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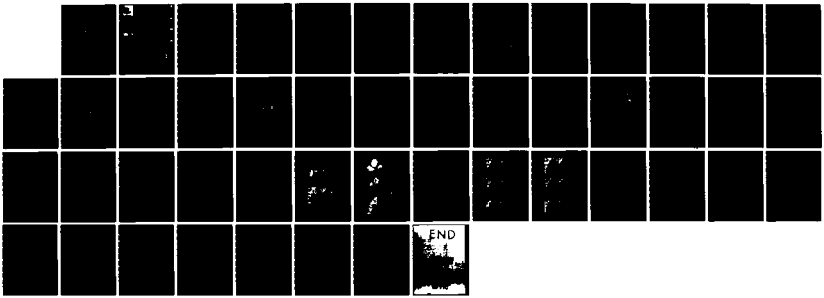

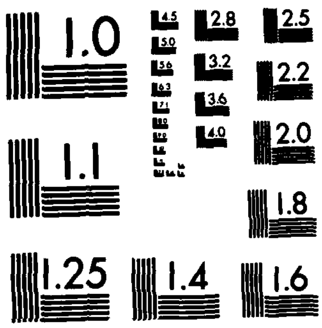

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TECHNICAL REPORT HL-82-15

THE ATCHAFALAYA RIVER DELTA

Report 6
INTERIM SUMMARY REPORT OF GROWTH PREDICTIONS

by

William H. McAnally, Jr., William A. Thomas, Joseph V. Letter, Jr., J. Philip Stewart

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The Atchafalaya River delta in Louisiana has grown dramatically. The importance of land growth for the Louisiana coast and concern for its possible impacts has led the Corps of Engineers to conduct an investigation to predict how the delta will evolve over the next 50 years and how that growth will affect flood control and navigation in the area. The investigation approach uses several analytical and numerical techniques applied separately to arrive at independent predictions of delta growth. The approach is arranged so as

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20. ABSTRACT (Continued).

to provide results from increasingly sophisticated techniques over a period of 5 years; results of an extrapolation of past behavior, a generic analysis of similar deltas' growth patterns, and a quasi-two-dimensional model have been completed thus far. They show that the delta will expand to about 19 square miles by 1990 and 60 square miles by 2030. Flood stages at Morgan City and Calumet will increase by at least 0.5 to 1.0 ft by 2030. All results are very sensitive to the amount of subsidence that will occur.

PREFACE

The work described herein was performed by the US Army Engineer Waterways Experiment Station (WES) from 1979 through 1982 and was funded by the US Army Engineer District, New Orleans (LMN).

Personnel of the WES Hydraulics Laboratory performed this work under the supervision of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, F. A. Herrmann, Jr, Assistant Chief of the Hydraulics Laboratory, R. A. Sager, Chief of the Estuaries Division, M. B. Boyd, Chief of the Hydraulic Analysis Division, and W. H. McAnally, Project Manager. The generic analysis work was performed by Drs. J. T. Wells and J. M. Coleman and Ms. S. J. Chinburg of the Center for Wetlands Resources, Louisiana State University. The extrapolation work was performed by Mr. J. V. Letter, Jr., of WES. The quasi-two-dimensional modeling was performed by Messrs. W. A. Thomas, R. E. Heath, and J. P. Stewart, and CPT D. Clark. Mr. A. M. Teeter contributed to the delta life cycle analyses. This report was written by Messrs. McAnally, Thomas, Letter, and Stewart.

Consultants to the project were Mr. L. R. Beard, Dr. R. B. Krone, Dr. C. R. Kolb (deceased), and Mr. F. B. Toffaleti (deceased). Mr. B. J. Garrett of LMN served as the district's project coordinator.

Commanders and Directors of WES during this study and the preparation and publication of this report were COL John L. Cannon, CE, Nelson P. Conover, CE, and Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

US customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
miles (US statute)	1.609344	kilometres
square miles (US statute)	2.589988	square kilometres
tons (2,000 lb, mass)	907.1847	kilograms

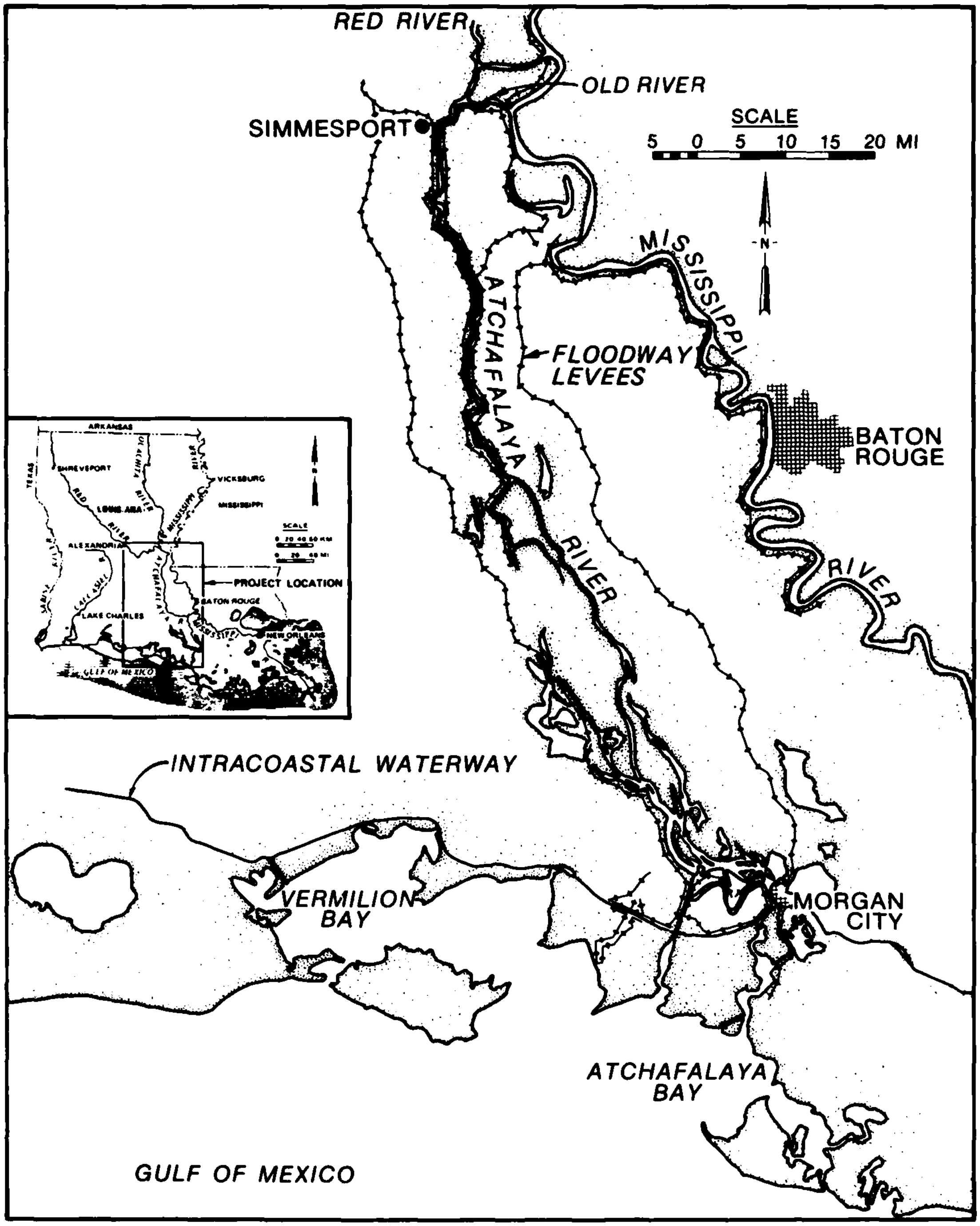

Figure 1. Project location

THE ATCHAFALAYA RIVER DELTA

INTERIM SUMMARY REPORT OF GROWTH PREDICTIONS

PART I: INTRODUCTION

Objectives

1. The objectives of the Atchafalaya Bay investigation are to answer these questions:

   a. For existing conditions and no actions other than those already practiced (i.e., maintenance of navigation channels), how will the delta evolve over the short-to-medium term (<10 years) and the long term (>10 years)?

   b. How will its evolution affect:

      (1) Flood stages at Morgan City?

      (2) Maintenance dredging of the navigation channels?

      (3) Flow distribution between Lower Atchafalaya River and Wax Lake Outlet?

      (4) Salinity in the Atchafalaya Bay system?

   c. What would be the impact of various alternatives on all of the above?

2. This report summarizes and combines results of the three predictive efforts completed to date. Its objective is to provide the Corps of Engineers with a single document that presents the best present predictions of delta growth and some of its effects while waiting for completion of the remaining, more sophisticated prediction methods.

Background

3. The Atchafalaya River captures about 30 percent of the latitude flow (combined flow of the Mississippi River and Red River at the latitude of 31 deg north) at the Old River Diversion Structure (Figure 1), and carries with it an average of 94 million tons* of sediment (Keown, Dardeau, and Causey 1981)

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

in suspension each year. This material has progessively filled in the Atchafalaya basin floodway between its natural levee systems over the past several decades and is now depositing rapidly in Atchafalaya Bay (Figure 2).

4. The evolving delta in Atchafalaya Bay is one of the most dynamic currently active deltas in the world. As the delta has evolved, converting shallow bays into marshes, a great deal of interest has been generated in deltaic processes in the bay and the impacts of man on this system.

5. Phenomenal growth of the subaerial delta since 1972 led the US Army Engineer District, New Orleans (LMN), to request that the US Army Engineer Waterways Experiment Station (WES) conduct a thorough model study to predict future growth of the delta and effects of that growth.

6. The plan of investivation includes multiple separate techniques to predict delta growth. These are:

- a. Extrapolation of observed bathymetric changes into the future.
- b. A generic analysis that predicts future growth by constructing an analogy between the behavior of the Atchafalaya delta and other deltas in similar environments.

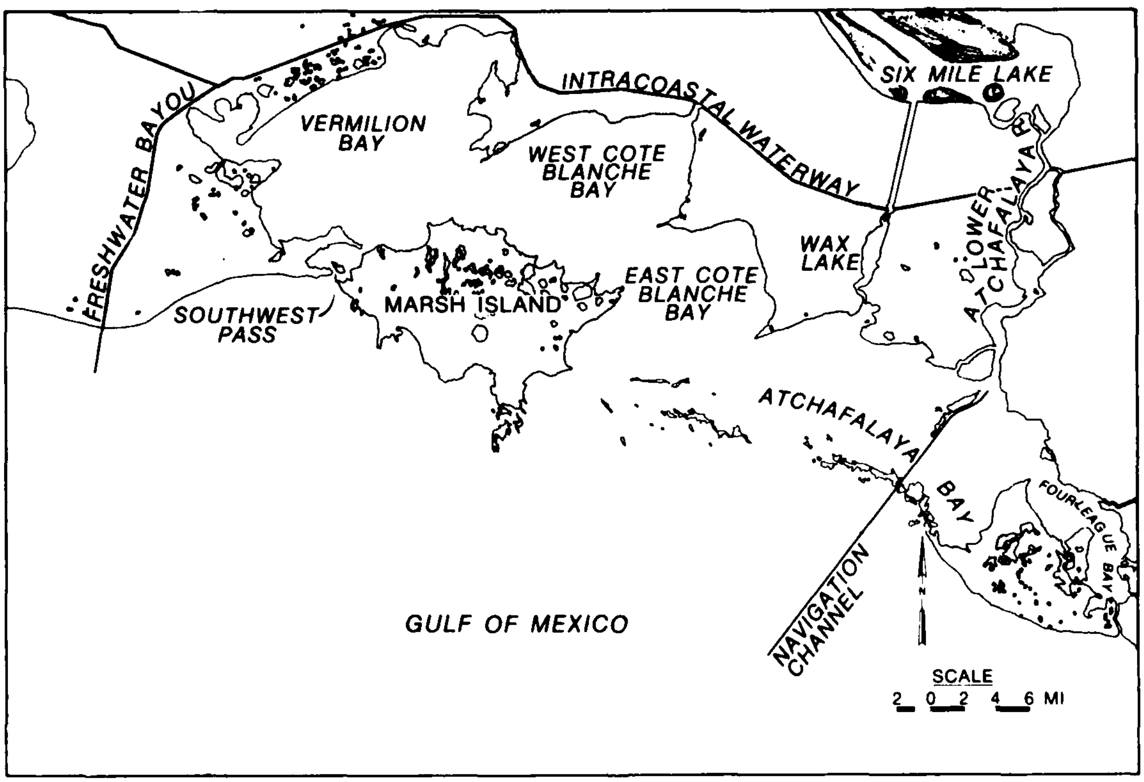


Figure 2. Location map of the Atchafalaya Bay area

c. Quasi-two-dimensional numerical modeling of hydrodynamics and sedimentation processes considering a river flowing into a quiescent bay.

d. Two- (and possibly three-) dimensional numerical modeling of hydrodynamics and sedimentation processes considering riverflow, tides, storm surges, wind-induced currents, wind waves, and density currents.

e. A 1:2,000-horizontal scale and 1:100-vertical scale physical model of the bay that is part of the Mississipi Basin Model.

