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Predicting Meander Migration: Evaluation of Some Existing Techniques

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ABSTRACT

River meanders migrate over time; this migration endangers civil engineering structures in general and highways bridges in particular. Predicting and preventing this migration is part of the responsibility of the hydraulic engineer and of the geotechnical engineer working together. 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 data bases 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, none of them are very accurate or precise. The time sequence method gives more information on the meander movement, is relatively precise and accurate to predict the radius of the best-fit circle of the future meander location, but is not precise to predict the migration rate of the center of that circle.

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 article gives details about two of them. Then, six meander migration case histories related to four rivers are presented including the measured movements. Finally, the measured movements are compared with the movements predicted by the two approaches and conclusions are drawn.

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 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 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 or 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.

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 in 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 that it 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. This method is commonly used by Departments of Transportation.

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 that it 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.

TIME-SEQUENCE MAPS AND EXTRAPOLATION METHOD

In this article the time-sequence maps and extrapolation method is 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. In a first step, a map of the meander is obtained 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 (Figure 3). 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. The location of the center, C_2 , and the radius R_2 of that second circle are recorded (Figure 3). 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 $M_{r(1-2)}$. This rate, which is the mean rate from t_1 to t_2 is assumed to be the same as the rate $M_{r(2-3)}$ 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:

$$C'_3C_2 = (t_3 - t_2) \times M_{r(1-2)} \quad (1)$$

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 .

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

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 vs. measured comparisons.

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:

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

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. For this article, both sets of data were merged and a single regression was derived (Figure 7). This is why the equation is called Hooke's modified equation:

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

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 in 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 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 equation is:

$$M_r = 0.01 b \quad (5)$$

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:

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

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

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.

BRAZOS RIVER AT SH 105: CASE HISTORIES 1 AND 2

The location of these two meander case histories is shown on Figure 11. The site of case history 1 is of concern because the river is getting dangerously close to the embankment of State Highway 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. The migration of the meanders was measured along the reference lines that are shown on Figures 1 and 12. These directions were chosen to represent the direction of concern for the 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 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. The variation of the monthly mean discharge Q (m^3/s) is shown in Figure 13 for the period from 1910 to 2000. Note that no data was collected from 1910 to 1918. The catchment area at the gage site is 77567 km^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). The width of the channel was measured on each one of the topographic maps and aerial photographs. The values obtained are listed in Table 1 and averaged 103 m for case 1. The radius of curvature was considered to be the radius of the circle that best fitted the mid stream shape of the meander. This was done by manual trial and error using a compass for each date (Figure 1). The values obtained are listed in Table 1 and averaged 564 m 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 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. The measurements for these case histories are summarized in Table 1.

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 was available nor is any soil data required in the prediction equations. Progress in this direction needs to be made.

OTHER CASE HISTORIES

The third case history is the case of the Nueces River near US 90 which was built in 1967. The site was of concern because in 1998 a flood nearly destroyed the right abutment of the bridge. 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 xx km from the meander site. The variation of the monthly discharge is shown in Figure 14 from 1958 to 2000. The other parameters for this case history are shown in Table 1.

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 on Figure 15. The discharge in the Trinity River was obtained from USGS gage station no. 08066500, which is at the bridge site. The variation of the monthly mean discharge is shown in Figure 16 from 1970 to 1999. The other parameters for this case history are shown in Table 1.

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 on Figure 5. The discharge in the Guadalupe River was obtained from USGS gage station no. 08176500 which is xx km from the meander site. The variation of the monthly mean discharge is shown in Figure 17 from 1959-1999. The other parameters for these two case histories are shown in Table 1.

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. Also shown in Table 2 are 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 4 values of the Trinity River deemed influenced by countermeasures. For each prediction, the parameter value (a , b , r_c) corresponding to the beginning of the period was used in the equation.

The comparisons are presented in Figure 18. 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 $M_{r(2-3)}$. Measured and predicted values of the radius and of the center of migration rates are shown in tables 3 and 4 and in Figure 18. Table 3 and 4 indicate 10 comparisons, however the Trinity River case was not used because it was influenced by countermeasures.

The comparisons are presented in Figure 19. 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.

CONCLUSIONS

Meander migration can be predicted using one of three types of approaches: time-sequence extrapolation, empirical equations, and fundamental modeling. This article 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), 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 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.

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.

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REFERENCES

1. Briaud J.-L., Chen H.-C., Edge W., Park S., 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 Dpt. of Transportation, 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.143-157, John Wiley, Chichester, NY.
4. Keady P.D., 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, CO, 80527.
6. Nanson G.C., 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.

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 SH105 (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 SH105 (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 US90 (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 FM787 (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 US59 (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 US59 (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

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 SH105 (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 SH105 (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 US90 (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 FM787 (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 US59 (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 US59 (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, ?? no data

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 (predicted) (m)
Brazos at SH105 (Case 1)	1910	747	
	1958	600	
	1981	453	530
	1988	558	408
	1995	460	663
Brazos at SH105 (Case 2)	1910	1733	
	1958	1173	
	1981	746	905
Nueces at US90 (Case 3)	1958	365	
	1969	300	
	1995	391	146
Trinity at FM787 (Case 4)	1971	182	
	1976	182	
	1983	??	182
	1988	201	
	1999	276	
Guadalupe at US59 (Case 5)	1959	88	
	1981	88	
	1988	100	88
	1995	125	119
Guadalupe at US59 (Case 6)	1959	137	
	1981	125	
	1988	108	121
	1995	104	91

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 (predicted) (m/yr)
Brazos at SH105 (Case 1)	1910 - 1958		
	1958 - 1981	6.7	6.7
	1981 - 1988	(-)19.0	12.2
	1988 - 1995	19.0	(-)19.0
Brazos at SH105 (Case 2)	1910 - 1958	15	
	1958 - 1981	22	15
Nueces at US90 (Case 3)	1958 - 1969	5	
	1969 - 1995	2.8	5
Trinity at FM787 (Case 4)	1971 - 1988	3.2	
	1988 - 1999	6.7	3.2
Guadalupe at US59 (Case 5)	1959 - 1981	1.0	
	1981 - 1988	14	1
	1988 - 1995	7.1	14
Guadalupe at US59 (Case 6)	1959 - 1981	0.4	
	1981 - 1988	4.8	0.4
	1988 - 1995	4.3	4.8

