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Noel Carbajal
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Cristina Noyola Medrano
Universidad Autónoma de San Luis Potosí
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ORIGINAL ARTICLE

Influence of friction on erosion and accretion processes in the Yavaros Bay, Gulf of California

Noel Carbajal · Juan A. Dworak · Yovani Montaño-Ley · Cristina Noyola-Medrano

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Abstract A two-dimensional, vertically integrated, nonlinear numerical model was applied to investigate the tide-driven bed load transport of sediments and morphodynamics in the shallow coastal lagoon of Yavaros, located in the southeastern part of the Gulf of California, Mexico. Satellite imagery exposes strong sediment dynamics in this coastal region. The dynamics in the lagoon were forced by 13 tidal constituents at the open boundary. Tides are of a mixed character and they are predominantly semidiurnal. The calculations showed areas of intense tidal currents and considerable water exchange with the Gulf of California. Numerical experiments revealed an ebb-dominant tidal distortion and a net export of sediment from the lagoon to the Gulf of California. A simulation of 20 years showed that the lagoon exported about 1,600 m^3 of sediment; however, the daily oscillating exchange of sediment reached values of around 8 m^3. The daily averaged flux of export–import sediments oscillates principally with semi-annual, monthly and fortnightly periods. By applying a threshold velocity, a variable friction coefficient and the calculated amplitude of tidal velocities, it was possible to determine that morphological changes occur in zones of sharp topographic gradients and to explain the effect of friction on the export–import process of sediments. A 10-year simulation revealed that accumulation of sediment ($\sim$20 cm) occurred in small areas, whereas erosion occurred in larger areas but with less intensity ($\sim$8 cm). Besides the importance for the morphodynamics, these kinds of erosion–accretion processes may be relevant for the marine ecology.

Keywords Coastal lagoon · Tides · Friction · Sediments · Morphodynamics

Introduction

Along the eastern coast of the Gulf of California sand dunes, rhythmic sea bed formations and sand barriers occur very often in bays, channels and coastal lagoons. The majority of these lagoons are shallow embayments associated with the deltaic systems of several rivers in the Western Sierra Madre that discharge water into the gulf.

The origin and formation of coastal lagoons in Mexico by these kinds of processes have been investigated by Lankford (1977). The water bodies located in the eastern coast of the gulf provide a comprehensive idea of the magnitude and complexity of the sediment dynamics. Even though it is difficult to understand sediment dynamics in coastal water bodies with complex geometry, the study of the transport of sediments is necessary due to the importance of the ecological conservation of marine life in these substrates and the needs of navigation channels for commercial vessels. Yavaros Harbor, in particular, is important for the economic development of the northwestern part of Mexico.

N. Carbajal (✉) · C. Noyola-Medrano
División de Geociencias Aplicadas, Instituto Potosino
de Investigación Científica y Tecnológica A.C.,
Camino a la Presa San José 2055, Lomas 4ª Sección,
San Luis Potosí 78216, Mexico
e-mail: noelc@ipicyt.edu.mx

J. A. Dworak
Instituto Tecnológico del Mar 03. Km 4, Carretera a Varadero
Nacional, Guaymas, Sonora, Mexico

Y. Montaño-Ley
Instituto de Ciencias del Mar y Limnología, Universidad
Nacional Autónoma de México, Unidad Académica Mazatlán.
Apdo. Postal 811, 82040 Mazatlán, Mexico

Although the transport of sediments is often discussed only in terms of dynamic aspects or seabed formations, the marine life is abundant in sediments getting the morphodynamics, a particular relevance. Benthos, i.e., organisms that live in or on the seabed, represent more than 90 % of all marine species. As they live and remain in a reduced spatial area, the mobility of sediments is very important to their existence. In general, a sandy sea bottom favors the subsistence of marine species because they find food and protection. The accumulated evidence on benthos (Gerlach 1978) provides information about the environmental factors (productivity, temperature, sediment grain-size diversity, erosion and accretion processes) that control patterns of species richness at regional scales. In tropical and temperate climates, sea grasses grow in the sediments of shallow coastal areas where rich species assemblages are found (Gray 2002). Considering only these few viewpoints on the importance of sediments in marine environments, the authors believe that the mobility of sediments is very important for the evolution and survival of marine life in these substrates.

Dynamics implies forcing mechanisms such as baroclinicity, tides and winds. Baroclinic-induced currents and wind currents are seasonal, or even intermittent. In very shallow coastal areas, water is vertically well mixed with small baroclinic currents. In contrast, tides are always working and influencing the morphodynamics and the marine ecosystems worldwide. Tides play a significant role in the dynamics of the Gulf of California, which varies from a semidiurnal nature in the northernmost part (Colorado River Delta region) to a mixed character which is predominantly semidiurnal in the rest of the northern part and in the central region and mainly diurnal in the southern region of the gulf (Carbajal 1993).

An orographic factor explains the source of sediments in the eastern coast of the Gulf of California. The Western Sierra Madre mountain chain along the continental part of Mexico parallels the Gulf of California. A series of rivers (Yaqui, Mayo, Fuerte, Culiacán, Presidio, Piaxtla, among others) and small tributaries descend from the mountainsides and empty into the gulf. As a consequence of the physical and chemical disintegration of rocks over a geological time period (Van Rijn 1993), there has been a huge accumulated flux of sediments flowing into coastal areas via the rivers. Satellite imagery clearly shows the presence of seabed formations and sediment dynamics in the coastal water bodies of this region. Nowadays, problems are associated with river discharges. As they make their way to the gulf, all of these rivers flow through cities or large agricultural areas where clean water is used and the wastewater channeled to the coast, or even to coastal lagoons. Thus, a relatively new contaminated sedimentation process is occurring in coastal water bodies. Evidence of heavy metals and pesticides has been found in sediments, water and organisms in the coastal lagoons of the Gulf of California (Soto-Jiménez and Páez-Osuna 2001; Ruiz-Fernández et al. 2001; Páez-Osuna et al. 1998). As these contaminants form aggregates with the sediments, the transport of sediments must also be relevant to the redistribution and dispersion of contaminants. An understanding of the transport processes is necessary to predict where substances such as toxic chemicals, sewage discharge or dredged materials will go or accumulate (Nichols and Boon 1994). When entering the brackish lagoon environment, fine particles deposit due to decrease in current velocities. Under these conditions, flocculation of negatively charged clay particles and a general decrease of metal species solubility occur. This leads to gradual accumulation of heavy metals on sediments. The Yavaros coastal lagoon is subject to pollution sources mainly from the effluents. Areas with small tidal currents favor the deposition of fine sediment and propitiate the sediment accumulation and pollution.

Sediment dynamics is essentially related to erosion and accretion processes as a consequence of hydrodynamic forces acting on single particles (Julien 1998). Their geometrical properties, such as roundness and angularity, have been determined by ongoing erosion, transport and deposition principally due to the action of tidal and wind currents and wind waves. Another interesting fact is that observations indicate that the hydrodynamics tend to separate the sand by grain size (very coarse, coarse, medium, fine and very fine). The transport of sediments occurs principally through two processes—transport of suspended sediment or suspended particle motion and bed load transport of sediment, or rolling and sliding particle motion. A third intermediate process, mentioned by Van Rijn (1993), is a saltating or hopping particle motion. The authors are more interested in bed load transport of sediments, as it is probably more related to deposition of contaminants and to seabed formations.

