

Bill ~~McAnally~~  
McAnally  
Vicksburg

BONNET CARRÉ FRESHWATER DIVERSION, LAKE PONTCHARTRAIN,  
LAKE BORGNE, BILOXI MARSHES, MRGO AND THE IHNC

AN EVALUATION BY THE COMMITTEE ON TIDAL HYDRAULICS

OCTOBER 1995

BONNET CARRÉ FRESHWATER DIVERSION, LAKE PONTCHARTRAIN,  
LAKE BORGNE, BILOXI MARSHES, MRGO AND THE IHNC

AN EVALUATION BY THE COMMITTEE ON TIDAL HYDRAULICS

OCTOBER 1995

EXECUTIVE SUMMARY

The USACE New Orleans District has been authorized by Congress to construct a structure at the Bonnet Carré floodway to divert Mississippi River water into Lake Pontchartrain in order to reduce salinities in the Mississippi-Louisiana estuarine area. The project involves consideration of the roles that the Mississippi River Gulf Outlet (MRGO) and Inner Harbor Navigation Canal (IHNC) play in the system's salinities, and the District asked the Committee on Tidal Hydraulics to review information on the Bonnet Carré Freshwater Diversion project and answer the questions listed below.

a. *Can the contribution of the MRGO-IHNC to the increase in salinity in Lake Pontchartrain and adjacent waterways be economically controlled by reducing either:*

(1) *The volume of MRGO flow into the Lake, or*

(2) *The salinity concentration of the MRGO flow into the Lake?*

b. *If so, can the Bonnet Carré freshwater diversions be reduced in magnitude while still producing:*

(1) *The desired freshening effect in project wetlands and marshes, and*

(2) *The target salinities for increased oyster production?*

This report by the Committee on Tidal Hydraulics provides the following conclusions and recommendations:

a. The Inner Harbor Navigation Canal (IHNC) contributes about 5 percent of the Lake Pontchartrain tidal prism, but about 9 percent of the salt flux into the lake.

b. The Mississippi River-Gulf Outlet (MRGO) contributes about six times as much salt to Lake Borgne as the IHNC contributes to Lake Pontchartrain.

c. Salinity intrusion to Lake Pontchartrain cannot be significantly reduced by controlling flows at the IHNC connection to the lake, but construction of a sill-weir combination might alleviate the hypoxia zone that forms in Lake Pontchartrain near the airport. Further field data are needed to determine how effective such a structure would be. X

d. Salinity reduction in Lakes Pontchartrain and Borgne and the nearby Biloxi Marshes might be achieved by controlling flows in the multiple connections between the MRGO and Lake Borgne and/or artificially mixing stratified waters in the MRGO. These alternatives offer the possibility that diversions through the Bonnet Carré structure could be reduced from the original design capacities without compromising the project's salinity reduction goals.

e. Salinity reduction efforts by other means might be enhanced by comparatively small Mississippi River water diversions through the IHNC lock to the Mississippi River.

f. Items (c)-(e) above should be the subjects of engineering studies to determine their feasibility.

g. The ongoing numerical modeling of the system should be continued, with verification and then testing of various alternatives, including those listed here. Additional field observations in support of the modeling may be required.

## 1 INTRODUCTION

### Background

1. The Bonnet Carré Spillway, located on the Mississippi River about 27 miles (43 km) upstream from New Orleans, was completed in 1931 for the purpose of providing a controlled discharge of a portion of above flood stage flows of the Mississippi River into Lake Pontchartrain, in order to reduce flooding of New Orleans and other down river communities. The spillway structure consists of 350 gate bays, and was intended to be used only for extreme flood conditions. In the 64 years since its construction, the spillway has only been used for its designed purpose during seven years (1937, 1945, 1950, 1973, 1975, 1979, and 1983).
2. Figure 1 is a map of Lake Pontchartrain and adjacent waterways, showing the various locations discussed in this report.
3. The Mississippi River Gulf Outlet (MRGO) canal is a man-made navigation waterway for ship and barge traffic, which extends some 76 miles (122 km) from deep water in the Gulf of Mexico northwestward to New Orleans. The MRGO, completed to its designed dimensions of 36 ft (11 m) by 500 ft (152 m) in 1965, includes a land cut 38 miles (61 km) long passing through marsh and shallow water areas. At its landward end the MRGO joins the Gulf Intracoastal Waterway (GIWW) for about five miles before ending in a turning basin within the Inner Harbor Navigation Canal (IHNC). The project was constructed in stages, and attained dimensions of 36 ft (11 m) by 250 feet (76 m) over the full reach from the GIWW to open waters in the Gulf in early July of 1963. Since completion to project dimensions the unstable marsh bank lines have eroded along the length of the land cut.
4. During the construction of the MRGO the U.S. Army Engineer Waterways Experimental Station (WES) conducted tests in an hydraulic model which included, at a horizontal scale of 1:2000 and a vertical scale of 1:100, all of Lake Pontchartrain, all of Lake Borgne, a part of Mississippi Sound, the full reach of the MRGO, the GIWW, and the IHNC, and all of the passes between these several waterways. This study (WES, 1963) predicted that the completion of the MRGO would result in significant increases in the salinities in Lake Pontchartrain, Lake Borgne, the IHNC, and in the passes interconnecting these water bodies. The average increase (low fresh water flow and high fresh water inflow years combined) in the salinities in Lake Pontchartrain as given by these hydraulic model tests was 5.03 ppt, from 1.15 ppt without MRGO to 6.18 ppt with MRGO installed in the model.
5. More recently Sikora and Kjerfve (1985) published a paper giving the results of an analysis of a record of daily salinity observations made at two stations in Lake Pontchartrain, and one station each in The Rigolets, in Chef Menteur, and in Pass Manchac. These data, collected by the U.S. Army Engineer District, New Orleans, extended over the 36 year period from 1946 through 1981. This data set and its analysis by Sikora and Kjerfve are described in detail in Appendix A, which includes an evaluation of this paper by the Committee. For the purposes of this introduction, the important conclusions reached by Sikora and Kjerfve are listed below:
  - a. For each of these five stations the post-MRGO (after 1963) record length mean salinity exceeds the pre-MRGO (before 1963) record length mean salinity, but by an increment much smaller than the 5.03 ppt increase predicted for Lake Pontchartrain using data collected in the 1963 WES hydraulic model. The maximum post-MRGO minus pre-MRGO salinity difference within Lake Pontchartrain as computed by Sikora and Kjerfve using the subject

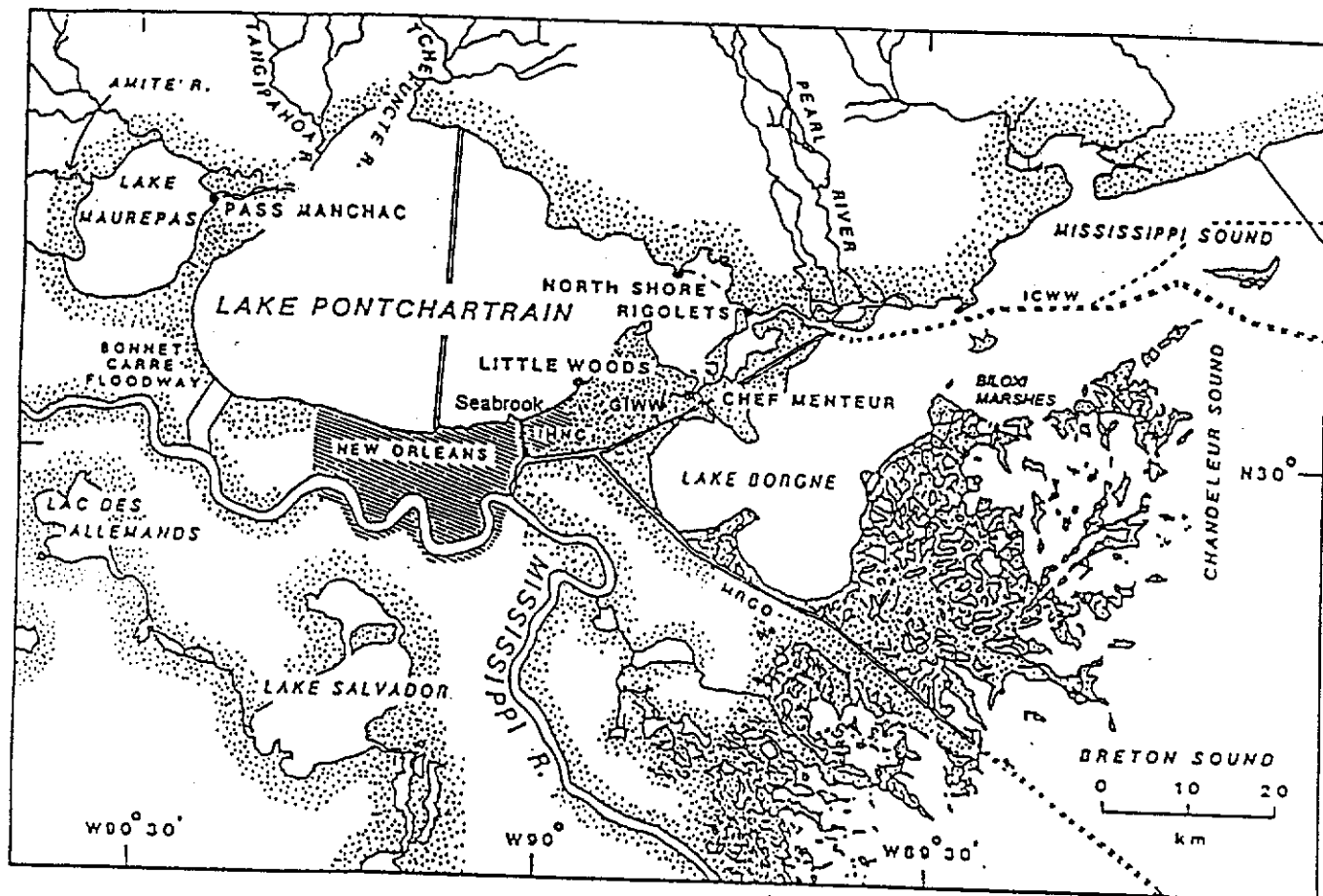


Figure 1. Map of Lake Pontchartrain and adjacent waterways. MRGO indicates the Mississippi River Gulf Outlet; IHNC indicates the Inner Harbor Navigation Canal; GIWW indicates the Gulf Intracoastal Waterway.

prototype data set was 1.6 ppt for the Little Woods station, located just off the southwestern shore of the Lake.

b. The subject data set is marked by large variances for each station at all time scales. Sikora and Kjerfve state that because of these large variances the computed values of the pre-MRGO to post-MRGO increases in salinities are statistically insignificant. These authors do not present any description of the statistical measures used to reach this conclusion.

6. Since the publication of the Sikora and Kjerfve paper, the U.S. Army Engineer District, New Orleans (USAENOD), used that same data base to analyze the pre-MRGO to post-MRGO monthly mean salinity differences for four of the five stations listed in the previous paragraph (USAENOD, 1984). This analysis by the District gave values for the pre-MRGO to post-MRGO record length mean salinity increases quite close to the values given in the paper by Sikora and Kjerfve. In addition, The District analysis included the computation of the characteristic seasonal variation in the pre-MRGO and post-MRGO mean salinities for each month, and in the month by month differences in these monthly average salinities. In the document the District did not discuss the statistical significance of the results of their analysis.

7. Prior to the completion of MRGO there was evidence of a loss of fresh water marshes throughout the Lake Pontchartrain Basin. Such loss probably resulted from the combined long term effects of subsidence, sea level rise, and the loss of sediment input to the Lake from overflow of the Mississippi River, which had been effectively eliminated over the last 100 years by improvements to the levees along the River. Exceptions to this last statement are of course the purposeful diversions of flood waters through the Bonnet Carré Spillway. When it was realized that the opening of the MRGO would likely result in some increase in the salinity of the Lake waters, there was concern expressed by various parties that the loss of freshwater wetlands would be accelerated. Also, the production of oyster seed on beds in the Biloxi Marshes on the east side of Lake Borgne is adversely impacted by salinities consistently greater than about 15 ppt as a result of the invasion of the oyster drill at these salinities. The U.S. Army Engineer District, New Orleans, and the State of Louisiana have undertaken projects, including freshwater diversions, to offset or at least reduce the loss of fresh water wetlands in other marsh areas as well as around Lake Pontchartrain, and to improve oyster seed production. A fresh water diversion has been constructed at Caernarvon; one is under construction at Davis Pond; and a third has been authorized for Bonnet Carré.

8. In 1988 the U.S. Congress authorized the expenditure of funds to modify the Bonnet Carré Spillway to provide for a controlled diversion of flow from the Mississippi River into Lake Pontchartrain under non-flood river stages. The purpose of this Bonnet Carré Diversion Project was to provide some mitigation for an increase in the salinity of Lake Pontchartrain, Lake Borgne, and in the Biloxi Marshes which had resulted since the opening of the Mississippi River-Gulf Outlet Canal in 1963. Although the MRGO was not completed to full project dimensions until 1965, its impact on the salinities of Lake Pontchartrain appears to have been felt beginning in the middle of 1963, when the Canal dimensions were 36 ft by 250 ft. The Bonnet Carré diversion project would provide for the diversion of Mississippi River water into western Lake Pontchartrain through the existing Bonnet Carré spillway, using a new control structure and a new channel within the spillway. This new control structure would allow diversions of up to 30,000 cfs (850 m<sup>3</sup>/sec.) The economic justification for the project is the reduction in the salinities in the Biloxi Marshes, which lie between Lake Borgne and Chandeleur Sound along the Louisiana-Mississippi boundary, for the purpose of increasing the production of oyster seed. Benefits from the project would also include the

reduction of salinities in the marshes surrounding Lake Pontchartrain and Lake Borgne.

9. The project's oyster production benefits have been tied to achieving a target range of salinities in the Biloxi Marshes. The targets, called the Chatry-Dugas Salinities, consist of an annual cycle of salinities that have been found to result in a superior oyster harvest the following year. It is claimed that if these targets are met one year in three, a two fold increase in oyster production would be achieved. To insure that the project would result in sufficient oysters in the seed grounds, the Corps designed the diversion structure for a maximum flow of 30,000 cfs with a 50 percent flow duration in the Mississippi River for April.

10. Since 1932 some 66,000 acres of marsh have been lost in the Pontchartrain Basin, and another 63,000 acres are expected to be lost in the next 50 years if no remedial action is taken. As noted above, some of these losses are the result of subsidence and sea level rise, as well as the loss of sediment replenishment, which previously occurred due to frequent natural flooding of the Basin from the Mississippi River. In addition to providing sediment replenishment, such past natural flow of Mississippi River water into Lake Pontchartrain significantly increased the annual input of fresh water to Lake Pontchartrain over that provided by the rivers and streams which enter directly to the lake, and consequently provided for lower salinities in the Lake than occurred after the levees closed off the supply of fresh water from the Mississippi River. The salinity increases resulting from the MRGO are considered to have increased the loss of fresh water marshes along the shores of western Lake Pontchartrain. The Bonnet Carré diversion project was designed to offset these processes by diverting fresh water into Lake Pontchartrain. This diversion would also push lower salinity water through the passes and into Lake Borgne.

11. Some of the commercial and sport fisheries which are now important in Lake Pontchartrain are favored by the higher salinities which have occurred there since the opening of the MRGO. A group of commercial and sports fisherman, together with other opponents of the project, have joined together under the umbrella of the Lake Pontchartrain Basin Foundation. This organization has asserted that introduction of Mississippi River water containing pollutants and excess nutrients will harm Lake Pontchartrain, leading to algal blooms, sediment resuspension and turbidity, and fisheries displacement. Federal and state agencies support the Bonnet Carré project.

12. Under the urging of some members of the Louisiana Congressional delegation, and representatives of the Governor's office, various state and federal agencies, including the U.S. Army Corps of Engineers, formed a Steering/Review Panel to oversee a Technical Team's reanalysis of the project. Included in the various findings and recommendations of the Technical Team and the Steering/Review Panel, under the general heading "ITEM 4 OTHER FINDINGS AND RECOMMENDATIONS BEYOND THE ORIGINAL CHARGE", was the following statement: "3. The Steering Panel requests Congress to pass additional authorization necessary to construct a sill or other barrier across the IHNC, as soon as possible."

13. As a result of the deliberations of the above described Steering/Review Panel, and the recommendations of its Technical Team, the New Orleans District asked the Committee on Tidal Hydraulics to review the available material on the effects of the opening and ultimate completion of the MRGO on the temporal and spatial variations in salinity within Lake Pontchartrain, Lake Borgne, the various passes and navigation projects connecting these waterways, and the marshes adjacent to them, and to answer several questions posed by the District.

Purpose

14. The purpose of this report is to answer the following questions posed by the New Orleans District:

a. Can the contribution of the MRGO-IHNC to the increase in salinity in Lake Pontchartrain and adjacent waterways be economically controlled by reducing either:

(1) The volume of MRGO flow into the Lake, or

(2) The salinity concentration of the MRGO flow into the Lake?

b. If so, can the Bonnet Carré freshwater diversions be reduced in magnitude while still producing:

(1) The desired freshening effect in project wetlands and marshes, and

(2) The target salinities for increased oyster production?

