

## Contribution of Tides and of Excess Evaporation to the Water Exchange Between the Arabian Gulf and the Gulf of Oman

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**ABSTRACT.** Both the residence time of water in the Arabian Gulf defined as the length of time required for the volume of water entering the Gulf through the Strait of Hormuz to completely equal the volume of water in the Gulf and the renewal period defined as the length of time required for the volume of new water from the Gulf of Oman to equal the volume of water in the Gulf are the shortest for any body of water of similar dimensions. Important among the factors contributing to these periods are the tidal exchange and the excess evaporation. Tidal exchange was modelled by using the four components  $M_2$ ,  $S_2$ ,  $K_1$  and  $O_1$ . The excess evaporation was estimated using meteorological data and river discharge. It is found that tides are potentially able to account for the shortness of the periods. The residence time was found to be less than one year, while the renewal time was found to be between 1.5 and 4.5 years with a mean of about three years.

The Arabian Gulf is a marginal sea of the Indian Ocean at the north west of the Gulf of Oman to which it is connected by the Strait of Hormuz. It is a shallow concentration basin with a mean depth of 36 m, and area of  $2.4 \times 10^{11} \text{ m}^2$  and a volume of  $8.6 \times 10^{12} \text{ m}^3$ . The Gulf lies in an arid zone where evaporation exceeds land runoff and precipitation. The shallowness of the Gulf and the absence of a sill at Hormuz facilitate the exchange of water with the Gulf of Oman and explain the absence of deep and bottom water in the Gulf similar to the cases of the Red and the Mediterranean Seas.

Eight coastal states surround the Gulf and utilise it as a source of food and fresh water. Other uses include mining oil and other minerals, dumping the effluents from the rapidly expanding industries and population centres, as well as using the Gulf as a major trade and oil route with the rest of the world. This heavy utilisation strains the capacity of the Gulf to satisfy the demands created by the human activity. This capacity is not known at present, but it varies from one usage

to the other. However it is known that the exchange of water between the Gulf and the Gulf of Oman plays a principal role in determining this capacity, and hence it is important to study this exchange.

It common with other marginal seas having a deficit in the annual fresh water budget, it is considered that this deficit plays an important role in shortening the residence time of the water in the Gulf. The residence time is defined here as the time required to fill the Gulf completely by water that enters the Gulf at the present rate. It has been estimated variously between less than one year and five years (Hughes and Hunter 1979, Hunter 1984, Hunter 1986). This is the shortest period estimated for any body of water of similar size.

### Material and Methods of Calculation

To investigate the contribution of the tides in the water exchange process between the Gulf and the Gulf of Oman, the Admiralty Co-tidal Chart No. 5018 (1976) (Fig. 1) was taken as the starting point. For the tidal components  $M_2$ ,  $S_2$ ,  $K_1$  and  $O_1$  these charts indicate the amphidromic points, the cotidal lines emanating from them and the cotidal heights in the Gulf (Fig. 1, a,b,c and d). From this information it was possible to calculate the tidal prism for each component defined as the maximum volume of water exchanged between the Gulf and the Gulf of Oman because of the tidal oscillation.

The basis and method of calculation are as follows:

The area of the Gulf is divided into "squares" of 20' of latitude by 20' of longitude. For any one component the volume ( $V_{ic}$ ) of water in the area  $i$  is given as

$$V_{ic} = V_{oi} + V_{tic} = V_{oi} + a_i A_{ic} \cos. ((2\pi t/T_c) + \alpha_{ic})$$

(Definition of the symbols is given in the nomenclature below).

The tidal amplitude at the square  $i$ : ( $A_{ic}$ ) was determined from the Admiralty Cotidal Chart of the Gulf (Fig. 1) by inspection.

The volume variation at time  $t$ : ( $V_{ic}$ ) for all of the Gulf resulting from one tidal component becomes:

$$\begin{aligned} V_{tc} &= \sum_{i=1,l} V_{tic} \\ &= \sum_{i=1,l} a_i A_{ic} \cos. ((2\pi t/T_c) + \alpha_{ic}) \end{aligned}$$

$$\begin{aligned}
&= \sum_{i=1,1} K_{ic} \cos.((2\pi t/T_c) + \alpha_{ic}) \\
&= \sum_{i=1,1} K_{ic} (\cos.(2\pi t/T_c) \cos.\alpha_{ic} - \sin.(2\pi t/T_c) \sin.\alpha_{ic}) \quad (1)
\end{aligned}$$

Take  $\cos.2\pi t/T_c$  and  $\sin.2\pi t/T_c$  outside the summation as they are independent of  $i$ . Then (1) becomes

$$V_{tc} = \cos.2(\pi t/T_c) \left( \sum_{i=1,1} K_{ic} \cos.\alpha_{ic} \right) - \sin.(2\pi t/T_c) \left( \sum_{i=1,1} K_{ic} \sin.\alpha_{ic} \right) \quad (2)$$

As the terms in the summation sign are not dependent on  $t$  and as  $K_{ic}$  and  $\alpha_{ic}$  are constants for each square and tidal component then (2) can be written as:

$$V_{tc} = L_{1c} (\cos.2\pi t/T_c) - L_{2c} \sin.(2\pi t/T_c) = M_c \cos.(2\pi t/T_c + B_c)$$

