Revista Internacional de Contaminación Ambiental
ISSN: 0188-4999
rvp@atmosfera.unam.mx
Universidad Nacional Autónoma de México
México

Montaño Ley, Yovani; Páez Osuna, Federico; Peraza Vizacarra, Ramón
Suspended and bed load sediment transport through a coastal lagoon entrance in Mazatlán, Sinaloa, México
Revista Internacional de Contaminación Ambiental, vol. 16, núm. 1, 2000, pp. 27-36
Universidad Nacional Autónoma de México
Distrito Federal, México

Rev. Int. Contam. Ambient. *16* (1) 27-36, 2000

SUSPENDED AND BED LOAD SEDIMENT TRANSPORT THROUGH A COASTAL LAGOON ENTRANCE IN MAZATLÁN, SINALOA, MÉXICO

Yovani MONTAÑO-LEY[1], Federico PÁEZ-OSUNA[1] and Ramón PERAZA-VIZCARRA[2]

[1]Instituto de Ciencias del Mar y Limnología, Estación Mazatlán, UNAM, Apdo. Postal 811, Mazatlán 82000 Sinaloa, México. Tel: + (69) 852845. Fax + (69) 826133. Correo electrónico: paez@servidor.unam.mx
[2]Facultad de Ciencias del Mar, UAS, Apdo. Postal 610, Mazatlán 82000 Sinaloa, México

(Recibido noviembre 1998, aceptado septiembre 1999)

Keywords: Sediment transport, lagoon, bed load, Mexico

ABSTRACT

A sediment transport study was carried out at the Urías Lagoon Entrance in Mazatlán, Sinaloa, México. Tidal velocities and elevations were measured every two hours over two tidal cycles at the Lagoon Entrance. Simultaneously suspended sediment was sampled at the same location from two levels of the water column. Phase differences (2-3 h) were found between maximum tidal velocities and maximum suspended sediment concentration. The axial distribution of sediment concentration near the water surface (1 m) in the lagoon was also investigated. Increasing sediment concentration values were found from the entrance (3.2 mg l^{-1}) to the head (19.9 mg l^{-1}) of the coastal lagoon. In addition, the field- work included measurements of waves, bed-forms and bed grain size parameters. Bed load and suspended sediment transport rates were computed at the lagoon entrance for critical tidal velocities by using a program developed by Van Rijn (1990). The largest suspended sediment transport (0.261 kg s^{-1} m^{-1}) and the largest bed load transport rate (0.009 kg s^{-1} m^{-1}) were found for ebb tide at cycle 2. The results also included instantaneous vertical profiles of sediment concentration, current velocities and sediment transport at the selected point. Most of the vertical profiles indicate a sediment concentration increase with depth through the water column. The suspended sediment flux increases from the upper water layers to the last 0.30 m layer near the bed where the increase is faster.

RESUMEN

Se investigó el transporte de sedimentos a través de la Entrada a la Laguna Costera de Urías en Mazatlán, Sinaloa, México. Como parte de la investigación se midieron durante dos ciclos de marea elevaciones del nivel del mar así como velocidades de las corrientes en la entrada a la laguna y se realizaron muestreos de la columna de agua a dos niveles de profundidad para determinar concentraciones de sedimento en suspensión. Se encontraron diferencias de fase de 2-3 h entre las velocidades máximas de las corrientes y las concentraciones máximas de sedimento en suspensión. Así mismo, se investigó la distribución axial de las concentraciones de sedimento cerca de la superficie (1 m) del agua encontrando un incremento en las concentraciones desde la entrada (3.2 mg l^{-1}) hasta la cabecera (19.9 mg l^{-1}) de la laguna costera. En adición, el trabajo de campo, incluyó mediciones del tamaño del sedimento y formas de fondo así como de olas. Con los datos obtenidos se evaluaron tasas de transporte de sedimentos en suspensión y como carga de fondo para velocidades críticas de corrientes a través del modelo de transporte desarrollado por Van Rijn (1990). Las tasas mayores de transporte en suspensión (0.261 kg.s^{-1} m^{-1}) y transporte como carga de fondo (0.009 kg.s^{-1} m^{-1}) se presentaron durante el ciclo de mareas 2 bajo condiciones de reflujo.

Los resultados incluyen también perfiles verticales de concentraciones de sedimentos, velocidades de corrientes y transporte de sedimentos. La mayoría de los perfiles indican un incremento en las concentraciones de sedimento con el aumento de la profundidad a través de la columna de agua. El flujo de sedimento en suspensión se incrementa desde las capas superiores de agua hasta la capa de 0.30 m de espesor cerca del fondo, donde el incremento es más marcado.

INTRODUCTION

Sediment beds are widely viewed as a potential sink/or source of pollutants to aquatic environments, and in shallow coastal waters where the cycling of heavy metals and organic pollutants is often dominated by re-suspension, sedimentation and horizontal transport of sediments, these contaminants have a strong tendency to concentrate in suspended material, and large pools can accumulate in coastal bottoms. This is evidently the case in the Urías Coastal Lagoon, Mazatlán, Sinaloa, México.

