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Prepared in cooperation with
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Streambed Stability and Scour Potential at Selected Bridge Sites in Michigan

Water-Resources Investigation Report 98-4024

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D.J. HOLTSCHLAG and R.L. MILLER

U.S. Geological Survey
Water-Resources Investigation Report 98-4024

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Lansing, Michigan
1998

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CONTENTS

Abstract 1
Introduction 1
Review of Literature 2
Identification of Study Sites 5
Acknowledgments 5
Characterization of Streambed Stability from Streamflow Measurement Data 6
Analysis of Data 6
Streambed Deviances at Study Sites 7
U.S. Highway 45 over Middle Branch Ontonagon River near Rockland (04035500) 7
Broadway Street over St. Joseph River at Niles (04101500) 8
Coloma Road over Paw Paw River at Riverside (04102500) 8
River Street over Kalamazoo River at Comstock (04106000) 14
State Highway 89 over Kalamazoo River near Fennville (04108500) 14
North Grand River Avenue over Grand River at Lansing (04113000) 20
Downstream Side of North Grand River Avenue Bridge 20
Upstream Side of North Grand River Avenue Bridge 20
State Highway 66 over Grand River at Ionia (04116000) 25
Scottville Road over Pere Marquette River at Scottville (04122500) 25
State Highway 37 over Manistee River near Sherman (04124000) 30
Fergus Road over Shiawassee River near Fergus (04145000) 30
State Highway 13 over Flint River near Fosters (04149000) 35
State Highway 46 over Saginaw River at Saginaw (04157000) 35
Moravian Drive over Clinton River at Mount Clemens (04165500) 40
Summary of Streambed Deviance Analyses 40
Characterization of Historical Scour Conditions from Geophysical Survey Information 44
Survey Methods 44
Ground-Penetrating Radar 44
Tuned Transducer 44
Scour Conditions at Study Sites 46
State Highway 89 over Kalamazoo River near Fennville (04108500) 46
North Grand River Avenue over Grand River at Lansing (04113000) 46
State Highway 66 over Grand River at Ionia (04116000) 46
Scottville Road over Pere Marquette River at Scottville (04122500) 46
Summary of Geophysical Survey Results 46
Estimation of Scour Potential on the Basis of Semi-Theoretical Equations 47
Application of Equations 47
Estimation of Scour Potential 48
U.S. Highway 45 over Middle Branch Ontonagon River near Rockland (04035500) 48
Broadway Street over St. Joseph River at Niles (04101500) 49
Coloma Road over Paw Paw River at Riverside (04102500) 52
River Street over Kalamazoo River at Comstock (04106000) 52
State Highway 89 over Kalamazoo River near Fennville (04108500) 55
North Grand River Avenue over Grand River at Lansing (04113000) 57
State Highway 66 over Grand River at Ionia (04116000) 57
Scottville Road over Pere Marquette River at Scottville (04122500) 59
State Highway 37 over Manistee River near Sherman (04124000) 62

Estimation of Scour Potential on the Basis of Semi-Theoretical Equations—*Continued*
Estimation of Scour Potential—*Continued*
Fergus Road over Shiawassee River near Fergus (04145000) 62
State Highway 13 over Flint River near Fosters (04149000) 64
State Highway 46 over Saginaw River at Saginaw (04157000) 67
Moravian Drive over Clinton River at Mount Clemens (04165500) 67
Relation of Streambed Stability with Scour Potential 69
Summary and Conclusions 71
References Cited 72

FIGURES

1. Map of Michigan showing the location of study sites 5
2. Section showing normal streambed profile and local streambed variability at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich. 9
3,4. Graphs showing:
3. Trend in streambed deviance at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich. 10
4. Relation between streambed deviance and streamflow at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich. 10
5. Section showing normal streambed profile and local streambed variability at Broadway Street over St. Joseph River at Niles, Mich. 11
6,7. Graphs showing:
6. Trend in streambed deviance at Broadway Street over St. Joseph River at Niles, Mich. 12
7. Relation between streambed deviance and streamflow at Broadway Street over St. Joseph River at Niles, Mich. 12
8. Section showing normal streambed profile and local streambed variability at Coloma Road over Paw Paw River at Riverside, Mich. 15
9,10. Graphs showing:
9. Trend in streambed deviance at Coloma Road over Paw Paw River at Riverside, Mich. 16
10. Relation between streambed deviance and streamflow at Coloma Road over Paw Paw River at Riverside, Mich. 16
11. Section showing normal streambed profile and local streambed variability at River Street over Kalamazoo River at Comstock, Mich. 17
12,13. Graphs showing:
12. Trend in streambed deviance at River Street over Kalamazoo River at Comstock, Mich. 18
13. Relation between streambed deviance and streamflow at River Street over Kalamazoo River at Comstock, Mich. 18
14. Section showing normal streambed profile and local streambed variability at State Highway 89 over Kalamazoo River near Fennville, Mich. 19
15,16. Graphs showing:
15. Trend in streambed deviance at State Highway 89 over Kalamazoo River near Fennville, Mich. 21
16. Relation between streambed deviance and streamflow at State Highway 89 over Kalamazoo River near Fennville, Mich. 21
17. Section showing normal streambed profile and local streambed variability at the downstream side of North Grand River Avenue over Grand River at Lansing, Mich. 22
18,19. Graphs showing:
18. Trend in streambed deviance at the downstream side of North Grand River Avenue over Grand River at Lansing, Mich. 23
19. Relation between streambed deviance and streamflow at the downstream side of North Grand River Avenue over Grand River at Lansing, Mich. 23
20. Section showing normal streambed profile and local streambed variability at the upstream side of North Grand River Avenue at Grand River at Lansing, Mich. 24

21,22. Graphs showing:
21. Trend in streambed deviance at the upstream side of North Grand River Avenue over Grand River in Lansing, Mich. 26
22. Relation between streambed deviance and streamflow at the upstream side of North Grand River Avenue over Grand River in Lansing, Mich. 26
23. Section showing normal streambed profile and local streambed variability at State Highway 66 over Grand River at Ionia, Mich. 27
24,25. Graphs showing:
24. Trend in streambed deviance at State Highway 66 over Grand River at Ionia, Mich. 28
25. Relation between streambed deviance and streamflow at State Highway 66 over Grand River at Ionia, Mich. 28
26. Section showing normal streambed profile and local streambed variability at Scottville Road over Pere Marquette River at Scottville, Mich. 29
27,28. Graphs showing:
27. Trend in streambed deviance at Scottville Road over Pere Marquette River at Scottville, Mich. 31
28. Relation between streambed deviance and streamflow at Scottville Road over Pere Marquette River at Scottville, Mich. 31
29. Section showing normal streambed profile and local streambed variability at State Highway 37 over Manistee River near Sherman, Mich. 32
30,31. Graphs showing:
30. Trend in streambed deviance at State Highway 37 over Manistee River near Sherman, Mich. 33
31. Relation between streamflow deviance and streamflow at State Highway 37 over Manistee River near Sherman, Mich. 33
32. Section showing normal streambed profile and local streambed variability at Fergus Road over Shiawassee River near Fergus, Mich. 34
33,34. Graphs showing:
33. Trend in streambed deviance at Fergus Road over Shiawassee River near Fergus, Mich. 36
34. Relation between streambed deviance and streamflow at Fergus Road over Shiawassee River near Fergus, Mich. 36
35. Section showing normal streambed profile and local streambed variability at State Highway 13 over Flint River near Fosters, Mich. 37
36,37. Graphs showing:
36. Trend in streambed deviance at State Highway 13 over Flint River near Fosters, Mich. 38
37. Relation between streambed deviance and streamflow at State Highway 13 over Flint River near Fosters, Mich. 38
38. Section showing normal streambed profile and local streambed variability at State Highway 46 over Saginaw River at Saginaw, Mich. 39
39,40. Graphs showing:
39. Trend in streambed deviance at State Highway 46 over Saginaw River at Saginaw, Mich. 41
40. Relation between streambed deviance and streamflow at State Highway 46 over Saginaw River at Saginaw, Mich. 41
41. Section showing normal streambed profile and local streambed variability at Moravian Drive over Clinton River at Mount Clemens, Mich. 42
42-44. Graphs showing:
42. Trend streambed deviance at Moravian Drive over Clinton River at Mount Clemens, Mich. 43
43. Relation between streambed deviance and streamflow at Moravian Drive over Clinton River at Mount Clemens, Mich. 43
44. Variability of deviances in the main channel and deviances adjacent to piers at selected sites in Michigan 45

45-57. Sections showing:
45. Estimated scour potential associated with the 100-yr flood at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich. 50
46. Estimated scour potential associated with the 100-yr flood at Broadway Street over St. Joseph River at Niles, Mich. 51
47. Estimated scour potential associated with the 100-yr flood at Coloma Road over Paw Paw River at Riverside, Mich. 53
48. Estimated scour potential associated with the 100-yr flood at River Street over Kalamazoo River at Comstock, Mich. 54
49. Estimated scour potential associated with the 100-yr flood at State Highway 89 over Kalamazoo River near Fennville, Mich. 56
50. Estimated scour potential associated with the 100-yr flood at North Grand River Avenue over Grand River in Lansing, Mich. 58
51. Estimated scour potential associated with the 100-yr flood at State Highway 66 over Grand River at Ionia, Mich. (Depiction of footings for abutments and piers is based on 1947 bridge design plans by MSHD.) 60
52. Estimated scour potential associated with the 100-yr flood at Scottville Road over Pere Marquette River at Scottville, Mich. 61
53. Estimated scour potential associated with the 100-yr flood at State Highway 37 over Manistee River near Sherman, Mich. 63
54. Estimated scour potential associated with the 100-yr flood at Fergus Road over Shiawassee River near Fergus, Mich. 65
55. Estimated scour potential associated with the 100-yr flood at State Highway 13 over Flint River near Fosters, Mich. 66
56. Estimated scour potential associated with the 100-yr flood at State Highway 46 over Saginaw River at Saginaw, Mich. 68
57. Estimated scour potential associated with the 100-yr flood at Moravian Drive over Clinton River at Mount Clemens, Mich. 70

TABLES

1. Bridge sites in Michigan selected for evaluation of streambed stability and scour potential 5
2. Correlation between streambed deviance and time, streamflow, flow velocity and flow depth 13
3. Scour potential of the 100-yr flood at U.S. Highway 45 bridge over Middle Branch Ontonagon River near Rockland, Mich. 49
4. Scour potential of the 100-yr flood at Broadway Street bridge over St. Joseph River at Niles, Mich. 49
5. Scour potential of the 100-yr flood at Coloma Road bridge over Paw Paw River at Riverside, Mich. 55
6. Scour potential of the 100-yr flood at River Street bridge at Kalamazoo River at Comstock, Mich. 55
7. Scour potential of the 100-yr flood at State Highway 89 bridge over Kalamazoo River near Fennville, Mich. 55
8. Scour potential of the 100-yr flood at North Grand River Avenue bridge over Grand River in Lansing, Mich. 57
9. Scour potential of the 100-yr flood at State Highway 66 bridge over Grand River at Ionia, Mich. 59
10. Scour potential of the 100-yr flood at Scottville Road bridge over Pere Marquette River at Scottville, Mich. 59
11. Scour potential of the 100-yr flood at State Highway 37 bridge over Manistee River near Sherman, Mich. 62
12. Scour potential of the 100-yr flood at Fergus Road bridge over Shiawassee River near Fergus, Mich. 64
13. Scour potential of the 100-yr flood at State Highway 13 over Flint River near Fosters, Mich. 64
14. Scour potential of the 100-yr flood at State Highway 46 bridge over Saginaw River at Saginaw, Mich. 67
15. Scour potential of the 100-yr flood at Moravian Drive bridge over Clinton River at Mount Clemens, Mich. 67

CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows: °C = 5/9 (°F - 32).

