BRIDGE SCOUR IN MISSISSIPPI

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INTRODUCTION

Exposure or undermining of bridge pier and bridge abutment foundations by the erosive action of flowing water, including tidal currents, can result in structural failure of a bridge. Bridge failure results in large capital expenditures for repair or replacement and may cause loss of life. Erosion (scour) of the ground in the vicinity of bridge piers and abutments during floods has resulted in more bridge failures than all other causes in recent history (Murillo 1987). Many bridges in Mississippi are at risk of failure due to scour. The design and maintenance of bridge foundations require consideration of the maximum depth of scour that could occur during an extreme flood. Bridge pier and abutment foundations need to extend below the anticipated maximum scour depths to provide support for bridges if scour does occur.

The term "scour," as used here, is defined as the lowering of the ground by erosion below an assumed natural level or other appropriate datum. "Scour depth" is the depth to which material is removed below the stated datum. Scour is a natural phenomenon that is of primary concern in alluvial streams. However, scour can be a problem in any waterway having erodible bed materials. Scour around bridges can be the result of any one of, or combination of, three interrelated components.

- o Local scour - erosion caused by local disturbances in the flow, such as vortices and eddies near piers, abutments, and debris piles.

- o Constriction scour - erosion caused by increased flow velocities through a bridge opening due to the decreased flow area formed by the bridge, the approach embankments, the piers, and any debris piles.

- o General scour - progressive degradation caused by natural processes or by changes in channel controls that occur over a long channel reach and, possibly, over many years. General scour could be part of a temporary fluctuation about some mean bed level. This is the scour that occurs in a channel even if no bridge is present.

Although these components of scour are not completely independent, general practice in bridge design is to estimate each component of scour separately and to combine the predicted scour depths to estimate the total scour depth at a bridge site.

Many empirical equations have been developed to compute constriction scour and local scour at bridges. These equations can provide a large range of scour depths for the same set of conditions. Most of the equations are based on scale-model laboratory experiments and have not been field verified due to the lack of onsite high-flow data. Bridge designers and bridge inspectors need more onsite high-flow data to validate computed scour depths for the varying conditions that occur in Mississippi and throughout the United States.

Adequate definition of potential scour at bridge sites is essential to proper bridge design, construction, and maintenance. Accurate estimates of scour depths for varying conditions are a prerequisite for safe, cost-effective bridge design. Underestimating scour depths puts bridges and human life at risk. Overestimating scour depths results in overdesign, which translates into an economic loss in the form of higher construction costs. Collection of onsite scour data is recognized as one way, and perhaps the only convincing way, to improve bridge design procedures (Highway Research Board 1970; Hopkins et al. 1980; Jones 1984; Laursen 1984; Murillo 1987).

The U.S. Geological Survey (USGS), in cooperation with the Mississippi Department of Transportation (MDOT), began a study of bridge scour in Mississippi in 1989. The objectives of this study were to: (1) perform onsite high-flow scour measurements at selected bridge sites, (2) evaluate the usefulness of available scour equations for estimating local pier scour, (3) develop a scour-prediction equation that could be used to better estimate local pier scour for Mississippi streams, and (4) analyze available discharge measurement soundings for an indication of total scour.

Purpose and Scope

This paper briefly summarizes pier-scour data collected during 1942-94 at 22 selected bridge sites in Mississippi

(Figure 1). These data and additional bridge-scour data collected during 1938-94 are described in more detail by Wilson (1995). The methods used to measure scour and selected characteristics at each site are described. Selected hydraulic and bridge-geometry characteristics are presented. An envelope-curve equation for the Mississippi pier-scour data was developed by relating measured pier-scour depth divided by normal pier width to measured approach-flow depth divided by normal pier width. The measured pier-scour depths were compared to the envelope curve and to the pier-scour prediction equation recommended in the Federal Highway Administration (FHWA) Hydraulic Engineering Circular No. 18 (HEC-18) by Richardson and others (1993).

Methods of Study

The scour data-collection sites presented in this paper were selected from a list of sites known by the MDOT to be susceptible to scour. Data were also obtained at a few additional sites if, during the study, high flow occurred at a site and the USGS and the MDOT considered the data useful for bridge maintenance. Scour data were collected as near the peak discharge as possible. If the high flow was of sufficient duration, additional measurements were obtained during the rising and falling limbs of the flood hydrograph.

Measurements of water depth and velocity to determine discharge were obtained using standard streamflow-gaging procedures as described by Rantz and others (1982). Depth, vertical position, and velocity were measured by suspending a 100-, 150-, or 200-pound Columbus-type sounding weight and Price AA-type current meter in the water.