15. In view of the quoted statement given in Paragraph 12, the Committee interprets question a. (1) above to include the construction of a lock or a submerged weir at or near Seabrook at the northern end of the IHNC.

## 2 PROCEDURE

16. To develop the basis for answers to the questions posed by the New Orleans District, the Committee found it necessary to first resolve certain matters related to but not directly a part of these questions. The Committee used published and unpublished documents and data to attempt to resolve these matters. The following is a list of these subjects that the Committee felt it necessary to consider prior to dealing with the questions posed by the District. Each item on this list is preceded by a brief introductory statement:

a. The paper by Sikora and Kjerfve raised questions concerning the statistical significance of the computed values of the pre-MRGO to post-MRGO increase in salinities of Lake Pontchartrain and adjacent waterways, but these authors did not present information on the statistical tests which led them to reach this conclusion. Although the District used the same data base to recalculate the pre-MRGO to post-MRGO difference in the annual average salinities, and in addition determined the pre-MRGO to post-MRGO change in the monthly mean salinities, the question of statistical significance was also not addressed. Therefore, the Committee has undertaken a determination of the probabilities that the available data support the statement that the post-MRGO salinities are in fact greater than the pre-MRGO salinities, and to determine the confidence limits around the computed salinity increases.

b. Several different estimates of the fraction that is provided by the IHNC of the tidal prism of Lake Pontchartrain, and of the total flux of salt to Lake Pontchartrain, were contained in the various published papers and reports provided to the Committee for use in the preparation of this report. The Committee considers it necessary to resolve these uncertainties since the benefits that a complete closure or partial control of the flow from the IHNC to Lake Pontchartrain depend on the relative contribution of this source of salt to the Lake.

c. Early in the study of various documents provided by the District and by WES dealing with the construction of the MRGO, and with the various modeling efforts made to evaluate the impact of the MRGO on the salinity in Lake Pontchartrain and the adjacent waterways, the Committee found several references to the possible input of high salinity waters directly from the MRGO to Lake Borgne via inlets which constitute the mouths of the several bayous which intersect and cross the MRGO. These inlets are particularly evident along the southern and southeastern shores of the Lake Borgne where the MRGO passes within a few hundred feet from the Lake shore over a reach of several miles. It appeared to the Committee that this source of salt to Lake Borgne could constitute a significant cause for the increases in the salinities over the oyster seed beds in the Biloxi Marshes. The Committee believed it was necessary to expend considerable effort to search for any existing data on the size of these inlets and on the tidal and subtidal flows between the MRGO and Lake Borgne via these bayou crossings. The committee has used the data it has found to estimate the salt flux to Lake Borgne directly from the MRGO.

17. In the next section of this report (Section 3), brief statements will be presented giving the results of the Committee's attempts to resolve the subjects listed in the above paragraph. More detailed descriptions of the basis for the Committee's conclusions regarding the three subjects listed in Paragraph 16 are given in Appendices A, B, and C. In Section 4 of this report, the Committee's answers to the questions posed by the District are given. Included in that section are brief descriptions of the basis for the

Committee's answers. Finally, Section 5 contains the Committee's recommendations to the District.

### 3 CONCLUSIONS ON THE THREE PRELIMINARY SUBJECTS TO BE RESOLVED

#### On the Statistical Significance of the Pre-MRGO to Post-MRGO Salinity Differences

18. A detailed description of the procedures employed in the resolution of this matter is given in Appendix A. The Committee undertook an independent analysis of the pre-MRGO to post-MRGO salinity increases using the same data set used by Sikora and Kjerfve (1985) and by the District in their analysis. For comparison, the following Table 3-1 lists the post-MRGO record length mean salinity minus the pre-MRGO record length mean salinity for each of the stations used by Sikora and Kjerfve, by the District, and by the Committee.

STATION	SIKORA & KJERFVE	USAENOD	Committee (Appendix A)
Rigolets	2.0	Not Published	Not Published
Chef Menteur	2.6	2.4	2.1
Little Woods	1.6	1.8	1.7
North Shore	1.3	1.3	1.1
Pass Manchac	0.2	0.4	0.3

The differences in the listed values for each station result from differences in the procedures used by each of the three groups in treating the transition year, 1963, and in dealing with missing data for one to three months in an otherwise complete year of monthly mean salinity values. The District and also the Committee (Appendix A) computed monthly mean salinity differences, pre-MRGO to post-MRGO, with very similar results. Table A1 of Appendix A lists the pertinent parameters used in and the computed results produced by the Committee's analysis. The following paragraphs briefly state the Committee's conclusions regarding the characteristics of the data set and the statistical significance of the computed values of the pre-MRGO to post MRGO salinity differences, both for annual averages and for monthly averages.

19. The data base of pre-MRGO and post-MRGO observed salinities at locations in Lake Pontchartrain and in the adjacent passes suffers from the shortness of the data record, particularly for the pre-MRGO period. Two of the four Pre-MRGO data sets contained salinity observations for just six years. One of these two stations had salinity data for the post-MRGO period covering only 12 years. The small data base is coupled with a large variability in the salinity values at all time scales (daily, and weekly, monthly and yearly averages), such that, considering each station independently from the others, there is a large range of uncertainty about the computed values of the post-MRGO minus pre-MRGO differences.

20. Even so, for the annual averaged data sets, the probability that the post-MRGO salinities exceed the pre-MRGO salinities is very high, being  $>0.995$  for the three higher salinity stations, and only slightly lower (0.992) for the station in Pass Manchac. It would thus appear that Sikora and Kjerfve were using the term "statistically insignificant" from a subjective standpoint and not from an objective, quantitative standpoint. For the case of monthly averaged data sets, the probabilities that the post-MRGO salinities exceed pre-MRGO salinities are smaller, and for two of the stations, very much smaller, than for the annually averaged data. For the station at Little Woods, which was the station for which there was the largest data set, and for which the data was the most evenly divided between pre- and post-MRGO periods, the values of the probability that the post-MRGO salinities are greater than the pre-MRGO salinities were sufficiently high for all months to justify the statement that the differences based on monthly data are significant. Although the values of the probability that the subject difference is positive for all 12 months for the station in the Chef Menteur are somewhat less than those for Little Woods, they are adequately high to also state that the case for the contention that the post-MRGO monthly mean salinities are greater than the pre-MRGO monthly mean salinities is essentially proven for this station. For the station at North Shore, and even more so for the station in Pass Manchac, the data do not provide a strong basis in support of the contention that post-MRGO monthly mean salinities are higher than pre-MRGO monthly mean salinities.

21. The 95% confidence limits about the mean difference, post-MRGO minus pre-MRGO, computed by the Committee from the annual average data sets, indicate a reasonably high degree of confidence in these differences for Little Woods and Chef Menteur. For Little Woods, the range of the 95% confidence limits is  $\pm 0.35$  ppt, or  $\pm 21\%$  of the mean difference. For Chef Menteur, the range in the 95% confidence limits is  $\pm 0.5$  ppt, or  $\pm 24\%$  of the mean difference. For the station at North Shore, the range of the 95% confidence limits about the mean difference is  $\pm 46\%$  of the mean, while at the station in Pass Manchac, it is  $\pm 67\%$  of the mean. The subject differences for the individual monthly average salinities are known with considerably less certainty. Even for Little Woods, one month had a lower 95% limit of  $-0.1$  ppt and an upper 95% limit of  $+3.0$  ppt. The average values over the 12 months for the lower limit was  $0.1$  ppt and for the upper limit  $3.0$  ppt. These values represent a range of  $\pm 85\%$  of the average mean difference of  $1.7$  ppt. For the station in the Chef Menteur, the average of the monthly values of the upper and lower 95% confidence limits is  $\pm 93\%$  of the average mean difference. For the North Shore, this range is  $\pm 160\%$  of the 12 month mean difference, while for the station in the Pass Manchac,  $\pm 238\%$  of the mean difference.

22. The above statements are made for the case of treating each station individually. Several comments have been included in earlier paragraphs noting that the seasonal variation shown by the monthly values of both the pre-MRGO and post-MRGO salinities, and the month to month variation in the post-MRGO minus the pre-MRGO differences, are quite consistent among the four stations, and particularly among the 3 higher salinity stations. These observations suggest that the confidence which could be placed in the computed values of the pre- to post-MRGO differences is greater than indicated by the simple statistical analysis described above. It was also noted that the difference in the mean values of the pre-to post-MRGO salinities, for both annual and monthly data sets, increased with increasing salinity. Otherwise, the statistical parameters, such as the standard deviation, of the distribution of the monthly mean salinities, appear to be the same, at least for the three higher salinity stations. These observations then suggest that combined data sets for these three stations could be formed by adjusting the data from two of the stations so that these data sets had the same record length mean as the third station. Thus, for the station in the Chef Menteur

serving as the master data set, the monthly mean salinities for, say, the station at Little Woods would be multiplied by a factor equal to the record length mean of the Chef Menteur monthly mean salinities divided by the record length mean of the Little Woods monthly mean salinities. The data set for the station at North Shore would be similarly treated, and a composite data base formed from the data set for the Chef Menteur and the modified data sets for the other two stations.

23. The Committee performed such an exercise, the results of which are shown in Table A2 of Appendix A. This analysis indicates that in fact the values of the post-MRGO minus the pre-MRGO salinities for the annual averaged data are quite well known. The range in the 95% confidence limits given by this analysis for the Chef Menteur and the Little Woods stations is just  $\pm 16\%$  of the mean difference, and for the North Shore station, just  $\pm 17\%$ . The average range of the confidence limits for the monthly differences was  $\pm 52\%$  of the mean difference for all three stations. This is a considerably narrower confidence band than was found from considering each station individually.

#### On the Question of the Several Estimates of the Tidal Prism of Lake Pontchartrain

24. The details of the Committee's analysis of the several estimates of the tidal prism of Lake Pontchartrain found in the various reference materials available to the Committee, and the Committee's conclusion as to the best estimate of the tidal prism, are given in Appendix B. At the start of this investigation the Committee had available three estimates of the tidal prism of the Lake. One of these was a value contained on a the cover sheet to an informal briefing document provided by the District. This value of  $3.0 \times 10^9 \text{ m}^3$  was not accompanied by any supporting data or any references to reports or publications supporting this estimate. A second estimate was a value of  $2.55 \times 10^9 \text{ m}^3$  contained in WES Technical Report No. 2-636, dated November, 1963. The third estimate of the tidal prism initially evaluated by the Committee was based on information contained in a WES Letter Report to the U.S. Army Engineer District, New Orleans, dated April 1976, and entitled "Reduction in Lake Pontchartrain Tidal Prism Caused by Hurricane Barriers." This report gave values of the flood and ebb tidal averaged volume fluxes through each of the three passes to the Lake based on velocity measurements made in the 1963 hydraulic model of the subject waterways. Details of the Committee's analysis of these flux values as estimates of the tidal prism of the Lake are given in paragraph B2 of Appendix B. The estimate of the tidal prism based on these data is  $1.44 \times 10^9 \text{ m}^3$ . These three estimates thus range from  $1.44 \times 10^9 \text{ m}^3$  to  $3.0 \times 10^9 \text{ m}^3$ . Considering the importance of narrowing the uncertainty of these estimates in order to evaluate the consequences of the construction of a structure to effectively close off the exchange of water and salt between the IHNC and the Lake, the Committee considered it necessary to search for other data which could be used as a basis for the computation of the tidal prism.

25. The tidal prism of a semi-enclosed coastal water body having a connection via one or more passes or entrance channels to the adjacent open coastal waters is the average difference between the maximum volume and the minimum volume of the water body over a tidal cycle, under conditions that the variations in volume is the result of the astronomical tide. That is, the effects of meteorological forced changes in water level within the subject water body are not included in the calculations. The simplest algorithm expressing this definition is that the tidal prism is equal to the product of the range of the tide times the surface area of the subject water body. This statement is correct only if the tide in the water body is a standing wave, that is, the phase lag of the tide is constant over the surface of the water

body. Corrections for the effect of varying phase lags across the water body can be made by subdividing the area of the water body into segments for which a constant value of the phase lag is assigned. In the case of Lake Pontchartrain it can be shown that the effect of a varying phase lag reduces the computed value of the tidal prism compared to that calculated using the simple algorithm by less than 1%. In any case, the product of mean tide range times the surface area of the Lake gives the maximum possible value of the tidal prism of the Lake.

26. The Committee found several slightly different values for the surface area of Lake Pontchartrain quoted in the various documents provided by the District and in referenced publications. The Committee chose to use a value of  $1.644 \times 10^3 \text{ km}^2$  given by Poirrier (1973), which is intermediate to the other values found in the reference material. Using data from six tide gages deployed by the District over a 182 day period described by Outlaw (1982), Swenson and Chuang (1983) computed the mean range of the tide in Lake Pontchartrain to be 10.88 cm. Based on these values of Lake surface area and tide range, the maximum tidal prism of Lake Pontchartrain is  $1.79 \times 10^9 \text{ m}^3$ . The slight correction for the fact that there is some variation in the phase lag of the tide wave within the Lake results in a best estimate for the tidal prism of Lake Pontchartrain of  $1.78 \times 10^9 \text{ m}^3$ .

27. A second procedure for determining the tidal prism of a water body involves the use of measurements of current velocities taken at a number of points in a transect across the pass, or passes, which connect the subject water body to the adjacent open coastal waters which constitute the proximate source of the tidal energy in the water body. In the case of Lake Pontchartrain, the ideal application of this procedure would be the deployment of a number of vertical moorings across a transect in each of the three passes, with each mooring containing up to five current meters in the vertical. The instruments should be capable of *in situ* recording or the transmission of data to a surface buoy or to a shore station. These arrays should be deployed for periods of 35 days or longer. The number of moorings required to obtain good estimates of the volume flux would depend on the geometric complexity of the pass, and the number of current meters in the vertical would depend on the depth of the water and the vertical structure of the velocity distribution. The sampling rate of the current meters would depend on the amplitude of short term time variations in the local velocity. Longer time intervals between recordings of current meter readout can be utilized if the current meter is capable of taking vector averages of the velocity signal over the interval between recordings.

28. In the real world the cost of instrumentation has precluded the attainment of this ideal deployment of current meters. An alternate approach is to use survey vessels equipped with current meters having sensor packages which can be lowered and raised rapidly through the water column and having deck mounted readout units (or acoustic Doppler current profiling (ADCP) instruments.) The survey vessels moves rapidly from station to station back and forth across the transect. The rate at which measurements are to be made at each station should be no less than once an hour, and preferably once each 30 minutes, so that the number of stations that can be occupied in the transect depends on the width of the waterway. Where the width of the pass is such that fewer than three stations could be occupied within 30 minutes to an hour, the use of multiple survey vessels should be considered. The cost and availability of suitably equipped survey vessels and trained field parties preclude the use of this moving vessel procedure for long periods. Measurements in the passes to Lake Pontchartrain using this procedure have been limited to a duration of 25 hours, or just one diurnal tidal cycle.

29. A procedure of combining the use of long term moored current meter arrays (35 days) with the use of moving survey vessels over short time periods (25 hours), could provide lower costs without causing serious degradation in the results. The idea is to use fewer moorings, with each mooring having fewer than the ideal number of current meters in the vertical, and to calibrate the volume flux values calculated from this reduced array with data obtained using the moving survey vessel procedure during several 25-hr surveys during the longer term period of current meter deployment.

30. The Committee located three additional data sets which could be used to compute the tidal prism of Lake Pontchartrain. Each of these data sets was used by the Committee to obtain estimates of the tidal volume flux per tidal cycle through the three passes to the Lake. One of these data sets was from the paper by Swenson and Chuang (1983). The other two data sets were from the document by Outlaw (1982). Details of the Committee's analysis of the data provided by these three sources are given in Appendix B, paragraphs B5 through B8. The three values of the tidal prism of Lake Pontchartrain obtained by the Committee in its analysis of the data from these three data sets were  $1.56 \times 10^8 \text{ m}^3$ ,  $1.54 \times 10^8 \text{ m}^3$ , and  $1.72 \times 10^8 \text{ m}^3$ .

31. It would appear that the  $3.0 \times 10^8 \text{ m}^3$  estimate of the tidal prism need not be considered further. The WES (1963) report, which was the source of the statement that the tidal prism of Lake Pontchartrain is  $2.55 \times 10^8 \text{ m}^3$ , does not provide information on the procedures used to obtain this value. Of the other five estimates, one is based on the tidal range times surface area concept, one is based on the use of current velocity measurements made in the 1963 hydraulic model, and three are based on current velocity measurements in the prototype. The value based on the tide range times the surface area concept,  $1.78 \times 10^8 \text{ m}^3$ , is considered by the Committee to be the most probable correct estimate. A common feature of the four estimates based on the measurements of tidal volume flux through the three passes,  $1.44 \times 10^8 \text{ m}^3$ ,  $1.56 \times 10^8 \text{ m}^3$ ,  $1.54 \times 10^8 \text{ m}^3$ , and  $1.72 \times 10^8 \text{ m}^3$ , is that all are less than the estimate based on the tide range times the surface area procedure. Possible reasons for what would appear to be a common error for this type of measurement include the neglect of Stokes transport, and the fact that current meters using rotor or propeller based speed sensors are subject to decay in response due to biological fouling. Also, in most cases, navigation requirements precluded the deployment of long term moorings in main shipping channels, where maximum tidal currents are usually located. Unfortunately, no single major cause of this apparent underestimation of the flux through the passes has been identified, and no firm basis for applying a correction term to these estimates has been put forward.

