IMPACT OF WATER RESOURCE DEVELOPMENT ON THE HYDROLOGY AND SEDIMENTOLOGY OF THE BRAZOS RIVER SYSTEM

A Thesis

by

LARRY LANE MINTER

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AND SEDIMENTOLOGY OF THE BRAZOS RIVER SYSTEM

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Approved as to style and content by:

C C Mathewson

(Chairman of Committee)

(Head of Department)

(Member)

R. E. Schiller Jr.

(Member)

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ABSTRACT

Impact of Water Resource Development on the Hydrology and Sedimentology of the Brazos River System. (August 1976)

Larry Lane Minter, B. S., Texas A&M University

Chairman of Advisory Committee: Dr. Christopher C. Mathewson

Major dam and reservoir development within the Brazos River Basin is correlative with a significant decrease in the suspended sediment load of the river and with increased coastal erosion rates near the delta. A hydrologic analysis of the river discharge, by use of cumulative frequency curves, shows that discharge control by dam regulation has reduced the frequency of high discharges, thus smoothing out the river hydrograph and reducing the amount of sediment the river is able to carry and deliver to the coastal zone. In addition, the reservoirs are presently trapping about 76% of all sand produced within the basin. An analysis of bed load samples taken downstream of the dams indicates that the sand sizes necessary for beach nourishment are not being transported through the lower reaches of the river. The amount of sand denied access to the coastal zone through the loss of the river's transporting ability and reservoir entrapment has been determined, and is shown to be enough to account for the entire increase in the coastal erosion rates in the study area since at least 1937. Future sand losses brought about by the construction of new reservoirs downstream of those presently on the Brazos River, or one of its major tributaries, can be predicted by the decrease in the effective drainage basin area.

ACKNOWLEDGEMENTS

I wish to express my appreciation to the members of my committee, Dr. C. C. Mathewson, Dr. R. J. Stanton, and Dr. R. E. Schiller, for their comments and suggestions during the preparation of this thesis. Special thanks go to Dr. C. C. Mathewson who endured hours of often rigorous debate concerning some sections of the manuscript. The drafting for this thesis was done by Douglas Jowell. I am also indebted to the Texas Highway Department for their assistance during field operations, the U. S. Army Corps of Engineers, the Texas Water Development Board, and the Texas Water Rights Commission for their aid in obtaining vital information used in this study. And finally, I thank my wife, Katherine, for her patience and encouragement during the past two years.

This project was funded by the U. S. Department of Interior, Office of Water Resources and Technology, through the Texas Water Resources Institute and Texas A&M University.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The Brazos River Basin stretches from eastern New Mexico through north and east central Texas to the Gulf of Mexico near Freeport (fig. 1). Large scale development of major reservoirs, those with storage capacities in excess of 5,000 acre feet, began within the basin in 1929. The construction of dams on the Brazos River and its tributaries has been cited as one of the probable causes of an increase in the coastal erosion rate southwest of the Brazos River delta between Freeport and Brown Cedar Cut (fig. 1) (U. S. Army Corps of Engineers, 1971; Seelig and Sorensen, 1973; Morton and Pieper, 1975). Figure 2, a plot of the measured coastline recession at Sargent Beach (fig. 1) since 1852, shows a significant increase in the recession rate after 1930. The initiation of the increase corresponds to the beginning of major water resource development of the Brazos River Basin. The construction of dams may reduce the sediment load of a river by two methods: first, the river hydrograph is smoothed out due to the reduction in peak flood flows and the sediment carrying capacity of the river is greatly reduced; second, the reservoir resulting from the dam will physically trap sediment.

Suspended load and water discharge have been measured at various gauging stations along the course of the Brazos River since 1889. The Richmond (formerly Rosenberg) gauging station, for example, which is the most downstream station on the Brazos River, measures discharge from 98.6% of the river basin, and has been in operation since 1923

The citations on these pages follow the style of the Bulletin of the Association of Engineering Geologists.

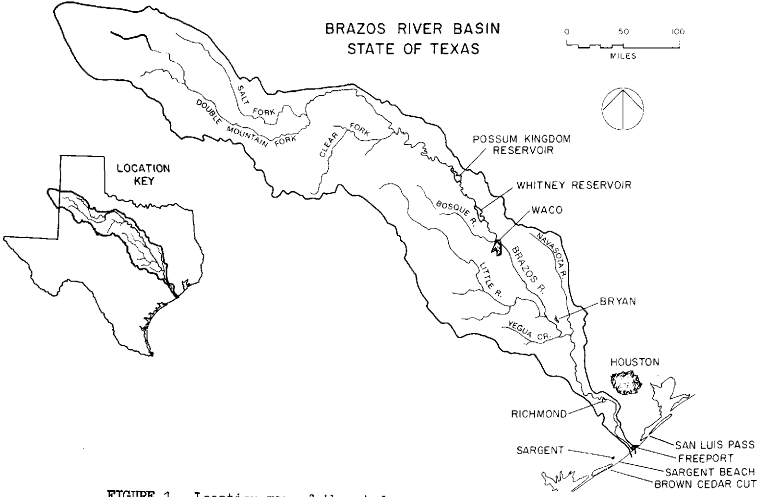

FIGURE 1. Location map of the study area

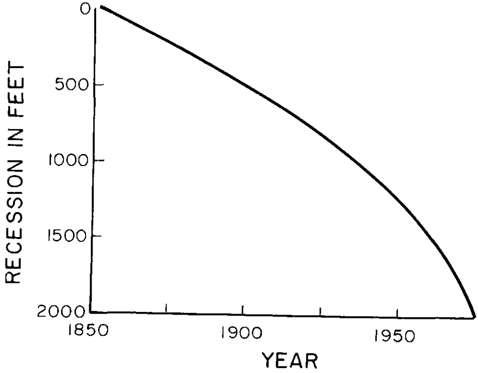

FIGURE 2. Shoreline recession for Sargent Beach, Texas based on 1852 shoreline (after Seelig and Sorensen, 1973)

(fig. 1). The decrease in the suspended load, measured at the Richmond station, can be correlated with the increase in storage volume of the major reservoirs within the basin (fig. 3).

The strong circumstantial evidence relating coastal erosion to water resource development has led Mathewson (1974) to modify figure 2 and separate this human influence upon coastal erosion from the geologic or natural causes (fig. 4). Because the record of beach erosion extends only from 1852, and because geologic processes and climatic cycles have significantly longer periods, Mathewson assumed a constant geologic recession rate for Sargent Beach since 1852 of about 13 feet per year. Consequently, the recession due to human influence has increased steadily since 1930 and by 1973 was equal to about 20 feet per year.

No previous study has attempted to analyze the impact of dam construction on the Brazos River system. The objective of the study is to determine the relationship between water resource development and the hydrology and sedimentology of the river system. This relationship is then related to coastal erosion to determine the total impact of the reservoir development on the coastal system.

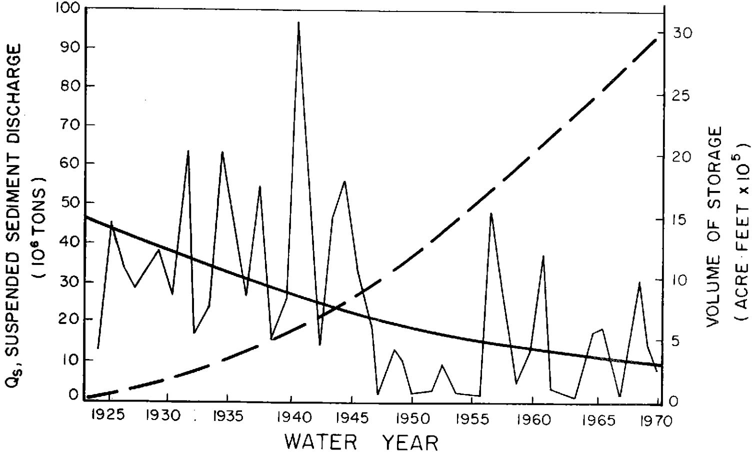

FIGURE 3. Historical suspended sediment discharge at Richmond. Heavy solid line is least squares fit. Dashed line is the approximate cumulative storage volume of major reservoirs upstream of Richmond through time

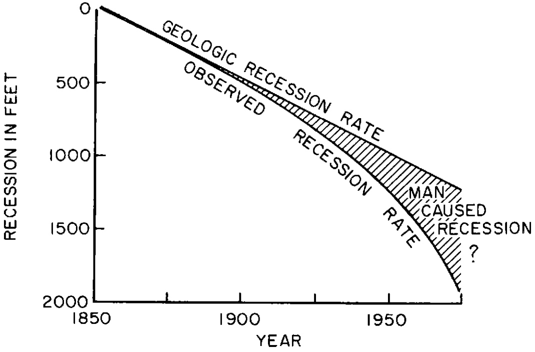

FIGURE 4. Possible man caused recession at Sargent Beach, Texas (after Mathewson, 1974)

BRAZOS RIVER AND COASTAL ZONE

Brazos River Physiography

The Brazos River Basin is the second largest river basin in Texas. Total drainage area of the basin is 44,640 square miles, but 9,240 square miles are probably noncontributing. 42,840 square miles are in Texas (Dowell and Breeding, 1967). The Brazos River is more than 1,200 miles long, about twice the length of the basin, and drops 4,600 feet in elevation along its course.

There are seven major tributaries of the Brazos River. The confluence of the Double Mountain Fork and the Salt Fork marks the beginning of the main stem of the Brazos River (fig. 1). The Clear Fork, Bosque and Little Rivers, and Yegua Creek enter the Brazos progressively farther downstream along the west bank; the Navasota River is the only major tributary entering the Brazos from the east bank (fig. 1).

The channel pattern of the Brazos River is dominantly that of a meandering river. Above Waco many segments of the river are deeply entrenched into Paleozoic sandstones and shales and Cretaceous limestones. Epps (1973) has suggested that many of the river bends in this section are controlled by regional fracture patterns. From a short distance below Waco to the Gulf of Mexico, the Brazos is characterized by wide meanders. Along the Salt and Clear Forks both meandering and braided segments occur. The deltaic plain of the Brazos River is characterized by many lakes, swamps, and coastal marshes.

The channel characteristics below Whitney Reservoir are of prime importance in this study (fig. 1). The longitudinal profile of the river (fig. 5) from the Whitney Dam to Freeport has been constructed to aid in the interpretation of river conditions discussed in later portions of this thesis.

Frye and Leonard (1959), Lewand (1969), Menzer and Slaughter (1970), Byrd (1971), and Epps (1973) have described the depositional history of the rock units within the river basin. A description and discussion of the geology and physical characteristics of these units is not relevant to this study. The reader is referred to Epps' work for the most complete account of the depositional history of rock units within the Brazos River Basin.

Potential Causes of Shoreline Recession

Historical Evidence of River Competence and Sediment Supply

The Brazos River may have had its origin as early as Eocene (Epps, 1973). Fisher and McGowen (1969) have noted that many of the modern coastal streams show a marked coincidence with the location of stacked delta systems in the early Eocene Rockdale Formation. The Brazos River flows along the axis of a Gulfward prograding Eocene delta. The Brazos was definitely established by Miocene time, as evidenced by an eastward flowing dendritic drainage pattern in the Texas High Plains of early Miocene age to which the modern drainage in the upper basin still conforms (Cronin, 1969).

Evidence for greater physical dimensions of the Brazos River during the Pleistocene has been given by Epps (1973). The volume of

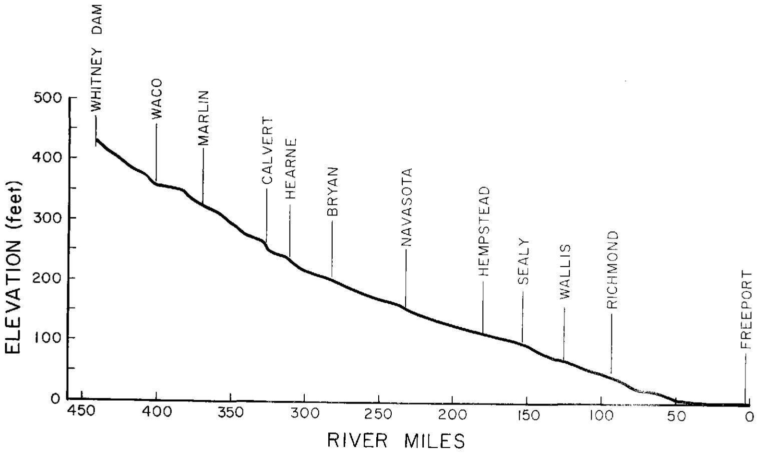

FIGURE 5. Longitudinal profile of the Brazos River, Whitney Dam to Brazos River delta

water carried was substantially increased as a result of glacial runoff. Using the size of gravel found within Pleistocene terraces in the river basin, and the dimensions of old river meander scars, Epps has calculated that the Brazos River, near Bryan (fig. 1), was 2,600 feet wide, 58 feet deep and probably possessed a much steeper gradient than the present day river. Bankfull discharge is estimated to have been 5 to 9 times greater than modern day discharge. The present day Brazos River near Bryan is approximately 300 feet wide, 6 feet deep and has an average discharge of about 5,000 cubic feet per second (cfs).