A basic description of the overall plan is given by McAnally and Heltzel (1978).

7. Development of these techniques was seen to be a 4- to 5-year effort, so an implementation plan was designed such that results would be produced early and at regular stages throughout the project. In the spring of 1981, the extrapolation technique results were produced, followed by the quasi-two-dimensional results in the winter of 1982. Next completed was the generic analysis in the spring of 1982. Separate reports have been prepared describing these efforts in detail. This report is a synthesis of those three reports. A second summary report will be prepared after completion of the two- and three-dimensional modeling efforts.

PART II: METHODS USED

Delta Growth Extrapolation

8. The delta growth extrapolation task was conceived to be a first approximation to predicted delta growth. The basic approach was to relate (by regression analysis) observed historical bathymetric change in the bay to the principal driving forces in delta growth; then use that relationship to predict future delta growth from expected driving forces. (For details of the work, see Letter (1982).)

9. Figure 3 illustrates the major steps in the extrapolation. The

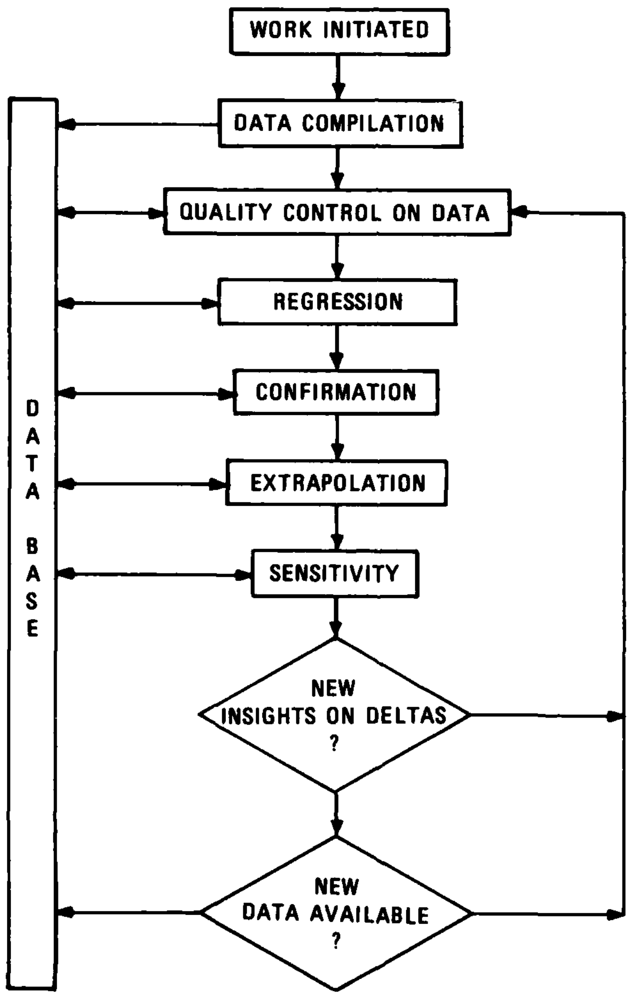


Figure 3. Approach for extrapolation study

data base is the common factor in each step of the analysis. The value of any scientific work can be in part measured by the accuracy of data used in the analysis; therefore considerable effort was expended in compiling and checking the quality of the prototype data used in the analysis. Because of this level of effort in data handling, the WES System A (LaGarde and Heltzel 1980) data management system (DMS) was utilized.

10. Regression work was performed using the Statistical Package for Social Sciences (SPSS) system on the WES G635 computer. This statistical package is a common feature on many large computing systems, and therefore some portability of the method is assured. The regression incorporated those parameters felt to be of significance to delta evolution. The regression model was applied to the historical data to confirm its ability to extend an initial condition forward in time with reasonable success. Extrapolation was performed using the regression model and a time series of parameters associated with a 50-year hydrograph. A series of tests were then made to check the sensitivity of the method to changes in the extrapolation hydrograph and associated time series.

11. A number of different sets of variables were tested in various forms. The independent variables ultimately included in the regression analyses were:

- a. Mean river discharge at Simmesport, in thousands of cubic feet per second.
- b. Annual sediment yield for the period, in million tons per year.
- c. Location in the bay, in thousands of feet.
- d. Center of mass of the delta, referenced in thousands of feet.
- e. Depth at the location in the bay, in feet.

12. The regression coefficient, R, for the overall regression was 0.465, which gives an R^2 of 0.216. This implies that the overall regression equation accounts for only about 22 percent of the total variance. The basic data seem to have quite a bit of randomness in them.

13. A confirmation analysis was performed with the regression model to ensure that it was able to reproduce past behavior of the delta. The quality of confirmation was found to be satisfactory within the limits imposed by the method.

Extrapolation procedure

14. The steps involved in the final procedure adopted for applying the regression model are:

a. Identify the initial condition of the bathymetry in the bay.

b. Define the centroid of mass for the Wax Lake Outlet and Lower Atchafalaya River deltas.

c. Define the mean river discharge and sediment yield for the period of the next time-step of the extrapolation.

d. Compute the rate of deposition at each point in the area of interest based on a or e and b and c.

e. Adjust the previous bathymetry by the rates computed in d and the duration of the time-step.

f. Recycle to b for new steps.

This sequence of tasks, b through e, is repeated for the number of steps to be executed by the extrapolation. For the confirmation sequences, the maximum number of steps was three.

Initial bathymetry

15. The initial bathymetry for the extrapolation sequence was compiled from the most current high-quality maps available for all areas. The primary survey used for coverage within the bay was the LMN 1977 survey. The data for the areas with no coverage in the 1977 survey were taken from NOAA-NOS Chart No. 11351, 1979 edition.

Extrapolation hydrograph

16. The extrapolation hydrograph was based on the Atchafalaya River hydrograph at Simmesport which was developed by LMN for use in the Hydrologic Engineering Center (HEC) models of the Atchafalaya River basin and bay. The basic hydrograph is shown in Figure 4. The duration of the hydrograph is 50 years, beginning with a portion of the 1974 prototype hydrograph and running through part of 1978, where it drops back to the 1949 hydrograph. Then the hydrograph follows sequentially each year through the same fraction of the 1978 hydrograph as before, whence it returns to the 1949 hydrograph and cycles up through a portion of the 1966 hydrograph. The flows were split 70 percent and 30 percent between the Lower Atchafalaya River and Wax Lake Outlet, respectively.

17. The time-step for the extrapolation sequence was selected to be 2-year intervals. Based on this selection, the extrapolation hydrograph was distilled down to 25 steps with associated mean river discharges for each 2-year period.

18. The actual deposition rate was determined by removing the zero-value shift in the deposition rate that was used to include the large number

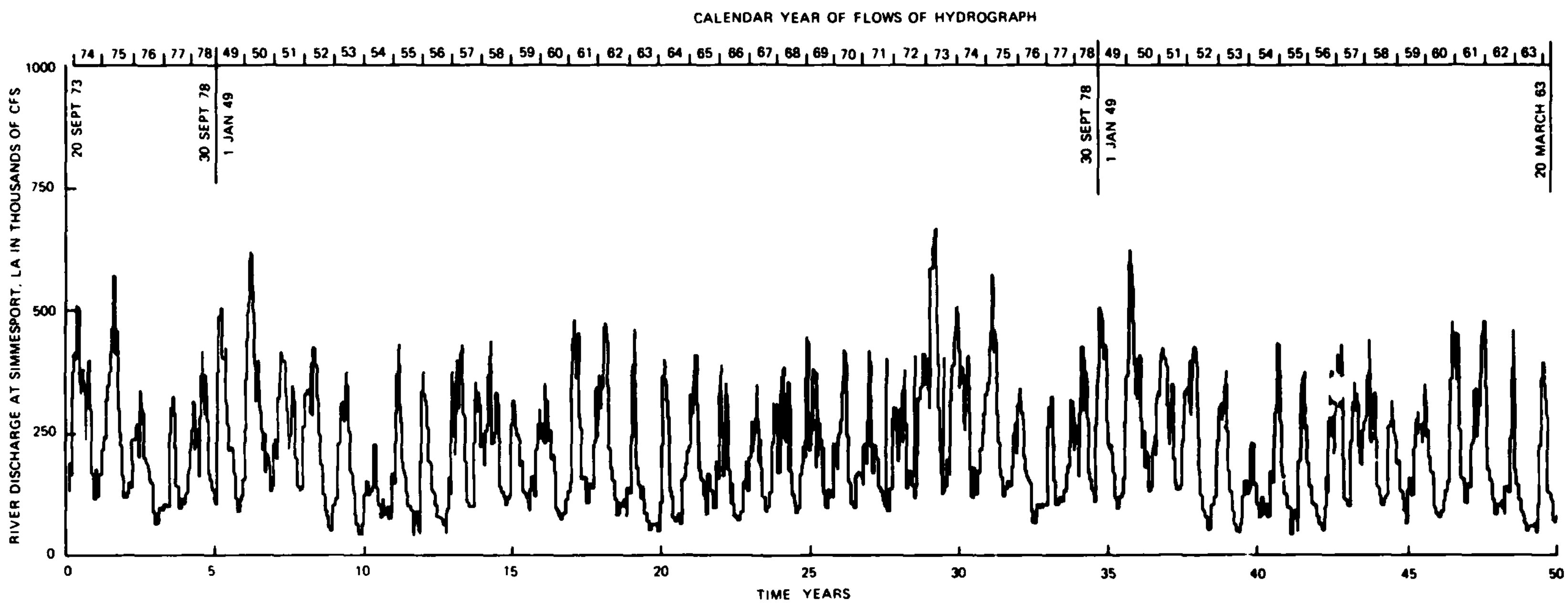


Figure 4. Fifty-year extrapolation hydrograph for Simmesport

of erosion data points. If after removing the shift the rate of deposition was less (more negative) than the generally accepted subsidence rate of -0.03 ft/yr, then the degree of apparent erosion was limited to the subsidence rate.

Bathymetric adjustment

19. After determining the thickness of deposition during each time-step, the deposited layer was added to the depths at the beginning of the time-step to yield the depth at the end of the time-step. The new depths were then used as the initial depth for the next time-step. An upper limit on the delta elevation was assumed to be +3 ft NGVD.

20. A sensitivity analysis was performed to evaluate the impact of extreme conditions on the results. The 50-year hydrograph was run in reverse order with the 1973 flood occurring first, with the 1973 flood last, with two 1973 floods, and with no 1973 flood. It was shown that the sequence did not significantly affect the final result. Eliminating or duplicating the 1973 flood noticeably changed the delta mass and amount of subaerial land.

Generic Analysis

21. The generic analysis task attempted to predict Atchafalaya Bay delta growth by comparing it with deltas formed under similar environmental conditions. It also served to provide a geologic framework for the investigation so that 50-year predictions could be viewed in comparison with the longer term processes involved. Details of the work are found in Wells, Chinburg, and Coleman (1984).

22. The generic analysis effort quantified the growth and decay of the Atchafalaya delta and four Mississippi River subdeltas by analyzing maps, survey sheets, aerial photographs, and LANDSAT images. Subaerial land areas for these deltas were computed by digitizing the land-water boundaries. Accumulated sediment volumes were computed using a contour-area method. The rate of depth contour advancement was calculated by measuring the linear progradation of the land-water boundary normal to the delta apex.

23. Growth patterns determined for the Atchafalaya delta were matched to those previously occurring in the Mississippi subdeltas, and an expected Atchafalaya growth pattern was projected similar to those of the Mississippi.