#### On the Relative Contributions Through the IHNC to the Tidal Prism of Lake Pontchartrain.

32. As noted earlier in this report, several of the documents made available to the Committee, or obtained from the published literature, state that about 60% of the tidal prism of Lake Pontchartrain passes into and out through the Rigolets, 30% through the Chef Menteur, and 10% through the IHNC at Seabrook. The origin of these figures appears to be the published paper by Swenson and Chuang (1983). The emphasis on the word about is the Committee's. Swenson and Chuang do use this caveat, but without emphasis, in the referenced statement. However, these authors give the actual numerical values of the tidal flux through each of the passes that they determined from their analysis of the current meter records. They state that "A calculation of the tidal prism volume for each pass yields values of  $9.7 \times 10^7$ ,  $5.2 \times 10^7$  and  $7.0 \times 10^6 \text{ m}^3$  for The Rigolets, Chef Menteur and the IHNC, respectively". Based on these values, the relative contributions of each pass to the total tidal prism of

the Lake is 62.2% for the Rigolets, 33.3% for Chef Menteur, and 4.5% for the IHNC. The value of 10% given by these authors for the relative contribution of the IHNC appears to have been the result of a rather gross round off procedure. 62.2% rounds to about 60%, and 33.3% rounds to about 30%. The remaining 10% was then stated to apply to the contribution of the IHNC without actually using their data to obtain the correct percentage. As noted in paragraph B5, the total tidal volume flux of  $1.56 \times 10^8 \text{ m}^3$  is probably too small by about  $0.21 \times 10^8 \text{ m}^3$ . If all of this uncertainty is attributable to the measurements of the tidal volume flux through the IHNC, the percent relative contribution of this pass to the tidal prism of the Lake would increase to 7.9%. It does not seem likely that measurements of the tidal volume flux in the IHNC should be less accurate than such measurements in the two larger passes.

33. Paragraphs B11 and B12 of Appendix B give further details which support the contention that although the total tidal volume flux through the passes as estimated by Swenson and Chuang is probable too small, the values for the relative contributions of the various passes to the actual total tidal flux are not seriously in error. Also included in the Swenson and Chuang paper, and described in some detail in paragraph B13 of Appendix B, are estimates of the subtidal volume flux through the three passes. This analysis shows that the subtidal volume exchanges into and out of the passes are quite large, indicating the importance of coastal meteorologic forcing of variations in coastal sea level, which are in turn readily transmitted into the Lake through the passes. The net subtidal volume fluxes indicate that the Rigolets is flood dominated and both the Chef Menteur and the IHNC are ebb dominated, with the total net subtidal volume flux directed into the Lake. This is opposite to the direction required to discharge a volume of water through the passes equal to the inflow of fresh water to the Lake from the tributary rivers. Assuming that the fresh water inflow to the Lake during the period in which the current meters were deployed by Swenson and Chuang was the mean annual river discharge, then the deficit in ebb directed subtidal volume flux through the passes as determined by Swenson and Chuang would represent about 7.5% of the total ebb subtidal volume flux, a value perhaps indicative of the uncertainty in this type of measurement.

34. In view of questions raised by this analysis of the Swenson and Chuang paper, and because of the importance of the best estimates possible of the relative contribution of the IHNC to the tidal exchange of water and salt through the several passes to Lake Pontchartrain, the Committee concluded that a search should be conducted to find other data sets which could be used to obtain estimates of the relative contribution of each of the passes to the combined tidal volume flux through the three passes. One of the sources found was the WES Letter Report dated April 1976 referred to in paragraph 24 above, and described in detail in paragraphs B2 and B14 of Appendix B. This report included estimates of the tidal cycle average of the flood and ebb volume exchanges into and out of the Lake through each of the three passes. The tidal volume flux values obtained by taking the average of the absolute values of the flood and ebb volume exchanges were  $8.74 \times 10^7 \text{ m}^3$  for the Rigolets;  $4.45 \times 10^7 \text{ m}^3$  for the Chef Menteur; and  $1.24 \times 10^8 \text{ m}^3$  for the IHNC; for a total tidal volume flux through the three passes of  $1.44 \times 10^8 \text{ m}^3$ . The relative contribution of the IHNC to the total tidal volume flux through the three passes given by this analysis is 8.4%, a value nearly twice as large as that computed from the Swenson and Chuang results. Paragraph B14 of Appendix B presents detailed arguments as to why lower confidence should be placed on this estimate of the contribution of the IHNC to the total tidal volume flux through the passes. Included in these arguments is the fact that the estimates in this paragraph are based on data obtained from the 1963 hydraulic model, which was built and verified before the MRGO was completed.

35. The two other data sets used by the Committee to evaluate the probable relative contribution to the tidal volume flux through the three passes to the Lake are the two data sets from Outlaw (1982) already mentioned in paragraph 30 above and described in detail in paragraphs B6 through B8, and paragraphs B15 through B17, of Appendix B. The estimates of the relative contribution of the IHNC to the total tidal volume flux through the three passes obtained by the Committee in its analysis of these two important data sets were 3.5% and 4.8%. More reliance should be placed on the second of these estimates, since it is based on current meter measurements in the three passes which returned good records with record lengths varying from 27 days to 47 days. The value of 3.5% listed above was obtained by an analysis of a 25-hr long study using survey boat based measurements at two stations in transects in each pass. This data set is valuable in that the measurements were made at three depths at two stations in each transect, but its length of just one tidal cycle places a higher uncertainty on the tidal flux calculations.

36. There were thus four estimates of the relative contribution of the IHNC to the total tidal volume flux through the three passes, and hence of the relative contribution of the IHNC to the tidal prism of Lake Pontchartrain, obtained in the Committee's analysis of the several data sets described in previous paragraphs. These estimates are: 4.5% from the analysis by Swenson and Chuang (1983); 8.4% from the analysis contained in the WES 1976 Letter Report, in which data from the 1963 hydraulic model study were utilized; 3.5% from the 25-hr data set tabulated in Outlaw (1982); 4.8% from the intensive 50 day survey data set given in Outlaw (1982). See Table B1 in Appendix B for a listing of the six estimates of the tidal prism of Lake Pontchartrain and of the four estimates of the tidal volume flux values through each of the passes. It appears unlikely that the relative contribution of the IHNC to the tidal prism of Lake Pontchartrain exceeds 5%.

On the Relative Contributions Through the IHNC to the Total Tidal Salt Flux into Lake Pontchartrain.

37. The proper procedure for the determination of the flux of salt through the passes connecting Lake Pontchartrain to the adjacent coastal waters involves the simultaneous measurements of current velocity and salinity at a number of points in a cross section in each of the three passes. These ranges should contain at least three stations distributed across each of the passes, and measurements should be made at up to five positions in the vertical. Current velocity and salinity measurements should be made at time intervals of between 30 minutes and one hour over a period of about 35 days, in order to obtain measurements at all epochs of the diurnal tidal cycle, at each measurement position in the vertical at each station in the range. The number of positions in the vertical at which measurements should be made depends on the vertical variation of the current velocity and salinity, while the number of stations in each range depends upon the lateral variation in current velocity and salinity, and also upon the width of the pass at the range selected for measurement.

38. One procedure for obtaining such a data set is to deploy vertical taut wire moorings at each station, on which are mounted *in situ* recording current meters and salinometers. The salinometers may be part of the current meter package or contained in a separate package which can be mounted close to each current meter. No such ideal data set has been obtained for the three passes of concern here. An alternate procedure for obtaining the desired data set is to use a survey vessel equipped with a current meter and a salinometer, the sensor packages of each having the capability of being lowered and raised rapidly through the water column and of transmitting data via cable or acoustically to deck mounted readout or recording units on the survey vessel.

ADCP equipment can replace the velocity part of these sensor packages, but not the salinity part. This survey vessel would move rapidly from station to station back and forth across the range. There would have to be at least one such survey vessel for each pass. The cost together with the logistic complexity of this approach has, however, generally limited such undertakings to durations of about 25 hours, or over a single diurnal tidal cycle. The Committee has located one such 25-hr data set, and made use of this data set to determine the salt flux through each of the three passes for that single diurnal tidal cycle. The procedure used in determining the tidal and subtidal salt flux over this 25-hr period is described in detail in paragraphs B21 and B22.

39. As a consequence of the lack of simultaneous measurements of current velocity and salinity at a number of positions in ranges in each of the three passes, over a number of diurnal tidal cycles, a less accurate procedure is employed that makes use of independent data sets of current velocity and salinity. The two sets of current velocity measurements which were utilized to obtain estimates of the tidal prism of Lake Pontchartrain, and of the volume flux in the three passes, as described in paragraphs 30, 32, and 32 above, and in more detail in Appendix B, were used again here. The available salinity observations for each of the three passes were used to obtain estimates to the mean salinity over the period of flood directed flow and over periods of ebb directed flow characteristic of the location and the season during which the current velocity measurements were made. The details of the procedure used to obtain estimates of the tidal and subtidal flux of salt from these data sets is described in paragraphs B20, and B24 through B27. The pertinent parameters of concern in comparing the contribution of each of the passes to the total flux of salt to Lake Pontchartrain is the net tidal and subtidal salt flux.

40. The results of use of these procedures on the 25-hr data set given in Outlaw (1982) follow: (a) For the Rigolets, the computed flood tidal salt flux was  $7.04 \times 10^8$  kg and the computed ebb directed tidal salt flux was  $-6.35 \times 10^8$  kg. (b) For the Chef Menteur, the computed flood directed salt flux was  $4.84 \times 10^8$  kg and the computed ebb directed tidal salt flux was  $-4.53 \times 10^8$  kg. (c) For the IHNC, computed flood directed tidal salt flux was  $5.23 \times 10^7$  kg and the computed ebb directed tidal salt flux was  $-4.23 \times 10^7$  kg. (d) The total computed tidal salt flux through all three passes was, for flood,  $1.24 \times 10^9$  kg, and for ebb,  $-1.13 \times 10^9$  kg. Note that by definition, the tidal volume flux is zero centered, so that there is the same absolute value of flood volume flux and the ebb volume flux. The tidal salt flux is not necessarily zero centered, since the time variations in salinity is a determining factor whether the flood directed or the ebb directed tidal salt flux will be the larger. For the case of an estuary, in which higher salinity water occurs toward the sea, the flood tidal salt flux will usually be larger than the ebb tidal salt flux, since the salinity during flood will usually be larger than the salinity during ebb. The net tidal salt flux, which is the difference between the flood tidal salt flux and the ebb tidal salt flux is the required quantity to consider here. (e) The computed net salt flux through the Rigolets for this data set was  $6.89 \times 10^7$  kg; through the Chef Menteur,  $3.12 \times 10^7$  kg; and through the IHNC,  $9.96 \times 10^6$  kg; the total net tidal salt flux was then  $1.10 \times 10^8$  kg. (f) The computed percentage contribution of each pass to the total net salt flux to Lake Pontchartrain was then 62.8% for the Rigolets, 28.4% for the Chef Menteur, and 9.0% for the IHNC.

41. Based on the data set from Swenson and Chuang (1983), the Committee made estimates of the tidal salt flux through each of the passes, as described in detail in paragraphs B22 and B26 through B28, which gave the following results:

(a) For the Rigolets, the computed value of the flood tidal salt flux is  $4.80 \times 10^8$  kg, and the ebb tidal salt flux is  $-4.51 \times 10^8$  kg. For the Chef Menteur, the computed value of the flood tidal salt flux is  $2.29 \times 10^8$  kg, and the ebb tidal salt flux is  $-2.13 \times 10^8$  kg. For the IHNC, the computed value of the flood tidal salt flux is  $5.25 \times 10^7$  kg, and the ebb tidal salt flux is  $-4.76 \times 10^7$  kg. Values of the net tidal salt flux, which is the parameter of concern for this analysis, are then  $2.91 \times 10^7$  kg for the Rigolets,  $1.56 \times 10^7$  kg for the Chef Menteur, and  $4.90 \times 10^6$  kg for the IHNC, for a total net tidal salt flux through the three passes of  $4.96 \times 10^7$  kg. The relative contributions of each of the passes to the total net tidal salt flux are then, for the Rigolets, 58.7%, for the Chef Menteur, 31.5%, and for the IHNC, 9.9%. Note that all of these net tidal salt flux values are positive, or into Lake Pontchartrain.

(b) The net subtidal salt flux values computed using the procedures described earlier together with the data from Swenson and Chuang are: for the Rigolets,  $-3.04 \times 10^7$  kg; for the Chef Menteur,  $-1.73 \times 10^7$  kg; and for the IHNC,  $-5.67 \times 10^6$  kg, for a total net subtidal salt flux of  $-5.33 \times 10^7$  kg. Note that this total is negative, as are the values for each pass, indicating a net discharge of salt from the Lake due to the subtidal processes. A discharge of salt from the lake by the subtidal processes is expected, in order to balance the net tidal flux of salt into the Lake. The computed discharge of salt from the Lake by the subtidal salt flux process is greater than the computed input of salt by the net tidal salt flux process. The computed value of this net tidal plus subtidal salt flux is  $-3.69 \times 10^6$  kg.

(c) As pointed out in paragraph B23, the characteristic seasonal pattern of salinity in Lake Pontchartrain requires that during roughly half of the year there must be a net flux of salt through the passes into the Lake and for the other half of the year there must be a net flux of salt through the passes out of the Lake. The 35 day long survey period in which Swenson and Chuang deployed their current meters extended from February 23 through March 29, 1980. This is during the spring period of decreasing average salinity of the Lake. From the salinity data described in Appendix A, the salinity of Lake Pontchartrain decreased during the spring of 1980 at a rate of  $1.81 \times 10^{-3}$  kg/m<sup>3</sup>/day. Such a decrease in average salinity requires a net tidal plus subtidal salt flux through the three passes of  $-1.08 \times 10^7$  kg per tidal cycle. Although of the correct sign, this value is much larger than that of the net tidal plus subtidal salt flux given in paragraph (b) above. Note that this discrepancy has no bearing on the computed values of the relative contributions of each of the three passes to the total tidal flux of salt through the passes.

42. Based on data from the 50 day intensive survey given in Outlaw (1982), the Committee made estimates of the tidal salt flux through each of the passes as described in detail in paragraph B27, which gave the following results:

(a) For the Rigolets, the computed value of the flood tidal salt flux is  $9.06 \times 10^8$  kg, and the ebb tidal salt flux is  $-8.00 \times 10^8$  kg. For the Chef Menteur, the computed value of the flood tidal salt flux is  $4.60 \times 10^8$  kg, and the ebb tidal salt flux is  $-4.03 \times 10^8$  kg. For the IHNC, the computed value of the flood tidal salt flux is  $8.94 \times 10^7$  kg, and the ebb tidal salt flux is  $-7.29 \times 10^7$  kg. Values of the net tidal salt flux, which is the parameter of concern for this analysis, are then  $1.07 \times 10^8$  kg for the Rigolets;  $5.68 \times 10^7$  kg for the Chef Menteur; and  $1.66 \times 10^7$  kg for the IHNC; for a total net tidal salt flux through the three passes of  $1.80 \times 10^8$  kg. The relative contributions of each of the passes to the total net tidal salt flux are then, for the Rigolets, 59.3%; for the Chef Menteur, 31.5%; and for the

IHNC, 9.2%. Note that all of these net tidal salt flux values are positive, of into Lake Pontchartrain.

(b) The net subtidal salt flux values computed using the procedures described earlier together with the data from Outlaw are: for the Rigolets,  $-7.55 \times 10^7$  kg; for the Chef Menteur,  $5.74 \times 10^7$  kg; and for the IHNC,  $-2.86 \times 10^6$  kg; for a total net subtidal salt flux of  $-2.10 \times 10^7$  kg. The net subtidal salt flux values for the Rigolets and the IHNC are ebb dominated while the value for the Chef Menteur is flood dominated. However, the total flux through all three passes is negative, indicating a net discharge of salt from the Lake due to the subtidal processes. A discharge of salt from the lake by the subtidal processes is expected, in order to balance the net tidal flux of salt into the Lake. The computed discharge of salt from the Lake by the subtidal salt flux process is, however, less than the computed input of salt by the net tidal salt flux process. The computed value of this net tidal plus subtidal salt flux is  $1.59 \times 10^8$  kg, indicating that there is a net tidal plus subtidal flux of salt into Lake Pontchartrain.

(c) The months of September and October of 1978 and of August and September of 1979, when the data processed by Outlaw were obtained, are at the end of the period of the year during which the salinity of Lake Pontchartrain is increasing. There is insufficient salinity data available for these specific months to determine an applicable rate of increase of salinity. The average spring to fall salinity increase for the Lake as described in Appendix A would require a combined net tidal plus subtidal flux of salt through the three passes into the Lake of  $1.26 \times 10^8$  kg. This is only slightly less than the value of  $1.59 \times 10^8$  kg given in the just previous paragraph.