$B_c$  and  $M_c$  are constants and can be obtained by calculating the volume at any two times separated by  $T_c/4$  in the following manner:

$$\begin{aligned}
V_{tc} &= M_c \cos.(2\pi t/T_c + B_c) \\
V_{(t_c+T_c/4)} &= M_c \cos.(2\pi(t+T_c/4)/T_c + B_c) \\
&= M_c \cos.((2\pi t/T_c + B_c) + \pi/2) \\
&= -M_c \sin.(2\pi t/T_c + B_c)
\end{aligned}$$

Thus:

$$\begin{aligned}
(V_{tc})^2 + (V_{(t_c+T_c/4)})^2 &= (M_c)^2 (\cos.^2(2\pi t/T_c + B_c) + \sin.^2(2\pi t/T_c + B_c)) \\
&= M_c^2
\end{aligned}$$

and  $B_c$  can then be obtained from  $M_c$  and  $V_{tc}$  or  $V_{(t+T_c/4)c}$

Repeating this procedure for  $M_2$ ,  $S_2$ ,  $K_1$  and  $O_1$  and adding as previously described results in the water exchange due to the tide.

### Nomenclature

- $a_i$      The area of the square  $i = 20'$  of lat.  $\times$   $20'$  of long.  
 $= 20 \times 1.85 \times 20 \times 1.85 \times \cos. \phi_i \text{ km.}^2$
- $\alpha, \beta$      The portion of the ebb-tide water that re-enters the Gulf in the flood tide, and the portion of the flood-tide water that re-exits from the Gulf in the ebb tide.