In spite of the importance that the Urías Coastal Lagoon has as a shipping and fisheries harbor, very few studies of hydraulics and sediment transport have been carried out in the study area. Villalba (1986) pointed out that tidal intrusion has a profound influence upon the lagoon water circulation. Similarly, Montaño-Ley and Páez-Osuna (1990) gave a brief description of the tidal prism and explained the importance of the bathymetric configuration of the lagoon in controlling the circulation pattern. As an important step to understand the sediment processes at the Lagoon Entrance, the present investigation was undertaken to determine an order of magnitude of both suspended and bed load transport rates for critical tidal velocities at the Lagoon Entrance. Field measurements of current, wave and sediment parameters were carried out and the information collected was used as input data to the computer program developed by Van Rijn (1990) to evaluate hydraulic parameters, sediment transport rates and vertical sediment concentration profiles. The predicted suspended sediment concentrations were compared with values obtained through direct measurements of suspended sediment at two levels of the water column. In addition, the axial distribution of suspended sediment concentrations at the coastal lagoon was investigated. The results of this investigation are important for a better planning of dredging operations. This study also contributes to the understanding of the problem of the sediment exchange processes between this particular coastal body of water and the ocean. The above information should help to make better decisions for regu-

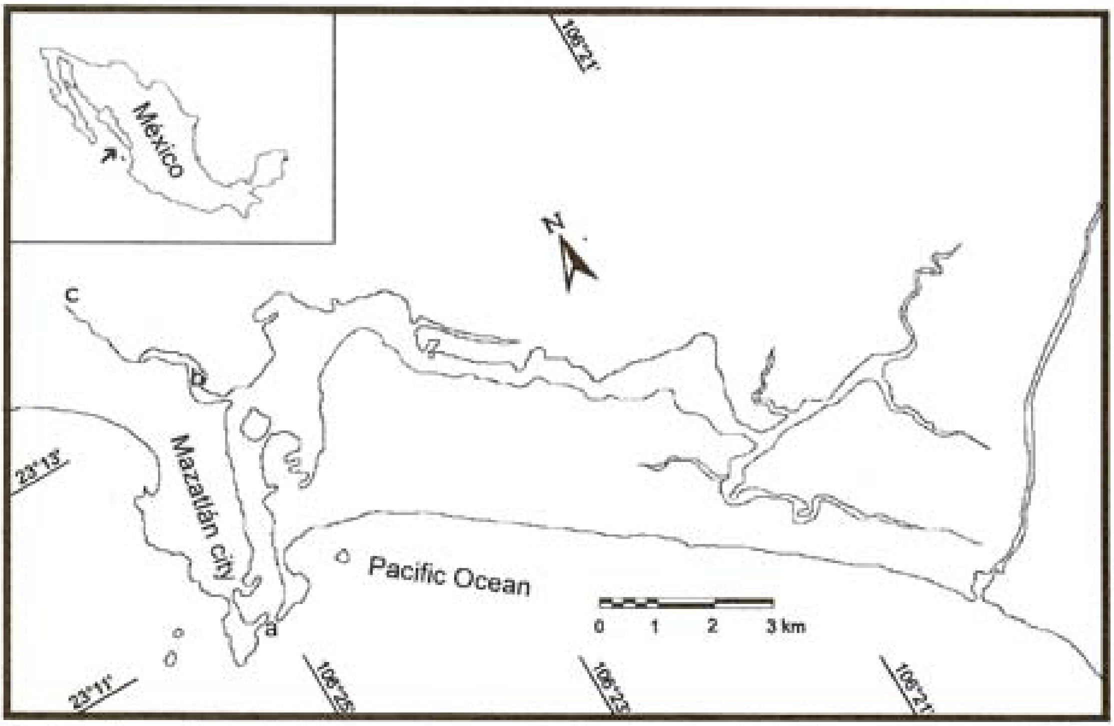

Fig. 1. Study area, showing the Urías Lagoon Entrance (site a), the Infiernillo tidal channel (b) and the Jabalíes Creek (c)

lations concerning the management and preservation of the system.

STUDY AREA

The study area is a coastal body of water located on the western coast of México (**Fig. 1**). This body of water which includes the Harbor of Mazatlán, has been classified by Lankford (1977) as a coastal lagoon with an internal platform barrier. The lagoon is tidally dominated (Montaño-Ley and Páez-Osuna 1990). It is characterized by a mixed tide with an average range of about 1.0 m. Because of limited fresh water discharges through Jabalies creek (**Fig. 1b**) during the rainy seasons, the salinity is usually high during the year in the range of 25.76 - 38.4 ‰. Water depth varies between 1 and 3 meters except in the navigation channel where it is up to 12 m. Prevailing winds are associated with weather systems from the N.W. (Montaño-Ley 1985). Occasionally, tropical storms migrate along the Pacific Coast of México from the S.W. striking Mazatlán city.

Confined by two breakwaters the Urías Lagoon Entrance is the access to Mazatlán Harbor through a navigation channel with depths up to 11 m. The channel is periodically dredged to maintain the required depth. Some areas of the inner system also have to be dredged to permit the safe maneuver of ships. Dredging has to be carried out approximately every two years. Such operations indicate that accumulation of sediment on the lagoon is taking place. The probable source of sediment is via littoral drift along the nearby sandy beaches (Montaño-Ley 1985).

MATERIALS AND METHODS

Physical (tidal currents and elevations) and sedimentary parameters were measured at the entrance (site a) of the Urías Lagoon (**Fig. 1**). One Braystoke BFM 0012 current meter was used to measure velocities every two hours. The meter was used in such a way that the velocity measurements were carried out every meter in the whole water column in approximately half an hour, so this short time interval allowed the determination of mean depth velocities. Water level was recorded by a tidal gauge placed close to the harbor entrance. Charts were digitized to obtain water levels and hence changes in the cross sectional area at two hour intervals. The measurements of tidal velocities and elevations were carried out during two tidal cycles. Additionally, water samples were collected every two hours for each tidal cycle, from two levels, surface and 5 m depth at the Lagoon Entrance to evaluate suspended sediment concentrations.

Visual observations of waves were carried out. Significant wave height and periods were calculated according the definition given by the U.S. Army Corps of Engineers (1973). Wave direction was estimated by using a magnetic compass.