Although the eastern part of the Gulf of California is characterized by a vast quantity of sediments resting in dunes, rhythmic seabed formations, sand barriers and other irregular bed forms, there is very little research about sediment dynamic in this region. In Yavaros coastal lagoon, only few studies concerning the tidal hydrodynamics have been carried out (Dworak and Gómez-Valdés 2003, 2005). As far as is known, no information about rates of sediment transport exists for this coastal body of water.

To fulfill this gap, the primary objective of the present investigation was to investigate the tidal hydrodynamic and the induced bed load sediment transport as well as to qualitatively analyze the mechanism of sea bed morphodynamics of the lagoon. In addition, the effects of friction on the erosion–accretion process have also been investigated. A depth-integrated numerical hydrodynamic model coupled with the sediment conservation equation has been applied to achieve the objectives.

Study area

The Yavaros coastal lagoon, or Yavaros Bay as it is also known in Mexico, is a water body enclosed by sand barriers, with an approximately 1,800 m wide opening to the Gulf of California (Fig. 1a). There are other lagoons with similar characteristics in the area, including Huivulai, Jitzamuri, Lechuguilla, Santa María, Topolobampo and Navachiste, which were also formed by sand barriers. The Yavaros coastal lagoon is a water body that is well connected with the adjacent Gulf of California. Considering its hydrodynamic properties, it can be regarded as a leaky coastal lagoon according to the classification by Kjerfve and Magill (1989). The Yavaros lagoon system is situated in the central-eastern coast of the Gulf of California, between 26°40′N and 26°45′33″N and 109°25′21″W and 109°34′31″W. Another important physical feature is that the Yavaros lagoon is located near the Tropic of Cancer, where there are strong shortwave radiation, large evaporation rates and a semiarid climate. These conditions lead to annual evaporation rates of about 1,500–2,000 mm and an annual rainfall between 300 and 500 mm; that is, evaporation is three times greater than rainfall. Two seasonal wind situations can be distinguished—winds flowing predominantly from the south in summer and from the north in winter (Dworak and Gómez-Valdés 2003).

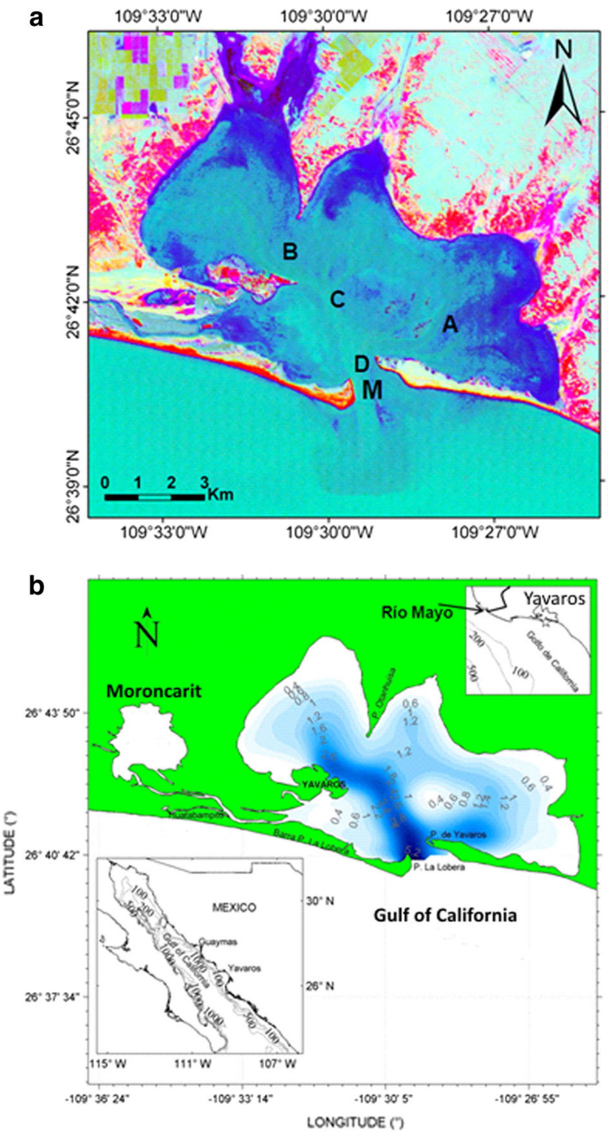

Fig. 1 **a** Landsat TM5 image, dated February 16, 2011, of the Yavaros coastal lagoon. It was obtained from the Global Visualization Viewer website (GLOVIS) managed by the United States Geological Survey (USGS). *Light blue areas* indicate the presence of a relatively high concentration of sediments. *A*, *B*, *C* and *D* indicate the position of time series presented in Fig. 2 and *M* indicates the position of measured tidal currents. **b** Geographical position and bathymetry (m) of the Yavaros coastal lagoon

The Mayo River Delta (Fig. 1b) is located roughly 20 km to the northwest of the lagoon Moroncarit. The river does not discharge water directly into the Yavaros lagoon. Although it is outside the study area, the sandbar system indicates that the Mayo River notably influenced the sediments in the area of the Yavaros lagoon where there are several generations of shore formations (Fig. 2). The most ancient are old, flattened, isolated dunes landward of the

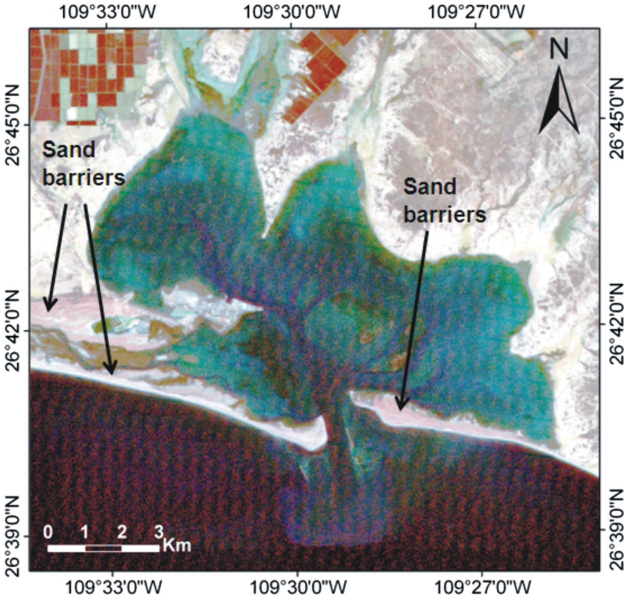

Fig. 2 Landsat TM5 image, dated February 16, 2011, of the Yavaros coastal lagoon. It was obtained from the Global Visualization Viewer website (GLOVIS) managed by the United States Geological Survey (USGS). Sand barriers, generated by the Mayo River, are indicated

Moroncarit lagoon (Fig. 1b). The dunes system begins at the low Mayo River course. Then there are flat sand spots and some high dunes (6–10 m) east of the river mouth. This chain of sand formations ends at the lighthouse, near the Yavaros lagoon. These sand formations are indicated in Fig. 2. A second dune generation borders the lagoon, on the seaward side (Zenkovich 1969). The bottom topography of the Yavaros coastal lagoon system is complex, with a main navigation channel extending from the mouth to the northwest. This channel connects the Yavaros Harbor with the Gulf of California. Maximum depths of around 8 m are found and very shallow areas of 1 m or less are situated on the northeastern side (Fig. 1b).