43. The Committee has thus made three estimates of the tidal and subtidal flux of salt through the three passes into Lake Pontchartrain, using three different data sets. The three estimates of the relative contribution of the IHNC at Seabrook to the combined net tidal salt flux through the three passes are 9.0%, 9.9%, and 9.2%. See Table B2 in Appendix B for a listing of the three estimates of the total net tidal salt flux into Lake Pontchartrain, and of the three estimates of the net tidal salt flux values through each of the passes.

#### On the Salt Flux to Lake Borgne from the MRGO via Three Bayou Inlets and the GIWW

44. As described in detail in Appendix C, paragraphs C3 through C9, the Committee undertook to obtain estimates of the salt flux from the MRGO into Lake Borgne via three bayou inlets. The WES report by Outlaw (1982) provides one of the data sets used for the analyses described in Appendix C. The other source of data used by the Committee in its appraisal of this route for salt flux from the MRGO is a WES report authored by Fagerburg (1990). Insight into the processes operating in the exchange of water and salt between the MRGO and Lake Borgne was provided by the WES report authored by Donnell and Letter (1991).

45. During the 50 day intensive survey period described by Outlaw (1982), current meters were deployed in three inlets at the mouths of bayous which cross the MRGO. The three bayous involved were Bayou Yscloskey which enters Lake Borgne near Mile Marker 41, Bayou Dupre which enters Lake Borgne near Mile Marker 51 at a landmark in the Lake called Martello Castle, and Bayou Bienvenue which enters Lake Borgne about 3.5 mile NNE from the Martello Castle. The current meters deployed in these three inlets returned good records for periods ranging from 27 to 32 days. Outlaw computed the significant tidal constituents for the tidal currents from these records. He also computed the record length residual mean current velocities and the root

mean square (rms) of the variations in the currents left unaccounted for by the tidal constituents. Using these tidal constituents, the Committee determined a mean diurnal tidal current amplitude for each of three inlet stations. The residual mean current plus the absolute value of the rms amplitude gives the flood directed subtidal current, while the residual mean current minus the absolute value of the rms amplitude gives the ebb directed subtidal current.

46. Fagerburg (1990) describes data collected by survey vessels in Bayou Yscloskey inlet, in Dupre Bayou inlet, and at three locations in the MRGO. These data provided estimates of the mean salinities in each of the inlets during periods of flood flow and during periods of ebb flow. Information on the depths of the inlets just lakeward from the MRGO is also given by Fagerburg. Paragraph C6 of Appendix C describes the additional sources of information used to obtain the cross-sectional areas of the inlets. This paragraph also gives the mean salinities for the flood and ebb periods as determined from the Fagerburg salinity data.

47. Using the above described data sets, the net tidal plus subtidal salt flux from the MRGO to Lake Borgne was computed to be  $4.09 \times 10^7$  kg. Since there are no continuity based constraints on the net subtidal salt flux values for these inlets as were described for the passes to Lake Pontchartrain, it is the net tidal plus subtidal salt flux values for these inlets which are the appropriate parameters to consider in comparing the input of salt to Lake Borgne from these inlets on the one hand to the input of salt to Lake Pontchartrain from the IHNC at Seabrook on the other. Of the three estimates made in Appendix B for the net tidal salt flux through the IHNC, the one most appropriate to use for this comparison is the one determined using the data set from the intensive 50 day survey given in Outlaw (1982), since this is the same source of the data used in obtaining the estimates of the salt flux through the three inlets to Lake Borgne from the MRGO. This estimate of the net tidal salt flux through the IHNC is also the largest of the three estimates made by the Committee. As given in subparagraph (a), paragraph B27, of Appendix B, the computed value of the net tidal salt flux through the IHNC, using the 50 day survey data set from Outlaw, is  $1.66 \times 10^7$  kg, a value smaller than the estimated net salt flux from the MRGO to Lake Borgne through the subject three inlets of  $4.09 \times 10^7$  kg. by a factor of about 2.5.

48. Outlaw (1982) also gives the results of computations of the significant tidal constituents for the tidal currents, as well as the record length residual mean current and the rms current amplitude, from a 32 day long record from an *in situ* recording current meter deployed in the GIWW. The current meter was moored about one km ENE from the intersection of the MRGO with the GIWW. The net subtidal volume flux at this location is directed ENE toward the intersection of the GIWW with the Chef Menteur and the Rigolets. The diurnal tidal current amplitude in the GIWW is relatively small, but the residual mean current is relatively large, and this station showed a relatively large rms amplitude.

49. Extrapolation of the salinity measurements at the three ranges in the MRGO provided an estimate of the mean salinities during the flood and ebb flow periods. Using these data with the flood and ebb volume flux values computed from the current meter data, the net tidal salt flux in the GIWW was estimated to be about  $1.44 \times 10^6$  kg, which is only 7.5% of the net tidal salt flux to Lake Borne from the MRGO through the three Bayou inlets for which current meter data is available. However, the net tidal plus subtidal salt flux through the GIWW and directed ENE is considerably larger than the net tidal salt flux alone. The calculated value is  $6.09 \times 10^7$  kg, which is larger than the either the net tidal plus subtidal salt flux through the three bayou

inlets or the net tidal salt flux to Lake Pontchartrain through the IHNC. The reason that the net subtidal salt flux is so high is that both the residual mean velocity and the rms amplitude at the current meter station in the GIWW are high compared to the value of these parameters in the IHNC and in the three bayou passes. Also, the subtidal volume flux is directed toward the Chef Menteur, while in the IHNC the subtidal volume flux, and hence the subtidal salt flux, must be directed out of Lake Pontchartrain in order to discharge a part of the fresh water which enters the Lake from tributary rivers, and in order to provide for the return out of the Lake a portion of the salt which has entered the Lake by the net tidal salt flux. Also note that even though the volume flux in the bayou passes is much smaller than the volume flux through the IHNC, the difference between the mean salinity during flood flow and the mean salinity during ebb flow is much larger in the bayou passes than in the IHNC.

50. The sum of the net tidal plus subtidal salt flux to Lake Borgne from the three bayou inlets and the GIWW is computed to be  $1.02 \times 10^8$  kg, which is about 6 times the maximum value salt flux through the IHNC to Lake Pontchartrain computed by the Committee. The intersection of the GIWW and the Chef Menteur is close to the Lake Borgne end of the Chef, and hence most of the salt flux from the GIWW will enter Lake Borgne at a location just across the Lake from the Biloxi Marshes. The following table is a summary of the averages of the various values of the tidal prism of Lake Pontchartrain and of the volume and salt fluxes computed by the Committee.

TABLE 3-2 Summary of Average Values of the Tidal Prism of Lake Pontchartrain ( $m^3$ ), and of the Tidal Volume Flux ( $m^3/tc$ ) and the Salt Flux ( $kg/tc$ ) and from the MRGO into Lake Borgne via the Bayou Inlets and the GIWW					
ITEM	LAKE PONTCHARTRAIN	RIGOLETS	CHEF MENTEUR	IHNC AT SEABROOK	MRGO INTO LAKE BORGNE
TIDAL PRISM	$1.77 \times 10^8$	N/A	N/A	N/A	N/A
VOLUME FLUX	N/A	$9.51 \times 10^7$ 60.7%	$5.33 \times 10^7$ 34.0%	$8.27 \times 10^6$ 5.3%	N/A
SALT FLUX	N/A	$6.82 \times 10^7$ 60.3%	$3.45 \times 10^7$ 30.5%	$1.05 \times 10^7$ 9.3%	$1.02 \times 10^8$

Total =  $1.13 \times 10^8$

51. The above observations suggest that overall salinity change questions should focus primarily on the MRGO-Lake Borgne connections. It is further noted that any future natural enlargement of those openings could increase Lake Borgne salinities further.

#### 4 ANSWERS TO THE QUESTIONS POSED BY THE DISTRICT

52. The questions as given in Section 1 under the heading Purpose have been divided into sub-questions in order to facilitate the presentation of the answers and of the supporting statements and comments. The thus modified questions and the Committee's response are given below.

Question: Can the contribution of the MRGO-IHNC to the increase in salinity in Lake Pontchartrain and adjacent waterways be economically controlled by reducing the volume of MRGO flow into the Lake?

Answer:

53. The answer to the above question will be subdivided in terms of the mechanisms which might be used to attain the reduction in volume of the MRGO flow into the Lake.

For the Case of Control of the Volume of MRGO Derived Salt Water by Construction of a Structure in the IHNC at Seabrook

54. For the case of control of the volume of MRGO flow into Lake Pontchartrain by construction of a solid barrier structure, such as a lock at Seabrook similar to the existing preliminary design, the answer to this question is no. The problem is not the physical ability to build such a structure and have it function to effectively stop the flux of MRGO derived salt water from passing through the IHNC into the Lake. The problem is, in part, that there is evidence that such a structure could not be economically justified in terms of the reduction in the mean salinity of Lake Pontchartrain and, in particular the salinities in Lake Borgne and over the Biloxi Marshes. Using five different data sets, the Committee concluded that the relative contribution of the tidal volume flux from the IHNC to the Lake is most probably less than 5% of the total tidal volume flux through all three passes, and that the relative contribution of the net tidal flux of salt from the IHNC into the Lake is most probably less than 10% of the total net tidal salt flux through all three passes. At the very most, the complete closure of the IHNC at Seabrook would reduce the salinity increase that has occurred in eastern Lake Pontchartrain since the completion of the MRGO from an average value, based on pre-MRGO to post MRGO salinities as measured at Little Woods and North Shore, of about 1.5 kg/m<sup>3</sup> (ppt), to a value of between 1.3 and 1.4 kg/m<sup>3</sup>. The District has a regression model which can be used to estimate the volume rate of fresh water input to the Lake via the proposed diversion at Bonnet Carré to provide the same decrease in the salinity of the Lake that complete closure of the IHNC at Seabrook would accomplish. The Committee has not made this detailed calculation, but a rough estimate indicates that a diversion of less than 1000 cfs ( $\approx 28 \text{ m}^3/\text{s}$ ) would be adequate.

55. In addition, the Committee concludes that the IHNC is not the only route by which MRGO derived salt can enter Lake Pontchartrain. Based on the analysis of data obtained from several sources, it appears likely that there is a net flux of salt from the MRGO directly into Lake Borgne via bayous which intercept and cross the MRGO along the reach of this waterway where it passes within a few hundred feet of the shore line of Lake Borgne. A net flux of salt directed towards the Chef Menteur and the Rigolets also occurs via the GIWW, and thus adds salt to the Chef Menteur near to its entrance into Lake Borgne. These higher salinity waters would then enter Lake Borgne, and possibly also Lake Pontchartrain, from the Chef Menteur. The Committee's calculations of the net tidal plus subtidal salt flux from the MRGO to Lake Borgne via the bayou inlets and the GIWW is considerably larger than the flux of salt into Lake Pontchartrain via the IHNC. Pre-MRGO and post-MRGO salinity

data obtained by the District indicates that the salinity increase following the completion of the MRGO was larger in the Chef Menteur and in the Rigolets than at locations within the eastern part (the portion of the lake nearest to these two passes). This condition indicates that Lake Pontchartrain is not the primary source of added salt to the two natural passes. The flux of salt to Lake Borgne directly from the MRGO would lead to an increase in salinity of that Lake, and would likely be the primary source of increased salinities over the Biloxi Marshes.

56. It is quite possible that the closure of the IHNC at Seabrook would lead to an increase in the net salt flux into Lake Borgne and the Chef Menteur from the bayou inlets and the GIWW. This possibility is based on the observations made by Donnell and Letter (1991) that the volume flux and consequently the salt flux through the bayou inlets depend upon the difference in the tidal average elevations in the MRGO and in the adjacent Lake Borgne. The closure of the IHNC at Seabrook would likely increase the head in the MRGO, thus increasing the net tidal plus subtidal salt flux into Lake Borgne. This in turn would increase the salt content in the Chef Menteur and the Rigolets, which would likely result in an increase in the salinity of Lake Pontchartrain by about the same amount as the decrease which might result from the closure of the IHNC. The complete closure of the IHNC at Seabrook is unlikely to have any measurable favorable effect on the salinities over the oyster beds in the Biloxi Marshes and adjacent areas. In fact, the converse is quite possible.

57. A comment is needed regarding observations of high salinities, particularly near the bottom, in Lake Pontchartrain close to the Seabrook, where the IHNC discharges to the Lake. Poirrier (1978) shows plots of surface and bottom salinity observations taken at monthly intervals during the period July 1976 through June 1977, missing only measurements in January. Observations were made at 12 stations. The four stations within 3.5 miles of the Seabrook end of the IHNC show that the largest differences between surface and bottom salinities occur in the July to September period. The measurements taken in August 1976 at the station nearest to Seabrook gave a surface salinity of 5.0 ppt and a bottom salinity of 14.6 ppt, for a difference of 9.4 ppt. Similar vertical gradients have been observed during the summer, usually in August, of other years, often at stations in the deep hole where bottom material was dredged to supply fill for the Lakefront Airport. Normally, salinities decrease rapidly with distance away from Seabrook.

58. However, the District provided the Committee with a handout showing contours of salinity in Lake Pontchartrain in August of 1980. These contours show a plume of higher than normal salinities extending northward from Seabrook. Bottom salinities of over 15 ppt occur within a plume which extends 3.9 miles northward from Seabrook, and the 9 ppt contour extends north northeastward about 11 miles, or two-thirds of the way across the Lake. At the same time, a separate 9 ppt contour indicates a plume of higher salinity water extending westward from the semi-enclosed basin in which the Chef Menteur and the Rigolets enter the Lake. This salinity distribution in August of 1980 appears to contradict the conclusion of the Committee that the IHNC contributes less than 10% of the salt flux to Lake Pontchartrain, and requires some explanation, which follows below.

59. This August 1980 distribution of high salinity water extending so far into the Lake appears to be an unusual condition. The WES report by Outlaw (1982) contains some salinity measurements made at mid-depth and a number of conductivity and temperature measurements made at the surface, middepth and bottom along transects which crisscross the Lake. The Committee has converted the conductivity and temperature readings to salinity. These data do not show any similar pattern of a high salinity plume extending

outward from Seabrook. Salinity data shown for the Lake side of Seabrook on the 10th of July 1979, gave a middepth value of 6.3 ppt, but a station about 4.2 miles further into the Lake had a middepth salinity of just 1.6 ppt. Data from a survey made on 17-18 July showed a middepth salinity at the station just lakeward from Seabrook of 4.0 ppt, but the station 4.2 miles farther into the Lake had a salinity of 1.8 ppt. On 2 August, the middepth salinity at the Seabrook station had a value of 2.3 ppt, as did the two other stations closest to Seabrook. On the 9th of August, the station at Seabrook had a salinity of 3.0 ppt, while the nearby stations each had salinities of 2.3 ppt. Two transect surveys were reported by Outlaw (1982). One was conducted between the 12th and the 15th of October during which some 114 stations were occupied on ranges which crisscrossed Lake Pontchartrain and Lake Borgne. The second was conducted between the 27th and 29th of August during which some 52 stations were occupied on the same ranges. Measurements were made at the surface, the middepth and the bottom. During the transect survey made in October of 1978, the station just lakeward from Seabrook had a bottom salinity of 7.21 ppt. There was otherwise no clear pattern in the salinity distribution over the Lake east of the causeway, with the exception of some low values near the mouths of streams entering the north shore. Salinities on the bottom varied from near 3.0 ppt to slightly over 5.0 ppt. Westward of the causeway lower salinities were observed. Vertical gradients were small except for the station at Seabrook where the surface salinity was 4.48 ppt and the bottom salinity, as already noted, was 7.21. During the August 1979 transect survey, there were no salinities higher than 3.73 ppt except within about 4.5 miles westward from the Chef Menteur and the Rigolets, where salinities ranging from 4.39 ppt to 6.23 ppt occurred.

60. As described in some detail by Chuang and Swenson (1981), Lake Pontchartrain is frequently subjected to relatively large subtidal variations in water surface elevations. These aperiodic variations in mean tide level within the Lake are caused by meteorological events over the open coastal waters which respond by alternately increasing and decreasing off shore sea level. Most of the energy in these subtidal variations in water surface elevations is associated with inverse frequencies of about 4 days, and hence is clearly distinct from the astronomical diurnal and semidiurnal tides. Occasionally an offshore meteorological event will cause an unusual high stand of tidal averaged water level in the Lake. During the period of rising water level the duration and strength of flood directed flow through the passes is increased and the strength and duration of the ebb directed flow is decreased. Such a circumstance results in an increase of the salt flux into the Lake. The subtidal flux of salt at Seabrook, which is normally ebb dominated, that is, normally carries salt out of the Lake, becomes flood dominated, thus adding to instead of subtracting from the flood dominated tidal salt flux. After several days this situation must reverse. The meteorological conditions causing the offshore rise in sea level cease and in fact often reverse. In any event, there must be a relaxing of the superelevation of the tidal mean water surface in the Lake, leading to an excess of ebb directed outflow of salt from the Lake. Over the long term, these meteorological events will average out.

For the Case of the Construction of a Structure or Structures in the MRGO for Control of the Flow of High Salinity Waters From the MRGO Into Lake Pontchartrain via the IHNC at Seabrook.