VERTICAL DATUM

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Streambed Stability and Scour Potential at Selected Bridge Sites in Michigan

By D. J. Holtschlag *and* R. L. Miller

Abstract

Contraction scour in the main stream channel at a bridge and local scour near piers and abutments can result in bridge failure. Estimates of contraction-scour and local-scour potentials associated with the 100-year flood were computed for 13 bridge sites in Michigan by use of semi-theoretical equations and procedures recommended by the Federal Highway Administration. These potentials were compared with measures of streambed stability obtained by use of data from 773 historical streamflow measurements, documenting 20,741 individual streambed soundings between 1959 and 1995. Analysis of these data indicate small, but statistically significant, monotonic trends in streambed elevation at 10 sites. No consistent patterns in relations between changes in streambed elevations and streamflow, flow velocity, or flow depth were evident. Also, estimates of contraction-scour potential were not correlated with measures of streambed stability, and no differences were detected between measures of streambed stability in the main channel and stability adjacent to piers. Despite the inconsistencies between measures of streambed stability and scour potential, data from a single, large flood (greater than a 100-year event) provided field evidence that the relation between scour and streamflow is highly nonlinear. This nonlinearity and the limited availability of measurements of extreme flood events may have reduced the utility of the empirical measures for confirming the nonlinear scour-potential equations and procedures. Results of field surveys using ground-penetrating radar and tuned transducers showed limited ability to aid interpretation of historical scour conditions at four bridge sites. Additional research is needed to confirm the applicability of scour-potential equations for hydrogeologic conditions in Michigan.

INTRODUCTION

Contraction scour in the main stream channel at a bridge and local scour near piers and abutments can result in bridge failure. Richardson and others (1990) have developed a set of semi-theoretical equations for estimating contraction-scour and local-scour potentials that are used nationwide to facilitate the design and maintenance of bridges. The applicability of these equations for hydrogeologic conditions in Michigan, however, has not been demonstrated with empirical data.

Direct measurements of streambed elevations and streamflow are not routinely obtained for the purpose of assessing scour at or near bridges. Ideally, such measurements would be made (1) during floods in which measurements are repeated throughout the flood event, including measurements of streambed elevation at the peak flow, and during rising and falling stages before and after the peak flow, (2) on both the upstream and downstream sides of bridges, and (3) at numerous sites where bridges cross streams. This type of data would enable a direct comparison between repeated measurements of scour and computed scour potentials for specific flood magnitudes. Such data are not available for Michigan.

Streambed soundings are obtained incidentally to maintaining the stage-discharge relation at streamflow-gaging stations operated by the U.S. Geological Survey (USGS) in cooperation with Michigan Department of Transportation (MDOT) and other governmental agencies. In Michigan, some of these stations are located in the vicinity of bridges, which are used for flow measurements when the streams are not wadeable. Here, routine measurements are commonly made on the downstream side of bridge openings, only occasionally at flows exceeding a 10-yr flood event, and seldom more than once in any 3-week interval. Despite these limitations, streambed profiles obtained during streamflow measurements provide important information about streambed stability.

The USGS, in cooperation with MDOT, conducted a study of scour at bridges in Michigan. Streambed stability in the main channel was assessed as an indicator of contraction-scour potential. Additionally, the geometry and stability of the streambed adjacent to piers was assessed as an indicator of local scour potential. Significant positive correlation between these empirical measures of streambed stability and semi-theoretical estimates of scour potential would provide statistical evidence to support the applicability of the scour-potential equations in Michigan. Finally, to supplement these analyses, field surveys were conducted to determine whether geophysical techniques could be used to assess historical scour conditions in Michigan.

This report describes (1) the historical variability in streambed elevations on the basis of data collected in connection with routine streamflow measurements at 13 sites, (2) trends in aggradation and degradation of streambed elevations as indicated by the 40 or more historical streamflow measurements at each site, and (3) the relation between streamflow and streambed elevations as indicated by historical streamflow measurement data. The report summarizes results of geophysical surveys near four selected bridge sites to evaluate the potential for assessing historical scour conditions. Finally, the report presents scour potentials associated with 100-yr (year) floods computed from semi-theoretical equations and procedures recommended for nationwide use by Federal Highway Administration (FHWA), and compares empirical measures of streambed stability in Michigan with scour-potential estimates computed by use of equations and procedures recommended by FHWA.

Review of Literature

Streambed elevations vary due to complex interrelated natural processes. Bridge crossings frequently disrupt and intensify these natural processes by constricting the flow area of a stream at flood flows and by disturbing local flow conditions with obstructions such as piers (Landers and Mueller, 1996). Estimates of the scour potential at bridge sites are needed to help identify sites where maintenance or structural enhancements are needed to avoid bridge failure.

Streambed elevation in a contraction can be estimated using three methods: (1) empirical relations similar to at-a-station hydraulic geometry relations for width and depth, (2) regime relations for channel size and shape, and (3) contraction scour equations based on particular sediment transport and uniform flow formulas. At-a-station hydraulic geometry relations are empirical and although some research has indicated a general agreement as to the exponent in the relations (Leopold and Maddock, 1953), other research (Park, 1977) showed a wide variation in the exponents. Even when the exponent is relatively stable the coefficient must be determined individually for any stream. Therefore, based on research of at-a-station hydraulic geometry, the general applicability of empirical relations for estimating depths in contractions is questionable. Regime relations for channel size and shape have been used and developed for many years for designing channel improvements; however, these relations are also empirical. Very little success has been achieved when these relations are applied to situations other than those from which they were developed. Several researchers have developed contraction scour equations for long contractions based on a selected sediment transport equations (Laursen, 1960, 1962, 1963; Straub, 1934, 1962; Komura, 1966; Culbertson and other, 1967). These published equations have not been adequately tested against field data to prove their applicability to varying conditions, especially to bridges where the assumptions of a long contraction may be violated. In addition, evaluations of sediment transport equations have shown a wide variation in the computed transport rates for identical situations (White and others, 1975, 1978; Alonso, 1980; Brownlie, 1981). If the sediment transport equation does not adequately represent the sediment transport, it is unlikely that a contraction scour equation based on the transport equation could provide accurate estimates of scour.

Contraction scour has traditionally been classified as live-bed or clear-water. The live-bed condition occurs when the flow upstream from the contracted section is transporting bedload into a scour hole and material transported from the scour hole consists of both material from the scour hole and material transported from upstream. Live-bed scour would be typical of scour that would occur in the main channel portion of a stream at high flow. The clear-water condition occurs when the flow upstream does not transport bedload and the only material being transported from the scoured area is the material being scoured. Clear-water scour can occur at a relief bridge or on the overbank areas of a bridge opening with abutments set back from the main channel. Scour occurring in vegetated overbank areas may be classified as clear-water scour even though the shear stress in the approach section exceeds the critical shear stress. The live-bed contraction scour equation recommended in Hydraulic Engineering Circular Number 18 (HEC-18) (Richardson and others, 1993, p. 11) is the equation developed by Laursen (1962) and the clear-water scour equation is the equation developed by Laursen (1963).

Straub (1935) was the first to develop an approach to predict contraction scour that most others would follow. He assumed that the bed in the contracted section would scour until it reached a depth at which the local transport capacity was equal to the amount of material being supplied from upstream (sediment discharge continuity). Straub estimated the slopes in the contracted and uncontracted reaches using Manning's equation. This assumption is reasonable in the case of a long contraction where the flow conditions in the contraction can be approximated a sufficient distance from the beginning of the contraction to allow the assumption of normal flow. The hydraulics in a short contraction, such as a bridge crossing where the contraction is due to the abutments and road embankment, however, require the consideration of additional energy losses not accounted for in a roughness coefficient based on the channel composition and configuration (Matthai, 1967; Schneider and others, 1977; Shearman and others, 1986). Straub's equation is lengthy, and includes the ratios of width, roughness coefficients, and discharges at the contracted and uncontracted sections and the ratio of critical shear stress to bed shear stress at the uncontracted section.

Laursen (1962) assumed live-bed conditions and used a discharge equation (Manning's equation), a sediment transport equation (Laursen, 1958), and discharge and sediment continuity to solve for the ratio of depth in a long contraction to that of a uniform reach. He then assumed, "A bridge crossing is in effect a long contraction foreshortened to such an extreme that it has only a beginning and an end" (Laursen, 1962, p. 171). Similar to Straub's approach, Laursen's derivation contains two very important and limiting assumptions. First, he used his own sediment transport equation (Laursen, 1958). Numerous comparisons of the sediment transport equations have been published, some of which included the Laursen equation (White and others, 1975, 1978; Alonso, 1980; Brownlie, 1981). These comparisons show that for many situations, the Laursen transport equation does not provide a good estimate of the measured bed material discharge. Therefore, the applicability of Laursen's contraction scour equation in these situations is questionable. Second, Laursen assumed that Manning's formula could be used to describe the flow conditions. The use of Manning's equation to estimate flow conditions for short contractions such as bridge crossings may provide inaccurate estimates.

Laursen (1963, p. 93) assumed, "that the limit of clear-water scour is a boundary shear equal to the critical tractive force." On the basis of this assumption, the depth of clear-water scour will be the depth at which the boundary shear is equal to the critical shear. Laursen also assumed that the difference in slope between the uncontracted and contracted reaches was negligible. Using these assumptions, the energy equation through the contraction and Manning's equation with Strickler's relation for n to estimate the boundary shear in the uncontracted reach associated with the sediment particles, Laursen derived a lengthy equation. To simplify this equation, Laursen assumed that the difference in the velocity heads and the loss through the transition were also negligible. This simplified form of the equation is the equation recommended by HEC-18 (Richardson and others, 1993). On the basis of work by Matthai (1967) and Schneider and others (1977), the losses may be significant and probably should not be neglected for short contractions.

