Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-02/2105-1		

4. Title and Subtitle	5. Report Date
PREDICTING MEANDER MIGRATION: EVALUATION OF SOME EXISTING TECHNIQUES	September 2001
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Jean-Louis Briaud, Hamn-Ching Chen, Siyoung Park	Report 2105-1
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Project 0-2105
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	Research: Sept. 2000 – Aug. 2001
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Research Project Title: Develop Guidance for Design of New Bridges and Mitigation of Existing Sites in Severely Degrading and Migrating Streams

16. Abstract

River meanders migrate over time; this migration endangers civil engineering structures in general and highway bridges in particular. The geotechnical engineer and the hydraulic engineer work together to predict and prevent this migration. This article describes and evaluates two approaches used to predict the migration of meanders: the empirical approach and the time-sequence maps and extrapolation approach. Empirical methods are based on correlations using databases of observed behavior, while the time-sequence method uses previously observed movement of a given meander to predict its future migration. Six case histories on four rivers are used to evaluate the precision and accuracy of these methods by comparing the predicted and measured migration. The results show that some empirical methods are conservative, some are unconservative, and none of them are very accurate or precise. The time sequence method gives more information on the meander movement, is relatively precise and accurate in predicting the radius of the best-fit circle of the future meander location, but is not precise in predicting the migration rate of the center of that circle.

17. Key Words	18. Distribution Statement
River, Migration, Migration Rate, Case Histories, Empirical Prediction Methods, Time-Sequence Maps, Extrapolation Prediction Method	No Restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	50	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

PREDICTING MEANDER MIGRATION: EVALUATION OF SOME EXISTING TECHNIQUES

by

Jean-Louis Briaud
Research Engineer
Texas A&M University

Hamn-Ching Chen
Professor
Texas A&M University

and

Siyoung Park
Graduate Student
Texas A&M University

Report 2105-1
Project Number 0-2105
Research Project Title: Develop Guidance for Design of New Bridges
and Mitigation of Existing Sites in Severely Degrading and Migrating Streams

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

September 2001

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. In addition, the above assume no liability for its contents or use thereof. The engineer in charge of the project was Dr. Jean-Louis Briaud, P.E. # 48690.

ACKNOWLEDGMENTS

This project was sponsored by TxDOT and FHWA. At TxDOT, the project director was Tom Dahl and the program coordinator was David Stolpa. They both helped in providing the field data as well as Pat Williams and Terry Paholek of the Bryan District, John Kilgore of the San Antonio District, Robert Balfour of the Beaumont District, and Gerald Freytag of the Yoakum District.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION

Rivers are dynamic systems. The action of the flowing water can change the elevation and the lateral location of the riverbed and the riverbanks. Meanders are particularly prone to changes in lateral location because of the centrifugal force that increases the shear stress at the interface between the water and the soil. Predicting the movement of a meander is both difficult and necessary. It is difficult because many factors influence the process and necessary because such a movement may create expensive maintenance problems for nearby bridges. A comprehensive survey of existing knowledge was assembled on this topic (Briaud et al., 2001).

After a presentation of the three general approaches available to predict meander migration, this report gives details about two of them. Then, six meander migration case histories related to four rivers are presented including the measured movements. Finally, researchers compare the measured movements with the movements predicted by the two approaches and draw conclusions.

2. DEFINITIONS

Figure 1 shows the migration of meanders on the Brazos River near Navasota, Texas. At the location labeled "reference line case 1" on the figure, the meander has moved over 300 meters (984 feet) towards the bridge abutment from 1910 to 1981. At the location labeled "reference line case 2" on the figure, the meander has moved over 200 meters (656 feet) towards the Navasota River over the same period. As in the case of any erosion problem, predicting such movements requires the knowledge of three input parameters: the geometry, the water, and the soil. The geometry of the meander and of the river cross-section impacts the hydraulic shear stress generated at the interface between the water and the soil. Figure 2 gives a definition of the factors used to describe a meander geometry. The water, including the flow velocity, also influences the hydraulic shear stress applied to the soil. The soil controls the erosion rate on the resistance side. These simple concepts are fundamental but one must also acknowledge the complexity of some factors. For example, the interface may not be soil; it could be rock, vegetation, or a man-made material used as a countermeasure. Also, the shear stress developing at the interface may lead to a slope failure of the bank; the slumped mass of soil is then eroded by the flowing water.

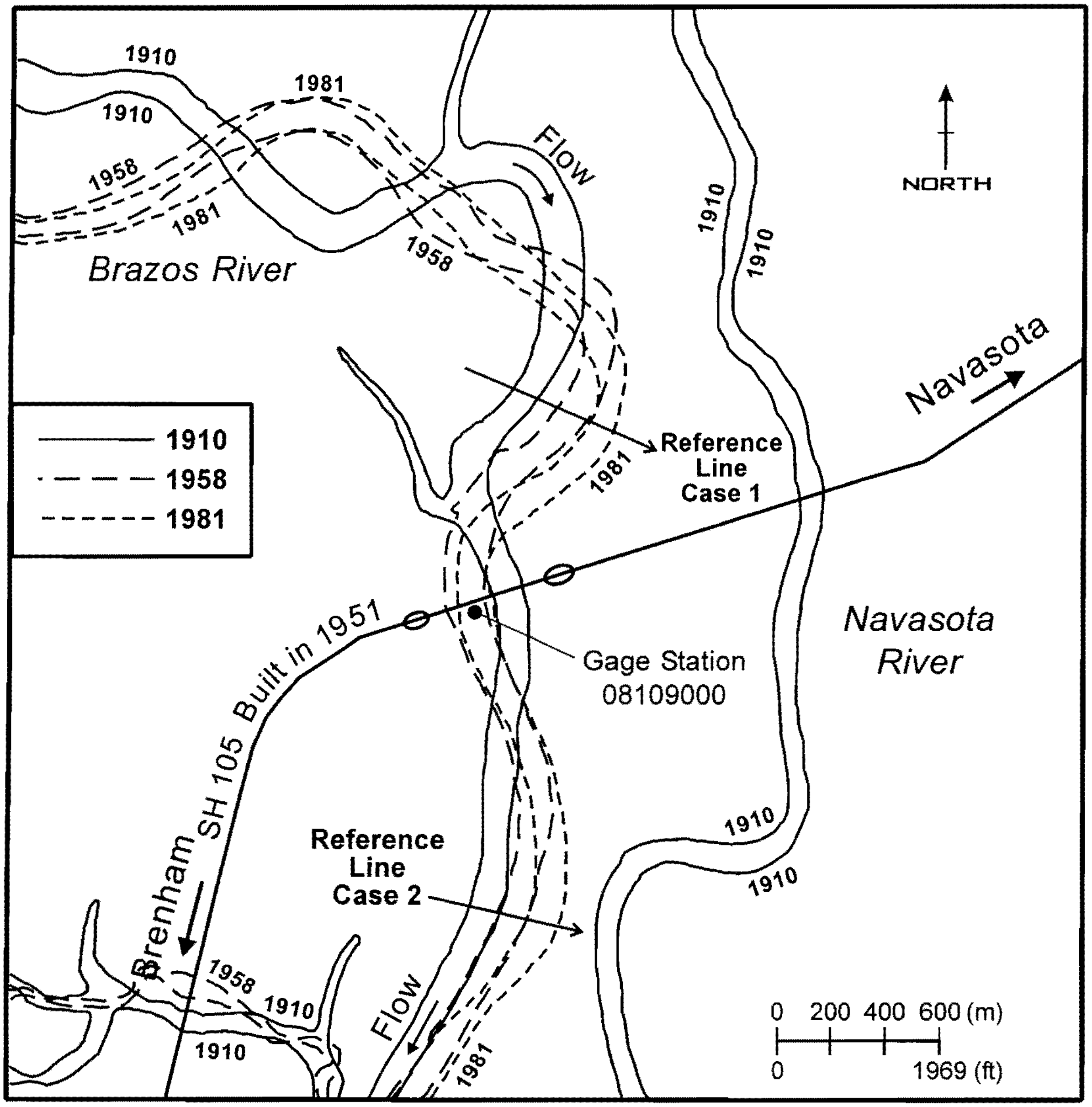


Figure 1. Meander Migration for the Brazos River at SH 105.

C = center of best fit meander circle
A = apex of meander
a = meander amplitude
b = channel width
r_c = radius of curvature of meander
ϕ = bend angle

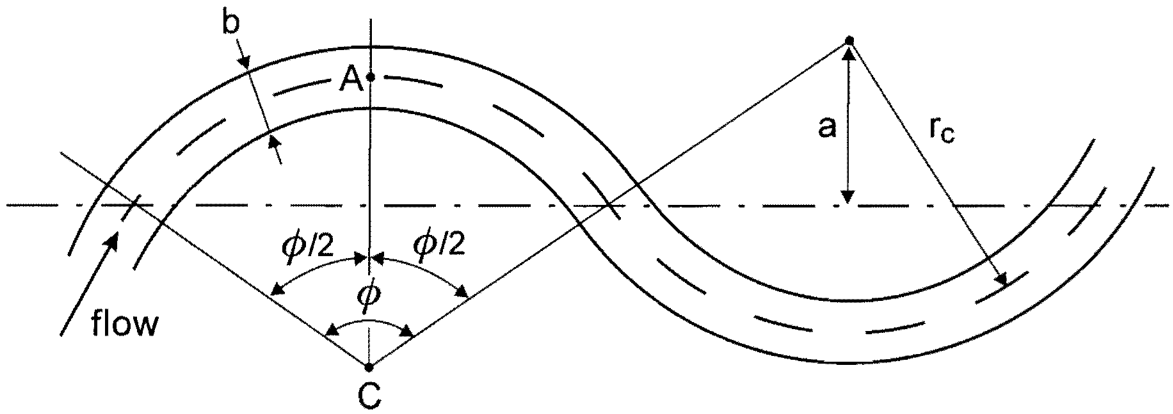


Figure 2. Geometry Parameters for Meanders.

3. GENERAL APPROACHES

The existing approaches to predict meander migration make use of geometry, water, and soil parameters in various ways. These approaches can be divided into three categories: those using time-sequence maps and extrapolation, those using empirical equations, and those using fundamental modeling.

With the time-sequence maps and extrapolation approach, meander migration is predicted by accumulating topographic maps and aerial photographs of the riverbanks at various dates in the past, measuring the migration rate from those maps, and extrapolating into the future. These maps and aerial photographs can be obtained from local libraries, or from web sites such as *http://mac.usgs.gov/mac/findmaps.html* or *http://terraserver.microsoft.com/.* The advantages of this approach are that it is relatively simple and is based on full-scale observations at the site. The drawbacks are the limited availability of maps and photographs, and the assumption that future flow and soil conditions will be the same as in the past. Departments of transportation commonly use this method.

