A STUDY OF ENVIRONMENTAL REMEDIATION OPTIONS FOR LAKE MARACAIBO, VENEZUELA

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Abstract: A study was conducted to evaluate different environmental remediation options for Lake Maracaibo in Venezuela. Lake Maracaibo is the largest lake in South America, and communicates with the ocean through the Strait of Maracaibo and Tablazo Bay. Under favorable tidal, river flow and other conditions, salt water flow from the ocean intrudes into the Lake contributing to elevated salinity levels, varying between 3 and 5 psu at the surface, and up to 11 psu at the bottom. High nutrient loads from the rivers discharging in the Lake are the major source of the eutrophication of the Lake. The combination of high organic matter concentrations and density stratification lead to anoxic conditions in the hypolimnion. The objectives of the study included a compilation of the existing knowledge about the source of the major environmental problems of the Lake, collection of additional environmental data, and develop analytical modeling tools that would allow the evaluation of alternative remediation strategies.

Keywords: Lake Maracaibo, stratification, eutrophication, anoxic hypolimnion, remediation

1 INTRODUCTION

This is the first in a series of five papers describing different aspects of a recent study on the environmental remediation of Lake Maracaibo. The study, supported by Petroleos de Venezuela SA (PDVSA), had as specific objectives to synthesize the existing knowledge about the source of the major environmental problems of the Lake, collect additional environmental data, and develop analytical modeling tools that would allow the evaluation of alternative remediation strategies. Because of the direct impact of different options involving changes to the present navigation channel on the on-land facilities serving the oil and other industries, the study also included an analysis of alternative pathways to maintain the transport of oil, coal and general merchandize. On the water quality side, one of the many issues addressed was the role of salinity and stratification on the overall environmental quality of the Lake. A basic question posed repeatedly over the years is whether reducing the salinity of the Lake would help reduce nutrient levels, increase dissolved oxygen concentrations in the Lake, and improve the overall environmental quality of the Lake.

The present paper provides general background information and an overview of the study, while subsequent papers describe the specifics of the field program and the numerical models developed in the context of the study.

1.1 The lake maracaibo system

Lake Maracaibo, located in western Venezuela, is the largest lake in South

America and a water body of great economic and ecological importance. The Lake Maracaibo area is the largest oil production center in Venezuela. The Lake is about 160 km long in the north-south direction and 110 km wide in the east-west direction, and has an area of about 12,000 km^2, a maximum depth of 30 m, and a volume of 300 10^9 m^3. It is connected with the Gulf of Venezuela through the Strait of Maracaibo and Tablazo Bay. Several rivers flow into the Lake draining a watershed of approximately 89,000 km^2, the largest of which is the Rio Catatumbo accounting for close to 60 percent of all fresh water flow into the Lake. The mean fresh water flow from all rivers draining in the Lake is about 52 10^9 m^3 per year, or about one sixth of the Lake volume. River flows vary also seasonally, being highest in May, and in October-November, and lowest during the January-March dry season. Flows also vary from year to year. During a 19-year period (1976-1990) for which there are systematic estimates of the total river flow into the Lake, the monthly flows varied between 0.3 and 2.7 times the mean flow for that period (CGR, 1993). Fresh water coming into the Lake from the rivers mixes with its surface waters and an equal volume of water leaves the Lake through the Strait.

Tidal action in combination with several other factors brings saline water from the Gulf of Venezuela into Tablazo Bay and the Strait of Maracaibo. The extent of the salt wedge intrusion entering the system depends on the combination of several factors, which, besides the tides, include the rate of fresh water flow into the Lake, wind direction and speed, and atmospheric pressure distribution. Under low river flow conditions, combined with favorable wind and barotropic conditions at the entrance to the system, the salt wedge can advance to the south end of the Strait of Maracaibo, and from there to the bottom of the Lake. This process raises the salinity of the Lake, especially in the hypolimnion, and contributes to its density stratification.

