Revista de Investigación de Física **23(3)**, (2020)
VICERRECTORADO DE INVESTIGACIÓN Y POSGRADO
eISSN:1728-2977

Hydrodynamic Modelling of a Coastal Lagoon in México

María Morales[1,*]
Julio Aquije[1,**]
Leonardo Carvalho[1]
Adán Mejía[2]

[1]UFES – Laboratorio de Simulación de Flujos con Superficie Libre (LABESUL)
[2]UABC- Instituto de Investigaciones Oceanológicas (IIO)

Recibido 02 abril 2020 – Aceptado 02 diciembre 2020

Abstract
To understand the local hydrodynamics of the hypersaline coastal lagoon San Quintín Bay Lagoon (SQBL), located in Northern Mexico, a bidimensional modelling was applied. The lagoon presents a complex bathymetry, so the mesh was locally refined in the main channels of the lagoon. It was used wind and the seven main harmonic constants of the tide to force the model. The calibration period took place during summer 2004. The results obtained for vertical integrated velocity and sea level elevation were compared with data from three Acoustic Doppler Current Profilers placed inside the lagoon, getting a satisfactory representation of the lagoon flow dynamics with errors of 4% in elevation and a 0.96 for the correlation coefficient R^2, while for currents the averaged error was around 12% and a correlation coefficient of 0.7 R^2. The 2D model was capable of representing both sea level and currents inside the lagoon.

Keywords: hydrodynamic, model, Ddelft3D, coastal lagoon.

Resumen
Para comprender la hidrodinámica local de la laguna costera hipersalina Laguna de la Bahía de San Quintín (SQBL), ubicada en el norte de México, se aplicó un modelo bidimensional. La laguna presenta una batimetría compleja, por lo que la malla se afinó localmente en los canales principales de la laguna. Se utilizó el viento y las siete principales constantes armónicas de la marea para forzar el modelo. El período de calibración se llevó a cabo durante el verano de 2004. Los resultados obtenidos para la velocidad vertical integrada y la elevación del nivel del mar se compararon con los datos de tres Perfiladores de Corriente Acústica Doppler colocados dentro de la laguna, obteniendo una representación satisfactoria de la dinámica de flujo de la laguna con errores de 4% en elevación y de 0.96 para el coeficiente de correlación R2, mientras que para las corrientes el error promedio fue de alrededor del 12% y un coeficiente de correlación de 0.7 R2. El modelo 2D fue capaz de representar tanto el nivel del mar como las corrientes dentro de la laguna.

Palabras clave: hidrodinámica, modelo, Ddelft3D, laguna costera.

1[*]marfer.santillan@hotmail.com
**julio.chacaltana@ufes.br

Introduction

In coastal lagoons tides are the most important constituent in their hydrodynamics. As a tidal wave that propagates in shallow water, the speed induced by it tends to be vertically uniform, but with horizontal spatial variation and, consequently, its hydrodynamics can be explained with a horizontal two-dimensional model. Another, but not less important, constituent that governs hydrodynamic behavior in coastal lagoons is the wind. The shape of the lagoon with its constrictions, variations in depth, areas of flooding and the presence of vegetation place a particular behavior in the hydrodynamics of the lagoon (Farreras, 2004).

In Mexico, coastal lagoons have great socio-economic importance, since they are the seat of food, energy, tourism, housing and communication resources, and it is urgent to take advantage of and develop harmoniously, simultaneously preserving the natural environment (balance between exploitation and preservation) (Farreras, 2006).

Rapid population and tourism growth, as well as the aquaculture and agriculture activities that have developed around these water bodies can cause negative environmental impacts in these ecosystems.

In order to understand the possible impacts on these water bodies, it's essential to understand the hydrodynamics of the studied water body.

The San Quintín Bay Lagoon (SQBL) is a coastal lagoon located in the Mexican State of Baja California between 30 ° 24 'and 30 ° 30' north latitude and 115 ° 57 'and 116 ° 01' west longitude, and covers an area of approximately 42 km2. This lagoon is one of the most important coastal lagoons at the Pacific of Baja California that is characterized by its high capacity of aquaculture and agricultural production (Delgado et al., 2012).

The lagoon is divided in two basins: the eastern arm named San Quintín Bay (same name of the lagoon but different abbreviation: SQB), and the western arm named False Bay (FB).

The wind is generally strong, and the direction does not change very much thus being also an important forcing agent for the lagoon hydrodynamics. Northwest surface dominant winds with a frequency of 72.5% (COMISIÓN NACIONAL DEL AGUA, 2004).