Soundings to the channel bed to measure channel geometry were obtained either by sounding with a weight or with an Eagle Model Mach 1 Graph (the use of trade of product names in this report is for identification purposes only and does not constitute endorsement by the USGS) recording fathometer. Transducers used with the fathometer produced an 8-degree beam width, allowing close access to bridge piers without creating echoes off the sides of the pier. Use of the fathometer made soundings possible at a large number of points across a cross section. During high flows, the transducer was attached to the bottom of the sounding weight, which was lowered into the water from a truck-mounted boom and winch assembly and was then towed through the water as the truck was driven across the bridge at a slow, nearly constant speed. Where piers were inset from the upstream side of the bridge, a flotation device was used to allow the flow to drag the transducer close to the upstream side of the pier. During low to medium flows, the transducer was attached at or near the bow of a boat, which traversed the cross section or longitudinal profile.

Bed samples were collected to characterize the streambed composition. They were collected primarily during low-flow conditions and are assumed to be representative of high-flow conditions. Sites generally were sampled at three cross sections through a channel reach of at least one bridge length upstream of the site. For some sites, bed-sample information was obtained from MDOT soils reports or from nearby sampled sites on the same stream, where bed conditions were considered to be similar.

Description of Bridge-Scour Sites

Scour data presented in this paper were collected at 22 selected bridge sites in Mississippi (Figure 1). The drainage area of the bridge-scour sites ranged from 60.8 to 5,720 mi2, and the slope in the vicinity of each site ranged from 0.00011 to 0.00163 ft/ft (Table 1). The bed material at most sites consisted of sand or gravel. In some cases, the sand or gravel was underlain by a clay stratum, which was thought to affect the measured scour depths.

PIER-SCOUR DATA

Measurements of pier-scour depths obtained during this study by fathometer and sounding weight were combined with soundings from concurrent and historical discharge measurements, which had soundings near the bridge piers. This information provided an approximation of pier-scour depth for 190 pier-scour measurements at 21 of the 22 sites. Of the 121 pier-scour measurements obtained since 1990, 112 were obtained with a fathometer and 9 were obtained with a sounding weight. Of the 69 pier-scour measurements obtained prior to 1990, all but 5 were determined from selected discharge measurements. Three of the five were pier-scour measurements obtained in 1989 at site 21, where upstream and downstream sides of the bridge were sounded. The remaining two pier-scour measurements were obtained in 1972 and 1973 by a scour-monitoring device installed at site 17 by Hopkins and others (1975, 1980) for the FHWA.

Both upstream and downstream sides of the bridge were usually sounded with the fathometer. The upstream and downstream pier-scour depths were compared for each pier, and the maximum pier-scour depth was used in this paper. By contrast, the pier-scour depths taken from the discharge measurements were limited to one side of the bridge and were not solely obtained on the downstream side of the bridge. The pier-scour depths were determined using an approximation of concurrent ambient bed level as described by Blodgett (1989) and Landers and Mueller (1993). Concurrent ambient bed level is representative of the typical bed elevation adjacent to the scour hole at the time of the measurement. Therefore, it is the elevation representing the streambed at the pier location without any pier scour. Each pier-scour measurement was assigned an approximate accuracy based on measuring conditions at a site. Assigned accuracy ranged from 0.5 ft for a fathometer for favorable conditions to 3 ft for a sounding weight under less favorable conditions. Measurement accuracy was adversely affected by sounding weight drift due to flow, turbulence of the flow, presence of debris piles, and the determination of concurrent ambient bed level.

With inclusion of the selected historical discharge measurements, the recurrence intervals of the measured discharges ranged from less than 2 to about 500 years. Recurrence intervals of the measured discharges were determined using procedures and information described by Landers and Wilson (1991) and Wilson and Landers (1991).

The majority of the pier-scour data presented in this paper have been entered in the National Bridge Scour Data Management System (BSDMS). The BSDMS is being developed by the USGS in cooperation with the FHWA to support preparation, compilation, and analysis of bridge-scour measurement data, and the primary functions of the BSDMS are data archival and retrieval (Landers 1992).

Pier-scour data were collected during high flows at selected bridge sites in Mississippi representing various hydraulic, bed-material, and pier-geometry characteristics. Measured pier-scour depths (Ys) ranged from 0.6 to 20.4 ft. Scour-hole top width, where determined, ranged from 8 to 180 ft. Approach-flow depth (Y1) ranged from 2.3 to 36.6 ft, approach-flow velocity (V1) ranged from 1.3 to 10.4 ft/s, and approach-flow skew ranged from 0 to 46 degrees. Median bed-material size (D50) ranged from 0.00092 to 0.02464 ft, and the geometric standard deviation of the bed-material sizes or the gradation coefficient

$$\sigma_g = \sqrt{\frac{D_{84}}{D_{16}}} \qquad (1)$$

ranged from 1.3 to 8.3. In this equation, D84 is bed-material size where 84 percent is finer, and D16 is bed-material size where 16 percent is finer. If sg is equal to 1, the material is considered uniform in size, and as sg increases, the material is less uniform.