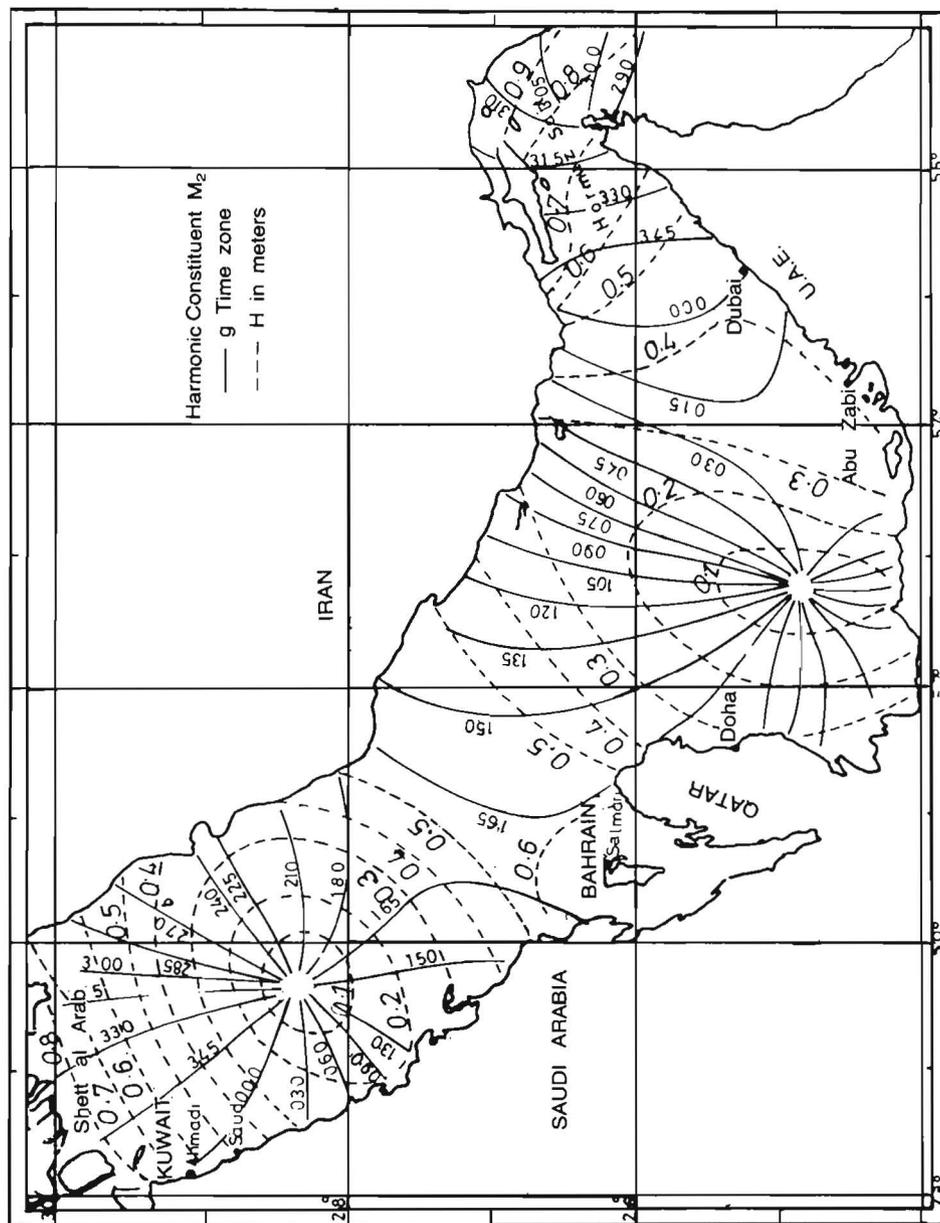


Fig. 1a

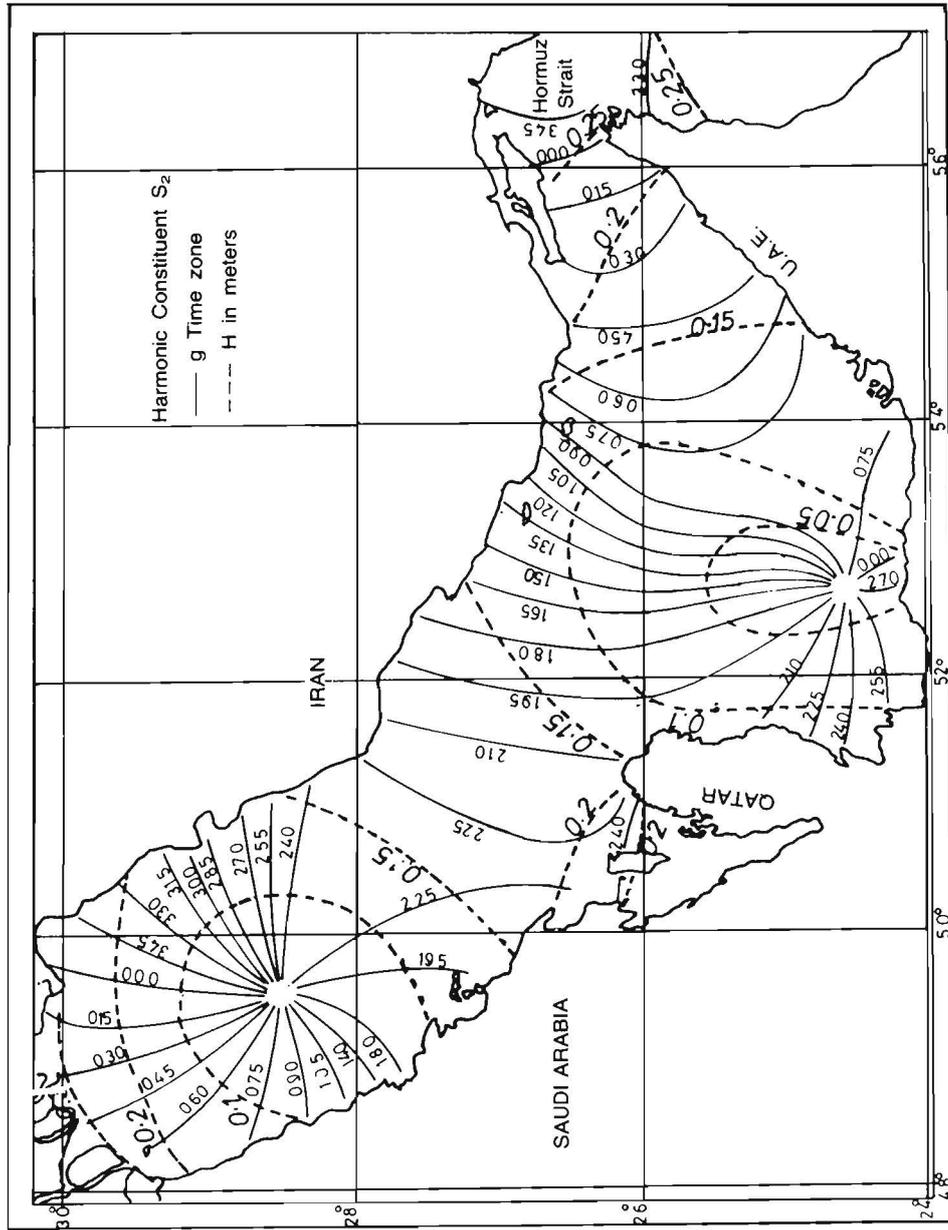


