REMEDIATION AND TRANSPORTATION PLANNING, LAKE MARACAIBO, VENEZUELA

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ABSTRACT: *Lake Maracaibo in western Venezuela is one of the major oil-producing areas of the world with over 12,000 platforms connected by 15,100 km of pipeline, capable of producing 3 million barrels/day. To expedite oil export, the entrance to the lake was dredged beginning in 1938 and reached its present depth (14 m or 45 ft) in 1960 to permit the utilization of Lakemax oil tankers. The deeper channel, however, also altered the water quality of the lake, principally raising salinity and influencing the development of an anoxic zone. Several solutions to these changes have been suggested including reclosure of the channel, therefore excluding tankers.*

This multiyear study focused on determining the quantity and sources of contaminants entering Lake Maracaibo, and then applied several computer models to determine short- and long-term changes in water quality due to modifications of the entry channel and in contaminant loadings. The final part of the study included development and cost analysis of alternative pathways to continue the transport of oil, coal, petrochemicals, and general cargo to and from the lake.

Results indicate that the oil industry contribution to contamination is minor compared to that from domestic discharges at the north end and from river inputs to the south, and that changes in channel configuration (including restoration to the predredged condition) do not improve water quality significantly. A concerted effort is needed to reduce land-based contamination to ensure any sustained improvement of the lake's water quality.

Introduction

This report provides an overview of the multiyear study supported by Petroleos de Venezuela SA (PDVSA) to analyze the environmental conditions of Lake Maracaibo and provide recommendations for improvement. The oil industry in general, and oil spillage in particular, has been blamed as a leading source of lake contamination and degraded water quality. Specific study objectives were to synthesize the existing knowledge about the source of the major environmental problems of Lake Maracaibo, collect additional environmental data, and apply analytical modeling tools that 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.

As the oil industry also has been the reason for channel dredging, which has had the side effect of increasing lake salinity, this study also analyzed whether a reduction in salinity would help reduce nutrient levels, thereby increasing dissolved oxygen concentrations in the lake and resulting in improved water quality. Several additional papers describing the modeling effort and other aspects of study will be forthcoming.

Lake Maracaibo in western Venezuela is about 160 km long in the north-south direction and 110 km wide in the east-west direction, with an area of about 12,000 km^2 and a maximum depth of 30 m. It is connected with the Gulf of Venezuela through the Strait of Maracaibo and Tablazo Bay (Figure 1). Several rivers flow into the lake from the south draining a watershed of approximately 89,000 km^2, the largest of which is the Rio Catatumbo, accounting for about 60% of all freshwater flow into the lake.

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, including high tides, low freshwater flow into the lake, and favorable wind and barotropic conditions. Under certain conditions, the salt wedge flows to the south end of the Strait of Maracaibo and then to the bottom of Lake Maracaibo. This process raises the salinity of the lake, which typically exhibits a salinity stratification.

Before 1938, navigation between the Gulf of Venezuela and Lake Maracaibo relied on natural channels, particularly the channel passing between San Carlos and Zapara Islands. Construction of a stable channel was initiated in 1939, and a 6-m deep