The pier geometry was determined from field observations and MDOT bridge plans. The pier type was classified as either a single or a group. A single refers to one pier or column supporting the entire bridge width; whereas, a group refers to spaced columns or piles. The pier shape refers to the upstream part of the pier and was classified as either cylinder, round, square, or sharp. The pier width (a) and the pier length (L) are depth-weighted averages for each respective measurement. The normal pier width (a') is the pier width adjusted for skew. If skew is zero, then a is equal to a'; otherwise, a' will be larger than a, depending on the degree of skew. For the approach flow skews ranging from 0 to 46 degrees, measured a and a' ranged from 1.3 to 23 ft and 1.8 to 23 ft, respectively.

PIER-SCOUR DATA ANALYSIS

Jones (1984) compared many pier-scour equations by plotting measured pier-scour depth divided by pier width (Ys/a) with approach depth divided by pier width (Y1/a) for various Froude numbers. However, in this paper, pier-scour depth (Ys) was divided by normal pier width (a'). Only 12 (6 percent) of the 190 measurements are plotted above Ys/a' = 1.1 (Figure 2). The envelope-curve equation developed for these data (Figure 2) is:

$$\frac{Y_s}{a'} = 0.9\left(\frac{Y_1}{a'}\right)^{0.4} \qquad (2)$$

where

Ys is pier-scour depth, in feet;
a' is normal pier width, in feet; and
Y1 is approach flow depth, in feet.

Measurement 179 at site 22 was the only measurement that plotted significantly above the envelope curve (Figure 2). Measurement 179 was affected by a jetty and stream bank deflecting flow toward the pier and possibly debris, which was not noted during the measurement. Using techniques described by Lagasse and others (1991) for estimating scour off the downstream end of the jetty, the jetty could have caused about 9 ft of scour off its downstream end, suggesting some of the measured pier scour could have been caused by the jetty. Equation 2 predicts 14.2 ft of pier scour, which is 6.2 ft less than the measured pier scour of 20.4 ft, suggesting about 6 ft of scour not caused by the pier.

Pier-scour depths predicted by the pier-scour equation currently (1995) recommended by FHWA in HEC-18 (Richardson et al. 1993) and by equation 2 were compared to measured pier-scour depths, which ranged from 0.6 to 20.4 ft. The HEC-18 equation predicted pier-scour depths ranging from 3.9 to 25.7 ft with residuals (measured pier scour minus predicted pier scour) ranging from -21.7 to 0.2 ft. Equation 2 predicted pier-scour depths ranging from 2.2 to 19.7 ft with residuals ranging from -16.8 to 6.2 ft. The residual of 6.2 ft was for measurement 179, where some of the measured pier scour could have been caused by a jetty and stream bank, as previously described. Excluding measurement 179, residuals ranged from -16.8 to 0.5 ft. Equation 2 could be used for reasonable verifications of the HEC-18 pier-scour predictions, which are currently required in the design and maintenance of bridges in Mississippi.

Measured pier-scour depths have been shown not to exceed a certain multiple of the pier width. F.M. Chang noted that there were no pier-scour depths greater than 2.3 times the pier width for all the pier-scour data he studied (Richardson et al. 1993). Melville and Sutherland (1988) reported from laboratory data there were no pier-scour depths greater than 2.4 times the pier width for cylindrical piers.

All of the Mississippi pier-scour depths were within 2.3 times the normal pier width, which agreed with previous research (Figure 3). Measured pier-scour depths were as much as 2.24 times a normal pier width of 3.3 ft. However, for normal pier widths greater than about 4 ft, measured pier-scour depths were significantly less than 2.3 times the normal pier width (Figure 3).

Effect of Debris Piles

During a few measurements, debris piles on bridge piers were present where the debris significantly obstructed more of the approach flow than did the pier. The debris accumulating on a pier can affect the location and magnitude of the maximum pier-scour depth caused by the combination of the pier and the debris pile. Where the debris pile was significant on the upstream side of the pier, the maximum measured pier-scour depth usually was on the downstream side of the pier. In most cases, if debris was present, it was considered insignificant because the debris at the water surface consisted of only a few logs, which did not significantly increase the pier obstruction of the approach flow. Some of the fathometer records indicated the possible presence of submerged debris, which might have had an effect on some of the measured pier-scour depths.

The largest debris pile observed in this study was for measurement 165 at site 21 in 1990. At the time of the pier-scour measurement, January 25, 1990, the size of the debris pile could not be easily determined. However, a low-water survey on September 18, 1990, documented the debris pile to be about 11 ft high, 10 ft wide at the top, and 40 ft wide at the bottom. If the debris did not slip downward, the debris pile projected about 5 ft above the ambient bed level during the pier-scour measurement on January 25, 1990. The maximum scour-hole depth of 9.4 ft was surveyed on September 18, 1990, at the upstream side of the debris pile, which was about 25 ft upstream of the upstream side of bridge pier. The surveyed scour-hole depth of 9.4 ft agreed reasonably well with the pier-scour depth of 8.8 ft obtained at the downstream side of the bridge during the pier-scour measurement on January 25, 1990. The used pier width of 23 ft includes the debris, which is about 8 ft wider than or 1.5 times as wide as the bridge-pier width of 15 ft.