61. The construction of a structure in the MRGO itself, particularly below Mile Marker 27, would effectively reverse the pre-MRGO to post-MRGO rise in salinity, not only in Lake Pontchartrain but also in Lake Borgne and in the Biloxi Marshes. The construction of such a structure in the MRGO would undoubtedly not be economically or operationally feasible. It is mentioned here in order to direct the readers attention to a variety of ways in which

the flux of salt into Lake Pontchartrain and into Lake Borgne and to the Biloxi Marshes might be reduced. The fact that there probably is a large salt flux from the MRGO into Lake Borgne via the bayou inlets has been described above, and treated in greater detail in Appendix C. If the flux of salt from the MRGO into Lake Borgne through the bayou inlets could be reduced, then lower salinities would certainly occur in Lake Borgne and the Biloxi Marshes. Salinities would also be lowered at the entrances to the Chef Menteur and the Rigolets, which would result in a lowering of the salinity in Lake Pontchartrain. Whether or not this chain of events would result in decreases in salinity large enough to be considered worth the cost of control is a question that the Committee has not undertaken to try to answer. It is recommended that this possibility of reducing the flux of salt from the MRGO directly into Lake Borgne via the bayou inlets should be a subject of an engineering study.

Question: Can the contribution of the MRGO-IHNC to the increase in salinity in Lake Pontchartrain and adjacent waterways be economically controlled by reducing the salinity of the MRGO flow into the Lake?

62. Even though the Committee has concluded that the contribution of the IHNC to the flux of salt into the Lake is too small to justify the costs of a lock at Seabrook, the fact that water of high salt content, the proximate source of which is the IHNC, does enter the Lake and accumulates in the deep holes just offshore from Seabrook is a matter of some concern. These holes have depths of over 60 feet, and the high salt content of the water which accumulates in them, coupled with the low salinity water at the surface, results in a highly stable vertical density distribution. Mixing is curtailed by such a situation, and the dissolved oxygen concentration in the holes is reduced, resulting in hypoxic and perhaps anoxic conditions. For these reasons other than the Biloxi Marshes salinity goals, the Committee believes that consideration should be given to the construction of a structure which might limit the salt content of the waters which enter the Lake from the IHNC.

63. One such structure would be a jetty - submerged sill combination built offshore from Seabrook. Figure 2 shows a possible location for such a structure. It would consist of a sheet piling or stone jetty extending in an arc from the both shores out to a central section which would be built up to a level of, say 12 feet below mean low water. As depicted in Figure 2, the center of the structure would be about 955 ft (291 m) north of the railroad bridge at Seabrook. The length along the arc of the structure, from shore to shore, would be about 2175 ft (663 m). The side reaches of the arc would be built above mean high water. The center submerged sill section would be about 710 ft (216 m) long, and would be bounded by the 20 foot depth contour. The cross sectional area above the sill would then be about 8520 ft<sup>2</sup> (792 m<sup>2</sup>). The flood and ebb peak currents over the sill would be about 1.25 ft/s (0.38 m/s).

64. The purpose of such a structure would be to limit the amount of higher salinity near bottom water that flows into the Lake from the IHNC. There is good evidence that the Lake waters close to Seabrook are partially stratified during the months of July through October, with maximum stratification occurring in August. The success of a sill structure to limit the flow of higher salinity deep water over the sill and into Lake Borgne depends on the degree of stratification of the water flowing from the IHNC. Although there is a considerable number of observations of the vertical salinity structure in the Lake just outside of the IHNC at Seabrook, and observations have shown the MRGO to be partially stratified, the Committee could find only one set of salinity data for the IHNC itself. This data set is the 25-hr time series study reported in Outlaw (1982). The vertical

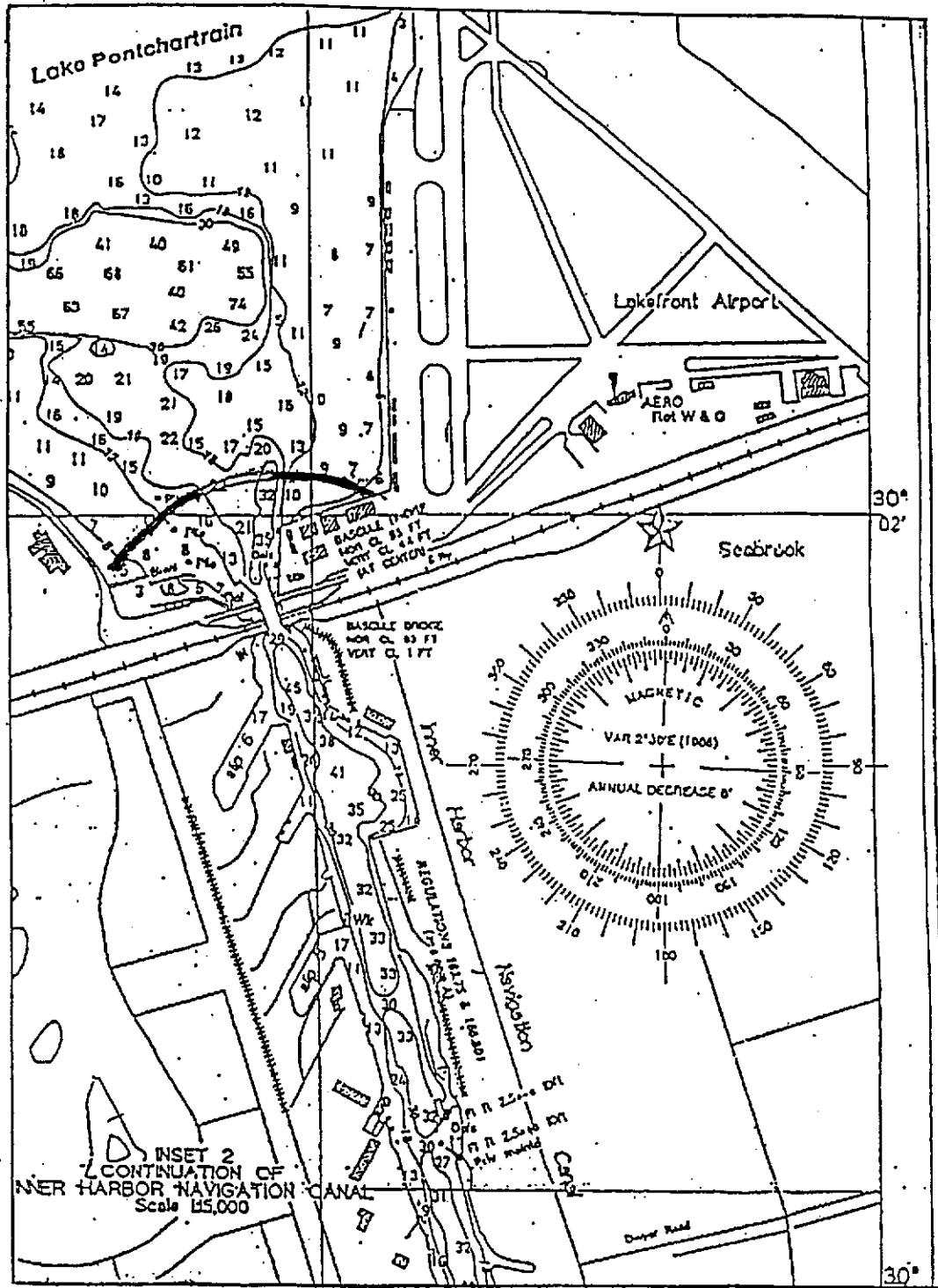


Figure 2. Suggested location of a passive control structure to limit the discharge to Lake Pontchartrain of the higher salinity near bottom waters in the flood discharge from the IHNC. The structure would consist of an arc shaped jetty - submerged weir combination. The center 955 ft (291 m) reach of the structure would be a submerged weir having a sill depth of, say, 12 ft (3.7 m), below mean lower low water. The two shoreward wings of the structure would be built to mean high tide or above.

salinity structure in the IHNC during this survey was only weakly stratified. This particular 25-hr period was not representative of normal conditions, since the Lake was in the process of relaxing from a superelevated condition. Flows were strongly ebb dominated through all of the passes in order to discharge the excess water volume in the Lake. This situation may have resulted in the water within the IHNC to destratify. In any case, no significant effort should be spent on engineering and economic studies of such a structure until the degree of stratification of the waters in the IHNC is determined by further observations.

65. Another way of reducing the salt content of water entering Lake Pontchartrain from the IHNC at Seabrook is to reduce the salt content of water reaching the IHNC from the MRGO. Fagerburg (1990) lists salinity data collected over several 8-hour long surveys of currents at three locations in the MRGO. Stations were occupied at three ranges in the MRGO from about 0730 to 1530 hours on each of three days (26 October, 11 November, and 27 November, 1988). These data indicate that, at least at this time of year, the MRGO is partially stratified. At Range 1, which is located at Mile Marker 27, the surface, middepth, and bottom salinities, averaged over the 8 hours of observation, were 20.36 ppt, 21.64 ppt, and 25.61 ppt, respectively, for the 26th October; they were 24.33 ppt, 25.11 ppt, and 27.45 ppt, on 11 November; and they were 20.93 ppt, 21.91 ppt, and 23.31 ppt on November 27. At Range 2, located at Mile Marker 41, the salinities at the three depths were 15.13 ppt, 20.54 ppt, and 25.52 ppt on 26 October; they were 17.76 ppt, 21.70 ppt, and 23.29 ppt on 11 November; and they are 17.62 ppt, 19.62 ppt, and 20.37 ppt on 27 November. At Range 3, located at Mile Marker 51, the salinities at the three depths were 13.33 ppt, 19.83 ppt, and 24.31 ppt on 26 October; they were 13.55 ppt, 21.46 ppt, and 22.97 ppt on 11 November; and they were 14.22 ppt, 15.79 ppt, and 17.25 ppt on 27 November. There is a trend toward lesser stratification on each successive survey date. Maximum vertical gradients in salinity occurred at Range 2 (MRGO mile marker 41) on 26 October, when the bottom salinity exceeded the surface salinity by more than 10 ppt. If such a vertical gradient occurs over a significant reach of the MRGO at frequent intervals it is likely that the flux of salt directed up the waterway could be decreased by the use of air or fresh water curtains to destratify the MRGO. One procedure would be to locate bubbler arrays at about three locations along the waterway. The process of destratification would produce a mixed water column which would then be the source of bottom water up the canal. A new, less stratified condition would prevail northwestward from the first mixing zone. A second bubbler array would mix the water in a segment about a tidal excursion long, and a new, less stratified condition would prevail. Each successive mixing zone should lead to lower salinities northwestward along the canal, since salinity intrudes less in a well-mixed system than in a stratified system.

66. There would be some advantage to the use of a fresh water bubbler system to provide the buoyant forces necessary to destratify the MRGO, since dilution of the high salinity waters in the canal would occur along with the destratification. The District has determined that the transport of fresh water from the Mississippi at Riverbend to the MRGO at flow rates sufficient to attain dilution goals in the canal would not be economically or technically feasible. However, the amount of fresh water necessary to provide destratification in the MRGO may be significantly less than that needed if the purpose is dilution alone.

67. The District has determined that neither physical nor operational modification of the existing lock in the IHNC could provide sufficient fresh water flow from the Mississippi through the IHNC to Lake Pontchartrain to provide the same freshening of the Lake that is projected for the Bonnet Carré Diversion Project. However, any possible economically feasible modification

of the operational procedures or of the physical structure of the lock which would provide additional flow of fresh water into the northern segment of the IHNC would offset a reduction in the diversion at Bonnet Carré. There would be little economic justification for a costly physical modification of the IHNC locks if the only result would be to decrease the salt flux from the IHNC into Lake Pontchartrain. However, it is possible that a diversion of fresh water from the Mississippi River into the IHNC would result in a freshening of the GIWW and perhaps the MRGO itself. If this were so, the flux of salt into Lake Borgne via the GIWW and via the bayou inlets, as described in Appendix C, would decrease, leading to a decrease in salinity in Lake Borgne and hence over the Biloxi Marshes, allowing a reduction to be made in the Bonnet Carré diversions.

68. Paragraph 14, item (b), is the second major question posed by the District. In view of the Committee's answer to the first major question posed to the Committee, this second major question needs to be modified slightly, to read as follows:

Question: Can the Bonnet Carré freshwater diversions be reduced in magnitude while still producing: (1) the desired freshening effect in project wetlands and marshes, and (2) the target salinities for increased oyster production?

69. The Committee has concluded that construction of a flow control structure at Seabrook would not allow any significant decrease in the supplemental fresh water flows into Lake Pontchartrain from Bonnet Carré required to attain the desired seasonal variations in salinity over the Biloxi Marshes. However there are other options which could result in a decrease in the salinities over the oyster seed bed areas, some of which have been discussed earlier in this section.

70. In preparing its answers to the questions posed above the Committee has temporarily assumed that the design schedule of supplemental flows into Lake Pontchartrain via the Bonnet Carré diversion project is that contained in Table C-1-26 of the Feasibility Study (USAENOD, 1984). This schedule, which the referenced document identifies as the supplemental flow requirements to achieve optimum salinity conditions at Location 2 (this location is in the Lake Borgne side of the Biloxi Marshes), is repeated below:

<u>Month</u>	<u>Supplemental Flows (cfs)</u>	<u>Month</u>	<u>Supplemental Flows (cfs)</u>	<u>Month</u>	<u>Supplemental Flows (cfs)</u>
Jan	0	May	16,700	Sept	2,000
Feb	0	June	14,600	Oct	5,560
Mar	10,800	July	3,200	Nov	3,200
Apr	30,000	Aug	2,600	Dec	0

This schedule (if constant for the month) is equivalent to an annual average supplemental flow of 7394 cfs (209 m<sup>3</sup>/s). Sikora and Kjerfve list the annual average natural fresh water inflow to Lake Pontchartrain as 188 m<sup>3</sup>/s (6639 cfs) while Swenson and Chuang give a value of 250 m<sup>3</sup>/s (8828 cfs). In any case, the supplemental flow schedule given above, added to the natural flow, would approximately double the total fresh water flow to the Lake.

71. The above schedule of supplemental flows was determined to be that necessary to achieve optimum oyster production in the Biloxi Marshes. These flows might be more than is necessary to reduce the salinities in the Lake to values which existed prior to the completion of the MRGO. Thus, from the standpoint of full mitigation of the effects of MRGO on the salinities in Lake Pontchartrain, it might well be that the Bonnet Carré freshwater diversion could be reduced. However, such a reduction in the diversion at Bonnet Carré would only be possible if there were other measures taken, such as a reduction

of the flux of salt from the MRGO directly into Lake Borgne via the bayou inlets, so that the target salinities over the oyster seed bed areas in the Biloxi Marshes could still be met.

72. There is evidence that the inlet mouths of the several bayous intersecting the MRGO, and through which there is a significant salt flux from the canal into Lake Borgne, are widening, thus increasing the conveyance for the flux of salt. The cross-sectional area of these bayou inlets should be stabilized, and if navigation usage of these bayous permit, the width and depth of the bayou inlets just lakeward from the MRGO should be reduced. Model studies could be used to determine whether the most effective control would result from decreasing the width or the depth in these inlets. Such controls of the flux of salt from the MRGO directly into Lake Borgne should result in a reduction in the salinity over the oyster beds on the Lake Borgne side of the Biloxi Marshes, thus allowing a reduction in the Bonnet Carré diversions. Closure of individual inlets may be an alternative.

73. It should also be noted that the three bayou inlets in which the measurements described in Appendix C were obtained are not the only inlets connecting the MRGO with Lake Borgne. An inspection of the Ysclosky Quadrangle map shows at least seven such connections in addition to the Bayou Ysclosky inlet, and there are another two in addition to the Bayou Dupre inlet and the Bayou Bienvenue inlet in the 8.5 mile (13.7 km) reach centered on Martello Castle. Although most of these additional inlets have relatively small cross-sectional areas compared to that for the Bayou Dupre, they must contribute some additional salt flux to Lake Borgne.

## 5 RECOMMENDATIONS

74. The Committee recognizes that a certain degree of uncertainty exists in regard to its analysis and consequent conclusions. Thus a general recommendation to the District from the Committee is that the answers to the questions posed by the District to the Committee should be subjected to further analysis and, where appropriate, testing by use of numerical models. More specific recommendations along these lines follow.

75. The existing USACE transient-state-three-dimensional numerical model of Lake Pontchartrain, Lake Borgne, the MRGO, the IHNC, the GIWW, the Rigolets, the Chef Menteur, a segment of Mississippi Sound, of Chandeleur Sound, and of Breton Sound as required to provide suitable boundary conditions, and at least a portion of the Biloxi Marshes, should be completed and verified. This model should include the simulation of the bayou inlets between the MRGO and Lake Borgne. This model should be used to test the validity of the Committee's conclusions with regard to a lock at Seabrook as well as the effectiveness of the jetty - submerged sill combination described in paragraph 62. Note that these tests should be run with the full model in operation and verified, since there may be an interaction between the effects of such structures at Seabrook and the flux of salt directly from the MRGO into Lake Borgne via the bayou inlets and via the GIWW, and thence ultimately via the Chef Menteur and the Rigolets into Lake Pontchartrain.