Fig. 1b

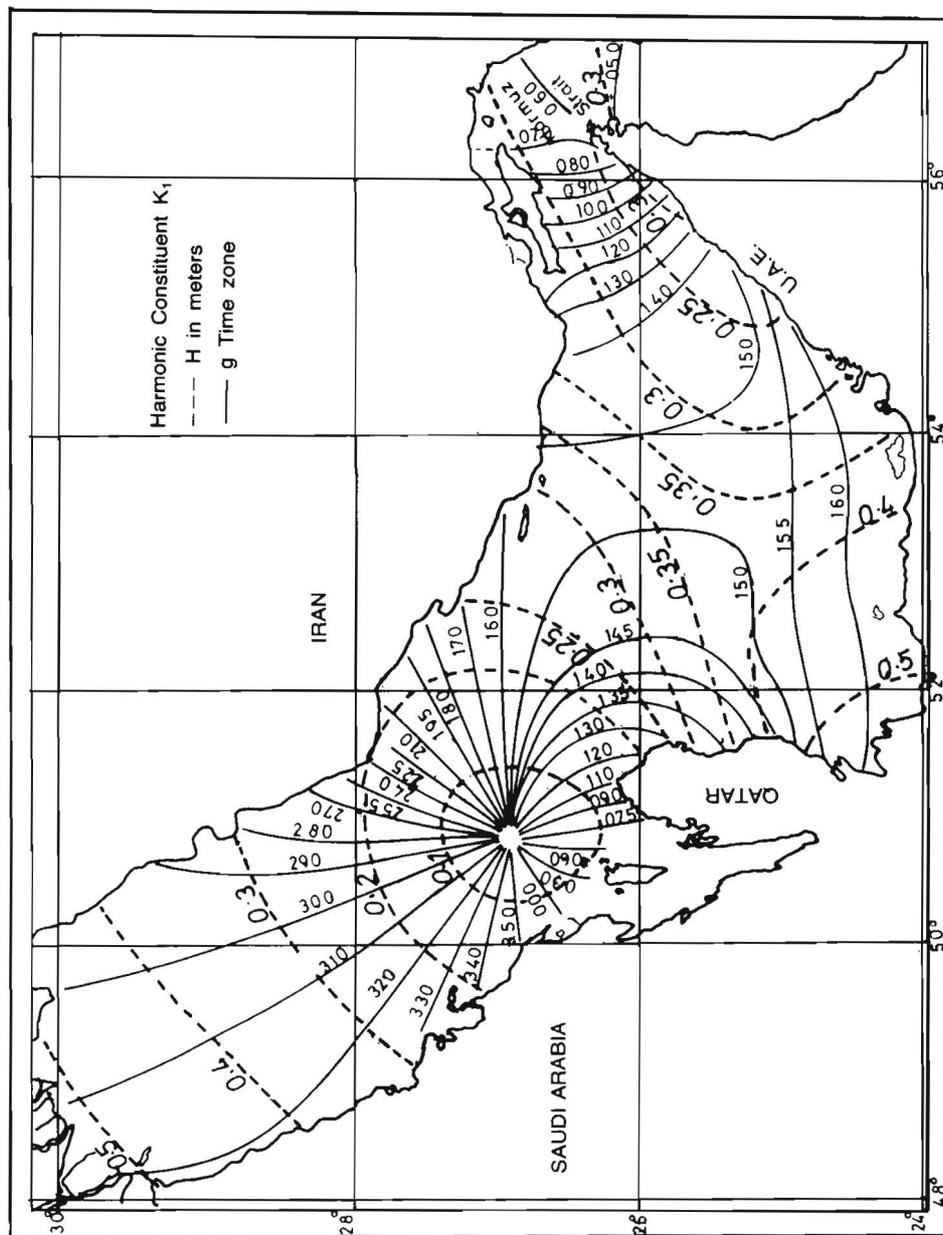
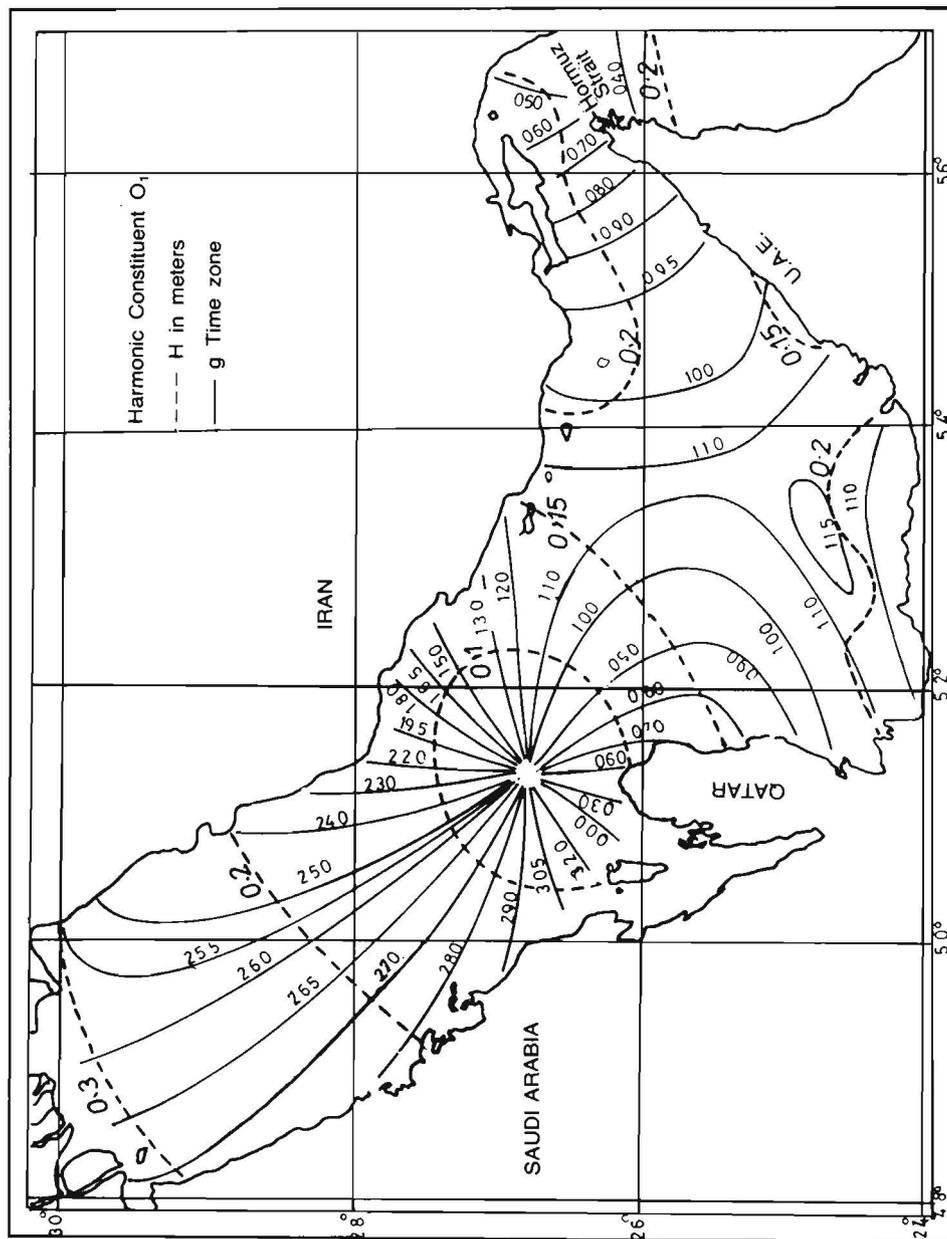


