International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:11, No:3, 2017

Sediment Transport Monitoring in the Port of Veracruz Expansion Project

Francisco Liaño-Carrera, José Isaac Ramírez-Macías, David Salas-Monreal, Mayra Lorena Riveron-Enzastiga, Marcos Rangel-Avalos, Adriana Andrea Roldán-Ubando

***Abstract*—**The construction of most coastal infrastructure developments around the world are usually made considering wave height, current velocities and river discharges; however, little effort has been paid to surveying sediment transport during dredging or the modification to currents outside the ports or marinas during and after the construction. This study shows a complete survey during the construction of one of the largest ports of the Gulf of Mexico. An anchored Acoustic Doppler Current Velocity profiler (ADCP), a towed ADCP and a combination of model outputs were used at the Veracruz port construction in order to describe the hourly sediment transport and current modifications in and out of the new port. Owing to the stability of the system the new port was construction inside Vergara Bay, a low wave energy system with a tidal range of up to 0.40 m. The results show a two-current system pattern within the bay. The north side of the bay has an anticyclonic gyre, while the southern part of the bay shows a cyclonic gyre. Sediment transport trajectories were made every hour using the anchored ADCP, a numerical model and the weekly data obtained from the towed ADCP within the entire bay. The sediment transport trajectories were carefully tracked since the bay is surrounded by coral reef structures which are sensitive to sedimentation rate and water turbidity. The survey shows that during dredging and rock input used to build the wave breaker sediments were locally added (< 2500 m^2) and local currents disperse it in less than 4 h. While the river input located in the middle of the bay and the sewer system plant may add more than 10 times this amount during a rainy day or during the tourist season. Finally, the coastal line obtained seasonally with a drone suggests that the southern part of the bay has not been modified by the construction of the new port located in the northern part of the bay, owing to the two subsystem division of the bay.

***Keywords*—**Acoustic Doppler current profiler, time series, port construction, construction around coral reefs, sediment transport monitoring.

I. Introduction

COSTAL infrastructures around the world are usually made with no previous studies of the area. Therefore, the modifications made to the surrounding waters are not described during the project construction planning phase. Coastal protection structures and landfill gains to the ocean around the world are made to preserve coastal line modifications [1] from its natural changes. The construction of groynes, jetties and water breakers used to preserve the actual coastal line, interfere with the natural sediment and plankton littoral transport modifying the sediment budgets and/or the high productivity areas in some places [1], [2]. Those places are usually located outside the construction areas where most contractors and governmental agencies do not pay attention. Therefore, most of the modifications to the coastal line, budget sedimentation and high productivity areas of its surrounding waters, are not reported or are neglected during the construction process.

In some cases, coastal structures are built in order to prevent erosion from landfill areas, coral reef structures or to avoid accretion of navigational channels and dredging areas; however, most of those structures modify the coastal dynamics, which in some cases may increase the desolation of some grassland areas or reef structures [3], but in others they may generate new coral reef areas, especially with the new artificial coral reef structures. Coral reef areas located in the vicinity of river discharges, ports or water treatment plants are usually subjected to high stress owing to the sedimentation rate, values over 25 mg cm^{-2} d^{-1}, cause mortality in most coral species [4].

This study reports the results of a monitoring program related to the expansion project of the port of Veracruz, Mexico, located on the western side of the Gulf of Mexico. The importance of the monitoring program survey is because the new port is surrounded by a national park, the Veracruz Reef System [5], which is a healthy ecosystem, despite the number of drainage of anthropogenic sources coming from the city of Veracruz. The series of data used within the survey varies from acoustic Doppler current velocities profilers (ADCP) data, to a series of model outputs which allowed for a quick response to any possible ecosystem damage coming from the dredging or rock dumping due to the construction of the new port of Veracruz.