In a previous survey, eight stations were occupied along the main channel of the lagoon in order to sample surface water and measure suspended sediment concentrations by gravimetric methods (Banse *et. al.* 1963). The implied error in this method, as a variation coefficient, range between 8 and 10 %. Lacking detailed data from which to calculate the degree of tidal mixing, a gross estimation of the tidal prism and flushing index was carried out according to the procedure given by Bowden (1967). For estimation of the total volume of the body of water data gathered with a portable fathometer was entered on the chart edited by the Secretaría de Marina (1988).

Divers sampled, also at the Lagoon entrance, the bottom sediments and measured bedform which consisted of ripples. Average ripple height at each stage of the tide was obtained. Grain size distributions were obtained by sieve analysis (Folk 1974). Suspended sediment fall velocities were measured by the hydrometer method applying the Stokes equation. The averaged ripple height (Δ_r) was used to estimate the current and wave related roughness and a reference level a= $\Delta_r/2$ given by Van Rijn (1990). Salinity was measured by using a salinometer (Beckman Instr. Inc), and temperature was recorded *in situ*. These parameters were used to calculate the fluid density and the kinematics viscosity (Riley and Skirrow 1975). The collected information was used as input data to the computer program designed by Van Rijn (1990), to evaluate suspended and bed load transport rates and suspended sediment concentration profiles for critical tidal velocities.

This program computed the current related bed load transport rate ($q_{b,c}$) according to the equation (Van Rijn, 1990):

$$q_{b,c} = 0.25 U_{*,c} d_{50} \frac{T^{1.5}}{D_*^{0.3}} \tag{1}$$

Where ($U_{*,c}$) is a current related grain bed-shear velocity and (d_{50}) is a median particle diameter of bed material.

The time averaged suspended load transport ($\overline{q}_{s,c}$) was computed by numerical integration over the depth of the product of velocity and concentration, as follows:

$$\overline{q}_{s,c} = \int_a^h UC\,dz \tag{2}$$

Where (*h*) is the water depth, (*a*) is a reference level (equal to the half ripple height), (*C*) is the suspended sediment concentration and (*U*) is the current velocity, both at elevation (*z*) above the bed.

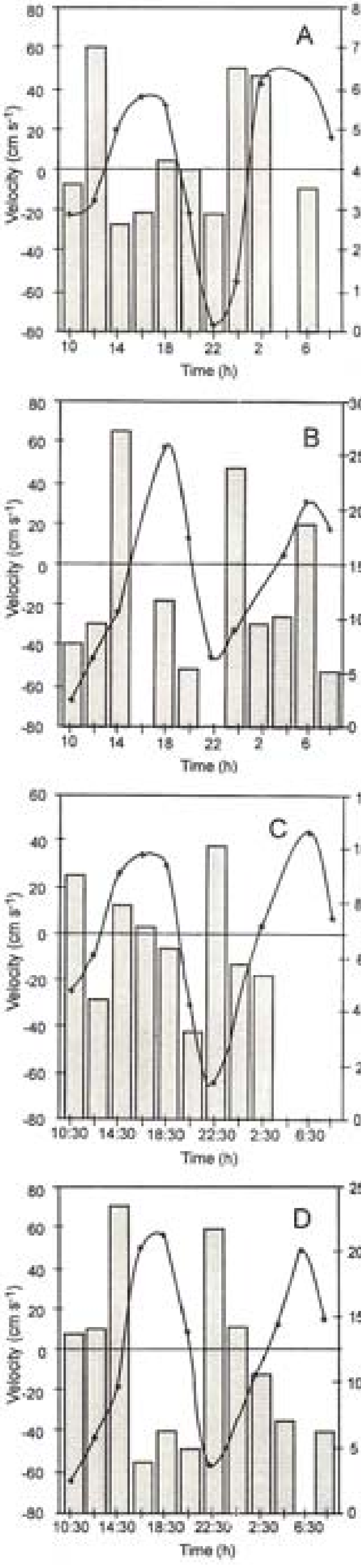

Fig. 2. Time series of tidal current velocities (•) and suspended sediment concentrations () measured in the Urias Lagoon Entrance. A) For tidal cycle 1 at 1.0 m depth, B) For tidal cycle 2 at 1.0 m depth, C) For tidal cycle 1 at 5.0 m depth, D) For tidal cycle 2 at 5.0 m depth

The suspended sediment concentration distribution along the vertical axis (z) was computed by numerical integration of the time averaged convection-diffusion equation.

$$\frac{dC}{dz} = \frac{(1-C)^5 w_s}{\varepsilon_{s,cw}} \qquad (3)$$

Where (w_s) is the sediment fall velocity in fresh water, ($\varepsilon_{s,cw}$) is the sediment mixing coefficient in combined currents and waves. This is assumed to be given by the sum of the squares of the current and the wave related sediment mixing values, the wave related coefficient depends on the near bed orbital velocity (U_w) which is a function of significant wave height (H_s), peak wave period (T_p), water depth (h), and wave length (L), as follows:

$$U_w = \frac{H_s \pi}{T_p \sinh \frac{2\pi h}{L}} \qquad (4)$$

Applying as a reference concentration

$$C_{ref} = 0.015 \frac{d_{50}}{\alpha} \frac{T^{1.5}}{D_*^{0.3}} \qquad (5)$$

Where (T) is a dimensionless bed shear stress parameter due to currents and waves and (D_*) is a dimensionless particle parameter, both parameters are defined by Van Rijn (1987).

Lacking detailed data from which to calculate the degree of tidal mixing, gross estimations of the tidal prism and flushing index were carried out according to the procedure given by Bowden (1967). For the estimation of the total volume of the body of water data gathered with a portable fathometer were entered on the chart edited by the Secretaría de Marina (1988).

