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Transport of Sediments in Water Bodies of the Gulf of California

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1. Introduction

The knowledge of transport of sediments in coastal ecosystems is relevant to understand forms of marine life. Many marine species find refuge and food in benthic substrates like rocky, sandy and muddy intertidal coastal areas. On the other side, and from an economical point of view, sands dynamics has a large influence on the design of harbors and on the development of industry zones along the coastline like installations for oil storage, refineries, vessel traffic and beach management. One of the principal problems is to find a balance among the conservation of the marine ecosystems and the needs for an additional development of coastal engineering structures like design of dikes and breakwaters, navigation channels and beach protection (Herbich, 2000). Strong mobility of sediments is observed in satellite imagery of many coastal areas of the world. It is an indication of the sediment dynamics and of the complexity of this kind of processes. Fundamentally, the transport of sediments has to do with erosion and accretion phenomena and with the transport of particles in suspension as a consequence of hydrodynamic forces acting on the single particles (Julien, 1998). In fact, these particles are fragmental material accumulated in the geological time as result of physical and chemical disintegration of rocks (Van Rijn, 1993). The continuous erosion, transport and deposition of these particles have modified their geometrical form and through hydrodynamic processes there is a tendency to be separated in particle sizes (very coarse, coarse, medium, fine, very fine). The analysis of source material has revealed that it is dominantly conformed of clay, quartz, silt and sand, among others.

The circulation in the ocean that causes the transport of sediment is the result of several forcing mechanisms; wind induced currents, baroclinic circulation and tidal currents. The dynamics generated by wind stress is an intermittent process but very effective in modifying sediment patterns through the induced currents and surface waves. Baroclinic or density induced currents vary seasonally and may contribute, together with changing wind systems, to reverse the transport of sediment along the coast, the so called littoral transport. Tidal currents are caused by the gravitational force of sun and moon. In the oceans and seas, the intensity of tidal currents varies from a water body to another, but a characteristic of tides is that they are always acting on the marine ecosystems, principally in diurnal,

semidiurnal and fortnightly cycles. Since the transport of sediments depends on the intensity of currents (or near bottom currents), regions, where tidal amplitudes are large and there is a sandy sea bottom, are of particular interest. In the North Sea, the Gulf of California, the English Channel, the Bohai Sea, the Patagonian Shelf, etc., tidal currents are very intense. The interaction of tidal currents and a sandy sea bottom may lead to the development of wave-like regular patterns of different spatial and temporal scales (Hulscher, 1995). A series of analytical studies on the formation of sandbanks, sand waves and other rhythmic patterns have been carried out (Hulscher, 1996a; Kamorova & Hulscher, 2000). They apply equations for the transport of sediments which have been derived experimentally (Van Rijn, 1993). They consider the generation of morphological features as a process of instability when currents and the sandy sea bottom interact. The range of scales of these rhythmic sea bottom patterns varies from ripples (0.1 – 1) m, beach cusps (1-100) m, nearshore bars (50-500) m, sand waves (300-700) m, shoreface-connected sand ridges (5-8) km, tidal sandbanks (2-10) km (Dodd et al, 2003). There are manifestation of sandbanks, sand waves and other rhythmic seabed features in important seas of the world. Sandbanks and sand waves formation in the North Sea has been investigated intensively (Huthnance, 1982; Hulscher, 1996a; Hulscher, 1996b; Komarova & Hulscher, 2000). The influence of geometry on the generation of groups of sandbanks in the North Sea was also investigated (Carbajal et. al, 2005). The scale of sandbanks and the presence of sand waves in the Gulf of California has also been investigated (Meckel, 1975, Carbajal & Montaño, 1999). In spite of the findings on the formation process of sandbanks, like the understanding of instability mechanisms, the prediction of wavelengths and other very interesting characteristics of seabed features, many of these studies suppose an infinite sea, i.e. they do not consider boundaries in the calculations. Bottom and geographical boundaries of a water body should play a fundamental role in the sediments dynamics, since satellite imagery of coastal areas of many parts of the world reveals sand features with a wide range of scales. Along the coasts of the world there are a lot of water bodies like semi-enclosed seas, bays, estuaries, inlets and coastal lagoons where a strong mobility of sediments occurs. It suggests that the geometry (geography and bathymetry) is an important factor in the generation of regular and irregular areas of erosion and accretion of sediments. The analytical study of rhythmic seabed features with consideration of realistic boundaries is, of course, extremely difficult. Therefore, numerical models are an important alternative tool to investigate the transport of sediments in complex coastal areas. We believe that a complementary work of experimental, theoretical and numerical research on transport of sediments is necessary.

2. Study area

The Gulf of California is a marginal sea with a length of about 1100 km and an averaged width of approximately 200 km (figure 1). In the central part of the gulf there is an archipelago formed by the islands of Angel de la Guarda, Tiburón, San Esteban, San Lorenzo, Salsipuedes and Partida. In the northernmost part is located the Colorado River Delta, a triangular shallow platform where the water discharge took place in the past. The huge quantities of discharged sediment and the combined tidal and water discharge dynamics led to the formation of the islands of Montague and Gore. The northern part can be considered as a continental shelf with maximum depths of 200 m. In the southern part of the gulf, depths of more than 3000 m can be found. In the Gulf of California, satellite imagery reveals an intense mobility of sediments in the area of the Colorado River Delta and in water bodies along the eastern coast like the bays of Adair, San Jorge and Yavaros and the

coastal lagoons of Topolobampo, Santa María la Reforma, among others (figure 1). Tides are very important in the dynamics of the Gulf of California. In the central part, tides have a mixed character but with dominant diurnal signals and maximum tidal ranges of about 1.6 m. In the southern part, mixed tides govern the sea level change, but with a dominance of semidiurnal signals and tidal ranges of approximately 2 m. In the northern part, tides have a semidiurnal character and the tidal ranges reach the largest values of the gulf. We are going to document the bedload sediment transport in the Gulf of California with the numerical study of two representative water bodies: the Colorado River Delta and the Yavaros Bay (see figure 1). These calculations will give an idea of the enormous work which has to be done to study the transport of sediment in all water bodies of the Gulf of California.