Effect of Heterogeneous Bed Material

At several sites, measured pier-scour depths possibly were affected by heterogeneous bed material, primarily where a clay stratum was overlain by sand or gravel. If the material was uniform with depth, then the bed sample taken during low-flow conditions was assumed to be representative of the bed material during high-flow conditions. If the material contained a range of fine to coarse material, then the coarse material would most likely be overlain with fine material during low-flow conditions. Therefore, the low-flow bed sample would not necessarily be representative of high-flow conditions.

Large-scale laboratory studies are being conducted by Albert Molinas at Colorado State University (CSU) for FHWA to test the effects of gradation and cohesion of streambed material on scour. Preliminary findings indicate the gradation of the material has a significant effect on the scour depth. If there is even a small amount of gravel mixed with sand, the gravel is deposited in the scour hole at the base of the pier, and the gravel possibly provides an armor layer during flow conditions below the initiation of motion of the gravel (A. Molinas, CSU, and J.S. Jones, FHWA, oral commun. 1995). For the Mississippi data, the range of measured pier-scour depths for a respective D50 generally decreased as D50 increased and as sg increased.

Osman and Thorne (1988) presented a method for calculating the rate and amount of erosion of cohesive material based on laboratory work by the U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi. Osman and Thorne noted that increasing the clay content in the soil increases the resistance of the soil to erosion.

Where MDOT soil reports were available, the cohesion and friction angles were approximated for the clays at sites where the clay stratum is thought to inhibit scour. Using the MDOT borings where the clay was overlain by sand or gravel, the top of the clay stratum was approximated in order to determine the net scour through the clay. The relation between Yscl/a' and approximate shear strength of the clay for pier-scour measurements, which were possibly affected by the presence of a clay, is shown in Figure 4. With the exception of measurement 79 at site 10, pier-scour depths generally decreased as shear strength increased. It is possible that the clay may have been removed and replaced with more easily erodible material during construction at site 10, resulting in an unusually large pier-scour depth. Most of the pier-scour measurements shown in Figure 4 probably are affected by some disturbance of the clays when the pier foundations were installed.

Figure 4 could be used graphically for comparison with predicted pier-scour depths for sites where the shear strength of a clay is thought to be inhibiting scour. A line through the highest points, with the exception of measurement 79 at site 10, possibly could be used as a guide for determining the largest amount of scour that could be expected for a given shear strength of a consolidated cohesive bed material at a site. Perhaps as more data become available, an envelope-curve equation could be developed.

SUMMARY

This paper briefly summarizes pier-scour data collected during 1942-94 at 22 selected bridge sites in Mississippi. The drainage area of the bridge-scour sites ranged from 60.8 to 5,720 mi2. At most sites, the bed material consisted of sand or gravel, and in some cases, the sand or gravel was underlain by a clay stratum, which is thought to affect the measured scour depths. Recurrence intervals of measured discharges ranged from less than 2 to about 500 years.

Pier-scour data were collected during high flows at sites representing various hydraulic, bed-material, and pier-geometry characteristics. Measured pier-scour depth ranged from 0.6 to 20.4 ft, with scour-hole top width, when determined, ranging from 8 to 180 ft. Approach-flow depth ranged from 2.3 to 36.6 ft, approach-flow velocity ranged from 1.3 to 10.4 ft/s, and approach-flow skew ranged from 0 to 46 degrees. Median bed-material size ranged from 0.00092 to 0.02464 ft, and the geometric standard deviation of the bed-material sizes or the gradation coefficient ranged from 1.3 to 8.3. Only 12 (6 percent) of the 190 pier-scour depths were greater than 1.1 times the normal pier width. An envelope-curve equation for the Mississippi pier-scour data was developed by relating pier-scour depth divided by normal pier width to approach-flow depth divided by normal pier width.

All of the Mississippi pier-scour depths were within 2.3 times the normal pier width, which agreed with previous research. Measured pier-scour depths were as much as 2.24 times a normal pier width of 3.3 ft. However, for pier widths greater than about 4 ft, measured pier-scour depths were significantly less than 2.3 times the normal pier width.