Measurements and numerical modeling reveal a predominance of mixed tides and diurnal signals in the central-eastern part of the Gulf of California. Recent studies of co-oscillation tides and the generation of high harmonics in the very shallow areas of the Yavaros Bay (Dworak and Gómez-Valdés 2003, 2005) found that lunar and solar declination effects to some extent control the behavior of tides in the lagoon system. The mixed character of tides in the area of the Yavaros Bay indicates significant oscillations with semidiurnal, diurnal and fortnightly frequencies. Observations indicate that the principal solar (S_2) and lunar (M_2) constituents, solar and lunar declination effects (K_2) and the lunar elliptic effect (N_2) generate the semidiurnal signal. Diurnal tides are produced by solar and lunar declination effects (K_1), by main lunar (O_1) and solar (P_1) contributions and by a lunar elliptic effect (Q_1). Fortnightly oscillations are due to the phases of the moon (synodic), declinational variations (tropical), and the time taken for the moon to move from perigee to perigee (anomalistic) (Dworak and Gómez-Valdés 2005).

The model

To model the co-oscillation of the Yavaros Bay with tidal waves propagating in the Gulf of California, a two-dimensional, nonlinear, vertically integrated numerical model was applied. The dynamics in the lagoon system was forced by 13 tidal constituents with amplitudes and phases specified along the open boundary. This model has been successfully used to simulate tidal dynamics in the Gulf of California and in coastal lagoons and to calculate the transport of sediments in water bodies such as the Colorado River Delta and the North Sea (Carbajal and Backhaus 1998; Montaño and Carbajal 2008; Carbajal et al. 2005). The model has been verified in several works by comparing observed and calculated data (Montaño-Ley et al. 2007). The model is based on the vertically integrated equations of motion

$$\frac{\partial U}{\partial t}+\frac{U}{H+\zeta}\frac{\partial U}{\partial x}+\frac{V}{H+\zeta}\frac{\partial U}{\partial y}-fV = -g(H+\zeta)\frac{\partial \zeta}{\partial x}+A_H\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)-r\frac{U\sqrt{U^2+V^2}}{(H+\zeta)^2} \tag{1}$$

and

$$\frac{\partial V}{\partial t}+\frac{U}{H+\zeta}\frac{\partial V}{\partial x}+\frac{V}{H+\zeta}\frac{\partial V}{\partial y}+fU = -g(H+\zeta)\frac{\partial \zeta}{\partial y}+A_H\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)-r\frac{V\sqrt{U^2+V^2}}{(H+\zeta)^2} \tag{2}$$

and the continuity equation

$$\frac{\partial \zeta}{\partial t}+\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \tag{3}$$

where (x, y) are the horizontal space variables, t the time, U the transport in the x direction, V the transport in the y direction, ζ the sea surface elevation, A_H the horizontal turbulent exchange coefficient, $f = 2\Omega \sin \phi$ is the Coriolis parameter, $\Omega = 7.29 \times 10^{-5}\ \mathrm{s}^{-1}$ the angular velocity of the earth, ϕ the latitude, H the depth, g the gravitational acceleration and r is the friction coefficient. The system was forced at the open boundary with a sea surface elevation oscillation of the form

$$\zeta = \zeta_0 \cos(\omega t - \varphi) \tag{4}$$

where ζ_0 is the amplitude, φ the phase and ω is the frequency of the forcing tidal wave. Basically, the calculation initiated from a static state. At the open boundary, the sea surface elevation gets higher (or decreases) according to (4) causing a sea surface elevation gradient which starts the propagation of motion inside the lagoon. Since friction is decisive for the transport of sediments, we applied a variable friction coefficient to our numerical calculations (Baumert and Radach 1992), given by the formula

$$r = \left\{\frac{\kappa}{\ln\left[E\left(1+\frac{1}{p}\right)^{1+p}\right]}\right\}^2 \tag{5}$$

where $\kappa = 0.4$ denotes the Karman constant, $p = K_s/H$ is a parameter with $K_s = 1.5$, which is the linear size of the roughness, H is the water depth and $E = 11.02$.

The bed load transport of non-cohesive sediment was calculated by applying the parameterization developed by Van Rijn (1993) for depth-integrated flows. This full sediment transport formula is given by

$$q_b = 0.005\bar{U}H\left[\frac{\bar{U}-U_{cr}}{[(s-1)gd_{50}]^{\frac{1}{2}}}\right]^{2.4}\left(\frac{d_{50}}{H}\right)^{1.2} \qquad (6)$$

It is used to calculate the bed sediment exchange, where

$$U_{cr} = 0.19(d_{50})^{0.1}\log_{10}\left(\frac{4H}{d_{90}}\right) \qquad (7)$$

for $100 \leq d_{50} \leq 500$ µm. U_{cr} is the threshold depth-averaged current speed, $\overline{U}$ the depth-averaged velocity, $s \approx 2.58$ the ratio of sediment density and water density, d_{50} the median grain diameter and d_{90} is the 90th percentile grain-size diameter (Thomas et al. 2002). The values $d_{50} = 170$ µm and $d_{90} = 300$ µm were applied (Ayala-Castañares et al. 1980).

Results

Numerical experiments of the bed load transport of sediments in the Yavaros coastal lagoon system were carried out. The dynamics inside the lagoon was forced at the open boundary by 13 tidal constituents (M_{sf}, O_1, K_1, M_2, S_2, N_2, MK_3, SK_3, M_4, MS_4, $2SK_5$, M_6, $2SM_6$). Using a pressure sensor installed at point M (Fig. 1a), Dworak and Gómez-Valdés (2003) calculated the amplitudes and phases of these tidal components from measured data with a length of record of 34 days. The amplitudes and phases are given in Table 1. From the harmonic analysis, a 95 % of significance was obtained for these tides, except M_{sf}. These tidal constituents are the most important in the Yavaros lagoon system. As simulations of bed load transport of sediments for relatively long periods were performed, it is relevant to mention that there are yearly astronomical corrections of amplitude and phase of tidal constituents. As these corrections are very small, the authors did not consider them in these calculations. Long-period tides (longer than 2 weeks) which arise from disturbances of the geoid by the sun and moon have amplitudes of only a few millimeters in the open ocean (Wunsch 1967). These kinds of tides in these simulations were not contemplated.

Table 1 Amplitudes and phases of tidal constituents measured at point M (Fig. 1a)

	Period (h)	Amplitude (cm)	Phase (°)
M_{sf}	354.3717	1.3	220
O_1	25.8193	17.1	176
K_1	23.9345	24.9	184
M_2	12.4206	21.1	140
S_2	12.0000	16.2	134
N_2	12.6584	4.7	158
MK_3	8.1771	0.3	126
SK_3	7.9927	0.5	309
M_4	6.2103	0.8	50
MS_4	6.1033	0.3	116
$2SK_5$	4.7974	0.2	133
M_6	4.1402	0.1	108
$2SM_6$	4.0924	0.2	60

Taken from Dworak and Gómez-Valdés (2003)

It is assumed that the applied bathymetry reflects the most recent state of the morphological evolution. In Fig. 1b, a principal channel extending from the opening to the northern part of the lagoon and bifurcating into channels of lesser depths is observed. Beyond the channels, the Yavaros lagoon system is very shallow and has relatively large areas with depths less than 1.0 m, which favor frictional effects. According to the bathymetry of the Yavaros lagoon system, the friction coefficient varied from $r = 0.0074$ in the deep areas of the channels to $r = 0.11$ in the adjacent flats.