The environmental condition of the Lake is a function of the combination of several natural and anthropogenic factors contributing to its advanced eutrophication state. The high primary production is the source of large quantities of dead organic matter settling to the bottom of the Lake. Algae, zooplankton and higher forms of aquatic life when they die settle at the bottom of the Lake, where they decompose consuming all available oxygen. This, in combination with the stratification of the Lake, which prevents oxygen transfer to the hypolimnion, leads to anoxic conditions below the pycnocline, which acts as a barrier to vertical oxygen transport.

The environmental condition of the Lake has also been affected by sewage and industrial discharges, which cause locally unsanitary conditions and contribute to the nutrient load of the Lake. However, the bulk of nutrients coming into Lake Maracaibo is from the rivers flowing into the Lake. The nitrogen and phosphorous in the river inflows is generally in particulate form. In their particulate forms, from river inflows and as organic detritus from primary production, nutrients enter the saline hypolimnion through sedimentation. Within the hypolimnion bacteria break down the organic nitrogen and phosphorus forming ammonium and dissolved reactive phosphorus respectively. The persistent anoxic conditions in the hypolimnion lead to the denitrification of nitrates and the release of phosphate from the sediments into the water column.

Because the thermal stratification of the Lake is relatively weak, the salinity stratification is the main contributor to the density stratification of the Lake and is viewed by many as the primary source of anoxic conditions in the bottom. Because the return of the bathymetry of the system to the conditions prior to dredging of the navigation channel has been the subject of considerable debate, it is important to consider the relatively few early studies of the system, which provide valuable insights into the conditions of the system prior to the construction of the channel.

Gessner (1954) observed in 1953 that Lake Maracaibo is one of the productive systems in the world. Redfield et al. (1955) reported some of the earliest systematic water quality data in the Lake. The nitrogen and phosphorus levels reported in these studies are comparable to those observed subsequently. Also, Gessner reported the existence of anoxic conditions in the hypolimnion prior to the deepening of the navigation channel, when the salinity of the lake was lower, and at a time that the lake was isohaline. According the to Redfield and Doe (1964) the thermal stratification was enough to cause anoxic conditions in the hypolimnion. Specifically they observed that in September 1956, *"when the lake was isohaline, the deep water was again anoxic. The thermal stratification which had developed during the summer apparently stabilized the water sufficiently to allow the anoxic condition to develop"*.

As already mentioned, the construction of a deeper navigation channel facilitated the flow of denser salt water into the Lake and led to a gradual increase of the salinity of the Lake, until the system reached a new dynamic equilibrium for the system. Over the last forty years the increase in the salinity of the Lake has been the subject of concern and the subject of many studies. The salinity of the Lake varies from year to year primarily in response to hydrologic conditions, increasing in dry years and decreasing during wet years. In general, surface salinities are vary between 3 and 5 psu and bottom salinities can be as high 11 psu.

Lake Maracaibo has been the subject of many studies over the last forty years. Besides the already mentioned work by Redfield, other examples of significant contributions to the subject are the work by Battelle (1974), Parra Pardi (1979), Herman de Bautista (1997) and Rodriguez (2000).

1.2 Environmental restoration options

Some of the environmental problems of the Lake have quite obvious solutions, like for example point source control and watershed management to reduce the of nutrient and BOD load coming into the Lake, and the control of toxic pollutant discharges into the Lake system.

The potential environmental restoration measures can be can be classified as:

- Engineering options involving physical changes in the Lake system through changes in its bathymetry and the construction of special works. The main objective of various engineering options proposed over the years was to reduce the salinity of the Lake, reducing thus its density stratification and affecting water quality.

- Management options that include point source control and watershed management. The management options aim primarily at reducing the nutrient loading of the Lake, as well as various pollution discharges.

These two types of options can of course be pursued in parallel.