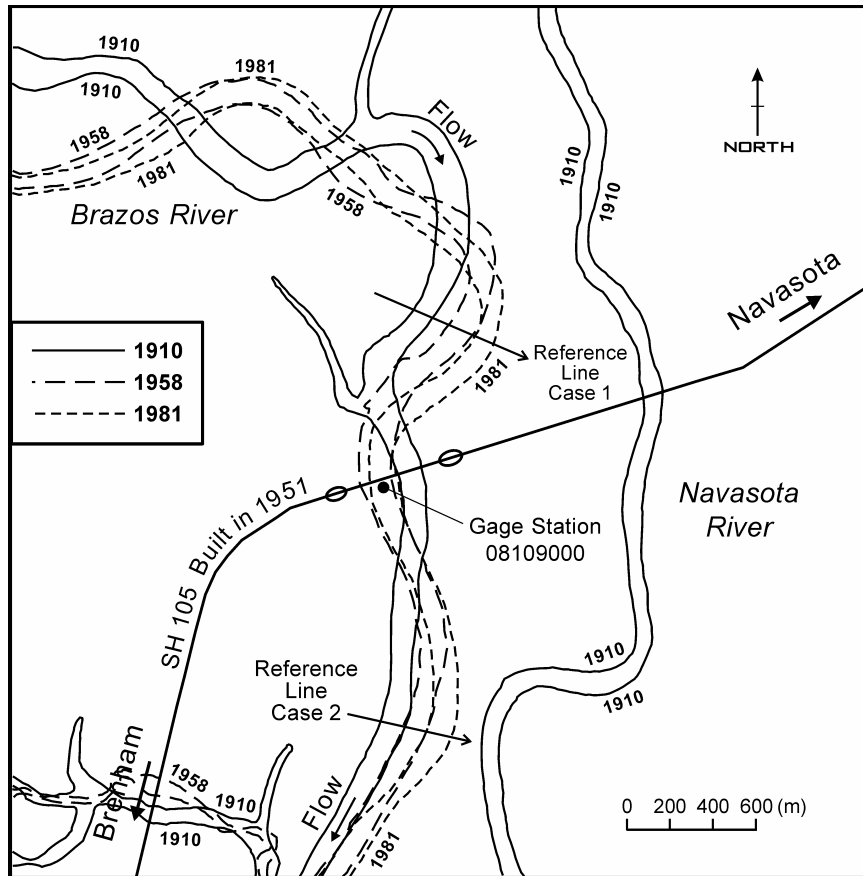


Figure 1 – Meander Migration for the Brazos River at SH 105

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

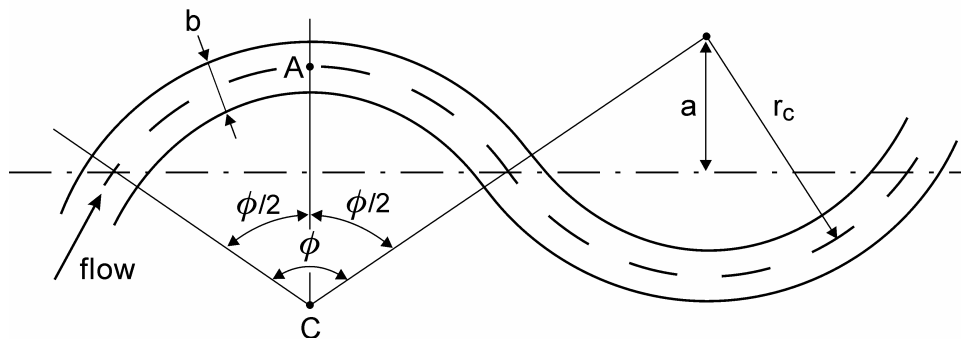


Figure 2 – Geometry Parameters for Meanders

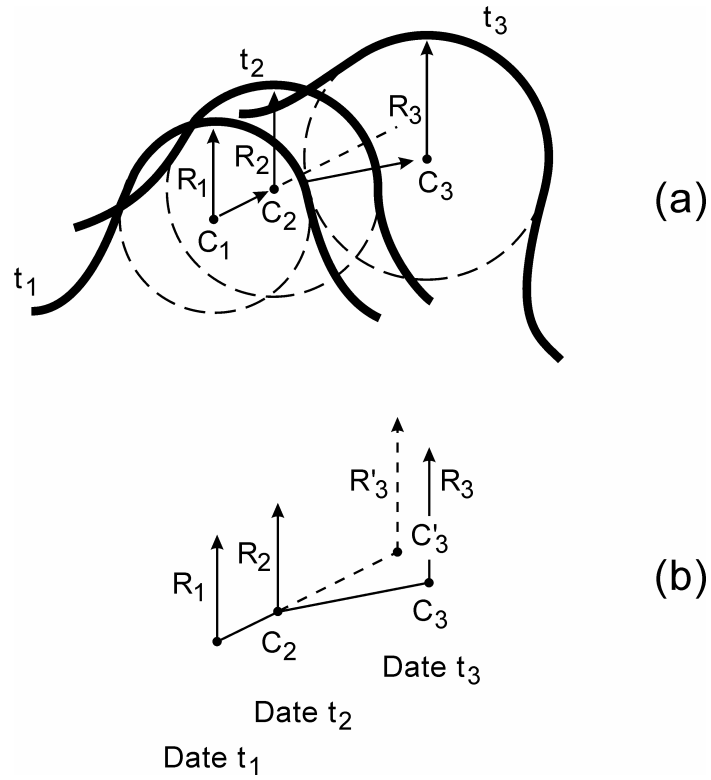