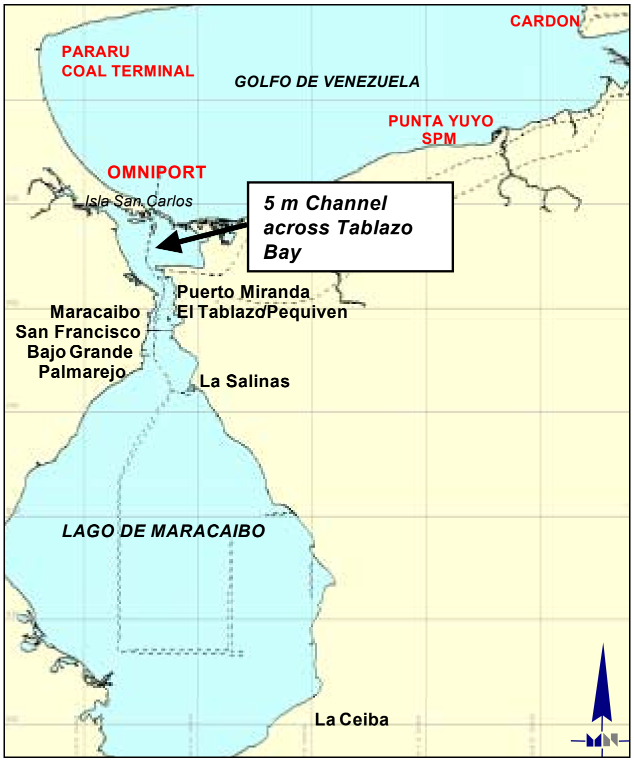

Figure 1. Facility locations and area of channel infilling under the "full" restriction to navigation case analyzed in this study.

channel was maintained until 1947. In 1952, the Instituto Nacional de Canalizaciones (INC) started the construction of a new navigation channel. The new channel, with a depth of 12 m and a 3-km breakwater at the western end of Zapara Island, was completed in 1956. By 1963, the depth of the canal was increased to 13.7 m to permit the most efficient utilization of Lakemax oil tankers. Through dredging, the navigation channel has been maintained until today.

Oil spillage

Lake Maracaibo basins oil reservoirs contain over 20 billion barrels of oil. It is not surprising that oil seeps were observed along the shores of the Lake during the time of the conquistadors (Baptista, 1966 referenced in Battelle, 1974). However, modern oil field development did not begin until after the Mene Grande field was discovered in 1914. The largest oil field in Venezuela, Lagunillas, was discovered along the eastern shore of the lake in 1926. The development of two other major oil fields, the Tia Juana and Bachaquero, followed. By 1965, these fields had produced 671 million barrels of oil.

The abundance of oil and its development create an extraordinary number of potential spill sources in and surrounding Lake Maracaibo. By 1970, there were 5,200 wells in the lake and 6,800 wells on the surrounding shores. These wells were connected by a total of 15,100 km of pipeline, of which 11,100 km were located on the floor of the lake. At this time, 200 pump stations existed to support a production of 3 million barrels. Data regarding historic spills during this time frame are limited. Battelle (1974) reports the occurrence of two major spills: in 1922, the Los Barrosos No. 2 well blew out, releasing 100,000 barrels of oil per day until being brought under control, and in 1972, another large (100,000-barrel) spill occurred.

By 1998, annual oil production exceeded 500 million barrels. The infrastructure necessary to support this level of production is extensive and includes over 13,000 operating wells, more than 400 pump stations (143 of which are in the lake), and over 150 generator facilities (gas, steam, and electrical). More than 1,400 additional wells are being utilized for steam injection to enhance recovery, over 500 new wells are being drilled, and another 1,000 wells are in the workover process. Of the 13,225 wells reported in western Venezuela in 1997, 6,505 are located in Lake Maracaibo. Over 15,000 employees currently are required to support these operations.

The greatest potential source of spillage is from the 42,693 km of gas and oil pipelines connecting the wellheads to the points of collection, distribution, and transport. Approximately 32,000 km of pipeline are located in the lake. The national government of Venezuela has developed a National Contingency Plan to respond to oil spills to control the near-constant rate of spillage in the Lake area. The plan gives PDVSA the responsibility to organize the response effort. PDVSA has formed an active response team for Lake Maracaibo, the OLAMAC Unit, which conducts several helicopter surveys per day to determine the extent of spillage and to direct its oil-skimming vessel to the appropriate location. This lake-based response team also keeps important statistics concerning oil spills observed and oil collected in Lake Maracaibo. These data were used to determine the sources of spills and the general level of oil contamination entering the lake.