Komura (1966) acknowledged the previous work on contraction scour but concluded that the previous work did not address the effects of the standard deviation of the sediment composing the beds. Komura followed the same approach as Straub (1935) except that he used the transport formula developed by Kalinske and Brown (Rouse, 1949). Equations were derived for both the live-bed and clear-water scour situations. The live-bed equation assumes that the discharge through the contracted and uncontracted sections are equal and that the resistance to flow can be described by a power function relating relative roughness to the ratio of the velocity and shear velocity. The derived live-bed equation relates the ratio of the depths to a ratio of the bed shear stresses and the widths at the contracted and uncontracted sections. The clear-water equation assumes that at equilibrium scour, both the contracted and uncontracted sections will be at the critical tractive force. Using a formula for critical tractive force presented by Iwagaki (1956), Komura derived an equation for clear water scour that relates the ratio of the depths to ratios of the bed shear stress, widths, and mean diameter of the bed material at the contracted and uncontracted sections. Although if one assumes that the contracted section is at the critical tractive force is reasonable, it would not appear reasonable to assume that the uncontracted section is also at the critical tractive force, because this would limit the equation to only one specific flow condition. It is also interesting to note that except for the influence of the grain size on the bed shear force, live-bed scour defined by Komura's equation is not dependent on the grain size. Komura (1966) also developed live-bed and clear-water scour equations based on dimensional analysis and regression of laboratory data. On the basis of results of these experiments, Komura concluded that the relative depth could be related to the Froude number of the uncontracted section, the ratio of the widths, and the standard deviation of the particle size distribution.

Culbertson and others (1967) reviewed the previously published research and concluded that none of the existing equations were applicable to all channels or to abrupt contractions resulting from bridges and road embankments. They, however, presented a derivation following Straub's (1935) approach using Colby's transport relations for sand bed streams (Colby, 1964). If Manning's *n* and Colby's coefficient, *K*, are assumed to be identical for the contracted and uncontracted sections, the resulting equation relates the relative depth to the ratio of the widths. Culbertson and others clearly recognized the difference between a long contraction and the contraction at a bridge, and believed that equations based on long contractions could provide only a very rough estimate of the potential scour. Vegetated overbanks, asymmetric flow on the overbanks, channel curvature, or any combination of these conditions, however, would result in scour being significantly different from uniform. "Careful consideration of these conditions can lead to rough prediction as to where the maximum scour might occur, but no reasonable estimate of the depth of maximum scour is possible." (Culbertson and others, 1967, p. 39). For the improvement of contraction scour prediction techniques Culbertson and others concluded:

"Although laboratory research on alluvial channels may lead to more reliable predictions of scour and fill based on hydraulic theory and empirical equations, the scour and fill problem is inherently complicated, and evaluations based on field experience are needed." (Culbertson and others, 1967, p. 43)

Nordin (in Simons and others, 1980) presented an approach for determining contraction scour for flows confined within the channel. This approach is based on water and sediment continuity expressed as width ratios and unit discharges (sediment and water). Relations between unit water discharge and depth and velocity at the contracted and uncontracted sections are developed. Then, by utilizing an unspecified sediment transport equation (Colby's was used only for example purposes), unit sediment discharge can be expressed as a function of depth and velocity. Combining the unit water discharge and sediment discharge expressed as a function of velocity and depth yields the depth of the contracted and uncontracted sections. The depth of scour is then the difference between the depths of these two sections. Although this method was presented for flows confined within the channel, it would appear to be applicable to contraction scour in general if the width was assumed to be the bottom width and the discharge was taken to be the discharge transported over this bottom width.

Table 1. Bridge sites in Michigan selected for evaluation of streambed stability and scour potential

Site index (USGS streamflow-gaging station number)	Site name	North latitude	West longitude	Drainage area (square miles)
04035500	U.S. Highway 45 over Middle Branch Ontonagon River near Rockland	46°41'57"	89°09'36"	671
04101500	Broadway Street over St. Joseph River at Niles	41°49'45"	86°15'35"	3,666
04102500	Coloma Road over Paw Paw River at Riverside	42°11'10"	86°22'06"	390
04106000	River Street over Kalamazoo River at Comstock	42°17'08"	85°30'50"	1,010
04108500	State Highway 89 over Kalamazoo River near Fennville	42°35'36"	85°59'03"	1,600
04113000	North Grand River Avenue over Grand River at Lansing	42°45'02"	84°33'19"	1,230
04116000	State Highway 66 over Grand River at Ionia	42°58'20"	85°04'13"	2,840
04122500	Scottville Road over Pere Marquette River at Scottville	43°56'42"	86°16'43"	681
04124000	State Highway 37 over Manistee River near Sherman	44°26'11"	85°41'55"	857
04145000	Fergus Road over Shiawassee River near Fergus	43°15'17"	84°06'20"	637
04149000	State Highway 13 over Flint River near Fosters	43°18'30"	83°57'13"	1,188
04157000	State Highway 46 over Saginaw River at Saginaw	43°24'46"	83°57'47"	6,060
04165500	Moravian Drive over Clinton River at Mount Clemens	42°35'45"	82°54'35"	734

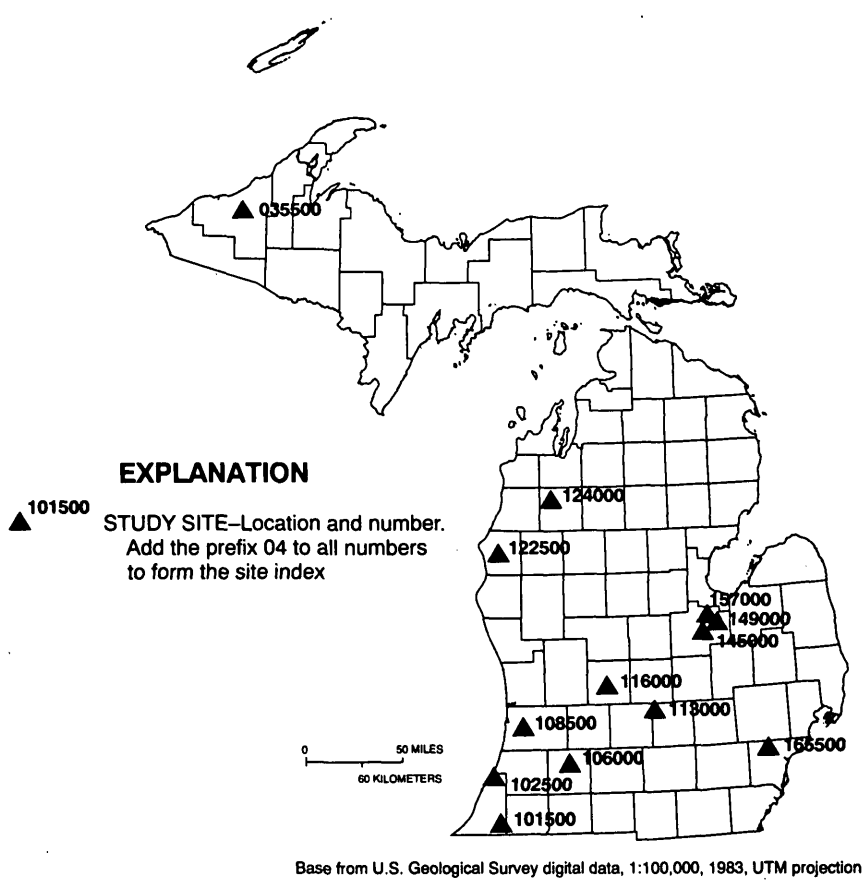

Figure 1. Map of Michigan showing the location of study sites.

Identification of Study Sites

Thirteen highway bridges crossing alluvial streams were selected for analysis of scour potential and streambed stability. Selected sites (fig.1, table 1) represent a range of hydrogeologic conditions in Michigan. Selection was restricted to those sites where streamflow was commonly measured from bridges near USGS streamflow-gaging stations for a period of 10 or more years. Geophysical surveys were conducted at four sites.

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provided information on flood frequency and magnitude and hydraulic data associated with flood insurance studies. David Westjohn and Michael Sweat, U.S. Geological Survey, Michigan District, collected geophysical data. David Mueller, U.S. Geological Survey, Kentucky District, contributed the review of literature.

CHARACTERIZATION OF STREAMBED STABILITY FROM STREAMFLOW MEASUREMENT DATA

Direct measurements of streamflow are obtained at approximately 6-week intervals at continuous streamflow-gaging stations operated by USGS. The measurements are used to develop and maintain a quantitative relation between stage (water-surface elevation) and discharge (streamflow). The direct streamflow measurements are used in concert with hourly or more frequent (and commonly continuously recorded) measurements of stage to compute hourly and daily-mean streamflow values. Long-term records of streamflow are used to quantify streamflow characteristics.

Streamflow measurements are commonly made by wading a hand-held rod and current-velocity meter across a shallow (less than 4 ft deep) stream. In cases where the water is deeper, measurements are commonly made by lowering a sounding weight and current-velocity meter from the deck of a bridge into a stream cross section formed by the bridge opening. As part of each streamflow measurement, water depths are measured along the measurement cross section. When the depth measurements are adjusted to a common datum, they provide an historical record of the changes in elevation of the streambed.

Measurements from bridges are particularly valuable for determining the changes in elevation of the streambed for several reasons. First, the location of the measurement cross section is accurately reproducible at the upstream or downstream side of the bridge opening. Second, the measurement protocol requires depth measurements adjacent to abutments and piers, which can be used to assess affects of local scour. And third, depth measurements at higher streamflow conditions and during floods, which commonly are associated with higher scour potential, are usually made from bridges.

Analysis of Data

Streambed elevation data from 40 or more historical streamflow measurements were compiled for each of 13 selected bridge sites. Although the measurements used in this analysis represent a wide range of flow conditions, measurements of relatively high flows (those greater than the mean discharge) were preferentially selected to document conditions with greatest scour potential. Also, selected measurements were restricted to a single interval of time so that there was a sufficient density of measurements to document trends in streambed elevation. Finally, selection of streamflow measurements progressed from more recent to older historical measurements so that the most recent streambed elevation conditions available were documented in the analysis.

Each streamflow measurement from a bridge includes about 25 individual soundings of the streambed within the bridge opening. Because the streambed elevation varies systematically across the channel, a constant value does not provide an adequate estimate of the mean streambed elevation. Instead, a long-term mean streambed cross-sectional profile was computed to represent the mean streambed elevation. The long-term mean cross-sectional profile, which is referred to as the normal profile in this report, was computed by use of a variable-span smoother[1] (Statistical Sciences, 1993, p. 17-7).