Fig. 1. Some water bodies in the Gulf of California where transport of sediments occurs (Landsat Image).

3. The model

We estimated the bedload sediment transport in several water bodies of the Gulf of California applying a vertically integrated two-dimensional, non-linear, semi-implicit numerical model. The model has been used previously for the study of tidal dynamics and transport of sediments in the Colorado River Delta (Montaño & Carbajal, 2008) and the dynamics of coastal lagoons like Topolobampo (Montaño-Ley et.al, 2007). The model is coupled with a semi-empirical bedload sediment transport equation (Van Rijn 1993). The applied vertically integrated equations of motion are

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

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

The used equation of continuity is

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

In this system of equations, U and V are the transports in the x and y directions respectively $(\mathrm{m^2\ s^{-1}})$, $\mathbf{v}$ is the velocity vector $(\mathrm{m\ s^{-1}})$, t is time (s), g is the gravitational acceleration $(\mathrm{m\ s^{-2}})$, H is the water depth (m), ζ is the sea surface elevation (m), $f=2\Omega\sin\varphi$ is the Coriolis parameter $(\mathrm{s^{-1}})$, Ω is the angular velocity of the Earth $(\mathrm{s^{-1}})$, φ is the latitude and A_H is the horizontal coefficient of Eddy viscosity $(\mathrm{m^2\ s^{-1}})$.
At the open boundary, the sea surface elevation is given by

$$\zeta(x,y,t)=A_0\cos(\omega t-\Phi) \quad (4)$$

where ω is the angular frequency of the M_2 tidal component. A_0 and Φ are the observed amplitudes and phases. The boundary condition for the velocity vector $\mathbf{v}$ at the closed sides is $\mathbf{v}\cdot\mathbf{n}=0$, where $\mathbf{n}$ is a unit vector normal to the coast. At the open side the condition is

$$\frac{\partial v_n}{\partial x_n}=0$$

where the velocity v_n and the coordinate x_n are perpendicular to the boundary.
The transport of sediment by a flow of water takes place in the form of bedload and suspended load. It depends on the particles size and on the intensity of the flows. The motion of the bed material particles occurs basically in three ways; rolling and sliding motion, saltation motion and suspended particle motion (Van Rijn, 1993). There are different mathematical formulae for the transport of bedload and suspended load. One of them is when the volumetric sediment flux, $\mathbf{S}=\mathbf{S}(S_x,S_y)$, is proportional to the velocities, i.e. $\mathbf{S}\propto(\bar{\mathbf{v}}-\bar{\mathbf{v}}_{cr})^m$, where $\bar{\mathbf{v}}$ is the depth-averaged velocity, $\bar{\mathbf{v}}_{cr}$ is the depth-averaged critical velocity and $3\le m\le 5$. Another form is $\mathbf{S}\propto(\boldsymbol{\tau}-\boldsymbol{\tau}_{cr})^n$, i.e. it is a function of the bed shear stress $\boldsymbol{\tau}$, with $n\approx 1.5$. We used the following conservation equation for bedload sediment transport,

$$\frac{\partial H}{\partial t}-\nabla\cdot\mathbf{S}=0 \quad (5)$$

And we applied an equation where the volumetric sediment flux $\mathbf{S}$ is proportional to the depth-averaged velocities (van Rijn, 1993; Hulscher, 1996a).

$$\mathbf{S} = \alpha \frac{|\mathbf{v}|^b}{u_c^b} \left(\frac{\mathbf{v}}{|\mathbf{v}|} - k_* \nabla H \right) \tag{6}$$

The volumetric sediment flux is given in $(\mathrm{m}^2\ \mathrm{s}^{-1})$ (cubic meters of sediment per meter of sea bottom width per second) and S_x and S_y are the flux components in the x and y directions. $\alpha = 10^{-6}$ is a function of the sediment properties $(\mathrm{m}^2\ \mathrm{s}^{-1})$, $b = 3.0$ is the potency of the transport, $k_* = 2.0$ is a coefficient for bed slope correction and u_c $(\mathrm{m\,s}^{-1})$ is the critical velocity for bedload sediment transport, i.e. if $|\mathbf{v}| \le u_c$ then no bedload sediment transport occurs.

4. Results

4.1 Colorado River Delta

In the Colorado River Delta, tidal ranges reach values of about 10 m at spring tides, with a dominant semidiurnal signal (Carbajal & Backhaus, 1998). Tidal currents of the order of 3 m/s have been estimated in areas where the water is channeled by the presence of sandbanks or islands. In figure 2, the distribution of sediments in the Colorado River Delta is shown at the time between neap and spring tides. The sediments mobility is very strong and occurs in form of filaments that extend more than 60 km to the south. This sediment was deposited principally by the discharge of the Colorado River in the geological time. It is important to mention that since the construction of the Hoover Dam in the thirties of the last century, the water and sediments discharge through the Colorado River came to an end (Carbajal et al., 1997). The large concentration of suspended sediments, visible in satellite imagery, has been previously discussed by the same authors. Since satellite imagery (LANDSAT TM5, March 2011) clearly shows evidences of high concentrations of suspended sediments (figure 2), it suggests a long-term changing sea-bottom morphology caused by a heavy suspended and bedload sediment transport.