Physical and mathematical modelling is the result of our understanding of the physical, chemical or biological processes that act simultaneously during the movement of the fluid and its respective mathematical representation. The resulting mathematical model can be used to understand the hydrodynamics of a coastal lagoon and the main ecological components.In general, the mathematical model can be used to obtain the response of the coastal lagoon when submitted to specific external agents. The model is commonly used either to predict the response of the coastal lagoon or to reconstruct past events. The coastal lagoons are of complex geometry; therefore, numerical methods are applied to find the discrete response inside the coastal lagoon. The discrete response is obtained through the use of a computer and is plotted using graphical visualization techniques (Abott; Price, 1994).

This work intends to carry out a study of the San Quintín Bay Lagoon (SQBL) hydrodynamics considering the tide and the wind as the main forcing mechanisms. To accomplish this we intend to use the Computational Fluid Mechanics technique.

Methodology

The Computational Fluid Mechanics technique is used to physically model the movement of the fluid. The mathematical model, when the fluid is incompressible, is composed of the continuity and Navier-Stokes equations. Applying the concept of long wave and hydrostatic pressure in the previous equations, the equations for the water level kinematics and for the dynamics of water movement are obtained, the latter is known as shallow water equations. In the present study, Delft3D-FLOW in 2DH mode is used to numerically solve the equations of water level and shallow water in an orthogonal curvilinear grid. (Gerritsen et al., 2004).

An orthogonal curvilinear mesh of variable size was set up on the SQBL (Figure 1): the area of the lagoon was refined locally (40 m x 120 m) to obtain a higher resolution, while the area corresponding to the open ocean has a lower resolution (100 m x 140 m).

The bathymetry far from the coast was taken from GEBCO (General Bathymetric Chart of the Oceans), while the bathymetry of the lagoon was taken during campaign in May-June, 2004. For the open ocean boundary, an astronomical forcing condition was applied using the seven main harmonics: M2, S2, K1, O1, N2, P1 and K2 (Delgado et al., 2012).Since the entrance to the bay is protected by a sand bar of 3 km long, the open ocean boundary was selected to be far from the entrance to allow the tidal wave to approach the lagoon in a natural way.

Initial conditions were set up for wind velocity field, and a water level of 1.9 m was considered in all the domain. In scenario **a**, the wind velocity field (315° direction and 3.5 m/s speed) is maintained constant for all the simulation period. But for scenario **b**, the wind velocity field is changing (direction and magnitude) each 10 minutes. These data were obtained from a meteorological station located between the two arms of the lagoon (Figure 2).

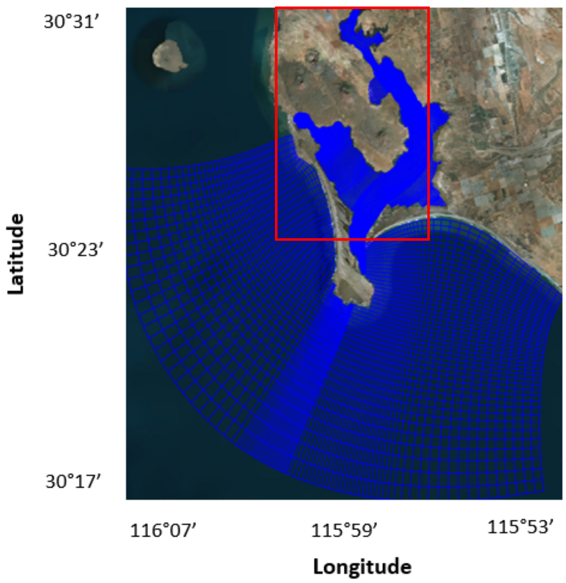

Figure 1. *Orthogonal Mesh of variable dimensions. In a red square the SQBL domain is marked.*

After running these two scenarios (**a** and **b**), sea water level and depth integrated velocity components were compared with those measurement *in situ.*

To calibrate the model, three monitoring points were established on the grid, located in the same positions where the ADCP's were placed in the field. The model time series for sea water elevation and currents were recorded at three points (Figure 2), and then compared to the field time series. To minimize uncertainty in the optimization process, the calibration was begun 25 days after the model was started.