II. Material and Methods

A series of Acoustic Doppler Current Profiler (ADCP) of 300 kHz were deployed in Vergara Bay, Mexico (Fig. 1) in order to describe the sediment trajectories during the dredging period. The ADCP was calibrated in order to obtain a direct correlation between the backscatter and the sediment particles located within the bay, the calibration was made following the methods reported by [6]

$$Log\,[Sed\,(mg\,/\,m^3)] = 6.253 + 0.048\,AAI\,(dB) \tag{1}$$

Francisco Liaño-Carrera is with the Administración Portuaria Integral de Veracruz. Gerencia de Ingeniería. Veracruz, México (e-mail: flcarrera@puertodeveracruz.com.mx).
José Isaac Ramírez-Macías, Marcos Rangel-Avalos, and Adriana Andrea Roldán-Ubando are with the Argo Consultores Ambientales. México Universidad Veracruzana, Veracruz, Mexico.
Mayra Lorena Riveron-Enzastiga is with the Noordwijk International College Veracruz, Veracruz, Mexico.

where *Sed* is the dry weight sediment obtained at 100 points within the bay and *AAI* is the absolute acoustic intensity obtained with the ADCP at the same point and depth as the sampling points taken with a Nansen bottle.

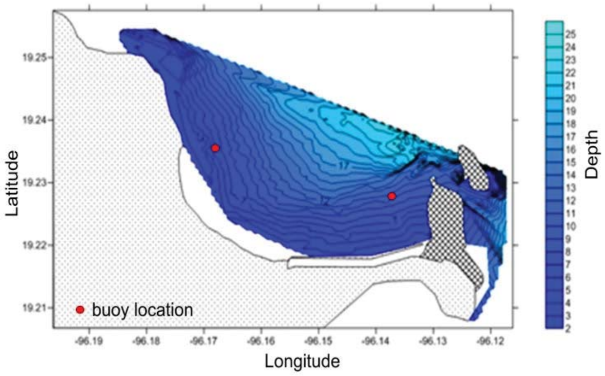

Fig. 1 Bathymetry and localization of the buoys within Vergara Bay, Mexico; the two squared areas represent two coral reef systems

The buoy was located in the western side of the bay before the construction of the new port of Veracruz. The data were used to obtain the average values of suspended sediments in the water column, as well as the velocity and temperature during the month prior to the construction of the new port of Veracruz (Table I).

TABLE I
VELOCITY, TEMPERATURE AND SEDIMENT VALUES BEFORE THE CONSTRUCTION OF THE NEW PORT OF VERACRUZ

	Date			Average value
	06-May-15	19-May-15	25-May-15	
Velocity (m/s)				
East-west	0.19	-0.36	-0.99	-0.39
North-south	-1.13	1.49	0.55	0.30
Temperature (°C)				
Minimum	26.91	26.87	27.55	27.11
Average	27.31	28.16	28.11	27.86
Maximum	28.50	29.48	28.78	28.92
Sediments (dB)				
Minimum	67.97	66.75	66.39	67.04
Average	71.22	70.56	70.77	70.85
Maximum	76.34	77.41	76.96	76.90

According to the data using a 24 h period, the sediment particles values located within the sediment column do not exceed 80 dB. Therefore, this was the value used as a limit value during the dredging periods. The temperature of the bay during the month of May 2015 was almost constant; however, there was a 2 ºC difference from day to night owing to solar irradiation. The water velocity values suggested a highly energetic system with velocities over 0.5 m/s, those values are important since most of the nets used to contain sediments during coastal infrastructure developments are built to support currents of up to 0.5 m/s. Therefore, the idea of an alert system using a series of buoys in order to avoid any possible damage to the adjacent coral reef areas was implemented. This problem should not be exclusive to the Gulf of Mexico, in areas such as the North Sea, the Mediterranean Sea or Chesapeake Bay (US) among others, currents should exceed 0.5 m/s during high tide or low tide faces [7].

Finally, using the Regional Ocean Model System (ROMS), which uses three dimensional primitive equations [8] with sigma coordinates in order to increase the vertical resolution, a series of daily recommendations were made base on the tidal time and tidal ellipses [9]. All the information was used to prevent any ecological contingence generated by the dredging or rock input during the construction of the new port of Veracruz.

The coastal line was also obtained using a drone in order to observe any possible modifications associated with the coastal infrastructure development. The adjacent coastal area to the new port of Veracruz was depicted seasonally (dry and cold front season), the main idea is to describe the natural modification of the coastal line during the seasons and any possible modification to those dynamics observed during the construction process or even after the inauguration of the new port. All those efforts are made in order to preserve the adjacent ecosystem as intact as possible and to provide useful data to those governmental agencies in the case of any possible contingence before, during and after the construction of the port.