RESULTS

Suspended sediment histograms and tidal velocity curves from the cross section area between the Mazatlán harbor breakwaters (lagoon entrance) are shown in **Fig. 2**. The surface sediment concentrations for tidal cycle 1 (**Fig. 2A**) ranged from 2.6 to 6.8 mg l⁻¹ and for tidal cycle 2 (**Fig. 2B**) between 5.2 and 27 mg l⁻¹. At the second depth level (5 m depth) the suspended sediment concentration ranged from 3.2 to 11.1 mg l^{-1} for tidal cycle 1 (**Fig. 2C**) and from 3.5 to 23.5 for tidal cycle 2 (**Fig. 2D**). The maximum suspended sediment concentration for tidal cycle 1 roughly follows both the peak of the ebb and flood tidal current. The tidal velocities are high enough to entrain sediment off the bed, and peaks of concentration occur after the times of maximum velocities. Tidal record 1 indicates a mixed tide within a range of 1.4 m and tidal record 2 shows a maximum range of about 0.9 m (**Fig. 3**).

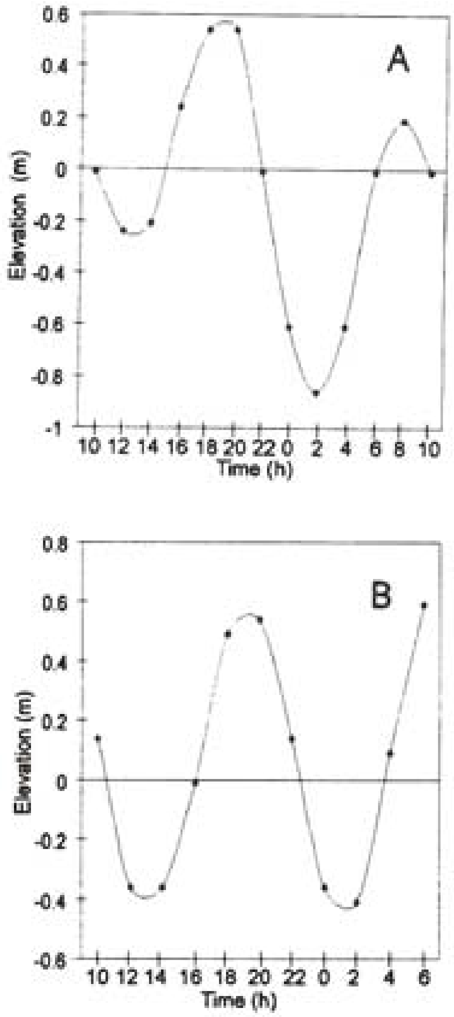

Fig. 3. Water level elevations at the Urías Lagoon Entrance for extended tidal cycle 1 (A) and tidal cycle 2 (B) ; elevation reference is mean tide level

The axial distribution of suspended sediment concentrations near the water surface in the Urías Lagoon System revealed an increasing sediment concentration from the entrance (3.2 mg l^{-1}) to the head (19.9 mg l^{-1}) of the coastal lagoon (**Fig. 4**). A remarkably high concentration value (10.7 mg l^{-1}) was found near the tidal channel known as the Infiernillo.

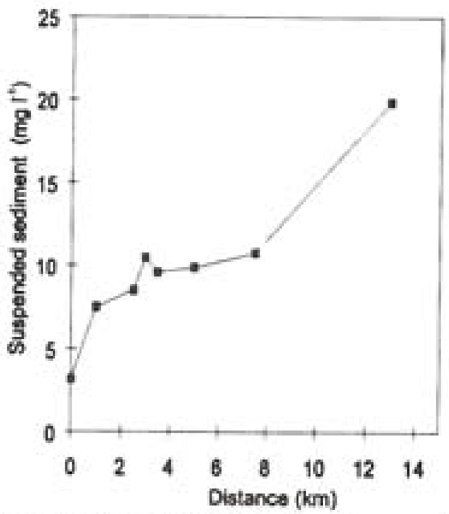

Fig. 4. Axial distribution of suspended sediment concentration from the Urías Lagoon Entrance (0 km) to the head (14 km)

The sediment transport model was run for critical values of tidal velocities and other physical and sedimentary parameters measured under laboratory conditions or in the field for tidal cycles 1 and 2 at the Urías Lagoon Entrance; these parameters are presented in **table 1**.

The model output parameters, including the suspended and bed load transport rates, are presented in **table 2**. The instantaneous sediment concentrations, current velocities, and sediment transport profiles, evaluated through the computer program for the two sets of environmental parameters at the Urías Lagoon Entrance, are shown in **Fig. 5**.

Bed load transport rates and suspended sediment trans-

TABLE I. PHYSICAL AND SEDIMENTARY PARAMETERS MEASURED EITHER IN THE FIELD OR LABORATORY USED AS INPUT TO THE MATHEMATICAL MODEL FOR TIDAL CYCLES 1 AND 2

Parameter	Units	Cycle 1	Cycle 2
Water depth	m	10.00	10.00
Critical current velocity	m/s	0.65	0.70
Significant wave height	m	0.50	0.50
Peak wave period	s	3.0	3.0
Angle current and waves	Degrees	0	180
Median particle size of bed	µm	175	175
90 %t particle size	µm	350	350
Fall velocity suspended sediment	m/s	0.01	0.01
Current related roughness	m	0.09	0.09
Wave related roughness	m	0.09	0.09
Mixed layer thickness near bed	m	0.09	0.09
Reference level	m	0.015	0.015
Kinematics viscosity coefficient	m	8.78E-07	9.17E-07
Fluid density	kg/m^3	1023	1022
Sediment density	kg/m^3	2650	2650
Ratio sediment and fluid mixing	-	1.00	1.00