Considerable efforts have been carried out to understand the sedimentation process in the Colorado River Delta. Baba et al. (1991) suggests that sediments in the wide and shallow platforms of the Northern Gulf of California are being intensely reworked, re-suspended and also transported southwards. Based mostly on north-migrating bed-forms and coastal sand bars, Meckel (1975) described a dominant sediment transport along the Sonora coast. Filloux (1960) described a dominant north to south sediment transport along the Baja California coast. Baumgartner et al. (1991) suggest that other sources of sediment have become important such as aeolian input from the northern Mexican desert. Applying principles of analytical geometry and vector analysis of textural data, Carriquiry and Sanchez (1999) estimated the direction of the mean transport vectors. Their results indicate the existence of two opposing littoral transport components along the Sonoran and Baja California coasts. With a few local exceptions, sediment transport occurs from SE to NW along the coast of the State of Sonora and from NW to SW along the Baja California. According to them, sediment supplied to the area comes from three different sources: (1) sediment derived from the actual delta structure (2) sediment provided by the adjacent La Mesa deposits that becomes exposed along the Sonora coastline, and (3) sediment supplied

by the coast of Baja California. Other studies concerning sedimentation on the Colorado River Delta were carried out by Baba et al (1991), Carriquiry (1993), Cupul (1994) and Zamora (1993). Most of the above studies have been based on geologic considerations, satellite imagery and textural data as well as measurements of suspended sediment concentration.

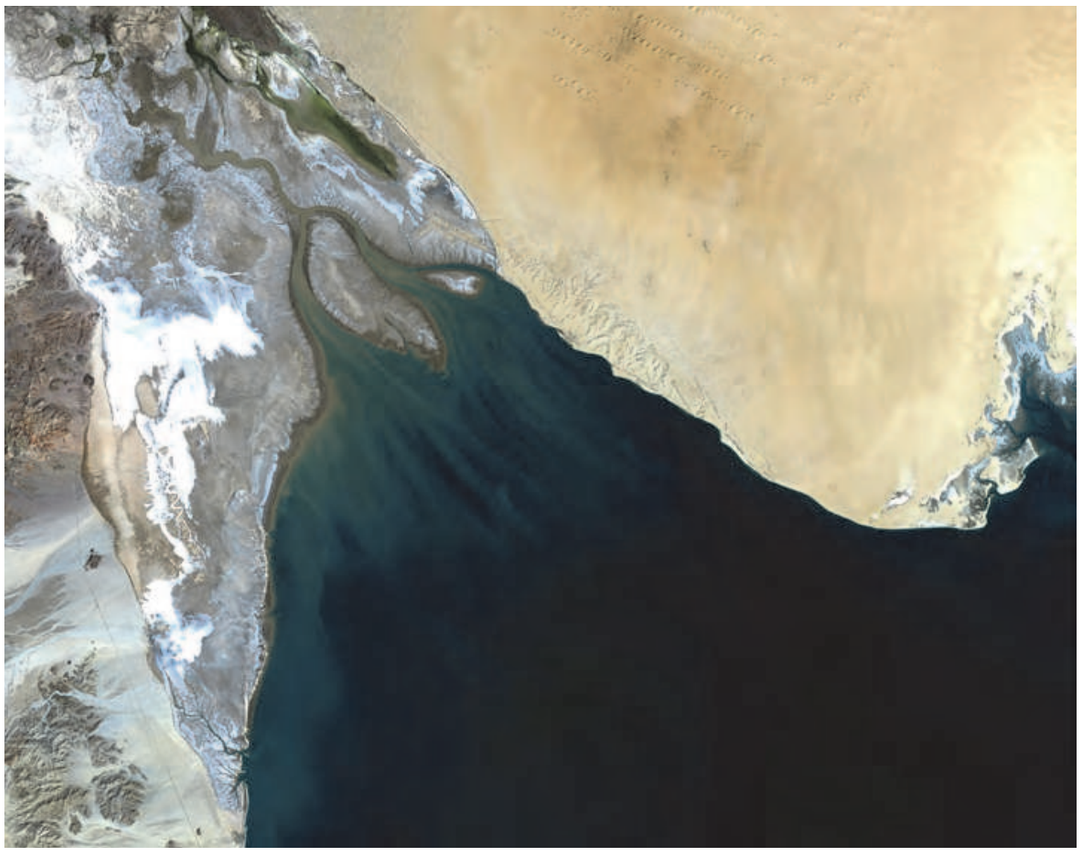


Fig. 2. Sediments distribution in the Colorado River Delta (LANDSAT TM5 March 2011), RGB321.

In figure 3, the bathymetry and the deltaic configuration of the studied area is displayed. The most important features are the mouth of the Colorado River, the islands of Montague and Gore and the Wagner basin in the south. The triangular form and the bathymetric convergence contribute notably trough the continuity equation to increase the tidal amplitudes. To investigate the dynamics and the transport of sediments in the Colorado River Delta and in other areas of the Gulf of California, we applied the vertically integrated numerical model described above.

In the northern part of the Gulf of California, the dominant signal is the M_2 tide (Principal lunar constituent). In figure 4, the calculated sea surface elevation at four different times of a M_2 tidal cycle is shown. Around the island Montague, amplitudes of more than 2 m are found. These large tidal amplitudes are associated to strong tidal currents that cause a bedload transport of sediments through the equations (5) and (6). In our simulations, the bathymetry evolves at each time step, maintaining completely the non linearity of the

calculations. Tidal currents in the Gulf of California and particularly in the Colorado River Delta have been investigated in several research works (Carbajal et. al, 1997; Carbajal & Backhaus, 1998); Salas et.al, 2003). We focus here our interest in the bedload transport of sediments.