Pier-scour depths predicted by the pier-scour equation currently (1995) recommended in the Federal Highway Administration Hydraulic Engineering Circular No. 18 (HEC-18) and by the envelope-curve equation developed for Mississippi pier-scour data during this study were compared to measured pier-scour depths. The HEC-18 equation predicted pier-scour depths ranging from 3.9 to 25.7 ft with residuals (measured pier-scour depth minus predicted pier-scour depth) ranging from -21.7 to 0.2 ft. The envelope-curve equation developed during this study predicted pier-scour depths ranging from 2.2 to 19.7 ft with residuals ranging from -16.8 to 6.2 ft. The residual of 6.2 ft for the envelope-curve equation developed during this study was at a site where some of the measured pier scour could have been caused by a jetty and stream bank. Excluding this measurement, residuals ranged from -16.8 to 0.5 ft. The envelope-curve equation predictions could be used for reasonable verifications of the HEC-18 pier-scour predictions, which currently are required in the design and maintenance of bridges in Mississippi.

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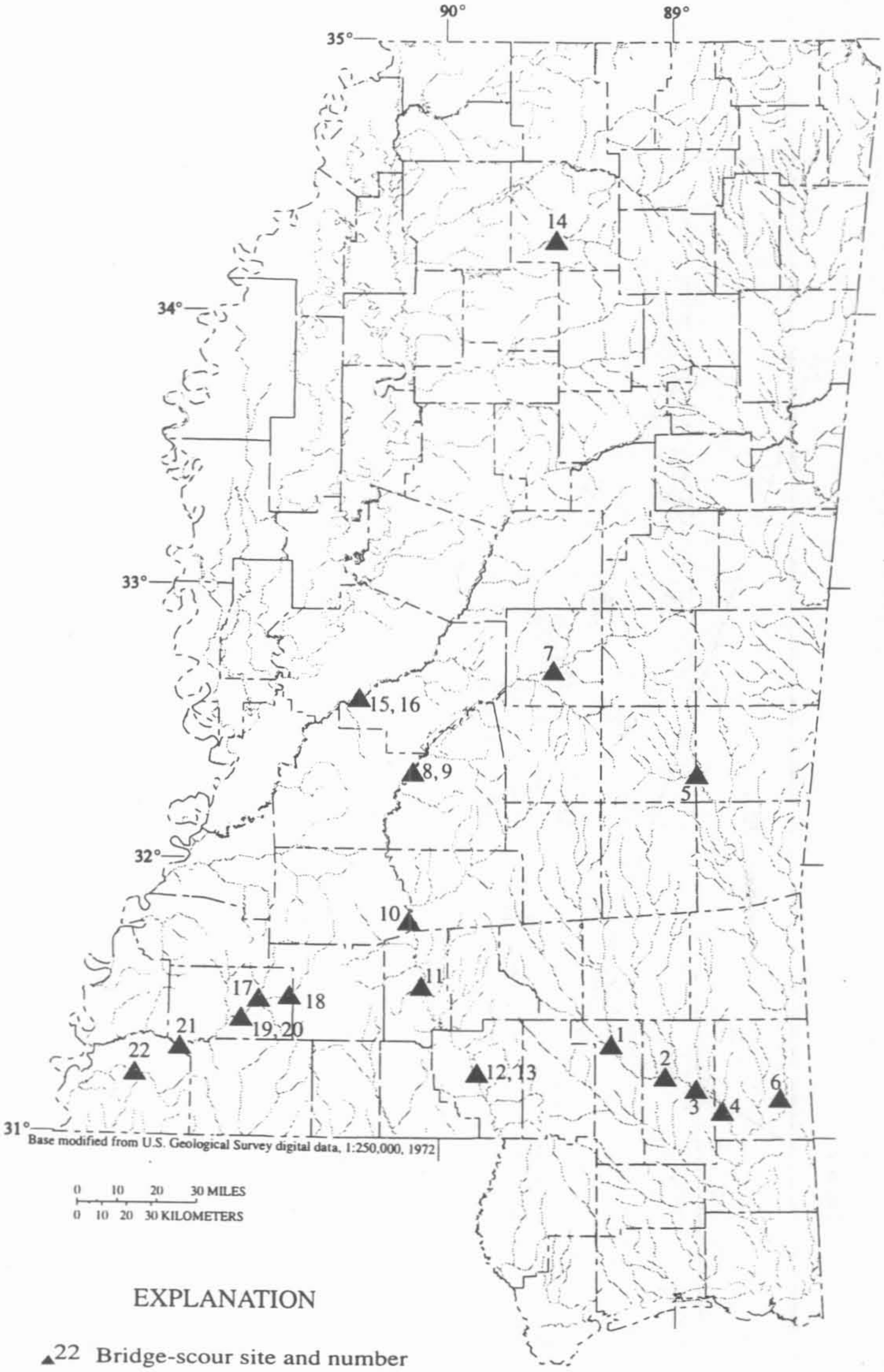

Figure 1. Location of bridge-scour sites in Mississippi.