TABLE. II. PHYSICAL PARAMETERS, SUSPENDED AND BED LOAD TRANSPORT RATES OBTAINED FROM THE MODEL (OUTPUT) FOR TIDAL CYCLES 1 AND 2

Parameter	Units	Cycle 1	Cycle 2
Particle parameter	-	4.76	4.63
Wave length	m	14.06	14.06
Peak orbital velocity	m/s	0.011	0.011
Peak orbital excursion at bed	m	0.005	0.005
Current related bed shear stress	N/m^2	1.33	1.54
Wave related bed shear stress	N/m^2	0.011	0.011
Wave related friction coefficient	-	0.300	0.300
Current related friction coefficient	-	0.024	0.024
Chezy coefficient	MO.5/s	56.25	56.25
Apparent roughness	m	0.091	0.091
Wave-current coefficient	-	1.00	1.00
Critical bed shear stress	N/m^2	0.143	0.146
Current related efficiency factor	-	0.381	0.381
Wave related efficiency factor	-	0.125	0.129
Bed shear stress parameter	-	2.54	3.03
Suspended load transport	kg/s m	0.149	0.262
Bed load transport	Kg/s m	0.0065	0.0093

port for critical velocities of tidal cycles 1 and 2 were obtained using the Equations 1 and 2, included in the model of Van Rijn (1990), respectively. A suspended sediment transport rate of 0.262 kg s^{-1} m^{-1} took place at a critical velocity of 0.70 m s^{-1} on the ebb tide for tidal cycle 2 and a bed load transport rate of 0.009 kg s^{-1} m^{-1} was found for the same critical velocity.

DISCUSSION

Sediment transport processes in the Urías Lagoon are modulated by the astronomical ocean tides, geometry of the lagoon and sediment supply. The energy available to transport the sediment is provided by tidal pumping which generate measured current velocities up of 70 cm s^{-1} at the lagoon entrance. The main source of sediment for lagoon is the littoral drift which according to Montaño (1986), is of reversing type reaching 6600 cm^3 s^{-1}. Sediment is cycled from one part of the lagoon to another with amounts added from diverse sources to balance the amount removed from the system by the ebb tide or dredging operations which are carried out eventually to keep the required depth for ships maneuvers in the harbor.

The maximum surface suspended sediment concentrations at the Urías Lagoon Entrance for tidal cycles 1 and 2 (**Fig. 2**) were found at the end of the ebb tide as the more turbid water is advected seaward from upstream. Uncles *et al.* (1994) found at the upper reaches of Tamar Estuary, U.K. that near bed suspended sediment concentrations, as in this study, were low at high water and increased as the ebb progressed and salinity stratification eroded. In this study maximum concentrations near the surface lag behind maximum current velocities by 2-4 hours. In the tidal cycle 1 the sediment concentrations increase with depth. In contrast, in the tidal cycle 2 the sediment concentrations decrease with depth. A possible explanation to the behavior of these sediment concentration distributions is as follow: beside the re-suspension sediment process by current velocities, the exchange between ocean water and lagoon water plays an important role on the sediment distribution. Hypothetically in the tidal cycle 1, the marine water with slightly lower sediment concentration than the lagoon water, could be mobilized close to the bottom, while the more turbid lagoon water could be mobilized near the surface, producing the contrasting suspended sediment distribution found in tidal cycles 1 and 2.

In The Urías Coastal Lagoon "lower low water" follows "higher high water". This condition usually produce maximum velocities during ebb tide (**Fig. 2**). Differentially higher ebb velocities should have the effect of flushing suspended sediment from the coastal lagoon. According to Lankford (1977), this is considered to be one of the major mechanisms which inhibits or slows the sedimentary infilling process typical of most coastal lagoons; if the tide curve is reversed and "higher high water", as in the case of the northern Gulf of California and to a lesser degree in the Gulf of México, the maximum expected velocities occur during flood tide. Net sediment transport will be from the turbulent surf zone into the lagoon.

The axial distribution of suspended sediment concentrations found near the water surface in the Urías Lagoon system show an increase from the entrance to the head of the coastal lagoon (**Fig. 4**). This distribution is explained as a result of the different wave and transport conditions between the entrance and the head of the system. The entrance is exposed to littoral sand transport. Tidal currents and waves remove fine material leaving only the heavier sediment. The inner part of the Urías Lagoon is exposed to only very small waves and weak currents (Montaño-Ley and Páez-Osuna 1990). However both near bed and suspended load transport, in the inner part of the lagoon, depend strongly on the flow field, because freshwater inflows from run off and wastewater discharges (800 m^3 h^{-1}) are negligible (Páez-Osuna *et al.* 1990). Because of this, gravitational effects are very limited. When river sediment influx is absent, sedimentation in a coastal lagoon depends primarily on reworking of material within the lagoon, influx of sediment through the tidal inlet from the ocean, runoff from marginal areas and biological sources (marsh grass, shell material, etc.). Therefore, without a river influx local bottom shear stresses will control much of the sediment transport either as near bed or suspended load (Aubrey 1986). This is the case of the Urías Lagoon System, fine sediment is eroded from marginal areas by rain. The eroded material is transported and drained into the la-