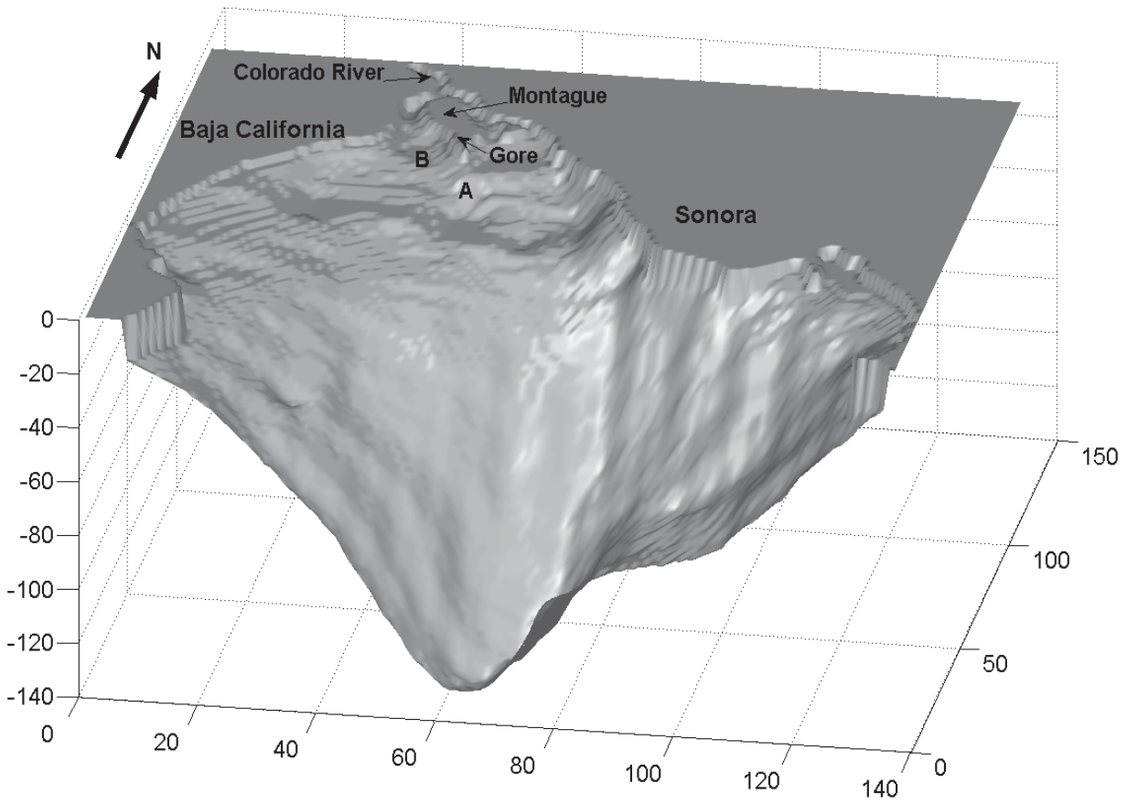


Fig. 3. Bathymetry and the deltaic structure of the northernmost part of the Gulf of California.

To give an idea how the process of erosion and accretion occurs in the Colorado River Delta, we show time series of the bottom evolution at the points A and B whose positions are indicated in figure 3. We simulated the bedload transport of sediments for one year. The variation during two M_2 tidal periods of the accumulated sediment, instantaneous bedload sediment transport, the instantaneous tidal velocities and the tidal elevation are displayed in figures 5a and 5b. All these variables are separated in the x-component (left side) and y-component (right side). The accumulated sediment indicate, at every time step, how much sediment has been built up separately by the x and y components of the volumetric sediment flux vector $\mathbf{S} = \mathbf{S}(S_x, S_y)$. We note that at point A, the x-component and the y-component are out of phase and their contribution cancels each other to some extent. At the point B, the accumulated sediment indicates a decreasing tendency in the x-component and a growing trend in the y-component. The behavior of the accumulated sediment at these two points gives us an idea about the complexity of the transport of sediment process. The instantaneous rate of bedload sediment transport, the components of the velocity vector and

the sea surface elevation reflects the nonlinearity of this kind of phenomena. A tidal distortion is observed in the bedload sediment transport, in the accumulated bedload sediment transport and in the two components of the velocity vector. Observe that the curves of these variables deviate clearly from a sinusoidal shape. When all net effects at all grid points are quantified, a general morphological change is then visualized. The largest accumulative sediment transport rate was found in the neighborhood of the island Montague, with a value of about 0.0005 m^2/s. But we have to remember that this parameter is oscillating continuously, sometimes it has a growing character and sometimes it has a decreasing trend.