With the empirical approach, a database of observed meander migrations and associated parameters is assembled, most influential parameters are selected, a regression is performed, and an equation is proposed. The advantages of this approach are that it is simple and is based on full scale observed data. The drawbacks are that the equation may not include all the essential parameters influencing the process, and that the applicability of the equation is limited by the extent of the database both in terms of quantity of data and geographical area. This approach is also quite common.

The fundamental modeling approach consists of modeling the erosion process at the water-soil interface and projecting it into time by using future hydrographs (water velocity versus time). This approach has the advantage of simulating the real phenomenon on a site-specific basis. It has the drawback of being more complicated because it requires the site-specific measurement of soil properties and the selection of future hydrographs. One such method is in the development stages at Texas A&M University.

4. TIME-SEQUENCE MAPS AND EXTRAPOLATION METHOD

In this article the time-sequence maps and extrapolation method are described and evaluated against case histories. This method was mentioned by Brice (1982) and is being refined by Lagasse and his colleagues at Ayres Associates in Fort Collins, Colorado (Lagasse, 2001). Figure 3 shows a sketch describing how the method is used and Figures 4 and 5 show real examples. The first step includes obtaining a map of the meander for a first date, t_1 (1958 on the example of Figure 4). A first best-fit circle is drawn to match as much of the t_1-dated meander shape as possible. The location of the center, C_1, and the radius, R_1, of that first circle are recorded (Figure3). Then a map of the meander is obtained for a second date t_2, more recent than the first date t_1 (1969 on the example of Figure 4). Again a second best-fit circle is drawn to match as much of the t_2-dated meander shape as possible. Figure 3 records the location of the center, C_2, and the radius, R_2, of that second circle. Now in order to predict the position of the meander at a future date t_3, the following linear extrapolation process is used. The distance C_2C_1 is measured, by using the scale on the map, and divided by the time (t_2-t_1) to obtain the meander migration rate $M_{r\,(1\text{-}2)}$. This rate, which is the mean rate from t_1 to t_2, is assumed to be the same as the rate $M_{r\,(2\text{-}3)}$ from t_2 to t_3. The distance C'_3C_2 between the predicted location C'_3 of the center of the t_3-dated best-fit circle and the measured location C_2 of the center of the t_2-dated best-fit circle is predicted by:

$$C'_3\,C_2 = (t_3 - t_2) \times M_{r(1-2)} \tag{1}$$

Furthermore, the direction of vector C'_3C_2 is assumed to be the same as the direction of vector C_1C_2; the location of C'_3 is thereby completely determined. The actual location of the center of the t_3-dated best-fit circle is C_3 (Figure 3) and the measured migration rate of the circle centers is C_3C_2 / (t_3 – t_2). The predicted radius R'_3 of the t_3-dated best-fit circle is obtained by linear extrapolation of radii R_1 and R_2.

$$R'_3 = R_2 + \frac{R_2 - R_1}{t_2 - t_1} \times (t_3 - t_2) \tag{2}$$

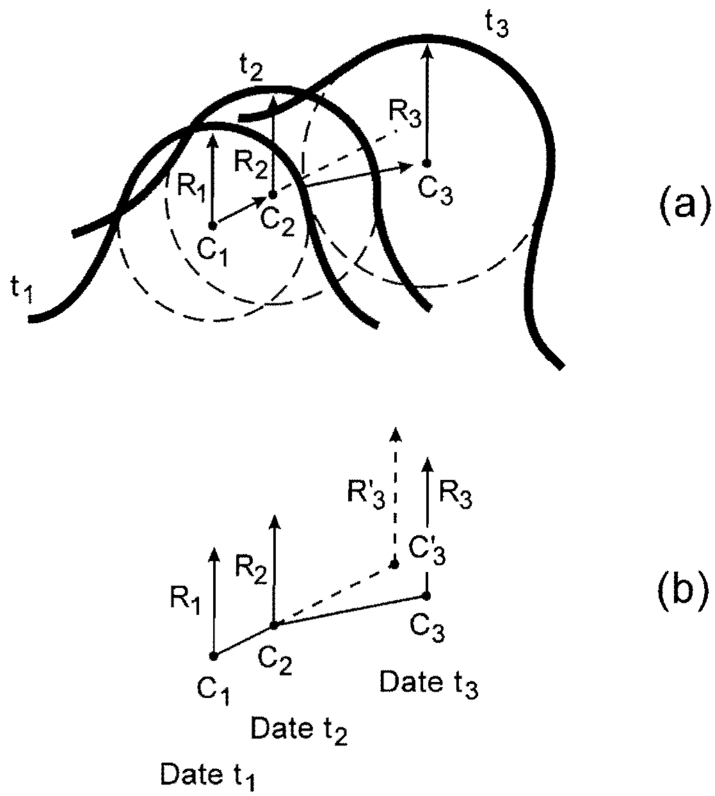


Figure 3. Definitions for the Time Sequence Maps and Extrapolation Method.

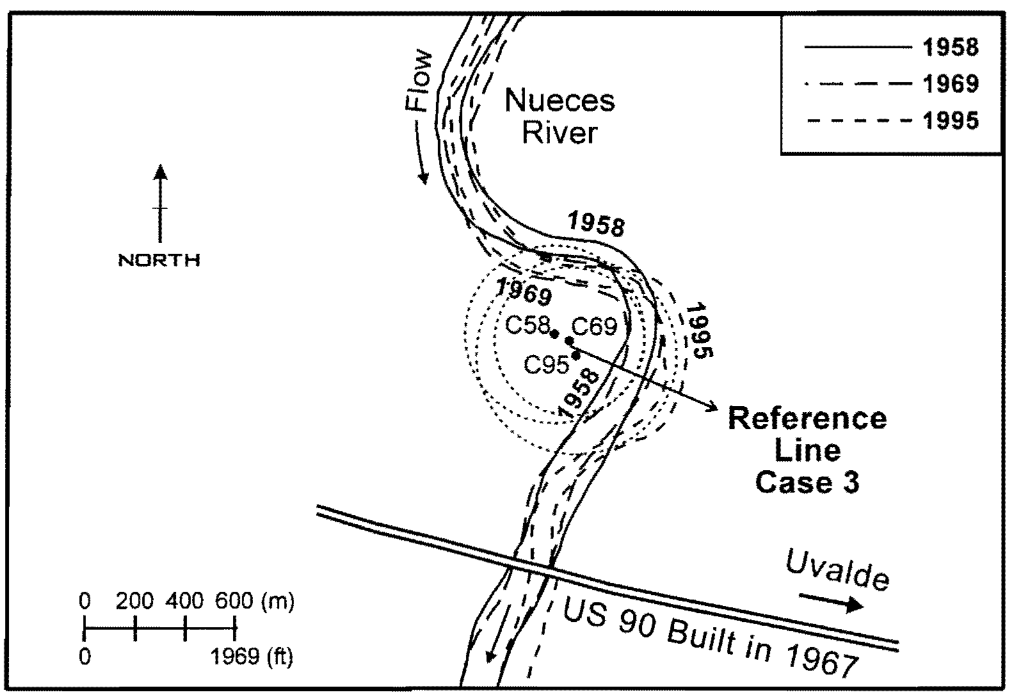


Figure 4. Meander Migration for the Nueces River at US 90.

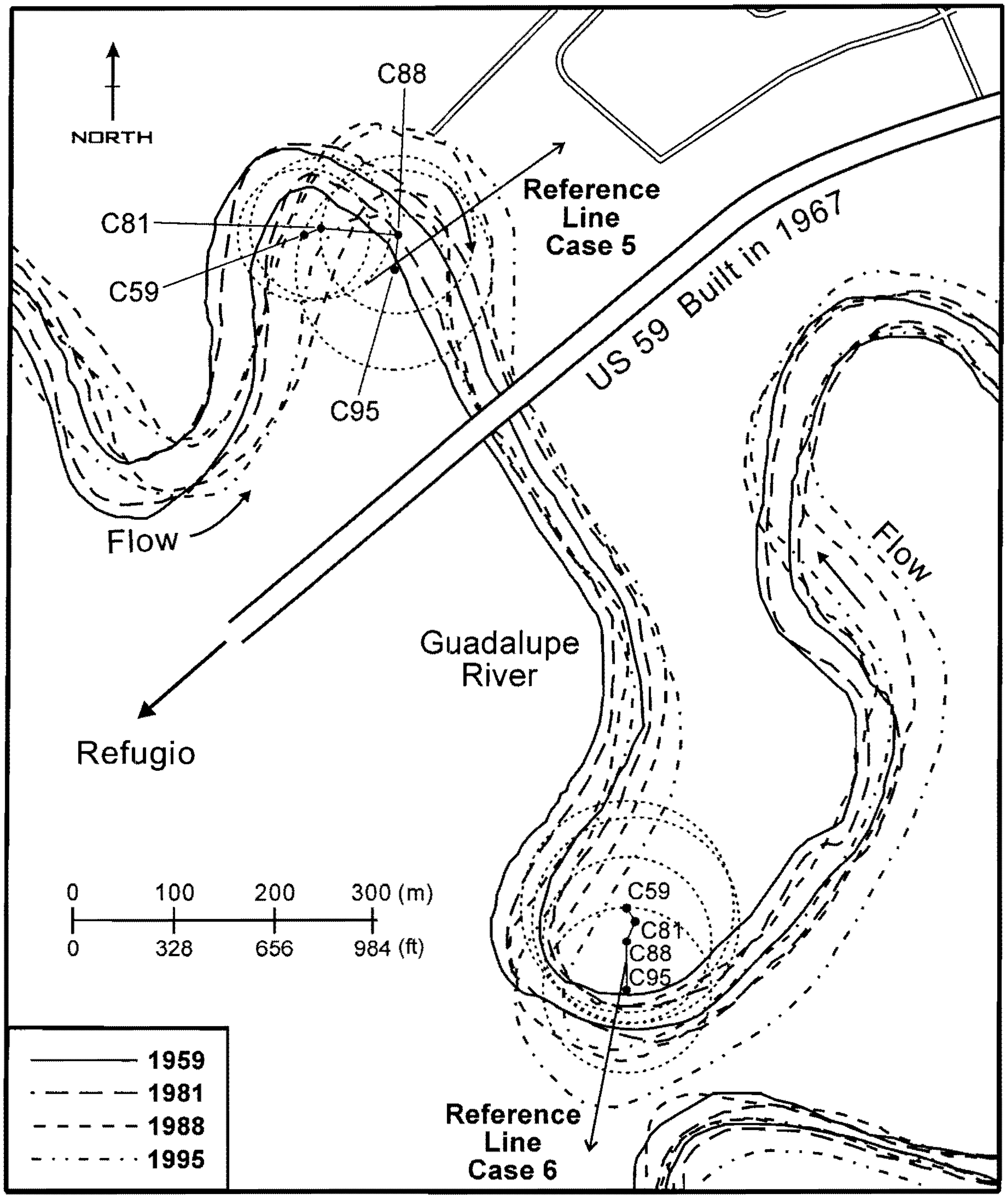


Figure 5. Meander Migration for the Guadalupe River at US 59.