Fig. 1c



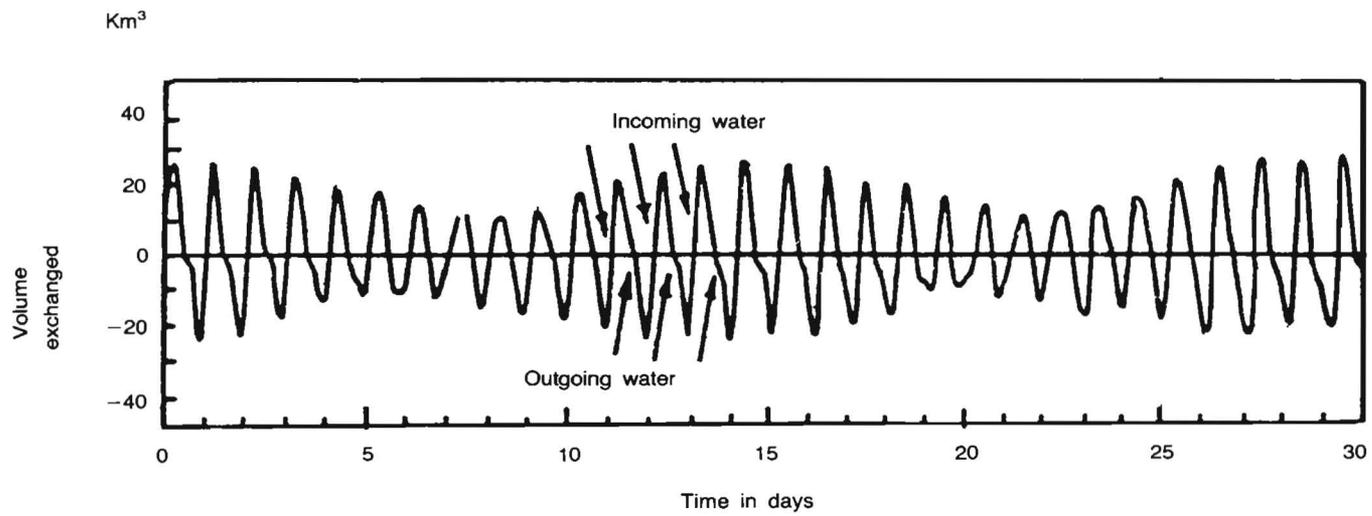


Fig. 2. Example of oscillation in the volume of water exchanged between the Arabian Gulf and the Gulf of Oman during one month.

- $\alpha_{ic}$  The phase difference between the tide in the square and the tide along the reference line, taken as the line 000 from the top amphidromic point in the Admiralty chart for the component c.
- c The tide components  $M_2$ ,  $S_2$ ,  $K_1$  and  $O_1$
- i Counter of the squares in the Gulf.
- t Time in hours after the starting moment.
- $A_{ic}$  The amplitude of the tidal component c in the square i.
- $B_c$  Constant, the phase angle difference between the tidal prism phase for the component c and the reference phase of the calculation.
- F The fresh water deficit.
- I The total number of squares in the Gulf.
- $K_{ic}$  Constant for the square i and component c and  $= a_i A_{ic}$ .
- $L_{1c}$  Constant  $= \sum_{i=1,I} K_{ic} \cos. \alpha_{ic}$ .
- $L_{2c}$  Constant  $= \sum_{i=1,I} K_{ic} \sin. \alpha_{ic}$ .
- Sala,  
Salo Typical salinities of the Arabian Gulf water and that of the Gulf of Oman near the Strait of Hormuz .
- $M_c$  Constant = the amplitude of the tidal prism for the Gulf for component c.
- $S_i, S_o$  The incoming and the outgoing water salinities respectively (salin, salout).
- $T_c$  The period of component c.
- $V_{ic}$  The water volume in square i considering component c.
- $V_o$  The total mean volume of the Gulf  $= \sum_{i=1,I} V_{oi} = 8.6 \times 10^{12} \text{ m}^3$ .
- $V_{oi}$  The mean volume of water in square i. It depends on the depth of the water, the lat. and long. of the area.
- $V_{ic}$  The mean volume of water in the Gulf in excess of  $V_o$  resulting from

$$\text{component } c_i = \sum_{i=1,1} V_{tic}$$

$V_{tic}$  The variable volume difference between the mean volume and the actual volume of water of square  $i$  at time  $t$  resulting from component  $c$ .

