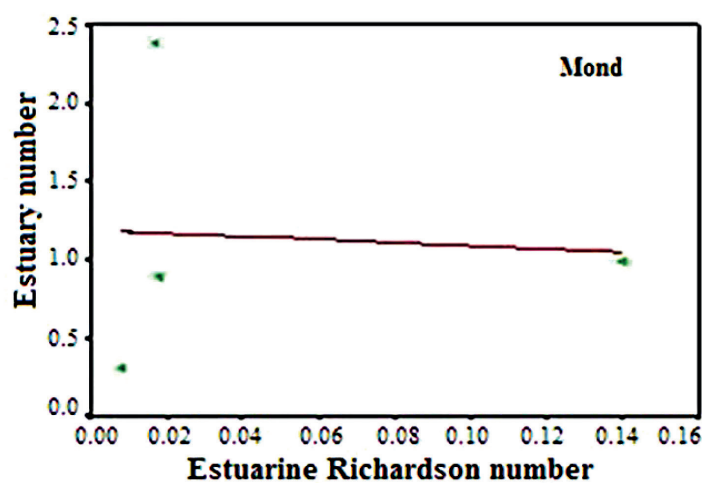


Figure 3. The relationship between estuary number and estuarine Richardson number for Mond

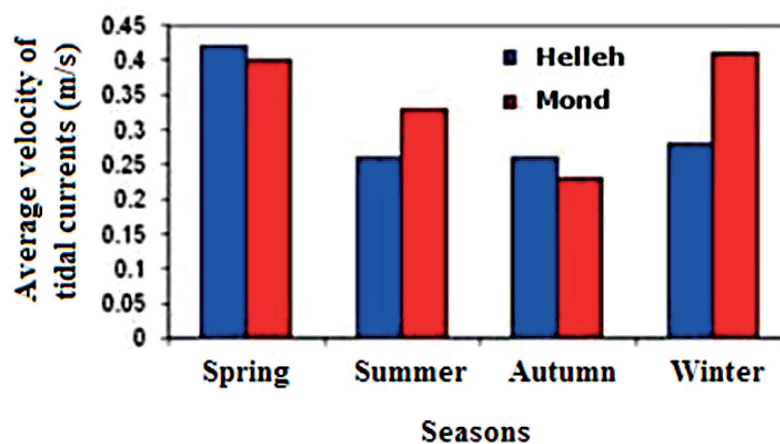


Figure 4. Mean of velocity of tidal flow calculated for the estuaries of Helleh and Mond rivers in different seasons



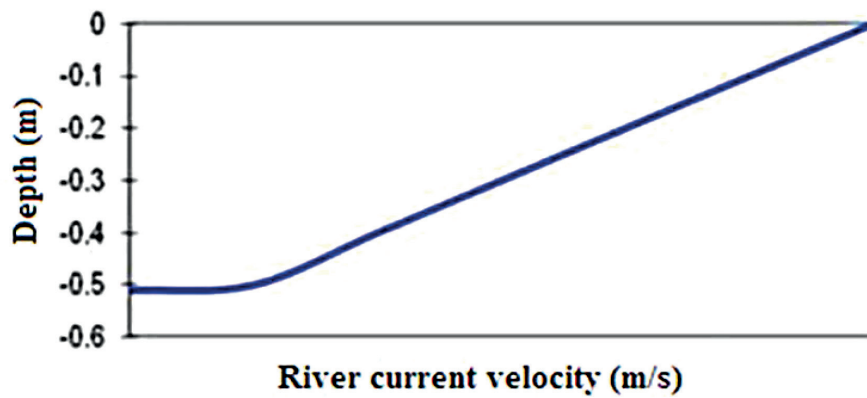


Figure 5. Vertical distribution of flow velocity of Hellah River in winter

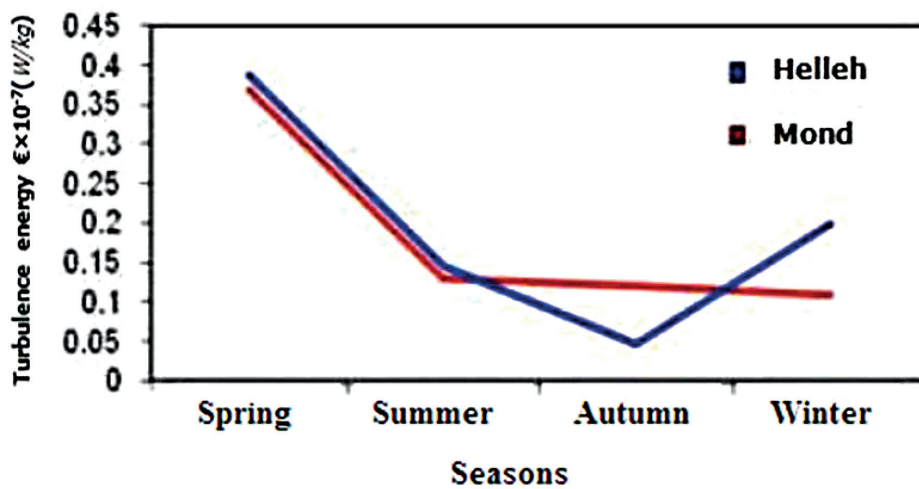


Figure 6. Changes of turbulence energy due to tidal flow with seasons of years for the estuary of Helleh and Mond rivers