The focus of most of the remediation schemes proposed over the last forty years, has been the reduction of salt-water intrusion into the Lake. Such schemes ranged from the construction of various engineered structures designed to block salt-water intrusion by isolating the Lake system from the Gulf of Venezuela, to the abandonment of the dredged navigation channel and return of the system to its natural condition. Such schemes had two general goals: a) reduce the density stratification of the Lake, therefore potentially eliminating the anoxic conditions in the hypolimnion, and b) reduce the salinity of the surface waters enough to allow their use for irrigation. Many of these salinity reduction schemes proposed over the years require the construction of significant infrastructure.

The salinity reduction options are classified in three groups according to the extent to which each option restricts navigation:

(1) options with no navigation restrictions, involving for example construction of hydraulic works that would reduce the salinity of the system without reducing the navigable depth of any channels,

(2) options leading to partial navigation restrictions, for example limiting the depth of the channel or constructing hydraulic works that would require a draft restriction, and

(3) the option to close the channel and let the system return to its bathymetry prior to the dredging of the navigation channel, restricting thus completely the navigation of large vessels.

Options that require navigation restrictions would also require the relocation of some, or all port and industrial facilities presently served by the navigation channel, and the construction of new such facilities, outside the Lake.

2 FIELD PROGRAM

The field work and data collection program conducted as part of the study had two general objectives: a) advance the understanding of the major processes that affect the environmental quality of the system, and b) provide the required data for the calibration of hydrodynamic and water quality numerical models.

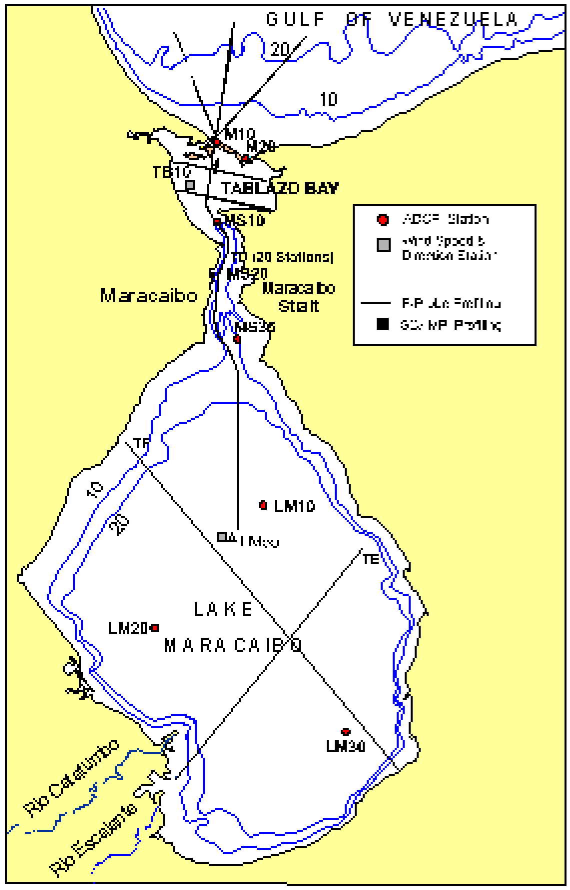
The program included the collection of hydrodynamic, hydrographic, water quality, and selected meteorological data, the compilation and use of meteorological data collected by others, and the estimation of river flows in the Lake. A comprehensive effort was made to document different basic aspects of the hydrodynamics of the system with state-of-the-art equipment, never before used in the Lake Maracaibo system.