Figure 3 – Definitions for the Time Sequence Maps and Extrapolation Method

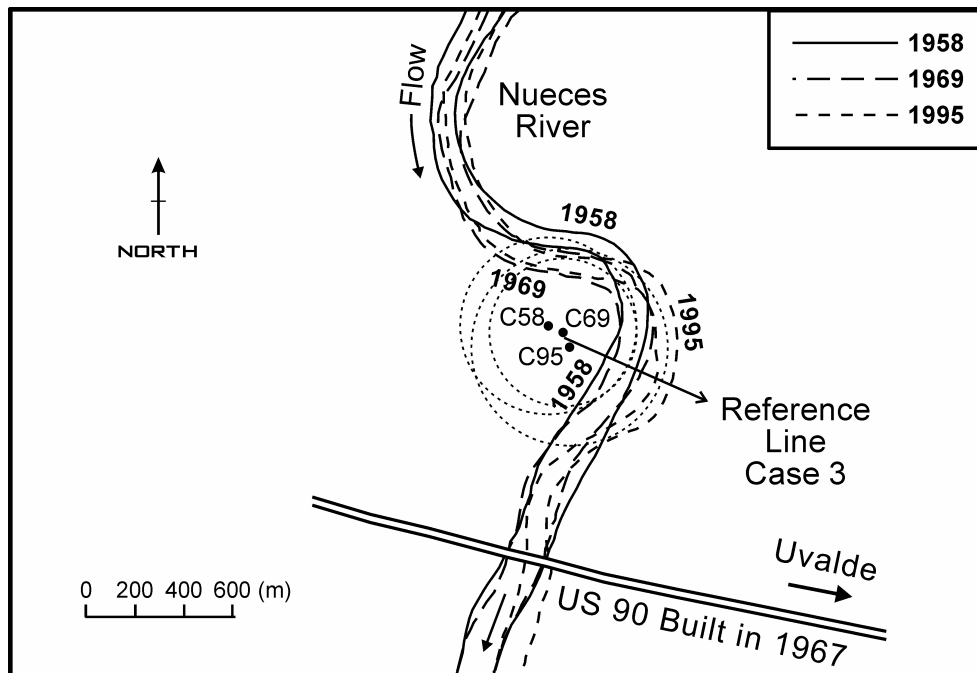


Figure 4 – Meander Migration for the Nueces River at US 90

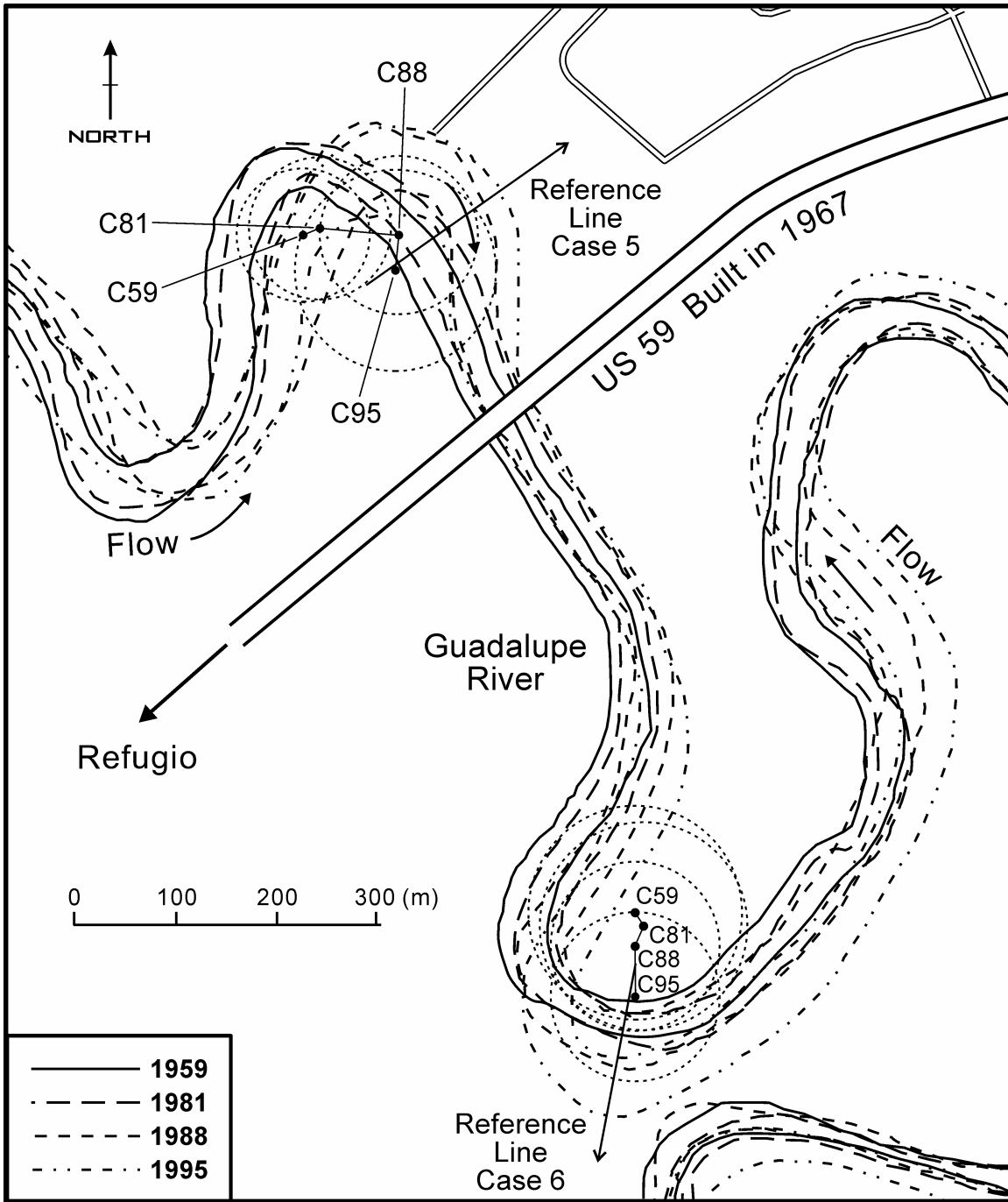


Figure 5 – Meander Migration for the Guadalupe River at US 59

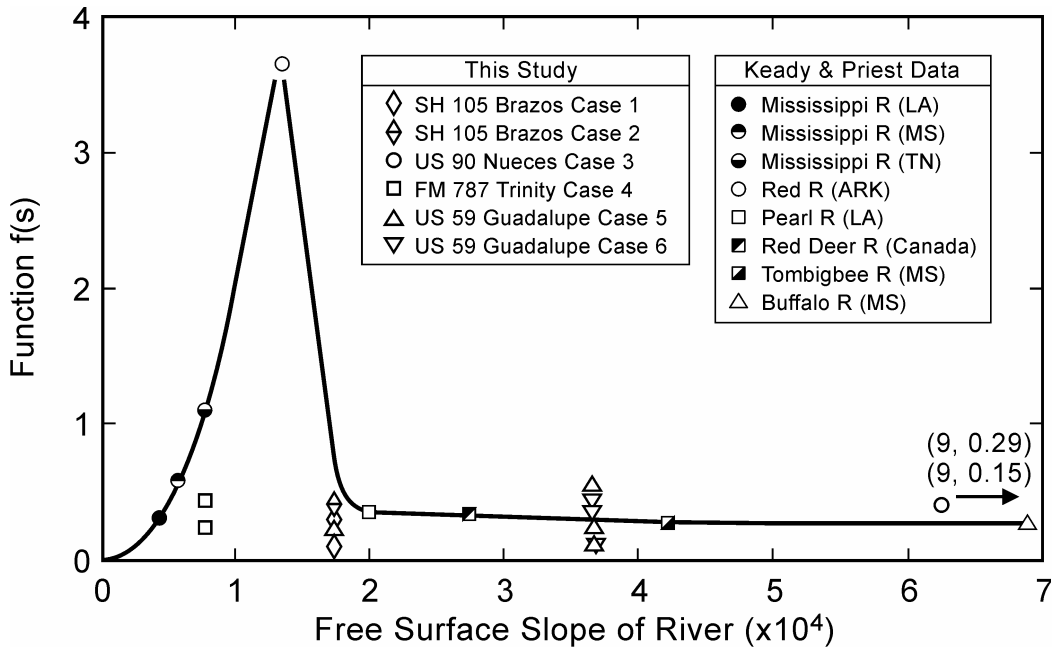