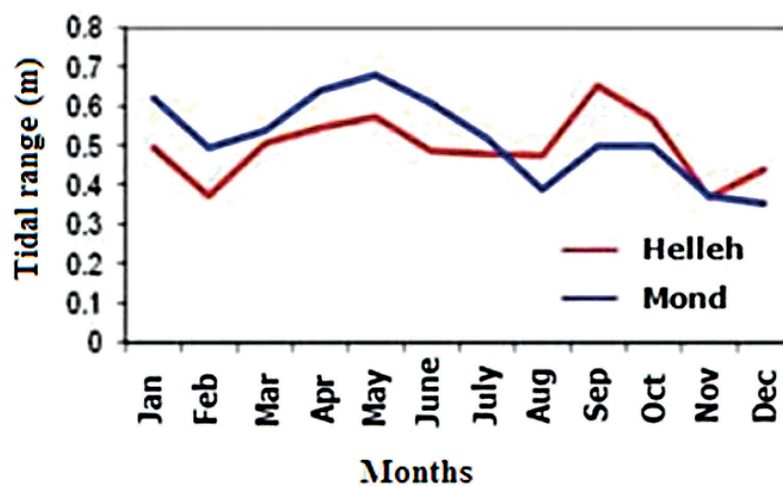


Figure 7. Changes of tidal range in all months of the year for estuaries of Helleh and Mond rivers



using Equation (8), vertical distribution of Helleh river flow's velocity was calculated for winter (Figure 5). The river flow decrease with increasing the depth and it will be zero in the bed due to bed friction.

Using the values of tidal flow in the rivers' estuaries, turbulence energy due to tidal currents was calculated in W/kg. Figure 6 indicates the energy changes in different seasons for the estuary of Helleh and Mond rivers. The average of turbulence energy at the estuary of Mond River is more than that in the Helleh River. Therefore, the effect of turbulence energy due to tidal current, which is required for mixing in water column and omitting the buoyancy forces, in the Mond estuary is greater than in the Helleh. Regarding that there are complete mixing to partial mixing in these estuaries, the turbulence flow can substitute with the water circulation at the estuary and it is the main factor to physical properties' transition and loss of flow due to buoyancy.

Analyzing the information of tidal tables related to Khark and Ameri Port stations in vicinity of Helleh and Mond rivers, respectively, concluded that dominant tide in this area is semi diurnal. Moreover, the range of tides in the rivers' estuary during all seasons of the year is less than 1 meter (Figure 7). The range of tides at the estuary of Helleh River is less than in the estuary of Mond River during winter and summer, and it is more than that during spring and autumn. The minimum height of tide at the estuary of two mentioned rivers was recorded in autumn and its maximum value was recorded in spring. The tides occurrence in the Helleh River has approximately two hours latency relative to the tides occurrence at the mouth of Mond River; therefore, the tides in the mouth of Helleh River have about 30 degrees phase

difference.

Up to now, the velocity of tidal currents in the estuary of mentioned rivers has not been measured, but this research's outcomes and the predictions by other studies have a good correspondence. According to the results of Le provost (1984) for the component of  $M_2$ , the velocity of tidal flow is in order of 20 cm/s in Persian Gulf and it cannot be more than 40 cm/s (Le Provost, 1984). Based on the Mojtahedi (2003) study results, the velocity of tidal currents, in coastal area adjacent to Bushehr province, was estimated in average about 17.5 cm/s in depth of 1.2 m (Mojtahedi, 2003). Using of the numerical models of mixing in the estuary of Mond River (Barbar, 2002), the average velocity of tidal flow in the middle part of river estuary was estimated about 12 cm/s. The results are comparable with average speed of tidal currents, which is presented in Table 1.

## Conclusion

- The estuary of mentioned rivers is the type of complete mixing or partial mixing in water column in most seasons of a year.
- The effects of river flow velocity are more than the effects of tidal currents and the tidal currents have more effect than the effects of density difference between sea and river at the rivers' estuary.
- Tidal currents in creation of turbidity and mixing in the estuary of these rivers have more powerful role than density difference between the river and the sea.
- The effect of river flow to the effects of tidal currents at the estuary of Helleh River is more than Mond River.
- The effect of tidal currents relative to density difference between river and sea at the estuary

of Mond River is more than one in Helleh River.

- Average calculations of tidal currents velocity are 0.31 m/s in Helleh and 0.35 m/s in Mond
- Dominant tide at the estuary of Helleh and Mond rivers is the type of semi diurnal and the tidal range at the estuary of these rivers is less than 1 meter in most season of a year.

#### *Suggestions*

- Numerical model for predicting the components of tidal velocity at the mouth of these rivers should be offered, so that, with the help of those elements, the tidal velocity is similar to what the Greeberg (1983) has done for the Gulf of Maine.
- Determining the turbulent role in classifying of estuaries circulation, which is necessary for estuaries' investigation.

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