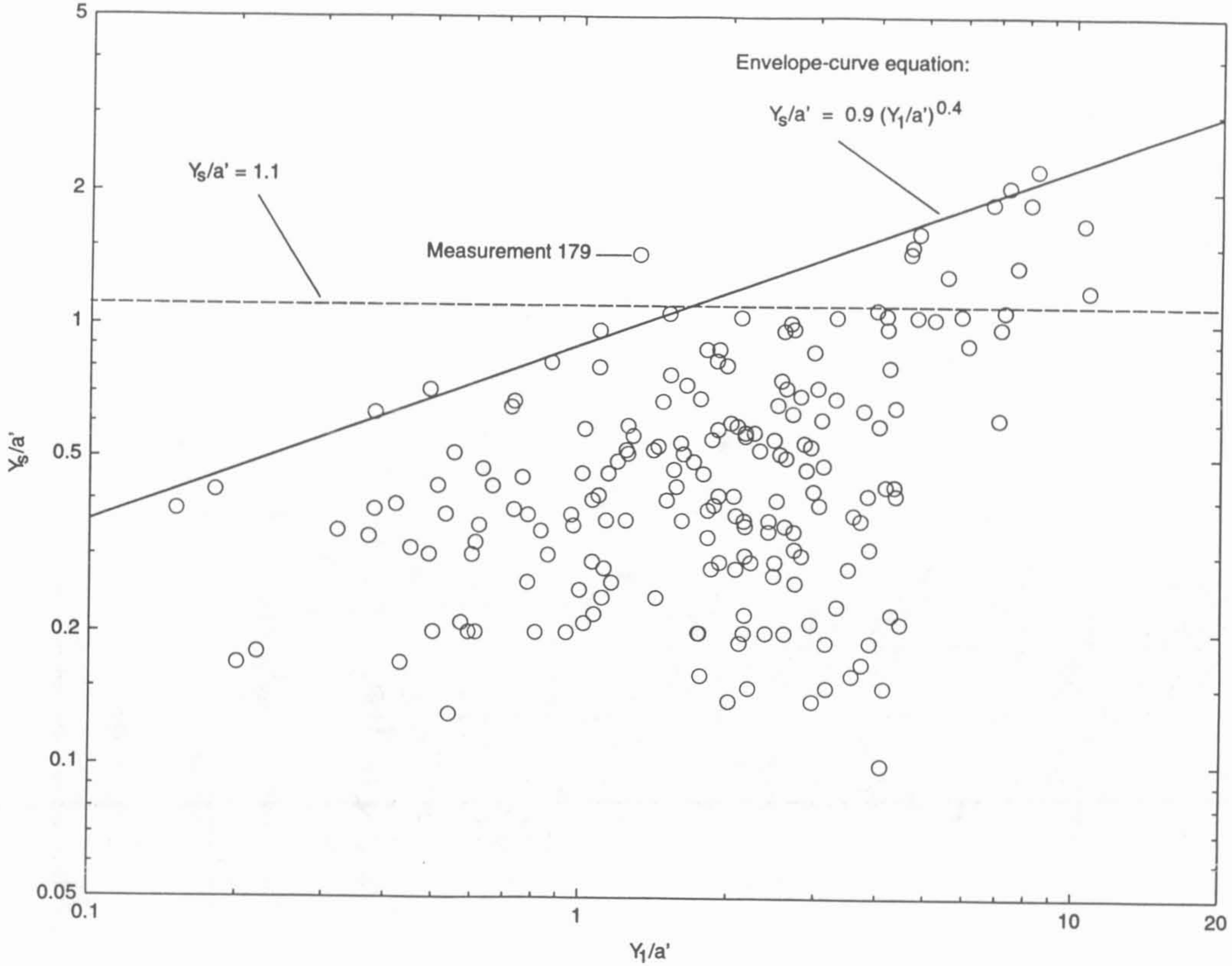

Figure 2. Relation between measured pier-scour depth divided by normal pier width (Y_s/a') and measured approach-flow depth divided by normal pier width (Y_1/a') for selected bridge sites in Mississippi.