Quasi-Two-Dimensional Modeling

24. The first numerical modeling task in this investigation uses the

general purpose computer program HAD-1 to compute flows and sediment transport, deposition, and erosion in the bay. Flood stages and flow distribution changes resulting from delta growth were modeled with the generalized computer program (Simulated Open-Channel Hydraulics in Multi-Junction Systems) SOCHMJ. Details of the model's application are given by Thomas et al. (in preparation).

25. The program HAD-1, quasi-two-dimensional sediment computations, was developed by substantially modifying the one-dimensional program HEC-6 to allow lateral transport of sediment. In HAD-1, the flow area is partitioned into strips of similar hydraulic properties and sediment can move both down a strip and laterally from one strip to another. Hydraulic computations are one-dimensional for energy loss and distributed among the strips based on their relative conveyance. Lateral water and sediment movement satisfies mass continuity. The sediment moves either in proportion to water flow or in a ratio of water movement based on calculated vertical concentration profiles.

26. The computational grid used by HAD-1 is shown in Figure 5. The grid consisted of 20 lateral segments each divided into 7 longitudinal strips. The upstream limit of the grid was at river mile 87 and the downstream limit was 5 miles into the Gulf of Mexico beyond Eugene Island. In the basin, lateral model limits were the levees. In Atchafalaya Bay, lateral limits were the eastern shoreline and an arbitrary limit drawn at the entrance to East Cote Blanche Bay.

27. The HAD-1 model was calibrated to reproduce water-surface profiles from the physical Mississippi Basin model and observed (field) sedimentation patterns for the period 1967 to 1977. The prediction runs were from 1961 through the present to the year 2030.

One-Dimensional Riverflow Model

28. The program SOCHMJ was applied to the computational grid shown in Figure 6 to form the multiple channel model (MCM) of the Atchafalaya River system. SOCHMJ solves the St. Venant equations describing unsteady, one-dimensional channel flows.

29. The MCM was verified to prototype data and to data from the Mississippi Basin Model. Tested riverflows consisted of 350,000 cfs, 800,000 cfs, and the project design flood, 58AEN, which has a total maximum flow of about 1,500,000 cfs occurring in a 3-month-long hydrograph.

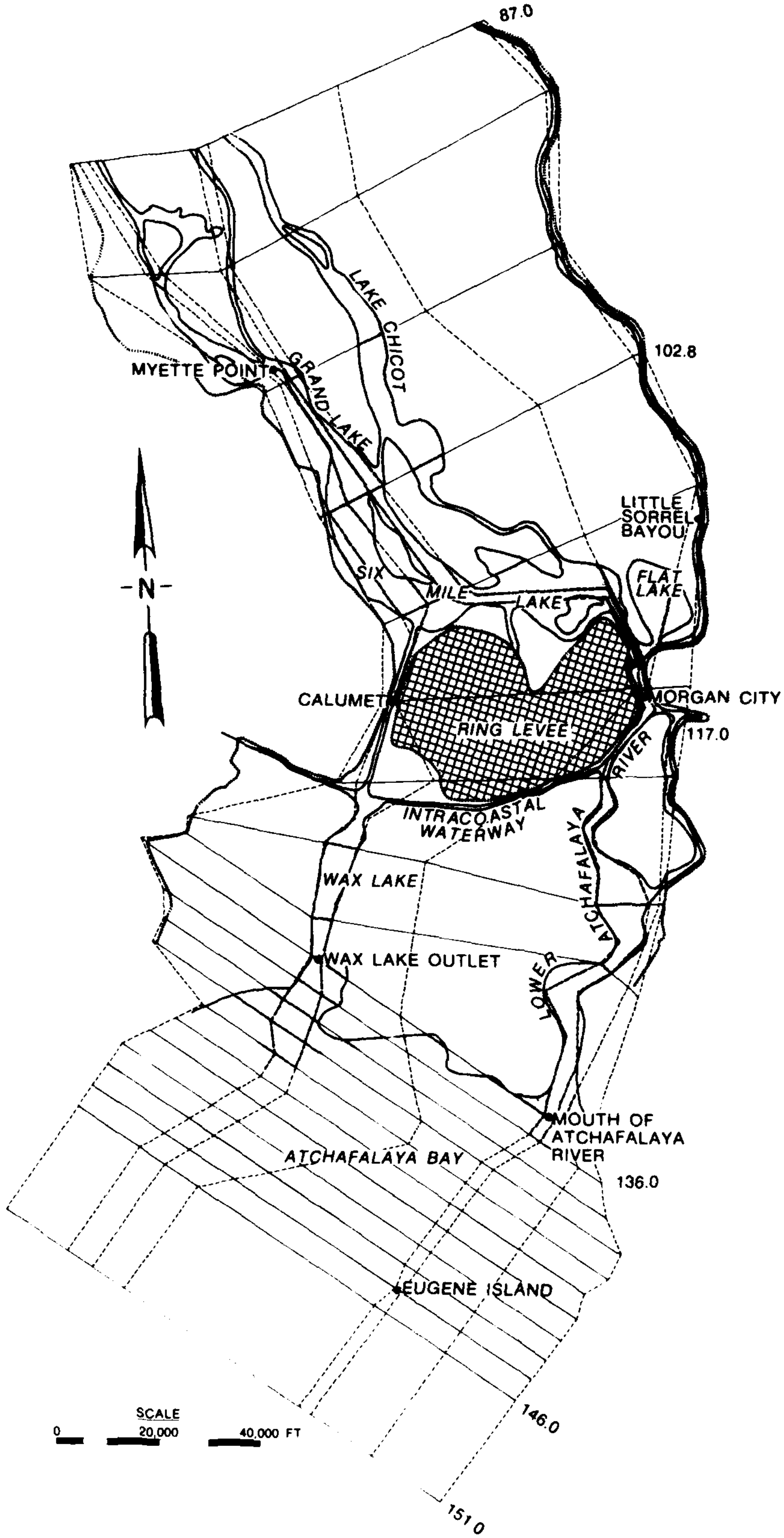


Figure 5. HAD-1 Computational grid

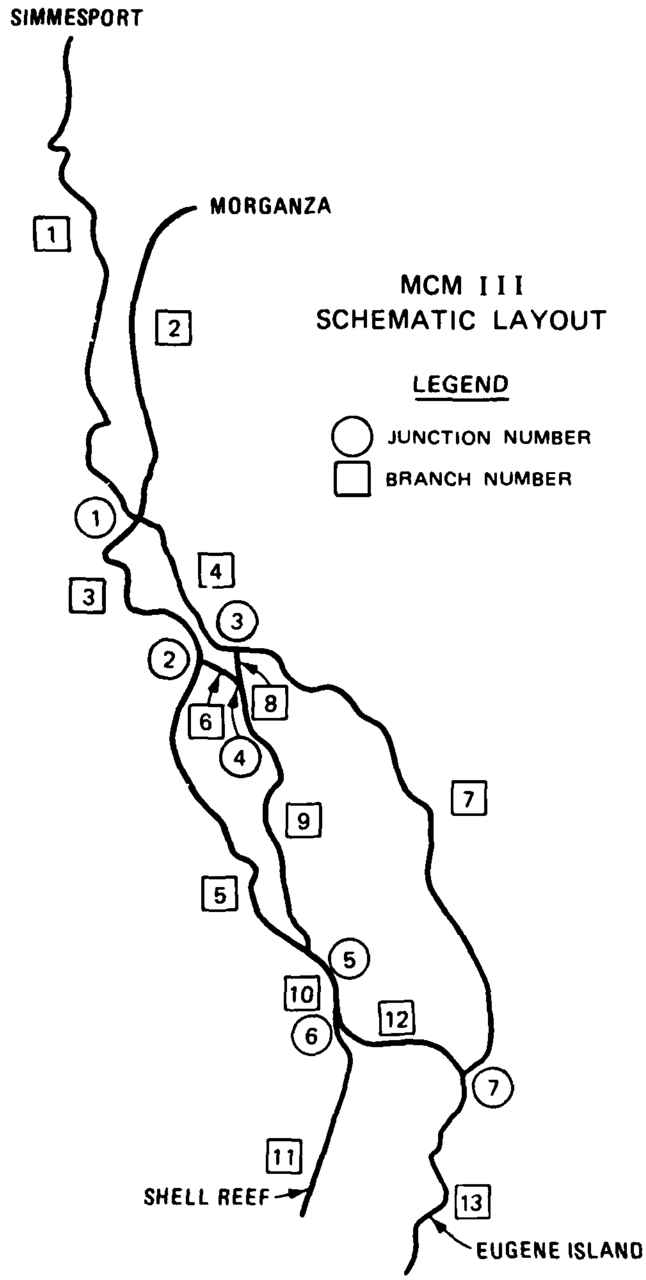


Figure 6. SOCHMJ network computational

30. Test runs consisted of the 58AEN hydrograph, the 1975 flood, and the 1973 flood. The bay geometry was modified to represent the 50-year conditions predicted by the HAD-1 model results. Two versions of the HAD-1 results were produced--one in which there was no subsidence in the bay and another in which a 1.3 cm/yr subsidence was applied to the bay.

PART III: RESULTS AND DISCUSSION

Apparent Subsidence

31. Subsidence as referred to herein is the relative lowering of the land surface with respect to sea level. The following factors contribute in varying degrees to subsidence in the Atchafalaya basin:

- a. Actual sea-level rise.
- b. Basement sinking caused by sediment load and/or subcrustal flow.
- c. Consolidation of sediments of the Gulf coast geosyncline.
  - (1) Pleistocene and pre-Pleistocene sediments.
  - (2) Recent sediments.
- d. Local consolidation.
  - (1) Caused by the weight of minor landforms.
  - (2) Caused by the weight of man-made structures.
  - (3) Caused by the withdrawal of oil, gas, and water from coastal substrata.
- e. Tectonic activity (faulting and slumping).

If total subsidence is designated as S, Kolb and Van Lopik (1958) have defined S by the equation $S = A + B + C_1 + C_2 + D_1 + D_2 + D_3 \pm E$. These factors are shown pictorially in Figure 7. In this report subsidence refers to S, actual subsidence to $S-A$.

Actual sea-level rise (A)

32. Actual sea-level rise, the result of glacial-eustatic effects, refers to a rise in sea level referenced to a stable coastline. Gutenberg (1941) has determined that the magnitude of this factor is 0.10 cm/yr, and his results are based on the records of 69 tide gages distributed around the world. Shlemon (1972) quotes a figure of 0.17 cm/yr for actual sea-level rise in the Atchafalaya Bay. Recently, Hoffman, Keyes, and Titus (1983) have suggested that global warming by the greenhouse effect may melt snow and ice packs, causing sea level to rise by 1.9 to 11 ft by the year 2100.