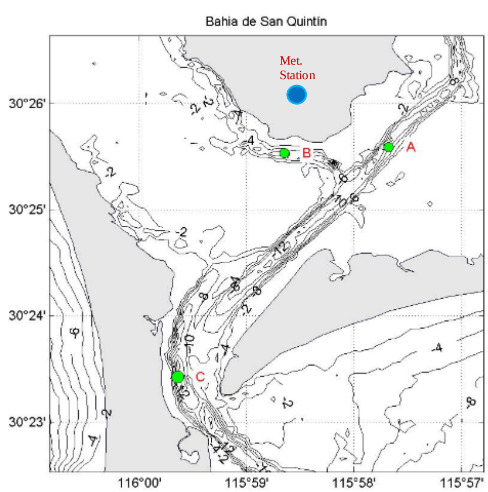

Figure 2.*ADCP's (green points) and meteorological station (blue point) locations.*

The simulation period was from 23-05-2004 up to 13-06-2004.

Comparisons between the measured and simulated series were performed based on the calculation of the following statistical parameters: Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and the correlation coefficient (R2) (Willmot, 1982).

Results

- *Calibration*

Results of the carried-out simulations for scenarios **a** and **b** satisfactorily represented the sea water level and the depth averaged velocity.

For sea water level, the three time series obtained at positions of the ADCP's were compared with those recorded data. The statistical parameters for the comparison of each scenario with the ADCP data are summarized in Table 1.

Table 1. *Statistical parameters obtained for water elevation comparing observed (ADCP) and simulated time series for scenarios **a** and **b** during calibration.*

ADCP	Scenario *a*			Scenario *b*		
	RMSE (m)	MAE (m)	R^2	RMSE (m)	MAE (m)	R^2
A	0.11	0.09	0.94	0.10	0.09	0.96
B	0.10	0.08	0.97	0.10	0.08	0.96
C	0.11	0.09	0.91	0.11	0.09	0.95

High correlation with measured data were found in both scenarios, however, for scenario **b** the R^2 showed a slightlyhigher value. Variability wind velocity over time and space is the second important force in this lagoon that interact with sea water level modifying locally the water velocity below it, as suggested by scenario **b** of this study.

The obtained statistical parameters for the depth averaged velocity of scenario **b** are summarized in Table 2. Although the time series obtained through the ADCP-B for sea water level did not show great inconsistencies, the measured data for the velocities were not reliable and their statistical parameters are not shown.

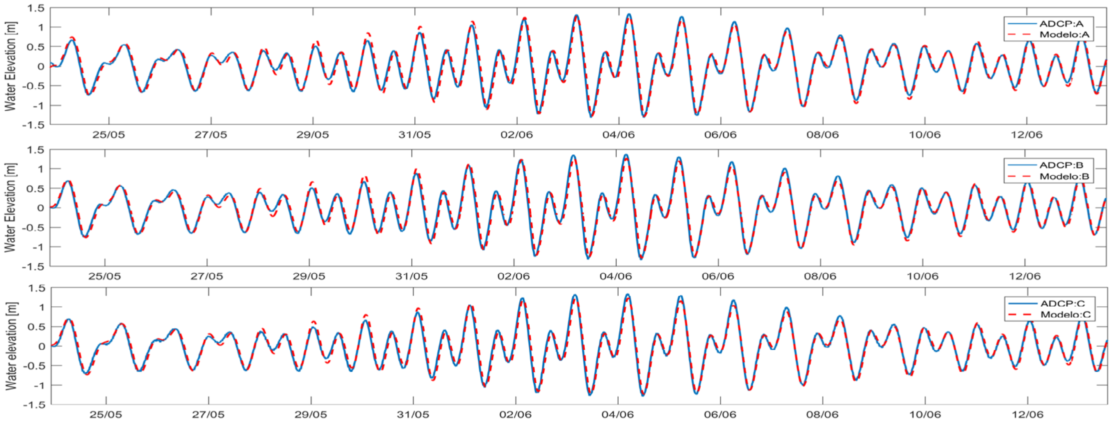

Figure 3. *Water elevation comparison between ADCP time series and the model results for Scenario* ***b****.*