Equation (2) expresses the assumption that the meander rate (dR/dt) remains constant. The actual radius of that circle is R_3 (Figure 3). The predicted location of the t_3-dated best-fit circle is thereby completely predicted.

The actual location and size of the t_3-dated circle can be obtained from a meander map corresponding to the date t_3. The difference between the location and size of the predicted t_3-dated circle and the measured t_3-dated circle help evaluate the precision and accuracy of the time-sequence maps and extrapolation method. In this article, four rivers' case histories are used to study a total of six meander sites. For each meander site, maps corresponding to several dates were collected and used to predict the location and size of the t_3-dated best-fit circle as well as to measure the location and size of the t_3-dated best-fit circle. This leads to a total of 10 predicted versus measured comparisons.

5. SELECTED EMPIRICAL METHODS

Some of the most commonly used empirical approaches are described and evaluated against case histories. They are the Keady and Priest (1977) approach, the Hooke (1980) approach, the Brice (1982) approach, and the Nanson and Hickin (1983) approach.

Keady and Priest (1977) collected meander migration data from published reports on the Mississippi River in Tennessee, Louisiana, and Mississippi, on the Red River in Arkansas, on the Pearl River in Louisiana, on the Tombigbee River in Mississippi, on the Buffalo River in Louisiana, and on the Red Deer River in Alberta, Canada. This gave them eight data points from which they obtained their equation. The selected influencing parameters are s, the free surface slope of the river, and a, the amplitude of the meander (Figure 2). The equation is:

$$M_r = 0.315\,(g\,a)^{0.5}\,f(s) \qquad (3)$$

where M_r is the meander migration rate (m/yr); g is the acceleration due to gravity (m/s^2); a is the meander amplitude (m) (Figure 2); f(s) is the function of s, the free surface slope of the river, shown in Figure 6.

Hooke (1980) collected meander migration data using field measurements and historical maps for 11 streams in Devon, England. Hooke isolated the catchment area, A, as the main influencing parameter and derived his equation based on those data. The catchment area is the area drained by the river or by the river system. Then, Hooke compared the rates obtained in Devon with rates found in the literature for 43 streams. Hooke's modified equation consists of merging both sets of data to derive a single regression (Figure 7):

$$M_r = 0.0669\,A^{0.46} \qquad (4)$$

where M_r is the meander migration rate (m/yr), and A is the catchment area (km^2).

Brice (1982) collected meander migration data for 43 meanders from four different river types (equiwidth, wide bend, braided point-bar, and braided). An equiwidth river is one where the width of the river is approximately constant; these tend to be small rivers. A wide bend river is one where the river width is larger at the meanders. A braided point-bar river is one where the inside of the meanders fills with sand bars and the main channel does not fill the entire width at

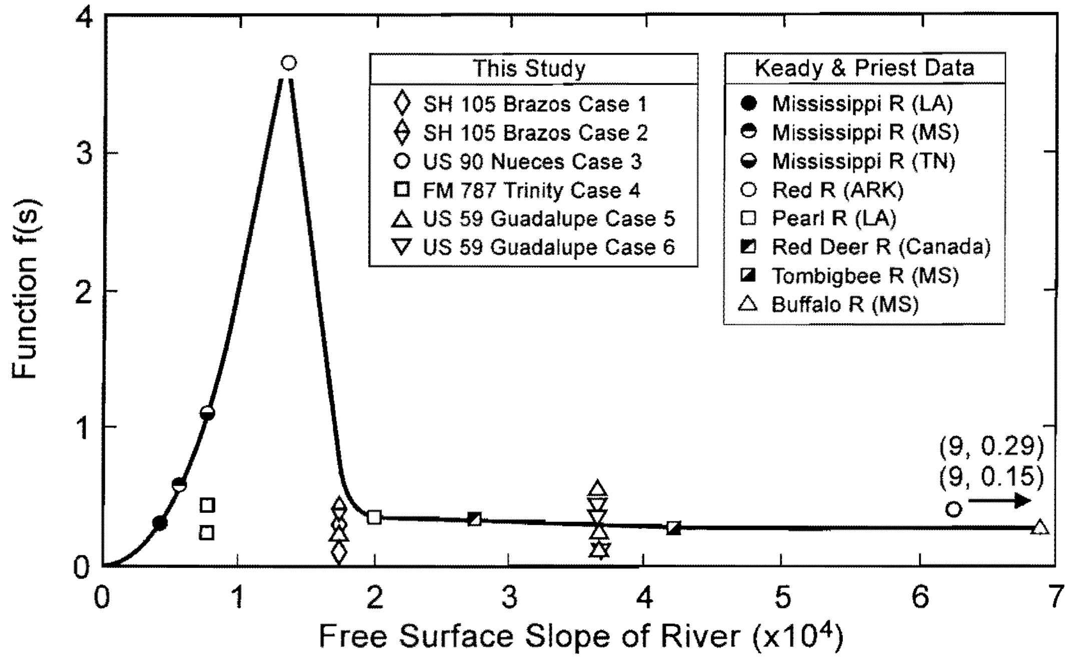


Figure 6. Function for Keady and Priest (1977) Method.

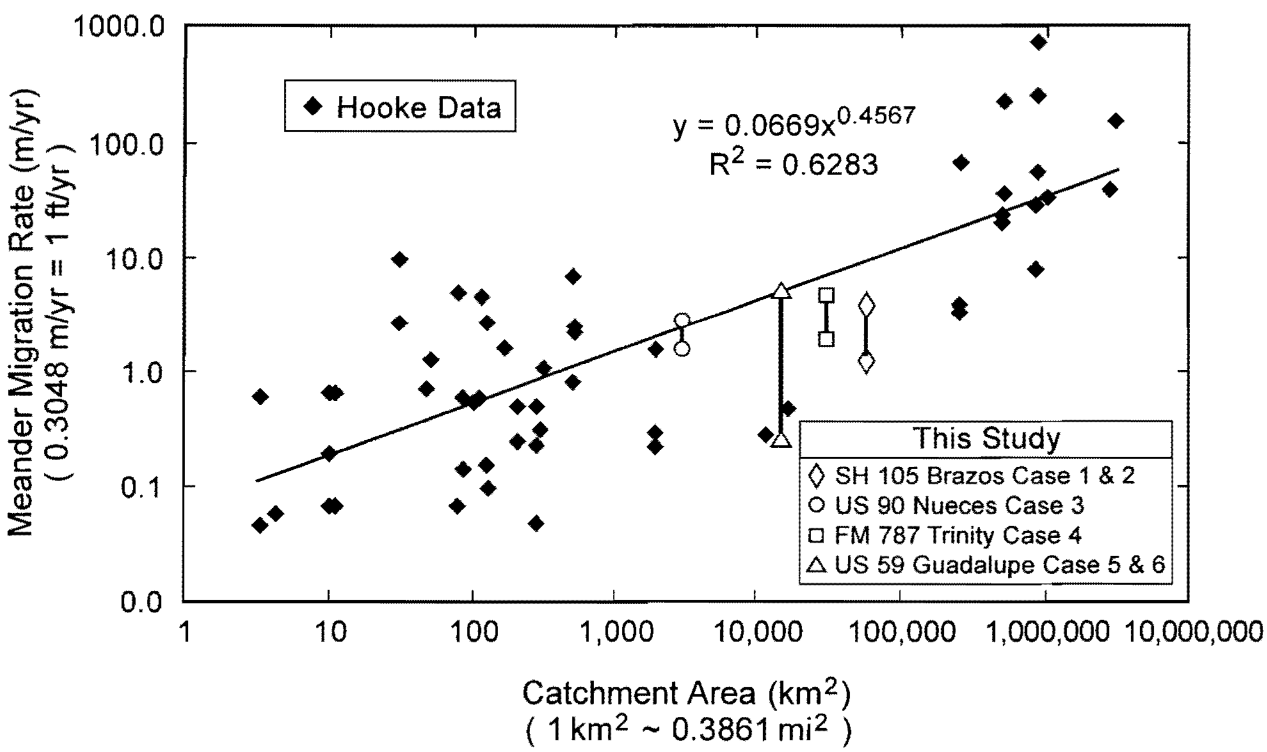


Figure 7. Data Used by Hooke (1980) to Develop His Method.

lower flows. A braided river is one where the main channel develops sinuosity within the larger width of the river; these tend to be very large rivers with high flow fluctuations. Brice selected the channel width, b, as the main influencing parameter and obtained his equation from regression against the 43 data points (Figure 8). Brice's equation is:

$$M_r = 0.01\,b \qquad (5)$$

where M is the meander migration rate (m/yr), and b is the width of the river channel (m). As can be seen on Figure 8, the meanders of braided rivers tend to migrate less than predicted by equation (5) while those of wide bend rivers tend to migrate more than predicted by equation (5).

Nanson and Hickin (1983) collected meander migration data for 18 river channels in Western Canada including the Beaton River. They selected the radius of curvature normalized with respect to the channel width, r_c / b, as the main influencing parameter. Then they plotted their data (Figure 9) and observed that when the ratio r_c / b was between 2 and 3 the migration rate tended to be maximum. They drew two envelopes on their data. The equations of these two lines were found to be:

$$M_r / b = 0.1\,((r_c / b) - 1) \qquad \text{when } r_c / b \text{ is smaller than 2.3} \qquad (6)$$

$$M_r / b = 0.35\,(r_c / b)^{-1} \qquad \text{when } r_c / b \text{ is larger than 2.3} \qquad (7)$$

where M_r is the meander migration rate (m/yr), b is the channel width (m), and r_c is the radius of curvature of the meander (m). As can be seen on Figure 9, these are envelopes that should lead to upper bound predictions. The idea that there is an optimum ratio r_c / b leading to a maximum migration rate, much like a resonance phenomenon, can be explained as follows (Figure 10). At large r_c / b ratios, the radius r_c is large compared to the channel width b and, for a given flow velocity, the centrifugal force which is inversely proportional to the radius of curvature is small; this leads to a small erosion rate. At very small r_c / b ratios, the width of the channel b is large compared to the radius of curvature; the water can actually flow almost straight through the river, and its flow tends to straighten it. When the ratio r_c / b is between 2 and 3, the centrifugal force is significant and the water is forced to follow the outer bank; this leads to the maximum migration rate.