The hydrodynamic data collection work was conducted in two phases, the first phase during the wet season (October-November 1998) and the second phase during the dry season (March-April 1999). The program included measurements for both neap and spring tide conditions. It included the collection of continuous velocity profiles at different parts of the system over several tidal cycles using 4 bottom-placed Acoustic Doppler Current Profilers (ADCP), velocity profiles with propeller current meters, several F-probe lines (CTD profiles) in different parts of the system, and measurements of the stratification microstructure in the Strait and the Lake using a Self Contained Autonomous MicroProfiler (SCAMP). The location of some of the stations and lines used for the collection of these data is shown in Figure 1a. A bathymetric survey was conducted in two areas of very active morphological features, the mouths between Zapara and San Carlos Island, and the mouth between Zapara and Cañonera Island. In addition to the existing tidal stations, two new stations were installed at Amuay and Punta Perret to obtain water levels at the entrance to the Gulf of Venezuela. More details on the field program are given in Horn, et al. (2001a).

A water quality monitoring campaign was conducted with the boat “El Bergantin” operated by the Instituto Para el Control y la Conservacion de la Cuenca del Lago de Maracaibo (ICLAM). The program was conducted under the direction of Bechtel and included two complete water quality surveys of the entire system (water quality profiles at 21 stations shown in Figure 1b). Also, a series of water quality profiles at station C-11, at the center of the lake (see Figure 1b), were collected every 2 to 4 weeks between the wet and dry season campaigns.

A meteorological station was installed on the oil platform Planta Lama in the Lake to collect wind, rainfall, and pan evaporation data. Also, a temporary wind station was installed in Tablazo Bay during the wet season campaign. Meteorological data from all operating land stations were obtained and used in the study. River flows into the Lake were estimated with the hydrologic watershed model of the Lake Maracaibo basin developed by C.G.R. Ingeniería.

(a)


GULF OF VENEZUELA
20
10
M10
M20
TB10
TABLAZO BAY
MS10
MS20
Maracaibo
Maracaibo
Strait
MS25
TR
10
20
LM10
TE
LAKE
MARACAIBO
LM20
LM30
Rio Catatumbo
Rio Escalante

(b)

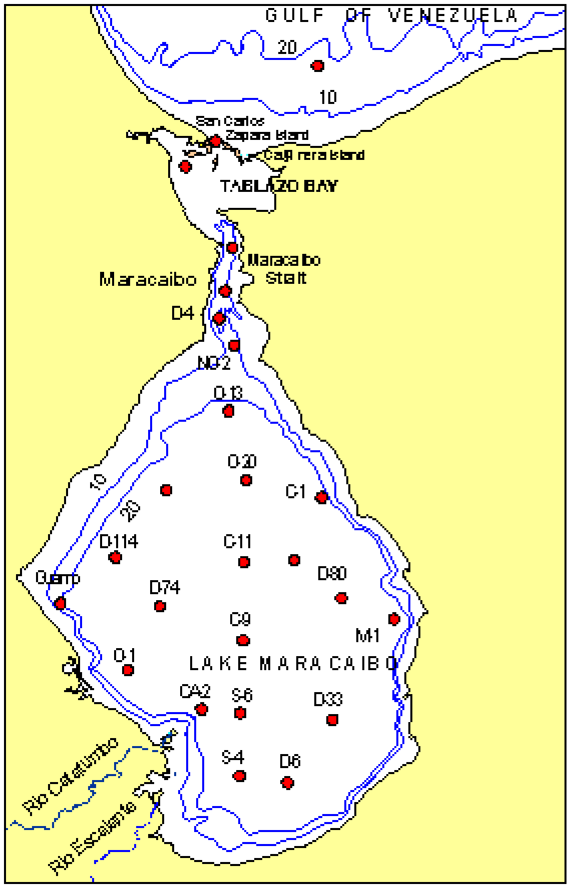


Fig.1 Hydrodynamic and water quality stations

3 MODELING

To evaluate the water quality impacts of the many options proposed over the years, special computer modeling tools were used to predict the expected changes under each option. The data from the field investigation were used to calibrate and validate the computer models.