Total spilled. The quantity of oil spilled is determined by OLAMAC in two manners: (1) by calculating the amount observed during the thrice daily helicopter overflights (designated as "barrels spilled"), and (2) by measuring the amount of oil collected during cleanup operations ("barrels collected"). Cleanup operations also include land-based spills, while the visually based barrels spilled do not. In addition, differences between the two methods also are expected because one is based on purely visual estimates while the other represents oil and water collected in a holding tank. For the visual estimate, quantity is determined by estimating surface coverage in km^2 and oil thickness based subtle changes in coloration.

The values of oil spilled and collected for spills above 5 barrels are presented in Table 1 for the years 1995–1997. The amount spilled (visually estimated) was below 1,000 barrels, and the amount collected was on the order of 3,000 barrels or less. From January to July 1998, a total of 1,731 barrels were spilled and 10,236 barrels collected, primarily because of collection from a land-based site that was not included in the lower value. From Table 1 it is estimated that the amount of oil entering Lake Maracaibo from oil spills was approximately 3,000 to 5,000 barrels per year from 1995 through 1997. This assumes that the barrels spilled and the barrels collected are on the low side.

During the first 8 months of 1998, there were approximately 1,740 spills reported, having an average size of 1.65 barrels per spill. Pipelines are the main source of spills, accounting for over half of the total number and 60% of the total barrels spilled (Table 2). Spills from surface equipment on the platforms are the second largest source, comprising approximately 19% of the total number of spills, but less than 7% of the total quantity lost. Lesser factors include spills from the stop press on the well, other causes at stations, barges, canals, and terminals. Terminals with a small number of spills had a large quantity lost (332 barrels) in May.

The largest spills into Lake Maracaibo from 1995 to 1998 are presented in Table 3. Flow and pump lines are again the most

Table 1. Spilled oil quantities (PDVSA data, 1998).

Year	Barrels spilled	Barrels collected
1995	140	950
1996	1291	3,210
1997	697	2,810
1998 (7 months)	1,731	10,236

Note: "Barrels Collected" includes land-based operations while "barrels spilled" represents visual estimates of oil on Lake Maracaibo.

Table 2. Principal sources of oil spilled in Lake Maracaibo, January–August 1998 (PDVSA data, 1998).

	Number	%	Barrels	%
Flow lines	917	52.7	1,635.9	60.4
Surface equipment	327	18.8	181.9	6.7
Stop press	199	11.4	45.2	1.7
Station other causes	120	6.9	218.2	8.1
Barge	74	4.3	88.4	3.3
Canals	50	2.9	78.8	2.9
Terminals	4	0.2	420.6	15.5
Total:	1,692	97.3	2,669.1	98.5

Note: Data from barges and canals were available only from January to May and were extrapolated to August. Data for terminals reflect only January to May (since extrapolation would lead to extraordinarily large and unrealistic losses).

Table 3. Sources of spills larger than 50 barrels in Lake Maracaibo (1995–May 1998) (PDVSA data, 1998).

Year	Source	Barrels spilled
1995	Flow line	140
1996	Terminal	515
	Pipeline	113
	Pump line	355
1997	Well surface equipment	52
	Blowout	512
	Pipeline	133
1998	Pipeline	64
	Pump line	79
	Terminal	332
	Pump line	88

common source of large spills (1,484 barrels from eight events). Terminals are the second most common, spilling 847 barrels from two events. One blowout in 1997 spilled 512 barrels.

The number of spills and associated barrels lost from 1998 are compared with data from 1971 in Table 4. Although subject to different methods of counting "spillage" (values as small as 0.01 barrel are counted today as a spill), these data provides an historic perspective on the level of spillage that has occurred. The number of spills has increased by approximately 25% while production has more than doubled, and the total amount spilled has decreased significantly.

Other petroleum sources (seepage and rivers). Naturally occurring underwater and shoreline seepage and riverine input are other sources of hydrocarbons in Lake Maracaibo. Although likely, the level of petroleum seepage has not been studied. In terms of river sources, the Catatumbo River is the most important because of its source in Colombia and the large number of Colombian oil spills that occur within its area of drainage.