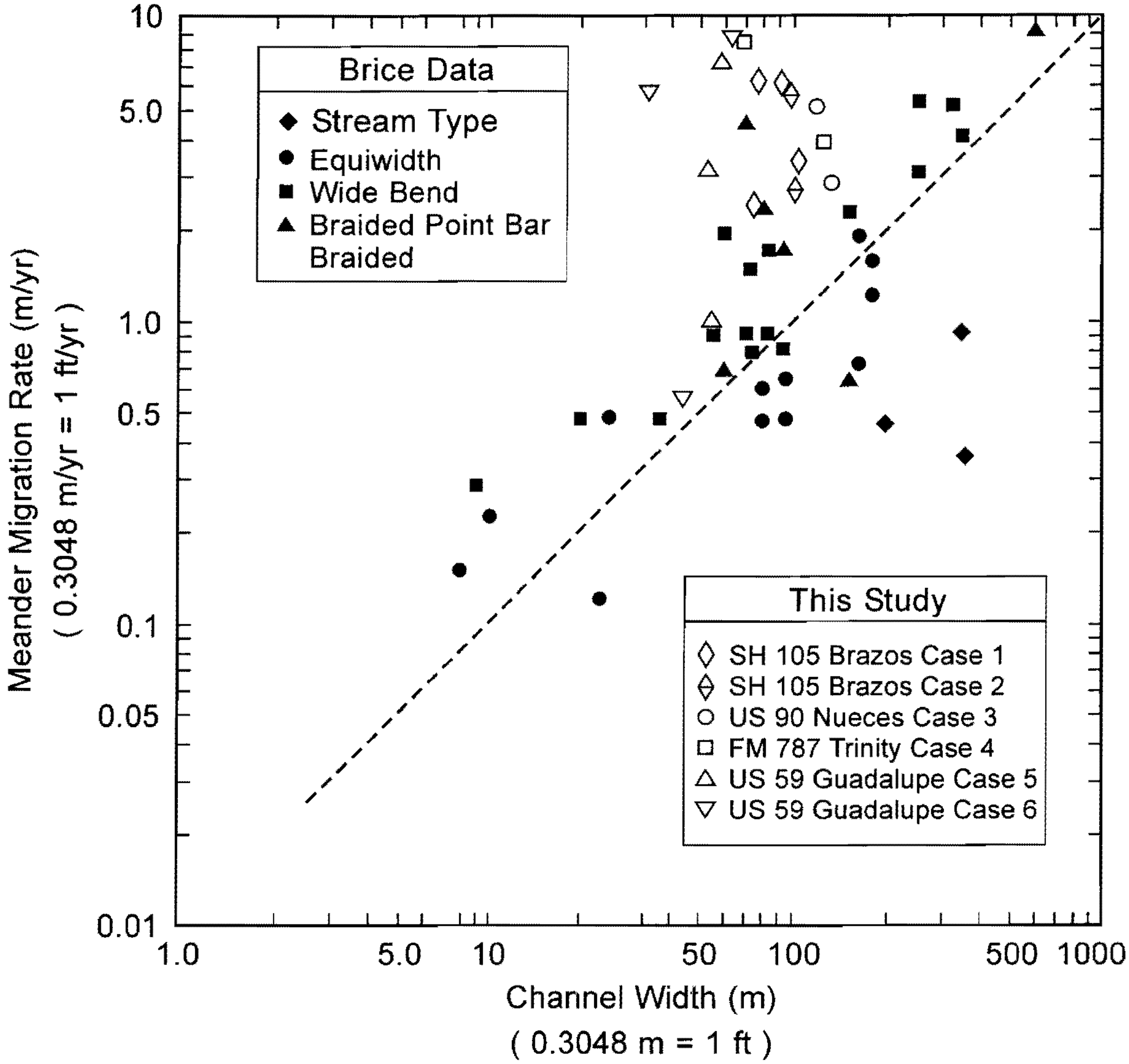


Figure 8. Data Used by Brice (1982) to Develop His Method.

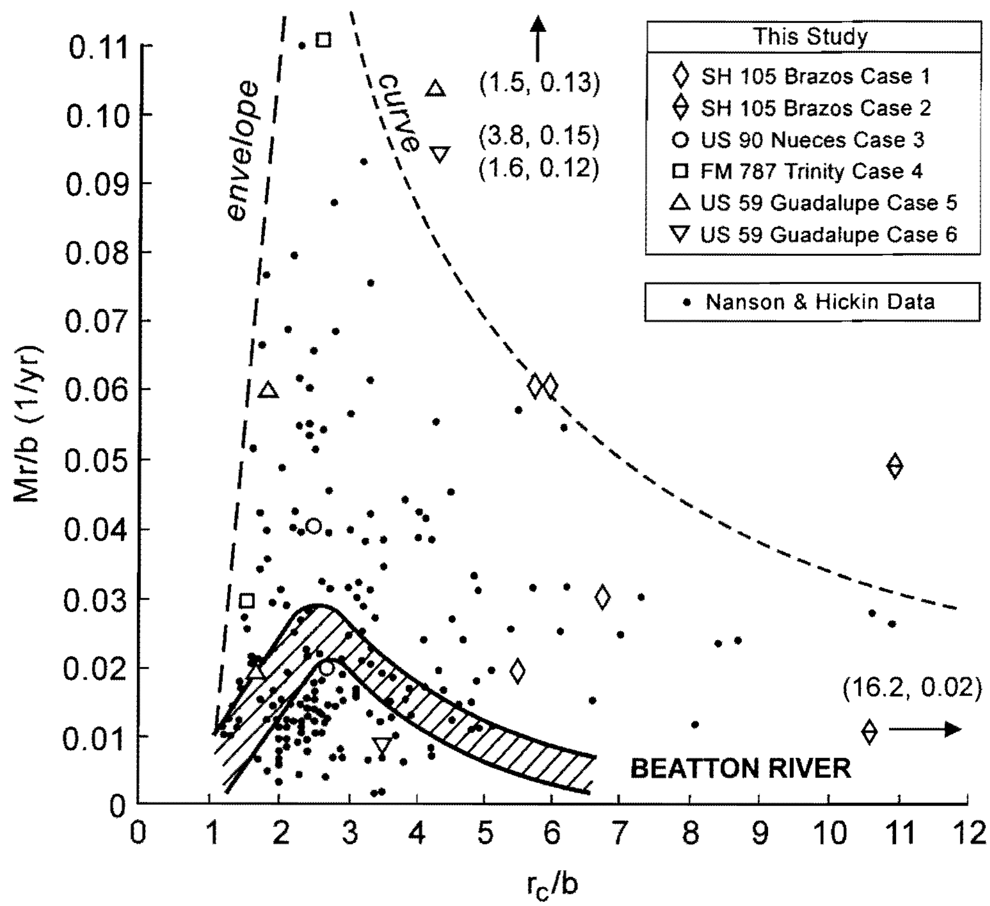


Figure 9. Data Used by Nanson and Hickin (1983) to Develop Their Method.

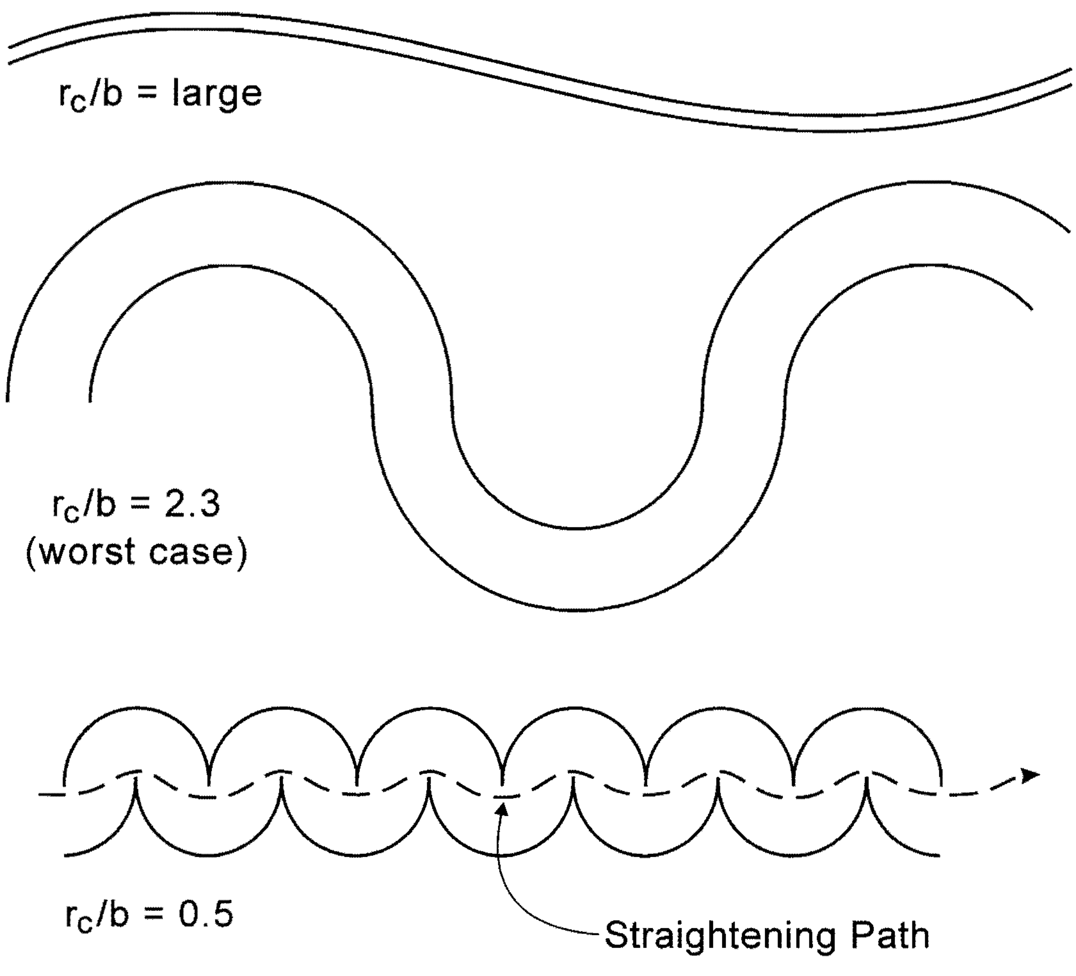


Figure 10. Rivers with Different Relative Radius of Curvature.

6. BRAZOS RIVER AT SH 105: CASE HISTORIES 1 AND 2

The location of these two meander case histories is shown in Figure 11. The site of case history 1 is of concern because the river is getting dangerously close to the embankment of State Highway (SH) 105, which was built in 1951 (Figure 1) and the site of case history 2 is of concern because the Brazos River is getting very close to the Navasota River. Six topographic maps and aerial photographs were collected covering the period from 1910 to 1999. Figure 1 shows the migration problem at location 1 and location 2 on the Brazos River while Figure 12 gives a close-up view of the migration problem at location 1 on Figure 1. Figures 1 and 12 show the migration of the meanders measured along the reference lines. These directions were chosen to represent the direction of concern for the Department of Transportation (DOT). Note that the prediction equations presented earlier do not specify the direction in which the migration takes place. It is understood that these predictions represent the maximum migration rate.