The Pleistocene rivers of Texas must all have been larger than their present day descendants. Copious quantities of fluvial sediments were available for beach nourishment. Onshore movement of sand from reworked Pleistocene and early Holocene sediment on the inner shelf during the Holocene sea level rise has been suggested as the probable source of much of the Texas beach sands (Shepard, 1956; Van Andel and Poole, 1960; McGowen, et al., 1972). However, Morton and Pieper (1975) feel that substantial amounts of sand were not available for reworking during the Holocene from San Luis Pass to Brown Cedar Cut and sands brought to the coast from the Brazos River must have contributed a significant portion of the beach material.

Bernard, et al. (1962) and LeBlanc and Hodgson (1959) have described the late Quaternary history of the Brazos River coastal plain. As the Holocene sea level rise progressed, the Brazos and Colorado Rivers were able to supply sufficient sediment to the coastal area to fill their lower valleys. The deltaic plains of the two rivers coalesced to form a broad fluvial-deltaic system. Many other rivers were unable to supply enough sediment to fill their lower valleys; as a result estuaries formed at their mouths with the rise in sea level.

At the end of the Pleistocene, the climate in Texas became drier, the Brazos River decreased in size and no longer transported the large quantities of sediment previously carried (Epps, 1973). The reduction in the amount of sand carried by the river has probably contributed to the normal geologic recession rate, defined by Mathewson, at Sargent Beach.

Subsidence

Subsidence could play an important role in increasing coastal erosion rates because in the low lying areas of the Texas coastal plain a small amount of subsidence may be responsible for a considerable landward transgression of the shoreline. In addition to natural subsidence caused by compaction of the coastal sediments, man-induced subsidence from the production of oil and water may result.

Swanson and Thurlow (1973) have used tide records to show that the Freeport area has experienced a relative rise in sea level as a result of compactional subsidence for the past 15 years. Brown, et al. (1974) have recorded a total land subsidence at Freeport between 1 and 2 feet as a result of oil and water production. However, the present shoreline in the study area does not appear to have been significantly altered as a result of fluid production (Morton and Pieper, 1975). In addition, Seelig and Sorensen (1973) have used published subsidence rates to show that subsidence near the Sargent Beach area accounts for less than 10% of the observed recession since 1852.

Coastal Modification

Previous studies concerning coastal erosion in the vicinity of the Brazos River delta have attempted to relate man-made modifications to changes in the nearshore sediment movement patterns and to the increase in coastal recession rates (Seelig and Sorensen, 1973; Morton and Pieper, 1975; Sealy and Ahr, 1975). The modifications require some discussion for a full understanding of their impact on the coastal environment.

The Brazos River is one of the few Texas rivers which empties directly into the Gulf of Mexico. For this reason, early shipping interests found it desirable to use the lower part of the river at Freeport as a harbor. Dredging operations to construct a canal from the open ocean to a turning basin upstream were begun in 1850 (U. S. Army Corps of Engineers, 1896-97). However, shifting sands and rapid sedimentation necessitated continual maintenance and dredging within the turning basin, channel, and harbor entrance.

In 1881, in hopes of diminishing the sedimentation problem, private interests commenced work on two parallel jetties, designed to extend about 2,400 feet seaward from the river mouth, but the project was abandoned in 1886 due to a lack of funds. The U. S. Army Corps of Engineers took over the construction of the jetties in 1889 and completed the project in 1896.

Construction of the jetties provided some relief from sedimentation problems, but periodic flooding and siltation within the channel still required excessive maintenance and dredging (U. S, Army Corps of Engineers, 1924, 1927). In 1928, a project for diversion of the Brazos

River at a point 7.3 miles above the river mouth was initiated by the Corps of Engineers. This project was completed in 1929 with the diversion channel entering the Gulf of Mexico 6.5 miles west of the old channel (Fox, 1931). Levees were constructed on either side of the new channel for flood protection. The channel plans called for the river to enlarge the channel by scour to meet the dimensions necessary to carry high discharge flows. Diversion of the river has allowed the harbor to operate with a minimum of dredging and maintenance costs.

Coastal modification has had an interesting affect on the development of the old and new Brazos River deltas. Prior to construction of the jetties the Brazos River was unable to build a subaerial delta (Seelig and Sorensen, 1973). The jetties, once constructed, acted as a sediment trap and a subaerial delta began to form. With the completion of the diversion channel a subaerial delta formed at the mouth of the new channel almost immediately and built out rapidly between 1929 and 1948. Morton and Pieper (1975) believe that the rapid progradation of the new delta was a result of an oversupply of sediment derived from: (1) normal fluvial sediment transport; (2) channel erosion during adjustment of the diversion channel and (3) erosion of the old Brazos delta.

Sealy and Ahr (1975) have proposed that sediment distribution patterns have been altered in the vicinity of the new Brazos River delta as a result of construction of the river diversion channel. Their model suggests that the new Brazos River delta formed rapidly because nearshore circulation patterns were disrupted by the presence of the old delta. Material eroded from the old delta was still transported southeastward but accumulated within the new delta.

Coastal modification certainly had an impact on sediment distribution within the study area. However, after 1948 the new Brazos delta began to be eroded. By 1952, the old delta had approximated its 1852 shoreline and was no longer supplying sediment to the new delta. Because the new delta was eroding and coastal erosion rates continued to increase, the sand loss must have resulted from a decreased sand supply from the Brazos River. Seelig and Sorensen (1973) and Sealy and Ahr (1975) have concluded that a significant reduction in sand supplied to the coastal area from the Brazos River is due to construction of major reservoirs within the river basin, although they did not prove their conclusions.

Water Resource Development

The history of major water resource development within the Brazos River Basin began with the completion of Mineral Wells Reservoir on Rock Creek in 1920 (Dowell and Breeding, 1967). Twenty-eight additional reservoirs with storage capacity in excess of 5,000 acre-feet were completed by 1972. Table 1 is a chronological listing of initial water impoundment in the major reservoirs of the Brazos River Basin. The location of these reservoirs are shown in figure 6.

The majority of the reservoirs were constructed to store water for municipal and industrial uses. Regulation of flow for flood control of the Brazos River began with the completion of Possum Kingdom Reservoir in 1941 (Dowell and Breeding, 1967). Other reservoir uses include recreation and diversion rights for irrigation purposes.

TABLE 1. Major Reservoirs of the Brazos River Basin

	Reservoir	Date of Initial Water Impoundment	Conservation Storage Capacity (acre feet)
1.	Mineral Wells	1920	6,760
2.	Abilene	1921	7,900
3.	Cisco	1923	26,000
4.	Kirby	1928	7,620
5.	Graham	1929	53,680
6.	Waco	1929	39,378
	Waco *	1965	104,100
7.	Sweetwater	1930	11,900
8.	Fort Phantom Hill	1938	74,310
9.	Possum Kingdom	1941	724,464
10.	Camp Creek	1948	8,550
11.	Daniel	1948	11,400
12.	Whitney	1951	379,100
13.	Lake Creek	1953	8,400
14.	Alcoa	1952	14,750
15.	Stamford	1953	57,630
16.	Belton	1954	372,700
17.	Leon	1954	26,420
18.	Brazoria	1954	21,970
19.	Smithers	1957	18,700
20.	Mexia	1961	10,000
21.	Hubbard Creek	1962	320,000

TABLE 1. (continued)

	Reservoir	Date of Initial Water Impoundment	Conservation Storage Capacity (acre feet)
22.	Proctor	1963	31,400
23.	White River	1963	37,950
24.	Palo Pinto	1964	42,200
25.	Pat Cleburne	1964	25,445
26.	Somerville	1966	143,900
27.	Stillhouse Hollow	1968	204,900
28.	Tradinghouse Creek	1968	35,124
29.	Granbury	1969	153,500
		Total	2,940,773

* Larger reservoir constructed at same location.

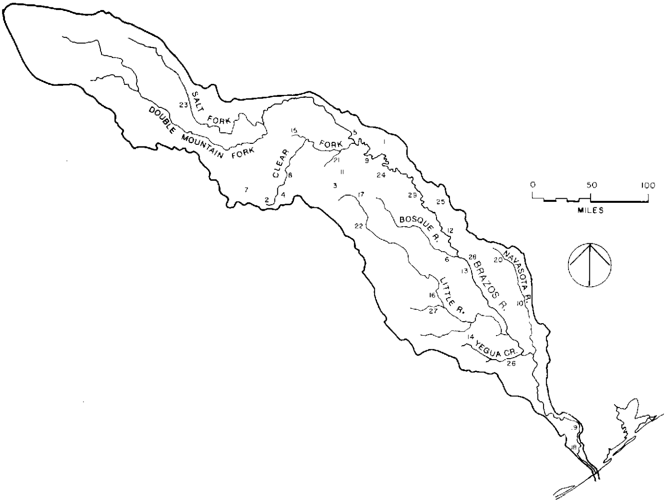

FIGURE 6. Location of major reservoirs in the Brazos River Basin. The numbers correspond to the reservoirs listed in Table 1

Conservation storage capacity, at the date of completion, of individual major reservoirs varies from 6,720 acre feet to 724,464 acre feet. The total cumulative volume of those reservoirs completed through 1972 is 2,940,773 acre feet.

There are also 714 smaller reservoirs within the Brazos Basin with storage capacities from less than 50 acre feet to 5,000 acre feet. Presently, the total storage capacity of these reservoirs is approximately 180,000 acre feet. Reservoir uses include water storage for municipal, industrial, recreational, and other uses. The data on small reservoirs were furnished by Tom Buckingham (personnal communication, 1976) of the Texas Water Rights Commission and are based on an inventory by the Commission in cooperation with the U. S. Army Corps of Engineers.

The Soil Conservation Service kept records concerning the number of small farm ponds constructed within the Brazos River Basin until 1959. At that time it was estimated that 93,000 ponds, with total storage capacity of 143,000 acre feet, had been constructed (Texas Board of Water Engineers, 1959). The basic use of the small ponds is for livestock watering. In addition, a number of ponds have been created by the construction of weirs for flood control on small watersheds.

More recent data concerning farm pond construction have not been kept by the Soil Conservation Service. Conservations with members of the Texas Water Development Board, now responsible for these records, revealed that this information is available, but processing of these data would require a lengthy study. Consequently, no present plans have been made to make such a study. It can only be estimated that the number of farm ponds has grown substantially since 1959.

HYDROLOGIC HISTORY OF THE BRAZOS RIVER

Historical Discharge

The United States Geological Survey and the Texas Water Development Board (formerly the Texas Baord of Water Engineers) have maintained a number of water discharge gauging stations on the Brazos River since 1889. Records of water discharge within the Brazos River Basin are reported as monthly and yearly totals by the Texas Water Development Board in Stout, et al., (1961), Adey and Cook (1964), Cook (1967; 1970) and Mirabel (1974). Daily stream flow records prior to 1961 are available in U.S.G.S. Water Supply Papers. Since 1961, the Brazos River discharge records have been published by the U.S.G.S. in yearly volumes entitled "Water Resources Data for Texas, Part 1, Surface Water Records."

Annual river discharge at the Waco and Richmond gauging stations during the period 1920-1970 is plotted in figures 7 and 8. The storage volume of major reservoirs above each station is also plotted in figures 7 and 8. Although discharge at both stations is variable, the average annual discharge, as given by the least squares curve, has been relatively constant. Although the average discharge appears to be declining somewhat at both stations in more recent years, this is due to a period of low discharge at both localities from 1948-56.