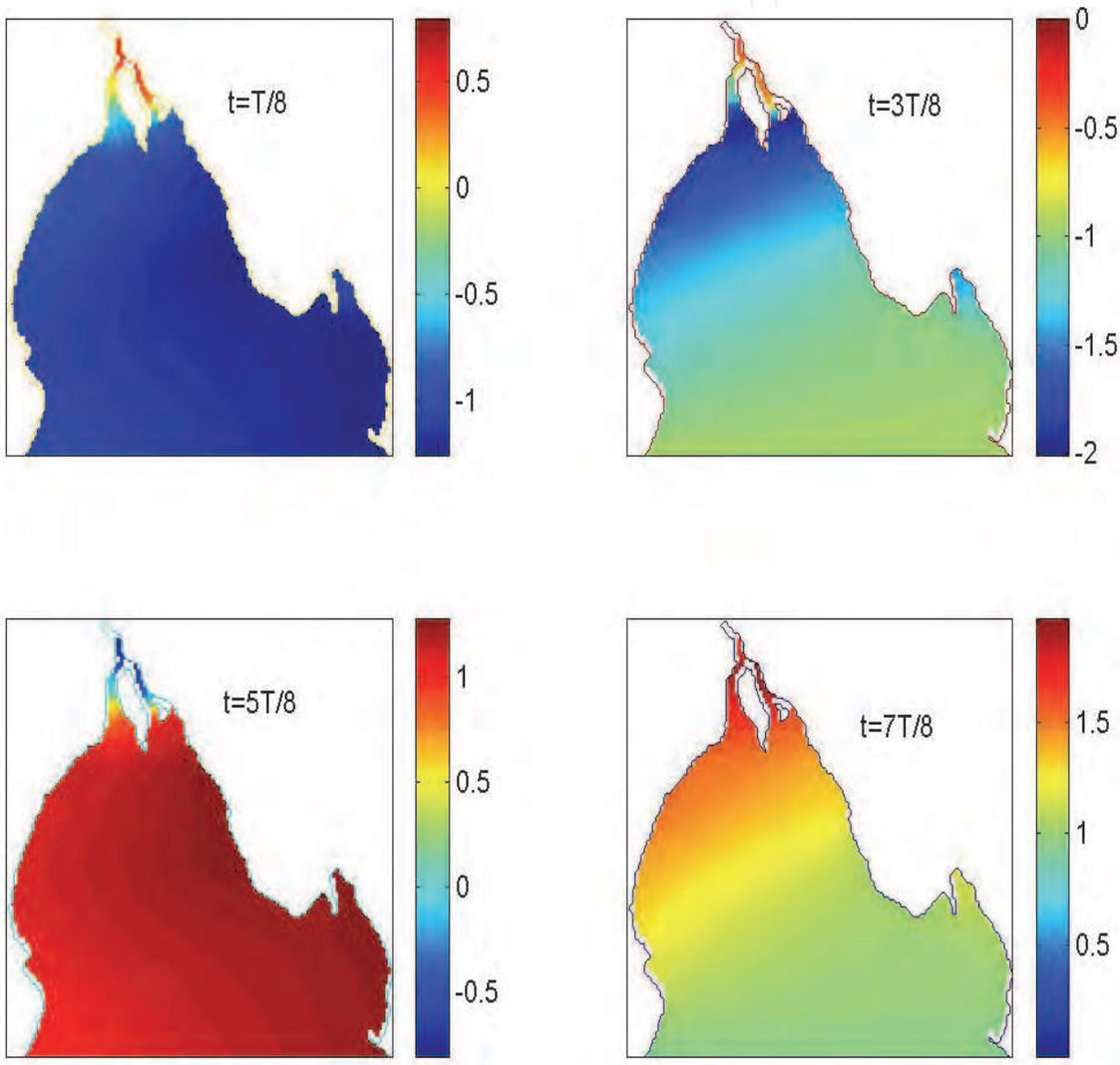


Fig. 4. The calculated sea surface elevation at four different times of a M_2 tidal cycle is shown. The sea surface elevation is given in meters.

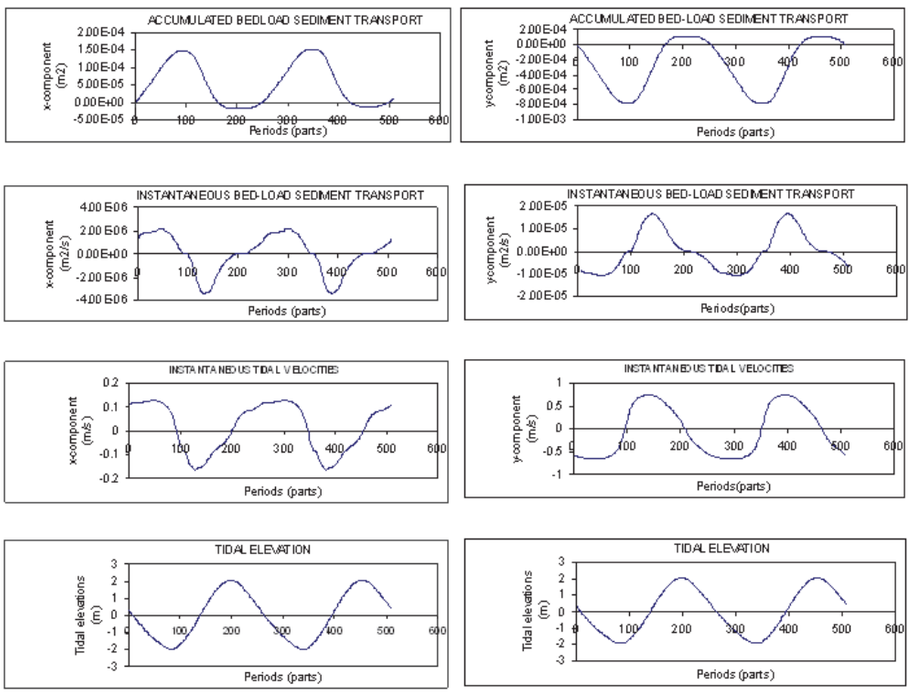


Fig. 5a. Sediment transport and hydrodynamic parameters obtained for two tidal periods at control point A.

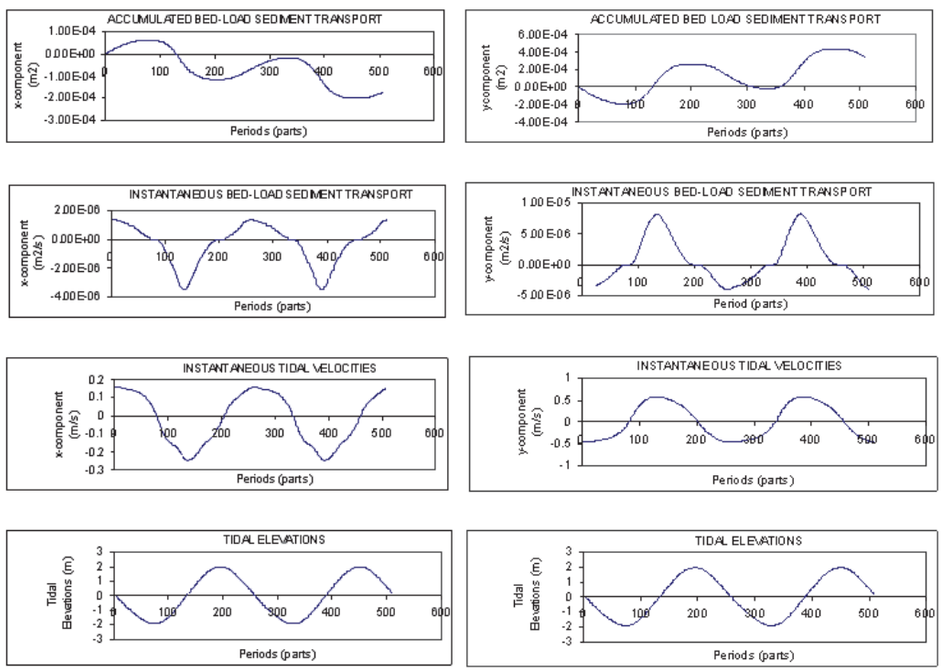


Fig. 5b. Sediment transport and hydrodynamic parameters obtained for two tidal periods at control point B.