Sinking of basement caused by sediment load and/or subcrustal flow (B)

33. As shown in Figure 7, a thickness of about 40,000 ft of shallow-water sediments has been deposited along the Louisiana coast since the beginning of the Tertiary period (approximately 60 million years ago). This great

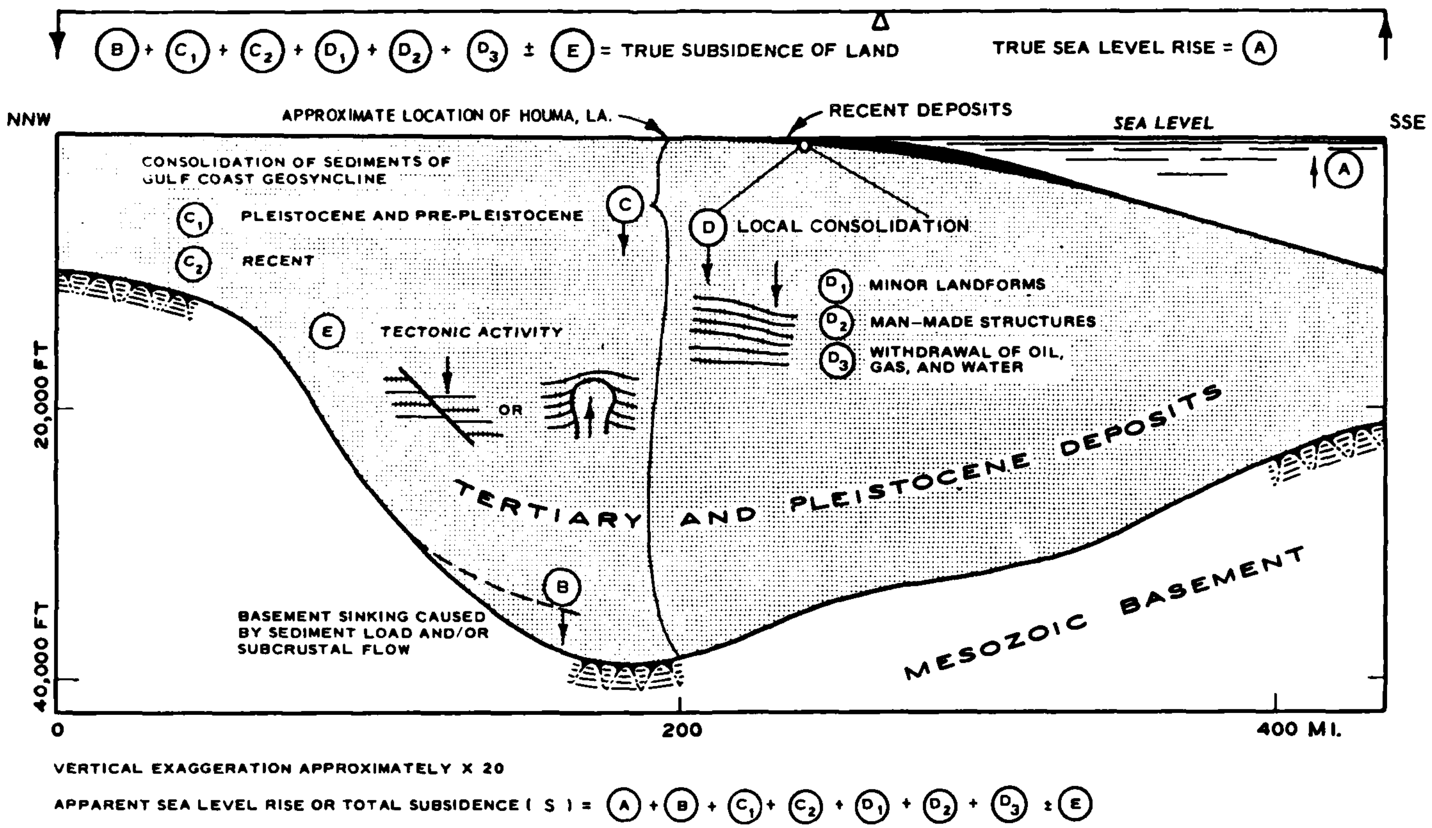


Figure 7. Generalized cross section of Gulf coast geosyncline depicting components of apparent sea level rise (adapted from Kolb and Van Lopik 1958)

mass of material was deposited here as both a result and a cause of regional downwarp, which has been occurring at an average rate of 0.02 cm/yr (Kolb and Van Lopik 1958). Regional downwarp is caused by the ever-increasing depositional load and/or by the process of subcrustal flow creating a gradually subsiding trough. The hinge-line of the downwarp occurs where the Recent sediments butt up against the Pleistocene Prairie Terrace. Fisk and McFarlan (1955) said the hinge line was near Franklin, Louisiana, about 40 miles northwest of Houma.

Consolidation of sediments of the Gulf coast geosyncline (C)

34. Pleistocene and pre-Pleistocene sediments (C_1). Consolidation refers to the adjustment of a soil in response to increased load and involves the squeezing of water from the pores and decreasing void ratio. This factor accounts for a significant percentage of the subsidence in coastal Louisiana. The most rapid consolidation of the thick wedge of Pleistocene sediments is believed to have occurred during Pleistocene time when sea level dropped approximately 400 ft. The sediments forming new land areas were dewatered, resulting in an above-average consolidation rate. A second cause for subsidence of the Pleistocene surface is the weight of Recent materials deposited on this surface subsequent to sea-level rise. Studies by Fisk and McFarlan (1955) show the Pleistocene surface to be bowed downward in a huge east-west trending, scoop-shaped depression extending from Vermilion Parish to the Mississippi-Alabama line, and southward along a line trending northeast-southwest through Donaldsonville. The estimated magnitude of this downwarping in the study area ranges from 0 at Donaldsonville to 75 ft at the Atchafalaya Bay shoreline to 100 ft at the reef (Figure 8). Assuming that this downwarping has occurred during the 25,000 years since the last major lowering of sea level, the rate of subsidence varies from 0 near the hinge line to 0.003 ft/yr (0.09 cm/yr) at the coastline to 0.004 ft/yr (0.12 cm/yr) at the reef.

35. Recent sediments (C_2). Subsidence of Recent sediments due to consolidation is most pronounced in areas of active deposition, and the rate of subsidence depends on the type of sediment being consolidated. According to Kolb and Van Lopik (1958), the rate of sedimentation of prodelta clays is such that consolidation occurs almost immediately, while the rate of sedimentation of intradelta and interdistributary materials is such that 3,000 years may be required before they are normally consolidated. In any case, once

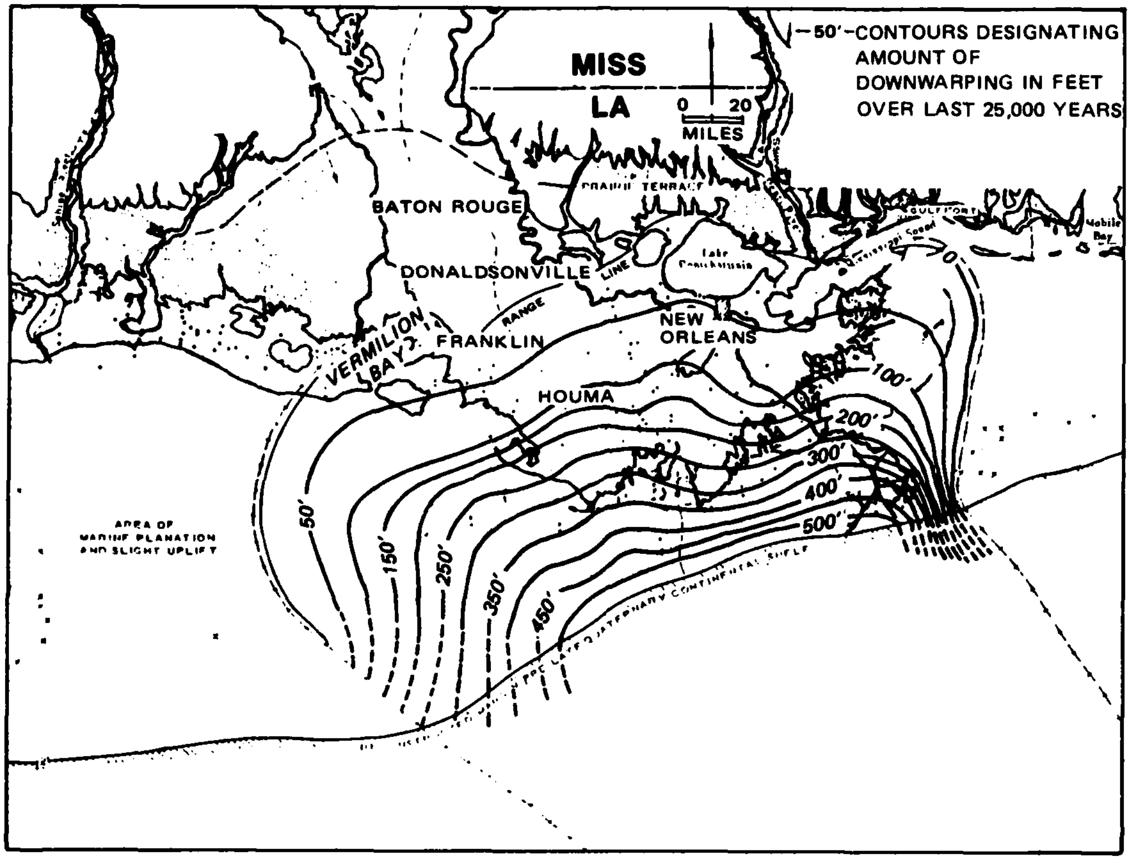


Figure 8. Amount of downwarping of the Prairie continental margin in area of late Quarternary Mississippi deltaic deposition (Fisk and McFarlan 1955)

Recent sediments become normally consolidated, any further subsidence can more logically be attributed to the factors A, B, C_1, and E.

Local consolidation (D)

36. Caused by the weight of minor landforms (D_1). Local consolidation is similar to the phenomena associated with consolidation of the Recent sediments (C_2). Where local consolidation occurs, the surface is depressed in amounts significantly in excess of those affecting the Recent deposits as a whole. There is also a tendency for natural landforms and man-made structures to "drag down" the adjacent areas (see following paragraphs). In these instances, downwarping occurs not only beneath the features but to considerable distances along their flanks.

37. Caused by the weight of man-made structures (D_2). It is possible to accurately predict consolidation that will occur beneath a given structure.

Structures built upon marsh often subside by half their height almost immediately and then continue a slow subsidence for years. Relating this local consolidation to overall subsidence is extremely difficult. This factor could significantly affect subsidence rates at Morgan City.

38. Caused by the withdrawal of oil, gas, and water from coastal substrata (D_3). The effects of withdrawal of oil, gas, and water from coastal substrata may also prove to be significant. It may stimulate or perhaps accelerate the rate of subsidence. These effects have not been quantified, however, and will be represented in analyses of more recent water-level changes.

Tectonic activity (E)

39. Most faults in the Gulf coast are down-dropped gulfward. As a result, any movement in the underlying strata accentuates the apparent sea-level rise. Detailed information concerning the location and movement along faults which would allow an estimate of the magnitude of this factor is not available. Most movement probably occurs in episodic events, making it difficult to establish an average rate of movement.

40. Two phenomena can cause upward movement, thus negating the effects of subsidence. The study area is underlain by salt domes, many of which have intruded to within a few hundred feet of the surface. Rates of uplift vary greatly. Mud lumps and mud waves formed by the displacement of bay-bottom clays might also create a local rise in the land surface, but once again it is impossible to establish an average rate of uplift.

Summary of subsidence factors

41. In summary, the factors for which various investigators have been able to establish average subsidence rates are actual sea-level rise (A), basement sinking (B), and consolidation of Pleistocene and pre-Pleistocene sediments (C_1). The estimated subsidence rate resulting from these factors is 0.28 cm/yr inland and 0.31 cm/yr at the reef. As shown in the following paragraphs, most investigators have estimated subsidence in the Atchafalaya Bay three to four times larger than this. It can be concluded that the difference results from factors C_2, D_1, D_2, D_3, and E.

Literature review

42. Most of the information presented in the preceding paragraphs was taken from Kolb and Van Lopik (1958). Numerous other studies have been done related to subsidence along the Gulf coast and/or the Atchafalaya River basin.

43. Morgan (1967) analyzed 140 detailed continuous hollow cores from the Mississippi Delta and calculated subsidence rates which varied over a 100-square-mile area from 1.52 to 3.96 cm/yr. He concluded that such rapid rates resulted from the initial high-water saturation of deltaic sediments. In addition, there is a lateral displacement by plastic flow in underlying fine-grained sediments which contributes to locally high subsidence rates.

44. Hicks (1968) analyzed the tide records at 41 locations around the world for the period 1940 to 1966 to determine the rate of change in apparent mean sea level at each site. These data include the effects of both actual sea-level rise and actual subsidence. The rate of change was computed as the slope of a least squares regression curve through the data. Along the Gulf coast, the rate ranged from 0.06 cm/yr at Pensacola, Florida, to 0.92 cm/yr at Eugene Island, Louisiana. An updated report in 1974 indicated that the subsidence rate at Eugene Island was still 0.92 cm/yr. The data used in the updated study covered the period 1940-1970. A subsidence rate of 1.3 cm/yr is obtained by computing the slope of a straight line connecting the end points of the curve in Figure 9. This is the rate estimated by Shlemon (1972).