III. RESULTS AND DISCUSSIONS

The results from the buoy shown at three different depths were used as follow; when the equivalent decibels to sediment reached 140 dB, using (1), but reported in decibels in this study owing to range size and color scale, showed a peak at the three chosen levels, the alert system reported the event regardless of the time of the event. The three different depths were chosen as follows: the first depth (2.5 m depth) represents the surface water layer, the second depth (5.5 m depth) represents the pycnocline depth, which ranged from 4.5 m to 6 m depending on the tidal stage, and finally, the third depth (7.5 m depth) represents the bottom layer depth. As shown in Fig. 2 when the three picks (2.5 m, 5.5 m and 7.5 m depth) reaches more than 140 dB, the system gives an alert in order to track any possible ecological contingence. Not all peaks will imply a contingence, when the surface peak reaches more than 140 dB before the other peak depths, the report will indicate an increase in the water treatment plant outputs or a heavy rainy period. The reason for this consideration was that most of those peaks will usually not increase the decibel report at the bottom layer, as could be observed for December 1st, 2015, when a heavy rain period was observed. The increase of sediments and suspended particles coming from the city drainage may stress the adjacent coral reef colonies, however, those colonies have been adversely affected by this problem since 1519 [5], [10] which coincides with the foundation of the City of Veracruz. This could be one of the causes of the increase bacterial beaching and mortality in the platform coral type. The second alert is given when the bottom layer decibels peak reaches to more than 140 dB before the surface peak, this was assumed to be produced when the rock was poured in the water breaker line or during dredging. When those peaks occurred, the towed ADCP data are analyzed in order to determine the affected area. Once the decibels values from the moored buoy reached 180 dB or more, as a vertical average using the data of the three depths, the system alert suggests the contractor in charge of the dredging and/or of the rock shedding, halt their activities. Finally, the water velocity values obtained at the three depths are been used to identify periods of strong wind events. When the cold fronts show up (locally called northern) the maneuvers stop, but the surface sediment budget registered in the water column increase. Those events are also reported by the survey system.

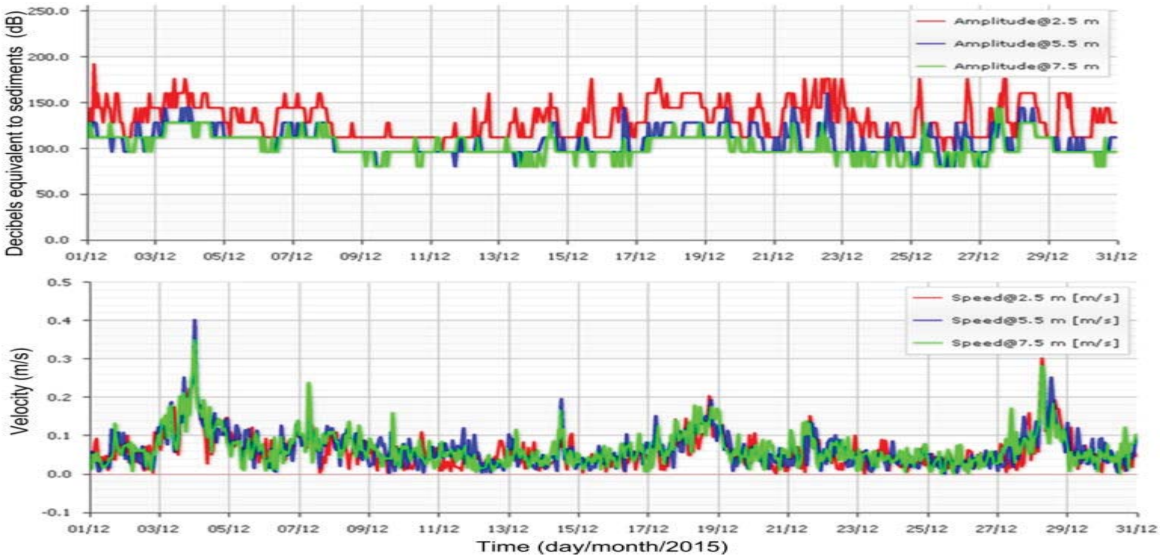

Fig. 2 The upper panel shows the decibel amplitude of the moored ADCP at the three different depths, while the lower panel shows the current velocity at the same depths during December 2015