In this report, deviances refer to deviations of individual streambed elevations from the normal profile. Streambed elevations above the normal profile retain a positive sign. Deviances were compiled in two ways to assess both temporal and spatial streambed stability. Temporal stability was assessed by grouping deviances by streamflow measurement. This grouping, referred to as the streambed deviance, describes the average (trimmed mean) difference in elevation between the streambed sounded during a measurement and the normal profile. The trimmed mean, which excludes 10 percent of the highest and lowest deviations, provides a robust estimator of the average. Thus, streambed deviances are not highly sensitive to transient accumulations of local debris piles, but are

[1]The variable-span smoother is based on a symmetric k-nearest neighbor linear least-squares procedure. That is $k/2$ data points on either sided of x are used in a linear regression to predict the value of x. This is run for three values of k, $n/2$, $n/5$, and $n/20$, where n is the number of measurements. Cross-validation is used to choose a value of k for x that is approximated by interpolation between these three (Venables and Ripley, 1994).

indicators of changes in average streambed elevations with time and streamflow rate, depth, and velocity. Spatial stability was also assessed by grouping deviances along subsections or categorical divisions (main channel or adjacent to piers) of the streambed profile. This spatial measure is referred to as the local deviance.

Streambed deviances were used with local-regression models to describe trends in streambed deviance and to describe the relation between streamflow and streambed deviances. Local-regression models provide a flexible mechanism for identifying the relation between two variables that is not limited to simple deterministic forms (Chambers and Hastie, 1992, p. 309). Thus, threshold effects or other nonlinear relations can be approximated by local-regression models if sufficient data are available. Local-regression models do not have a concise closed-form expression or parameters that can be individually tested for statistical significance. Therefore, local-regression models are considered an exploratory data analysis tool, which are not well suited for forecasting or projecting beyond the range of data utilized in the analysis.

To supplement the qualitative relations described by local-regression models, Spearman's rank correlation (Conover, 1980, p. 252) was computed to test the statistical significance of monotonic[2] trends in streambed deviances and monotonic relations between streambed deviances and streamflows, flow velocities, and flow depths. The measure of correlation, Spearman's *rho*, equals Pearson's *rho*, a common measure of linear correlation, on rank transforms of the data when no ties are present in the data set. Values of Spearman's *rho* are reported along with their associated *p*-value (the probability that the absolute value of *RHO*, the true value of the correlation, is greater than zero, given the sample *rho* value). When computed *p*-values were greater than 0.05, correlation coefficients were not considered significantly different than zero and it was inferred that no monotonic relation existed.

Magnitudes of local deviances are shown by use of box plots and expressed numerically as trimmed ranges. Box plots, adjusted to the local estimate of the normal profile, are positioned on plots of the bridge opening near the center of the interval from which streambed elevations were obtained to show the local variability. The 1-percent trimmed range was use to quantify the magnitude of local deviances. The trimmed range was computed as the difference between the 1st and 99th quantiles of the sample data. Quantiles were computed from the sample data by linearly interpolating between i^{th} order statistics computed as (i-1)/(number of samples - 1). Thus, for a sample of size 40 with maximum values of 1.0 and 0.9, and minimum values of -0.9 and -1.0, the trimmed range would be 1.922. The trimmed range provides a robust measure of the variability in local deviance that is not biased by the sample size. A Wilcoxon Signed-Rank Test (Conover, 1980, p. 280) was used to determine whether the range of local deviances near piers was statistically greater than the range of deviances in the main channel.

[2]Monotonic trends are non-decreasing or non-increasing with functions of time.

Streambed Deviances at Study Sites

U.S. Highway 45 over Middle Branch Ontonagon River near Rockland (04035500)[3]

U.S. Highway 45 bridge crosses Middle Branch Ontonagon River about 4 mi south of Rockland, Michigan in northeastern Ontonagon County. A USGS streamflow gaging station (Middle Branch Ontonagon River near Rockland, Mich., number 04035500) has operated at the site continuously since July 1942. Records from the gaging station indicate that the mean streamflow is 516 ft^3/s (cubic feet per second); a maximum instantaneous streamflow of 27,000 ft^3/s occurred on August 22, 1942; and a minimum daily mean streamflow of 145 ft^3/s occurred on December 3, 1963 (Blumer and others, 1996, p. 38). The gaging station, which is located on the left bank[4] about 10 ft (feet) upstream from the upstream-side of the bridge opening, has a datum[5] of 661.1 ft above sea level.

[3]The locations of study sites are shown on figure 1.

[4]References to left bank and right bank assume the observer is facing downstream.

[5]The datum is an elevation, which when added to the gage height, describes the stage or elevation of the water surface above a common reference datum, such as sea level. The datum often corresponds approximately to the point of zero flow in the stream.

Streamflow is commonly measured at low and medium stages by wading a section about 500 ft downstream from the gaging station. At higher stages, streamflow is measured from the bridge deck along the downstream side of the bridge opening. A normal streambed profile was computed for the downstream side of the bridge opening (fig. 2) by use of 1,528 soundings obtained from 58 streamflow measurements between April 10, 1959 and May 11, 1993. Measurements used in developing the normal profile represent mean and maximum streamflows of 3,240 and 11,200 ft^3/s, mean and maximum velocities of 3.64 and 5.76 ft/s; and mean and maximum mean flow depths of 3.69 and 9.42 ft, respectively. At this gaging station, 11,200 ft^3/s is a 5.4-yr (recurrence interval[6]) flood.

Deviances had a mean and standard deviation of -0.048 and 0.84 ft, respectively, and ranged from -5.10 to 3.48 ft. Streambed deviances ranged from -0.65 to 0.79 ft and had a mean and standard deviation of -0.05 and 0.40 ft, respectively. These deviances tended gradually downward between 1959 and 1979 (fig. 3). In 1979, the streambed deviances abruptly decreased about 0.75 ft. Since 1979, streambed deviances have generally increased, but remain below pre-1979 levels. Trend analysis indicates that streambed deviances were generally negative during this period (table 2). Although streambed deviations and streamflow (fig. 4) and flow velocity are positively correlated (table 2), these relations may be confounded by effects of trends. In general, higher streamflows and flow velocities would be expected to be associated with greater scour (negative streambed deviances). Local deviances had greatest variability in the center of the main channel.

Broadway Street over St. Joseph River at Niles (04101500)

Broadway Street bridge crosses St. Joseph River within the City of Niles, Michigan in the southeastern corner of Berrien County. A gaging station has been maintained at this site from October 1930 to the present. Based on records for this gaging station, the mean streamflow is 3,400 ft^3/s; a maximum instantaneous streamflow of 20,200 ft^3/s occurred on April 5, 1950; and a minimum daily mean streamflow of 420 ft^3/s occurred on August 30, 1931 (Blumer and others, 1996, p. 101). Due to low stream gradients, which cause variable backwater conditions in the river, two points of simultaneous stage measurement are used to compute streamflow. The base station is located on the right bank, 100 ft upstream from the U.S. Highway 31/ U.S. Business 12 (about 1,000 ft north (downstream) of Broadway Street). The auxiliary station is located about 1.1 mi downstream from the base station. The datum of the gaging station is 633.02 ft above sea level.

All streamflow measurements are made from the upstream side of Broadway Street bridge. A normal profile was computed on the basis of 1,335 soundings obtained from 50 streamflow measurements between May 17, 1971 and April 11, 1995 (fig. 5). Measurements used in developing the normal profile represent mean and maximum streamflows of 5,820 and 19,400 ft^3/s, mean and maximum velocities of 2.81 and 5.11 ft/s; and mean and maximum flow depths of 8.02 and 13.60 ft, respectively. At this gaging station, 19,400 ft^3/s is a 41.2-yr flood.

Deviances had a mean and standard deviation was -0.01 and 0.57 ft, respectively, and ranged from -2.26 to 5.05 ft. Streambed deviances ranged from -0.42 to 0.40 ft and had a mean and standard deviation of -0.02 and 0.17 ft, respectively. Trend analysis indicate that streambed deviances were generally positive (fig. 6) during the period represented by the selected streamflow measurements (table 2). Steambed deviances show no consistent relation to streamflow (fig. 7) velocity, or depth (table 2). Variability of the local deviances was greatest between the left abutment and the left-most pier.

Coloma Road over Paw Paw River at Riverside (04102500)

Coloma Road bridge crosses Paw Paw River about 0.8 mi east of the Village of Riverside, Michigan, in northern Berrien County. The gaging station has operated continuously from October 1951 to the present. Based on this period of record, the mean streamflow is 462 ft^3/s; a maximum instantaneous streamflow of 3,580 ft^3/s occurred on October 4, 1986; and a minimum daily mean streamflow of 120 ft^3/s occurred on September 8, 1964 (Blumer and others, 1996, p. 105). The gaging station, which is located on the left bank, 40 ft upstream from the bridge on Coloma Road, has a datum of 588.80 ft above sea level.

[6]The recurrence interval indicates the average length of time between floods that equal or exceed a specified magnitude.