Regulation of the river discharge as a result of dam control cannot be detected from these figures. Discharge control should not significantly alter the amount of water passing through the system, except for losses due to reservoir evaporation, because the quantity

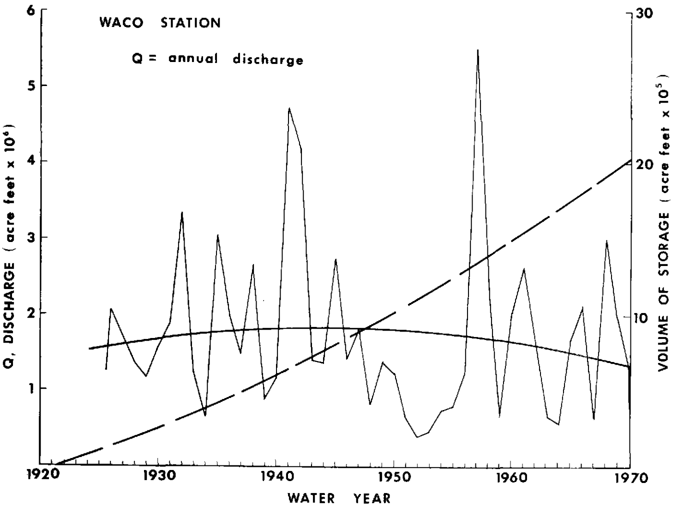

FIGURE 7. River discharge at Waco. Heavy solid line is least squares fit. Dashed line is the approximate storage volume of major reservoirs above Waco during this period

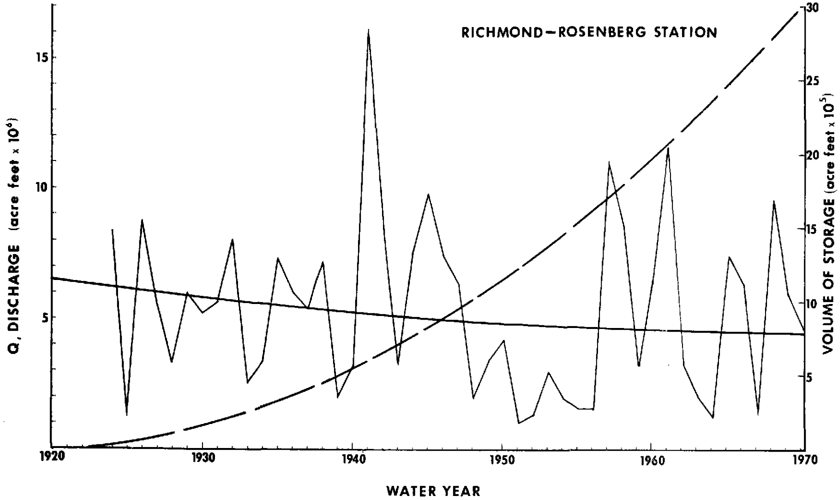

FIGURE 8. River discharge at Richmond. Heavy solid line is least squares fit. Dashed line is the approximate storage volume of major reservoirs upstream of Richmond during this period

of water stored within the reservoirs is insignificant when compared to the total annual discharge. However, the rate at which the water is allowed to flow through the system may be drastically altered as a result of discharge control by the dams. Other methods must therefore be employed to observe the effect of discharge control on the hydrology of the Brazos River.

Hydrologic Changes From Discharge Control

A common method used to observe the hydrologic characteristics of a river is by use of a cumulative frequency, or flow-duration curve. The cumulative frequency curve is a plot of discharge against the percent of time any given discharge was equalled or exceeded during some time interval at a particular location. Because the curves can be drawn for specific time intervals they can be very useful in observing hydrologic changes between intervals of interest. This fact makes the use of such curves valuable in observing the hydrologic changes of the Brazos River brought about by dam construction.

In order for the cumulative frequency curve to be a valid indication of the Brazos River discharge conditions, it is desirable that long term discharge records be available for each locality. Short term records may not reflect normal river conditions as they may have been recorded during low or high precipitation cycles within the basin. Two stations, Waco and Richmond, were chosen for this study because of their long term discharge records and because they reflect extremes in their distance from the major dam construction on the Brazos; Waco being upstream near Whitney Dam and

Richmond being far down the river near the coast.

The cumulative frequency curves show the percentage of time that any discharge was equalled or exceeded during the time interval under consideration. The discharge employed in the construction of the curves for this thesis is the average daily discharge, therefore, the percent of time is actually the percent of days the flow equalled or exceeded the indicated discharge during the time interval. Daily discharges were recorded not by actual value, but as a data point between predetermined increments of discharge. The accuracy of a cumulative frequency curve is dependent upon the number of increments used in the compilation of the discharge values. To assure accurate data representation a total of 30 increments were used in the construction of each curve. The incremental values used and the tabulated values for each curve are listed in the Appendix.

The first time interval selected was from the beginning of records at each station through 1941. This interval can be considered the period of unregulated flow of the Brazos River. Possum Kingdom Reservoir began water impoundment in 1941 so all records after this date should reflect regulation of the river. Whitney Reservoir began impoundment in late 1951, so the second interval chosen was 1942-51. This interval should reflect the hydrologic changes of the Brazos due to the Possum Kingdom Dam. The period 1952-74 should reflect the changes brought about by the Whitney Dam and was chosen as the third interval. The final interval selected, 1942-74, reflects the cumulative impact of both reservoirs on the lower part of the river basin. It should be noted that the third interval is of short duration, only 10 years of data, and perhaps may not accurately portray the long term hydrologic changes which the Possum Kingdom Dam may have produced.

Interval 1; 1920's - 41:

Figures 9 and 10 represent the unregulated conditions of river flow at Waco and Richmond. The shape of both curves indicates extreme variance in discharge conditions. At Waco, discharge exceeded 100,000 cfs 0.06% of the time and was less than 10 cfs about 0.6% of the time. At Richmond, 100,000 cfs discharge was slightly more common, being exceeded 0.19% of the time, but flow was never lower than 10 cfs. The lowest flows recorded were between 10-100 cfs and occurred about 0.2% of the time. The Richmond curve indicates that very low discharges were uncommon. Flow exceeded 400 cfs about 98% of the time between 1923 and 1941.

Mean annual and median discharges are also listed on each figure. Mean annual discharge is the numerical average of all daily discharges for the interval. Median discharge is that flow which is exceeded 50% of the time.

Interval 2; 1942 - 51:

This interval reflects the hydrologic changes brought about by the construction of Possum Kingdom Dam. Waco and Richmond cumulative frequency curves for this interval are shown in figures 11 and 12.

The Waco curve shows significant changes in discharge conditions after 1941. The middle portion of the curve is more nearly horizontal,

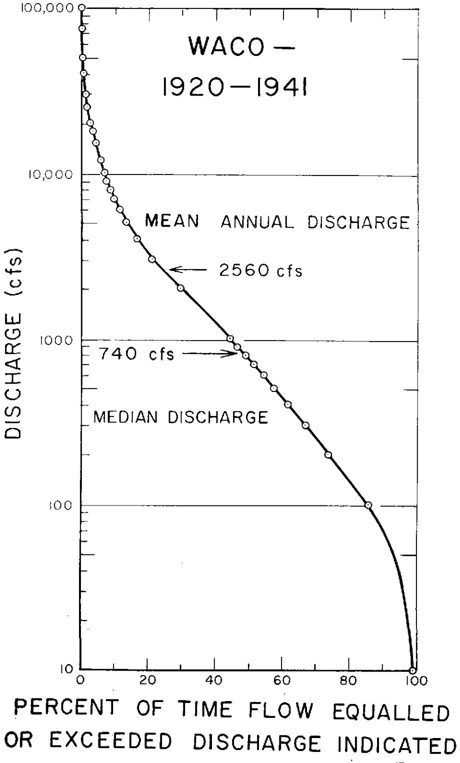

FIGURE 9. Waco cumulative frequency curve, 1920-41

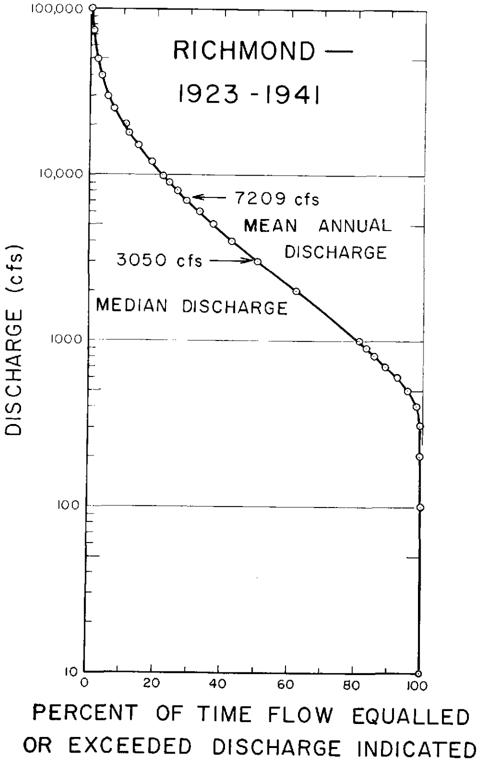

FIGURE 10. Richmond cumulative frequency curve, 1923-41

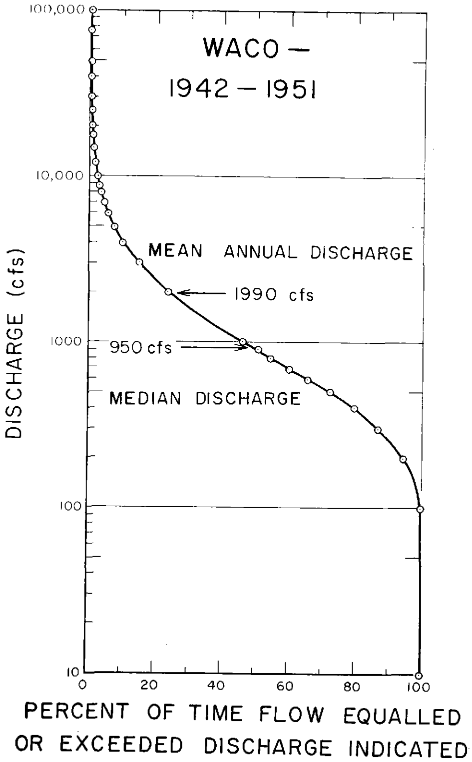

FIGURE 11. Waco cumulative frequency curve, 1942-51

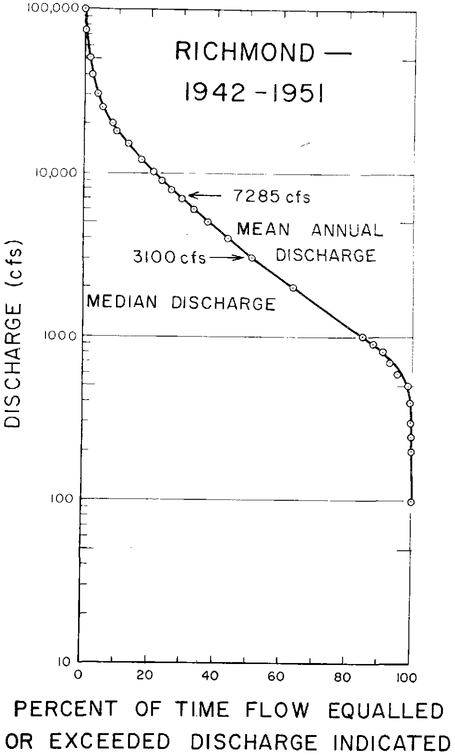

FIGURE 12. Richmond cumulative frequency curve, 1942-51

indicating that river regulation was effective in producing more consistant discharge conditions between 1942 - 51. For example, moderate discharges (between 500 and 5,000 cfs) occurred 44% of the time from 1920-41, but occurred 65% of the time from 1942-51. For this short interval, it is difficult to determine how effective river control was, but discharges below 500 cfs and above 5,000 cfs were greatly reduced. However, flow above 75,000 cfs was slightly more common than before regulation. This anomaly must be attributed to the short period of record.

Mean annual discharge for the period 1942-51 was reduced 22% from that of 1920-41 while median discharge increased 28%. Normally, mean annual discharge should not be reduced by any significant amount due to dam control because the amount of water held within the reservoirs is insignificant when compared to total river discharge. Water records indicate that discharge conditions were not normal at Waco during this period.

In contrast to the Waco curve, the Richmond curve shows little change from the 1923-41 curve. Discharge between 200-3,000 cfs is slightly more common, and that above 3,000 cfs is slightly less common, than the earlier period, but these changes are hardly noteworthy other than the fact that no flow below 100 cfs, or no flow greater than 100,000 cfs was experienced.