Tidal distortion arises from the nonlinear interaction of the forcing tide with the topography of a coastal water body where it propagates. Tidal distortion is also an indication of how friction modulates the net bed load and suspended load sediment transport in shallow estuaries, lagoons and bays (Speer et al. 1991). Distortion is defined as the duration of the asymmetry of the rise and fall of the tidal signal. Tidal asymmetries in shallow water bodies are classified as flood dominant and ebb dominant, with stronger currents in the dominant situation (Speer et al. 1991). In Fig. 3, calculated tidal signals at four different locations inside the Yavaros lagoon are shown. The sea surface elevation, ς, and the horizontal components of the velocity in the west-east direction, u, and in the south-north direction, v, reflect the diurnal–semidiurnal mixed character of the tidal signal. Near the entrance to the lagoon at point D (see Fig. 1a for the position of the points), the v component of the velocity is overriding and the tidal currents are aligned along the principal channel, which is oriented from south to north. The u component is near zero. At point A, the two components of the velocity are in phase and u is slightly larger than v. The calculated duration of rise and fall of the tide revealed in the sea surface elevation (ς) a signal distortion of ebb-dominant type, i.e., a longer rise and a short tidal fall. Tidal distortion also occurs at points B and C, u and v are 180° out of phase, with the amplitudes of u slightly smaller than v. These few time series provide an idea of the complex behavior of the tidal flow in the shallow and relatively small Yavaros lagoon system. These flows are clearly controlled by bathymetric features. The time series of the components (u, v) of the horizontal velocity vector show a larger distortion of the tidal signal, indicating a more complicated behavior of acceleration processes. The duration of falling and rising tidal velocities varied for the different flats and channels.

Tidal asymmetry was detected practically at all grid positions inside the lagoon. This shallow coastal lagoon can be classified as ebb dominant with stronger ebb than flood tidal currents. In fact, the largest absolute value of u and v occurred at negative values (Fig. 3). According to Speer and Aubrey (1985), two principal factors indicate whether a coastal lagoon or estuary undergoes an asymmetry of the tidal signal. A lagoon dominantly characterized by channels develops an asymmetry typified by a longer falling tide. This asymmetry increases with greater friction and with a time-variable channel cross-sectional area as the tide propagates. If the coastal lagoon is characterized by channels and flats, it can produce a longer rising tide if the area with tidal flats is large enough to overcome the effect of channels. Figure 1a, b reveals that the Yavaros coastal lagoon contains both characteristics—a channel mesh and extensive flat areas. According to the above discussion, the effect of channels is overruled in the Yavaros lagoon by the tidal flats and, consequently, it produces an asymmetry with a longer rising tide, i.e., it is an ebb-dominant coastal lagoon.

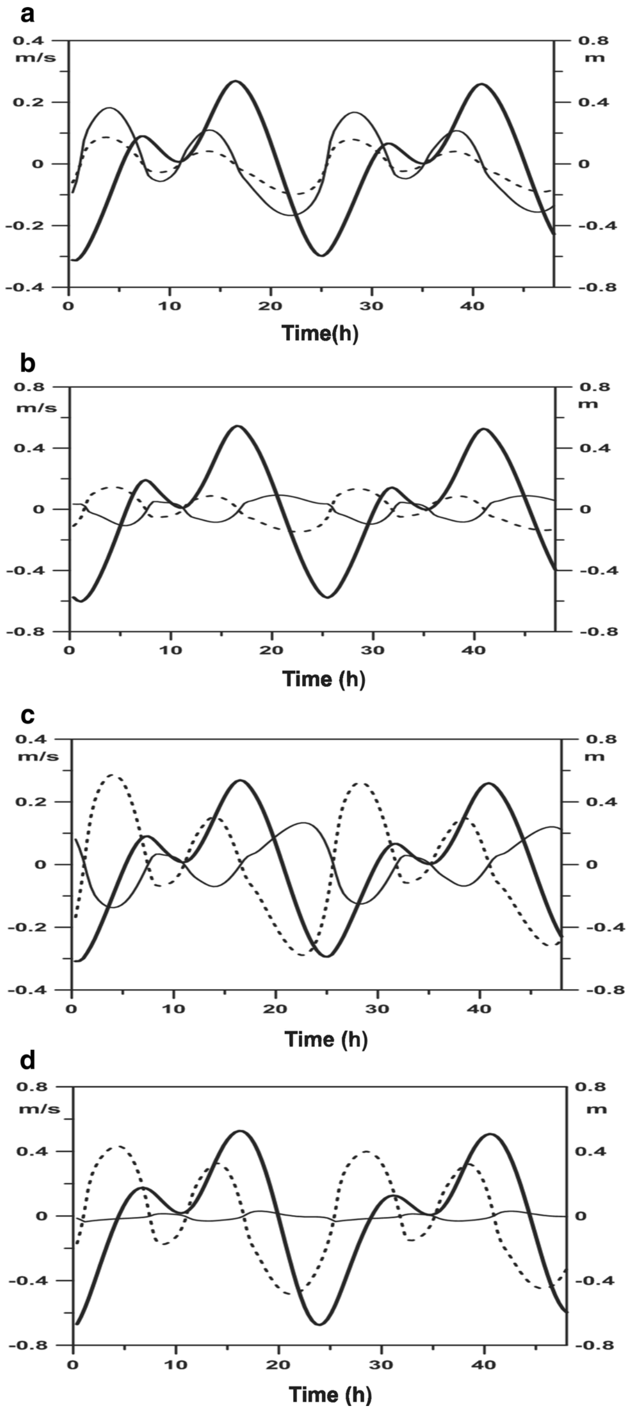

Fig. 3 Tidal signals at four different points in the Yavaros lagoon (see Fig. 1). *Thick lines* represent the water elevation (m), discontinuous lines indicate the north–south component, v, of the velocity vector (m/s) and the *thin lines* correspond to the west–east component, u, of the velocity vector (m/s). The asymmetry of the tidal signal is clearly distinguished in all time series, with flood duration longer than ebb

In Fig. 4, tidal currents at four different times over a period of 24 h are depicted to establish the areas of the lagoon with intense tidal currents and where one would expect to find the largest bed load transport of sediments. Although the tidal currents depicted in Fig. 4 are of the order of 0.5 m/s, maxima amplitudes of the order of 0.65 m/s were simulated at spring tides. This order of magnitude for maximum tidal currents agrees well with that measured by Dworak and Gómez-Valdés (2005). In the description of their measurements, they noted that at spring tides the semidiurnal character is dominant but at neap tides a diurnal pattern governs. Tidal energy flows and dissipation of energy were also estimated for the Yavaros lagoon system (Dworak and Gómez-Valdés 2003). By comparing with Fig. 1b, it is noted that the most intense tidal currents are in the areas of the channels and in some parts of the adjacent flats. Tidal velocities play a very important role in the calculation of bed load transport of sediments. Although Dworak and Valdés-Gómez (2003, 2005) discussed already in detail about the principal tidal constituents forcing the dynamics of the Yavaros lagoon system, a comparison of their observed tidal currents at the opening of the lagoon to the Gulf of California (point M in Fig. 1a) with the calculated tidal currents was carried out (Fig. 5). The time series of observed (Fig. 5a) and calculated (Fig. 5b) tidal currents are quite similar.