Figure 6 – Function for Keady and Priest (1977) Method

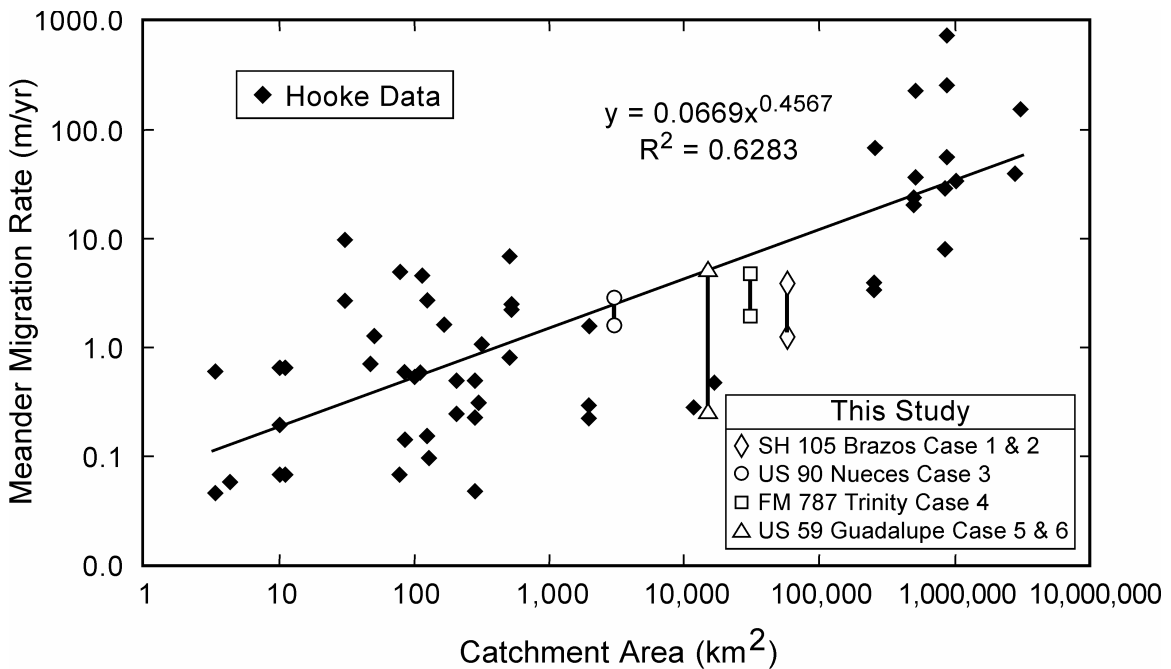


Figure 7 – Data Used by Hooke (1980) to Develop his Method

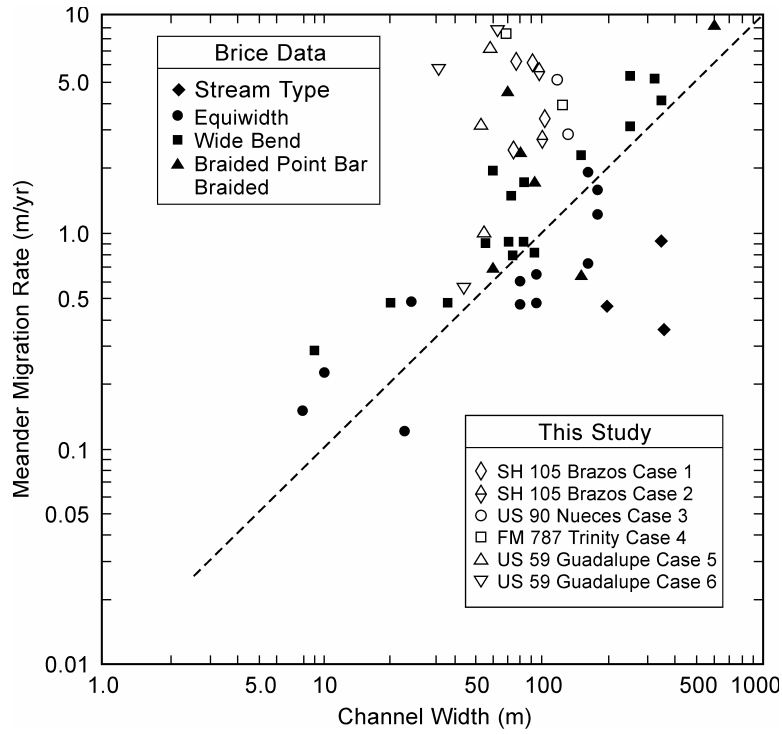


Figure 8 – Data Used by Brice (1982) to Develop his Method

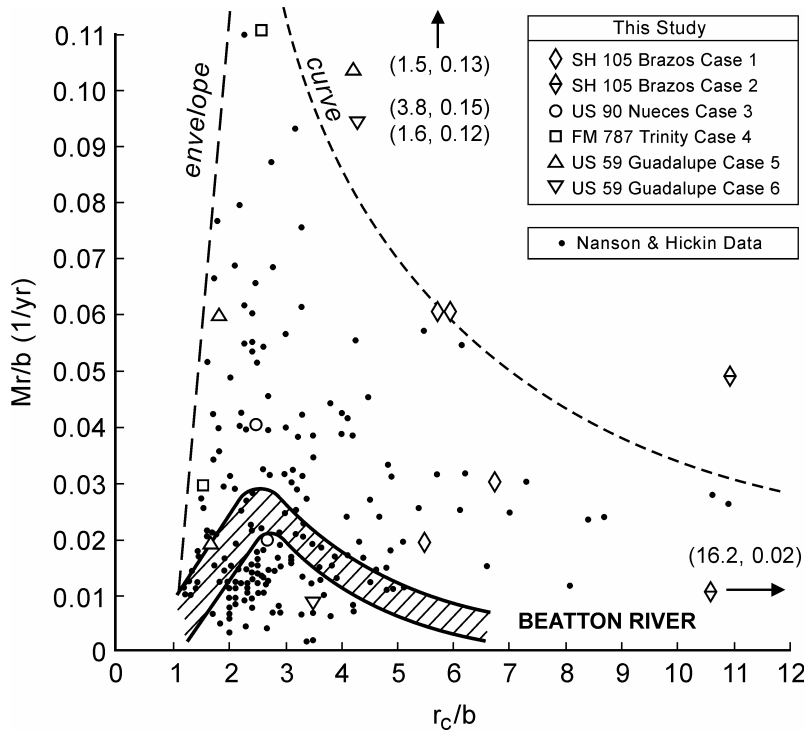