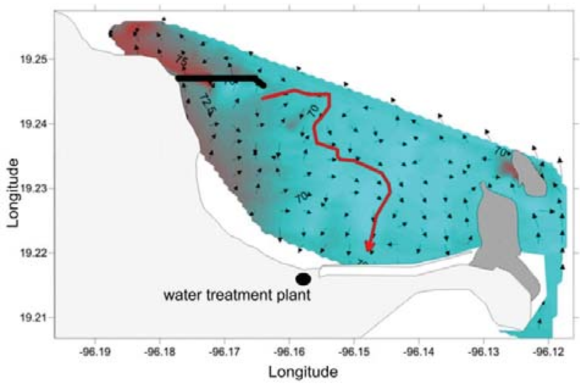

Fig. 3 Vergara Bay: the water breaker as a black line in the northern side of the bay, the two coral reef colonies in gray color in the southern part of the bay and the water treatment plant location. The contours represent the decibels values (dB) obtained from the towed ADCP, the black arrows are the water velocities within the bay and the red arrow represent the trace vector of the sediment particles coming from the water breaker end side, where rocks are dropped

The towed ADCP has usually been used to describe high productivity areas [5], [6], [11]; however, using the method reported by [6], the decibels outputs where calibrated to estimate the sediment amount within the water column. The ADCP has been towed weekly in order to elucidate any possible change on the water column. Current velocities, sediment concentration reported in dB, temperature and the bathymetry are obtained weekly. As shown in Fig. 3, for May 27th, 2016, the decibel scale of the towed ADCP varies from 60 dB to 75 dB, the highest values were found in the northern side of the water breaker, this is mainly due to the current pattern which concentrates most of the suspended particles in this particular area. The tracer vector (represented with a red arrow) suggested that from the place where most of the dropped rocks are poured, its joined sediment particles will move toward the coastal line located southerly from the water breaker. Therefore, those particles should not move seaward toward the reef areas.

The most common current pattern observed at Vergara Bay is the division of the bay in two, due to current dynamics, as could be observed during the sampling performed on April 27th, 2016 (Fig. 4). The bay was clearly divided in two by a current front located perpendicular to the place where the water treatment plant is located. This feature favors the coral reef location from getting stressed by sediments coming from the manipulation of the new port. As could be observed, most of the sediment emanating from the dredging area will be accumulated at the coastal line on the western side of the bay. This is an area that will eventually be filled in, in order to be used as a deck. The second place, the area where the rocks are dropped, has a high value of suspended sediments, as could be observed in Fig. 4, the red square located at the dredging side of one of the red arrows is constant, implying that most of the sediments will not leave this area. The place where the rocks are dropped generates a high suspended sediment area, due to resuspension from rock deposition and to the added sediment coming from rocks' mud. This area is usually around 2,500 m^2 long and is deposited again in less than 4 h due to the grain particle size.

In general, the suspended particles do not exceed 75 dB, and the only places where those values exceed 80 dB are those places where the rocks are being dropped, or in some cases, the dredging areas. In those cases the survey system creates an alarm when three conditions are met; the decibel values exceeds 80 dB as an average in the water column, the area where the decibel value exceeds 80 dB is greater than 10,000 m^2, and the duration of the event exceeds 4 h, under these circumstance the survey system suggests the contractor of the activities where the event is occurring (drop rock and/or dredging) to halt works until the level of suspended particles (sediments) decreases to values below 80 dB in an area under 2,500 m^2.