76. The above described model should be used to determine if controlling the flux of salt to Lake Borgne from the MRGO is feasible and if such control is effective in reducing the salinities over the Biloxi Marshes. Such control might be attained by reducing the area of the critical cross section in the several bayou inlets lakeward from the MRGO. Reduction of both the width and the depth of the bayou inlets should be simulated in the model, separately and in combination. The Committee recommends an engineering study of reducing salt flux from the MRGO to Lake Borgne via the bayou inlets (see Paragraph 71).

77. The model could also be used to determine if destratification at one or more locations in the MRGO would result in a decreased salinity in the waters up the canal from the destratified section or sections. There exists considerable experience in destratification of reservoirs by bubbler systems, and algorithms have been developed for use in calculating the power needed to overturn, or mix these water bodies. No comparable experience exists with respect to the vertical mixing of tidal waterways. In fresh water reservoirs vertical stratification results from the vertical temperature structure, which in turn is controlled by the net input of solar radiation at the surface on the one hand and wind induced mixing on the other. Once complete vertical mixing over a significant segment of the reservoir has been accomplished, the bubbler system can be put on hold for the period of time it takes for the excess surface heating to reestablish some threshold vertical density gradient. In tidal waterways which have an input of fresh water at one end and are connected to the open coastal waters at the other end, there always exists a longitudinal gradient in salt content which due to gravitational effects results in an advective flow of lower salinity water seaward in the near surface layers and of higher salinity water up the waterway in the deeper layers, thus establishing a vertical salinity gradient. The counter force resisting stratification is the turbulence produced by the oscillatory tidal flow, and a balance is reached in which some degree of vertical stratification exists, depending on the degree of tidal induced mixing. The characteristic estuarine advective pattern always exists, and if an artificial mixing process is stopped, a vertical salinity gradient is very quickly reestablished. This phenomena is the reason why the mixing by the passing of large ships has not

been shown to be very effective in destratification of an estuarine waterway. Thus in a waterway such as the MRGO, a bubbler system installed to destratify the waterway would have to be operated continuously during periods of natural stratification.

78. The calculation of the work required to destratify the MRGO under a given vertical salinity structure is not difficult. The procedure involves the determination of the center of mass of a vertical water column under the existing stratified conditions. Since the deeper water layers have a higher density than the upper layers, the center of mass of a vertical column will be below middepth. In a completely mixed condition, the center of mass of the water column will be at middepth. The work required to mix the stratified water column is then simply the work required to lift the water column a distance equal to the difference between the center of mass of the stratified column and the center mass of the mixed column. Consider a segment of the MRGO bounded by two cross sections separated longitudinally by one meter. A typical cross section in the MRGO has the dimensions of 1500 feet across the waterway at the surface, and a mean depth across the central 500 feet of about 38 feet. To simplify the calculations without seriously compromising accuracy an equivalent segment one meter in longitudinal dimensions bounded by U-shaped cross sections 1000 feet (304.8 m) across and 38 feet (11.58 m) deep is used. The upper half of the segment is assumed to have a salinity of 15 kg/m<sup>3</sup> while the bottom half is assumed to have a salinity of 25 kg/m<sup>3</sup>. These salinities were observed by Fagerburg (1990) at MRGO mile marker 41. Although the center of mass of this segment in the stratified condition and that in a completely mixed condition is only 2.12 cm, the mass of the segment is  $3.569 \times 10^6$  kg. The work required to mix this segment is then  $7.416 \times 10^3$  joules.

79. The theoretical minimum power required to vertically mix the MRGO is the rate of doing the above calculated work. The water in the example segment is continually being replaced by new water from down the waterway during flood flow and from up the estuary during ebb flow. Based on data from Fagerburg (1990), the average tidal current speed is about 0.4 m/s. The average time it would take to replace the water in the segment is then  $(1.0 \text{ m} \div 0.4 \text{ m/s})$ , or 2.5 seconds. The required rate of doing work is then  $2.966 \times 10^3$  joules/s. The minimum required theoretical power is then  $2.966 \times 10^3$  watts, or 398 HP. Such a power requirement does not, on the face of it, appear to involve an unreasonable cost if destratification of the MRGO would decrease the salt flux from the MRGO into Lake Borgne and into Lake Pontchartrain. However, this minimum theoretical power is not the only power required to vertically mix the MRGO.

80. The additional information needed to estimate the probable power required to mix the MRGO is information on the additional power required to overcome the frictional losses in the bubbler distribution system, and on the volume rate of flow of the air or fresh water used to induce vertical mixing in the waterway. Although such information is available for reservoirs, how much of this information can be transferred to the MRGO has not been determined by the committee. It is recommended that the District undertake a study to obtain the remaining information needed to determine the economical and operational feasibility of destratifying the MRGO, and to determine the degree to which such destratification of the waterway would decrease the salt flux from the MRGO to Lake Borgne and to Lake Pontchartrain.

81. The District has determined that neither physical nor operational modification of the existing lock in the IHNC could result in sufficient fresh water flow from the Mississippi through the IHNC to Lake Pontchartrain to provide the same freshening of the Lake that is projected for the Bonnet Carré Diversion Project. However, any possible economically feasible modification of the operational procedures or of the physical structure of the lock which

would provide additional flow of fresh water into the northern segment of the IHNC would offset a reduction in the diversion at Bonnet Carré. There would be little economic justification for a costly physical modification of the IHNC locks if the only result would be to decrease the salt flux from the IHNC into Lake Pontchartrain. However, it is possible that a diversion of fresh water from the Mississippi River into the IHNC would result in a freshening of the GIWW and perhaps the MRGO itself. If this were so, the flux of salt into Lake Borgne via the GIWW and via the bayou inlets as described in Appendix C would decrease, leading to a decrease in salinity in Lake Borgne and hence over the Biloxi Marshes, and allowing a reduction to be made in the Bonnet Carré diversions. It is recommended that the District reevaluate this alternate, keeping in mind that the freshening of the IHNC northward of the existing locks might result in some freshening of the GIWW and the MRGO. The numerical model described in paragraph 74 above is the best tool to use in carrying out such a reevaluation.

82. Additional direct measurement of salt fluxes across the major MRGO-IHNC connections (similar to those described earlier) will be needed to verify the model(s) if modification of those inlets is to be tested.

## REFERENCES

- Donnell, Barbara Park and Joseph V. Letter, Jr. 1991. Tabs-MD numerical modeling investigation of shoaling in the Mississippi River-Gulf Outlet. WES Technical Report HL-91-2, January 1991.
- Fagerburg, T.L. 1990. Mississippi River-Gulf Outlet, Louisiana, Field Data Report. WES Technical Report HL-90-7, August 1990.
- Outlaw, Douglas G. 1982. Lake Pontchartrain and vicinity hurricane protection plan, Report 1, Prototype data acquisition and analysis. WES Technical Report HL-82-2, January 1982.
- Sikora, W. B. and B. Kjerfve. 1985. Factors influencing the salinity regime of Lake Pontchartrain, Louisiana, a shallow coastal lagoon: Analysis of a long term data set. *Estuaries*, Vol 8, No. 2A, pp 170-180.
- Swenson, E. M. 1980. The general hydrology of the tidal passes of Lake Pontchartrain, Louisiana. In *Environmental Analysis of Lake Pontchartrain, Louisiana, its Surrounding Wetlands, and Selected Land Uses* (Stone, J. H., ed). Prepared for U. S. Army Engineer District, New Orleans. Contract Mo. DACW20-77-C-0253.
- Swenson, E. M. and W-S. Chuang. 1983. Tidal and subtidal water volume exchange in an estuarine system. *Estuarine, Coastal, and Shelf Science*, No.16, pp 229-240.
- USAENOD, 1984. Mississippi and Louisiana Estuarine Areas, Freshwater Diversion to Lake Pontchartrain Basin and Mississippi Sound, Feasibility Study, Volume 2, Technical Appendixes, A, B, C, D, April 1984.
- WES, 1963. Effects on Lake Pontchartrain, LA, of Hurricane Surge Control Structures and Mississippi River-Gulf Outlet Channel. TR 2-636, Nov USAE Waterways Experimental Station, Vicksburg, MS.
- WES, 1976. Reduction of Lake Pontchartrain Tidal Prism Caused by Hurricane Barriers. Letter Report, U. S. Army Engineer Waterways Experimental Station, Vicksburg, Mississippi, Sponsored by U. S. Army Engineer District, New Orleans. April 1976.

APPENDIX A

ON THE MATTER OF THE STATISTICAL SIGNIFICANCE OF  
POST-MRGO MINUS PRE-MRGO SALINITY DIFFERENCES

A1. In their published paper, Sikora and Kjerfve (1985) gave the results of an analysis of a data set of daily salinity observations made at two stations in Lake Pontchartrain, and one station each in The Rigolets, in Chef Menteur, and in Pass Manchac. The locations of these stations are shown in Figure 1-1 in the main body of this report. These data, collected by the U.S. Army Engineer District, New Orleans, extended over the 36 year period from 1946 through 1981. Even a quick analysis of this data set reveals that there is a high variance in the daily values. For example, the record length mean of the salinity values observed at the station in the Rigolets was 5.34 ppt, with a standard deviation of  $\pm 3.60$  ppt. During 28 years period for which data were available for this station, the reported daily salinities varied from a low of 0.08 ppt to a high of 22.35 ppt. The very low values probably occurred following each of the large diversions of flood waters from the Mississippi River via the Bonnet Carré Spillway into Lake Pontchartrain. The maintenance of such a data base of daily salinity values without some observational and recording errors is difficult. From a practical standpoint, a much more useful ecological measure is the monthly mean salinities in this waterway. Sikora and Kjerfve did not include any analysis of monthly mean salinities for these stations, nor did they comment on the characteristic seasonal pattern in the salinities of Lake Pontchartrain, which contributes to the variations of the data set as a whole. In any case these authors computed the average of all of the salinity data in the pre-MRGO period (1962 and earlier), and the average of all of the salinity data in the post-MRGO period (1964 to 1981), for each of the five stations. They then reported the difference, post-MRGO average minus pre-MRGO average as follows: (a) for the two stations in Lake Pontchartrain, Little Woods and North shore, an increase of 1.6 ppt and 1.3 ppt respectively; (b) for Pass Manchac, an increase of 0.2 ppt; (c) for the Chef Menteur, an increase of 2.6 ppt; and (d) for the Rigolets, an increase of 2.0 ppt. In spite of the consistent results for the five stations (all differences were positive), Sikora and Kjerfve go on to state that because of the large variance in the recorded salinities for each of the five stations, the computed differences in the pre-MRGO to post-MRGO mean salinity values are statistically insignificant. No description of the statistical measures used to support this statement is included in the referenced paper.

A2. The U.S. Army Engineer District, New Orleans (USAENOD, 1984), using the same data base that was used by Sikora and Kjerfve, presented an analysis of the pre-MRGO to post-MRGO monthly mean salinities for four of the five stations listed in the previous paragraph. This analysis by the District gave values for the differences between the pre-MRGO and post-MRGO annual mean salinities quite close to the values quoted above from Sikora and Kjerfve (1.8 ppt for Little Woods; 1.3 ppt for North Shore; 0.4 ppt for Pass Manchac; and 2.4 ppt for the Chef Menteur). In addition, The District analysis included the computation of the characteristic seasonal variation in the pre-MRGO and post-MRGO mean salinities for each month. Although the District did not discuss the issue of statistical significance of these measures of the apparent effect of MRGO on the salinities of Lake Pontchartrain and adjacent waterways, the consistency among these stations of the patterns of the month to month variations in the pre-MRGO and post-MRGO mean monthly salinities, and in the increases in the salinity from the pre-MRGO to post-MRGO periods, suggests a greater reliance on these results than might be shown by the use of statistical probability measures on each of the sets of data from each station..

A3. The New Orleans District provided the Committee with the same salinity data base used by Sikora and Kjerfve (1985) and by the District for computations of the differences between pre-MRGO and post-MRGO salinities in the subject waterways, for the four stations analyzed by both parties.. Figure 1 shows the location of these four stations. The Committee used the provided data set to repeat the computations made by the District, but included the use of statistical measures of the significance of the values of the mean quantities so calculated. See Table 3-1 in the main body of this report for a side-by-side comparison of the pre-MRGO record length mean to the post-MRGO record length mean salinity differences as computed by Sikora and Kjerfve, by the District, and by the Committee. The following paragraphs list the comments and conclusions reached by the Committee in its analysis.

A4. None of the data sets for the individual stations cover the full 36 years encompassed within the starting and ending dates of the observational program (1946 through 1981) described in the referenced documents. Only one station has data starting in 1946 (Little Woods). Collection of salinity data from Pass Manchac was initiated in 1951, while collection of data from the Chef Menteur and North Shore was initiated in 1957. No data were reported for any of the stations in 1978, and no data were collected after 1977 at Little Woods. At the Chef Menteur insufficient data were available for 1981 to be included in the Committee's analysis. The MRGO was opened at the dimensions of 36 ft by 250 feet in early July of 1963. The District included data collected for the first six months of that year in the pre-MRGO data set, and data collected in the last six months of that year in the post MRGO data set.

A5. An access channel 18 ft by 140 ft from the GIWW to Breton Sound had been completed in February of 1960, and a significant portion of the 36 ft by 250 ft cut had been made by the first of 1963, thus providing for increasingly easier access for passage of higher salinity water to the IHNC, and even more so to Lake Borgne via the intersecting bayous. Some time delay would be expected in the response of the system of waterways to the effects of the completion of the 36 ft by 250 ft canal. Consequently the Committee elected not to include data for 1963 in either the pre-MRGO or the post-MRGO data sets. Thus for both the station at North Shore, and the one in the Chef Menteur, only six years of data were available for the pre-MRGO calculations. It is these small data sets, coupled with the high variance in the monthly mean salinity values in both the pre-MRGO and post MRGO data, which contributes to an increased uncertainty in the computed differences between the pre- and post-MRGO salinities, as compared to stations with a longer period of available data. Little Woods has the most complete data set, with 17 years of pre-MRGO salinities, and 14 years of post-MRGO observations.

A6. It is not a surprise that the Committee computations gave values for the pre-MRGO and post-MRGO means of the annual average salinities and of the monthly average salinities for each of these four stations which are very close to the values found by the District. The slight differences resulted primarily from the procedure used to deal with the dividing year of 1963, and from differences in the treatment of missing monthly average salinity values for periods of one to three months during an otherwise complete year of data. Figure A1 shows the monthly means for both pre and post MRGO data from the station at Little Woods in Lake Pontchartrain. The characteristic seasonal variations in both data sets shown in this figure is similar to the results for the other stations, though at the other stations the salinity levels were lower. The Committee has asked additional questions of these data sets. These are: first, what is the probability that the data supports the statement that the post-MRGO salinities are larger than the pre-MRGO salinities; and second, what are the confidence limits for the pre- and post-MRGO differences in the annual mean and monthly mean salinities. Probabilities that the post-MRGO salinities are larger than the pre-MRGO salinities having values greater

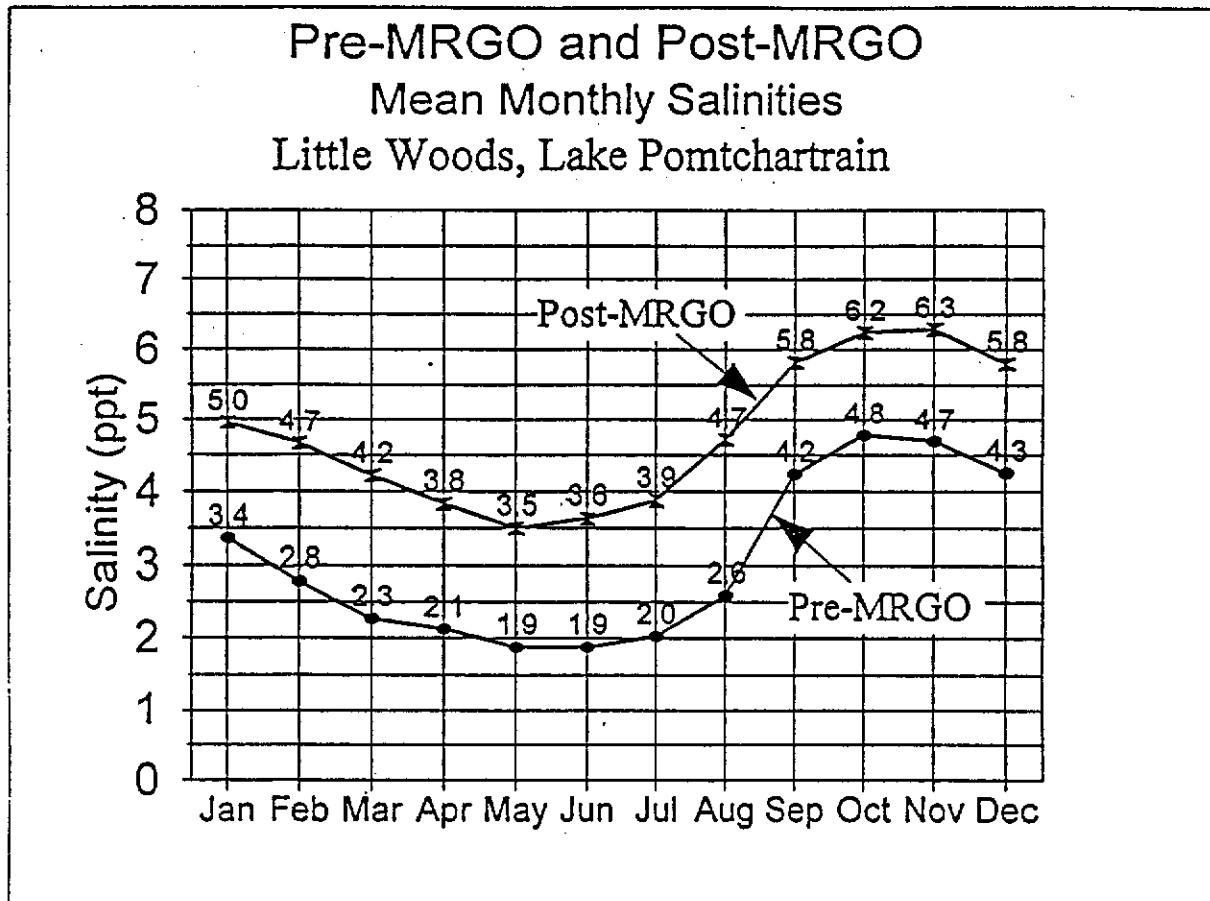


Figure A1. Pre-MRGO and Post MRGO averages of the monthly mean salinities for the station at Little Woods, Lake Pontchartrain. Note that the seasonal variations shown by these curves are characteristic of the variations found for the station at North Shore, Lake Pontchartrain, and for the station in the Chef Menteur.

than, say 0.975, would indicate a high degree of certainty that the hypothesis is correct. The probability values computed by the Committee for the differences in the annual means were in fact greater than 0.995 for all stations except Pass Manchac, which had only a slightly lower probability of 0.992. It would thus appear that Sikora and Kjerfve were using the term "statistically insignificant" from a subjective standpoint and not from an objective, quantitative standpoint. One problem with the Sikora and Kjerfve analysis is that they did not take into account the fact that a part of the variance in these data sets results from the characteristic seasonal variation in salinity, for both pre- and post-MRGO data sets. To obtain a true measure of the significance of the pre- to post-MRGO differences it is necessary to subtract out the variances arising from the characteristic seasonal variations in salinity before calculating values for the probabilities and the confidence limits.