Oil spills affecting the Catatumbo River are a result of guerilla sabotage of the Caño Limon-Coveñas oil pipeline in Colombia, which transports crude, extracted from the Caño Limon field to the export terminal at Coveñas. The pipeline crosses different sections of the Catatumbo along a 160-km path, of which some 12 km is directly parallel to the river (ECOPETROL/PDVSA, 1996). Fortunately, most of 62 attacks on the pipeline between January and September 1998 have been in other areas. The number of attacks nearly eclipses the previous record of 66 attacks in 1997 (Golob's Oil Pollution Bulletin, 1998).

Table 4. Comparison of number and quantity of Lake Maracaibo spills from 1971 and 1998 (Battelle, 1974; PDVSA 1998 data).

Year	Number of spills	Barrels spilled	Production level
1971	1,650	20,000	2,500,000
1998*	2,160	4,315	5,400,000

Note: The production level from 1998 includes land-based production.
* Estimate based on extrapolating 8 months of data to 12 months.

ECOPETROL (Empresa Colombiana de Petroleos) has a fixed-oil capture location approximately 20 km above the Venezuelan border in Colombia. However, the swiftness of the river inhibits the collection of all oil spilled (estimated not to exceed 60% of the total lost). For this reason, there is a bilateral agreement between PDVSA and ECOPETROL under which PDVSA will respond within Venezuelan territory to capture the oil that passes across the border. This plan was activated once October 1998, at which time the spill was estimated at 9,000 barrels lost in Colombia. More than 4,000 barrels of the spill were recovered along the Rio Tarra, a tributary of the Catatumbo River. The OLAMAC team reported that no visible oil reached Lake Maracaibo from this incident.

Dissolved hydrocarbons in riverine waters that are not as obvious as a surface slick can also lead to an increase in hydrocarbon levels in the lake. Realizing that the level of hydrocarbons in sediments can represent the longer-term hydrocarbon levels in river waters, PDVSA/ECOPETROL (1996) undertook hydrocarbon analyses of the sediments throughout the length of the Catatumbo River and found mostly low to nondetectable levels of hydrocarbons. Values as high as 14.6 ppm were reported at the mouth of the Catatumbo during the first wet season sampling period. However, these were lowered to less than 1 ppm during the dry season. This difference was attributed to samples taken higher on the banks, where oil is most likely to reside during the high water stage of the river in the rainy season. In contrast, during the dry season, water levels are lower and the area sampled is be below the rainy season water level and only exposed to dissolved or subsurface oiling.

Principal water quality issues

The construction of a deeper navigation channel facilitated the flow of denser salt water into Lake Maracaibo 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 40 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, generally increasing in dry years and decreasing during wet years.

Today the lake is in a state of advanced eutrophication. The high primary production is eventually of large quantities of dead organic matter settling to the bottom of Lake Maracaibo. In combination with the stratification of the lake, this leads to anoxic conditions below the density gradient (pynocline), as the latter acts as a barrier to the vertical mixing of oxygenated waters. Because the thermal stratification of the lake is relatively weak, the salinity stratification of the lake is viewed by many as the primary source of anoxic conditions in the bottom. The environmental condition of the lake also has been affected by sewage and industrial discharges, which cause locally unsanitary conditions in their vicinity and contribute to a heavy nutrient loading.

Although the rivers show near natural levels, they provide the major quantity of nutrients entering the lake because of high water volume. The other major source (about 10%) is the discharge of untreated sewage from the city of Maracaibo and other towns around the lake, having a population of over 4 million.

The reason for the low oxygen levels in Lake Maracaibo, even under reduced stratification and increased vertical mixing, is the high concentration of organic matter in the lake. Algae, zooplankton, and higher forms of aquatic life when they die settle in the bottom of the lake where they decompose consuming all available oxygen.