Figure 9 – Data Used by Nanson and Hickin (1983) to Develop Their Method

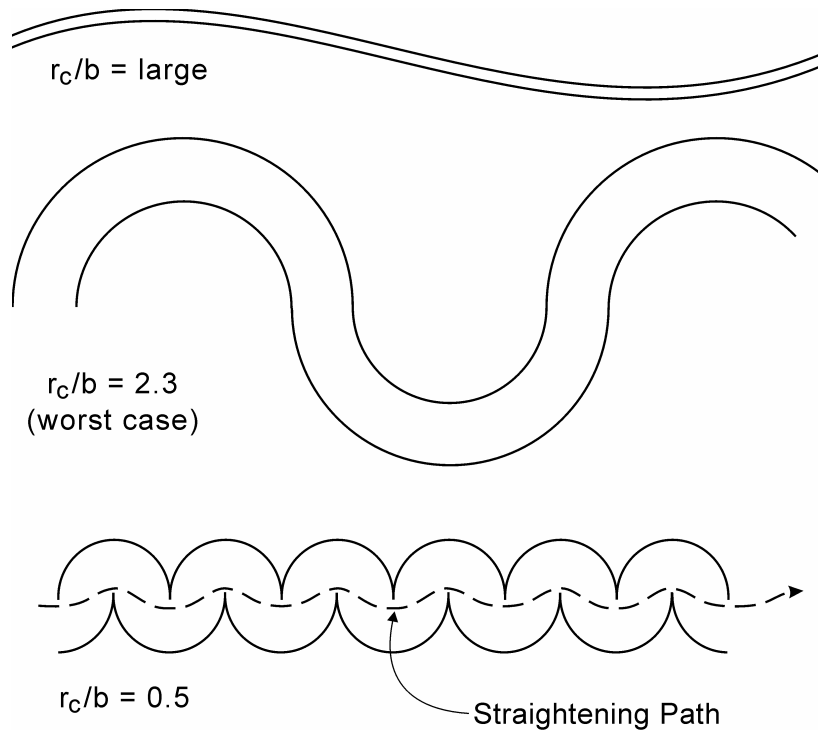


Figure 10 – Rivers with Different Relative Radius of Curvature

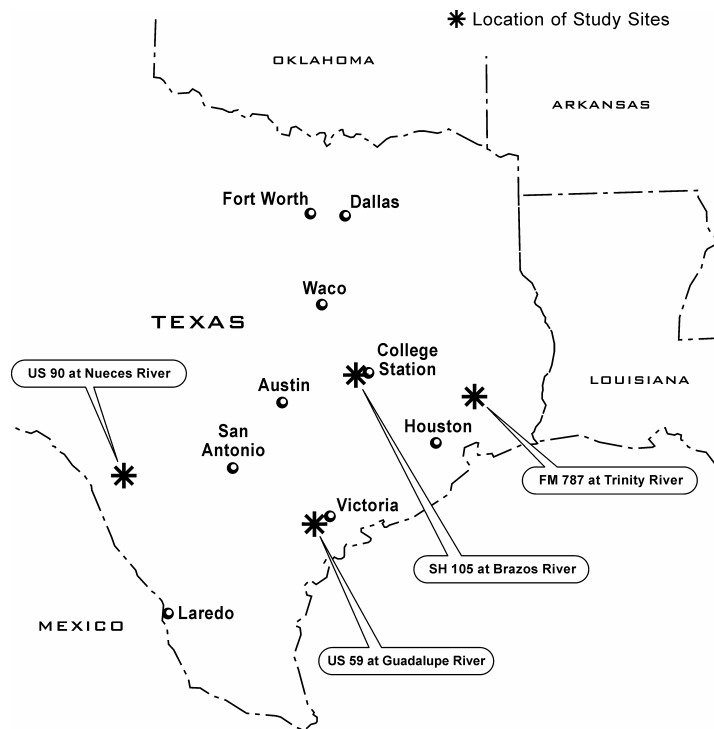


Figure 11 – Map Showing the Location of the Case Histories

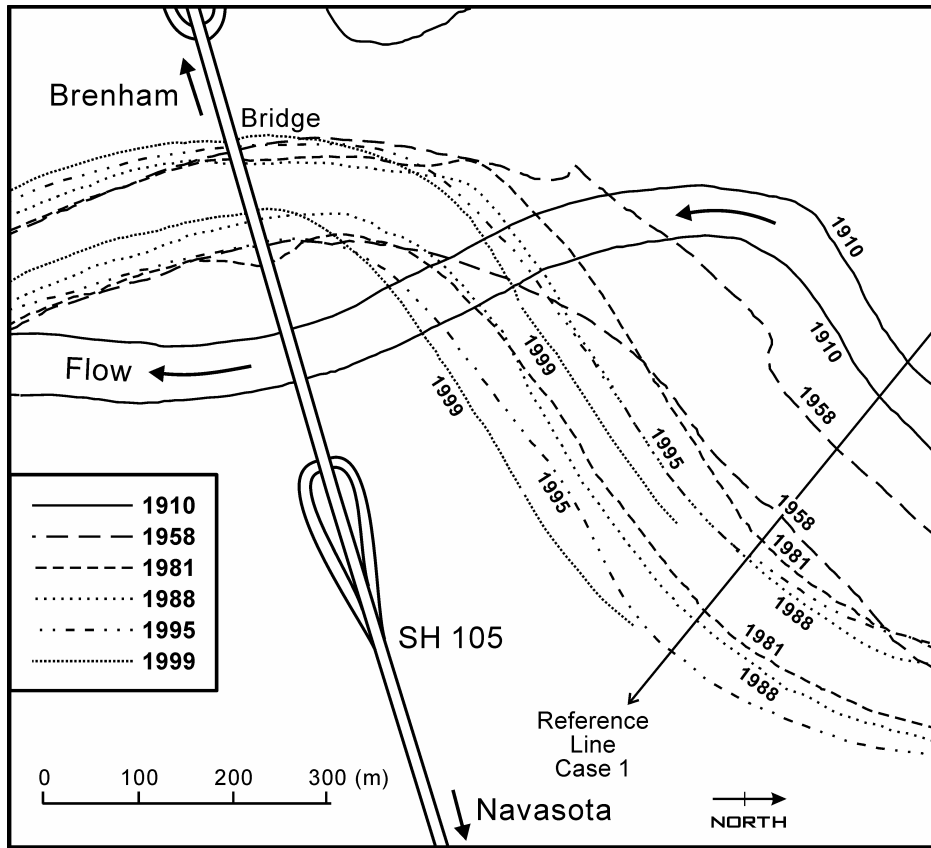