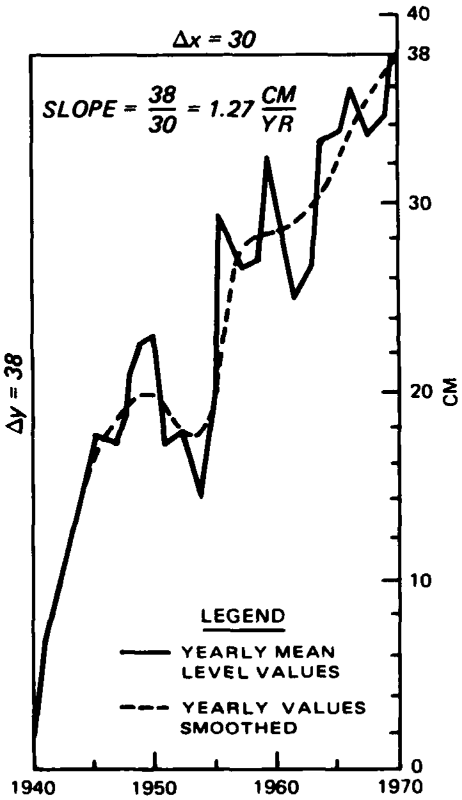


Figure 9. Relative change in sea level, 1940-1970, as interpreted from tide-gage data at Eugene Island, Louisiana (after Hicks 1972) (Shlemon 1972)

45. Swanson and Thurlow (1973) determined actual subsidence rates along the Louisiana and Texas coasts by comparing tide records at 14 locations with the long-term tide record at Pensacola, Florida, which was assumed to be stable. The records were analyzed in two parts, pre-1959 and post-1959. At those stations for which pre-1959 records were available, actual subsidence rates were found to be significantly greater during the post-1959 period. At Eugene Island, the actual subsidence rate from 1948 to 1959 was found to be 0.83 cm/yr and from 1959 to 1970 the rate was 1.12 cm/yr, or

0.975 cm/yr for 1948-1970. The recent trend, therefore, is 15 percent greater than the long-term average. Since their analysis filtered out the effects of actual sea-level rise, a value of 0.17 cm/yr must be added to their results to obtain total subsidence. Thus their results indicate that the subsidence rate at Eugene Island has increased from 1.00 cm/yr prior to 1959 to 1.29 cm/yr since 1959.

46. Holdahl and Morrison (1974) have reported on the results of regional investigations of vertical crustal movements using precise relevelings and marigraph data. Their results have filtered out the contribution of actual sea-level rise. The surface elevation changes measured in the Gulf coast region were plotted as a contour map (Figure 10). They estimated an actual subsidence rate of 0.50 cm/yr near the coastline to about 0.30 cm/yr near Morgan City. This corresponds reasonably well to the regional subsidence rate quoted by Kolb and Van Lopik (1958).

47. Baumann and Adams (1981) correlated the water stages at Amelia, Louisiana (east-southeast of Morgan City, Figure 5), with the Atchafalaya River discharge for the period 1955-1980. They plotted the residuals versus time in order to detect any temporal trend. The results suggested that water stages at Amelia have been rising at a rate of 0.85 cm/yr independent of river discharge.

Summary of reported values

48. The studies by Kolb and Van Lopik (1958) and Holdahl and Morrison (1974) indicated that the regional subsidence rate due to downwarping and consolidation of Pleistocene and pre-Pleistocene sediments in the Atchafalaya basin is about 0.30 cm/yr. Baumann and Adams (1981) estimated a rate of 0.85 cm/yr at Amelia. In the coastal zone and in the bay, estimates of the subsidence rates range from 0.92 (Hicks and Crosby 1974) to 1.29 cm/yr. The analysis of Swanson and Thurlow (1973), designed to filter the actual sea-level rise out of the tide records in order to estimate the actual subsidence, showed that the recent actual subsidence rate is greater than the long-term average by 15 percent. The studies by Hicks simply averaged the observed changes in apparent mean sea level. An independent estimate of actual sea-level rise based on glacial melting may then be used to determine the magnitude of actual subsidence. This approach seems more straightforward and less susceptible to error. The regression was performed on the period of record, however, and gives no indication of trends. It was noted in a study by

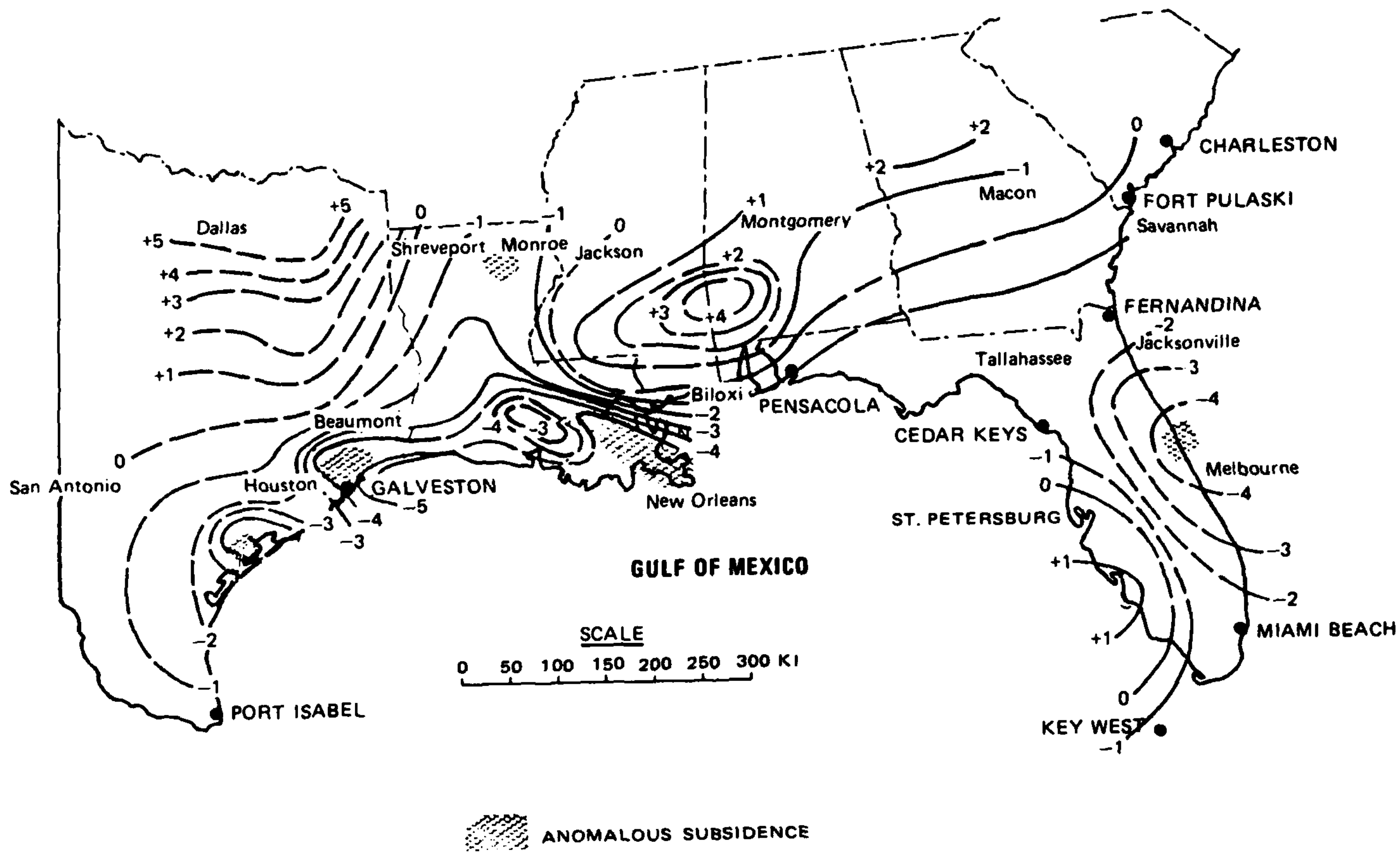


Figure 10. Preliminary rates of elevation change (units for contour levels are mm/year) (Holdahl and Morrison 1974)

Shlemon (1972) that subsidence in this area is likely to increase as the subaerial phase of delta growth develops and sands prograde over the subdelta. In this same study, Shlemon computes a subsidence rate of 1.3 cm/yr by connecting the end points of Hick's data. It is felt that this interpretation of the data is too restrictive and gives too high an estimate. However, a rate somewhat larger than 0.92 cm/yr may be advisable in predictions of delta growth.

49. To incorporate the findings of previous investigation into a best estimate of the subsidence rate in the Atchafalaya Bay, we must start with the rate estimated by Hicks (1974), 0.92 cm/yr. The temporal trend noted by Swanson and Thurlow (1973) should be included. Since their results filtered out actual sea-level rise, this rate must be subtracted before applying the 15 percent increase indicated by their study. Thus $(0.92 - 0.17) \times 1.15 = 0.86$ cm/yr. Adding the actual sea-level rise back in, we arrive at an estimated subsidence rate of 1.03 cm/yr in the bay. The best prior estimate at Morgan City appears to be 0.30 cm/yr based on the results of Kolb and Van Lopik (1958) and Holdahl and Morrison (1974).

Size Of the Delta

50. Delta extent can be measured in several ways and comparisons between the several predictions must be done carefully to ensure true comparability. In this report, the size of the delta will be presented in terms of the accumulated volume of sediment, delta extent as defined by the area between the shoreline (0 ft NGVD in 1969) and the -3 ft NGVD contour, and subaerial land as defined by the area between the 1969 0-ft NGVD contour and the 0-ft contour at the time of the prediction.

51. The predictions are for years 1990 and to 2030. The extrapolation predictions based on conditions existing in 1977 are actually for 1987 and 2027 but shall be considered to be equivalent to the prediction years.

Subaerial land

52. The predictions for subaerial land in 1990 (Table 1) ranged from a low of 17 square miles from quasi-two-dimensional modeling to a high of 22 square miles for the generic analysis. These result in an average prediction of 19 square miles for all three approaches compared with a 1980 land area of 8 square miles.

53. At 50 years, the predicted extent of land covers a wide range--32

Table 1

Predictions of Total Subaerial Land, Square Miles

Source	Year 1990	Year 2030
Extrapolation	19	87
Generic analysis	22	60
Quasi-2D modeling	17	32
Average	19	60
Variation	26%	91%

to 87 square miles. For this period, the extrapolation effort gave the largest figure while the quasi-two-dimensional modeling again gave the lowest. The average of the three methods is 60 square miles.

54. Of the three prediction methods, only the generic analysis effort is directly based on predicting the extent of subaerial land. This leads us to emphasize that approach's results in interpreting the land prediction. Reinforcing this choice, the average predictions are quite close to the generic results. The variation in the results is 26 to 91 percent of the average values.

55. Atchafalaya Bay itself covers about 200 square miles. Therefore the prediction suggests that about 10 percent of the bay in 1990 and 30 percent in 2030 will be subaerial land.

56. Figure 11 shows growth of subaerial land over time for the three prediction methods. For the extrapolation technique, only the points at 10 years, 30 years, and 50 years are shown. Generic analysis results are displayed for two growth rates--one in which a least squares curve was fit to past growth in order to obtain a 1980 starting point and one in which the observed land in 1980 was used. These result in a higher and a lower estimate. Results given in Table 1 are for an intermediate estimate.

57. For the quasi-two-dimensional results, two curves are presented in Figure 11. A lower estimate is based on model results with a 1.3 cm/yr subsidence rate. The higher estimate curve is for a 1.0 cm/yr rate. The 1.0 cm/yr rate was not modeled; it was obtained by applying a ratio to modeled land areas for 1.3 cm/yr and for no subsidence. For no subsidence, the quasi-two-dimensional modeling predicted a land area of 91 square miles in year 50.