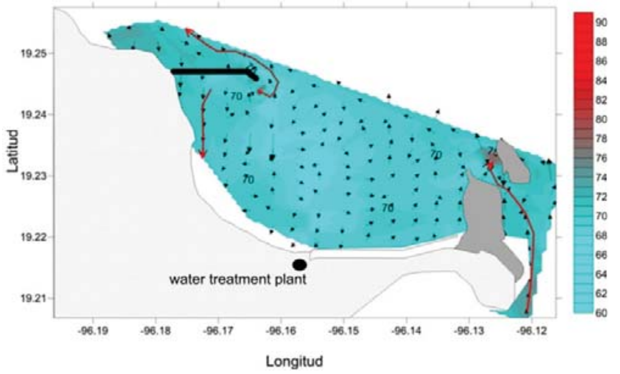

Fig. 4 Vergara Bay; the water breaker as a black line in the northern side of the bay, the two coral reef colonies in gray color in the southern part of the bay and the water treatment plant location. The contours represent the decibels values (dB) obtained from the towed ADCP, the black arrows are the water velocities within the bay and the red arrow represent the trace vector of the sediment particles coming from the water breaker, where rocks are dropped, the dredging area in the inside part of the water breaker and from the old port of Veracruz, at the bottom left side of the figure

When the rocks are dropped from a vessel the survey system supervise the maneuvers using a towed ADCP. The towed ADCP made circles concentrically from the shedding area until a radius of at least 500 m in order to elucidate any possible increment of the suspended particles. As could be observed in Fig. 5 after the rocks were dropped from the vessel the suspended particles values increase, most of the vertical averaged values in the area exceeds 80 dB, however, as it could be observed the area is punctual and the 80 dB do not stay for more than 4 h; therefore, the survey system did not suggest the constructor halt activities. The trace vector suggested that most of the suspended particles will move southwesterly, depositing in the coastal area located in the western side of the bay. Those particles will not stress the coral colonies located in the southern part of the bay, but they still need to be monitored in case the currents changes owing to the tidal stage.

In addition, the towed ADCP and the buoy system, a drone usually fly every time the ADCP is been towed. The objective of the drone is to visually describe the areas where the water changes color and all the places the sediments are been concentrate. One of the advantages of using a drone is the availability of the photos and videos during the dredging periods and when the vessel dropped the rocks, allowing us to describe the sediment plume and the origin of such plume, paying special attention to the areas located near the reefs and water breaker. Other advantage of the drone is the availability to provide the area where the sediment concentration is located. Those areas are used to confirm if the plume exceeds the 10,000 m^2 considered as a critical value.

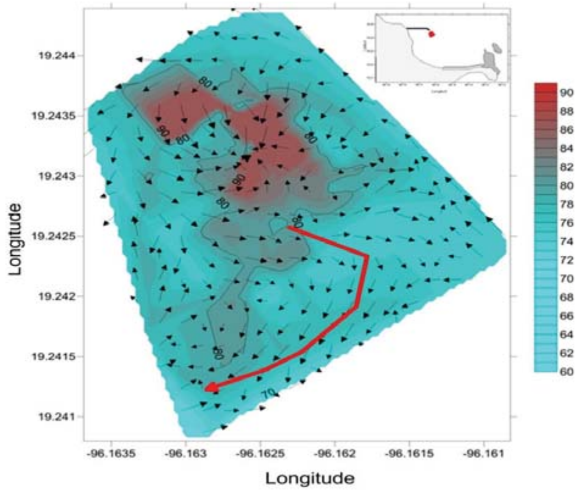

Fig. 5 The area after a vessel dropped rocks in order to continue the water breaker line. The contours represent the decibels values (dB) obtained from the towed ADCP, the black arrows are the water velocities within the bay and the red arrow represent the trace vector of the sediment particles coming from the water breaker, where rocks are dropped, the dredging area in the inside part of the water breaker and from the old port of Veracruz, at the bottom left side of the figure

Using the forecast model outputs, based on tidal amplitude and phases and reinforced using the reanalysis data obtained with the weekly towed ADCP data, a third survey method was applied to the coastal infrastructure development. Tidal current velocity data are used to describe the day and time of inflows and outflows during a diurnal tidal cycle. When the predicted currents suggest that the tracer vector will move all suspended particles from the manipulated areas to the coral reef colonies and southeastward toward the Veracruz Reef System (a coral reef national park), the period of time is reported as not favorable for the maneuvers (Table II). This will not imply that the contractor should halt activities, but instead a close survey to the dredging areas and rock vessel trajectories should take place. On the other hand, the period of time when the tidal current velocities suggest that the suspended particles within the water column will move toward the coast inside the bay, will be reported as favorable time. The favorable time is pretty much assumed when all sediment and suspended particles will arrive to the coast in places where the dock is built, since those will eventually be landfill areas gained to the sea. All the other periods of time are not reported as favorable or not favorable, since the trace vector will move the suspended particles within the water column to other places, however, the trajectories will still be monitored.