The solution to the problem of anoxic conditions in the hypolimnion requires reduction of the dead organic in the lake, which requires reduction of the primary production (phytoplankton, algae), which in turn requires reduction of the nutrients coming into the lake. This could 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.

Environmental restoration options

Several solutions to the environmental problems of Lake Maracaibo have been proposed over the years. Most of them have focused on ways to reduce the salinity of the lake. They range from complete isolation of the lake system from the Gulf of Venezuela through the construction of various hydraulic works, to the abandonment of the navigation channel, and the return of the system to its natural condition prior to the dredging of the channel. Some of the solution schemes proposed over the years require the construction of significant infrastructure. Some of the environmental problems of the lake have quite obvious solutions—for example, point source control and watershed management to reduce nutrient and BOD load coming into the lake, and the control of toxic pollutant discharges into the lake system.

The potential environmental restoration can be can be classified as (1) engineering options involving physical changes in the lake system through changes in its bathymetry and the construction of special works, and (2) management options that include point source control and watershed management. The main objective of the engineering options is to reduce the salinity of Lake Maracaibo; reducing its density stratification affects water quality parameters. The management options aim primarily at reducing the nutrient loading of the lake, as well as various pollution discharges. Both options can of course be pursued in parallel.

Navigation options and associated infrastructure requirements. Salinity reduction options are classified in three groups according to the extent to which each option restricts navigation: (1) options no navigation restrictions, (2) options leading to partial navigation restrictions, and (3) the option to close the channel and let the system return to its bathymetry prior to the dredging of the navigation channel, thereby completely restricting the navigation by large vessels.

Options that do not require relocation of any existing port operations or attendant infrastructure (e.g., pipeline systems, tanks, roads) include the construction hydraulic works that would reduce the salinity of the system without reducing the navigable depth of any channels. An example of such a scheme is the closure of Boca San Carlos and Boca Cañonera with dikes and the construction of a navigation lock that would accommodate the largest the oil takers coming to the lake. Other options in this group include the construction of a dikes across the Strait of Maracaibo and the construction of a navigation lock, or a navigation opening with submerged gates, that would facilitate movement of vessels without limiting the vessel drafts that call at Lake Maracaibo and that would block salinity intrusion.

Options that would lead to partial navigation restriction include limiting the depth of the channel or constructing hydraulic works that constitute a draft restriction. Many of the options are similar to those that do not impose any navigation restrictions as discussed earlier, with the additional element of a depth restriction. For example one such option involves the construction of dike across the Strait of Maracaibo with a navigation opening having a sill that would restrict the depth of flow in and out of the lake. The disadvantages of the partial navigation restriction options include the need to relocate the crude export operations within

Lake Maracaibo (e.g., Las Salinas, Bajo Grande) to Puerto Miranda, which would be expanded; the relatively high costs for construction of the hydraulic works; and the environmental impacts of the hydraulic works. Under some conditions, Bajo Grande terminal operations would be restricted to shallower draft vessels importing and exporting products (i.e., crude exports including Boscan crude would be relocated to Puerto Miranda). Expanding Puerto Miranda outside of the area of depth restriction would make it the main oil export terminal in the region. Many existing crude oil and product pipelines would have to be relocated. These partial navigation restriction options would not impact petrochemical port operations at Puerto Miranda or El Tablazo/Pequiven. Coal would be relocated from San Francisco, Palmarejo, and La Ceiba to a new terminal outside the lake system (i.e., at either Isla San Carlos or Pararú). Depending on the location of the dikes, general cargo and container traffic could remain at the existing Maracaibo facilities, or it would be have to be handled partly elsewhere. In the latter case, one of the options is the handling of such cargo at a new omniport complex at Isla San Carlos.

The full restriction option would close the navigation channel completely and let the channel bathymetry return to its state prior to dredging (about 5 m across Tablazo Bay; see Figure 1). All crude oil, petrochemicals, deep draft coal, and general cargo operations would have to be relocated outside the Lake at a number of possible locations. Port relocation would also require a substantial investment for on-land infrastructure (i.e., pipelines, roads, and railways). The financial feasibility of a new port may depend critically on revenue associated with crude and coal operations. Depending on the selected alternative, the port also may have a significant environmental impact to beach and barrier island habitats and maintenance dredging may be extensive.