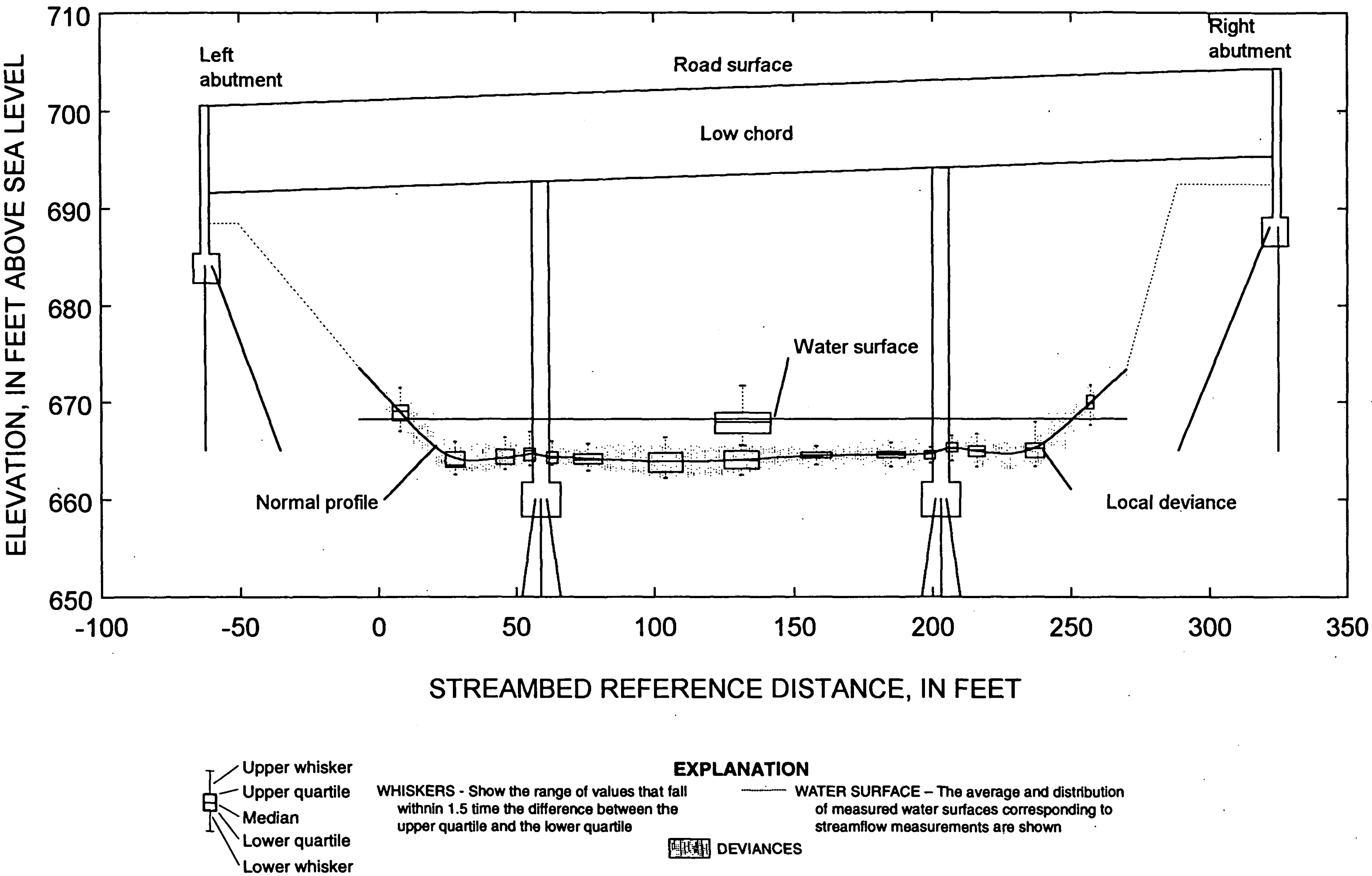

Figure 2. Normal streambed profile and local streambed variability at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich. The relative widths of the boxes are proportional to the square root of the number of measurements.

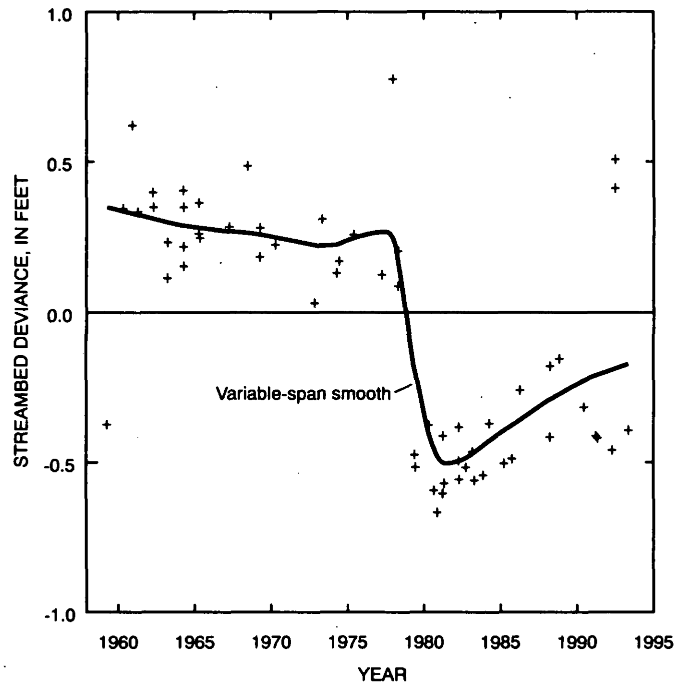

Figure 3. Trend in streambed deviance at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich.

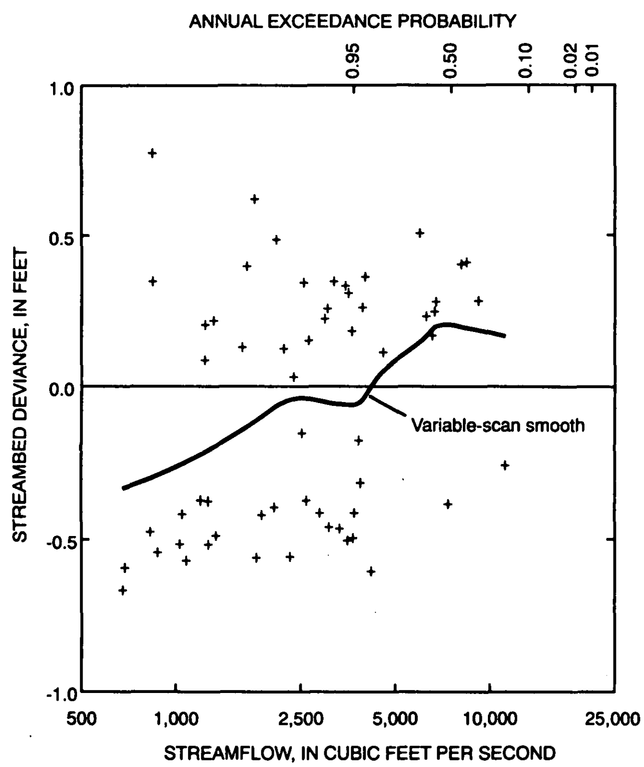

Figure 4. Relation between streambed deviance and streamflow at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich.

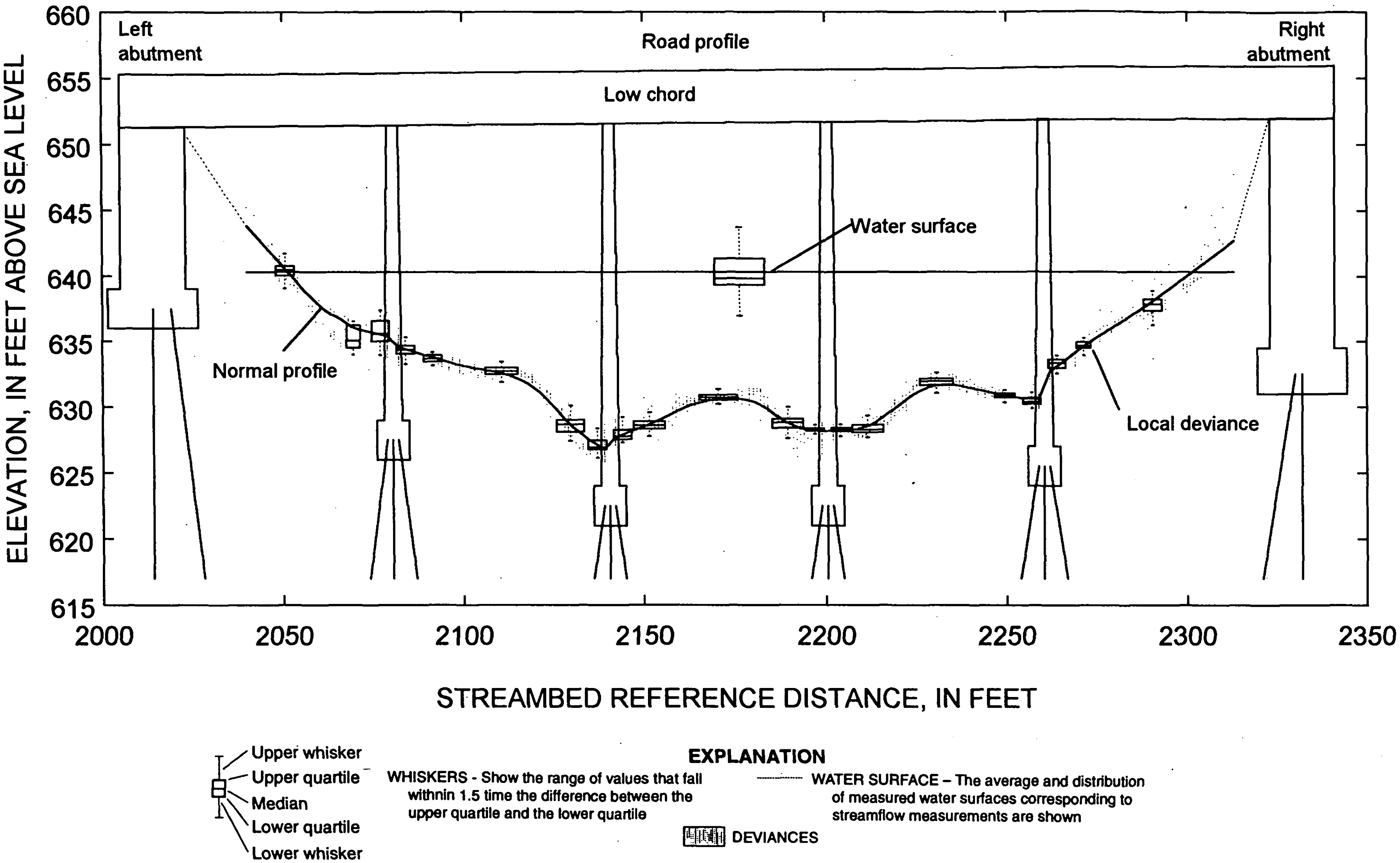

Figure 5. Normal streambed profile and local streambed variability at Broadway Street over St. Joseph River at Niles, Mich.

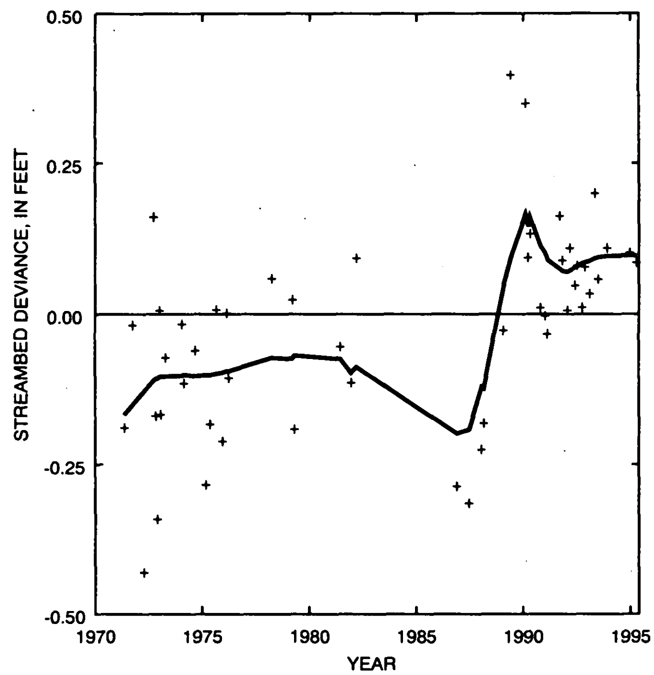

Figure 6. Trend in streambed deviance at Broadway Street over St. Joseph River at Niles, Mich.