Several morphological scales (microscale, mesoscale, macroscale and megascale) have been identified in coastal areas (De Vriend 1996). They include bed forms such as ripples, dunes, flood channels, sand waves, sandbanks, inlets and bed forms around the entire estuary. Hibma et al. (2004) discussed morphological scales in estuaries. The evolution of a coastal water body depends principally on the long-term averaged supply and long-term averaged transport process of sediment. Although it may lead to the

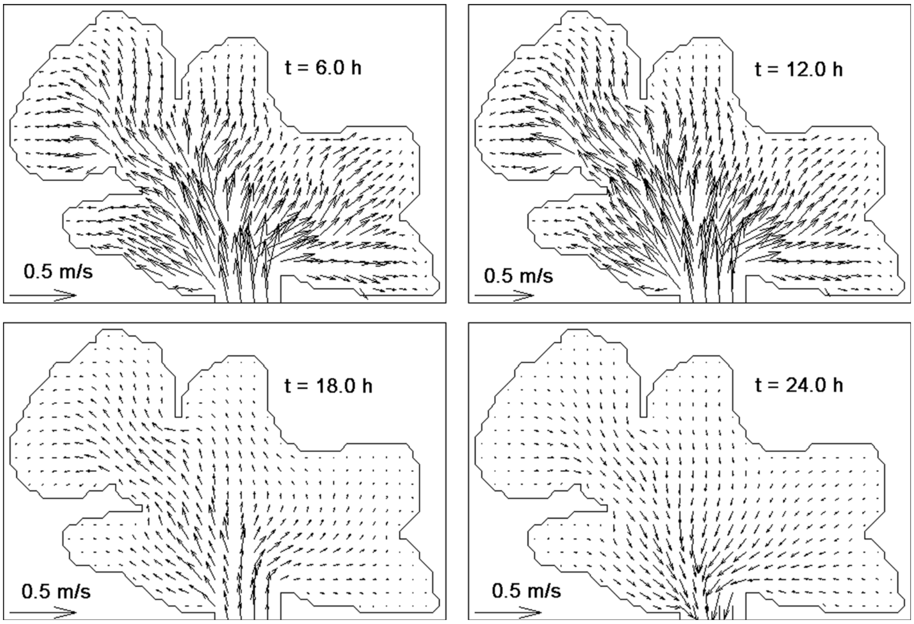

Fig. 4 Tidal currents (m/s) at four different times of a day. Strong tidal currents are confined to the channels and adjacent areas

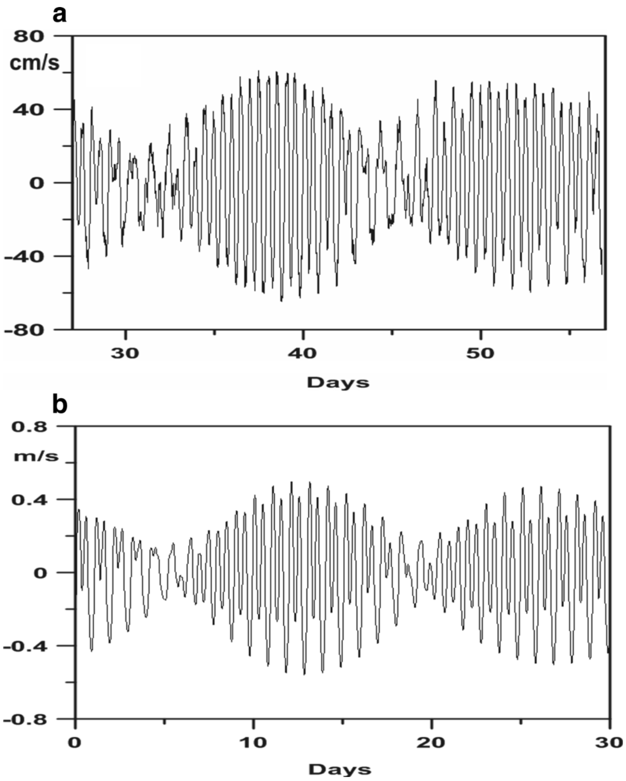

Fig. 5 Comparison of observed tidal currents (m/s) (**a**) at the opening of the lagoon to the Gulf of California against calculated tidal currents (m/s) (**b**). The observed data were obtained from Dworak and Gómez-Valdés (2003, 2005)

idea of stable coastal water bodies, it is difficult to find stable coastal water bodies with an average balance between inflow and outflow of sediments (Dronkers 1986). Although near-stable conditions were found in estuaries, for example along the Dutch coast in the North Sea (Dronkers 1998), most coastal water bodies are strictly of the erosion type. In this research work, the authors are interested in the morphodynamics of the Yavaros coastal lagoon as a consequence of the bed load transport of sediments caused by tidal currents. The Yavaros lagoon system is located in a region of the Gulf of California where the presence of large quantities of sediment along the coastal area is evident on satellite imagery. Wastewater and sediment flow from large agricultural areas to the lagoon through small tributaries. The light blue color in Fig. 1a indicates the presence of a relatively high concentration and dark blue indicates a low concentration of sediments. As there are sediments inside and outside the lagoon system, the process of export–import of non-cohesive sediments based on the lagoon's dynamics was investigated.

A series of calculations applying the variable friction coefficient as defined above were carried out. Although the Yavaros lagoon is characterized by heterogeneous sediments, we used the measured values of $d_{50} = 170$ µm and $d_{90} = 300$ µm to estimate the threshold velocity defined by Eq. (7). These values were measured by Ayala-Castañares et al. (1980) and are found in extensive areas of the Yavaros lagoon. This assumption is a custom used widely when dealing with the numerical modeling of sediment transport and morphodynamics processes (Mason and Garg 2001). Considering the water depth distribution of the lagoon, the threshold velocity for the onset of the transport of sediments varied from roughly $U_{cr} \approx 0.4$ m/s in the channels to around $U_{cr} \approx 0.33$ m/s in the adjacent flats. In Fig. 6a, we show the calculated rates of export–import of sediments through the open boundary generated by the tide-driven bed load transport of sediments. Every point on the time series