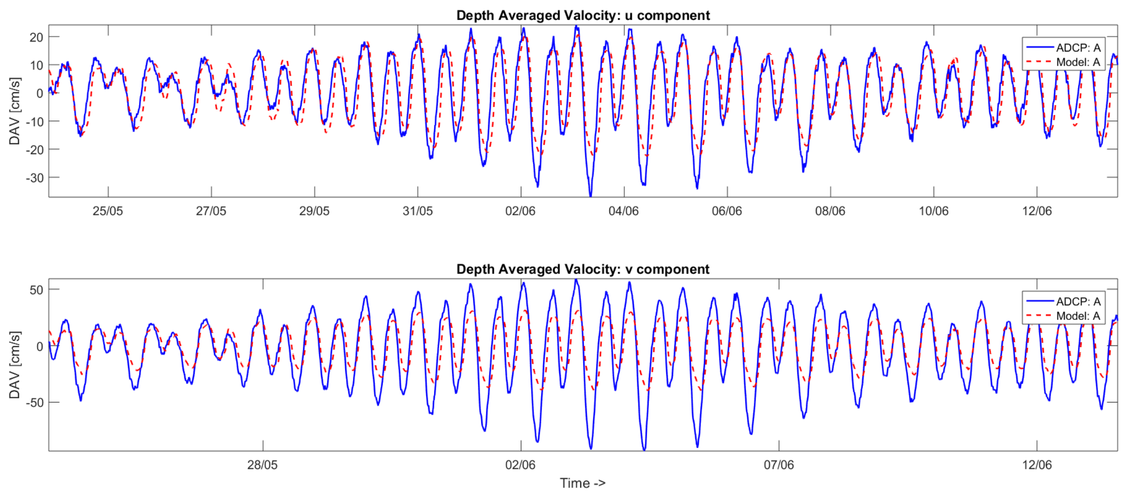

Figure 4. *Depth Averaged Velocity comparison between measured data (blue) and simulated data (red)*

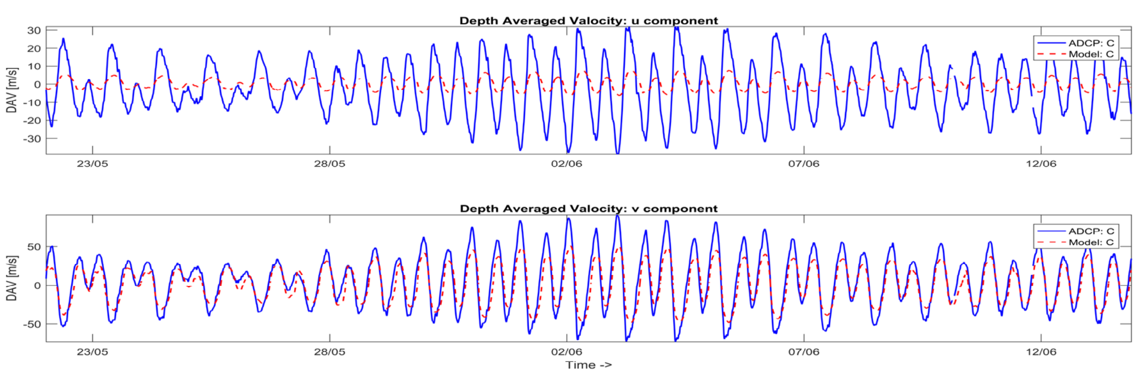

Figure 5. *Depth Averaged Velocity comparison between measured data (blue) and simulated data (red) for u and v components for point C.*

- *Hydrodynamics*

Results for the sea water oscillations and their related depth averaged velocities are presented below.

In figure 3 the time series of the sea water elevation collected by the three ADCP's and those obtained by the present work are shown. As it can be observed, the model results match the trend and dynamics of the observed data with a high correlation of 0.95 for all the case. A tidal range of 2.75 m was found during spring tide.

Examination of sea-level records shown that the interval from low to high water is shorter than the interval from high to low water: the rise time is more rapid than the fall.

The time series for the depth averaged velocities recorded by the ADCP-A and those obtained numerically in the present work are show in Figure 4. In general, the amplitude oscillation of the numerical velocity components is smaller than the measured one. Their amplitude differences along the time are greater during spring tide and are lower during neap tide, especially for the meridional velocity component.

For the depth averaged velocities time series in ADCP-A point, the mean values of the observed time series for the zonal and meridional velocity components were 10.2 cm/s and 26.4 cm/s respectively, while for the simulated time series the results were 10.4 cm/s for the zonal component and 17 cm/s for the meridional component.

The major difference between measured data by ADCP-A and those obtained numerically along the time is in the spring tide (01/06/2004 to 04/06/2004), with an underestimation of 1.2 cm/s for the zonal component and 15.5 cm/s for the meridional component, indicating an underestimation mainly during the ebbing in spring tide.