Four port relocation alternatives were considered for the full navigation restriction option. One concept is to develop a multicommodity port or omniport at the entrance to Tablazo Bay that would handle all of the existing and future cargo for the Lake Maracaibo region. The government already is considering such a project. There are several variants of this regional or multiproduct port. These variations involve alternative means for handling the principal cargo commodities (i.e., petroleum, petrochemicals, coal, and general cargo.) Each of the alternatives considered below, however, involves a new port facility at Isla San Carlos.

An alternative is to handle all crude oil and petroleum products export and import through five single-point moorings (SPMs) in the Gulf of Venezuela off the coastline of the state of Zulia. To accommodate the handling of multiple blends of crude oil and products dedicated loading and return lines would be considered because of the long sub-marine section of these lines. Puerto Miranda would be the focal point of pipelines from La Salina on the east side and Bajo Grande on the west side of the lake. Shipping lines would then move oil and products from Puerto Miranda to the SPMs. A pipeline from Puerto Miranda to Bajo Grande would be required to import products to Bajo Grande.

The third alternative would be to handle all crude oil and petroleum products export and import at new marine loading piers on the west coast of Paraguana near the Cardón Refinery. In addition to pipelines from La Salina to Puerto Miranda and Bajo Grande to Puerto Miranda, new pipelines would be required to transport oil and products from Puerto Miranda to the marine terminal at Cardón.

Handling of petrochemicals at the omniport would be problematic. Specifically, it would be necessary to transfer bulk petrochemical products (e.g., salt and urea) to the omniport by barge or truck. Either mode would be more expensive than existing operations. Similarly, it would be necessary to pipeline liquid products to the new port. Given the large number and diverse nature of the liquid products currently handled at El Tablazo/Pequiven, costs associated with transferring these products to the omniport would be significant. Coal could be handled either at the omniport or at a new facility at Pararú, west of the entrance to Lake Maracaibo along the Gulf of Venezuela.

Modeling efforts

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. To calibrate and validate the computer models a field investigation was undertaken to collect hydrodynamic, hydrographic, water quality, and selected meteorological information.

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 models were used for the analysis: a three-dimensional model hydrodynamic water quality and eutrophication model called MIKE 3, and a one-dimensional dynamic reservoir simulation and water quality model called DYRESM-WQ. Two different setups of MIKE 3 were developed: the regional model and the lake model. The *regional model* included the entire Gulf of Venezuela, Tablazo Bay, Strait of Maracaibo, 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 saltwater fluxes between the strait and the lake. The *lake model* performed 10-year simulations of the most promising options using boundary condition flows and salt fluxes into the Lake derived from the Regional MIKE 3 model simulations. 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.

Results

The Lake Maracaibo system contains roughly $2 billion of port- and petroleum-related transport infrastructure developed over the past 50 years. Costs of the various channel modification/facility movement options range from very low (e.g., maintaining the existing channel) to very high (~$2.5 billion for the case of allowing the navigation channel to silt in and relocating all major facilities).

Two remediation options were selected for in-depth modeling analysis: (1) maintain the existing channel as is today, and (2) 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 Lake Maracaibo. Both options are accompanied the theoretical 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 from rivers. These two options bracket the range of potential water quality improvement short of sealing off the lake from all marine influence.

Modeling results indicate that the option to 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 predredging condition in combination with pollution source control measures produces a marginal improvement in water quality, not significant to warrant acceptance of the costs and environmental impacts associated with the movement of facilities. Important water quality improvements can come from the implementation of a long-term watershed management plan aimed at reducing the nutrient and pollutant loadings from point discharges and the rivers discharging into Lake Maracaibo. 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, provided that sewage and industrial inputs do not increase.

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