The discharge in the Brazos River over the period of meander migration observation was obtained from the U. S. Geological Survey (USGS) web site (*http://www.usgs.gov*) for the gage station at the bridge site (Gage no. 08109000). The discharge is usually quoted in m^3/s, it is recorded daily and averages can be obtained over chosen periods. Figure 13 shows the variation of the monthly mean discharge Q (m^3/s) for the period from 1910 to 2000. Note that no data were collected from 1910 to 1918. The catchment area at the gage site is 77567 km^2 (29948.8 mi^2) according to the USGS web site. The free surface slope of the river was obtained by using the elevation of two consecutive gage stations near the meander site (read at *http://www.usgs.gov*) and dividing the elevation difference by the distance between the two gages read on the topographic map. The value obtained was 0.00018. The discharge history, the catchment area, and the free surface slope are some of the parameters quantifying the water influence on meander migration.

The prediction methods also require parameters quantifying the influence of the geometry of the meander. These parameters include the width of the channel, the radius of curvature of the meander, and the amplitude of the meander (Figure 2). Each one of the topographic maps and aerial photographs shows the measurements of the channel width. Table 1 lists the values obtained, which averaged 103 m (338 ft) for case 1. The radius of curvature was considered to be the radius of the circle that best fit the mid–stream shape of the meander. This was done by manual trial and error using a compass for each date (Figure 1). Table 1 lists the values obtained, which averaged 564 m (1850 ft) for case 1. The meander amplitude was obtained by using the meander considered and the adjacent one, and applying the definition of Figure 2. The values obtained are listed in Table 1 and averaged 206 m (675 ft) for case 1. The process followed to determine these geometric factors involves a certain amount of subjectivity; therefore, the measurements may vary somewhat from one person to another. Table 1 summarizes the measurements for these case histories.

As mentioned earlier, it is reasonable to assume that the best prediction methods for meander migration require the knowledge of geometric factors, water factors, and soil factors. Unfortunately in these case histories, no detailed soil data were available, nor were any soil data required in the prediction equations. Progress in this direction needs to be made.

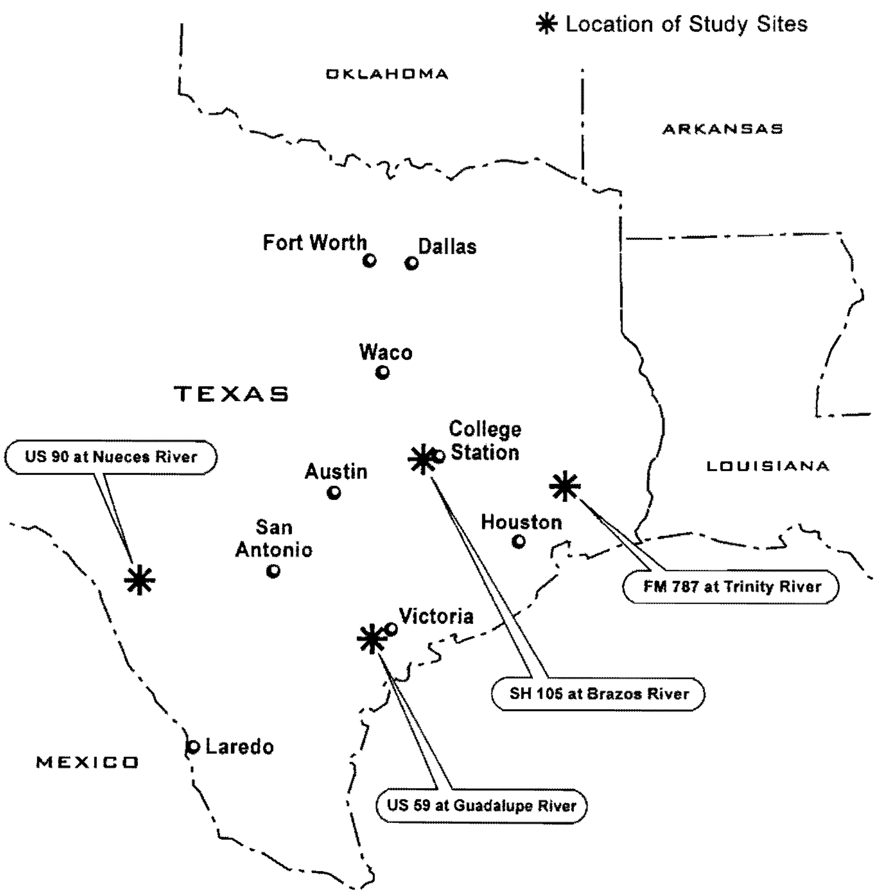


Figure 11. Map Showing the Location of the Case Histories.

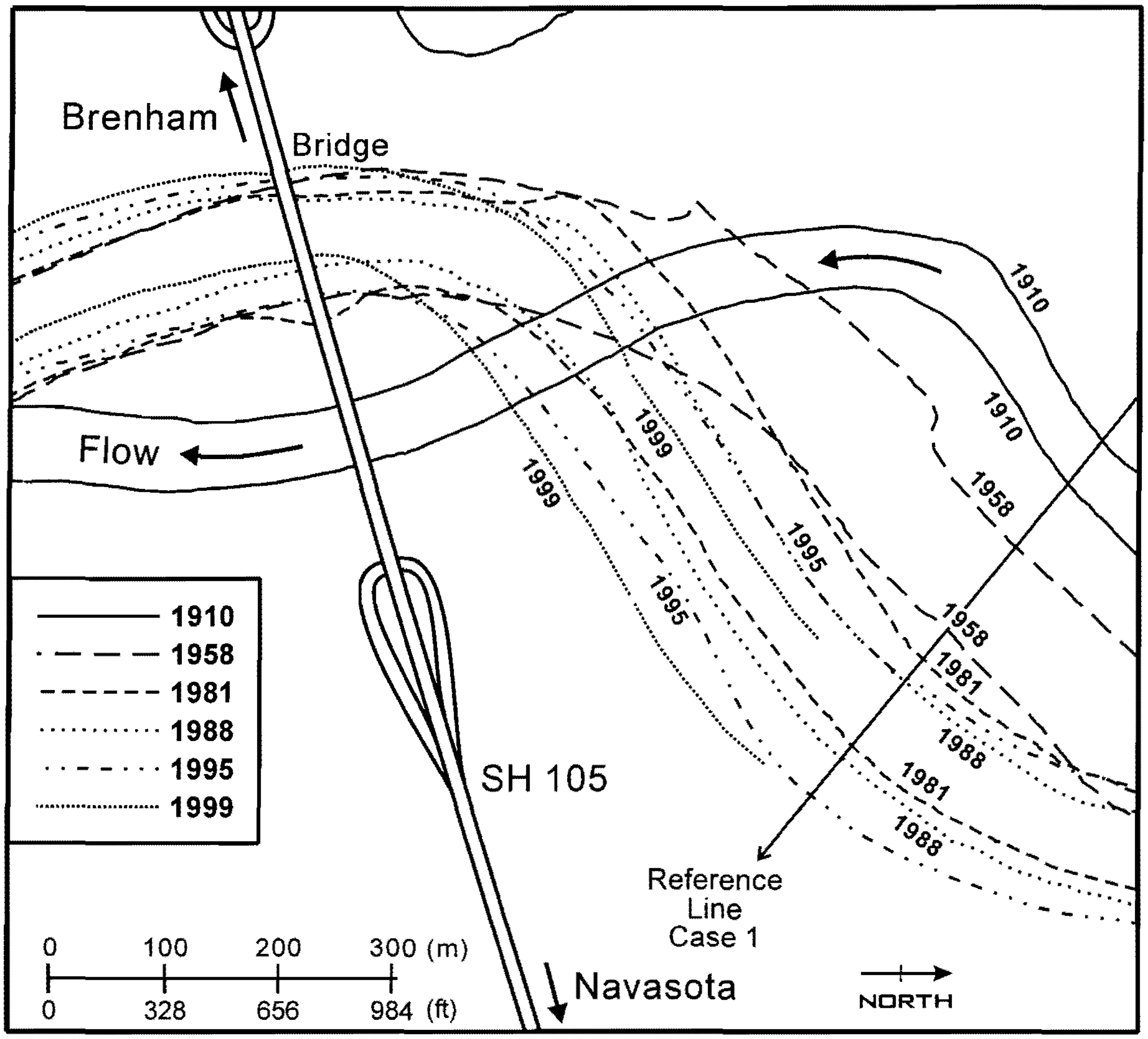


Figure 12. Close up of the Meander Migration for the Brazos River at SH 105.

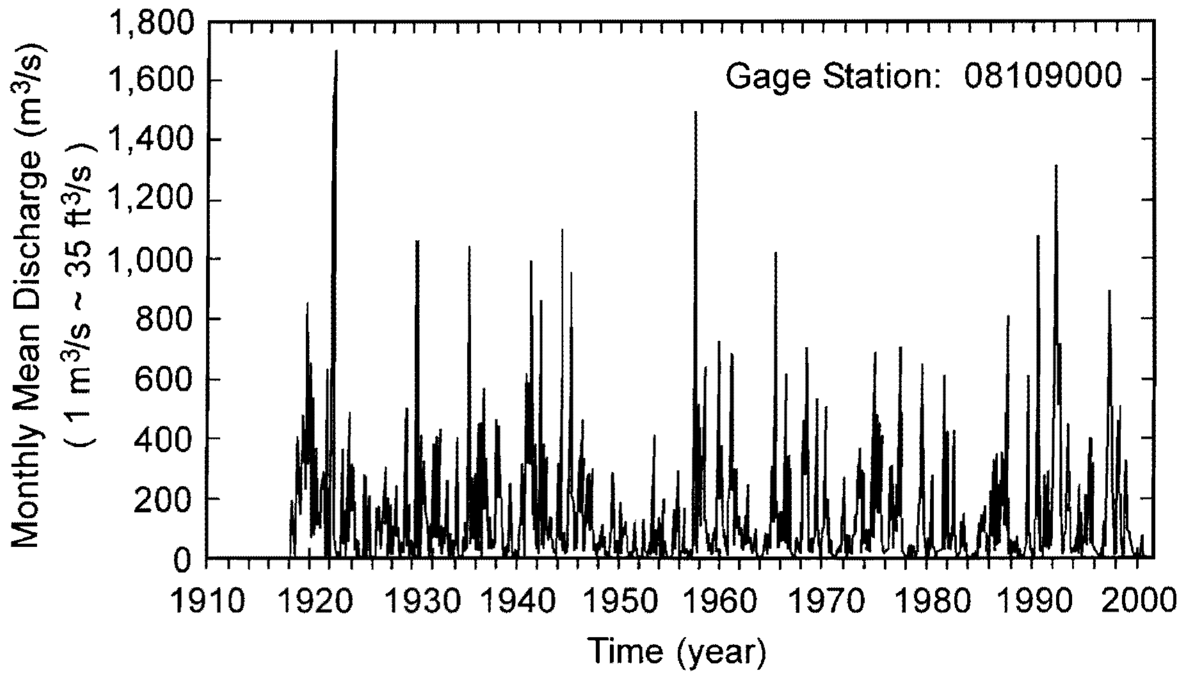


Figure 13. Mean Monthly Discharge versus Time for the Brazos River at SH 105.