$\phi_i$  Mean lat. of square  $i$ .

### Results and Analysis

The variation of water volume in the Gulf resulting from the four tidal components was calculated every hour starting from an arbitrary point when all the four tidal components had the same phase. This point in time was chosen since the calculation was not made for a particular year, but was made for a series of 10 years. Since, because of the different periods of the components each component changes phase continuously with respect to all the others, all possible phase differences can exist among them including a point in time when all components have the same phase, and though more rarely, that phase is equal to 0. This choice is arbitrary, but so would be any other choice. However it simplifies the calculations without affecting the general conclusions. At the starting point the volume of water in the gulf is equal to the mean volume, and water enters due to every tidal component. Progressing in the calculation by advancing each component at its appropriate speed resulted in maxima and minima following each other. The difference between the first maximum and the following minimum represented the volume of water leaving the Gulf. Subtracting each minimum from the maximum that preceded it gave the volume of the outgoing water, while subtracting each minimum from the maximum that followed it gave the volume of the incoming water to the Gulf. The sum of volumes of the outgoing water over one year thus represented the volume of water that leaves the Gulf in one year due to the tides, and similarly for the incoming water. The two can be seen to be very nearly equal. This is because the water entering the Gulf balances the water leaving the Gulf in one complete tidal cycle. Any year contains a complete number of tidal cycles plus a part at the end. The difference between the incoming and the outgoing volumes would be due to that incomplete cycle and is less than 0.3% of the amount exchanged during the year. It averages out to zero when many consecutive years are considered.

The maximum amount of water that enters the Gulf in one hour during a tidal period was found to be  $6 \times 10^9 \text{ m}^3$  (Table 1), representing a mean rate of rise in the water level of 2.50 cm/hr and a mean current through Hormuz of 90.6 cm/s. The volumes of water in the tidal prism for the components  $M_2$ ,  $S_2$ ,  $K_1$  and  $O_1$  were found to be  $5.722 \times 10^9$ ,  $3.734 \times 10^9$ ,  $16.312 \times 10^9$  and  $4.758 \times 10^9 \text{ m}^3$  respectively. The order of importance of the components in their contribution to the currents at Hormuz are in the order  $K_1$ ,  $M_2$ ,  $S_2$  and  $O_1$  as the speed of the component is taken

**Table 1.** The maximum amount of water exchanged per hour and the total amount exchanged per year between the Arabian Gulf and the Gulf of Oman (incoming or outgoing)

Year	Maximum amount of water exchanged per hour in 10 m	Water exchanged per year (Incoming or Outgoing) in 10 m
1	5.317	1.4353
2	5.449	1.4397
3	5.501	1.4363
4	5.559	1.4342
5	5.713	1.4368
6	5.854	1.4337
7	6.047	1.4298
8	5.770	1.4313
9	5.890	1.4261
10	6.002	1.4190
Mean	5.710	1.4322

into account. It is interesting to note here that  $K_1$  and  $S_2$  are amplified with respect to their ratios in the equilibrium tide while  $O_1$  is diminished (Forrester 1983), the amplification factors being 1.6, 1.4 and 0.7 respectively. This indicates that the free period of the Gulf lies nearer to 23h56m (the period of  $K_1$ ) than to that of any other components. As the free period depends on the dimensions of the Gulf, changes in these dimensions would change the amplification factors and consequently the exchange.

The land runoff and precipitation in the Gulf area are extremely erratic and undergo wide variations in the short and long terms. The fresh water discharge of Shatt Alarab River is a minimum from August to December while it is high in the other months. It is reported as 5700 m<sup>3</sup>/s in April during the flood period compared to 700 m<sup>3</sup>/s in October during the drought season (Shott 1918). If the average of the two above figures is taken then the discharge would be 3200 m<sup>3</sup>/s which corresponds to  $10 \times 10^{10}$  m<sup>3</sup>/yr. On the other hand Hartmann *et al.* (1971) reported a total discharge of  $.5 \times 10^{10}$  m<sup>3</sup>/yr. The great discrepancy between the two reported values could have resulted from the damming of rivers and the irrigation projects in the intervening period. Accurate estimates of the discharge at present are difficult to obtain and it was decided to take the mean of the two values as an estimate of the present runoff.