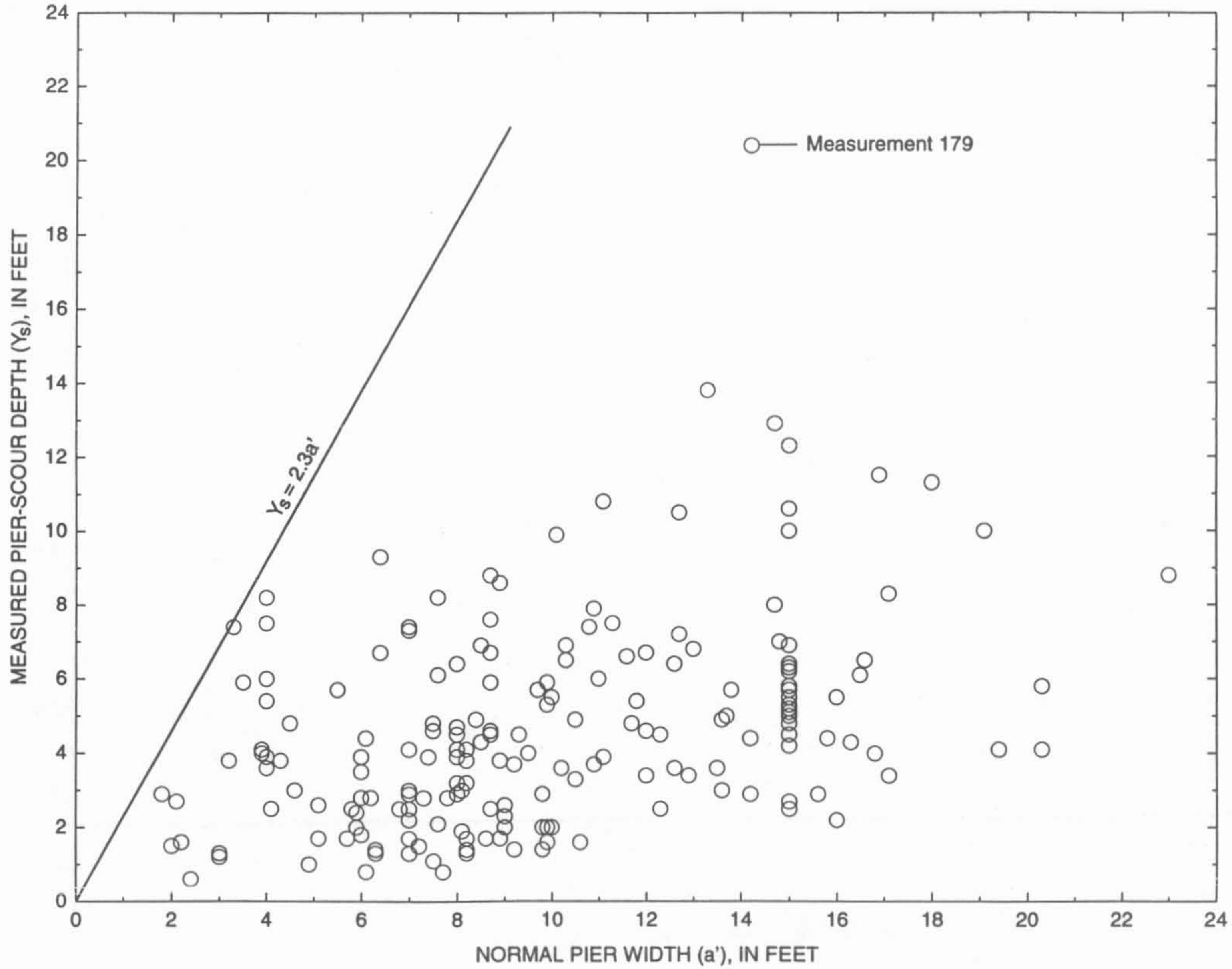

Figure 3. Relation between measured pier-scour depth (Y_S) and normal pier width (a') for selected bridge sites in Mississippi.