Table 1. Summary of Case History Data.

Case History	Year	Channel Width b(m)	Radius of Curvature r_c(m)	Ratio r_c/b	Meander Amplitude a(m)	Free Surface Slope s (mm)	Catchment Area A (km^2)
Brazos at SH 105 (Case 1)	1910	109	747	6.9	120	0.00018	77567
	1958	98	600	6.1	187	0.00018	77567
	1981	84	453	5.4	220	0.00018	77567
	1988	89	558	6.3	244	0.00018	77567
	1995	133	460	3.5	258	0.00018	77567
Brazos at SH 105 (Case 2)	1910	107	1733	16.2	120	0.00018	77567
	1958	107	1173	11.0	187	0.00018	77567
	1981	120	746	6.2	220	0.00018	77567
Nueces at US 90 (Case 3)	1958	134	365	2.7	261	0.0009	4820
	1969	122	300	2.5	248	0.0009	4820
	1995	70	391	5.6	274	0.0009	4820
Trinity at FM 787 (Case 4)	1971	125	182	1.5	254	0.00008	44512
	1976	73	182	2.5	259	0.00008	44512
	1983	112	??	1.5	191?	0.00008	44512
	1988	132	201	1.5	207	0.00008	44512
	1999	155	276	1.8	201	0.00008	44512
Guadalupe at US 59 (Case 5)	1959	50	88	1.8	187	0.00037	13468
	1981	58	88	1.5	183	0.00037	13468
	1988	54	100	1.9	204	0.00037	13468
	1995	92	125	1.4	204	0.00037	13468
Guadalupe at US 59 (Case 6)	1959	42	137	3.3	475	0.00037	13468
	1981	33	125	3.8	475	0.00037	13468
	1988	67	108	1.6	483	0.00037	13468
	1995	75	104	1.4	516	0.00037	13468

? doubt in the data
?? no data

0.3048 m = 1 ft
25.4 mm = 1 inch
1 km^2 ~ 0.3861 mi^2

7. OTHER CASE HISTORIES

The third case history is the case of the Nueces River near US 90 which was built in 1967. In 1998 a flood nearly destroyed the right abutment of the bridge, therefore causing concern for the site. Three topographic maps and aerial photographs could be found covering the period from 1958 to 1995. Figure 4 shows the migration of the meander upstream of the bridge; the migration movements were measured along the reference line shown on Figure 4. The discharge in the Nueces River was obtained from USGS gage station no. 08192000 which is approximately 13 km (8.1 miles) downstream from the meander site. The catchment area of the gaging site was used and not that of the meander site. Figure 14 shows the variation of the monthly discharge from 1958 to 2000. Table 1 shows the other parameters for this case history.

The fourth meander case history is the case of the Trinity River near FM 787 which was built in 1975 (Figure 15). The site of this meander is of concern because the meander is migrating dangerously close to the FM 787 embankment. Three topographic and aerial photographs were found covering the period 1971 to 1999. Figure 15 shows the migration of the meander upstream of the bridge; the migration movements were measured along the reference line shown. The discharge in the Trinity River was obtained from USGS gage station no. 08066500, which is at the bridge site. Figure 16 shows the variation of the monthly mean discharge from 1970 to 1999. Table 1 shows the other parameters for this case history.

The fifth and sixth meander case histories are located on the Guadalupe River near US 59 which was built in 1967. The site is of concern because the meander upstream from the bridge is attacking the left abutment and the meander downstream from the bridge may lead to a cut-off. Such a cut-off would increase the slope of the river locally and impact the migration rate of the upstream meander. Four topographic maps and aerial photographs were found covering the period 1959–1995. Figure 5 shows the migration of the two meanders; the migration movements were measured along the reference lines shown. The discharge in the Guadalupe River was obtained from USGS gage station no. 08176500 which is approximately 4 km (2.5 miles) upstream from the meander site. The catchment area of the gaging site was used and not that of the meander sites. Figure 17 shows the variation of the monthly mean discharge from 1959-1999. Table 1 shows the other parameters for these two case histories.

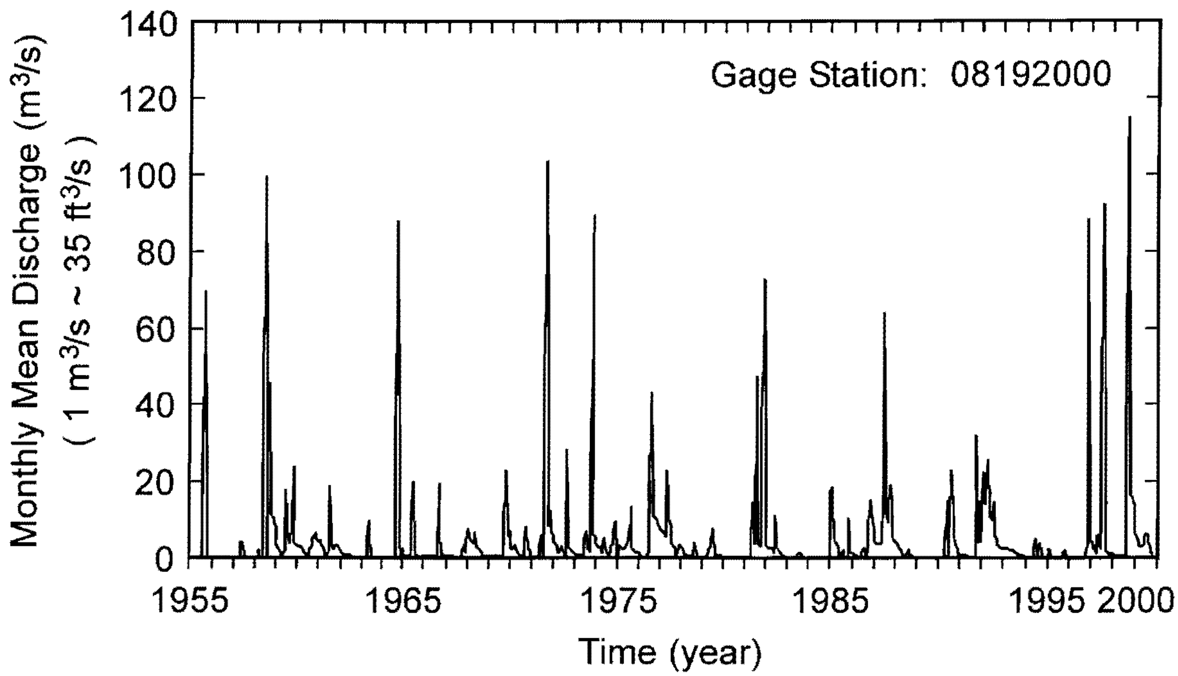


Figure 14. Mean Monthly Discharge versus Time for the Nueces River at US 90.

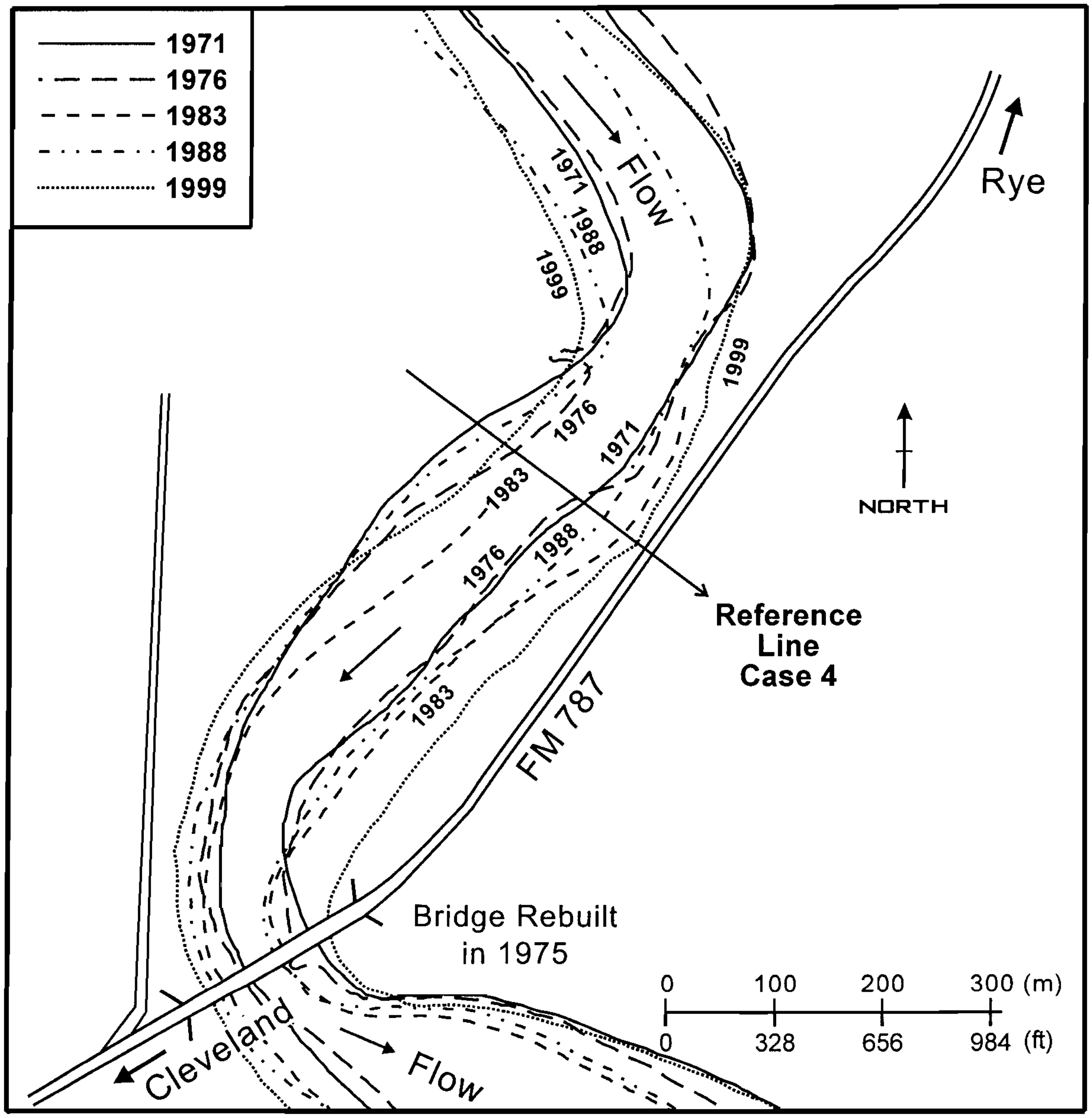


Figure 15. Meander Migration for the Trinity River at FM 787.