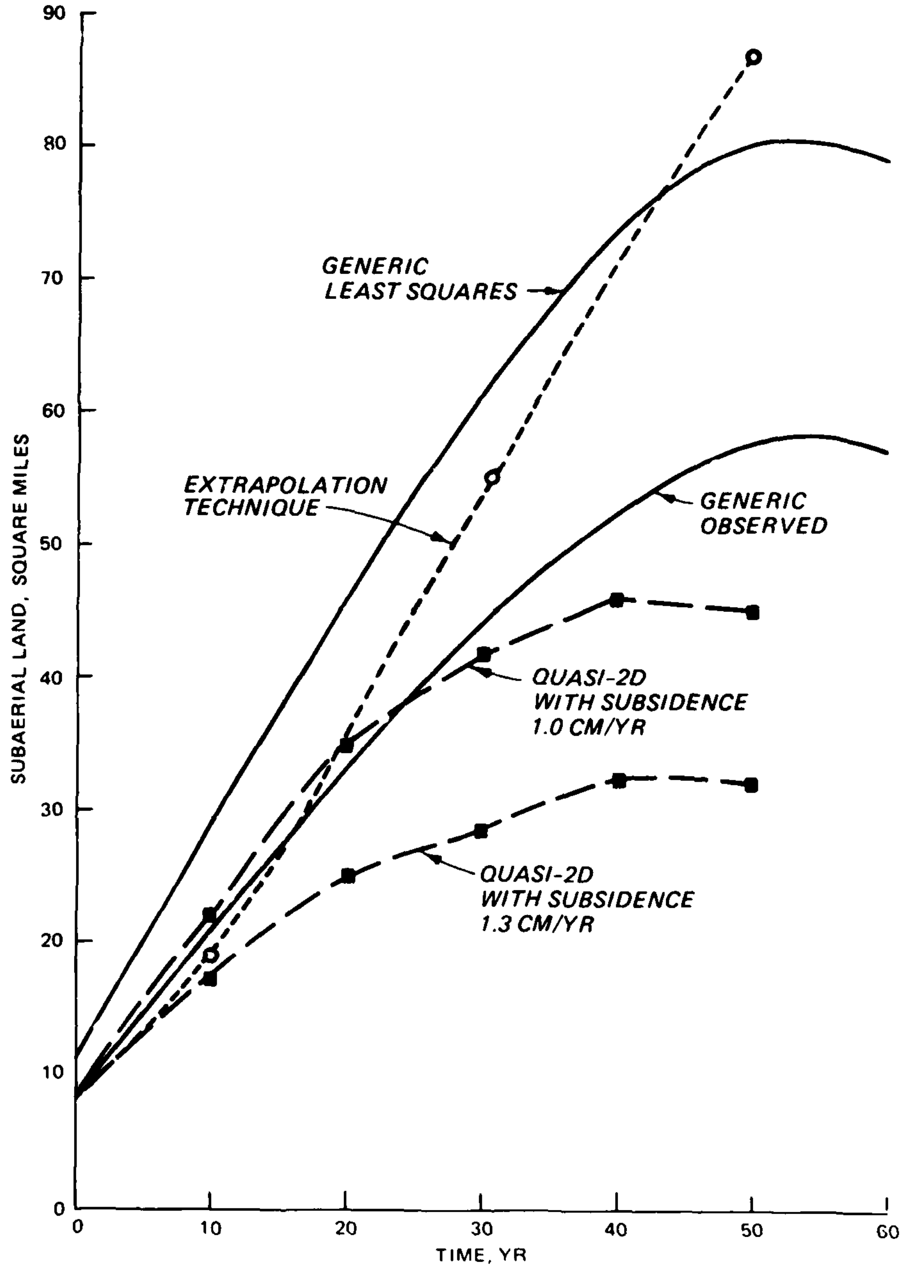


Figure 11. Time rates of growth, subaerial land

58. These results show the impact of subsidence on the results. The extrapolation technique did not directly consider subsidence but would tend to include the effect during the period over which regression was applied--1967 to 1977. The generic analysis results include subsidence implicitly in the technique but would primarily reflect subsidence in the Mississippi Delta.

59. Figures 12 and 13 show the predicted shapes of the land by the three methods. At 50 years, the land shapes predicted by extrapolation and generic analysis are quite similar, but the generic land area is larger and includes land beyond Eugene Island. The quasi-two-dimensional predicted land area is smaller than the other two and shows more land to the east of the navigation channel.

60. Since the extrapolation predictions are considered to be primarily a subaqueous result and land area was predicted in an intuitive sense, its predictions for total land area are considered less persuasive than those of the generic analysis. On the other hand, the generic analysis is based on a prediction of subaerial area, but its distribution of subaerial land is primarily intuitive. The quasi-two-dimensional modeling prediction of land area is only slightly a product of interpretation, but it lacks consideration of delta reworking forces such as tides and waves. Therefore we consider all three predictions of subaerial land shape to be highly subjective.

Delta extent

61. The -3 ft NGVD contour has been selected as a measure of delta extent because much of the bathymetric field data used is restricted to depths greater than 3 ft. Several of the earlier predictions of delta extent did not specify the contour used on the delta boundary, and we have interpreted these to mean the -3 ft contour.

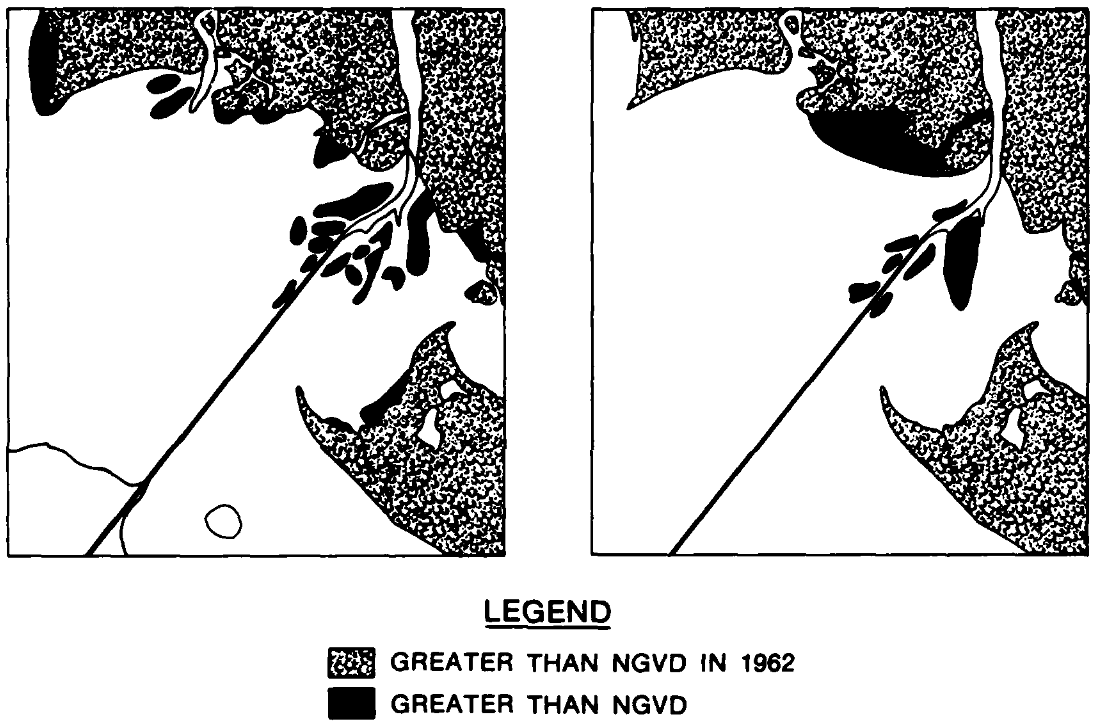
62. Table 2 shows the areas enclosed by the predicted -3 ft contour and

Table 2

Predicted Delta Extent,* Square Miles

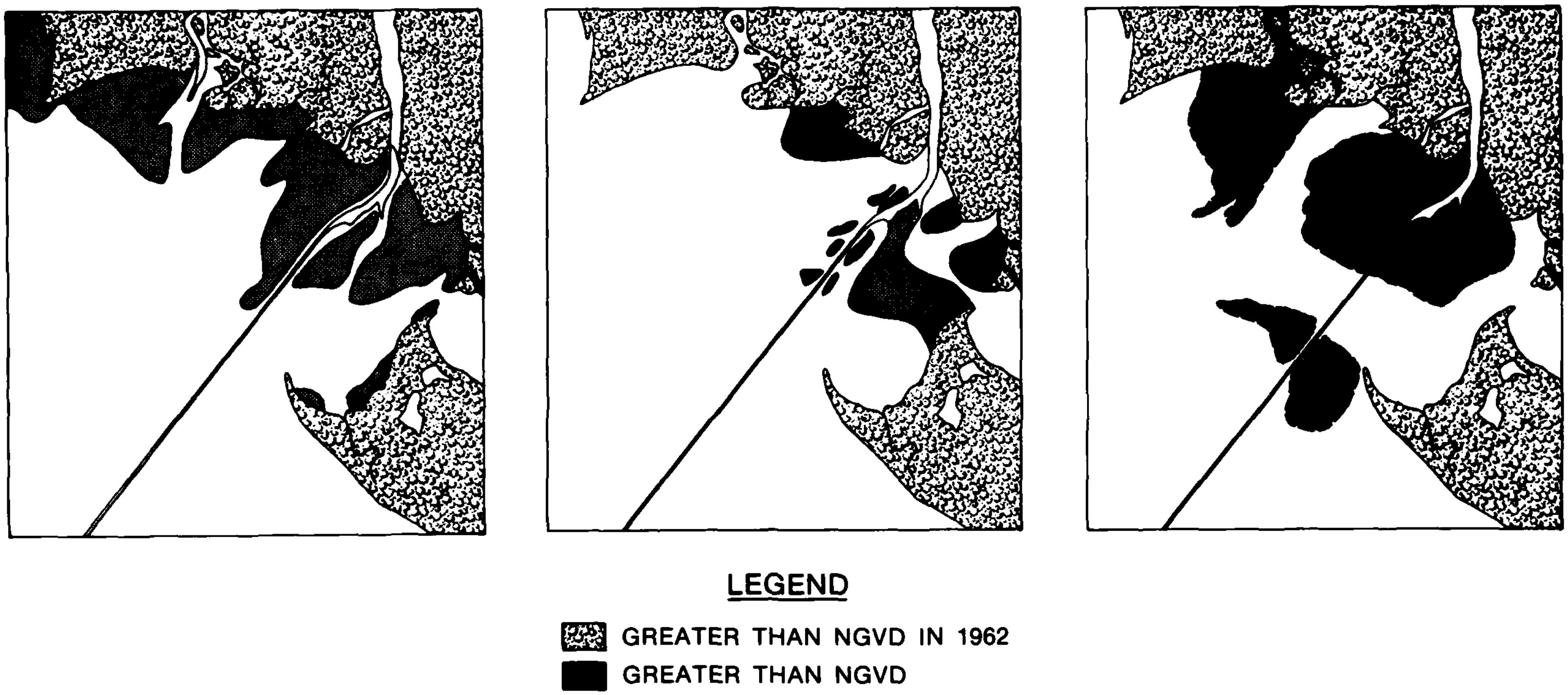
Source	Year 1990	Year 2030
Extrapolation	123	377
Quasi-2D modeling	98	**
Average	110	--
Variation†	23%	--

* Area within the -3 ft NGVD contour.
** Delta extended beyond area of reliable model predictions.
† Range of values/average value.



a. Extrapolation b. Quasi-two-dimensional

Figure 12. Land distribution at 10 years



a. Extrapolation

b. Quasi-two-dimensional modeling

c. Generic analysis

Figure 13. Land distribution at 50 years

the 1967 shoreline. The generic analysis did not produce a separate result for the -3 ft contour. At year 1990, the extrapolation predicted an area of 123 square miles enclosed by the -3 ft contour, and the quasi-two-dimensional modeling predicted a somewhat smaller area--98 square miles. For a lower subsidence rate, the two techniques would make the results nearly equal. For comparison, a prediction of 140 square miles was made by Shlemon (1972), using data from Garrett, Hawkhurst, and Miller (1969). The predictions made by this project vary by 23 percent from the average.

63. For year 2030, the -3 ft contour extended beyond Eugene Island and into the last row of computation points in the quasi-two-dimensional model. Since the results in that zone were considered unreliable, no areal extent figure was produced. The extrapolation task predicted a -3 ft contour area of 377 square miles. This is somewhat larger than Shlemon's range of 290 to 350 square miles.

64. All of the predictions support a location of the -3 ft contour out into the Gulf by 2030, although both the quasi-two-dimensional modeling and generic analysis show small pockets of deeper water left inside Atchafalaya Bay.