In contrast, during neap tides the behavior changes drastically, finding an overestimation for the zonal component of 6% average (1.6 cm/s), and an underestimation of the meridional component of 16% averaged (3 cm/s).

The model currents underestimation was probably due to poor understanding of the bottom shear stress parameterization for unsteady flow and the bottom roughness coefficient chosen to represent the greater atrium in the shallowest areas with vegetation. The increase in roughness and the blockage of water flow due to vegetation is an important factor influencing the flow velocities. This causes a notable characteristic of the hydrodynamics: the tide asymmetry and the dominance of the ebb currents.

As seeing from Figure 4, the amplitude of the measured oscillation of the meridional velocity is approximately twice the amplitude of the zonal velocity component, showing the influence of the flooded region with vegetation around ADCP-A. This behavior is not captured by the model that provides a result with practically equal amplitudes in agreement with the 45 degree alignment of the channel axis at the ADCP-A position.

The comparison for ADCP-C point, between the measured data and numerical one is showed in Figure 5. The time series shows an underestimation of model velocities that is much bigger for the zonal velocity component.

As happened for ADCP-A point, int the ADCP-C point an underestimation of the velocities for both components was obtained for the simulated results, once again, mainly during spring tides.

Although, in the simulated time series, the zonal component presented a 76.5% (10 cm/s) underestimation for the simulated series, this is small taking into account that the dominant component is the meridional one (*v)*, which presented an underestimation of just 7.4% (1.8 cm/s) when comparing simulated and observed time series.

The ADCP-C point registered higher currents than the ADCP-A point. This was because ADPC-C point is located in the mouth of the SQBL, where the higher currents are present, while ADCP-A point is located in the east arm (SQB), close to the main and deeper channel, but velocities are lower than those registered in the mouth.

In general, the simulations satisfactorily represented the local elevation and velocities, as indicated for R2 with values of 0.95 for elevation and 0.80 for currents.

In the times series obtained by the simulation, the magnitude of the velocity for both monitored points (ADCP-A and ADCP-C), it was observed that, in average, the values for spring tides were 63% higher than those for neap tides (over the simulated period).

Throughout the ebbing period, the flow follows the main channel and then forms a fan shaped flow field with the strongest currents observed at the west section of the estuary entrance. As the tide changes and the flooding starts, water propagates inwards mainly through the east section of the mouth. Inside the lagoon, the flow propagates mainly through the deeper channels. The large seagrass areas that covers the lagoon (except for the main channels), have an impact on the lower magnitude currents during flooding tide. After the mouth, the highest values are attained along the navigation channel, in particular, in the central portion of the constriction.

During the simulated period, a spring tide moment was identified, this in order to analyze the maximum values of currents, at the ADCP-C point. The Maximum Flood (MF) current at the mouth attains values close to 0.80 m/s, while for Maximum Ebb (ME) was close to 1 m/s (during spring tides). In general, it was found that the values for ebb currents were higher than those for flood currents.

Spring tides will be associated with higher current velocities in the main channels. While the maximum currents happened, the sea level is mean water level. The simulated results reported by Juárez (2014) for the currents were close to those found in the simulations carried on this work. Juárez (2014) reported the maximum currents in the mouth of the lagoon, with magnitude velocity values just above the 100 cm/s and lower velocities in the main channels of the lagoon, with a variation between 35 cm/s and 70 cm/s along the main channels, depending on the location of the point.

In the following figures two moments are plotted: maximum ebbing and flooding during spring tide. In the Figure 6, all the domain is in ebb tide with the highest velocities found in the mouth of the lagoon and in the Figure 7, all the domain is in flood tide with the maximum velocities also located in the mouth of the lagoon

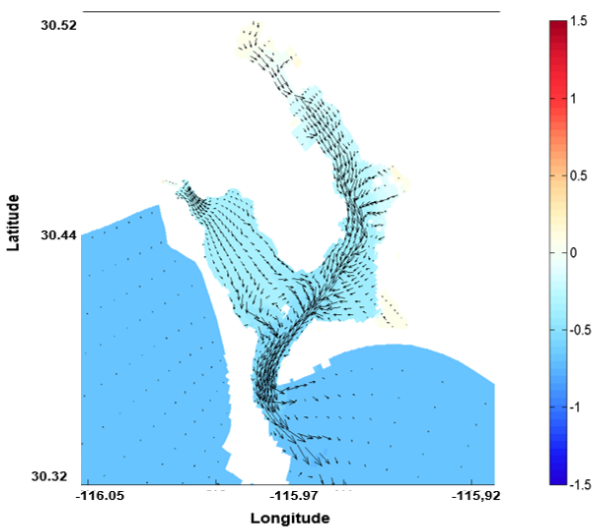

Figure 6.*The vectors show the velocity field and the colormap represents the water elevations for ebbing during spring tide.*