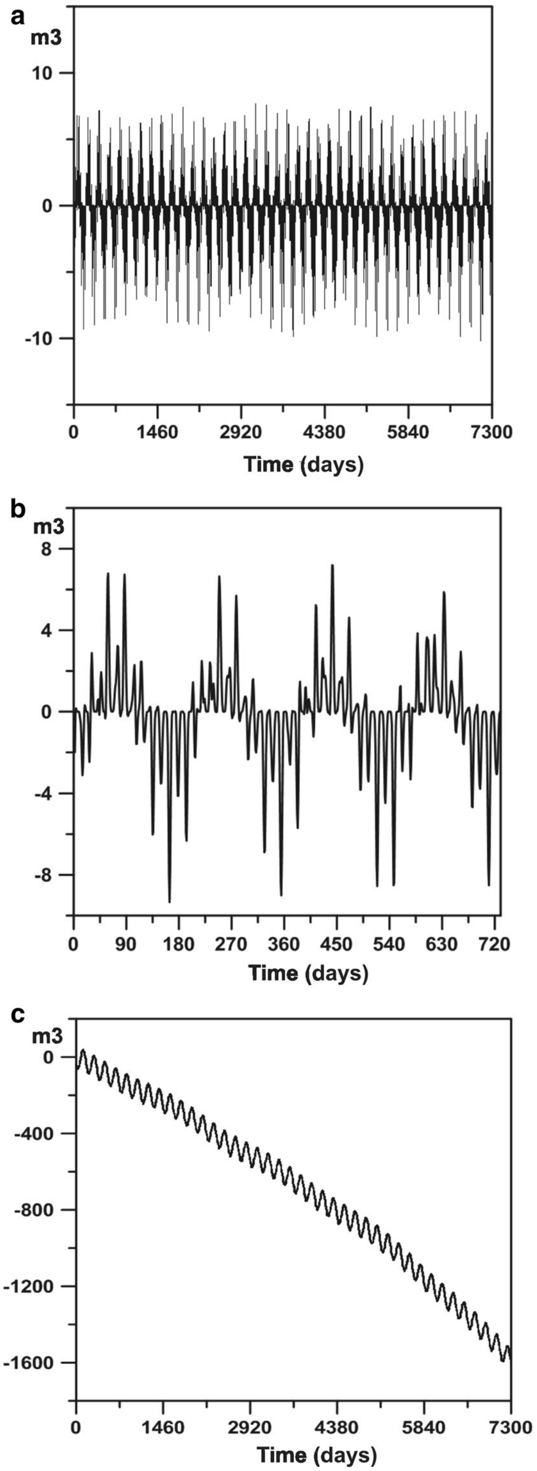

Fig. 6 Daily averaged rates of export–import of sediments for a period of 7,300 days (20 years) (**a**). An amplification of the time series where semiannual and fortnightly oscillations are observed (**b**). Exported volume of sediments after 20 years of simulation (**c**). We applied a variable friction coefficient according to Eq. (7)

represents the integration over the open boundary over the course of 1 day. The calculated export–import process reveals several oscillations which will be discussed below.

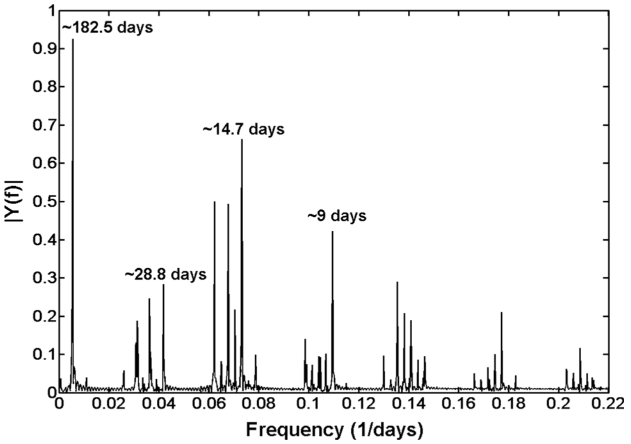

Fig. 7 Normalized spectrum density of the time series shown in Fig. 5a. Semiannual, monthly and fortnightly periods can be distinguished. Other peaks probably are the result of nonlinear interactions

Figure 6b shows a high resolution of the oscillating export–import process, which describes a semiannual and a fortnightly behavior. This apparently balanced export–import developmental results in a net bed load sediment transport across the open boundary over the entire simulated time. The Yavaros lagoon system exported about 1,600 m^3 of sediment over 20 years (Fig. 6c), corresponding to a net average export volume of 0.22 m^3/day. Although this quantity may seem small, the daily oscillating exchange of sediment can reach values of around 8 m^3. To know explicitly the periods contained in the rates of export–import of sediments, the normalized spectrum density of the time series, shown in Fig. 6a, was calculated. In Fig. 7, semiannual, monthly and fortnightly periods can be clearly distinguished. The calculated frequencies or periods contained in the time series of rates of sediment transport are closely related to the superposition of tidal harmonics. The other not explained peaks are probably the result of nonlinear interaction among tides and sediment. The time series shown in Fig. 6a is alike to that produced by the 13 tidal constituents considered in this research work (not shown). The differences arise from the fact that at the open boundary, a linear superposition of all constituents to force the dynamics in the lagoon system was applied whereas the time series shown in Fig. 6a is the result of nonlinear interactions.

Discussion

Another important subject associated with the transport of sediments is the morphological evolution of a coastal water body. For the Dutch coast, Dronkers (1998) found that most of the tidal basins are close to morphodynamic equilibrium. This means that the long-term averaged sediment flux through the open boundary should be roughly zero. In addition, equilibrium requires ebb and flood duration to be approximately equal. According to these results, these requirements are not met in the Yavaros lagoon system, since it presents ebb-dominant tidal distortion and it exports sediment through the open boundary (Fig. 6c). In fact, Fig. 1a shows evidence of a situation where sediment is exported to the adjacent Gulf of California. If one considers very long time periods, or geological times, the lagoon would have exported large quantities of sediment under these conditions. It has been already mentioned that Fig. 1a reveals several tributaries around the lagoon with flows of mostly wastewater and sediments. These facts suggest that the lagoon system is dynamic in relation to the transport of sediments, i.e., there is a net export through the open boundary and an import of sediments through small tributaries. With the obtained information, it is difficult to say whether it is in equilibrium or not. It is important to mention that information about the temporal runoff of small tributaries and drainage from agriculture areas of water and sediments is unavailable. This kind of runoff was not considered in the calculations.

In addition to tidal forcing, two other factors play a very important role in the numerical modeling of the transport of sediments; the threshold, or value for the critical velocity needed to initiate the bed load transport of sediment, and the friction coefficient value. These two parameters are a function of the water depth, i.e., they vary throughout the entire lagoon system. For every mesh point, maximum amplitude of tidal currents and the value of the critical velocity were calculated. The difference between these two parameters provides information on where the bed load transport of sediments occurs. Figure 8a shows the area where the amplitude of tidal velocities exceeds the critical velocity value ($V_{\mathrm{max}} > V_{\mathrm{critical}}$). It is important to mention that this condition may not occur at neap tides. It only indicates, at any time, the area where transport of sediments takes place. It encompasses the channel zone near the opening and the area of the adjacent flats. The morphological changes should also occur in this area. The morphology of the Yavaros lagoon system evolved at every time step. The morphological changes for a 10-year simulation were obtained by calculating the differences between the final bathymetric data and the initial ones. Figure 8b shows the morphological changes. Accretion occurs in relatively small areas of the lagoon (light gray) where changes in water depth of about 20 cm were produced. Erosion happens in larger areas (dark gray) but with less intensity since changes in water depths due to erosion are less than 8 cm. The analysis of bathymetry (Fig. 8b, c) reveals that erosion and accretion processes occur partially in the channels and predominantly in the adjacent tidal flats, i.e., in zones with topographic gradients. A comparison of Fig. 8b, and a indicates that the largest morphological changes do not necessarily occur in areas where the difference between maximum velocity amplitudes and critical velocity is the largest (light gray areas in Fig. 8a). It may occur in areas where this difference is even smaller but with a larger divergence. It happens principally at the channel edges and the adjacent flats. It suggests that this area is very critical to the morphodynamics of the Yavaros lagoon and