65. Figures 14 and 15 show the predicted shapes of the delta extent for 10 years and 50 years by the three prediction methods and an earlier prediction by Garrett.*

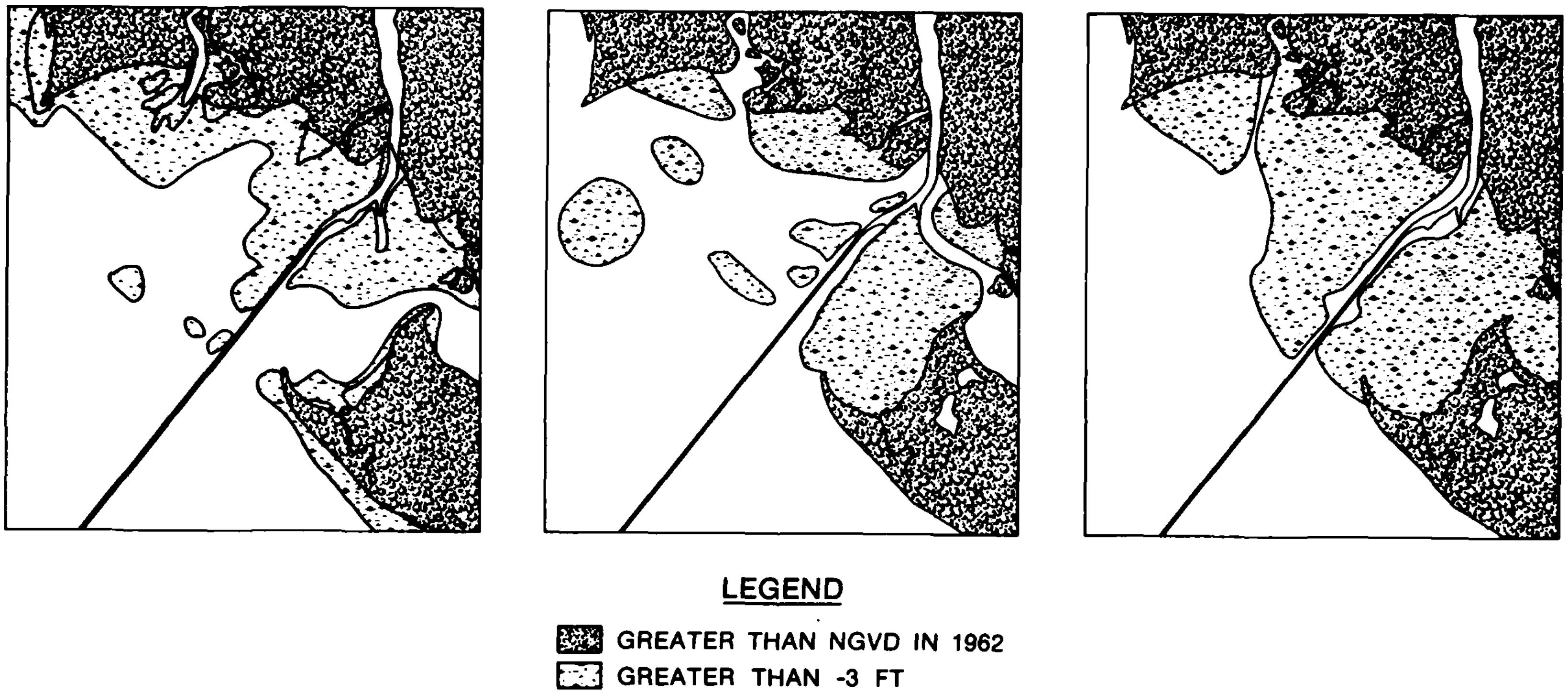
Delta volume

66. Table 3 shows the predicted volume of sediment accumulated above the 1980 bay bottom and within the -3 ft contour. In 1990, the predictions ranged from 4.9 billion cu ft from generic analysis to 7.2 billion cu ft from quasi-two-dimensional modeling, for a variation of about ±38 percent from the average of 6 billion cu ft.

67. For year 2030, the predictions ranged from a low of 18 billion cu ft from the extrapolation to a high of 25 billion cu ft. This is a variation of 33 percent about the average of 21 billion cu ft.

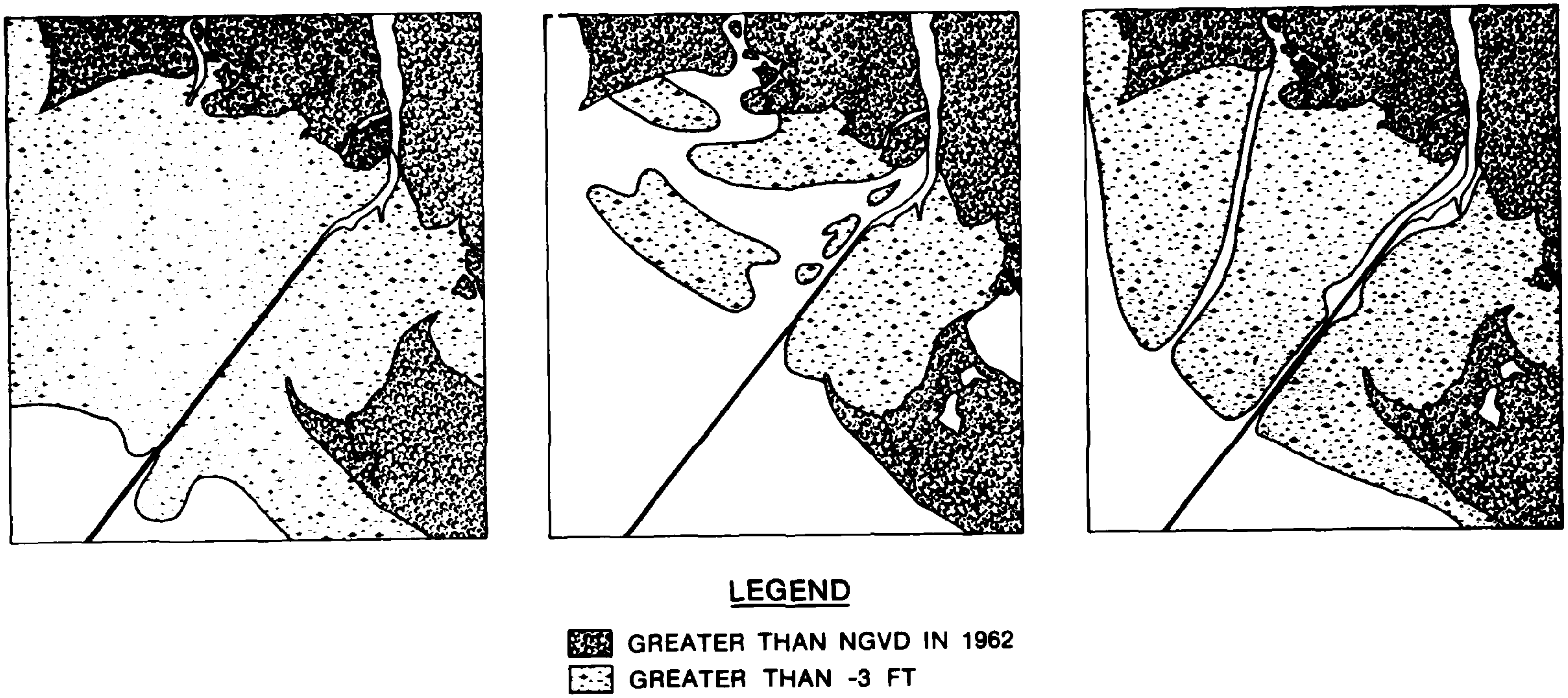
68. It is immediately noticed that the three predictions for delta volume exhibit substantially less variation than those for subaerial area. The three methods were in general agreement on the supply of sediment and trapping efficiency of the system, but differed primarily in the way that the predicted sediment volumes were distributed. The quasi-two-dimensional modeling results,

* B. J. Garrett. 1972. Unpublished data.



a. Extrapolation b. Quasi-two-dimensional modeling c. Garrett (1972)

Figure 14. Delta extent at 10 years



a. Extrapolation

b. Quasi-two-dimensional modeling

c. Garrett (1972)

Figure 15. Delta extent at 50 years

Table 3

Predicted Delta Volume, 10^9 Cu Ft

Source	Year 1990	Year 2030
Extrapolation	5.9	18
Generic Analysis	4.9	25
Quasi-2D modeling	7.2	21
Average	6.0	21
Variation†	38%	33%

† Range of values/average value.

which were lower than the other methods' results in land area, were somewhat higher in predicted delta volume at 10 years and near the average at 50 years.

69. The predicted variation in delta volume over time is shown in Figure 16. Actual results are displayed for quasi-two-dimensional modeling and extrapolation. An annual accumulation rate given in the generic analysis report has been shown as a straight line out to 50 years in the figure. It

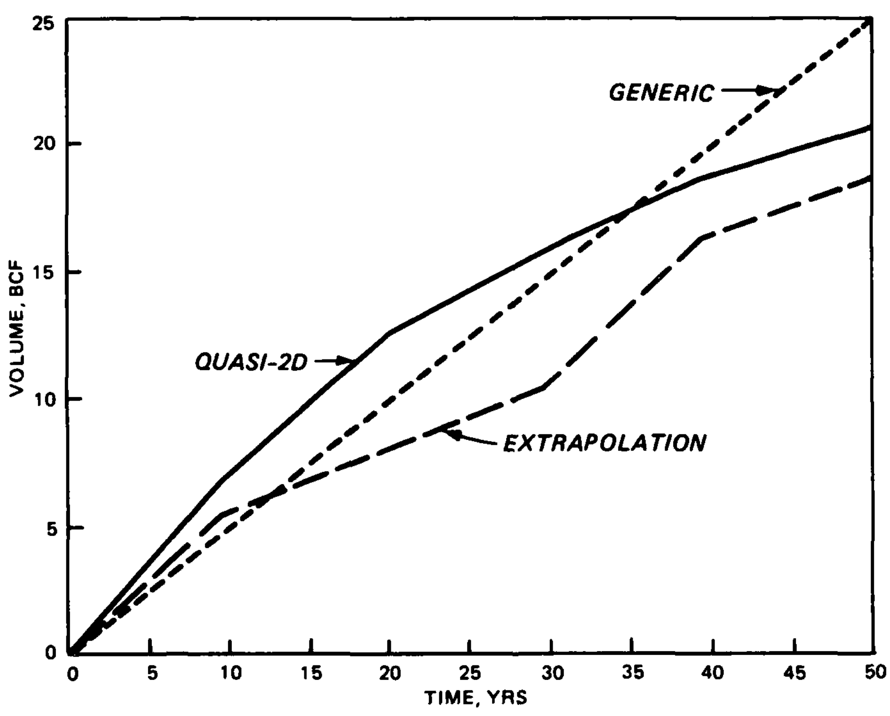


Figure 16. Predicted growth of delta volume over 50 years

can be seen that the variation is not too great at 50 years or in the first 10 years, but between those points the methods yield considerably different results. This is probably due to differences in sequences of flow events used in the quasi-two-dimensional modeling and extrapolation.

Flood Stage Predictions

70. The MCM predictive runs were made for the three floods described in paragraph 29.

71. Table 4 shows predicted changes in flood stages at four locations for three specific floods. The changes are the increases in stage that will occur as a result of increased resistance to flow by the growing delta and apparent subsidence at the gage location. The one-dimensional numerical model for flow used the quasi-two-dimensional delta growth prediction including the effect of bay area subsidence at a rate of 1.3 cm/yr. The predicted stages were then increased to account for the predicted rate of local subsidence at the gage location. For Morgan City and Calumet, a subsidence rate of 0.3 cm/yr (see paragraph 49) was applied for a 50-year increase of 0.5 ft in stage. At Wax Lake Outlet and Deer Island, it was assumed that the subsidence rate varied linearly from 0.3 cm/yr at Morgan City to 1.3 cm/yr at Eugene Island. The calculated 50-year subsidence at these locations was 1.8 ft.

Table 4

Increase in Peak Stage at Year 2030 Caused by Delta Growth and Subsidence, Ft

Location	1973 Flood	1975 Flood	58AEN
Morgan City	1.0	1.1	1.0
Calumet	0.5	0.7	0.5
Deer Island	3.6	3.6	3.6
Wax Lake Outlet	2.1	3.0	2.0

Life Cycle Of the Delta

72. In their report on the generic analysis work, Wells, Chinburg, and

Coleman (1984) showed a predicted growth curve for the Atchafalaya delta subaerial extent that peaked at about year 2035 and showed land loss after that time (Figure 11). This curve was questioned by project consultants who said that a life cycle hundreds of years long was more appropriate for the Atchafalaya.

73. Wells' report noted that a 600- to 800-year life cycle may be more appropriate, but that the total subaerial land after 50 years is about the same whether the expected life is 150 years or 600 years. Thus he considers his projections as shown in previous paragraphs to be appropriate even if growth continues beyond 60 years. However, even if it will not affect our 50-year predictions of delta growth, the life cycle question deserves further consideration because of the importance of coastal land growth in Louisiana.