Mean annual and median discharges were very close to those of the interval 1923-41. Even though the records for this period are short term, one significant fact can be interpreted; regulation of the river by the Possum Kingdom Dam had little effect at Richmond. The coincidence of the two curves attests to this statement. Flood control may have been effective to some extent, but normal river conditions appear unaltered. This is no doubt a result of the distance between the dam and Richmond.

Interval 3; 1952 - 74:

Waco and Richmond cumulative flow curves for the period 1952-74 (figs. 13 and 14) represent the river conditions after the completion of the Whitney Dam. The Waco curve for this interval has shifted back toward the shape of the 1920-41 curve, although not completely. This is somewhat surprising in that Whitney is only 40 river miles upstream of Waco, 250 river miles closer than Possum Kingdom. However, the 1952-74 records are for a more extended period of time and probably reflect the discharge conditions more accurately than those of 1942-51. The 1952-74 curve for Waco does show that river discharge was less variable than during unregulated flow conditions, but of greatest importance is that flows greater than 75,000 cfs have not occurred since the construction of the Whitney Dam.

The Richmond flow curve for the period 1952-74 has the same shape as that of the other two intervals, but the frequency of discharge above 2,000 cfs was reduced somewhat from that of the unregulated period, indicating that Whitney Dam had a noticeable effect on discharge conditions during this interval. Mean annual discharge is very nearly that of the period 1923-41, but median discharge has been reduced by about 21% as a result of the reduction in higher discharges.

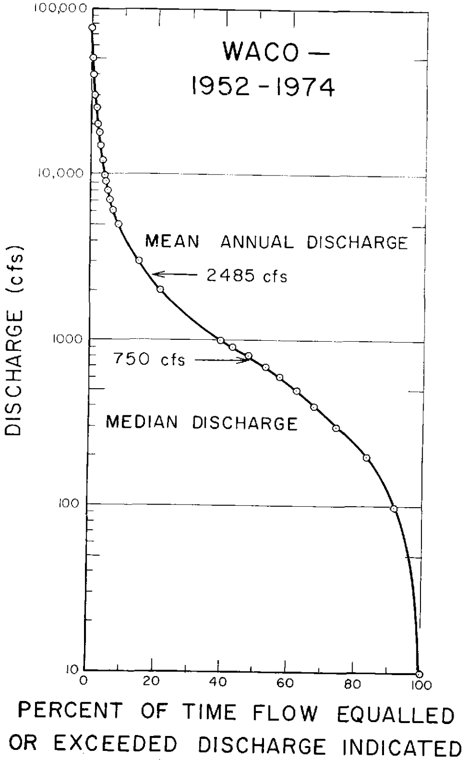

FIGURE 13. Waco cumulative frequency curve, 1952-74

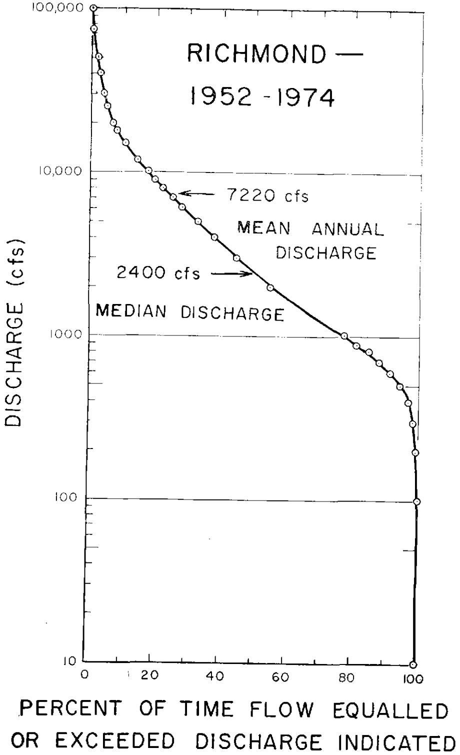

FIGURE 14. Richmond cumulative frequency curve, 1952-74

Interval 4; 1942 - 74:

The curves for this interval represent the total impact of flow regulation of the Brazos River at Waco and Richmond (figs. 15 and 16). These curves are only slight variations of those of 1952-74. The mean annual discharge at Waco is slightly lower than 1920-41 as a result of the lower discharge at Waco during the period 1942-51. The Richmond curve does show a slightly lower frequency of discharge above 2,000 cfs compared to that of 1923-41, but mean annual discharge is very nearly the same for both intervals. The median discharge for 1942-74 is somewhat lower than that of 1923-41 due to the lowered frequency of the 1,000-10,000 cfs discharges.

In summary, flow regulation by both Possum Kingdom and Whitney Dams has significantly altered the hydrologic conditions at Waco by reducing the frequency of high and low discharge, thus creating more constant flow conditions. The construction of the Possum Kingdom Dam did not alter the discharge conditions at Richmond to any large extent, but the Whitney dam has slightly reduced the frequency of higher discharges.

Discharge Control During Flood Stages

The cumulative frequency curves are excellent as indicators of altered discharge conditions, but are not useful for analyzing the reduction in the momentary maximum discharge during flood stages. To determine the reduction in peak flood flows as a result of flow regulation requires that pre-dam and post-dam flood flows be compared. Patterson (1963) lists the yearly momentary maximum discharge for all

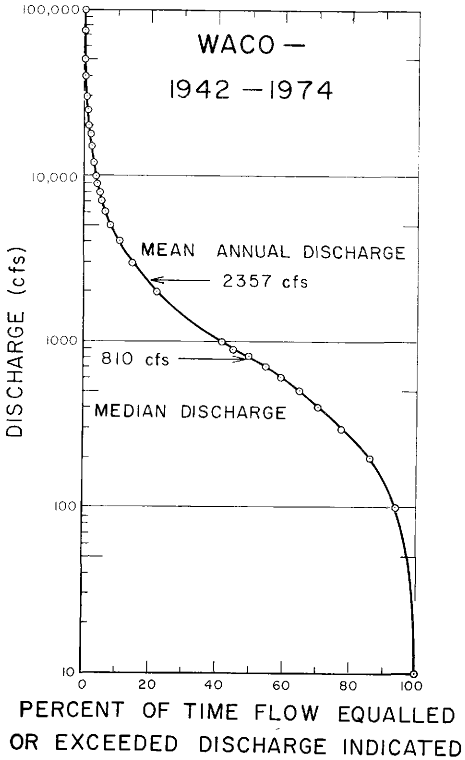

FIGURE 15. Waco cumulative frequency curve, 1942-74

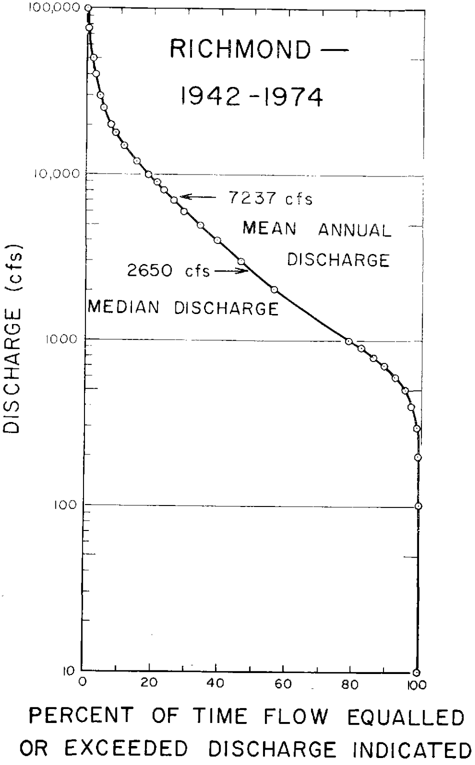

FIGURE 16. Richmond cumulative frequency curve, 1942-74

gauging stations in Texas through 1961. Records after this date are available in the U. S. Geological Survey's Water Supply Papers and "Water Resources Data for Texas, Part 1, Surface Water Records."

Waco, Bryan, and Richmond stations were selected for comparison of pre-dam and post-dam floods because they are located progressively farther downstream from the dam sites. Flood records of years prior to 1942 were used as pre-dam conditions and those of 1952-74 were used as post-dam conditions. No records for the period 1942-51 were used due to the short time interval. The data therefore represent flood control after completion of the Whitney Dam.

For the 23 year period prior to 1942, the yearly maximum flood discharges were recorded and listed in descending order of magnitude at each station. The same was done for the 23 year period 1952-74. The pre-dam and post-dam ratios of the flood maximums were obtained in successive order down the list and the 23 ratios for each station were then averaged to obtain the final ratio at each station. The results are listed in Table 2. These data show precisely what is to be expected, that the effect of flood control decreases progressively farther downstream.

TABLE 2. Pre- and Post-Dam Peak Discharge Ratios

Station	$\frac{\text{Pre-Dam Maximum Flood Discharge}}{\text{Post-Dam Maximum Flood Discharge}}$	% Reduction in Peak Flood Discharge
Waco	2.10	52
Bryan	1.85	46
Richmond	1.42	30

SEDIMENTOLOGY

Suspended Load

In addition to water discharge records, the Texas Water Development Board has also carried out suspended sediment discharge measurements at several gauging stations. These data are available in the same publications as the water discharge records. Determination of the suspended load is based on the average of three 8-ounce water samples, taken approximately 1 foot below the water surface, at points located 1/6, 1/2, and 5/6 of the distance across the river. The average percentage of suspended sediment, by weight, is then multiplied by a correction factor of 1.102 to obtain a mean percentage of suspended sediment in the vertical profile (Cook, 1967).

Few gauging stations have maintained long term suspended sediment records. Of those which have, the Richmond station is most important in considering the sediment discharge through the river system because it is located less than 100 river miles from the coast and measures discharge from 98.6% of the Brazos River system. By assuming that the total sediment load passing Richmond reaches the coast, the computation of the amount of sediment available to the coast is greatly aided.

The decrease in the amount of suspended load passing the Richmond station is not a result of a decrease in the annual water discharge. The hydrologic studies have shown that mean annual discharge has not decreased through time. Figure 17, a plot of the suspended sediment-water discharge ratio through time, shows that the amount of suspended load carried per unit of water discharge is decreasing. This decrease is inversely correlated with an increase in the storage

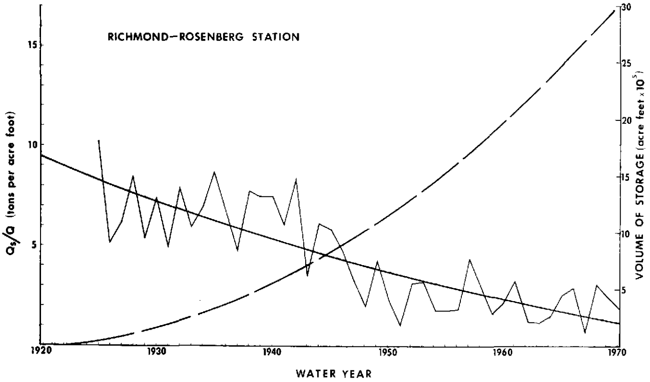

FIGURE 17. Ratio of suspended sediment discharge, Q_S, to water discharge, Q, at Richmond. Heavy solid line is least squares fit. Dashed line is the approximate storage volume of major reservoirs upstream of Richmond during this period

volume of major reservoirs above the Richmond station, as seen in figure 17.

Bed Load

The quantity of bed load transported through the Brazos River is difficult to ascertain because no accurate method of measuring the bed load discharge has been devised. The Texas Board of Water Engineers (1959) has estimated the bed load at several gauging stations by determining the percentage of coarse grained sediment entering reservoirs downstream of the stations.

C. T. Welborn of the U. S. Geological Survey in Austin, Texas, has employed a method devised by Colby (1957) for estimating bed load discharge at the Richmond station (Seelig and Soresen, 1973). Welborn has determined a relationship for both suspended and bed load discharge in tons per day as a function of the mean daily discharge (fig. 18).

Seelig and Sorensen (1973) have used Welborn's chart to estimate the historic annual bed load and sand discharge at Richmond. They were aware of the historic relationship between suspended load and water discharge at Richmond (fig. 2), so a correction factor, based on Colby's availability ratio, was used to correct all yearly values prior to 1950. The availability ratio is the ratio of the measured concentration of suspended sediment to the predicted concentration taken from the chart. This was necessary because Welborn's chart estimates bed load from the concentration of suspended load. Their data indicates an average annual reduction of 35% in the bed load discharge at Richmond since 1941.