Figure 12 – Close up of the Meander Migration for the Brazos River at SH105

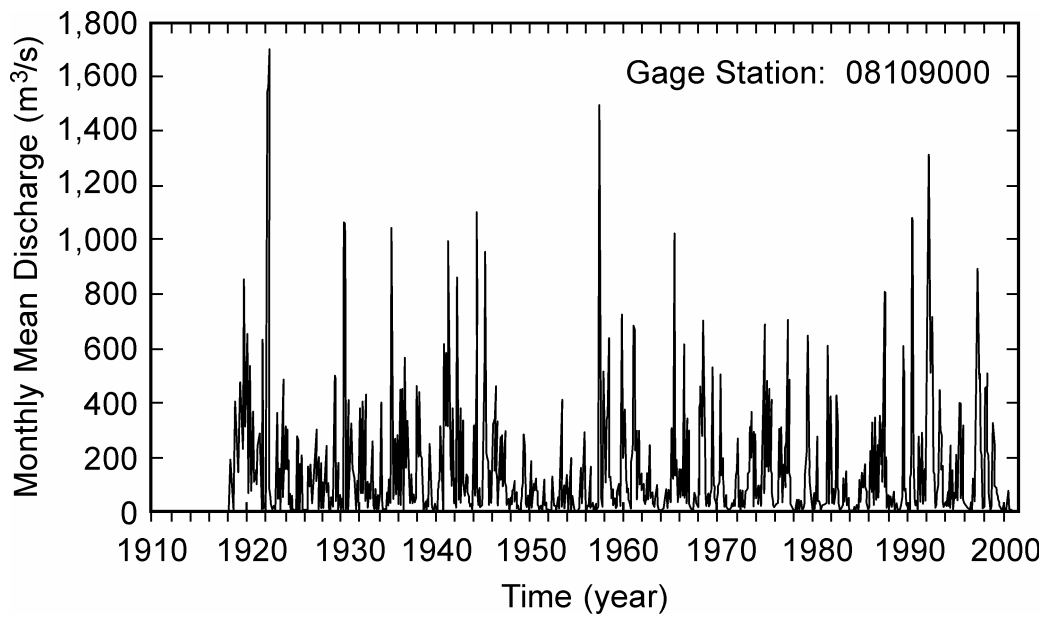


Figure 13 – Mean Monthly Discharge versus Time for the Brazos River at SH 105

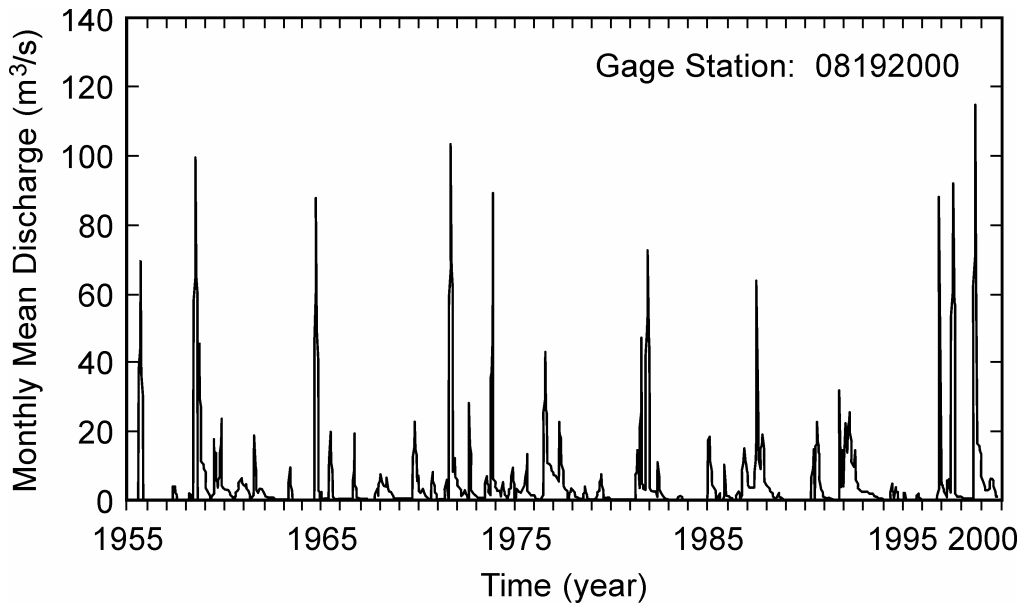


Figure 14 - Mean Monthly Discharge versus Time for the Nueces River at US 90