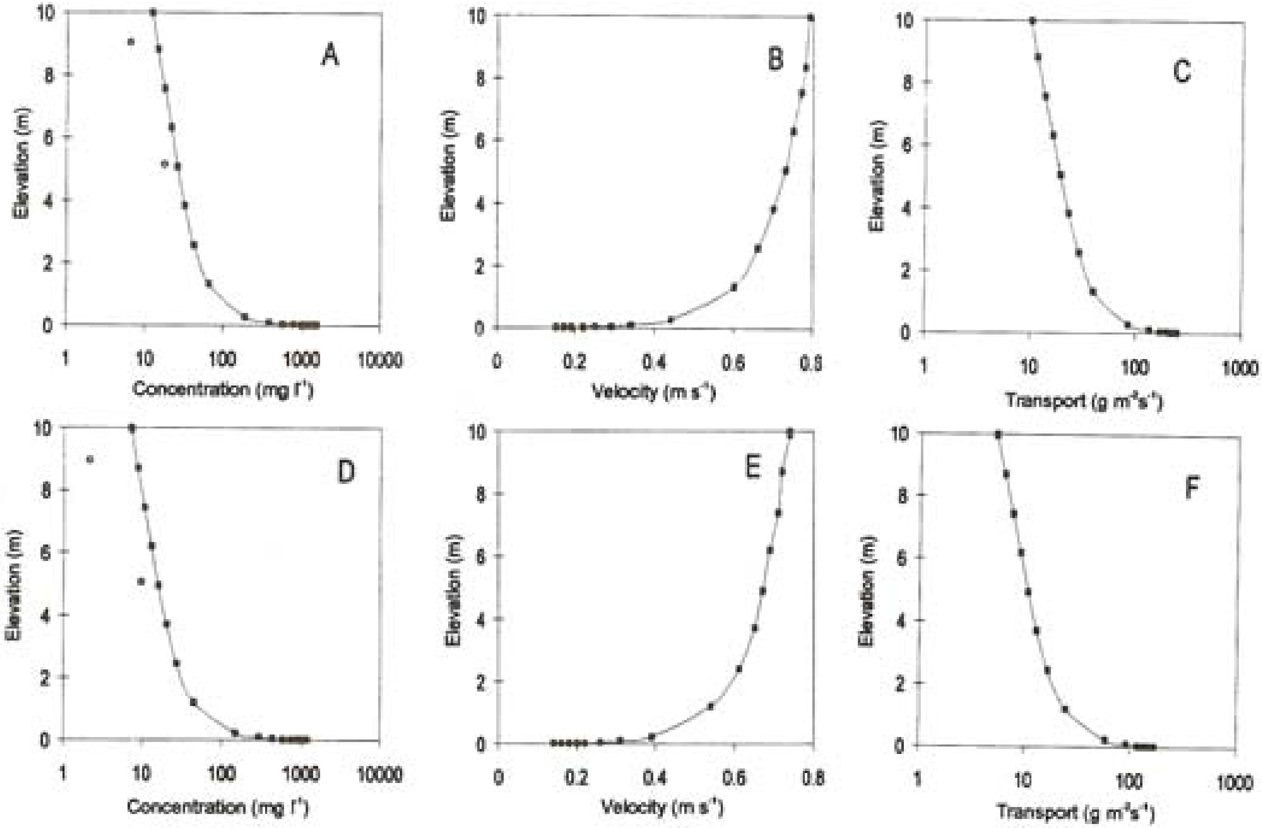

Fig. 5. Sediment concentrations, current velocities and sediment transport vertical profiles, predicted (▪) and measured (○) in tidal cycles 1 (D, E, F) and tidal cycle 2 (A, B, C) for critical velocities of 0.65 and 0.70 m s^{-1}, respectively

goon. Therefore the bottom of the lagoon consists mainly of fine sediment (Osuna-López *et al.* 1986). When strong winds blow, a great deal of sediment is set into suspension by the intense mixing effect of the wind in shallow water. High bottom shear velocities entrain sediment off the bed causing high suspended sediment concentrations. Postma (1961) found in the Eastern Scheldt Estuary, a suspended sediment distribution similar to the pattern presented in this investigation. This was explained as a result of a settling and scour lag process and a superimposed effect, the time velocity asyimmetry of tidal current, which account for net landward transport. Fichez *et al.* (1992) found that the location of the turbidity maximum in the Great Ouse Estuary, England, was related to the fresh water inputs moving downstream when the river flow was high. Usually, sediment concentration decreases as in this study in the downstream direction. Ward and Twilley (1986) found that suspended sediment concentrations in the Choptank River, an estuarine tributary of the Chesapeake Bay, varied from 3.3 to 98.6 mg l^{-1}. A normal increase of concentrations in the landward direction was observed. Maximum concentration occurred in the upper estuary, whereas, lowest concentrations were found, as in this study, near the mouth.

Predicted suspended sediment profiles (**Figs. 5A** and **5D**) present a sharp increase in concentration near the bottom of the lagoon entrance. Results of direct measurements of suspended sediment concentrations at two levels in the water column (5 and 9 m above the bottom) are of the same order of magnitude (11-30 %) as the predicted values. All the concentration profiles present only little changes from the upper level of the water column to a level close to the bottom where the concentrations increase sharply because of the energy dissipation processes generated at the sediment-water interface (McDowell and O 'Connor 1977). Sediment concentrations measured in other coastal lagoons allow us to compare results. Postma (1965), found in Guerrero Negro Coastal Lagoon, México, that the vertical distribution of sediment concentration in the upper part of the water column is approximately a lineal distribution. In this study the suspended sediment concentration values for the two sampled depth levels fluctuated between 2.6 and 27 mg l^{-1}. This values remain within the concentrations range reported by Postma. Sternberg *et al.* (1985) studied time series of suspended sediment and velocities vertical ve-