TABLE II
EXAMPLE OF THE FAVORABLE AND NOT FAVORABLE HOURS DURING THE FIRST 15 DAYS OF DECEMBER, 2015

December	Not favorable hours	Favorable hours
1	12-18	0-12
2	12-18	0-12
3	12-18	0-12
4	15-24	0-6
5	6-12	0-6
6	6-12	0-6
7	6-15	0-6
8	6-15	0-6
9	6-15	0-6
10	6-15	0-6
11	6-15	0-6
12	6-15	0-6
13	12-18	0-12
14	12-18	0-12
15	12-18	0-12

Using all the above data, a general table was constructed describing the number of events that exceeds the 140 dB, as a vertical average obtained from the buoy (Table III). Every time an extreme event of sediment concentration was reported by the buoy with the duration of one hour, it was reported as an extreme event. Once four consecutive events were reported, i.e. four consecutive hours with values over 140 dB, with an area of at least 10,000 m^2 obtained via the drone and the towed ADCP the alert was sent to the constructors. As it could be observed in Table III, some months reported more than 30 events; this is due to the fact that each event represents one hour of high decibel values (> 140 dB) and not one day (24 h). The month of August had several events with a high sediment particle concentration, those events are mainly due to strong rain events observed during August and September. Those events are mainly attributed to city drainage and to river discharges from adjacent rivers. There are two rivers near the bay, the first river (Jamapa River) is located 18 km southward from the bay and the second river (La Antigua River) is located 15 km northward from the bay. The other peaks were observed during December 2015 and January 2016. Those picks correspond to northern events (cold front events), which re-suspends the seafloor sediments. Those events show high concentration levels of suspended sediments within the water column due to bottom resuspension and to near surface sand added owing to the wind. The strong winds disperse most of the sand from the sand dunes located in the coastal area near the bay (< 5 km). During the dry season no high concentration of sediment events were reported by the buoy, this is mainly due to the absence of strong winds and no rain during this period.

TABLE III
THE MOST REPRESENTATIVE dB VALUE OBTAINED MONTHLY AND THE NUMBER OF EVENTS THAT EXCEEDS 140 dB. EACH EVENT IS SUPPOSED TO LAST ONE HOUR

month (2015-2016)	Suspended particles mode (dB)	number of events over 140 dB
July	128	2
August	144	21
September	128	19
October	128	2
November	128	7
December	144	34
January	112	22
February	112	5
March	112	7
April	112	7
May	112	0
June	112	0

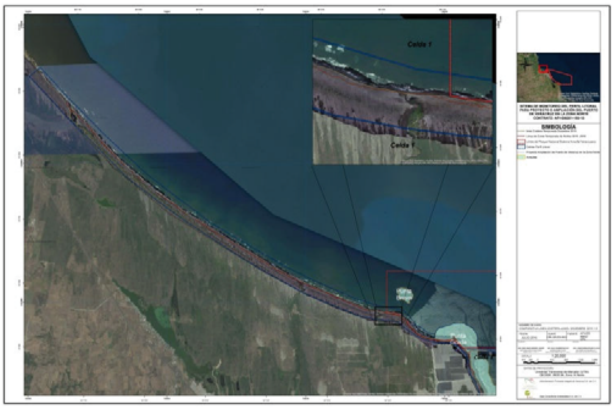

Fig. 6 Coastal line during the northern (cold front) season represented with a red line and during the dry season represented with a red line, the construction area of the new port is located in the bay inside the red square at the bottom right side

Finally, the costal line from the northern season to the dry season was compared at the northern side of the construction area. The coastal line from the northern end area of the new port facilities (represented with a black square) to the northern end of the sampled area (upper left side of Fig. 6) shows accretion of the beach, this was mainly due to the absence of the winds that erode the sandy beaches. South of the construction area is considered as an erosion area. Most of the sandy beaches located in the touristic area of the city are artificial beaches, refilled with sand trucks coming from the nearby dunes.