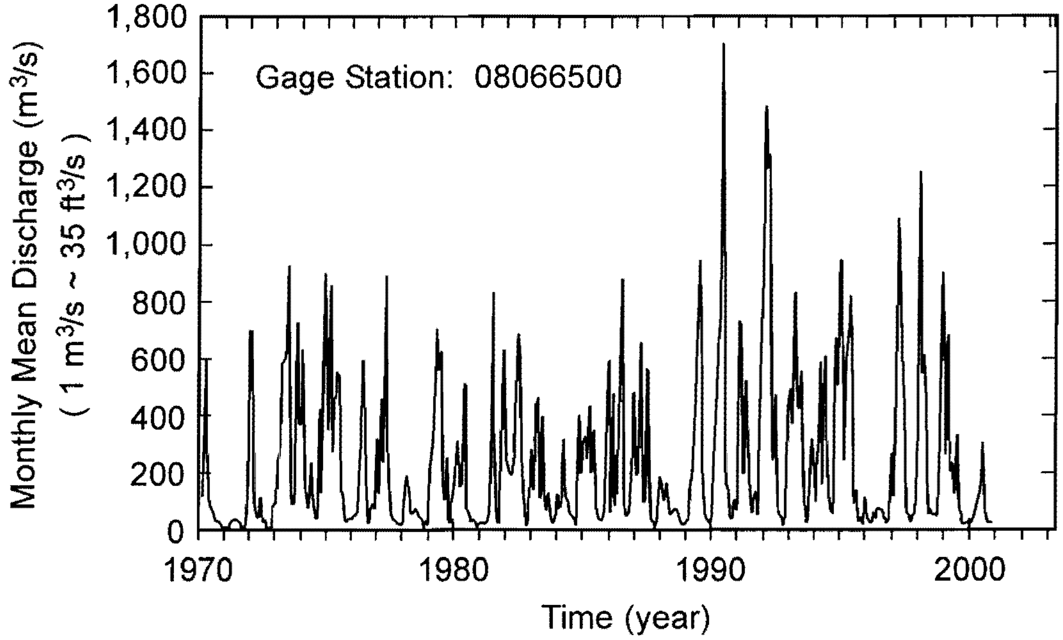


Figure 16. Mean Monthly Discharge versus Time for the Trinity River at FM 787.

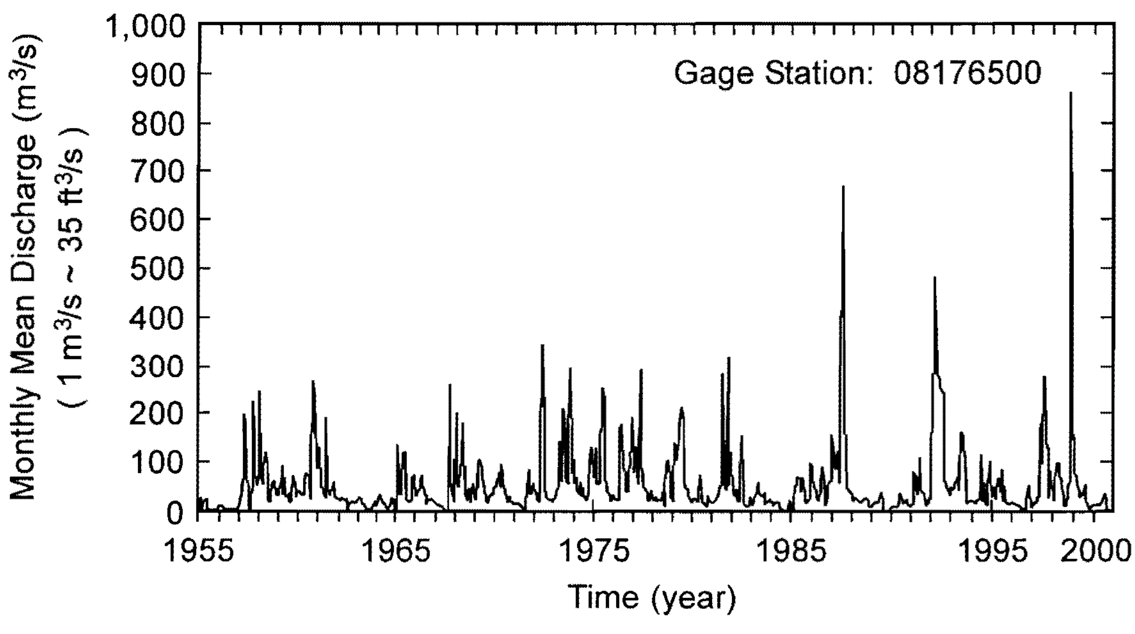


Figure 17. Mean Monthly Discharge versus Time for the Guadalupe River at US 59.

8. PREDICTED vs. MEASURED MEANDER MIGRATION

In order to evaluate the accuracy and precision of the empirical methods, equations 3 through 7 were used together with the data of Table 1 to obtain the predicted migration rates of Table 2. Table 2 also shows the measured migration rates for the case histories. Note that some of the migration rates for the Trinity River are negative, indicating that the meander moved back towards earlier positions. This is due to the fact that countermeasures were installed on the Trinity River during those periods of time and were successful in reversing the migrating process. Such cases were removed from the comparisons. Migration rate predictions and measurements were made for each period of observation leading to a total of 18 comparisons in Table 2 minus the four values of the Trinity River deemed influenced by countermeasures. For each prediction, the parameter value (a, b, and r_c) corresponding to the beginning of the period was used in the equation.

Figure 18 presents the comparisons. As can be seen, the Keady and Priest method is reasonably conservative, the Hooke method seems overly conservative, the Brice method is seriously underpredicting the measurements, and the Nanson and Hickin method splits the measured data. On the basis of this data alone, the Keady and Priest method appears to be a reasonably safe method to use keeping in mind that the scatter is significant.

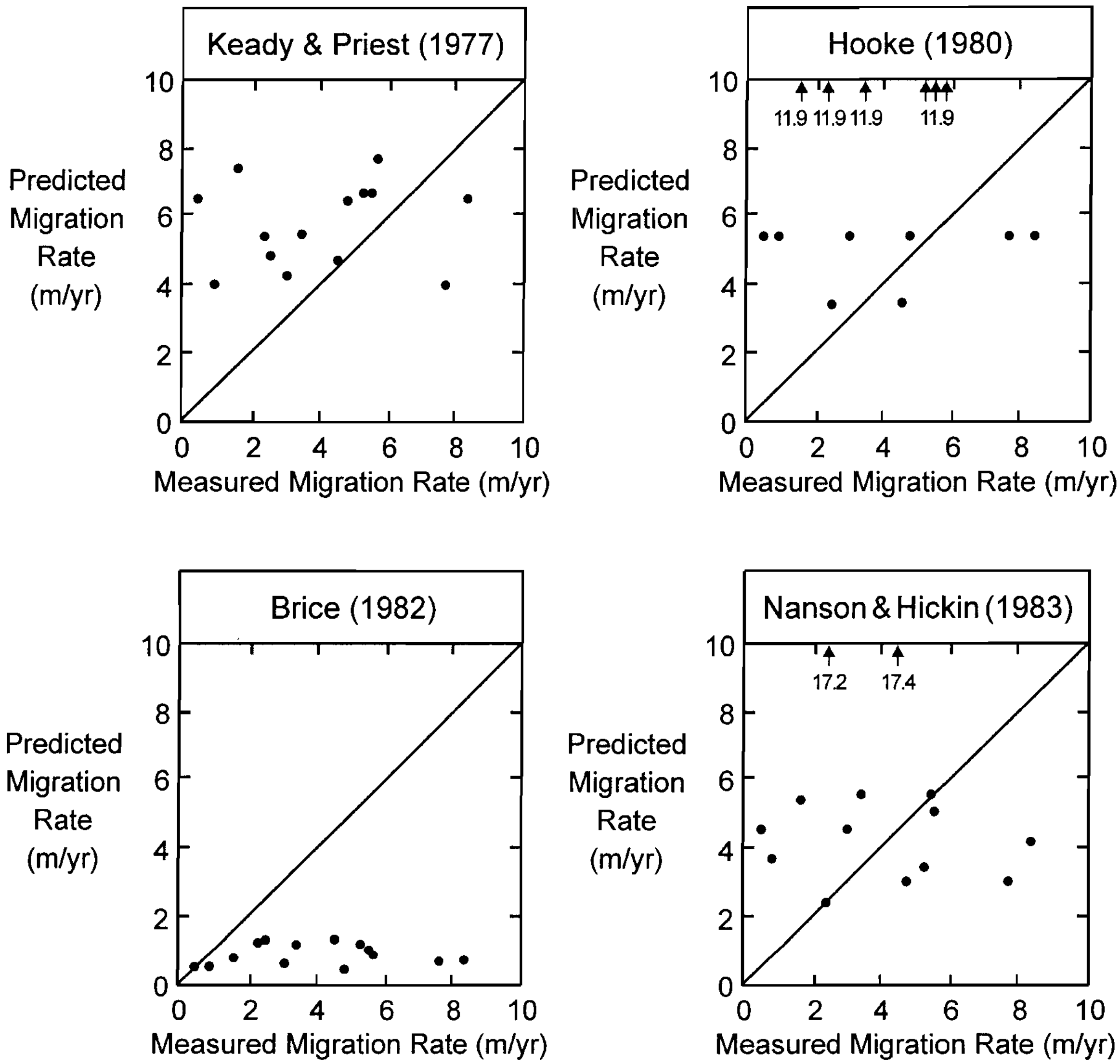
In order to evaluate the accuracy and the precision of the time-sequence and extrapolation method, the following process was used. For a given date t_1, the best-fit circle was found by trial and error; the center location C_1 and the radius R_1 were recorded (Figure 3). For the next available date t_2, the best-fit circle was also found; again, the center location C_2 and the radius R_2 were recorded. Using R_1, R_2, t_1, and t_2, the radius R'_3 of the best-fit circle for the meander at the next available date t_3 was predicted using equation 2. The predicted value R'_3 could then be compared to the measured value R_3 obtained from the best-fit circle corresponding to the actual meander shape at the date t_3. The migration rate of the center of the best-fit circle $M_{r(1-2)}$ between the dates t_1 and t_2 was calculated. The time sequence maps and extrapolation method consists of assuming that the migration rate $M_{r(2-3)}$ of the center between the dates t_2 and t_3 is the same as $M_{r(1-2)}$; this is stated in equation 2. Therefore comparing the predicted value $M'_{r(2-3)}$ of the measured value $M_{r(2-3)}$ is the same as comparing the measured values of $M_{r(1-2)}$ and $M_{r(2-3)}$.