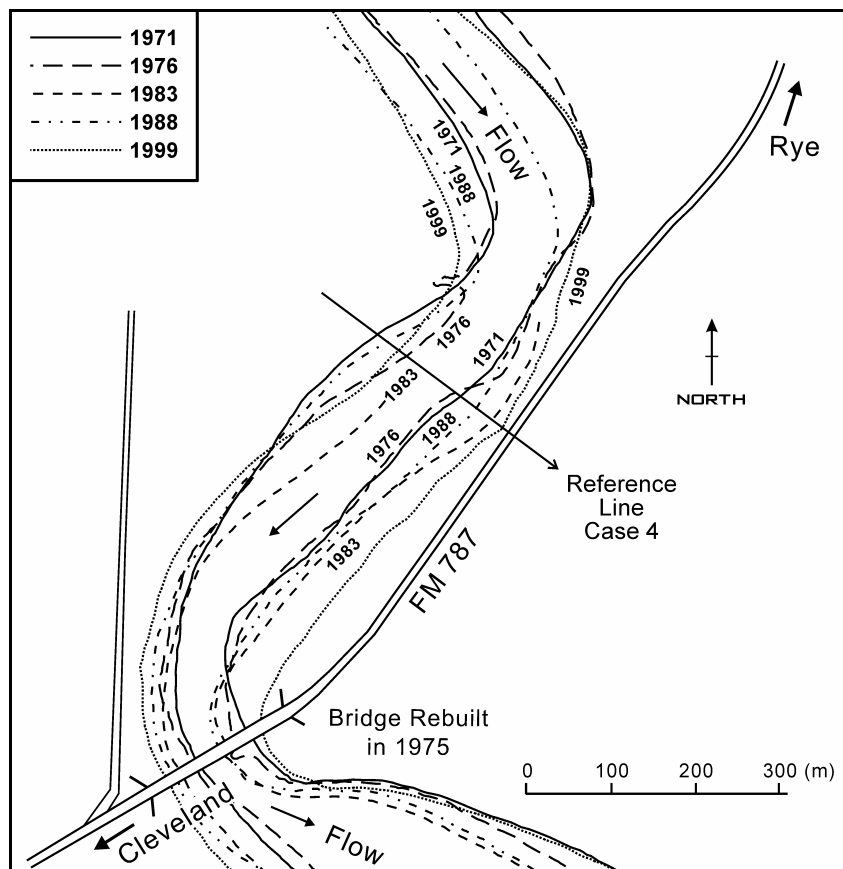


Figure 15 - Meander Migration for the Trinity River at FM 787

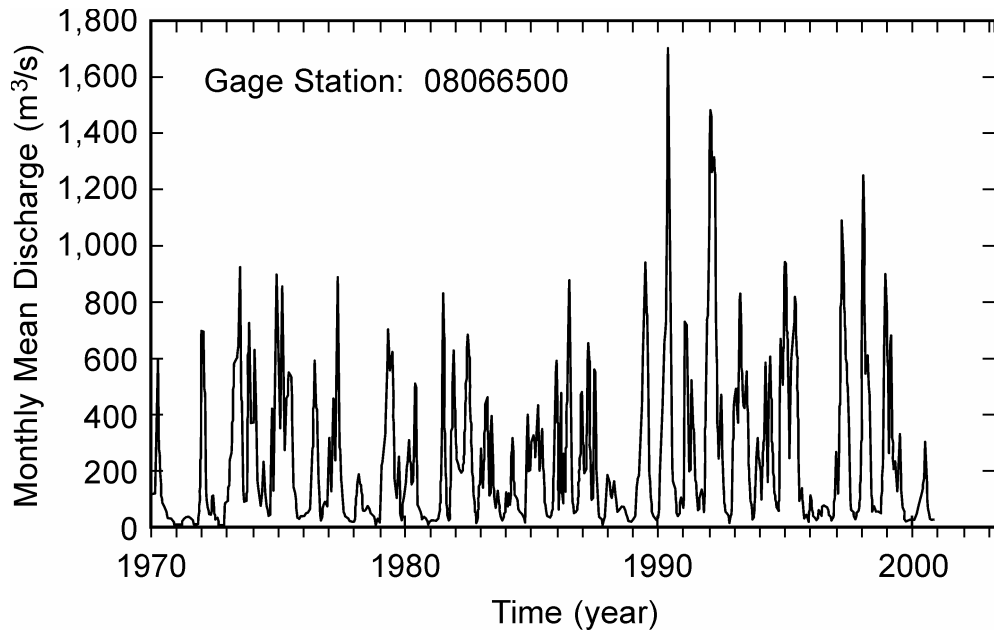


Figure 16 - Mean Monthly Discharge versus Time for the Trinity River at FM 787

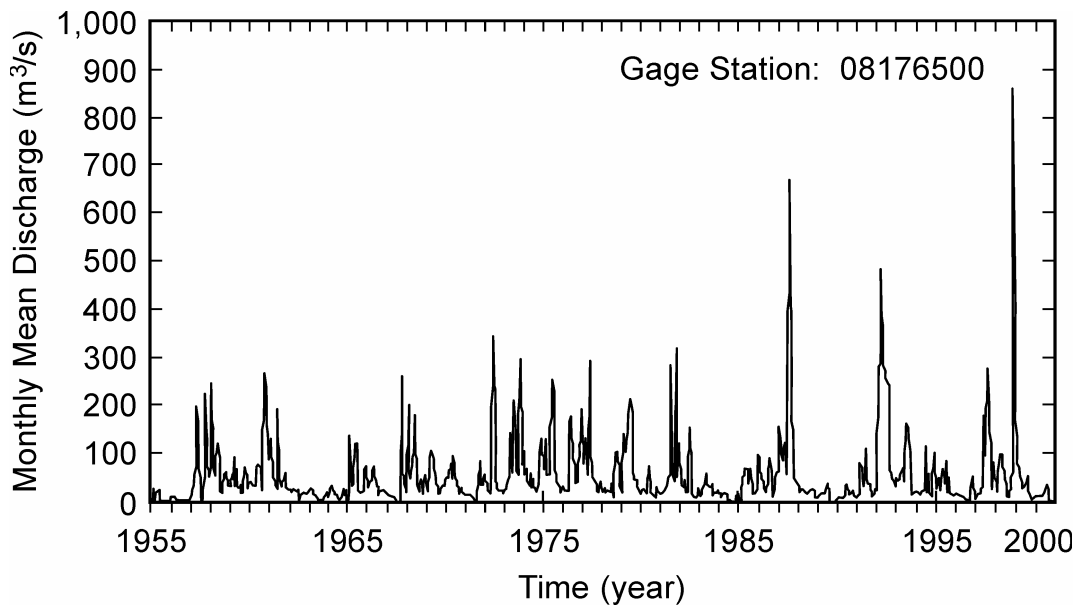


Figure 17 - Mean Monthly Discharge versus Time for the Guadalupe River at US 59