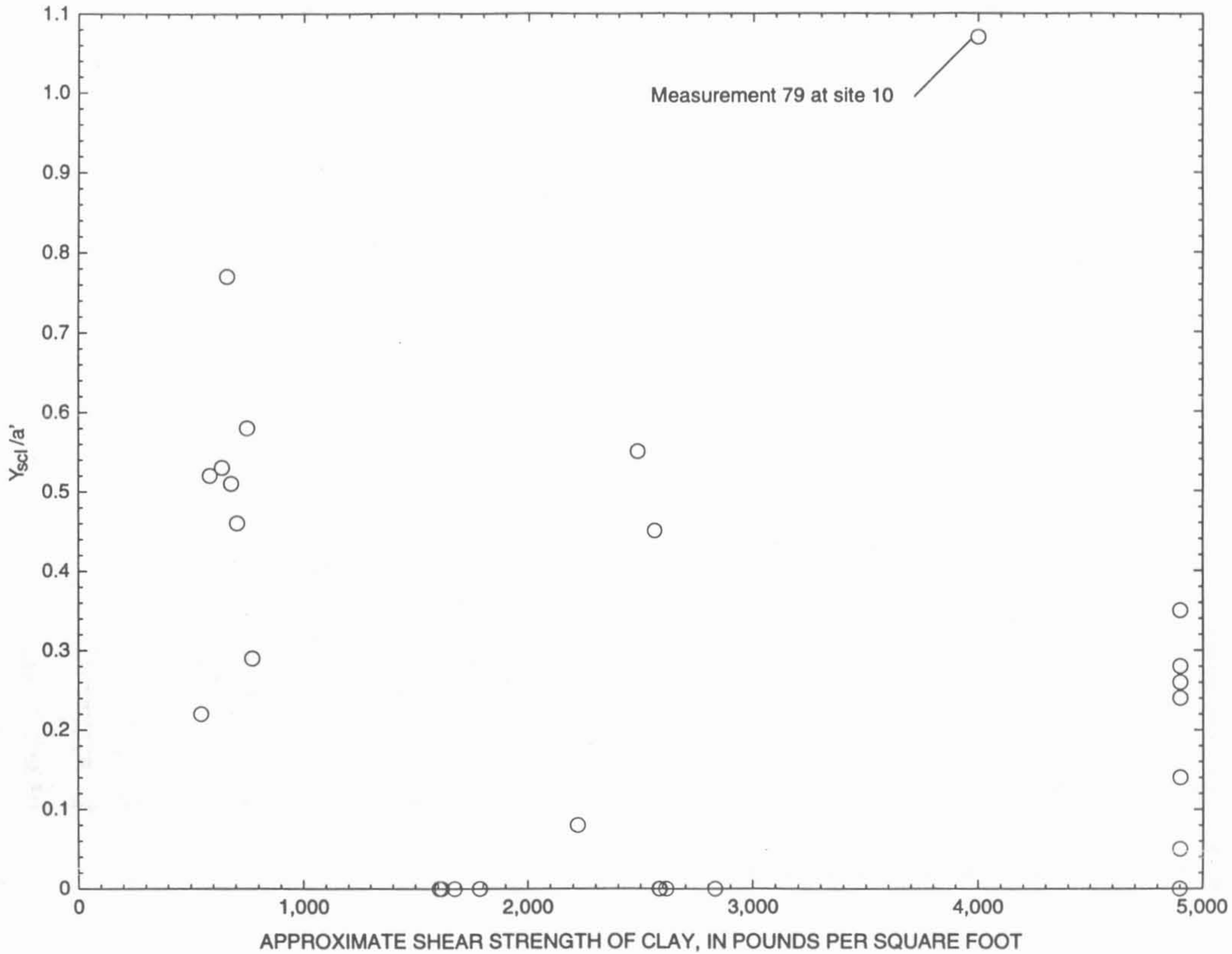

Figure 4. Relation between net pier-scour depth through clay divided by normal pier width (Y_{scl}/a') and approximate shear strength of clay for selected bridge sites in Mississippi.

Table 1. Selected bridge sites in Mississippi where scour data were collected
[mi^2, square miles; ft/ft, feet per foot]

Site no.	Station no.	Site name and location	Drainage area (mi^2)	Slope in vicinity (ft/ft)
1	02473000	Leaf River at U.S. Highway 11 at Hattiesburg, Miss.	1,750	0.00040
2	02474560	Leaf River at State Highway 29 near New Augusta, Miss.	2,540	0.00013
3	02474740	Leaf River at old State Highway 15 at Beaumont, Miss.	3,010	0.00019
4	02475000	Leaf River at U.S. Highway 98 near McLain, Miss.	3,500	0.00011
5	02475500	Chunky River at U.S. Highway 80 near Chunky, Miss.	369	0.00051
6	02478500	Chickasawhay River at State Highway 63 at Leakesville, Miss.	2,690	0.00025
7	02482550	Pearl River at old State Highway 35 near Carthage, Miss.	1,350	0.00034
8	02485735	Pearl River at westbound State Highway 25 at Jackson,Miss.	3,130	0.00019
9	02485735	Pearl River at eastbound State Highway 25 at Jackson, Miss.	3,130	0.00019
10	02488000	Pearl River at county road bridge at Rockport, Miss.	4,560	0.00015
11	02488500	Pearl River at U.S. Highway 84 near Monticello, Miss.	4,990	0.00011
12	02489000	Pearl River at westbound U.S. Highway 98 near Columbia, Miss.	5,720	0.00019
13	02489000	Pearl River at eastbound U.S. Highway 98 near Columbia, Miss.	5,720	0.00019
14	07274000	Yocona River at State Highway 7 near Oxford, Miss.	254	0.00062
15	07289730	Big Black River at northbound U.S. Highway 49 near Bentonia, Miss.	2,340	0.00019
16	07289730	Big Black River at southbound U.S. Highway 49 near Bentonia, Miss.	2,340	0.00019
17	07291000	Homochitto River at U.S. Highway 84 at Eddiceton, Miss.	181	0.00093
18	07291250	McCall Creek at U.S. Highway 84 near Lucien, Miss.	60.8	0.00163
19	07291500	Homochitto River at old U.S. Highway 98 near Bude, Miss.	407	0.00083
20	07291500	Homochitto River at U.S. Highway 98 near Bude, Miss.	407	0.00083
21	07292500	Homochitto River at State Highway 33 at Rosetta, Miss.	787	0.00100
22	07295000	Buffalo River at old U.S. Highway 61 near Woodville, Miss.	180	0.00059