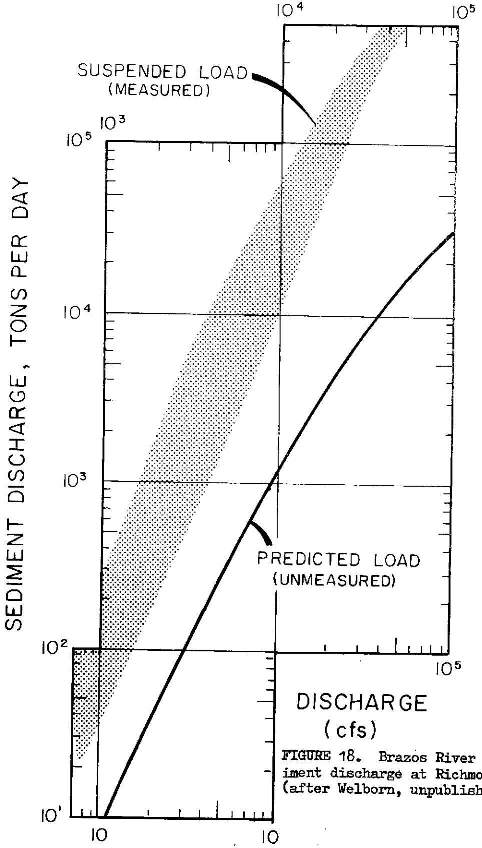

FIGURE 18. Brazos River sediment discharge at Richmond (after Welborn, unpublished)

Using Seelig and Sorensen's annual sand discharge data, figure 19, an historic plot of the ratio of the annual sand, Q_{SD}, and water, Q, discharge has been constructed. This chart, similar to figure 17, shows that the amount of sand carried per unit of water discharge has been decreasing through time.

Coastal Sand

By far, the most important constituent of beach sediments are the sand size particles, and coastal erosion along the Texas coast is primarily a result of a net sand loss. Therefore, this study is most concerned with the distribution and quantity of sand throughout the study area.

Size distribution of coastal sands near the Brazos River delta have been described by Odem (1953), Nienaber (1963), and Seelig and Sorensen (1973). Cores taken by Odem revealed that the new Brazos delta is composed of about 70% sand sized material. Nienaber collected bottom samples offshore from both the old and new deltas and found a normal deltaic size distribution, decreasing median grain size with increasing distance from shore.

Seelig and Sorensen (1973) discussed the size distribution of beach sands within the study area. From San Luis Pass to the San Bernard River, median grain size is approximately 0.15mm (fig. 20). Median grain size increases southwest of the San Bernard River and rises to a maximum of 0.3mm at Sargent Beach, falling off to 0.2mm on the east side of Brown Cedar Cut.

Nienaber (1963) described the beach at Sargent as a thin veneer

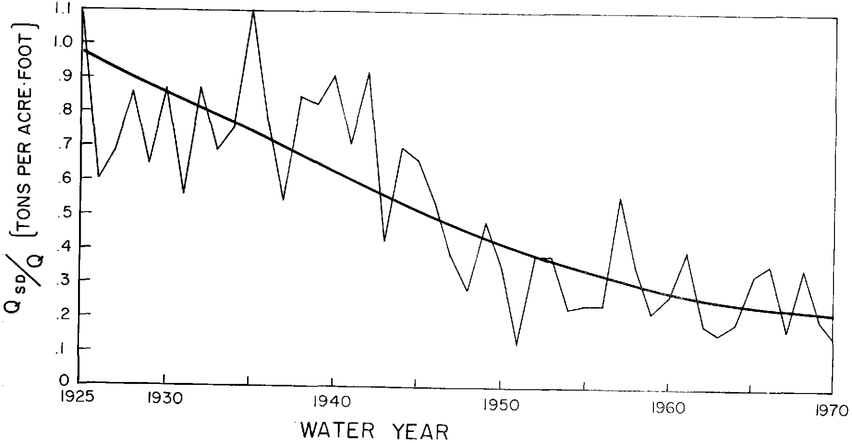

FIGURE 19. Ratio of sand discharge, Q_{SD}, to water discharge, Q, at Richmond. Heavy line is least squares fit

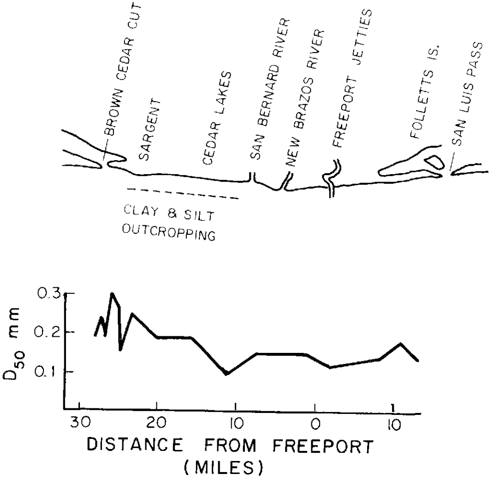

FIGURE 20. Median grain size of beach sands in study area (from Seelig and Sorensen, 1973)

of sands which give way to a hard, slippery clay surface during increased wave activity. Seelig and Sorensen (1973) report that the entire area from the San Bernard River to Sargent Beach has scattered clay outcroppings which are exposed at low tide (fig. 20). Of the sands present in the study area, only the Sargent Beach sands contain more than 10% shell by weight. Shell at Sargent ranges between 20 and 70% by weight of the total sample (Seelig and Sorensen, 1973). The effect of the clay has probably been to keep the rate of erosion lower than it might have been, as the clay is much more difficult to erode than sand (Nienaber, 1963).

Brazos River Sand

No analysis of the size distribution of sand carried by the Brazos River has been made. In order to determine the relationship between the river and coastal sands it was necessary to obtain bed load samples. Sampling of the Brazos River bed load was accomplished from bridges spanning the river. Original plans called for taking four foot gravity cores, 1.5 inches in diameter, from all bridges spanning the river below Lake Whitney and one bridge upstream of the lake. A special A-frame was designed and built to operate from either side and the rear of a pickup truck. The core was lowered over the side of the bridge until the weights were just touching the water surface, and it was then allowed to free fall from that point.

Several problems were encountered using the coring device. Sandy material was difficult to core because the grains were not cohesive and ran out of the core barrel while retrieving the core. Those cores which were successful in returning some sample did not gain full penetration into the bottom. This may have been a result of the core striking larger particles beneath the surface, or the river may not have been deep enough to allow the free falling core enough momentum to fully penetrate the bottom.

Due to continued problems with the coring operation, it was eventually discontinued in favor of grab sampling from the bridges. This is unfortunate because the bed load samples obtained can only be correlated with the most recent discharge conditions at that time. Deeper cores may have allowed a better evaluation of bed load characteristics during fluctuating discharge conditions.

Sediment Transport

Prior to a discussion of the analysis of the bed load samples, some fundamentals of sediment transport will be discussed. Some relationships concerning the movement of bed load past the Bryan, Hempstead, and Richmond stations have been developed which are important in discussing sediment movement and distribution in the river.

The ability of a river to transport detrital material has long been studied by sedimentologists and hydraulic engineers. As early as 1880 Gilbert recognized that the size and amount of sediment moved through a channel is dependent upon the stream discharge, velocity, and slope. Later work demonstrated the importance of additional parameters such as the width, depth, and wetted perimeter of the channel. Much of the initial work in sediment transport was concerned with the role of stream velocity in initiating grain motion, but it was found that velocity and grain motion varied with changes in the slope and channel dimensions. For this reason it has become common practice to define the initiation of grain movement in terms of a critical tractive force, or critical bed shear.

The bed shear, τ, is the amount of force per unit area generated at the water-sediment interface as a function of water weight, channel slope, and channel dimensions. The quantitative expression for the value of τ, in pounds per square foot, can be written as:

$$\tau = \gamma \, d \, S \qquad (1)$$

where γ = unit weight of water in pounds per cubic foot

d = depth of the channel in feet (wide channels)

S = channel slope in feet per foot

Grain motion will be initiated when the bed shear reaches a critical value for the grain size in question. The critical shear stress, τ_c, for any given grain size is determined by the following expression:

$$\tau_c = c \frac{\pi}{6} D \tan\alpha \, (\rho_s - \rho) \qquad (2)$$

where c = a paking coefficient determined by the number of grains in a unit area

D = grain diameter in feet

ρ_s = grain density

ρ = water density

α = angle of repose of grain size

The units of equations (1) and (2), pounds per square foot, can be converted to dynes per square centimeter by dividing by 2.089×10^{-3}. The derivation of these formulas may be found in many textbooks on sediment transport, such as Allen (1970) and Graf (1971).

In 1936, Shields determined a method for predicting sediment movement along the bed of a river channel through a series of empirical relationships which involve the determination of a Shields' entrainment function and the particle Reynold's number. Blatt, et al. (1972) present a graph of the critical shear stress necessary to initiate grain motion as a function of the grain diameter calculated from the Shields' diagram. This graph, presented in figure 21, is based on the solid material being quartz, a water temperature of 16°C, and a plane bed boundary at the water-channel interface.

Epps (1973) has determined the following depth-discharge relationships of the Brazos River at Bryan, Hempstead, and Richmond as:

Bryan	$d = .148Q^{.451}$
Hempstead	$d = .177Q^{.493}$
Richmond	$d = .088Q^{.519}$

where d = river depth in feet

Q = river discharge in cubic feet per second

Using these relationships, figure 22 has been constructed to facilitate the determination of grain sizes in motion for various discharge conditions. The shape of the curves are dependent upon the slope of the river channel at each locality. The slope of the channel at Hempstead is less than that at Bryan and Richmond (fig. 5), therefore requiring a greater discharge to generate the same bed shear.

The construction of figure 22 was accomplished in the following manner. For a number of given discharges at the three localities, the depth of the river at each discharge was computed using Epps' relationships. Obtaining the slope at each locality from figure 5, and using equation (1), the bed shear for each depth was calculated. Since discharge and depth are related by the above relationships, they can be interchanged when plotted against bed shear because discharge is

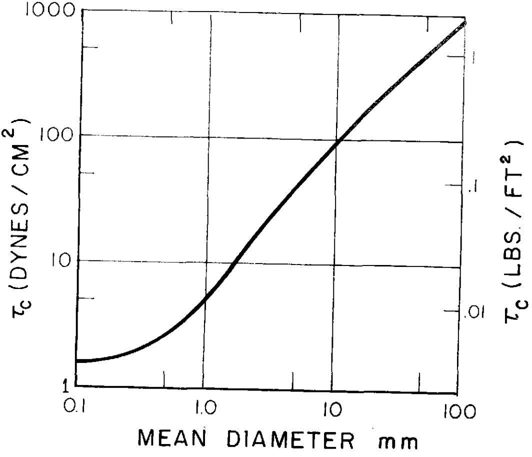

FIGURE 21. Critical shear stress, τ_c, necessary for initial movement of quartz grain on a plane bed surface (after Blatt, Middleton, and Murray, 1972)

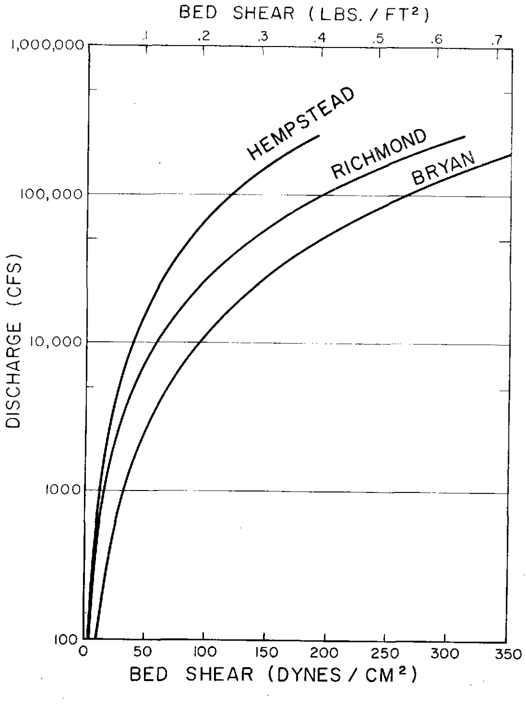

FIGURE 22. Discharge-bed shear relationships for Bryan, Hempstead, and Richmond

a more easily obtained parameter.