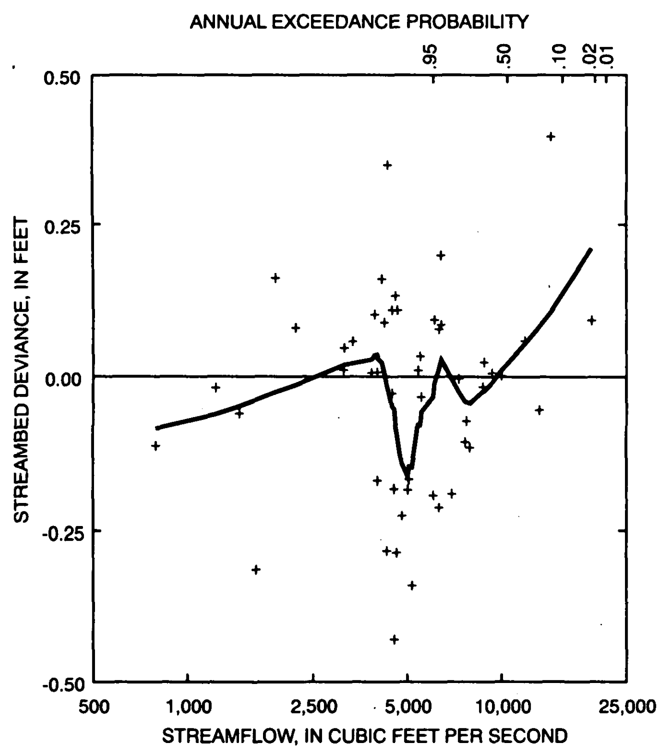

Figure 7. Relation between streambed deviance and streamflow at Broadway Street over St. Joseph River at Niles, Mich.

Table 2. Correlation between streambed deviance and time, streamflow, flow velocity, and flow depth

[*rho* indicates the Spearman correlation coefficient and the p-value indicates the statistical significance level]

Site name	Spearman correlation between streambed deviance and:							
	Trend		Streamflow		Velocity		Depth	
	rho	*p*-value	*rho*	*p*-value	*rho*	*p*-value	*rho*	*p*-value
U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich.	-.562	<0.001	0.339	0.010	0.480	<0.001	0.219	0.098
Broadway Street over St. Joseph River at Niles, Mich	.593	<.001	.012	.931	.036	.804	-.036	.801
Coloma Road over Paw Paw River at Riverside, Mich.	-.258	.084	.244	.101	.262	.079	.234	.117
River Street over Kalamazoo River at Comstock, Mich.	-.303	.017	-.278	.029	-.237	.062	-.275	.031
State Highway 89 over Kalamazoo River near Fennville, Mich.	-.777	<.001	.134	.354	.179	.214	-.095	.508
North Grand River Avenue over Grand River at Lansing, Mich.								
Upstream side	-.285	.083	-.299	.069	-.102	.533	-.370	.024
Downstream side	-.746	<.001	.069	.690	.133	.438	.019	.910
State Highway 66 over Grand River at Ionia, Mich.	.456	.001	-.228	.110	-.079	.581	-.304	.033
Scottville Road over Pere Marquette River at Scottville, Mich.	-.536	<.001	-.189	.109	.129	.272	-.520	<.001
State Highway 37 over Manistee River near Sherman, Mich.	-.111	.359	-.634	<.001	-.317	.009	-.700	<.001
Fergus Road over Shiawassee River near Fergus, Mich.	-.657	<.001	-.106	.446	-.178	.204	-.115	.413
State Highway 13 over Flint River near Fosters, Mich.	-.513	<.001	.320	.013	.032	.804	.284	.028
State Highway 46 over Saginaw River at Saginaw, Mich.	.469	<.001	-.139	.258	.030	.809	.220	.074
Moravian Drive over Clinton River at Mount Clemens, Mich.	-.225	.079	-.015	.906	.076	.552	.120	.349

All open-water streamflow measurements are made from the downstream side of Coloma Road bridge. The normal profile was computed on the basis of 1,113 soundings of the streambed obtained from 46 streamflow measurements between February 2, 1985 and August 8, 1994 (fig. 8). Streamflow measurements used in developing the normal profile represented mean and maximum streamflows of 643 and 1,860 ft^3/s, mean and maximum velocities of 1.20 and 2.70 ft/s; and mean and maximum flow depths of 5.22 and 6.83 ft, respectively. At this gaging station, 1,860 ft^3/s is a 3.7-yr flood.

Deviances had a mean and standard deviation of 0.04 and 0.48 ft, respectively, and ranged from -4.77 to 3.29 ft. Streambed deviances ranged from -0.12 to 0.54 ft and had a mean and standard deviation of 0.01 and 0.11 ft, respectively. Although streambed deviances generally decreased about 0.3 ft during the first part of the period represented by the selected measurements (fig. 9), there was no statistically significant trend in streambed deviances over the entire period (table 2). Similarly, there is no significant monotonic relation between streambed deviance and streamflow, velocity, or depth (table 2). The apparent increase in steambed deviances at higher streamflow may be incidental to the degradation between 1985 and 1990 (fig. 10). Variability of local deviances was greatest between the left abutment and the left most pier.

River Street over Kalamazoo River at Comstock (04106000)

River Street bridge crosses Kalamazoo River in Comstock, Michigan, 3 mi east of the City of Kalamazoo, Michigan, in Kalamazoo County. The gaging station has been maintained at the site from April to August 1931, October 1932 to December 1979, and October 1984 to the present. On the basis of these streamflow records, mean streamflow was 895 ft^3/s, minimum daily flow, which occurred on August 7, 1934, was 185 ft^3/s, and maximum instantaneous flow, which occurred on April 8, 1947, was 6,910 ft^3/s (Blumer and others, 1996, p. 117). The gaging station, which is located on the left bank at the downstream side of the bridge, has a datum of 756.12 ft above sea level.

Streamflow measurements at low stages are commonly measured by wading a section about 500 ft downstream from the gaging station; medium and high stages are measured from the downstream side of the River Street bridge. A normal streambed profile was computed on the basis of 1,520 soundings from 63 streamflow measurements obtained between October 17, 1970 and June 10, 1993 (fig. 11). Streamflow measurements used in developing the normal profile represented mean and maximum streamflows of 1,773 and 5,070 ft^3/s, mean and maximum velocities of 2.04 and 3.62 ft/s; and mean and maximum flow depths of 6.03 and 10.00 ft, respectively. At this gaging station, 5,070 ft^3/s is a 12.9-yr flood.

Deviances had a mean and standard deviation of -0.02 and 0.38 ft, respectively, and ranged from -1.34 to 2.18 ft. Streambed deviances ranged -0.29 to 0.30 ft; the mean and standard deviation of these deviances was -0.04 and 0.11, respectively. Trend analysis indicates that streambed deviances decreased slightly (fig. 12) during the period represented by the selected measurements (table 2). In addition, streambed deviances were negatively associated with streamflow (fig. 13) and flow depth (table 2). The variability of local deviances was fairly uniformly across the channel.

State Highway 89 over Kalamazoo River near Fennville (04108500)

State Highway 89 bridge crosses Kalamazoo River 6.1 mi east of Fennville, Michigan in Allegan County. Streamflow data was collected at the gaging station from April 1929 to September 1936 and from October 1937 to September 1993. On the basis of available records, mean streamflow was 1,480 ft^3/s, minimum daily flow, which occurred on August 19, 1976, was 50 ft^3/s, and maximum instantaneous flow, which occurred on April 11, 1947, was 17,500 ft^3/s (Blumer and others, 1994, p. 116). The gaging station, which was located on the left bank 40 ft upstream of the bridge, had a datum of 586.51 ft above sea level.

All streamflow measurements were made from the downstream side of the State Highway 89 bridge. A normal profile was computed on the basis of 1,261 soundings obtained from 49 streamflow measurements between March 16, 1971 and October 22, 1993 (fig. 14). Streamflow measurements used in developing the normal profile represent mean and maximum streamflows of 2,300 and 5,840 ft^3/s, mean and maximum velocities of 1.60 and 2.69 ft/s; and mean and maximum flow depths of 6.18 and 8.10 ft, respectively. At this gaging station, 5,840 ft^3/s is a 3.9-yr flood.