Evaporation from the Gulf is so great that the different values of discharge from Shatt Alarab do not alter the calculations in this paper to any significant degree. The mean of Shott's and Hrtmann's values gives an estimate for the river

discharge of around  $5.3 \times 10^{10} \text{ m}^3/\text{yr}$ . Similarly the amount of the annual rainfall on the Gulf fluctuated considerably but the average precipitation over a period of 17 years is 78 mm/yr. (Meteorology Department, Doha, unpublished data) which corresponds to  $1.9 \times 10^{10} \text{ m}^3/\text{yr}$ ; thus the average total gain of fresh water equals  $7.2 \times 10^{10} \text{ m}^3/\text{yr}$ . Annual evaporation from the Gulf is given by Privett (1959) as 1.44 m for the open water and by Meshal and Hassan (1986) as 2.01 m for the coastal waters. Evaporation from the whole Gulf may be taken as the mean of the two above mentioned values *i.e.* 1.72 m/yr. This means that the Gulf loss  $41.2 \times 10^{10} \text{ m}^3/\text{yr}$  of fresh water through evaporation while it gains  $7.2 \times 10^{10} \text{ m}^3/\text{yr}$  from the runoff and precipitation. Thus there is a net loss of fresh water from the Gulf of about  $3.4 \times 10^{11} \text{ m}^3/\text{yr}$  which must be compensated for by a flow of surface water from the Gulf of Oman through the Strait of Hormuz. The incoming water has relatively low salinity (salin) of 36.5%, which increases during its circulation in the inner parts of the Gulf to exceed 41% near the Arabian coast. The outgoing water has an average salinity (salout) of 37.5% close to the Arabian side of Hormuz (Hassan 1987). Water of this salinity flows into the Gulf of Oman and sinks along the continental slope to levels having the same density, at depths near 250-300 m (Tchernia 1980).

Because of the nature of the tidal exchange, the incoming water to the Arabian Gulf (flood tide) contains a portion ( $\alpha$ ) of the Arabian Gulf water that had previously left (ebb tide) and the ebb tide contains a portion ( $\beta$ ) of the Gulf of Oman water that had previously entered in the flood tide. The salinity of the flood tide water (salin) and of the ebb tide water (salout) will therefore be intermediate between that of the Arabian Gulf water (sala) and the Gulf of Oman water (salo). Otherwise salout would have equalled sala and salin would have equalled salo. Since there is a net loss of fresh water from the Arabian Gulf due to excess evaporation, salout will be greater than salin. These salinities will not be of constant values, but will change within ranges depending on meteorological and tidal conditions. These ranges were assumed, based on observed values, and appear, together with the steps of changes in Table 2.

**Table 2.** Ranges for Sala, Salo, Salin and Salout

Variable	Sala	Salo	Salin	Salout
Range	38.00–41.50	35.40–35.70	36.30–36.60	37.10–37.49
Interval	0.5	0.1	0.1	0.13
No. of alternates	8	4	4	4

A renewal time (time), defined as the time it takes water from the Gulf of Oman to completely fill the Arabian Gulf basin was calculated for each possible set of these values and a subset was chosen which lies within 2% of Teve, the renewal time considering the evaporation values from the Arabian Gulf of 1.33 m/yr. to 1.55 m/yr. Time ranged between 1.45 yrs and 4.47 yrs. The shortest 10 such periods and the longest 10 appear in Table 3.

**Table 3.** Assumed values of evaporation rates (E), salinities of the Arabian Gulf water (Sala), that of the Gulf of Oman water (Salo), the incoming and outgoing water salinities (Salin and Salout) and the corresponding alpha and beta in addition to the renewal time utilising the tidal exchange (Time) and that resulting from evaporation considerations (Teve). Values were selected when Teve and Time were within 2% of each other. The shortest 10 and the longest 10 renewal times appear in the table. More than one hundred intermediate values were also found

E m/yr	Sala %	Salo %	Salin %	Salout %	Alpha	Beta	Time yr	Teve yr
1.55	38.00	35.70	36.40	37.36	0.42	0.40	1.44	1.45
1.50	38.00	35.70	36.30	37.23	0.39	0.45	1.49	1.50
1.55	38.00	35.60	36.40	37.36	0.45	0.40	1.50	1.52
1.55	38.00	35.60	36.30	37.23	0.53	0.45	1.55	1.52
1.45	38.00	35.70	36.60	37.49	0.50	0.36	1.55	1.56
1.55	38.00	35.60	36.30	37.23	0.43	0.45	1.55	1.57
1.55	38.00	35.50	36.30	37.23	0.46	0.45	1.52	1.59
1.55	38.00	35.50	36.40	37.36	0.48	0.40	1.67	1.59
1.40	38.00	35.70	36.50	37.36	0.48	0.43	1.61	1.61
1.45	38.00	35.60	36.60	37.49	0.53	0.36	1.62	1.63
1.40	41.50	35.70	36.50	37.36	0.48	0.83	4.06	4.06
1.45	41.50	35.50	36.60	37.49	0.55	0.82	4.05	4.08
1.35	41.50	35.40	36.40	37.23	0.55	0.82	4.06	4.10
1.40	41.50	35.60	36.50	37.36	0.51	0.83	4.13	4.14
1.45	41.50	35.40	36.60	37.49	0.57	0.82	4.12	4.15
1.40	41.50	35.50	36.50	37.36	0.54	0.83	4.20	4.23
1.35	41.50	35.60	36.40	37.23	0.49	0.48	4.28	4.30
1.40	41.50	35.40	36.50	37.36	0.56	0.83	4.27	4.31
1.35	41.50	35.50	36.40	37.36	0.52	0.84	4.35	4.38
1.35	41.50	35.40	36.40	37.23	0.55	0.84	4.42	4.47

Another approach suggested by Pearce (private communication) appears in the following and gives values within the same range (1 to 5 yrs).