In figure 6, the net morphological change caused by the M_2 tide after one year of numerical simulation is displayed. The major morphological evolution takes place around the islands of Montague and Gore, in the northernmost part of the Colorado River Delta. Changes due to erosion and accretion processes larger than 0.1 m were observed. The presence of sandbanks in the Colorado River Delta has been detected by bathymetric measurements (Meckel, 1975; Alvarez et al., 2009). It is interesting to observe that in our calculation there is a tendency to the formation of sandbanks to the south of Montague Island. Although we carried out calculations for the bedload sediment transport alone, there are some dynamic similarities among the distribution of suspended sediment shown in figure 2 and the pattern of the morphological change by bedload sediment transport after one year of simulation of the M_2 tide. The modeled areas of erosion and accretion show a similar tendency like the direction of the sediment filaments depicted in figure 2. The general morphological pattern calculated in this research work agrees with that showed by Montaño and Carbajal (2008). However, we make here emphasis in the morphological changes described in the time series of the accumulated sediment and of the instantaneous sediment transport (Figure 5).

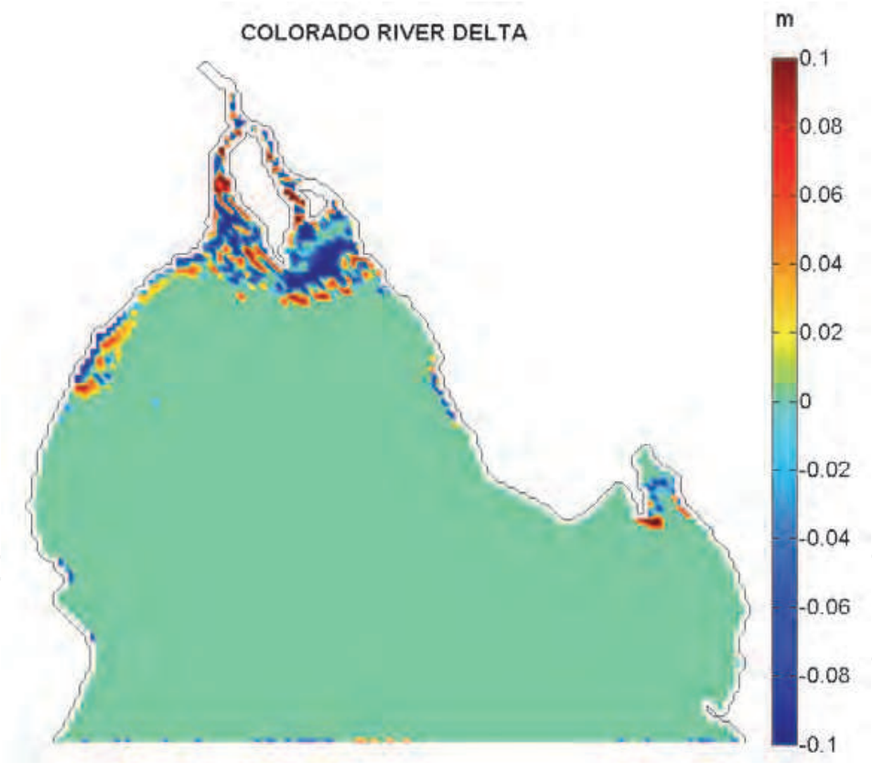


Fig. 6. Areas of erosion and accretion caused by the M_2 tide after one year of simulation.

4.2 Yavaros Bay

The Yavaros Bay is located 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. The region is characterized by a semi-arid climate with winds predominantly from the southwest in the summer months and from the northeast in winter. As many coastal lagoons, this water body arose by

the developing of sand bars, keeping on an opening of about 1.7 km. The Yavaros Bay can be considered a well connected coastal lagoon with the adjacent Gulf of California. The formation of coastal lagoons in the Gulf of California was investigated by Lankford (1976). He stated that most of these water bodies are shallow embayments associated with deltaic systems. Yavaros Bay is located in a region where the rivers Yaqui, Mayo and El Fuerte have discharged huge quantities of sediment to this part the Gulf of California. Located not so far away from the tropic of cancer, the direct solar radiation is intense with large evaporation rates. In this region, evaporation exceeds precipitation by far, since average annual evaporation values from 1500 to 2000 mm have been estimated whereas the average annual rainfall varies among 300 and 500 mm (Dworak & Gómez-Valdés, 2003). With exception of the months from July to September, rainfall is in general scarce. The bottom topography of the Yavaros Bay is very complex with a dominant navigation channel from the mouth to the northwest direction (figure 7). Maximum depths of about 8 meters are found and very shallow areas of one meter or less are situated on the northeastern side.

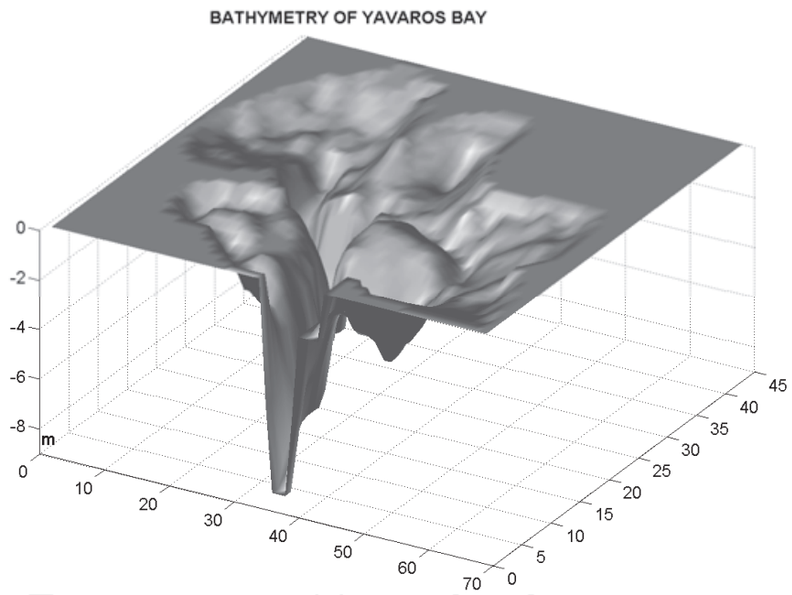


Fig. 7. Bathymetry of the Yavaros Bay.