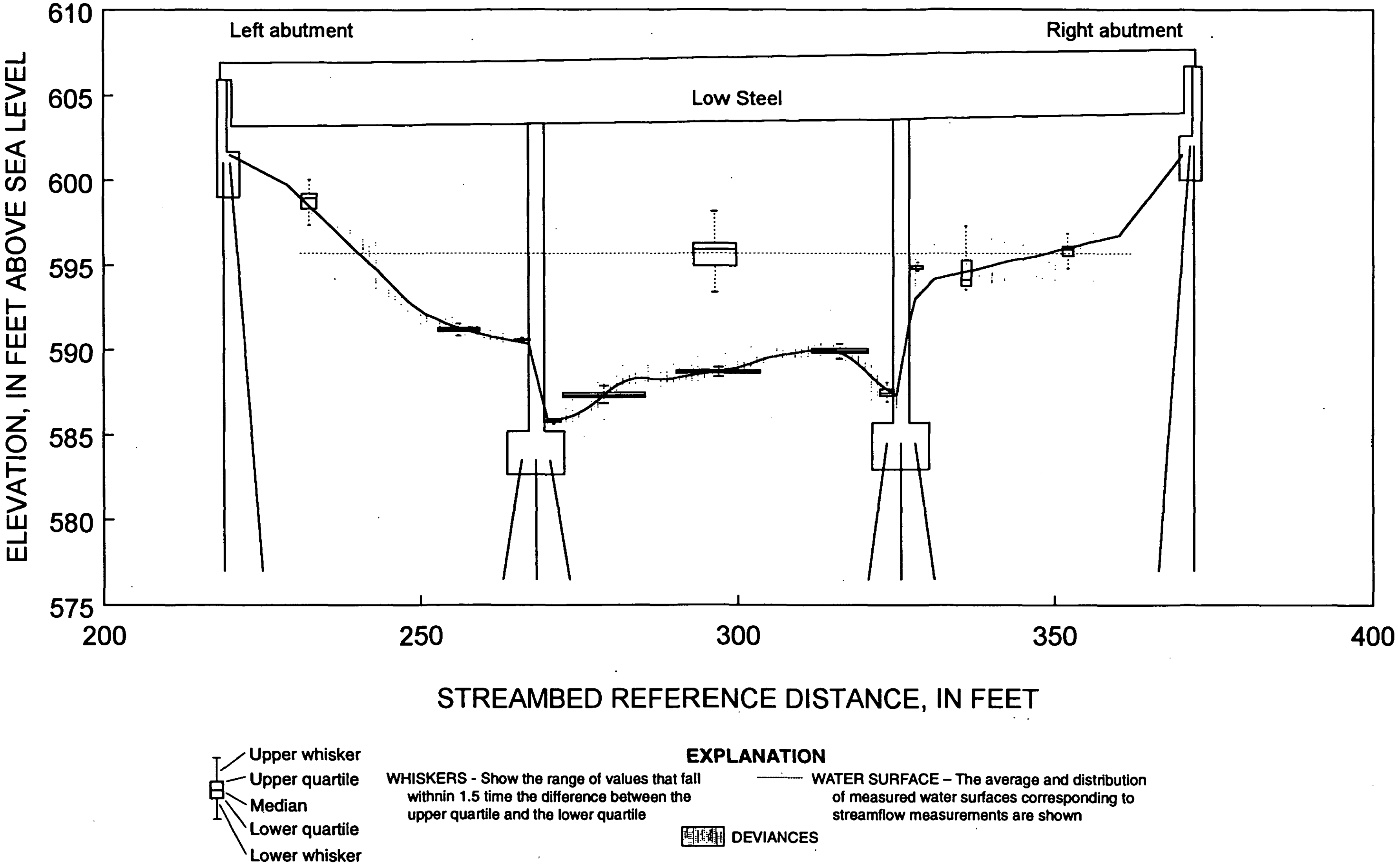

Figure 8. Normal streambed profile and local streambed variability at Coloma Road over Paw Paw River at Riverside, Mich.

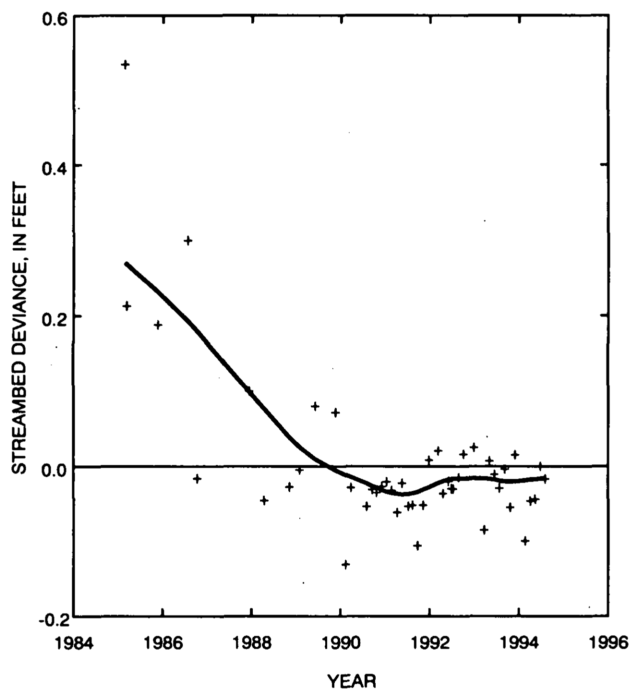

Figure 9. Trend in streambed deviance at Coloma Road over Paw Paw River at Riverside, Mich.

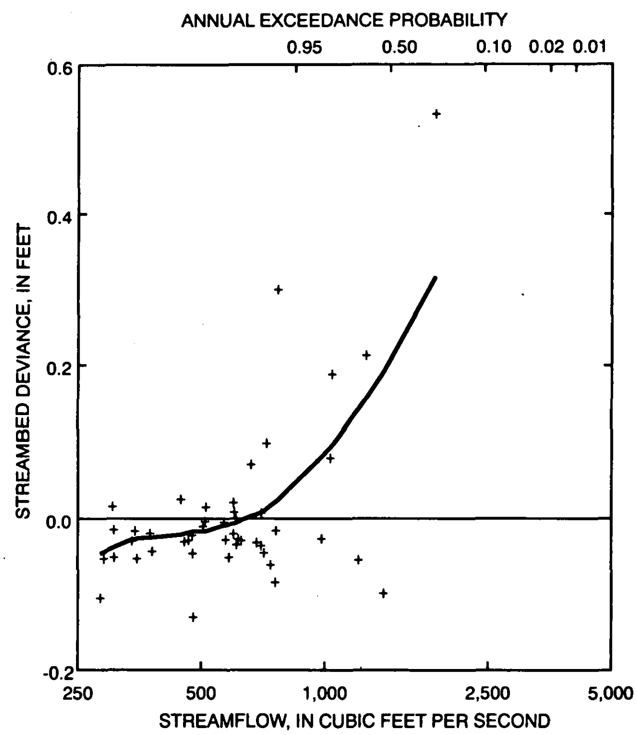

Figure 10. Relation between streambed deviance and streamflow at Coloma Road over Paw Paw River at Riverside, Mich.

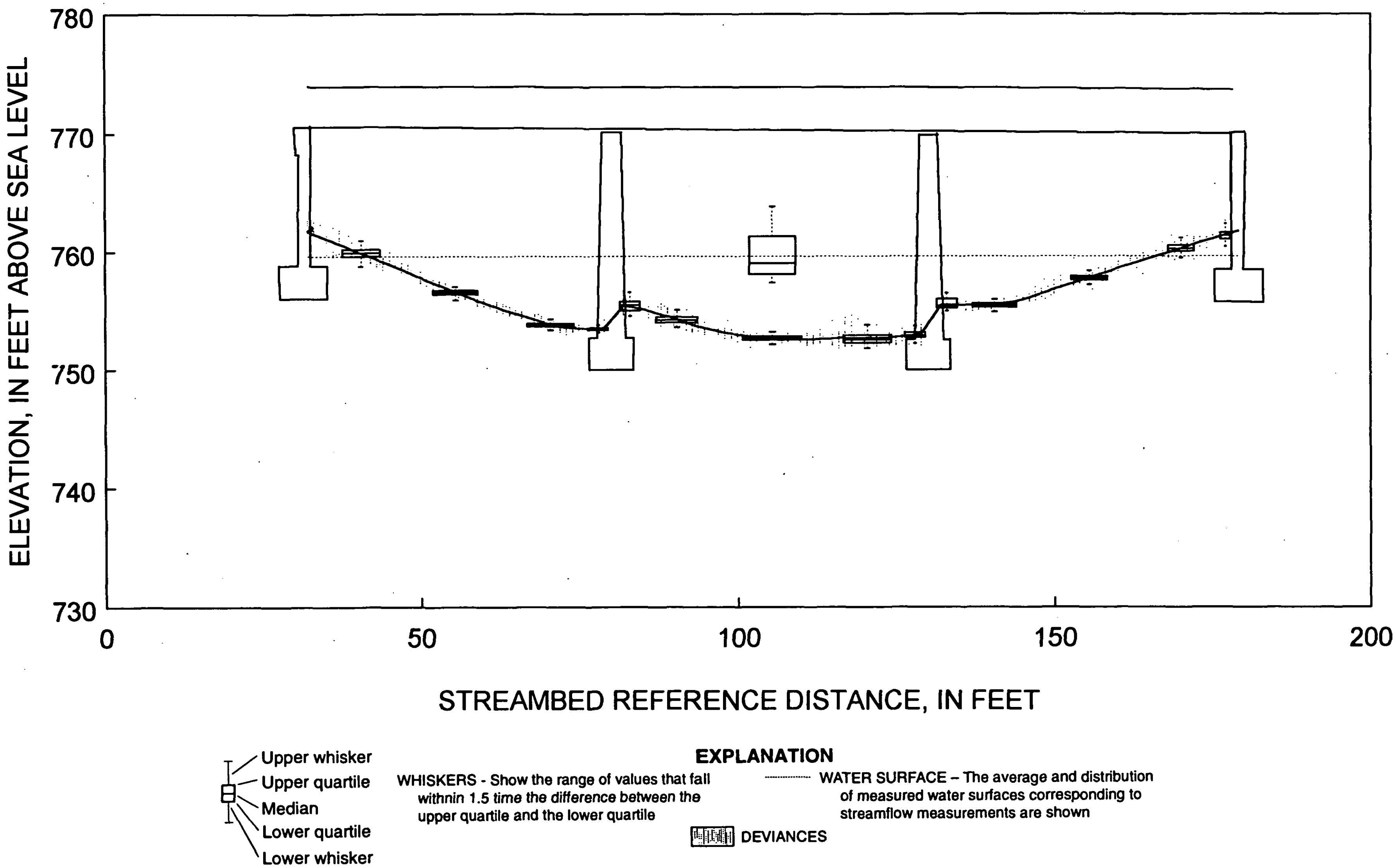

Figure 11. Normal streambed profile and local streambed variability at River Street over Kalamazoo River at Comstock, Mich.

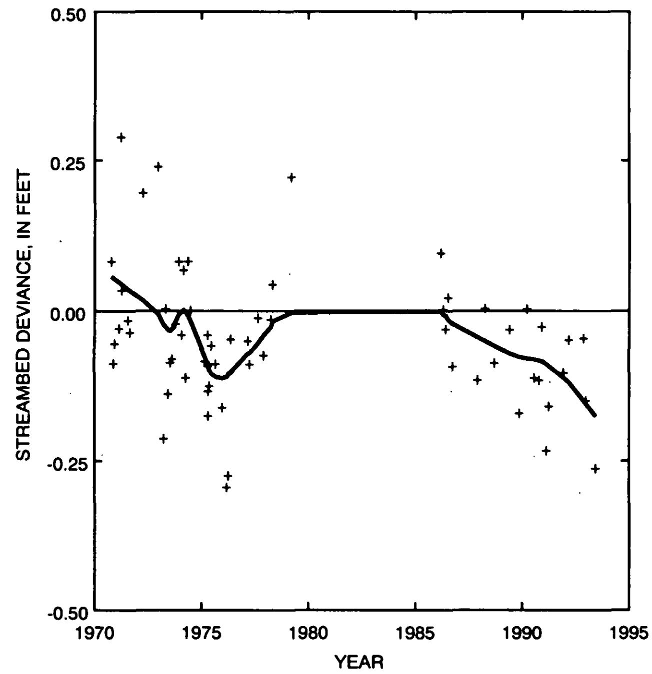

Figure 12. Trend in streambed deviance at River Street over Kalamazoo River at Comstock, Mich.