IV. CONCLUSION

The new Port of Veracruz, Mexico is under survey from a series of monitoring systems that have previously not been implemented before at the same time. A series of buoys, towed acoustic Doppler current profilers (ADCP), sediment meshes, a drone and several temperature and conductivity sensor devices were implemented in order to avoid any possible ecological contingence within the area. The moored instruments report data every 10 minutes, while the towed

ADCP instrument and the drone report data were recorded twice a week within the bay. One of the most important findings is the flow dynamics which naturally divide the bay in two subsystems, and which enhance most of the sediments generated at the manipulation areas in the northern side of the bay to stay in this area. The natural division of the bay favors the conservation of the reefs, since most of the coral reef areas are located in the southern part of the bay. Therefore, the sediments generated in the northern bay area should not affect them on a regular basis. The survey system strategy implemented in the construction area of the new Port of Veracruz prevents any sediment plume from harming or stressing the coral reefs due to the construction of the port.

Acknowledgment

The authors would like to acknowledge the help of all the scientist and technicians how helped during the different stages of data collection, analysis and reports. Thanks also go to the Port Authority of Veracruz (Administracion Portuaria Integral) for the implementation of new survey techniques during the construction of the Port of Veracruz.

References

[1] B. Cisin-Sain, S. Belfiore, "Linking marine protected areas to integrated coastal and ocean management: a review of theory and practice". *Ocean Coast Manage* 48: 847-868, 2005.

[2] T. Hsu, T. Lin, I. Tseng, "Human impact on coastal erosion in Taiwan". *J Coast Res* 23:961-973, 2007.

[3] R.J. Maharaj, "Monitoring and control of coral reef dredging in Pacific Small Island" *SOPAC Miscellaneous Report* 404, 2001.

[4] M.A. Rangel-Avalos, L.K.B. Jordan, B.K. Walker, D.S. Gilliam, E. Carvajal-Hinojosa, R.E. Spieler, "Fish and coral reef communities of the Parque Nacional Sistema Arrecifal Veracruzano (Veracruz Coral Reef System National Park) Veracruz, Mexico: preliminary results". *Proc Gulf and Caribb Fish Inst* 60:427-435, 2008.

[5] D. Salas-Monreal, D.A. Salas-de-León, M.A. Monreal-Gómez, M.L. Riverón-Enzástiga "Current rectification in a tropical coral reef system" *Coral Reefs* DOI 10.1007/s00338-009-0521-9, 2009.

[6] D. Salas-Monreal, D.A. Salas-de-Leon, M.A. Monreal-Gomez, M.L. Riveron-Enzastiga, E. Mojica-Ramirez "Hydraulic jump in the Goulf of California" *Open Journal of Marine Science*, Pag.1-9, 2012.

[7] D Salas-Monreal, A. Valle-Levinson, "Continuously stratified flow dynamics over a hollow" *Journal of Geophysical Research – oceans* (doi:10.1029/2007JC004648), Vol.114, 2009.

[8] M.A. Monreal-Gomez, D.A. Salas-de-León, "Simulación de la Circulación en la Bahía de Campeche," *Geofisica Internacional*, Vol. 29, 1990, pp. 101-111, 2010.

[9] J.J. Salas-Pérez, D. Salas-Monreal, M.A. Monreal-Gómez, M.L. Riveron-Enzastiga, C. Llasat, "Seasonal aabsolute acoustic intensity, atmospheric forcing and currents in a tropical coral reef system" *Estuarine, Coastal and Shelf Science* (DOI 10.1016/J.ECSS.2012.01.002), Vol.3, Pag.1-11, 2012.

[10] O. Gallegos, A. López. "Fragmentación y segregación en el espacio litoral-urbano: el caso del corredor turístico Veracruz-Boca del Río". *Estudios multidisciplinarios en turismo*. Volumen 1. Secretaría de Turismo. ISBN 978-968-814-111-3. P. 139-174, 2006

[11] I.C. Chacon-Gomez, D. Salas-Monreal, M.L. Riveron-Enzastiga "Current pattern and coral larval dispersión in a tropical coral reef system" *Continental Shelf Research* (DOI: 10.1016/J.CSR.2013.08.014), Vol.1, Pag.1-14, 2013.