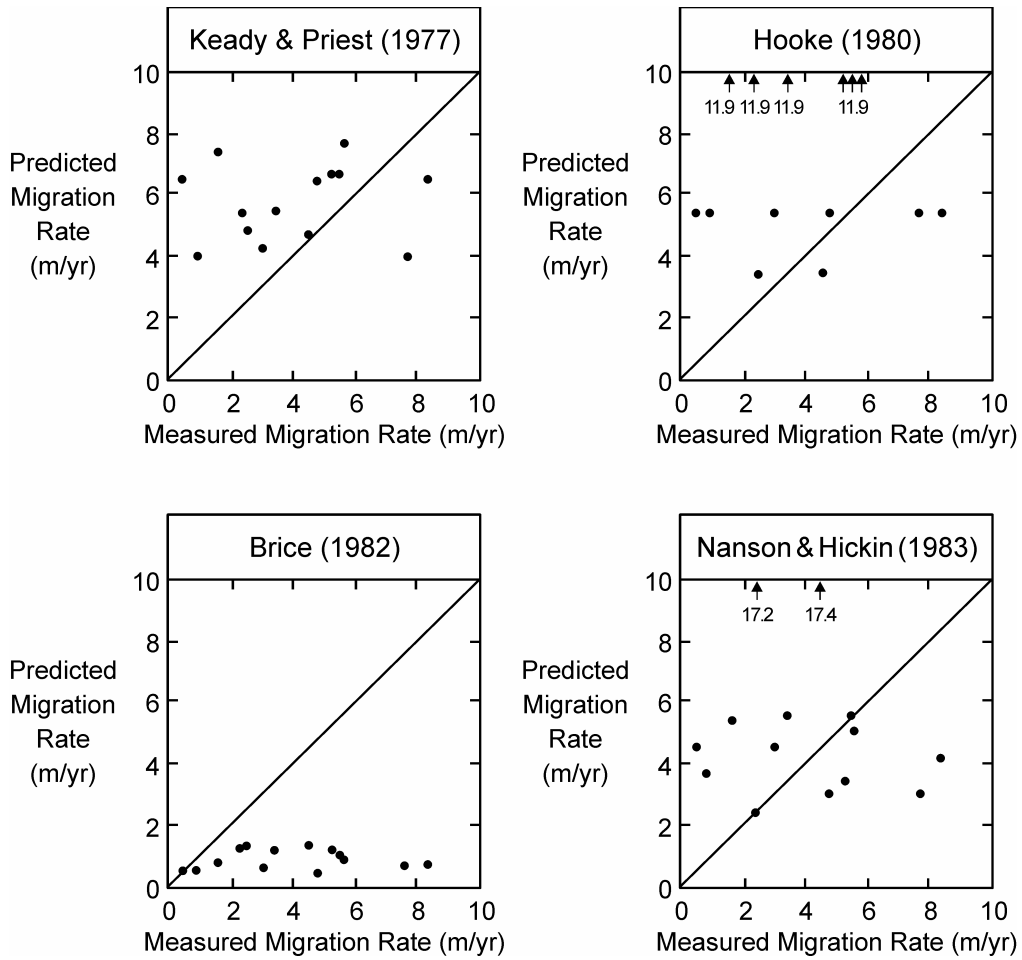


Figure 18 – Predicted versus Measured Migration Parameters for the Time-Sequence Maps and Extrapolation Method

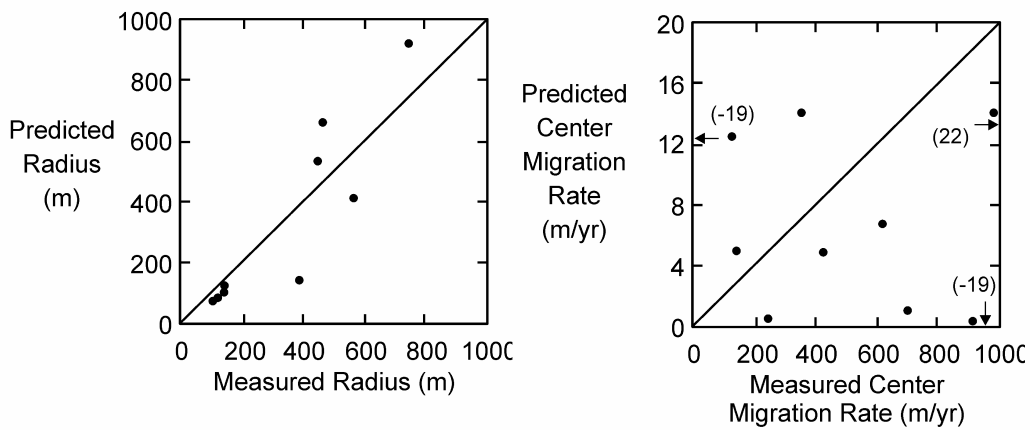


Figure 19 - Predicted versus Measured Migration Rates for the Empirical Methods