By knowing the discharge of the river on any particular day at any of the three localities, it is possible to estimate the competency of the river. Any discharge corresponds to a certain bed shear, figure 22, which in turn, corresponds to a maximum grain size which the river should be able to transport, taken from figure 21.

Sample Analysis

The location of bed load samples taken along the course of the river is shown in figure 23. The samples were analyzed by use of a visual accumulation tube to determine size distribution and median grain size (D_{50}) by particle fall diameter according to the procedure described by Colby and Christenson (1956). The results of the grain size analysis are presented in the form of a grain size, percent of sample, distance space contour map originated by Dowling (1975) (fig. 24).

In order to construct the contour map it was necessary to prepare frequency curves for each sample. From the frequency curve the values of the percent of sample to be used as contour intervals were projected vertically onto a base line. The base lines were keyed to grain size along the abcissa and needed only to be superimposed on the map at the proper scaled distance above the delta. Contours were then drawn connecting the points of equal percent of sample in the same manner as topographic contours are drawn from profile data. The technique allows correlation of the entire grain size distribution from one sample to another.

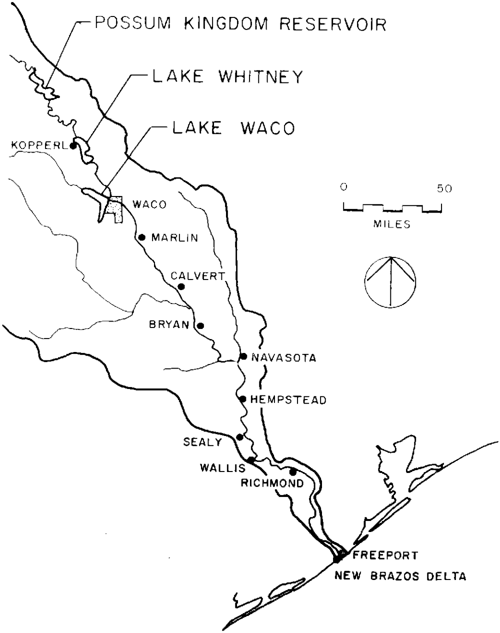

FIGURE 23. Bed load sampling locations

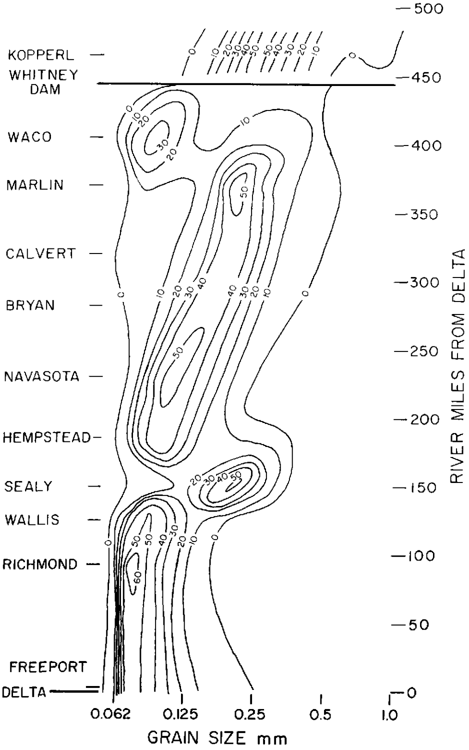

FIGURE 24. Dowling grain-size contour map of bed load samples

In general, the Dowling grain-size contour map reveals typical fluvial sorting of the bed load. Samples contain higher percentages of coarser material upstream and gradually become finer downstream. However, the grain size distribution for Waco and Sealy is not characteristic of the general trend.

The pod of smaller sand sizes at Waco reflects the bed load contribution of the Bosque River. The confluence of the Bosque and Brazos Rivers is 4 miles upstream of the sampling station and only fine grained sediments pass the nearby Waco Dam. The low percentages of coarse sand may also be attributed to the proximity of the sampling station to the Whitney Dam, only 40 river miles north. From the grain size distribution above Lake Whitney it is evident that the reservoir is trapping the larger sand sizes which would otherwise pass the Waco station. Additionally, the river between the two sites cannot truly be classified as flowing in an alluvial valley; the pattern is more that of an entrenched channel controlled by Cretaceous limestones and clays with little sand size material available.

Below Waco the contribution of these fine sands as bed load is significantly reduced. The fine sands are put into suspension and carried as suspended load for a considerable distance downstream. A decrease in channel slope below Bryan (fig. 5) may be responsible for the increase in the portion of fine sands in the bed load at Navasota. However, since the Navasota River is largely uncontrolled and annually overflows the floodplain as a sluggish river, the Navasota sediments may also be responsible for the shift to a finer grain size.

The high percent of larger sand sizes at Sealy may be a result of locally derived bank material from coarse grained deposits of the Quaternary Willis Formation. At this sampling station the river is flowing along the western edge of its floodplain and deriving material directly from both the Willis and Lissie Formations.

There is no indication from figure 23 that the larger sand areas found in the bed load at Sealy were moving downstream under the prevailing discharge conditions, approximately 5,000 cfs. Assuming the discharge-bed shear curve at Sealy approximates that at Hempstead, a bed shear of about 5.85×10^{-2} pounds per square foot (28 dynes per square centimeter) was generated in the channel (fig. 22). Grain sizes of about 3.5mm should have been transported (fig. 21). That this sand is not moving suggests that the sample may not be indicative of the bed load at this locality. The sample may have been retrieved from a slump from the nearby steep banks, taken from a scour pool behind a bridge abutment where larger sand sizes may congregate, or taken from a submerged river bar composed of coarser sediment. In any of these cases the sample might be strongly biased toward the coarser grain sizes and would not necessarily be reflected in samples taken farther downstream.

An enlargement of the grain-size contour map for the Freeport and delta stations is shown in figure 25. At Freeport there is a slight shift toward a higher percent of larger sand sizes in the bed load. The sampling station at Freeport is strongly influenced by tidal action and the increase in grain size is probably a result of 0.125mm and larger size sand being transported upstream during rising tides.

Beach samples taken near the mouth of the river have the highest

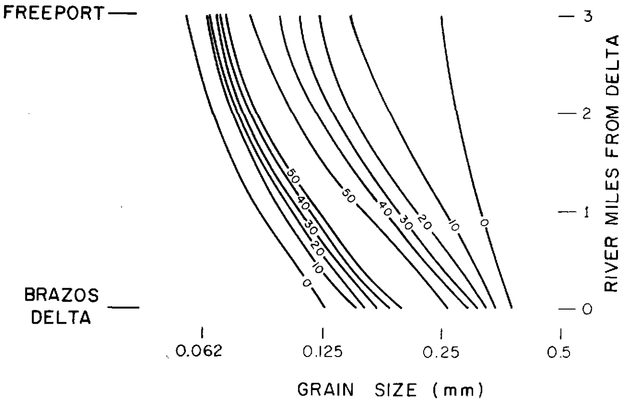

FIGURE 25. Dowling grain-size contour map for Freeport and delta samples

percent of sample near the D_{50} size at 0.22mm. During this study grain sizes of 0.22mm were not found in the lower 150 river miles. The area near Sealy may be a source for beach sands, but the sand was not being transported during the time of sampling.

The grain-size contour map also reveals that the region near Marlin is a potential source area for beach sands. However, none of the beach size sand is moving farther downstream than Sealy. A large amount of the sand is probably being deposited in point bar and channel bar deposits long before it reaches the coast.

Sampling from above the Whitney Reservoir near Kopperl shows that beach size sands were available prior to dam construction (fig. 24). The Texas Board of Water Engineers (1959) has estimated that reservoir trap efficiency for sand size material may be well over 95%. An extreme difference between the bed load above the Whitney Dam and that at Waco shows the effectiveness of this reservoir as a sediment trap.

During this study the average discharge for the Bryan, Hempstead, and Richmond gauging stations was 3,360 cfs, about 5,000 cfs, and 6,080 cfs. These discharges generate bed shears of 12.3×10^{-2} pounds per square foot, 5.85×10^{-2} pounds per square foot, and 9.4×10^{-2} pounds per square foot (59, 28, and 45 dynes per square centimeter), respectively, indicating that the river was capable of transporting all of the bed load found at each locality. In fact, the river was capable of transporting much larger grain sizes at each station than was actually being moved, but the larger sizes are not seen in the bed load. Perhaps the larger sand and gravel size material is available below the zone of sampling, but much higher discharges would be required to uncover and subject them to transport. The evidence suggests that both the quantity and character of the river load is incongruous with past sediment loads and present river conditions.

PROCESSES REDUCING THE SAND LOAD OF THE RIVER

Reservoir Sedimentation

The Texas Board of Water Engineers (1959) has estimated that reservoir trap efficiency for both suspended and bed load material may be well over 95%. Circumstantial evidence presented in figures 3, 17, and 19 suggest that reservoir development has been instrumental in the decrease of detrital material reaching the coastal zone in the study area. The quantity of sand trapped within the reservoirs of the Brazos River Basin must therefore by investigated to evaluate the impact of water resource development on the sand load of the river.

In determining the amount of sand trapped within the reservoirs, the following assumptions have been made, unless otherwise stated: (1) 30% of the total load, by volume, is considered to be bed load, (2) 70% of the bed load, by volume, is considered to be sand size, and (3) 10% of the suspended load, by volume, is considered to be sand size material. These figures are in general agreement with those of the Texas Board of Water Engineers (1959).

Data concerning the infilling rates of the various water impoundment sources have come from the Texas Board of Water Engineers (1959), Dowell and Breeding (1967), the U. S. Army Corps of Engineers (personnal communication, 1975), and from supplemental hydrographic surveys of Lakes Waco and Whitney carried out by a five man field party led by the author in July, 1975. In many cases the data were conflicting, so the usual policy was to use the most recent infilling rates. From recent sedimentation surveys of several reservoirs it was constantly found that the sedimentation rates estimated by the Texas Board of

Water Engineers (1959) is between 25 and 30% higher than the actual surveyed rates. It is believed that the difference is a result of increased soil conservation practices within the basin since 1959. Therefore, when using the rates of infilling from the Board of Water Engineers, 70% of their estimated value is employed in this thesis.

Major reservoirs considered to be important in effectively reducing the source area for coastal sands have been investigated separately. Each of these reservoirs, when originally constructed, were the most downstream structures on the Brazos River or one of its tributaries. Other sediment entrapment sources are grouped together and the computation of the amount of sand trapped within each group is made as best as can be done with the available data.

Major Reservoirs

Possum Kingdom. The latest infilling rate determined for Possum Kingdom Reservoir is 4,156 acre feet per year. Mirabel's (1974) figures show that 2,887 acre feet is suspended load, leaving 1,269 acre feet as bed load. Using the above assumptions, the total amount of sand trapped annually within the reservoir is 1,177 acre feet. One acre foot is equivalent to 43,560 cubic feet, therefore, 51.3 million cubic feet of sand is trapped annually in this reservoir.

Whitney-Granbury. The total amount of sediment entering Lake Whitney between 1952-59 was 1,762 acre feet per year. With the construction of Lake Granbury in 1968, between Possum Kingdom and Whitney, this figure has undoubtedly been reduced. Since Granbury is trapping sediment which otherwise would have reached Whitney, it is reasonable to assume that the total infilling rate of both reservoirs closely approximates that of Whitney prior to construction of the Granbury Reservoir.

Bed load entering these reservoirs has been determined to be only 15% of the total load of the river. The total quantity of sand trapped annually within the two reservoirs is determined to be 335 acre feet, or 14.6 million cubic feet.

Waco. Based on a comparison of sedimentation surveys run by the Corps of Engineers in 1964, the hydrographic survey conducted during this study obtained an infilling rate of 764 acre feet per year. No previous data concerning the percentage of bed load in the total load of the Bosque River near Waco have been published. Analysis of grab samples taken during the survey revealed that only 6% by weight of the bottom sediment was larger than 0.062mm, and of this, only 51% was sand size. Since discharge conditions were low during this period, it will be assumed that 10% of the total load is bed load and 70% of this is sand size. The total volume of sand trapped annually is computed to be 122 acre feet, or 5.3 million cubic feet.

Belton. The infilling rate for Belton Reservoir is assumed to be 782 acre feet per year by the Texas Board of Water Engineers. Of this amount, 219 acre feet are considered to be sand, an amount equal to 9.5 million cubic feet.