“Suppose that over each tidal cycle volume  $v_1$  of water flows through the Strait of Hormuz out of the Arabian Gulf (AG) during the ebb tide and a volume  $v_2$  back again during the flood tide. Let volume E evaporate from AG. Then

$$v_2 = v_1 + E \quad (1)$$

The salt balance for AG gives

$$v_1 \times \text{salout} = v_2 \times \text{salin}$$

*i.e.*, using (1),

$$v_1 \times (\text{salout} - \text{salin}) = E \times \text{salin} \quad (2)$$

The left of (2) is the loss of salt from AG associated with the tidal flow  $v_1$ ; the right of (2) expresses this loss in terms of evaporation. This loss of salt from AG due to evaporation can be envisaged as effectively an exchange of volume  $\delta v$  of Gulf of Oman water with a similar volume of AG water, *i.e.* as  $\delta v$  (sala-salo), *i.e.*

$$\delta v \times (\text{sala} - \text{salo}) = E \times \text{salin} \quad (3)$$

Thus, from (2) and (3),

$\delta v = v_1 \times (\text{salout} - \text{salin}) / (\text{sala} - \text{salo})$ , and if  $V$  is the volume of AG, the renewal time is  $V / \delta v$  tidal cycles, *i.e.*

$$T_{\text{tid}} = \frac{V}{v_1} \frac{(\text{sala} - \text{salo})}{(\text{salout} - \text{salin})}$$

It is most reasonable to expect that under natural variability (year to year variability in excess evaporation, tidal conditions) the instantaneous renewal period would lie between these two extremes *i.e.* between 1.5 yrs and 4.5 yrs.

The tidal mixing calculated in this paper represents the major part of the tides, but adding other components would increase it even more. The residence time due to tidal mixing alone equals 7 months while the renewal time exceeds one year but is less than 5 years. The renewal time is intimately related to the carrying capacity of the Gulf, and its calculation is important for the planning process of the Gulf area development. Because of the dominance of tides in the exchange it is logical that changes affecting the tides would have more influence in varying the exchange than other factors. Major projects going on in the Gulf area at this time are the rapid growth in the capacity of desalination plants, the river regulation affecting the outflow from Shatt Alarab, the bridge between Bahrain and Saudi Arabia and the land reclamation project in Bahrain. The last two projects change the bottom topography at the entrance to Salwa Bay (a major appendix to the Gulf lying between Saudi Arabia, Bahrain and Qatar). Desalination at present removes about 10 gallons of fresh water per day from the Gulf, equivalent to an increase of evaporation of less than one cm/yr from the surface water. This is within the natural year to year variability of evaporation. More important is the river control that could in the extreme deprive the Gulf of the equivalent of 22 cm/yr but

represents an increase in the magnitude of the incoming current through Hormuz by about 0.1 cm/s. This again would not change the pattern of exchange. The restriction to the connection between the Gulf and Salwa Bay needs further studies as it has the potential of changing the tidal characteristics of the Gulf. The free period of the Arabian Gulf is near to that of the diurnal component  $K_1$  and a small change in the free period can either increase the tidal amplitude and hence the tidal prism due to that component or decrease it. New measurements of tidal heights around the Gulf to redetermine the tidal constants and patterns assume therefore added importance and urgency.

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## تأثير المد والجزر والبخر على تبادل المياه بين الخليج العربي وخليج عُمان

السيد محمد حسن و حسن مصطفى حسن

قسم علوم البحار - جامعة قطر - ص. ب. ٢٧١٣ الدوحة - قطر

تبقى المياه في البحار فترة زمنية قبل أن تتجدد مع البحار المجاورة وتسمى هذه الفترة «زمن المكوث» ويتميز الخليج العربي بقصر زمن مكوث المياه فيه مقارنة بأي جسم مائي آخر يماثله في الابعاد. ويعتبر المد والجزر من العوامل الهامة المؤثرة في زمن مكوث المياه في الخليج. وقد حسب مقدار المياه المتبادلة من الخليج العربي وخليج عُمان وتأثير المد والجزر باستعمال نموذج رياضي لمركبات المد والجزر الأربعة  $O_1, K_1, S_2, M_2$  وحسب مقدار زيادة البخر من بيانات الارصاد الجوية ومياه الانهار التي تصب في الخليج.

وقد وجد أن المد والجزر هو المتسبب الرئيسي في تقصير زمن مكوث المياه في الخليج. ولكن لا يمكن التأكد من هذا الاستنتاج من دراسة الخليج العربي وحده ولذلك ينوى المؤلفان إجراء دراسات على بحار أخرى لبيان أهمية العاملين المذكورين على عملية تبادل المياه.