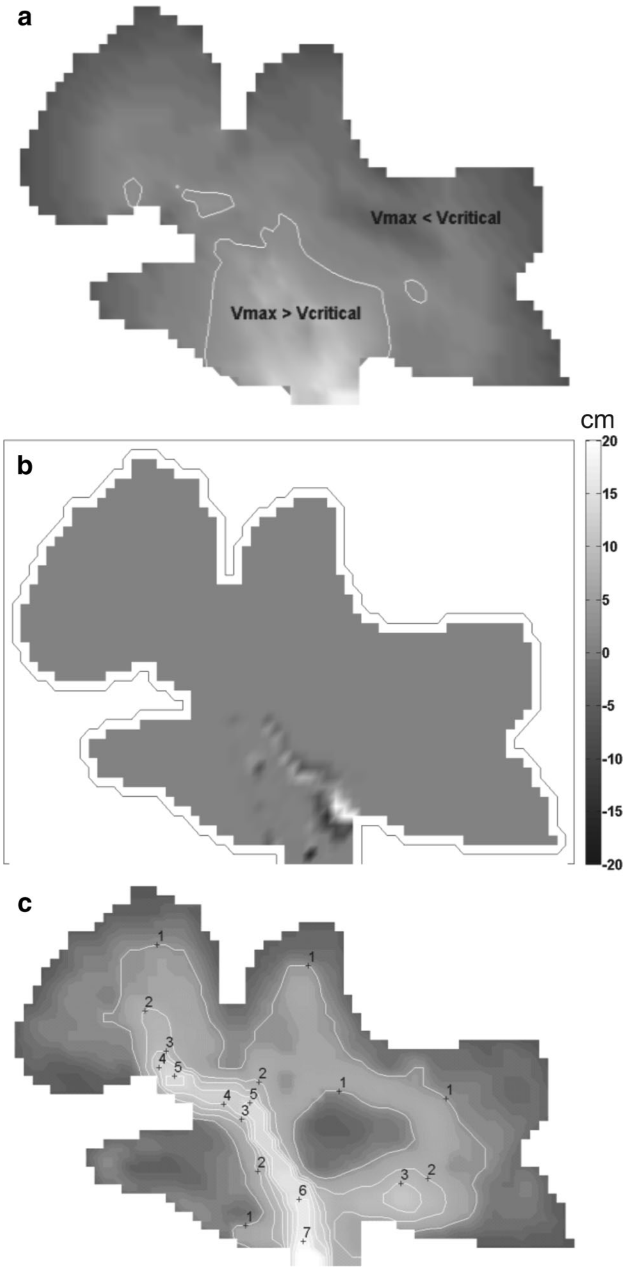

Fig. 8 Areas where tidal amplitude maxima exceeds critical velocity values ($V_{\mathrm{max}} > V_{\mathrm{critical}}$, *enclosed areas* with *white lines*). *Light gray areas* indicate a larger difference between V_{max} and V_{critical} (**a**). Morphological changes after a 10-year simulation (**b**). For comparison, the bathymetry of the coastal lagoon is also shown (**c**). The morphodynamics is more intense in areas with sharp topographic gradients

probably to the distortion of the propagating tides. There are several interpretations of the factors that could explain tidal distortion in shallow coastal water bodies. It seems that channels and tidal flats play a very important role in the generation of tidal asymmetries (Speer and Aubrey 1985). Tidal distortion has also been examined in function of the primary interaction of the M_2 tide and its first harmonic, M_4 (Friedrichs and Aubrey 1988), finding that an increase in the surface amplitude ratio, M_4/M_2, reflects the degree of tidal distortion. According to these findings, a coastal water body is termed flood dominant if the relation for the phases, $0° < 2M_2 - M_4 < 180°$, is satisfied and it is ebb dominant if the relation $180° < 2M_2° - M_4 < 360°$ is true. For the Yavaros lagoon, $2M_2 - M_4 \approx 230°$, thus it should be an ebb-dominant coastal lagoon, according to the previous analysis. Dronkers (1998) demonstrated that the ratio of ebb and flood durations depends on the relation

$$\gamma = \left(\frac{H+a}{H-a}\right)^2 \frac{S_{\mathrm{LW}}}{S_{\mathrm{HW}}}$$

where a is the tidal amplitude, H the water depth, S_{LW} the flooded surface at low water and S_{HW} is the flooded area at high water. For a tidal basin to be in equilibrium, it is required that $\gamma \approx 1$, i.e., flood and ebb durations must be similar. Dronkers also indicates that the stability of tidal basins is related to the capability for morphological adjustments. Friedrichs and Aubrey (1988) found that tidal distortion is primarily generated by two effects: first, the frictional interaction between the tide and channel bottoms, causing shorter floods and second, the intertidal storage, producing relatively shorter ebbs. These interpretations are related to each other by a parameter such as $(H + a)/(H - a)$, which involves the amplitude of tidal currents and water depth. Our calculations reveal that areas with sharp water depth gradients and strong frictional gradients, for example between channels and tidal flats, seem to be also very important. It is observed that the sharpest depth gradients occur on the right side of the principal channel, exactly where the major morphological changes take place.

To investigate the influence of friction on the export–import process at the open boundary, calculations were performed where a maximum limit for the friction coefficient was introduced. As the friction coefficient reaches values of $r = 0.0074$ in the channels and around $r = 0.1$ in the adjacent tidal flats, several experiments were carried out where the maximum allowed value for the friction coefficient was $r_{\max} = 0.0078$, $r_{\max} = 0.008$ and $r_{\max} = 0.009$. As the largest values for the friction coefficient occur in the tidal flats and the maximum amplitude of the velocity exceeds the critical velocity only in channel zones and in the adjacent tidal flat areas (Fig. 8), the limits for the friction coefficient only affect the adjacent tidal flats. In other words, the introduced limit for the friction coefficient only affects the bed load transport of sediments in the adjacent tidal flats. The results of these numerical experiments for 10-year simulations are shown in Fig. 9. For the