Somerville. The Texas Board of Water Engineers estimates that Somerville Reservoir is filling at a rate of 176 acre feet per year. The amount of sand delivered to the reservoir is approximately 49 acre feet, or 2.1 million cubic feet per year.

Other Major Reservoirs

The remaining major reservoirs are located upstream of those discussed above. The 23 additional reservoirs represent only 36% of the total storage volume of the major water resource development within the basin. Infilling rates of these reservoirs were tabulated using the sediment production rates of the individual watersheds compiled by the Board of Water Engineers (1959). The combined rate of infilling of these 23 reservoirs is 2,437 acre feet per year, of which 682 acre feet, or 29.7 million cubic feet, is sand.

Reservoirs Less Than 5,000 Acre Feet Capacity

<u>Reservoirs</u>. Data concerning the infilling rates of the 714 smaller reservoirs within the basin is not available. If it is assumed that these reservoirs are losing storage capacity due to sedimentation at the same rate as the major reservoirs, 0.23% per year, then the total annual loss is 414 acre feet of the total 180,000 acre feet of storage capacity. The amount of sand trapped yearly is 120 acre feet, or 5.2 million cubic feet.

<u>Farm ponds</u>. Because no data has been kept on the number of farm ponds within the basin since 1959, it is necessary to estimate their number. Since 93,000 were constructed by 1959, it seems reasonable to assume that 125,000 are within the basin today. The Texas Board of Water Engineers estimated that the 93,000 farm ponds in existence in 1959 were filling at a rate of 0.039 acre feet each per year. This value will be reduced to 0.027 acre feet each per year to account for the normally high rates estimated by the Board. It will be assumed

that 30% of all sediment delivered to these ponds is greater than 0.062mm, and that 70% of this amount is sand. The annual quantity of sand deposited in the ponds is 709 acre feet, or 30.9 million cubic feet.

The total amount of sand trapped annually within all types of water resource structures in the Brazos River Basin is 3,413 acre feet, or approximately 148.6 million cubic feet. The Texas Board of Water Engineers (1959) has estimated the total amount of sediment production within the Brazos River Basin to be 23,912 acre feet per year. Assuming a 30% reduction due to soil conservation practices, this figure can be reduced to 16,738 acre feet per year. The average amount of bed load carried by the Brazos River and its tributaries is about 28% of the total load. If 70% of the bed load is sand size material and 10% of the suspended load is sand sized, then the amount of sand produced annually within the basin is 4,486 acre feet, or 195.4 million cubic feet.

These figures indicate that the reservoirs are trapping 76% of all sand produced in the basin. All of the sand trapped by the reservoirs would certainly never reach the coast were the reservoirs not present, but the high percentage of entrapment significantly reduces the quantity of sand which is capable of nourishing the coast.

Channel Sedimentation

Although the reservoirs are very effective in reducing the source area from which the lower Brazos River can obtain a sand supply, a large amount of sand is still delivered to the lower channel by small tributaries which remain unregulated and by lateral erosion of bank material within the lower alluvial valley. Seelig and Sorensen (1973) have determined that an average of 31.6 million cubic feet of sand have passed the Richmond gauging station annually since 1952. If the total sand production within the basin is 195.4 million cubic feet per year and the reservoirs are trapping 148.6 million cubic feet per year, then slightly over 15 million cubic feet of sand per year are left unaccounted for. This is actually a minimum value for the period of time since 1952 because the quantity of sand trapped presently is much greater than the amount being trapped in the 1950's and early 1960's.

In determining the quantity of sand trapped in the reservoirs it has been assumed that all of the sediment passing an upstream gauging station from which sediment loads have been calculated has been deposited in the first reservoir downstream of that station. Therefore, the 15 million cubic feet of surplus sand must be deposited in the Brazos River and its tributaries downstream of reservoir development. Because all of the tributaries enter the Brazos, and because the Brazos River below Whitney is so much larger than the other streams, the vast majority of the sand is probably deposited within the main channel of the Brazos River below the Whitney Dam. The abundance of sand within the channel of the Brazos River and the presence of numerous actively building point bar deposits between Waco and Wallis was noted during field work in the summer of 1975 and in subsequent aerial reconnaissance of the river in January, 1976. Deposition of the surplus sand apparently occurs between Waco and Wallis as indicated by the observed distribution of channel and point bar deposits in the river.

Below Wallis the number of actively building point bars and other channel sand deposits begins to decrease, and eight miles below the Richmond station they have all but vanished. Evidence for the inactivity of the point bars is the density in vegetation cover over the bars. Most of the river bends below Richmond show an indication of past lateral accretion, but vegetation has almost enitrely covered them. Aerial photographs of this region taken in 1959 reveal that the situation was much the same, although the vegetal cover does not appear to be as dense as at the present time. Unfortunately, the author was unable to compare aerial photography taken prior to construction of the major reservoirs with the post-dam photography, so the time of cessation of actively building point bars below Richmond is not known.

The Effect of Changed Hydrology on Sand Distribution

From the previous discussion of channel sedimentation, it appears that there is a substantial amount of sand available for transport in the channel below the Whitney Dam. Both figures 19 and 24 suggest that much of the sand is not being transported downstream. With increasing dam construction the amount of sand passing Richmond since 1941 has been steadily decreasing. Seelig and Sorensen's (1973) figures show that, for the periods 1942-51, 1952-61, and 1962-71, sand loads were reduced 25%, 29%, and 48% compared to pre-dam records.

The pattern of sand distribution within the river channel below the Whitney Dam can be explained by the change in the hydrology of the river since the completion of the Whitney Dam in 1952. A prime source area for much of the coastal sand is just below Waco (fig. 24). At Waco, peak flood discharge has been reduced 52% and the frequency of discharge above 5,000 cfs has been reduced about 38%. High discharge conditions act to clean out the channel of sediment accumulated during low discharge conditions. With the reduction in both peak discharge and frequency of high discharge, much sand which otherwise would have been carried downstream remains in the channel, near, and just below, Waco.

The peak discharge at Bryan has been reduced 46%, but this locality is being starved of a sand supply due to the lower discharge conditions upstream near Waco. A reduction in the sand supply plus the lowered discharge at Bryan further reduces the sediment supply downstream. Even though peak discharge has been reduced only 30% and frequency of flow above 10,000 cfs has been reduced only 15% at Richmond, there is far less sand available for transport through this station than there was prior to the regulation of flow past the Whitney Dam.

This cumulative impact of reducing the energy necessary to transport sand size material to the lower reaches of the river system may explain why active point bar deposition below Richmond has virtually ceased. The Brazos River is still able to transport sand below Richmond if sand eroded from upstream had been delivered. Since no loose sand is available, active point bar deposition would cease. The flow conditions below Richmond, however, may not be able to erode the clayey sands that make up the existing point bars, as they have been allowed to dry and compact to some degree since deposition. In addition, the vegetal cover would also act to retard stream erosion. This would therefore form a river channel that cannot actively receive new sediment, due to upstream deposition, or erode the channel, due to an increase in the cohesion of the deposited sediments and erosion protection provided by vegetation.

SEDIMENT LOSSES TO THE COAST

The preceding discussion has shown that the amount of sediment the Brazos River is able to transport and supply to the coastal zone has been greatly reduced by the construction of reservoirs which trap tremendous quantities of sediment, and their associated dams which regulate the discharge of the river. Future reservoir construction will continue to decrease the sediment load delivered to the coast. Figures 26 and 27 relate the changes in the ratios of suspended load, Q_S, and the total sand load, Q_{SD}, to water discharge, Q, at the Richmond station against the effective drainage basin area above the Brazos River delta. The effective drainage area is the size of the drainage basin below all major water resource structures. It is assumed that all of the suspended and bed load material passing the Richmond station reaches the coast so that the following calculations will apply to the loss of sediment at the river delta.

The data points for both of these figures represent the average ratios of Q_S/Q and Q_{SD}/Q, taken from the least squares fit curves of figures 17 and 19, at the year of initial water impoundment for six major reservoirs. Each reservoir selected for use was the most downstream facility on the Brazos, or one of its tributaries, at the time of its completion. Thus, each of these reservoirs has progressively reduced the effective drainage area, and consequently the sediment source area, above the delta. The reservoirs selected for use, their date of completion, and the effective drainage area resulting from their construction are: Waco, 1929 (33,748 square miles), Possum Kingdom, 1941 (20,438 square miles), Whitney, 1951 (16,818 square miles),

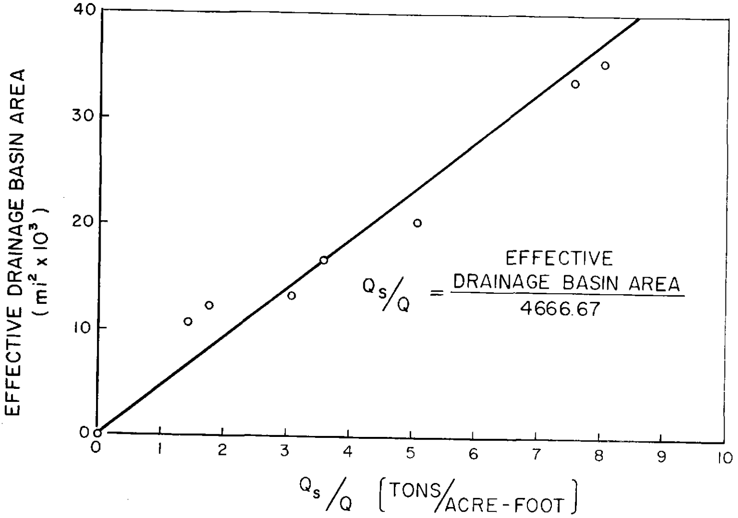

FIGURE 26. Q_S/Q versus effective drainage basin area for the Brazos River Basin

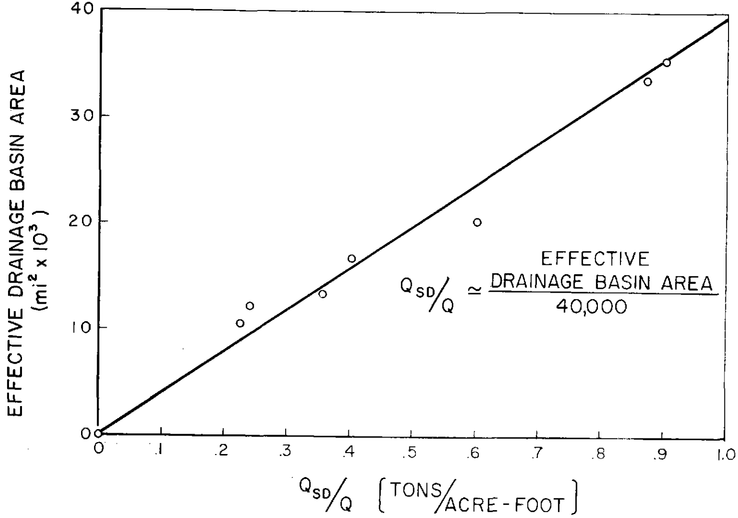

FIGURE 27. Q_{SD}/Q versus effective drainage basin area for the Brazos River Basin

Belton, 1954 (13,258 square miles), Somerville 1966 (12,252 square miles), and Stillhouse Hollow, 1968 (10,934 square miles).

Figures 26 and 27 show that decreases in the Q_S/Q and Q_{SD}/Q ratios approximate a linear relationship with the decrease in the effective drainage basin area. The equations for each line are given in their respective figures. Additional reservoirs built downstream of any of the six reservoirs used in this analysis would further reduce the effective drainage basin area and the Q_S/Q and Q_{SD}/Q ratios.

With the completion of the Stillhouse Hollow Reservoir the effective drainage area was reduced to the present 10,934 square miles, giving approximate Q_S/Q and Q_{SD}/Q ratios of 2.34 and 0.27 tons per acre foot. Average water discharge for the past 20 years at Richmond has been 4.79 million acre feet per year, so about 11.2 million tons of suspended sediment and 1.29 million tons of sand pass Richmond each year at the present time.

The amount of sediment reduction brought about by further reservoir development can be estimated from figures 26 and 27. Assume the proposed Millican Reservoir, located on the Navasota River near its confluence with the Brazos, were to be built. The effective drainage area of the Brazos River Basin would be reduced to approximately 9,000 square miles. The Q_S/Q and Q_{SD}/Q ratios would then be 1.93 and 0.23 tons per acre foot of water discharge, respectively. The suspended sediment load would be reduced to about 9.24 million tons per year and the sand load to 1.1 million tons per year. Assuming the suspended sediment has a specific weight of 70 pounds per cubic foot, the difference in the quantity presently delivered to the coast would be about 56 million cubic feet per year. The sand loss, assuming sand weighs 93 pounds per cubic foot, would be over 4 million cubic feet per year. A specific weight of 93 pounds per cubic foot for sand has been employed in this thesis to conform to calculations made by Seelig and Sorensen (1973) in their sediment budget of the coastal area.