The central part of the Gulf of California is characterized by mixed tides with predominance of diurnal signals. Tides in the Yavaros Bay have been studied in detail (Dworak & Gómez-Valdés, 2003; Dworak & Gómez-Valdés, 2005). Through non-linear processes, the propagation of tides in very shallow areas leads to generation of high harmonics that are controlled by astronomical configurations. The generation and behavior of tides in shallow waters like this coastal lagoon is affected, for example, by the lunar and solar declination effects. Since tides in this coastal lagoon have a mixed character, semidiurnal, diurnal and fortnightly oscillations can be distinguished in measurements. Semidiurnal tides are dominantly originated by the principal solar (S_2) and lunar (M_2) constituents, by solar and lunar declination effects (K_2) and by longer lunar elliptic effect (N_2). Diurnal tides are due to solar and lunar declination effects (K_1), to main lunar (O_1) and solar (P_1) contributions and to 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 & Gómez-Valdés, 2005). The numerical modeling of tides and, of course, measurements indicate velocities of the order of 1 m/s. In figure 8, tidal currents produced by the soli-lunar declinational K_1 are displayed. Velocities larger than 0.3 m/s are found in the navigation channel and adjacent areas.

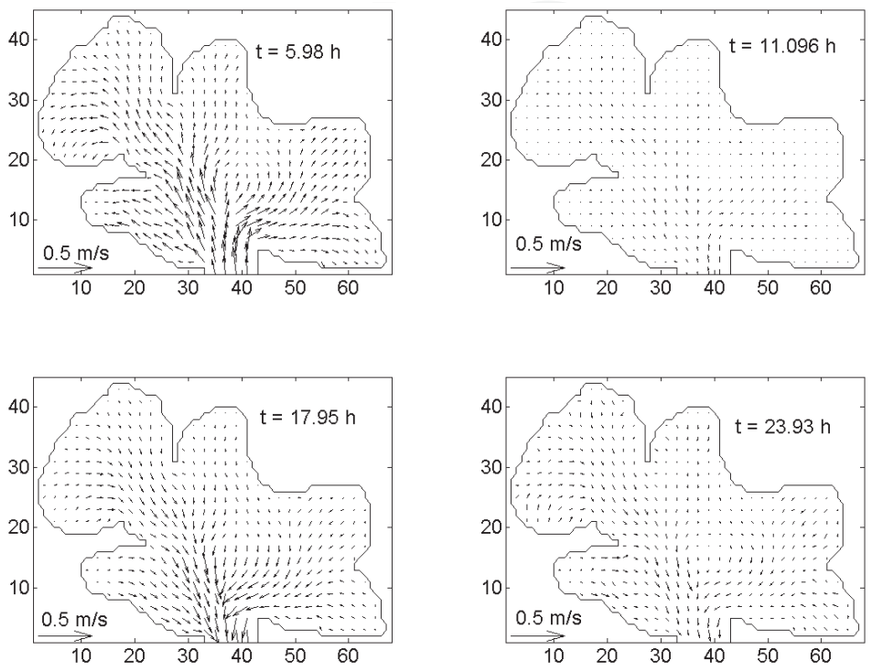


Fig. 8. Numerical modeling of currents produced by the soli-lunar declinational K_1 tide in the Yavaros Bay.

As an example, we document the bedload transport of sediment with a calculation where the K_1 tidal constituent is forcing the dynamics in the Yavaros Bay. The amplitude of the K_1 tide at the entrance of the lagoon system is 0.249 m. Although recent research work on tides in the Yavaros Bay reveal that 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 and $2SM_6$) (Dworak and Gómez-Valdés, 2003), are of relative importance, the amplitude of the K_1 is the largest and to some extent, the dominant signal. In figure 9, the morphological changes after one year of simulation are shown. Areas of erosion (blue) and accretion (red) reach for one year heights of a few centimeters. If one considers that the time scale of sandbanks formation is of centuries, then a linear extrapolation to one century of the results shown in figure 9 would reach heights of a few meters. However, this linear extrapolation is, of course, not correct due to the intrinsic non-linearity of the hydrodynamic and transport of sediment processes. An accretion or erosion area, formed by the hydrodynamics, modifies the flow and the flow modifies again the transport of sediment and so on. The area of intense mobility of sediment is at the entrance of this coastal lagoon, therefore it is very important to understand the sedimentation process and to develop mathematical models to predict correctly the evolution of the morphology in this kind of coastal lagoons.