Table 2. Predicted and Measured Meander Migration Rates (Empirical Methods).

Case History	Period	Keady & Priest (1977) m/yr	Hooke (1980) m/yr	Brice (1982) m/yr	Nanson & Hickin (1983) m/yr	Measured m/yr
Brazos at SH 105 (Case 1)	1910 - 1958	5.4	11.9	1.1	5.6	3.4
	1958 - 1981	6.7	11.9	1.0	5.6	5.5
	1981 - 1988	7.3	11.9	0.8	5.4	1.6
	1988 - 1995	7.7	11.9	0.9	5.0	5.6
	1995- 1999	7.9	11.9	1.3	13.4	??
Brazos at SH 105 (Case 2)	1910 - 1958	5.4	11.9	1.1	2.3	2.2
	1958 - 1981	6.7	11.9	1.1	3.4	5.2
	1981 - 1988	7.3	11.9	1.2	6.7	??
Nueces at US 90 (Case 3)	1958 - 1969	4.8	3.3	1.3	17.2	2.4
	1969 - 1995	4.7	3.3	1.2	17.4	4.5
Trinity at FM 787 (Case 4)	1971 - 1976	22.0	9.2	1.2	5.7	-1.3
	1976 - 1983	22.2	9.2	0.7	10.2	8.0
	1983 - 1988	19.1?	9.2	1.1	??	-4.9
	1988 - 1999	19.9	9.2	1.3	6.9	3.6
Guadalupe at US 59 (Case 5)	1959 - 1981	4.0	5.3	0.5	3.8	0.95
	1981 - 1988	4.0	5.3	0.6	3.0	7.7
	1988 - 1995	4.2	5.3	0.5	4.6	3.0
Guadalupe at US 59 (Case 6)	1959 - 1981	6.4	5.3	0.4	4.5	0.4
	1981 - 1988	6.4	5.3	0.3	3.0	4.8
	1988 - 1995	6.5	5.3	0.7	4.1	8.3

? doubt in the data   0.3048 m = 1 ft

?? no data



(0.3048 m/yr = 1 ft/yr)

Figure 18. Predicted versus Measured Migration Rates for the Empirical Methods .

Tables 3 and 4 and Figure 18 show the measured and predicted values of the radius and of the center of migration rates. Tables 3 and 4 indicate 10 comparisons; however, the Trinity River case was not used because it was influenced by countermeasures.

Figure 19 presents comparisons. As can be seen, the time-sequence maps and extrapolation method gives a reasonably satisfactory prediction of the radius of the meander but not of the center migration rate. Note that in some cases (Brazos River, Table 4, 1981-1988, and 1988-1995) the predicted movement of the center of the circle is in opposite direction to the measured movement. As pointed out earlier, this method is much more operator dependent than the empirical methods; however, it is superior to the empirical method in that it gives a much more complete position of the meander.

Table 1 shows a column of the values of the ratio r_c / b. Inspection of this column of r_c / b values indicates that if the initial ratio is high, the meander tends to evolve by decreasing its r_c / b ratio towards a value around 2, which corresponds to the highest migration rate shown by Nanson and Hickin on Figure 9. If the initial value of r_c / b is about 2, the value remains about equal to 2 and the meander migrates at its highest migration rate.

Table 3. Predicted and Measured Radius for the Best-Fit Meander Circle (Time Sequence Maps and Extrapolation Method).

Case History	Year	Radius (measured) (m)	Radius (measured) (ft)	Radius (predicted) (m)	Radius (predicted) (ft)
Brazos at SH 105 (Case 1)	1910	747	2451		
	1958	600	1969		
	1981	453	1486	530	1739
	1988	558	1831	408	1339
	1995	460	1509	663	2175
Brazos at SH 105 (Case 2)	1910	1733	5686		
	1958	1173	3848		
	1981	746	2448	905	2969
Nueces at US 90 (Case 3)	1958	365	1198		
	1969	300	984		
	1995	391	1283	146	479
Trinity at FM 787 (Case 4)	1971	182	597		
	1976	182	597		
	1983	??	??	182	597
	1988	201	659		
	1999	276	906		
Guadalupe at US 59 (Case 5)	1959	88	289		
	1981	88	289		
	1988	100	328	88	289
	1995	125	410	119	390
Guadalupe at US 59 (Case 6)	1959	137	449		
	1981	125	410		
	1988	108	354	121	397
	1995	104	341	91	299

Table 4. Predicted and Measured Movement Rate for the Center of the Best-Fit Circle (Time Sequence Maps and Extrapolation Method).

Case History	Period (yr)	Center Migration Rate (measured) (m/yr)	Center Migration Rate (measured) (ft/yr)	Center Migration Rate (predicted) (m/yr)	Center Migration Rate (predicted) (ft/yr)
Brazos at SH 105 (Case 1)	1910 – 1958 1958 – 1981 1981 – 1988 1988 – 1995	6.7 12.2 (-)19.0 19.0	22 40 (-)62 62	6.7 12.2 (-)19.0	22 40 (-)62
Brazos at SH 105 (Case 2)	1910 – 1958 1958 – 1981	15 22	49 72	15	49
Nueces at US 90 (Case 3)	1958 – 1969 1969 – 1995	5 2.8	16 9	5	16
Trinity at FM 787 (Case 4)	1971 – 1988 1988 – 1999	3.2 6.7	10 22	3.2	10
Guadalupe at US 59 (Case 5)	1959 – 1981 1981 – 1988 1988 – 1995	1.0 14 7.1	3 46 23	1 14	3 46
Guadalupe at US 59 (Case 6)	1959 – 1981 1981 – 1988 1988 – 1995	0.4 4.8 4.3	1 16 14	0.4 4.8	1 16

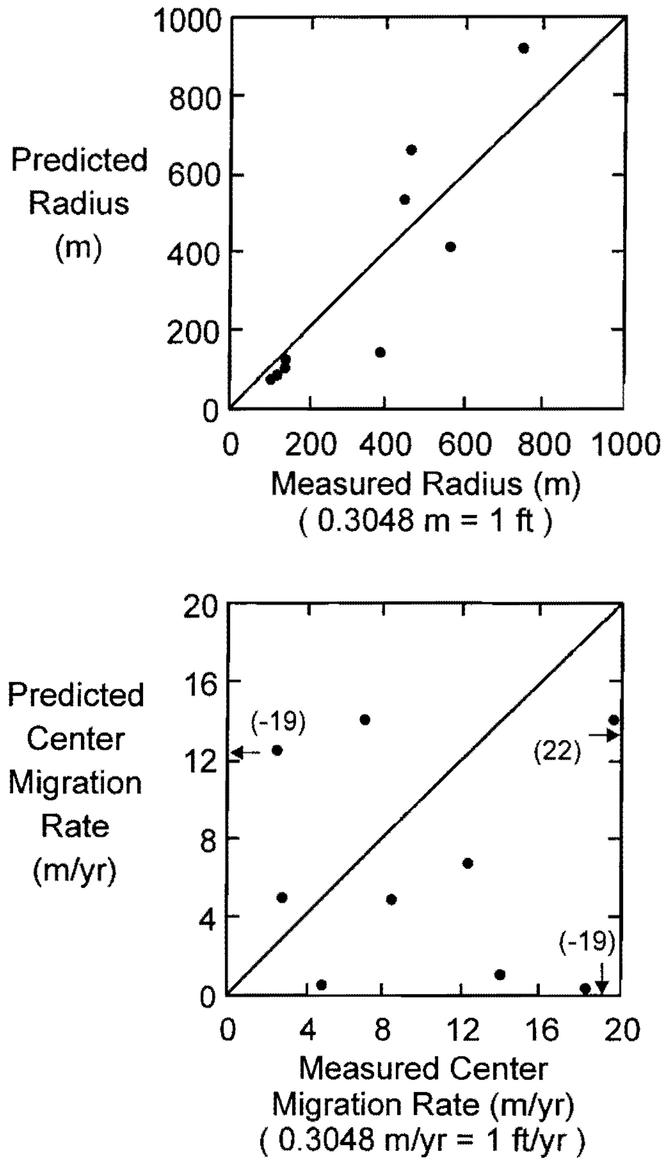


Figure 19. Predicted versus Measured Migration Parameters for the Time-Sequence Maps and Extrapolation Method.

9. CONCLUSIONS

Meander migration can be predicted using one of three types of approaches: time sequence extrapolation, empirical equations, and fundamental modeling. This report describes the time-sequence and extrapolation approach and four empirical equations used to predict meander migration rates: Keady and Priest (1977), Hooke (1980), Brice (1982), and Nanson and Hickin (1983). Then four case histories of meander migration are presented, including maps indicating the movement over long periods of time and the flow history over that same period. Predictions are made according to the methods presented and compared to the measurements from the case histories.

For the empirical methods, the comparisons indicate that the Keady and Priest method is reasonably conservative, that the Hooke method is overly conservative, that the Brice method is seriously underpredicting the measurements, and that the Nanson and Hickin method splits the measured data with significant scatter. On the basis of these data alone, the Keady and Priest method appears to be a reasonably safe method to use keeping in mind that the scatter is significant.

For the time-sequence and extrapolation method, the comparisons indicate that this method gives a reasonably satisfactory prediction of the radius of the meander but not of the center migration rate. In some cases, the predicted movement of the center of the circle is in opposite direction to the measured movement. This method is much more operator dependent than the empirical methods; however, it is superior to the empirical method in that it gives a much more complete position of the meander.

10. REFERENCES

1. Briaud J.-L., Chen H.-C., Edge W., Park S., and Shaw A., 2001, "Guidelines for Bridges Over Degrading and Migrating Streams; Part 1: Synthesis of Existing Knowledge," Texas Transportation Institute Report No. 2105-1 for the Texas Department of Transportation, The Texas A&M University System, College Station, Texas, USA, pp. #174.
2. Brice J.C., 1982, "Stream Channel Stability Assessment," Report No. FHWA/RD-82/021, Federal Highway Administration, Washington, DC, USA, p. #41.
3. Hooke J.M., 1980, "Magnitude and Distribution of Rates of River Bank Erosion," Earth Surface Processes, Vol. 5, No. 2, pp. #363-377.
4. Keady P.D., and Priest M.S., 1977, "The Downstream Migration Rate of River Meandering Patterns," Proceedings, 12th Mississippi Water Resources Conference, Jackson, Mississippi, USA, pp. #29-34.
5. Lagasse P., 2001, Personal Communication, Ayres Associates, 3665 JFK Parkway, Bldg 2, Ste. 200, Fort Collins, Colorado, USA 80527.
6. Nanson G.C., and Hickin E.J., 1983, "Channel Migration and Incision on the Beatton River," Journal of Hydraulic Engineering, Vol. 117, No. 7, (Discussion and Closure), ASCE, Reston, Virginia, USA, pp. #942-946.