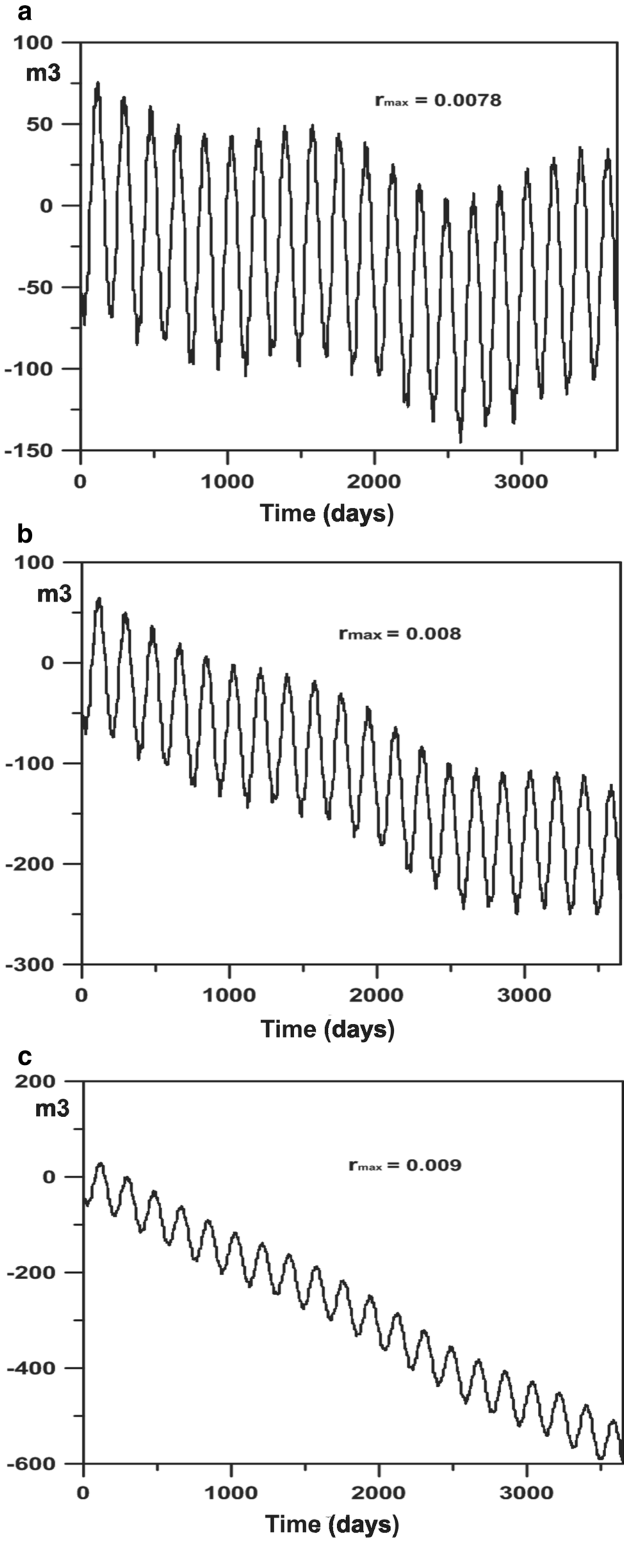

Fig. 9 The 10-year time series describe the behavior of the export–import process for different permissible maximum values of the friction coefficient: **a** $r_{\max} = 0.0078$, **b** $r_{\max} = 0.008$ and **c** $r_{\max} = 0.009$

friction coefficient value, $r_{\max} = 0.0078$, the export–import process of sediments oscillates near an equilibium state. As the limit for the friction coefficient increases ($r_{\max} = 0.008$, $r_{\max} = 0.009$), the Yavaros lagoon system tends to intensify the net export of sediments. These numerical experiments show that the Yavaros lagoon system tends to export sediment which agrees with the satellite image depicted in Fig. 1a. This export seems to be associated with a differential friction at topographic gradients, favorably at sharp topographic gradients, where the channels and the adjacent flats are relevant.

The area of morphological changes is determined by the bottom friction, amplitude of the tidal currents and the critical velocity to initiate bed load transport of sediments. This area establishes an ecological differentiation with respect to other areas where the transport of sediments does not occur. The erosion and accretion processes should alter the living conditions of benthos, as they live only a few centimeters below the surface. As the morphological changes may be much larger than a few centimeters, it should define areas where benthos have more difficulties to survive and to find protection.

Finally, it is worth mentioning that remote sensing technology has shown excellent promises for investigating coastal erosion. This could be of relevance for the sediment dynamics in coastal areas of the Gulf of California, for example outside the Yavaros lagoon. For instance, Marghany (2013) used radar interferometry techniques to simulate a three-dimensional coastal geomorphology. In addition, Marghany et al. (2011) simulated shoreline change rates from airborne radar data, based on retrieving wave spectra information, and their effects on sediment transport along Malaysian coastal waters.

Conclusions

Numerical calculations were performed to investigate the tidal hydrodynamics, the bed load sediment transport and the induced process for the export–import of sediments in the Yavaros coastal lagoon. Critical areas for the survival capability of benthos were determined. The bathymetric features of the Yavaros coastal lagoon include a complex network of channels and tidal flats that lead to the distortion of the tidal signal, with longer rising tides than falling tides. Time series of the components of the velocity and tidal elevation revealed that the lagoon is characterized by asymmetric tides. The asymmetry is more complex for tidal currents. This fact is better evidenced in the time series of the components (u, v) of the horizontal velocity vector.

Other relevant conclusions drawn from this research is the oscillatory character of the net sediment transport. Rates of export and import of sediments revealed semiannual, monthly and fortnightly oscillations. During 20 years of numerical simulation, the coastal lagoon exported 1,600 m^3 of sediment. This work emphasizes the relevance of the numerical modeling of sediment transport to supply information about tidal distortion, export–import processes of sediment and the role of friction in the morphodynamics of the lagoon systems. To sustain an export process over long-term scales, the amount of sediment must be compensated by sediment supplied by several tributary creeks discharging sediment into the lagoon. As a result of this source of sediment, significant morphodynamic changes in the lagoon are avoided. Under these circumstances, the lagoon system is characterized by an export–import process that is not necessarily in equilibrium.

It has been demonstrated that friction is crucial to define the magnitude and direction of the net sediment transport and whether a coastal water body behaves as an exporter or importer of sediment. One of the major findings of this research is that a coastal lagoon may export or import sediment or even it may reach a morphodynamic equilibrium depending on the friction coefficient value. The sensitivity of the export–import process to variations in the frictional coefficient was investigated. The experiments showed that the coastal lagoon acts as an importer if the highest friction permitted value is <0.0078. If the friction is greater than this value, the lagoon becomes an exporter. Since the tidal distortion inside the lagoon of Yavaros is of ebb-dominant type, then according to previous research, the lagoon should export sediments. This agrees with our calculations and with satellite images.

Critical velocities are of fundamental importance to sediment transport. The largest morphological changes do not necessarily take place in areas where the difference between maximum tidal velocities and critical velocities is greatest. The most intense morphological changes occurred in areas with sharp topographic gradients, i.e., in channel edges and tidal flats. This is because relatively strong water depth gradients lead to friction gradients, as well as to divergence in sediment transport and, finally, to more intense morphodynamic processes. As distortion of tidal signals in coastal water bodies has been related to maximum and minimum flooded areas, the authors believe that our findings regarding the importance of friction in specific areas merit further research in other coastal water bodies.

Another finding is that the Yavaros lagoon exports sediment to the Gulf of California. It agrees with the export process shown in Fig. 1a. The tidal distortion is of ebb-dominant type. It agrees with other studies which indicate that ebb-dominant tidal signals are associated with export of sediments. An important conclusion is that in a coastal lagoon system, there are selective areas (determined by friction, critical velocity and amplitude of the tidal currents) where the erosion–accretion processes are particularly intense which may affect the survival capability of benthos.

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