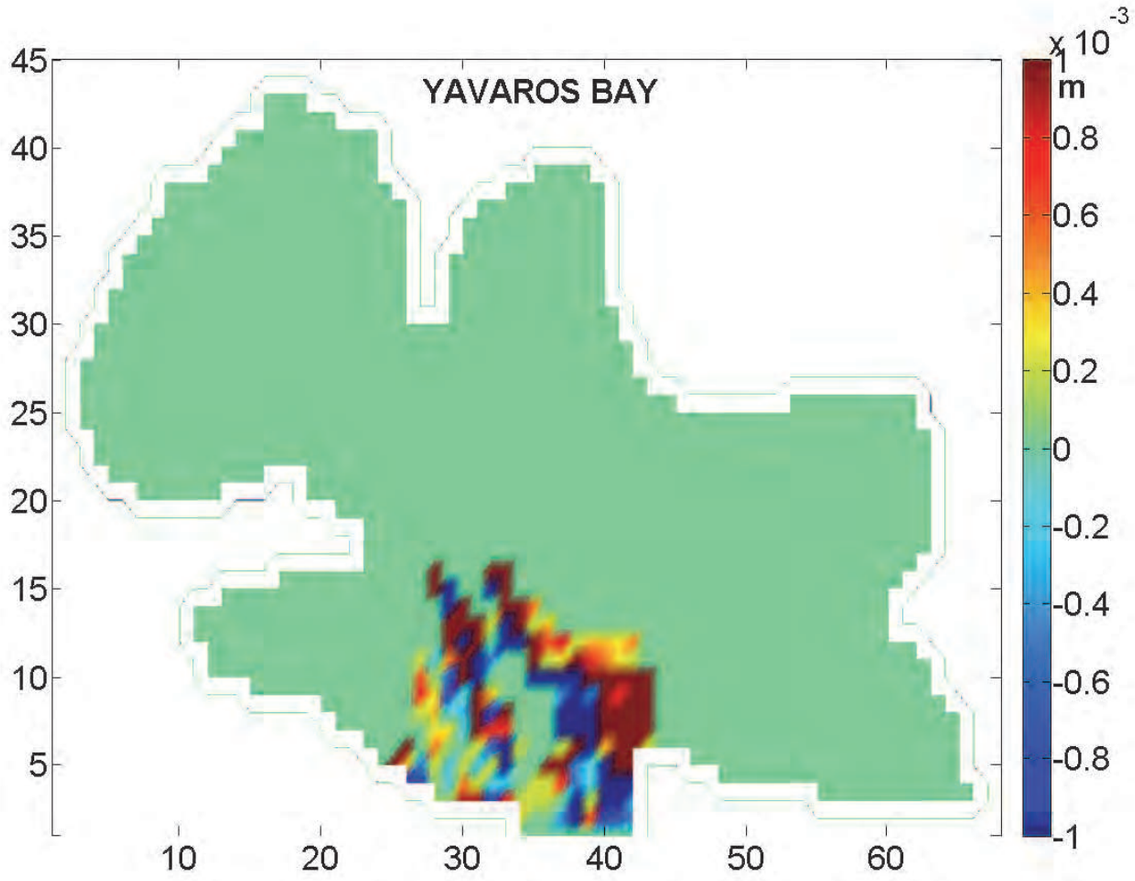


Fig. 9. Morphological changes caused by 13 tidal constituents in the yavaros Bay after one year of simulation.

5. Conclusions

In general terms, we have described the problematic associated with the transport of sediments in coastal areas. We commented several methods (theoretical, experimental and numerical) to investigate the mechanisms involved in transport of sediments. We mentioned several seas of the world where tidal amplitudes and the transport of sediment are large. We have shown that satellite imagery reveals large sand patterns in the northernmost part and along the eastern coast of the Gulf of California, where an important number of water bodies (Bays of Adair, San Jorge, Yavaros) and coastal lagoons (Topolobampo and Santa María la Reforma) are located. We presented a methodology to investigate the transport of sediments based on the application of a vertically-integrated two-dimensional numerical model together with the use of a volumetric sediment flux vector and an equation of conservation of sediment. We documented the application of this methodology with the numerical modeling of the bedload sediment transport in two water bodies of the Gulf of California, namely the Colorado River Delta and the Yavaros Bay. For the Colorado River Delta, we calculated a morphological change (figure 6) which is similar to the distribution of suspended sediment depicted in figure 2. In time series of accumulated bedload sediment

transport and of instantaneous bedload sediment transport we explained the complexity associated with this kind of non-linear processes. Erosion and accretion areas arise as a consequence of the interaction of the tidal induced flow and a sandy bottom. These areas may grow or decrease with the time, or even the rate of grow. We presented results of the bedload sediment transport in the Yavaros Bay caused by the diurnal tide K_1. We calculated the morphological change after one year of numerical simulation, finding changes of the order of a few centimeters. These grow rates are in concordance with observed and theoretically calculated grow rates. Finally, there is a huge quantity of research work to be done to understand and to quantify the transport of sediments in the Gulf of California. There are many water bodies, particularly along the eastern coast, interacting with the littoral transport of sediments, or simply coastal lagoons interacting or exchanging sediment with Gulf of California.

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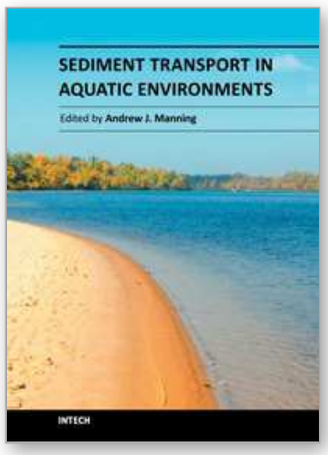
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Sediment Transport in Aquatic Environments is a book which covers a wide range of topics. The effective management of many aquatic environments, requires a detailed understanding of sediment dynamics. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often the tool used for predicting the transport and fate of sediment movement in these situations, as they can estimate the various spatial and temporal fluxes. However, the physical sedimentary processes can vary quite considerably depending upon whether the local sediments are fully cohesive, non-cohesive, or a mixture of both types. For this reason for more than half a century, scientists, engineers, hydrologists and mathematicians have all been continuing to conduct research into the many aspects which influence sediment transport. These issues range from processes such as erosion and deposition to how sediment process observations can be applied in sediment transport modeling frameworks. This book reports the findings from recent research in applied sediment transport which has been conducted in a wide range of aquatic environments. The research was carried out by researchers who specialize in the transport of sediments and related issues. I highly recommend this textbook to both scientists and engineers who deal with sediment transport issues.

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