74. Inspection of the growth curves (Figure 11) produced by the quasi-two-dimensional modeling for 1.3 cm/yr subsidence showed a peak in subaerial extent between years 40 and 50. The accumulated volume was continuing to increase throughout the 50-year period. If a lower subsidence rate were applied, it is expected that the peak in subaerial extent would occur later.

75. These results and those of Dr. Wells were presented at a project review meeting held at WES in July 1982. At that time Dr. Charles Kolb, consultant to the project, made these remarks.

> "I was very puzzled by a summary statement that Atchafalaya delta growth would peak out in 30 years according to WES predictions and at 50 years based on LSU predictions. After this, presumably, the delta would supposedly get smaller. This doesn't make sense to me. Unless the delta is abandoned I would think the delta land area would continue to enlarge. There might be some areas where delta lobes cease to get sediment supply. These would tend to deteriorate. But the whole history of delta growth in the Mississippi is the gradual enlargement of land area in central and eastern Louisiana during the past 4,000 years. The St. Bernard, the Plaquemines, the Lafourche, the Teche, and previous earlier deltas all built seaward over a shallow gulf shelf, in much the same way the Atchafalaya is doing. The overall result has been the building seaward of as much as a third of what is now Louisiana.
>
> In other words, delta advance into a receiving area very similar to that into which the Atchafalaya is now building has been going on during the past 4,000 years and the net result has been the formation of a huge mass of land. I see no reason why the Atchafalaya should behave differently. You might argue that the Atchafalaya is a small delta, carrying only a third of the Mississippi's flow. But there

is good evidence that the Lafourche course of the Mississippi wasn't much larger than this, yet it advanced all the way to Grand Isle and over a much deeper body of water than that into which the Atchafalaya is debouching.

It's only after a given delta is abandoned that it really begins to deteriorate and decrease in overall size. Again you might argue that the present Mississippi delta doesn't seem to be increasing very rapidly in size, and the answer there is that for the first time in the last 4,000 years or so, the Mississippi is building its delta at the very edge of the continental shelf into truly deep water. The Atchafalaya delta has a long way to go, over a comparatively shallow continental shelf. In my opinion, it and the land area associated with it will continue to grow through time."

76. Perhaps some (but not all) of the apparent disagreement can be resolved by clarifying how the terms are used and how results are interpreted in view of time scales greater that 50 years. First, it should be noted that the generic analysis results and the model results showed a decline only in subaerial extent of the delta. The methods either showed or implied a constant growth in delta volume over the entire 50 years. Second, it is expected that the model would show another episode of subaerial growth at a later stage of development following deposition of additional prodelta clay base over a much wider delta front.

77. Although these observations are important to interpretation of the generic analysis and modeling results, the fundamental question remains--will the subaerial extent of the Atchafalaya delta undergo a period of substantial decline during the 50-year period of interest? Five general statements that apply to complete delta units are proposed.

a. The delta consists of those sediments deposited contiguous to the river mouth or within the delta. In the Atchafalaya, the area in which delta sediments accumulate includes much of the basin also.

b. A delta will lose sediment mass only if resuspension and subsequent offshore sediment loss exceed the supply of sediment to the delta (river supply times trap efficiency). This condition is very unlikely to occur in the Atchafalaya in the next 50 years short of substantial diversion of the river to another location.

c. Delta volume is the volume of sediment above an arbitrary datum plane. A delta will decrease in volume of deposits only if the average rate of deposition (river supply times trap efficiency divided by the product of deposit density times area of deposition) is less than the average rate of depth increase due to apparent subsidence (sea-level rise, subsidence, compaction, etc.). Such an imbalance could be caused by reduction in sediment supply, reduction in trap efficiency, increase in length of the delta front that causes the sediment to be spread over a larger area (decreasing the average rate of deposition), and/or a change in subsidence rate.

d. A delta can lose subaerial land if volume loss occurs or if the combination of reduction of sediment supply to the subaerial zone, resuspension and redistribution of sediments from land to water, and loss of elevation due to apparent subsidence exceeds the rate of subaerial accretion. Some combination of these effects is much more likely to occur than either b or c above, for several reasons. For example, the total sediment supply need not decrease--only the supply to the subaerial zone. This could be caused by a reduction in the height of flood crests by upstream retention, thereby reducing frequency and extent of delta land submergence. As another example, increasing channelization of a delta's distributaries tends to confine coarse sediments to the deeper channels, denying it to the adjacent subaerial zones. Subaerial repletion by principally fine sediments will be less effective in maintaining land because they will be more readily resuspended by wave attack.

e. Local delta subaerial growth and decay cycles are superimposed on much longer cycles of delta evolution. Thus the Salę-Cypremort delta, which occupied the Atchafalaya area about 5,000 years ago, grew and then submerged as the river mouth moved eastward, but now the growth cycle in that area has resumed with a new bump on what is a repeatable cycle on a geologic time scale. If the entire Mississippi system delta area is considered, a consistent gross trend of land growth is seen. Limiting our attention to specific areas and shorter time intervals, repeated periods of alternate land growth and decay can be observed within the long-term trend of net growth.

Sediment supply

78. Keown, Dardeau, and Causey (1981) report that subsequent to upstream improvements (improved land management, streambank protection, and sediment retaining structures) in the Mississippi River basin the average annual suspended sediment discharge of the river at Vicksburg dropped from about 480 million tons prior to 1963 to about 230 million tons after 1970. They also state that the Old River diversion has consistently (since before 1963) passed one-fourth of the Mississippi's suspended load into the Atchafalaya River. Our own analysis of Simmesport data (Thomas et al., in preparation) shows a consistent decline in the quantity of sediment entering the Atchafalaya floodway. Thus in the last 40 years, both rivers have experienced a sharp decline in sediment supply to the deltas. Mr. Keown (personal communication) has noted that based on observation of the present trends in sediment measurements,

he believes that the average supply will continue to remain about what it is now or to decline slightly during the next 50 years.

79. Possible causes for the observed reduction in sediment supply include those listed by Keown, Dardeau, and Causey (1981) plus others. Between 1930 and 1940, a number of cutoffs were made in the Mississippi River to reduce sharp bends and to shorten the navigation channel. Such a procedure increases storage of sediment in the reach as the cutoff bend fills. Another potential effect is a change in the grain size distribution of sediments in transport.

80. As the delta grows and increases water levels upstream in the Atchafalaya floodway, deposition rates will increase upstream, reducing sediment supply to the delta until a new equilibrium is reached and the floodway begins to pass more sediment through to the bay again.

81. The proposed Atchafalaya Basin Floodway system includes use of management units in the floodway. Reduction of sediment supply to these management units is among the goals of this work, so if the plans are implemented an increase in sediment supply to the lower river and ultimately to the delta may be expected.

Apparent subsidence

82. An evaluation of the rate and distribution of apparent subsidence (sea-level rise, downwarping, subsidence and compaction) has not been completed. A value of about 1.3 cm/yr has been widely cited but appears somewhat too high at Eugene Island. Values of 0.3 cm/yr at Morgan City and 1.0 cm/yr at Eugene Island may be more reasonable estimates. It should be noted that subsidence estimates for the Mississippi delta range as high as 4 cm/yr with a notable acceleration in rate after 1959 (Swanson and Thurlow 1973). This would obviously affect the comparison between the Mississippi subdeltas and the Atchafalaya delta and may presage a higher future rate for the Atchafalaya. It is plain that subsidence is occurring and is a major factor in land loss in coastal Louisiana. It is hoped that a continuing evaluation will be able to show more closely the spatial and temporal distribution of apparent subsidence in the lower Atchafalaya area.

Generic analysis

83. It should be noted that the period of time analyzed in the generic analysis included the time in which the sediment supply of the Mississippi River was observed to be decreasing. Although most of the subaerial land area

decline in the Mississippi delta began in the 1940's, prior to much of the control structure work in the upper and middle basins, a large number of Mississippi river cutoffs and levees were constructed in the 1930's and 1940's. As stated earlier, these changes and others may have altered both the amount and character of the sediment supplied to the delta. During the post-1940 period, subaerial land in the Atchafalaya floodway was increasing dramatically.

84. A further important point to consider in the generic analysis is that the growth/decay cycles documented for the Mississippi subdeltas were occurring in the latter stages of maturity for the current Balize delta, which is about 800 years old. Thus while the time scales of the Mississippi subdeltas may be appropriate for subdeltas of the Atchafalaya (they may not be if subdelta life is a function of the stage of total delta growth), they are not indicative of the total Mississippi delta life span and may not be indicative of the total Atchafalya delta life cycle.

Quasi-two-dimensional modeling

85. As noted previously, the subsidence rate that was used in the quasi-two-dimensional modeling may be higher than appropriate. Future work will use a figure based on subsequent analyses. The work shows how sensitive the results are to the subsidence rate.

86. In their report on the quasi-two-dimensional modeling, Thomas et al. (in preparation) note the impact on subsidence on their results and also mention that the bay begins to lose some of its sediment trapping efficiency as it fills. They offer the opinion that the delta will begin forming subaerial land beyond Eugene Island only when large amounts of sand begin to pass through the bay into the Gulf. That does not occur within the 50-year simulation of the model.

Coastal land loss

87. The loss of land in coastal Louisiana is a phenomenon that is of obvious concern to the Corps and the people of Louisiana. As discussed in paragraph 76, it is not believed that there is an overall loss of mass or of volume. Land loss is due principally to the combination of subsidence and reduction of sediment supply by the Mississippi-Red River systems. All other processes are secondary.

88. The causes of subsidence and reduced sediment supply are both arguable and thoroughly argued. A recent series of articles in the Baton Rouge Morning Advocate state that the Mississippi River levees are the causative

factor. This demonstrates somewhat obscure logic. If the Mississippi were totally unrestrained, it might well have already abandoned its present course (either for the Atchafalaya route or another) to build a delta in a new location. Though it is doubtful that consequence would be preferred over the present land loss, even that would not reverse the land loss other than locally and the existing losses of land in the Balize delta would offset most or all of the local gains.

89. The main-line levees should increase the sediment supply to the Atchafalaya delta if they have any effect at all. By confining floodflows to the channel, the levees reduce upstream deposition in the original floodplain, thus delivering more sediment to the active delta.

90. Arguments that portray both levees and dredging as reasons for land loss do not satisfactorily explain the land loss occurring in the modern Mississippi delta. The levees end at Venice on the west bank and higher up on the east, yet the entire delta below that point is losing land, including the natural subdeltas that are not dredged.

91. Other cited causes for the land loss are canals in the marshes and oil and gas removal. Canals can permit increased salt intrusion, which can kill marsh grasses and reduce their capacity to trap sediments. However, canals do not materially affect the principal mechanisms of subsidence and reduction of sediment supply. Oil and gas removal seems to be a more likely cause as it can greatly increase subsidence (e.g. in Long Beach, California, and Houston, Texas), but properly apportioning the amount of land loss to one such factor would be difficult, if not impossible.

PART IV: CONCLUSIONS

92. From results produced thus far in the Atchafalaya Bay investigation, it is concluded that

a. Subsidence in the range of 1 cm/yr is occurring in Atchafalaya Bay. Further work is required to obtain a more precise number and to predict the future trend of subsidence rates.

b. The delta will expand to about 19 square miles of subaerial land, about 110 square miles of depths less than 3 ft (NGVD), and about 6 billion cu ft of sediment by 1990. The ranges of individual predictions about these average predictions are 26 percent for subaerial land and about 23 percent for areas shallower than 3 ft and 38 percent accumulated sediment volume.

c. The delta will expand to about 60 square miles of subaerial land, 377 square miles of depths less than 3 ft, and 21 billion cu ft of accumulated sediment by year 2030. The range of individual predictions is 91 percent for subaerial land and 33 percent for accumulated volume.

d. Flood stages at all locations at and below Morgan City and Calumet will increase with increasing unmodified delta expansion. Preliminary results suggest stage increases of at least 1 ft at Morgan City, 0.5 ft at Calumet, and 3.6 ft at Deer Island for floods of the 1973, 1975, and 58AEN form. These figures may need to be revised as better subsidence data and fully two-dimensional model results become available.

e. Essentially continuous delta growth is expected through year 2020 with minor interruptions. The delta may experience brief periods of subaerial land loss prior to subsequent episodes of land building. The longer term trend will be of continued land growth and roughly constant growth of accumulated sediment volume.

f. These interim results are subject to modification as later more rigorous methods are applied and as additional data become available.

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