Figure 27 has been used to estimate the amount of sand denied access to the coastal zone during the period of reservoir construction, 1930-70, as a result of decreasing the size of the effective drainage area. It was necessary to divide this time period into the six intervals which correspond to intervals of time during which the effective drainage area has remained relatively constant. The results are given in Table 3. The period prior to 1930 was calculated using the average water discharge of the river for the 41 year period 1930-70. Multiplying the Q_{SD}/Q ratio prior to 1930, 0.89 tons per acre foot, by 41 gives the amount of sand, 4,143 million cubic feet, which should have passed Richmond from 1930-70 had no water development structures been built. The difference between this amount and the amount which did pass Richmond, 2,527 million cubic feet, is the quantity of sand which has been denied access to the coast, 1,616 million cubic feet.

Seelig and Sorensen (1973) have determined the net loss of sand for the Brazos delta and coastal zone under investigation to be 1,200 million cubic feet between 1937-73. Adjusting the average discharge for the interval 1930-41 to that of 1937-41, and adding three years of sand discharge at the 1969-70 rate, the total amount of sand reaching the coast between 1937-73 can be calculated as 1,931 million

TABLE 3. Sand Discharge at the Brazos River Delta

(1)	(2)		(3)	(4)	(5)	(6)	
Effective Drainage Basin Area (mi^2)	Time Effective Drainage Basin Area Existed		Average Q During Time Interval (10^6 acre feet)	Q_{SD}/Q (10^6 tons/acre foot)	Average Q_{SD} Per Year (3) x (4) x $\frac{2,000}{93}$ (10^6 ft^3)	Total Q_{SD} at coast (2) x (5) (10^6 ft^3)	
	interval	years					
35,400	Pre 1930	41	5.28	0.89	101.06	4,143.38	
						1930-70	1937-73
33,748	1930 - 41 1937 - 41	12 5	6.00 6.77	0.84	108.39 122.29	1,300.68	611.48
20,438	1942 - 51	10	5.35	0.51	58.68	586.80	586.80
16,818	1952 - 54	3	2.09	0.42	18.88	56.64	56.64
13,258	1955 - 66	12	5.27	0.33	37.4	448.80	448.80
12,252	1967 - 68	2	5.47	0.31	36.47	72.94	72.94
10,934	1969 - 70 1969 - 73	2 5	5.31	0.27	30.83	61.66	154.15
						2,527.52	1,930.81

cubic feet (Table 3). The amount of sand which should have reached the coast from 1937-73 is 3,739 million cubic feet, which means that modification of the Brazos River has caused a loss of 1,808 million cubic feet. Since Seelig and Sorensen (1973) have calculated 1,200 million cubic feet of sand loss for the coastal zone between 1937-73, these figures suggest that sand transport through the Brazos River has been reduced enough to account for the entire amount of sand loss in the coastal zone since at least 1937. The excess 608 million cubic feet of sand loss determined in this study suggests that the sediment budget, as determined by Seelig and Sorensen (1973), might be improved.

The normal geologic recession rate at Sargent Beach, defined by Mathewson (1974), is 13 feet per year. The recession rate has increased an additional 7 feet per year since reservoir development began, so the 1,808 million cubic feet of sand trapped upstream between 1937-73 must account for the increased recession. For the 37 year period an average annual loss of 49 million cubic feet per year can be determined. Each foot of beach loss above the normal geologic recession rate therefore corresponds to a loss of 7 million cubic feet of sand per year. Seelig and Sorensen (1973) calculated an actual volume of lost sediment for each foot of beach erosion as 1.2 million cubic feet for the entire Sargent Beach area. The difference between the 7 million cubic feet of sand required to neutralize each foot of beach loss and the 1.2 million cubic feet of actual sediment volume needed is a consequence of the difference in the rate of erosion of the clay beach at Sargent, as opposed to a beach that is all sand, and the normal longshore transport of sand through the study area.

Using 7 million cubic feet of sand per foot of beach loss as the Sargent Beach recession conditions, an analysis of the recession along the beach can be made assuming conditions of no reservoir development and reservoir development for the period 1937-73. Had no reservoirs or dams been built, the Brazos River would have supplied 3,739 million cubic feet of sand to the coast, an average of 101 million cubic feet per year. However, the normal geologic recession rate would still have been 13 feet per year. For complete stabilization of the beach, no erosion conditions, an excess amount of sand above the 101 million cubic feet per year would be required. This would be 7 million cubic feet for each foot of erosion, or an additional 91 million cubic feet per year. A total of 192 million cubic feet of sand per year is therefore required to stabilize Sargent Beach. For the 37 year period, 7,104 million cubic feet would be required for no erosion conditions (fig. 28 A). Since the Brazos River would have delivered only 3,739 million cubic feet for the entire period had no dams been built, a sand deficit of 3,365 million cubic feet would have resulted, accounting for an erosion rate of 13 feet per year (fig. 28 B).

With reservoir development only 1,931 million cubic feet of sand was delivered for the 1937-73 period. The sand deficit of 5,173 million cubic feet accounts for an erosion rate of 20 feet per year for the entire period (fig. 28 C). The annual average amount of sand delivered to the coast has been 52 million cubic feet per year. This is a deficit of 140 million cubic feet per year for no erosion conditions. This amount of sand would therefore be required to artificially supplement the Brazos River sand discharge and completely

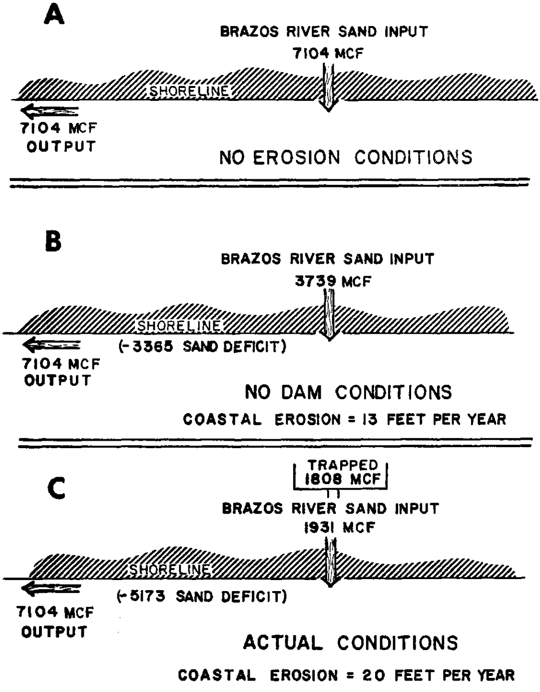

FIGURE 28. Coastal erosion models

CONCLUSIONS

The increase in the rate of beach erosion along the Texas coastline supplied by sediments from the Brazos River can be related to increased water resource development within the Brazos River Basin. The major changes to the river system brought about by reservoir construction are a change in the hydrology of the river and a reduction in the amount of sand available to be delivered to the coastal zone.

The frequency of occurrence of high discharges and a reduction in the peak flood discharges at gauging stations below the Whitney Dam have greatly reduced the Brazos River's ability to transport large quantities of sand downstream. Control of river discharge by dams is less effective at greater distances downstream, and as a result, much of the sand is left in the upstream portion of the channel. Even though the river farther downstream has the potential of carrying a larger sand load, the sand is not available to be transported.

Of the 195.4 million cubic feet of sand produced annually within the Brazos River Basin, approximately 76% is trapped within the reservoirs and other smaller ponds within the basin. Although all of the sand trapped would not reach the coast were it allowed to naturally pass through the system, the reduction in the amount of sand available for transport has obvious implications. Calculations of the amount of sand denied access to the coast since major water resource development was initiated shows that it is sufficient to account for the entire increase in coastal erosion since at least 1937. The amount of additional sand loss resulting from future water resource development downstream of present reservoirs can be predicted from figure 27.

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APPENDIX

WACO AND RICHMOND

CUMULATIVE FREQUENCY DATA

% OF TIME FLOW ≥ DISCHARGE INCREMENT

DISCHARGE INCREMENT	WACO 1920-41	WACO 1942-51	WACO 1952-74	WACO 1942-74	RICHMOND 1923-41	RICHMOND 1942-51	RICHMOND 1952-74	RICHMOND 1942-74
0-9	100	100	100	100	100	100	100	100
10-99	99.4	100	100	100	100	100	99.9	100
100-199	85.5	99.4	91.5	93.9	99.8	100	99.9	99.9
200-299	73.1	95.0	82.8	86.5	99.4	99.9	99.6	99.7
300-399	66.1	88.1	73.8	78.2	99.0	99.6	98.4	98.8
400-499	60.9	81.2	67.0	71.3	98.0	99.3	96.7	97.5
500-599	56.9	73.9	61.8	65.5	95.2	98.8	94.4	95.7
600-699	54.0	67.3	56.9	60.1	91.6	96.2	91.1	92.7
700-799	51.0	62.2	52.5	55.4	87.8	93.9	87.7	89.6
800-899	48.5	56.9	47.4	50.3	84.1	90.7	84.5	86.6
900-999	45.9	52.4	42.5	45.5	81.4	87.9	80.8	83.0
1,000-1,999	44.0	48.1	39.0	41.8	78.9	84.5	77.1	79.3
2,000-2,999	29.8	24.4	20.7	21.8	60.6	63.1	54.6	57.2
3,000-3,999	21.1	16.1	14.3	14.9	50.4	50.4	44.4	46.2
4,000-4,999	16.3	11.4	11.1	11.2	43.1	42.8	37.6	39.2
5,000-5,999	13.2	8.9	8.1	8.3	37.5	36.9	32.5	33.9
6,000-6,999	11.1	7.3	6.7	6.9	33.2	32.6	27.9	29.3
7,000-7,999	9.5	6.1	5.8	5.9	29.5	29.0	24.8	26.1
8,000-8,999	8.3	5.3	5.1	5.2	26.5	26.1	22.1	23.3
9,000-9,999	7.2	4.5	4.5	4.5	24.1	23.3	19.7	20.8
10,000-11,999	6.6	4.1	4.0	4.1	22.0	21.2	17.5	18.7

% OF TIME FLOW ≥ DISCHARGE INCREMENT (continued)

DISCHARGE INCREMENT	WACO 1920-41	WACO 1942-51	WACO 1952-74	WACO 1942-74	RICHMOND 1923-41	RICHMOND 1942-51	RICHMOND 1952-74	RICHMOND 1942-74
12,000-14,999	5.3	3.2	3.5	3.4	18.4	17.8	14.2	15.3
15,000-17,999	4.0	2.4	2.8	2.7	14.3	13.8	10.5	11.5
18,000-19,000	3.0	1.8	2.3	2.1	11.8	10.5	7.9	7.8
20,000-24,999	2.6	1.5	1.9	1.8	11.0	9.0	6.8	7.5
25,000-29,999	1.7	1.1	1.3	1.2	7.6	6.1	5.1	5.4
30,000-39,999	1.2	0.79	0.88	0.85	5.7	4.5	4.0	4.2
40,000-49,999	0.61	0.52	0.29	0.36	3.5	2.6	2.8	2.7
50,000-74,999	0.31	0.22	0.13	0.16	2.2	1.6	2.0	1.9
75,000-99,999	0.07	0.11	0.00	0.03	0.76	0.52	0.49	0.50
> 100,000	0.05	0.08	0.00	0.02	0.19	0.00	0.06	0.04

VITA

Name: Larry Lane Minter

Birthdate: December 19, 1947

Birthplace: Dallas, Texas

Parents: Mr. and Mrs. James Ralph Minter

Wife: Katherine Rebecca (Prehn) Minter

Education: Texas A&M University
Bachelor of Science, Geology
May 1970

Military Service: National Oceanic and Atmospheric Administration, February 1971 - July 1974
Rank: Lieutenant (Junior Grade) at discharge

Professional Experience: Texaco, Inc., Houston, Texas
Geologist
June 1970 - February 1971

Mailing Address: 4014 Texas Drive
Dallas, Texas 75211

The typist for this thesis was Miss Beverly Bowen.