Because of the different time and space scales of the processes affecting the environmental quality of Lake Maracaibo, as well as the computational requirements for their proper simulation, a combination of models and methods was used to evaluate the options under consideration. Two different models were used for this purpose: a) the three-dimensional model hydrodynamic, water quality and eutrophication model MIKE 3, and b) the one-dimensional dynamic reservoir simulation and water quality model DYRESM-WQ. Two different setups of MIKE 3 were developed, the Regional and the Lake model. The Regional model included the entire Gulf of Venezuela, Tablazo Bay, the Strait and Lake Maracaibo. It was developed primarily to analyze the hydrodynamics of the entire system, and predict the mixing and flow exchange processes between its major components. Special emphasis was placed in the analysis of flows and salt-water fluxes between the Strait and the Lake. The Lake model was developed primarily to perform ten-year simulations of the most promising options, using as boundary conditions flows and salt fluxes into the Lake derived from the *Regional MIKE 3 model* simulations. The development, calibration and validation of MIKE 3 are described in Hansen, et al (2001a, 2001b).

DYRESM-WQ was used both as a diagnostic and a predictive tool to provide longer-term assessments and sensitivity analysis, which, because of high computational requirements, were not practically possible with the three-dimensional models. The calibration and validation of DYRESM-WQ for Lake Maracaibo is discussed in Horn, et al. (2001b).

4 EVALUATION OF OPTIONS

The Lake Maracaibo system contains roughly $2 billion of port and petroleum-related transport infrastructure developed over the past 50 years. The costs of the evaluated options range from very low for the case of maintaining the existing channel to very high, of the order of $2.5 billion, for the case of allowing the navigation channel to silt in and relocating all major facilities. The costs considered were those associated with the various proposed hydraulic works as well as those associated with infrastructure relocation and development, and exclude those for domestic and industrial point source control, which should supplement any option.

Two remediation options were selected for in-depth modeling analysis: a) to maintain the existing channel as is today, and b) let the navigation channel to silt in to return the system to its bathymetry prior to dredging which would require relocation of all major ports within the Lake. Both options are accompanied by a program for the control of all domestic and industrial point pollution sources and the development of water management plan for the reduction of nutrients and other pollution loading coming to the Lake. These two options bracket the range of potential water quality changes short of sealing off the Lake from all marine influence. The first option—maintaining the present navigation channel configuration in combination with pollution source control measures—has a locally positive water quality impact and serves to provide a baseline for other analyses as well as answering policy-related questions. The option of returning to the pre-dredging bathymetry, in combination with the implementation of a watershed management program and pollution source control measures produces the greatest positive changes in water quality. The assessment of the relative contribution of the closure of the navigation channel and a watershed management program to water quality changes in the Lake is still in progress.

At the time of the submittal of this paper, modeling evaluation continues. Preliminary results indicate that control of direct point source discharges by itself will not have a major effect on the eutrophication of the Lake. Point source control is though essential for improving water quality locally and for protecting public health. More significant improvements can come in from the implementation of a long-term watershed management plan, aimed at reducing the nutrient and pollutant loadings from the rivers discharging into the Lake. Considering that the system seems to be in a state of dynamic equilibrium, maintaining the navigation channel will not lead to increased degradation of water quality. Closing the navigation channel will eventually return the salinity of the Lake to its historic levels prior to the dredging of the channel, of about 1.2 ppt., and will significantly reduce the salinity stratification. Weaker density stratification will continue to exist seasonally due to the variability of water temperatures. The reduction of salinity stratification will increase dissolved oxygen levels in the Lake, however the thermal stratification may still provide enough density gradients during part of the year to prevent the oxygenation of the hypolimnion. The extent of the impact of the elimination of salinity stratification on anoxic conditions in the hypolimnion is still under evaluation.

An essential element of the solution to the problem of anoxic conditions in the hypolimnion is the reduction of the dead organic matter in the Lake, which requires reduction of the primary production (phytoplankton, i.e. algae). This in turn requires reduction of the nutrients coming into the Lake, which can be achieved primarily through control and management of different activities in the watershed and secondarily through treatment of all wastewater directly discharged in the Lake.

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