TABLE III. SUMMARY OF THE PHYSICAL CHARACTERISTICS OF SELECTED LAGOONS OF THE GULF OF CALIFORNIA

Lagoon	Area ($m^2 \times 10^6$)	Volume ($m^3 \times 10^6$) Tidal	Volume ($m^3 \times 10^6$) Total	Mean depth (m)	Flushing index	Reference
Bahía Concepción	282	221	4553	15.4	0.05	(a)
Ensenada de La Paz	50	45	145	1.9	0.31	(a)
Laguna de la Cruz	25	22	58	1.4	0.38	(a)
Bahía de Guaymas	28	30	93	2.3	0.32	(a)
Bahía de Yavaros	62	139	154	1.1	0.56	(a)
Bahía Ohuira	149	199	359	1.0	0.55	(a)
Bahía Santa María	492	285	1761	3.0	0.16	(a)
Altata-Ensenada Pabellón	360	390	1080	3.5	0.36	(b)(c)
Estero de Urías	12	18	36	3.0	0.50	(d)

(a) Gilmartin and Revelante (1978), (b) Peraza-Vizcarra (1973), (c) Páez-Osuna *et al.* (1993), (d) this study

locity profiles in the one meter water column above the bottom in a tidal channel in San Francisco Bay (U.S.A.) and concluded that mass flux was almost uniform between $z = 20$ cm and $z = 1.0$ m and that below $z = 0.20$ m the mass flux increased sharply reflecting as predicted in the present investigation, a sharp increase of suspended sediment concentration near the bottom. Also, Van Rijn (1987) obtained sediment concentrations on vertical profiles similar to those of this work, in the Eastern Scheldt in the Netherlands. Rodríguez-Espinoza (1982) found suspended sediment concentrations of 19 and 30 mg l^{-1} for current velocities of 0.70 and 0.50 m s^{-1} in La Machona and El Carmen Lagoon in Tabasco, México. Concentrations obtained by the same author are of the same order of magnitude as the concentrations obtained in this investigation at the surface level for current velocities of 0.7 m s^{-1}.

The vertical velocity profiles presented in **Fig. 5B** and **5E** at the Urías Lagoon Entrance, show a gradual decrease of the current velocity from the water surface to a 0.30 m level over the bottom; from this level to the bed, logarithmic velocity profiles were predicted. Similarly, Mehta *et al.* (1975) found a well defined logarithmic character at velocity profiles measured at John Pass and Blind Pass, Florida, U.S.A.

Vertical profiles of sediment transport of the Urías entrance showed greater values in the lower part of the water column than in the upper part (**Fig. 5C** and **5F**). Above $z = 1.00$ m the magnitude of sediment transport was relatively uniform exhibiting only minor variations with distance above the bed. Below $z = 1.00$ m the magnitude of sediment transport increased sharply towards the seabed, reflecting the high suspended concentration gradients predicted in all concentration profiles near the bottom.

The computer model developed by Van Rijn (1990) was used to evaluate sediment transport parameters as a first step to understand the sediment processes at the Urías Coastal Lagoon entrance. The obtained results of this investigation such as sediment transport rates (suspended and bed load transport), sediment concentration, velocities and transport vertical profiles and the axial distribution of suspended sediment concentrations are important for a better planning of dredging operations. Another interesting feature of this research was the measurements of tidal velocities and elevations at the inlet and a gross estimation of tidal prism and flushing index. These results also contribute to the understanding of the exchange processes between this particular coastal body of water and the ocean. The above information will help to make better decisions for regulations concerning the preservation of water quality of the system.

The total volume value of 36×10^6 m^3 obtained in this study is small compared with values given by Gilmartin and Revelante (1978) for eigth coastal lagoons adjacent to the study area in the Gulf of California (**Table III**). On this basis the Urías Lagoon may be considered as an small and shallow coastal body of water. As a consequence of the shallow depths in a tidal regimen where the mean tidal range is approximately 1 m, the flushing index of 0.50 is high compared with the larger coastal lagoons of the region such as Bahía Concepción, Bahía de Santa María and Altata-Ensenada del Pabellón where the flushing index were of 0.05, 0.16 and 0.36, respectively.

CONCLUSIONS

Sediment transport processes in the Urías Coastal Lagoon are modulated by astronomical ocean tide, geometry of the lagoon and sediment supply. The energy available to transport the sediment is provided by tidal pumping which generates surface current velocities up to the 70 cm s^{-1} at the lagoon entrance.

In this coastal body of water "lower low water" follows " higher high water" (**Fig. 3**). This condition usually produces maximum velocities during ebb tide. Differentially higher ebb velocities should have the effect of flushing suspended sediment. The maximum surface suspended sediment concentrations of 7 and 27 mg l^{-1} measured at the lagoon entrance for tidal cycle1 and 2, respectively, were found at the end of the ebb tide as the more turbid water was advected seaward from upstream.

The axial suspended sediment concentration along the Urías Coastal Lagoon shows a maximum concentration of 19.9 mg l^{-1} at the head of the lagoon. The suspended sediment concentration decreases toward the lagoon entrance where the concentration was 3.2 mg l^{-1}. This distribution may be explained as a result of runoff from marginal areas and the different tidal currents and wave conditions between the entrance and the head of the lagoon, where shallowness favors the increase of turbidity.

The predicted sediment concentration and velocities profiles show a logarithmic character close to the bottom. The sediment transport profile exhibited the same tendency as well (**Fig. 5**).

Based on this tidal prism ($18\mathrm{x}10^6$ m^3), the Urías lagoon may be considered as an small and shallow coastal body of water. The flushing index of 0.50 is high compared with the larger coastal lagoons of the region such as Bahía Concepción, Bahía Santa María, and Altata- Ensenada del Pabellón, where the flushing indexes are of 0.05, 0.16, and 0.36, respectively.

The dispersion and distribution of contaminants in the Urías Coastal Lagoon depend on water circulation and sediment transport rates and paths rather than other physical agents. Since sediments act like a trap, evidently the sites with high suspended sediment concentrations may be considered vulnerable to the contamination: specifically the head of the lagoon where the sediment is difficult to be removed by the tidal currents. The main channel, where the tidal currents exceed 0.7 m s^{-1} and the sediment transport rates reach 0.26 kg s^{-1}m^{-1}, behaves as a natural conduct for water and sediment. The forces involved in water and sediment circulation within the channel would be the best driving mechanism to flush contaminants attached to the suspended matter.