A7. The probabilities that the post-MRGO minus the pre-MRGO salinities are positive numbers are expected to be lower for monthly means than for the annual means since the number of degrees of freedom are less for the case of the monthly means. Even so, as shown in Table A1, the probabilities computed for the differences in the monthly means for the station at Little Woods, which had the longest data set and the one most evenly divided between pre-MRGO and post-MRGO periods, were greater than 0.995 for eight months, greater than 0.975 for three other months. The remaining month had a 0.968 probability that the hypothesis is correct. For the station in the Chef Menteur, values for the probability that the post-MRGO monthly mean salinities exceeded the pre-MRGO monthly mean salinities were greater than 0.975 for eight months, and the lowest value was 0.932, which was for the month of September. In the case of the station at North Shore of Lake Pontchartrain, which had only 6 years of observations in the pre-MRGO data set and just 13 years in the post-MRGO data set, only three months have probabilities greater than 0.95 that post-MRGO salinities exceed pre-MRGO salinities. Two other months have probability values exceeding 0.90. For one month (June), there is only a 6 out of 10 chance that post-MRGO salinities are larger than pre-MRGO salinities. Despite these values, the similarity in the seasonal variations in both pre- and post-MRGO monthly mean salinities, and in the month to month variations in the differences between the pre- and post-MRGO monthly mean values, for the three stations of Little Woods, Chef Menteur, and North Shore lends confidence to the validity of the computed increases in the salinities in the Chef Menteur and in the eastern reach of Lake Pontchartrain. Only for Pass Manchac are the computed probability values for the differences in the monthly mean salinities sufficiently low for some months to suggest that the validity of the contention that the post-MRGO salinities are higher than the pre-MRGO salinities may be questionable. For one month (December), there is no support in the data that post-MRGO salinities are greater than pre-MRGO salinities. There are three other months for which there is only about a 6 in 10 chance that the post-MRGO salinities exceed the pre-MRGO salinities. However, for one month the probability is greater than 0.95, and four other months have probability values greater than 0.8.

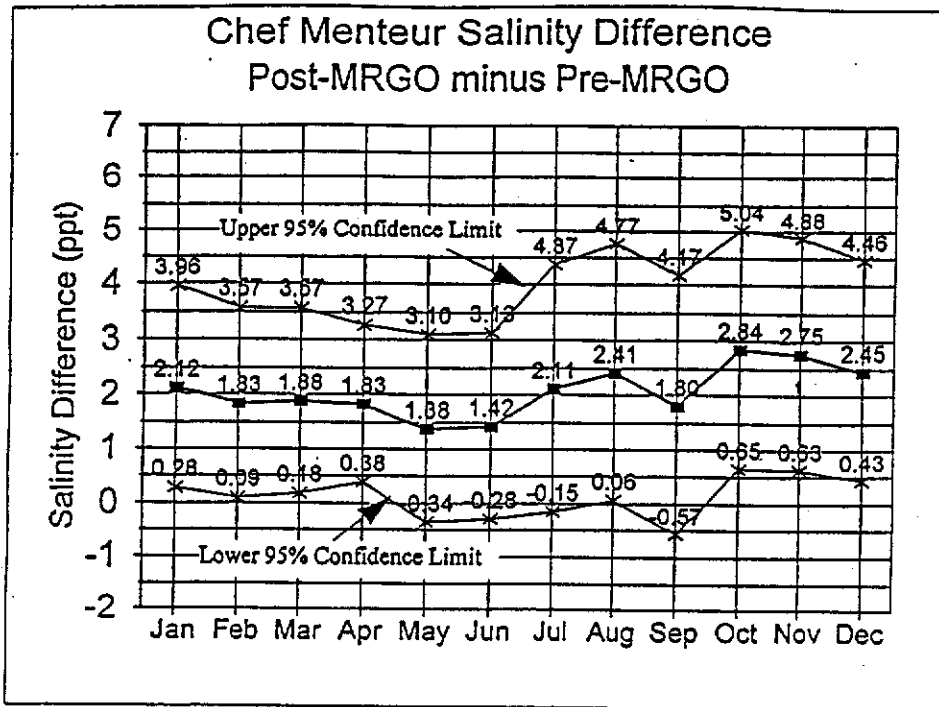


Figure A2. Mean difference, Post-MRGO minus Pre-MRGO, of the monthly average salinity for the station in the Chef Menteur near Lake Borgne. The upper and lower 95% confidence limits about the mean are also shown.

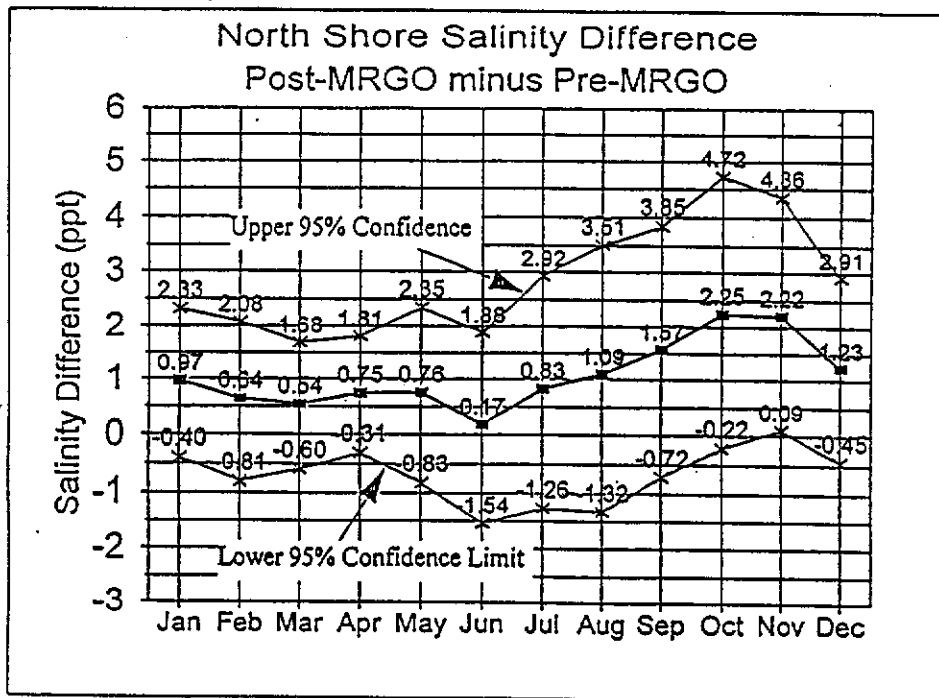


Figure A3. Mean difference, Post-MRGO minus Pre-MRGO, of the monthly average salinity for the station in at North Shore, Lake Pontchartrain. The upper and lower 95% confidence limits about the mean are also shown.

Table A1

Computed Values of the Pre-MRGO Mean Salinity, the Post-MRGO Mean Salinity, Post-MRGO minus Pre-MRGO Salinity Difference, the Probability that the Difference is Positive, and the Upper and Lower 95% Confidence Limits about the Mean Differences for Four Stations in and nearby Lake Pontchartrain

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
<u>Chef Menteur (6,16)</u>													
Pre-MRGO Mean	3.4	2.7	2.3	2.1	2.1	2.5	3.4	4.9	6.2	5.3	5.1	4.5	3.7
Post-MRGO Mean	5.5	4.5	4.2	3.9	3.5	4.0	5.5	7.3	8.0	8.1	7.8	6.9	5.8
Difference	2.1	1.8	1.9	1.8	1.4	1.4	2.1	2.4	1.8	2.8	2.8	2.4	2.1
Probability Diff >0	0.980	0.982	0.979	0.992	0.943	0.951	0.966	0.977	0.932	0.993	0.993	0.990	>0.995
Lower 95% Limit	0.3	0.1	0.2	0.4	-0.3	-0.3	-0.2	0.1	-0.6	0.6	0.6	0.4	1.6
Upper 95% Limit	4.0	3.6	3.6	3.3	3.1	3.1	4.4	4.8	4.2	5.0	4.9	4.5	2.6
<u>Little Woods (17,14)</u>													
Pre-MRGO Mean	3.4	2.8	2.3	2.1	1.9	1.9	2.0	2.6	4.2	4.8	4.7	4.3	3.1
Post-MRGO Mean	5.0	4.7	4.2	3.8	3.5	3.6	3.9	4.7	5.8	6.2	6.3	5.8	4.8
Difference	1.6	1.9	1.9	1.7	1.6	1.8	1.9	2.1	1.6	1.5	1.6	1.6	1.7
Probability Diff >0	0.986	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	0.986	0.968	0.975	>0.995	>0.995
Lower 95% Limit	0.2	0.5	0.7	0.6	0.5	0.6	0.8	0.9	0.2	-0.1	0.0	0.1	1.4
Upper 95% Limit	3.0	3.2	3.2	2.9	2.8	2.9	2.9	3.3	3.0	3.0	3.2	3.0	2.1
<u>North Shore (6,13)</u>													
Pre-MRGO Mean	2.9	2.4	2.0	1.7	1.9	2.5	2.9	4.1	5.1	4.1	4.0	3.5	3.1
Post-MRGO Mean	3.8	3.1	2.5	2.4	2.6	2.6	3.7	5.2	6.7	6.4	6.2	4.7	4.2
Difference	1.0	0.6	0.5	0.7	0.8	0.2	0.8	1.1	1.6	2.3	2.2	1.2	1.1
Probability Diff >0	0.852	0.710	0.889	0.953	0.877	0.607	0.793	0.822	0.914	0.963	0.978	0.927	>0.995
Lower 95% Limit	-0.4	-0.8	-0.6	-0.3	-0.8	-1.5	-1.3	-1.3	-0.7	-0.2	0.1	-0.4	0.6
Upper 95% Limit	2.3	2.1	1.7	1.8	2.4	1.9	2.9	3.5	3.9	4.7	4.4	2.9	1.6
<u>Pass Manchac (12,17)</u>													
Pre-MRGO Mean	1.3	0.9	0.8	0.6	0.6	0.8	1.1	1.2	1.6	1.8	2.0	1.7	1.2
Post-MRGO Mean	1.4	1.2	1.1	1.2	1.0	1.2	1.3	1.4	1.7	2.2	2.1	1.7	1.5
Difference	0.1	0.2	0.3	0.6	0.4	0.3	0.2	0.2	0.1	0.4	0.1	0.0	0.3
Probability Diff >0	0.58	0.75	0.84	0.96	0.87	0.84	0.70	0.74	0.62	0.84	0.58	<0.01	0.992
Lower 95% Limit	-0.6	-0.5	-0.3	-0.1	-0.2	-0.3	-0.5	-0.5	-0.7	-0.4	-0.8	-0.9	0.1
Upper 95% Limit	0.8	1.0	1.0	1.2	1.0	1.0	0.9	0.9	0.9	1.3	0.9	0.9	0.5

Note: The numbers in parens following each station name are the number of years in the pre-MRGO and post-MRGO data sets.

A8. The calculated values for the upper and lower 95% confidence limits on the post-MRGO minus pre-MRGO salinity differences reveal something about how well these differences are known. Thus, for the station at Little Woods, the difference for the annual mean salinities is 1.7 ppt, and the lower and upper 95% confidence limits were calculated to be 1.4 ppt and 2.1 ppt respectively, indicating that this particular difference in the annual mean salinities is reasonably well known. However, for the post-MRGO minus pre-MRGO differences in the individual monthly mean salinities, the confidence in how well the differences are known is much lower. For three months for which the computed difference ranges from 1.5 to 1.6, the lower 99.5% confidence limits are less than 0.1 and the upper 95% confidence limits are greater than 3.0. More representative values for the lower and upper 95% confidence limits for the post-MRGO minus pre-MRGO monthly mean salinity difference at this station are 0.6 ppt and 2.9 ppt, respectively, still indicating a rather large uncertainty in how well the individual monthly differences are known. Figures A2 and A3 are plots of the post-MRGO minus pre-MRGO differences in the monthly mean salinities for the Chef Menteur station and the station at North Shore in Lake Pontchartrain. Upper and lower 95% confidence limits are also shown on these two figures. These figures suggest a rather large uncertainty in how well the differences for the individual monthly salinities are known. However, in the case of the Chef Menteur, the post-MRGO minus pre-MRGO difference in the annual mean salinities is calculated to be 2.1 ppt, with lower and upper 95% limits of 1.6 ppt and 2.6 ppt, indicating that for the annual average the difference is fairly well known.

A9. The seasonal variation in both the pre-MRGO and post-MRGO monthly mean salinities, and the month by month variation in the post-MRGO minus pre-MRGO differences in the monthly mean salinities, are very similar among the three higher salinity stations. There are also similarities in these variations between the Pass Manchac station and the other three, but this low salinity station shows considerably greater irregularities than do the other three stations. An examination of the monthly mean salinity data for the Chef Menteur station and the two stations in the eastern portion of Lake Pontchartrain, shows the following: (a) the larger the record mean salinity, the greater the salinity difference pre- to post-MRGO; (b) the distribution of the monthly mean salinities in both the pre- and post-MRGO data sets for each of these stations appears to be a normal distribution; (c) the statistical parameters of these distributions (such as the standard deviations), are roughly the same for these three stations, or at least their differences are not statistically significant. If it is assumed that these data bases represent populations which differ only in their record length means, and not in other statistical parameters, then it should be possible to combine these data sets and thus significantly increase the number of degrees of freedom. The consequent of such an increase in the size of the pre- and post-MRGO data base would be an increase in the significance which can be attached to the computed values of the pre- to post-MRGO salinity differences, as well as a narrowing of the confidence limits about the computed mean difference.