Conclusions

A 2DH hydrodynamic model was applied to the San Quintín Bay coastal lagoon (SQBL). The hydrodynamic model was evaluated for sensitivity between astronomical tide and wind, and subsequently validated with the time series for currents and water level. The model satisfactorily represented both sea level and velocities, obtaining large correlation coefficients and low values for errors (MAE and RMSE). The model results showed that is capable of reproduce the essential hydrodynamics in the San Quintín Bay Lagoon, and can be forced by the astronomical tide and wind.

The results of the simulations carried out, to assess the sensitivity of the hydrodynamic model, indicate that the forcement with the greatest influence on the elevations and currents in San Quintín Bay Lagoon is the astronomical tide.

The model results show that the Delft3D model is capable of reproduce the essential processes in the San Quintín Bay Lagoon. Delft3D in 2D mode was able to capture changes in water level with a high correlation with the data measured by three different ADCP's inside the lagoon.

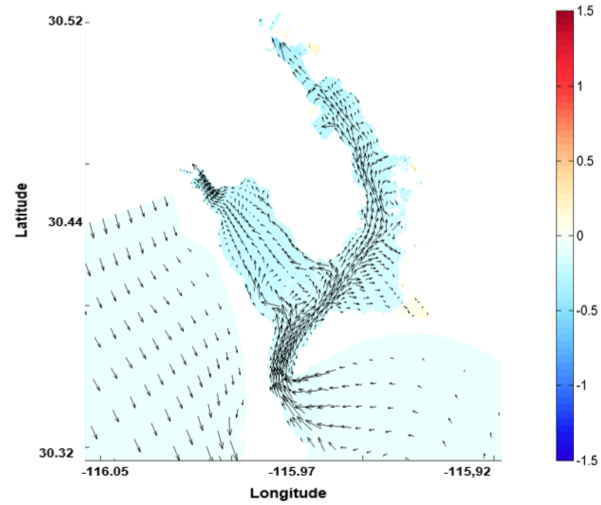

Figure 7.*The vectors show the velocity field and the colormap represents the water elevations for flooding during neap tide*

The statistical analysis of the errors corresponding to the time series for the sea level show a good performance of the model. The model follows the semidiurnal mixed regime.

For the velocities, in the ADCP-A point, the *v* component presented a higher correlation with the measured data than *u* component while for ADCP-C the opposite occurred. The maximum velocities for low and high tide are observed in the deepest sections of the lagoon, following the main deeper channels. The highest flow intensity is observed during the ebb tide, while during the flood tide the magnitude velocity appears to be lower.

This model was used to create an understanding of the hydrodynamics and could be used as a basis for future investigations that involve sediment transport and water quality. It is paramount to be able to predict the consequences and effectiveness of the alternatives as accurately as possible, thus incorporating this information into decision making.

References

Abbott, M., Price, W. (1994). Coastal, Estuarial and Harbour Engineers Reference Book. [S.l.]: [s.n.].

Comisión Nacional del Agua (México, Baja California). Servicio Meteorológico Nacional. Catálogo de Estaciones. México, 2004. Avaliable in:
http://smn1.conagua.gob.mx/emas/catalogo/SQNBN.html. Acceso: 20 ago. 2019.

Delgado O., Marvan, F., Mejia, A. and Gil, E. (2012). San Quintin Lagoon Hydrodynamics Case Study. Water Resources Management and Modelling. pp 127–144.

Farreras, S. (2004). Hidrodinámica de Lagunas Costeras. Ensenada. Ed. CICESE, 193 p. v. 1.

Gerritsen, H., De Goede, E., Platzek, F., Van Kester, J., Th.M., Genseberger, M., Uittenbogaard, R. (2004). Validation Document Delft3D-FLOW: A software system for 3D flow simulations. Delft. Ed. Deltares.

Juarez, T. (2014). Influencia de remolinos y procesos de mezcla en el intercambio de agua entre una laguna y el mar abierto, Bahía San Quintín, Baja California, México. Ensenada: [s.n.].

Willmot, C. (1982). Some Comments on the Evaluation of Model Performance. Bulletin of the American Meteorological Society, v. 63, p. 1309- 1313.