ACKNOWLEDGEMENTS

This research was supported by the Consejo Nacional de Ciencia y Tecnología (CONACyT) grant 0625-N9110. Our thanks to M. Frías-Espericueta and C. Ruiz-Fernández (word processing), S. Guerrero-Galván (graphics) and H. Bojórquez-Leyva (critical review).

REFERENCES

Aubrey D.G. (1986). Hydrodynamics controls or sediment transport in well mixed bays and estuaries. In *Lecture notes of coastal and estuarine studies*. (J. van de Kreeks, Ed.) Springer Verlag Vol. 16, pp. 246-257.

Banse K., Falls, C.P., and Hobson L.A. (1963). A gravimetric method for determining suspended matter in sea water using millipore filters. Deep Sea Res. *10*, 639-642.

Bowden, K.F. (1967). Circulation and diffusion. In: *Estuaries* (G. H. Lauff, Ed.) American Association for the Advancement of Science, Publ. 83, pp. 15-36.

Fischez R., Jickells T.D. and Edmunds H.M.(1992). Algal blooms in high turbidity, a result of the conflicting consequences of turbulence on nutrient cycling in a shallow water estuary. Est., Coast. Shelf Sci. *35*, 577-592.

Folk R. (1974). *Petrology of sedimentary rocks*. Hemphill Publications Company, Austin, Texas, 170 p.

Gilmartin M. and Revelante N. (1978). The phytoplancton characteristics of the barrier island lagoons of the Gulf of California. Est., Coast. Shelf Sci. *7*, 29-47.

Lankford R.R. (1977). Coastal lagoons of Mexico: their origin and classification. In: *Estuarine Processes* (M. Wiley, Ed.) Academic Press, New York, pp. 182-215.

McDowell D. M. and O´Connor B.A. (1977). Hydraulic behavior of estuaries. Macmillan Press, London and Basingstoke.

Mehta A.J., Byrne J. and De Alteris J. (1975). *Hydraulic constants of tidal entrances* III: Bed friction measurements at John´s Pass. Tech. Report No. 26, Coast. and Ocean. Eng. Lab., Univ. of Florida.

Montaño-Ley Y. (1985). Estudio del transporte litoral de arenas en Isla de La Piedra, Mazatlán, Sin., usando trazadores fluorescentes. An. Inst. Cienc. Mar y Limnol., Univ. Nal. Autón. México *12*, 15-32.

Montaño-Ley Y. and Páez-Osuna F. (1990). Estudio preliminar del régimen hidráulico del Puerto de Mazatlán, Sinaloa, México. Geof. Int. *29*, 237-247.

Osuna-López J.I., Ortega-Romero P. and Paez-Osuna F. (1986). Cd, Co, Cr, Cu, Fe, Ni, Pb y Zn en los sedimentos del puerto y antepuerto de Mazatlán. Cienc. Mar. 12, 35-45.

Páez-Osuna F., Montaño-Ley Y. and Bojorquez-Leyva H. (1990). Intercambio de agua, fósforo y material suspendido entre el sistema lagunar del Puerto de Mazatlán y las aguas costeras adyacentes. Rev. Int. Contam. Ambient. *6*, 19-32.

Peraza-Vizcarra R. (1973). Características hidrográficas y distribución de los sedimentos en el Sistema Lagunar Bahía Altata Ensenada del Pabellón, Sinaloa. Tesis de Licenciatura, Universidad Autónoma de Baja California, Ensenada, Baja California Norte.

Postma H. (1961). Transport and accumulation of suspended matter in the Dutch Wadden Sea. Neth. J. Sea Res. *1*, 148-190.

Postma H. (1965). Water circulation and suspended matter in Baja California lagoons. Neth. J. Sea Res. *2*, 566-604.

Riley J.P. and Skirrow G. (1975). *Chemical Oceanography*. Academic Press, New York.

Rodríguez-Espinoza P. (1982). Impacto en las lagunas costeras Carmen-Pajonal-Machona, Tabasco, México a partir de la abertura de una boca artificial. Tesis de Licenciatura en Geografía. Facultad de Filosofía y Letras. UNAM, México, D.F.

Secretaría de Marina. (1988). Carta náutica SM 368. Portulano de Mazatlán. Esc. 1-7500. Secretaría de Marina. Dirección General de Oceanografía y Señalamiento Marítimo, México.

Sternberg R.W., Cacchione D.A., Drake D.E. and Kranck F. (1985). Suspended sediment transport in an estuarine tidal channel within San Francisco Bay, California. Mar. Geol. 71, 237-258.

Uncles R.J., Barton M.L. and Stephens J.A. (1994). Seasonal variability of fine sediment concentration in the turbidity maximum region of the Tamar Estuary. Est. Coast. Shelf Sci. 38, 19-39.

U.S. Army Corps of Engineers.(1973). *Shore Protection Manual*. Washington, D.C.

Van Rijn L.C., 1990. Handbook of sediment transport by currents and waves. Delf Hydraulics. The Netherlands, Report 1-1461.

Van Rijn L.C. (1987). Data base sand concentration profiles for currents and/or waves. Delf Hydraulics. The Netherlands, Report M1695-04-1.

Villalba A. (1986). Descripción general del Estero de Urías, Mazatlán, Sinaloa, México. Rev. Cienc. Mar, U.A.S. *8*, 32-37.

Ward L.G. and Twilley R.R. (1986). Seasonal distribution of suspended particulate material and dissolved nutrients in a coastal plain estuary. Estuaries *9*, 156-168.