A10. Creating such a combined data base for these three stations would require that the individual data sets be normalized to the same record length average. For example, a combined data set to be used to make new, and it is to be hoped, better estimates of the various statistical measures of probability and confidence limits for, say the station in the Chef Menteur, then the data at each of the other stations would be adjusted to have the same record length mean as the station in the Chef Menteur by multiplying these data sets by the ratio of the record length mean for the Chef Menteur station by the record length mean for each of the other stations. The Committee has performed this exercise for each of these three stations, and again have

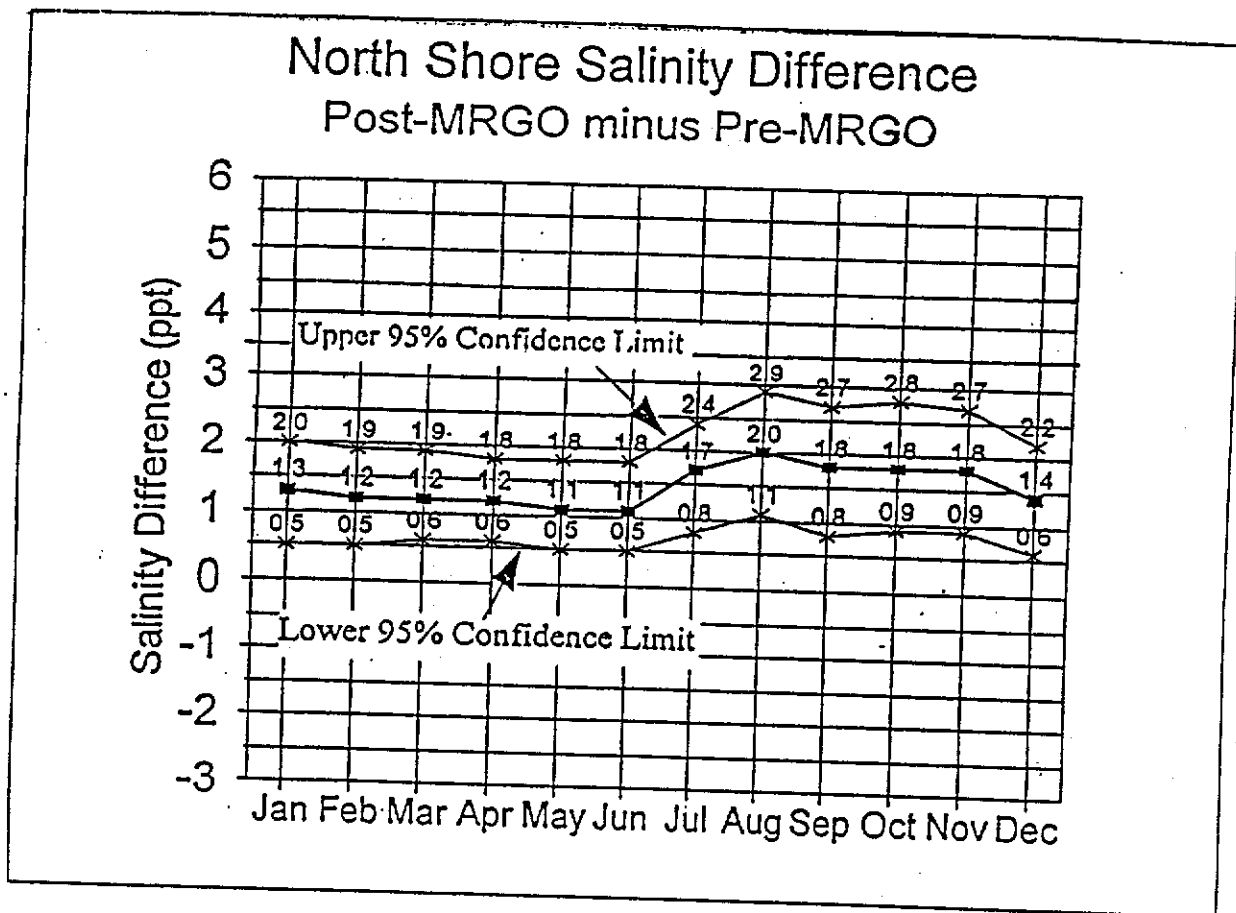


Figure A4. Mean difference, Post-MRGO minus Pre-MRGO, of the three station composite monthly average salinity for the station at North Shore, Lake Pontchartrain. The upper and lower 95% confidence limits about the mean are also shown. Comparison of this figure with Figure A3 demonstrates the smaller range of the 95% Confidence Limits for the three station composite data set.

computed the various statistical tests described earlier. Table A2 contains the results of these calculations.

A11. Figure A4 is a plot of the mean differences, post-MRGO minus pre-MRGO, of the monthly average salinities for the station at North Shore, Lake Pontchartrain, using the combined three-station data set normalized for this station. Comparing this figure with Figure A3, and also comparing the values of the various statistical parameters listed in Table A2 with those listed in Table A1, clearly shows that using the combined data sets significantly narrows the range of the 95% confidence limits about the mean differences, and also leaves no doubt that the post-MRGO monthly mean salinities, as well as the annual mean salinities, are higher than the pre-MRGO salinities.

Table A2

Computed Values of the Pre-MRGO Mean Salinity, the Post-MRGO Mean Salinity, Post-MRGO minus Pre-MRGO Salinity Difference, the Probability that the Difference is Positive, and the Upper and Lower 95% Confidence Limits about the Mean Differences for Three Station Combinations

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
<b>Chef Menteur (6,16)</b>													
Pre-MRGO Mean	3.8	3.1	2.6	2.4	2.3	2.5	2.9	4.0	5.6	5.5	5.4	4.8	3.7
Post-MRGO Mean	5.5	4.7	4.2	3.8	3.7	4.0	5.0	6.6	7.9	7.9	7.8	6.7	5.6
Difference	1.7	1.6	1.6	1.6	1.4	1.4	2.2	2.6	2.3	2.4	2.4	1.8	1.9
Probability Diff >0	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995
Lower 95% Limit	0.7	0.6	0.7	0.7	0.6	0.6	1.1	1.4	1.1	1.2	1.2	0.8	1.6
Upper 95% Limit	2.6	2.5	2.5	2.3	2.3	2.3	3.1	3.8	3.5	3.6	3.5	2.9	2.2
<b>Little Woods (17,14)</b>													
Pre-MRGO Mean	3.2	2.6	2.2	2.2	1.9	2.1	2.4	3.3	4.7	4.6	4.5	4.0	3.1
Post-MRGO Mean	4.6	3.9	3.5	3.2	3.1	3.3	4.2	5.5	6.6	6.6	6.5	5.6	4.7
Difference	1.4	1.3	1.3	1.3	1.2	1.2	1.8	2.2	1.9	2.0	2.0	1.5	1.6
Probability Diff >0	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995
Lower 95% Limit	0.6	0.5	0.6	0.6	0.5	0.5	0.9	1.2	0.9	1.0	1.0	0.7	1.3
Upper 95% Limit	2.2	2.1	2.1	1.9	1.9	1.9	2.6	3.2	2.9	3.0	2.9	2.4	1.8
<b>North Shore (6,13)</b>													
Pre-MRGO Mean	2.9	2.4	2.0	1.7	1.8	1.8	2.2	3.0	4.3	4.2	4.1	3.7	2.9
Post-MRGO Mean	4.2	3.6	3.2	2.4	2.9	2.9	3.9	5.1	6.1	6.1	6.0	5.2	4.3
Difference	1.3	1.2	1.2	1.2	1.1	1.1	1.7	2.0	1.8	1.8	1.8	1.4	1.5
Probability Diff >0	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995	>0.995
Lower 95% Limit	0.5	0.5	0.6	0.6	0.5	0.5	0.8	1.1	0.8	0.9	0.9	0.6	1.2
Upper 95% Limit	2.0	1.9	1.9	1.8	1.8	1.8	2.4	2.9	2.7	2.8	2.7	2.2	1.7

Note: The numbers in parens following each station name are the number of years in the pre-MRGO and post-MRGO data sets.

## APPENDIX B

### ON THE MATTER OF THE CONTRIBUTION OF THE IHNC AT SEABROOK TO THE TIDAL PRISM OF AND THE TOTAL SALT FLUX TO LAKE PONTCHARTRAIN

B1. During the briefing given to the Committee by staff from the New Orleans District, it was stated that 60% of the tidal prism of Lake Pontchartrain was provided by volume flux through the Rigolets, 30 percent through the Chef Menteur, and 10% through the IHNC at Seabrook. It was also stated that 40% of the salt flux into the Lake was supplied via the Rigolets, 40 % via the Chef Menteur, and 20% via the IHNC at Seabrook. The origins of these estimates was not given to the Committee at the time of the briefing, but references were later provided which contained estimates of the fraction of the tidal prism of the Lake provided via the IHNC. The Committee did not find any references giving estimations of the salt flux through the various passes. The Committee felt it was important to determine the best estimate possible of both the volume flux and the salt flux through the passes, since the amount of decrease in the salinity of the Lake which might result from the full or partial closing of the passage of salt water from the IHNC into Lake Pontchartrain depends upon what fraction of the flux of salt to the Lake comes through the IHNC at Seabrook.

#### What is the Tidal Prism of Lake Pontchartrain?

B2. The reference material provided to the Committee also contained differing estimates of the tidal prism of the Lake. The material handed out to the Committee during the presentation by the District at the San Francisco meeting in April gave the value of the tidal prism for the Lake as  $3 \times 10^8 \text{ m}^3$ . In Technical Report No. 2-636, WES, dated November, 1963, the statement is made that the mean tidal prism of the Lake is  $9 \times 10^9 \text{ ft}^3$ , or  $2.55 \times 10^8 \text{ m}^3$ . In a WES letter report dated April 1976, entitled "Reduction of Lake Pontchartrain Tidal Prism Caused by Hurricane Barriers", results obtained from the 1963 hydraulic model of Lake Pontchartrain, Lake Borgne, the MRGO, the GIWW, the IHNC, and the various passes connecting these tidal waterways, are presented. The volume flux through the Rigolets, the Chef Menteur and the IHNC are given. The total of these volume fluxes as given in the referenced report is  $4.99 \times 10^9 \text{ ft}^3$  for flood flow and  $5.20 \times 10^9 \text{ ft}^3$  for ebb flow. The ebb flow should exceed the flood flow since the model included a simulated fresh water inflow to the Lake. The total tidal volume flux into and out of Lake Pontchartrain through the three passes based on these hydraulic model results is then  $5.10 \times 10^9 \text{ ft}^3$ , or  $1.44 \times 10^8 \text{ m}^3$ . Assuming that the tidal flows through each of the passes are in phase, the total tidal volume flux through the three passes should equal the tidal prism of the Lake. The Committee could find no support, written or verbal, for the value of  $3.0 \times 10^8 \text{ m}^3$ . There are thus two estimates of the tidal prism of Lake Pontchartrain given in the references quoted in this paragraph, one for  $1.44 \times 10^8 \text{ m}^3$  and the other  $2.55 \times 10^8 \text{ m}^3$ . These estimates are included in Table B1.

B3. There are two basic methods of computing the tidal prism of a water body such as Lake Pontchartrain, which have several entrances (passes) through which tidal volume flux takes place. The most basic approach involves multiplying the surface area of the tidal waterway by the mean tidal range. Since good tidal data exists for most estuaries in the United States, and the geometry of these waterways are also well known, this method involves a straight forward calculation, providing that the tidal wave within the waterway is a standing wave. In any case, this method gives a maximum estimate of the tidal prism for the water body. Sikora and Kjerfve (1985) give the area of the Lake as  $1.630 \text{ km}^2$  ( $630 \text{ mi}^2$ ). This is slightly smaller than the

640 mi<sup>2</sup> (1656 km<sup>2</sup>) value given in one of the handouts from the District. Poirrier (1978) gives a third, intermediate value of 1,644 km<sup>2</sup>, and this is the value used by the Committee in its further calculations. The area mean tidal range for the Lake as given by Swenson and Chuang (1983), using tidal data from Outlaw (1982), is 10.88 cm. The maximum possible tidal prism for Lake Pontchartrain is therefore given by:

$$TP \leq (1.644 \times 10^9 \text{ m}^2) \times (0.1088 \text{ m}) = 1.789 \times 10^8 \text{ m}^3$$

B4. The tide in Lake Pontchartrain is not quite a pure standing wave, since the phase lag in the Lake relative to the phase of the tide at a station in Mississippi Sound just outside of the Rigolets varies somewhat from place to place in the Lake. There are six locations in the Lake for which tidal data were obtained by the District over a 182 day period in 1978 and 1979 (Outlaw, 1982). Using the amplitude and phase determined from the analysis of each of these tide records, and assigning these parameters to a subsection of the Lake, provides a basis for a better estimate of the tidal prism. The procedure involves computing the time varying tidal volume for each of these subsection over a tidal cycle, using closely spaced time steps. The sum of the six tidal sub-volumes is then taken at each time step, and the maximum and minimum volumes of the time varying sum are determined. The procedure is readily accomplished using a spreadsheet. This method gives a value for the tidal prism of Lake Pontchartrain of  $1.780 \times 10^8 \text{ m}^3$ . This value is only slightly smaller than the value computed under the assumption that the tide in the Lake is a standing wave, but does represent the best estimate possible of the true tidal prism, since it is based on the classical definition of the term "tidal prism".

B5. The second method of determining the tidal prism of a tidal waterway is to measure the tidal volume flux through all of the entrances to the subject water body from more seaward waterways. This is the method used by WES and described in paragraph B2 above, in which velocity measurements were made in the 1963 hydraulic model in the each of the three passes to the Lake. These velocity measurements were then integrated over the cross section of each pass to obtain a time varying volume flux, which in turn was integrated over time for each phase of the tide to obtain the flood directed and ebb directed volume exchange through each of the passes, and hence the total flood and ebb volume exchange into and out of the Lake. These estimates of the volume exchanges include subtidal as well as tidal volume fluxes. In the case of the measurements made in the hydraulic model, there were no subtidal meteorological forced variations in sea level at the seaward end of the model; consequently the only subtidal volume flux through the passes must arise from the input of fresh water to the Lake to simulate river discharge. Since by definition, tidal volume flux must be zero centered, the tidal volume flux through the passes to the Lake must be the absolute average of the measured flood and ebb volume exchanges in and out of the passes. This type of determination of the tidal fluxes through the passes, and hence of the tidal prism of the Lake, is described in the publication by Swenson and Chuang (1983). These authors made use of current meter measurements made over a 35 day period in each of the passes to Lake Pontchartrain during February and March of 1980. They utilized standard numerical filters to separate the velocity records into tidal and subtidal components. The filter they used had a very tight window, resulting in a decrease in the length of the filtered record compared to the unfiltered data to about 25 days from an initial length of 35 days. In this paper the authors state that the combined tidal volume flux through the three passes amounts to  $1.56 \times 10^8 \text{ m}^3$ . Swenson and Chuang then used the surface area times the range in tidal elevation procedure in reverse to calculate the tidal range which would satisfy their tidal volume flux calculations. This calculation gives a value of the tidal range of 9.4 cm, which these authors claim agrees well with the known tidal range of 10.9

cm. On the face of it, their determination of the tidal prism using the volume flux method is too low by about 16%. Applying this correction to the computed value of  $1.56 \times 10^9 \text{ m}^3$  gives a value of  $1.81 \times 10^9 \text{ m}^3$  for the tidal prism of Lake Pontchartrain, a value just slightly above the estimate made in paragraph B4 using the more classical measure of tidal prism. The primary reason for the difference is that Swenson and Chuang used a value of  $1.66 \times 10^9 \text{ m}^2$  for the surface area of the Lake rather than the value of  $1.64 \times 10^9 \text{ m}^2$  used by the Committee.

B6. Another source of data which can be used to determine the tidal prism of Lake Pontchartrain was found in Outlaw (1982). This WES report contains a very large amount of tide gauge and current meter observations. Among the most useful data sets for the purposed of this report are tables giving the date, time in decimal hours, current speed, current direction, temperature, and salinity over a 25 hour period on October 19th and October 20th, 1978. The time intervals between measurements were about 30 minutes for most of the velocity measurements, but over a small part of the records these measurements were made at about 1 hour intervals. The observations were made at three depths, at each of two stations in one cross section (designated as a range in the subject report) in the IHNC, in five ranges in the Chef Menteur, and in two ranges of the Rigolets. The Committee has analyzed these data for the range in the IHNC, one of the ranges in the Chef Menteur, and one of the ranges in the Rigolets. The selection of the range to be analyzed in the Chef Menteur and the Rigolets was based on having the selected range at a location in a reasonably straight section of each of these passes. Since there were observations made near the surface (3 ft below the surface), at middepth, and near the bottom (at 2 feet above the bottom), at two stations in each cross section, the velocities for each depth interval were averaged and assigned to a given fraction of the areas of each cross section. Based on the shape of characteristic cross sections in these waterways, the fraction of the area of the cross section considered to be applicable to the depth intervals of the current meter observations were taken as 40% for the near surface observations, 45% for the middepth observations, and 15% for the near bottom observations. Swenson and Chuang had given the areas of the transects they utilized in their study as  $800 \text{ m}^2$  for the IHNC,  $3200 \text{ m}^2$  for the Chef Menteur, and  $6400 \text{ m}^2$  for the Rigolets. No better information was available to the Committee for the ranges selected for analysis in the Chef Menteur and in the Rigolets. However, the District had supplied the Committee with bathymetric data for several ranges in the IHNC, and computations using these data for the range which appears to be close to the range for the data given in the Outlaw report gives an area below mean tide level of  $857 \text{ m}^2$ , and this is the area used in the Committee's analysis of the set of observations. The calculations of the total tidal volume flux through the three passes using this 25-hr data set from Outlaw (1982) gave a value of  $1.54 \times 10^9 \text{ m}^3$ .

B7 The WES 1982 publication by Outlaw includes a fifth set of data that can be used to obtain an estimate of the tidal prism of Lake Pontchartrain. During an intensive 50 day long survey period 35 *in situ* recording current meters were deployed on vertical moorings at 21 stations located in Lake Pontchartrain, the various passes connecting the Lake to adjacent bodies of water, in the MRGO and bayou inlets connecting the MRGO with Lake Borgne, and in the IHNC and the GIWW. There were 13 stations with a single meter at middepth on the mooring; 2 stations with two meters on the mooring (near surface and near bottom); and 6 stations with 3 meters on the mooring (near the surface, at middepth, and near the bottom). Complete or very nearly complete data records were recovered from 14 current meters, with record lengths of 28 to 44 days. Records were also recovered from two other meters that were sufficiently long (19 and 22 days) to allow tidal constituent analysis. A data record with 12 days of good data was recovered from a 17th meter. This record was too short for tidal constituent analysis, but was