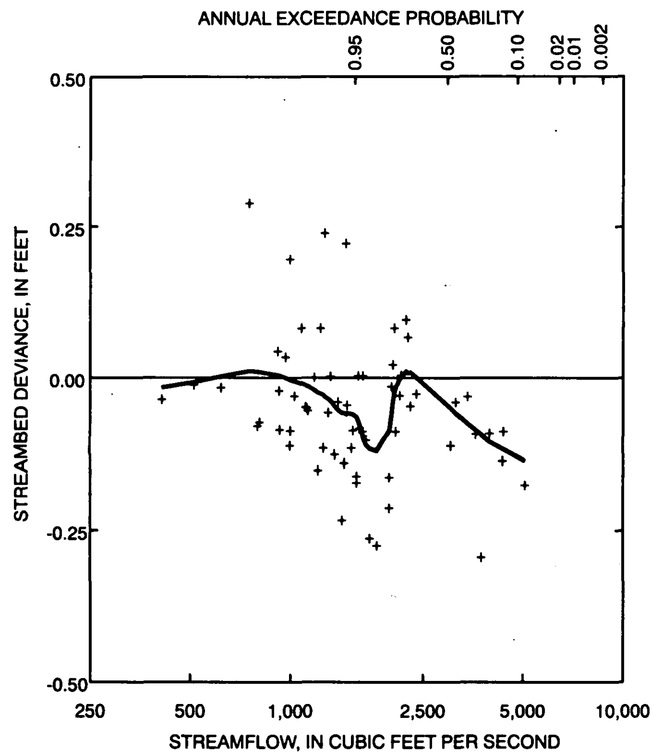

Figure 13. Relation between streambed deviance and streamflow at River Street over Kalamazoo River at Comstock, Mich.

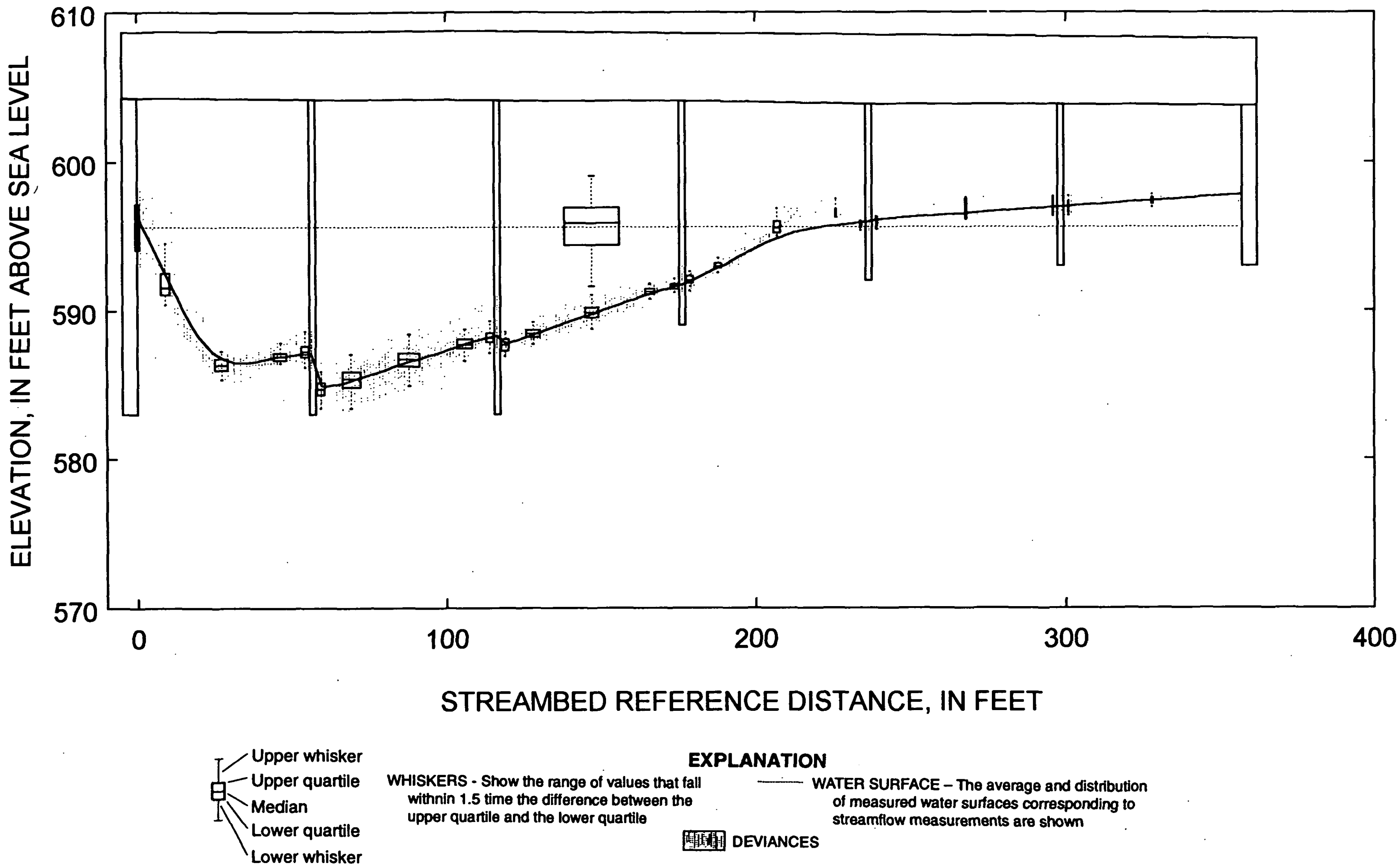

Figure 14. Normal streambed profile and local streambed variability at State Highway 89 over Kalamazoo River near Fennville, Mich.

Deviances had a mean and standard deviation of -0.01 and 0.77 ft, respectively, and ranged from -7.74 to 5.02 ft. Streambed deviances ranged from -0.74 to 1.05 ft; the mean and standard deviation of these deviances was -0.0093 and 0.4003 ft, respectively. Trend analysis indicated a significant degradation of streambed elevations (fig. 15) during the period represented by the selected streamflow measurements (table 2). No consistent relation was apparent between streambed deviance and streamflow (fig. 16), velocity, or depth (table 2). The variability of local deviances was greatest within the deepest part of the channel.

North Grand River Avenue over Grand River in Lansing (04113000)

North Grand River Avenue bridge crosses Grand River in the north-central part of the City of Lansing, Michigan, in Ingham County. Streamflow records have been collected at this site from March 1901 to September 1906 and from October 1934 to the present. On the basis of this record, the mean streamflow is 875 ft^3/s, minimum daily flow, which occurred on August 25, 1941, was 20 ft^3/s, and maximum instantaneous flow, which occurred on March 26, 1904, was 24,500 ft^3/s (Blumer and others, 1996, p. 133). The gaging station, which is located on the right bank 30 ft upstream of the bridge on North Grand River Avenue, has a datum of 805.53 ft above sea level.

Direct measurements of streamflow are generally made on the downstream side of the bridges to avoid debris piles that commonly form on the upstream side of piers and abutments. Measurements on the upstream side of the bridges, however, are sometimes preferred because it allows the person making the measurement to see and avoid ice-flows that might otherwise damage the current meter used in measuring point velocities in the stream. Usually, either the downstream or upstream side of a bridge is selected and measured consistently. At North Grand River Avenue over Grand River in Lansing, however, streamflow measurements are available from both the downstream and the upstream side of the bridge. This data provides a unique opportunity to compare streambed stability on the downstream side with stability on the upstream side of a bridge.

Downstream Side of North Grand River Avenue Bridge

A streambed profile was computed for the downstream side of the bridge on the basis of 880 soundings obtained from 35 streamflow measurements between June 27, 1968 and April 21, 1993 (fig. 17). Streamflow measurements used in developing the normal profile represented mean and maximum streamflows of 2,709 and 11,000 ft^3/s, mean and maximum velocities of 2.62 and 3.96 ft/s; and mean and maximum flow depths of 4.78 and 12.33 ft, respectively. At this gaging station, 11,000 ft^3/s is a 12.6-yr flood.

Deviances had a mean and standard deviation of -0.05 and 0.14 ft, respectively, and ranged from -2.56 to 4.30 ft. Streambed deviances ranged from -0.40 to 0.22 ft; the mean and standard deviation of these deviances was -0.0534 and 0.1382 ft, respectively. Trend analysis indicated a significant degradation (fig. 18) in mean channel elevation during the period represented by the selected measurements (table 2). No consistent relation was apparent between streambed deviances and streamflow (fig. 19), velocity, or depth (table 2). Variability of local deviances was fairly uniform within the main channel; variability near the right pier was greater than streambed variability near the left pier.

Upstream Side of North Grand River Avenue Bridge

A normal profile was computed for the upstream side of the bridge opening on the basis of 951 soundings of the streambed obtained from 38 streamflow measurements between April 22, 1967, and April 24, 1995 (fig. 20). Streamflow measurements used in developing the normal profile represented mean and maximum streamflows of 2,160 and 10,800 ft^3/s, mean and maximum velocities of 2.42 and 3.77 ft/s; and mean and maximum flow depths of 4.28 and 12.21 ft, respectively.

Deviances had a mean and standard deviation of -0.06 and 0.07 ft, respectively, and ranged from -2.11 to 6.26 ft. Streambed deviances ranged from -0.22 to 0.12 ft; the mean and standard deviation of streambed deviances was -0.06 and 0.07 ft, respectively.

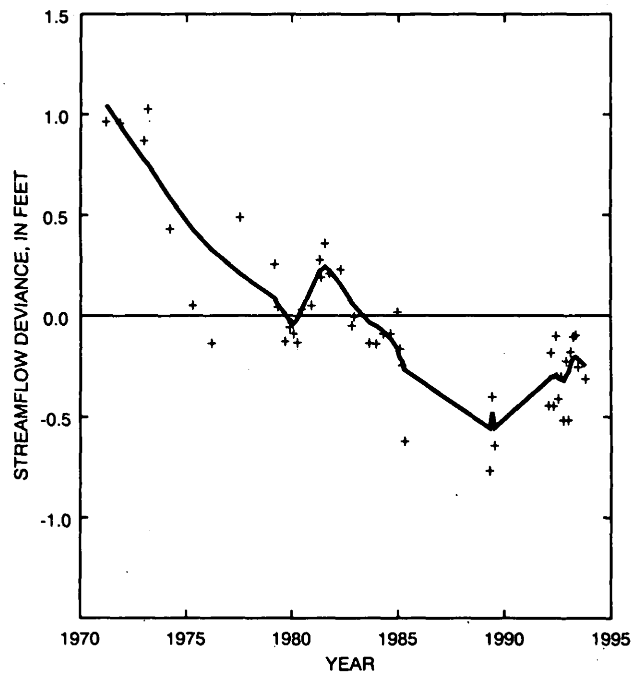

Figure 15. Trend in streambed deviance at State Highway 89 over Kalamazoo River near Fennville, Mich.

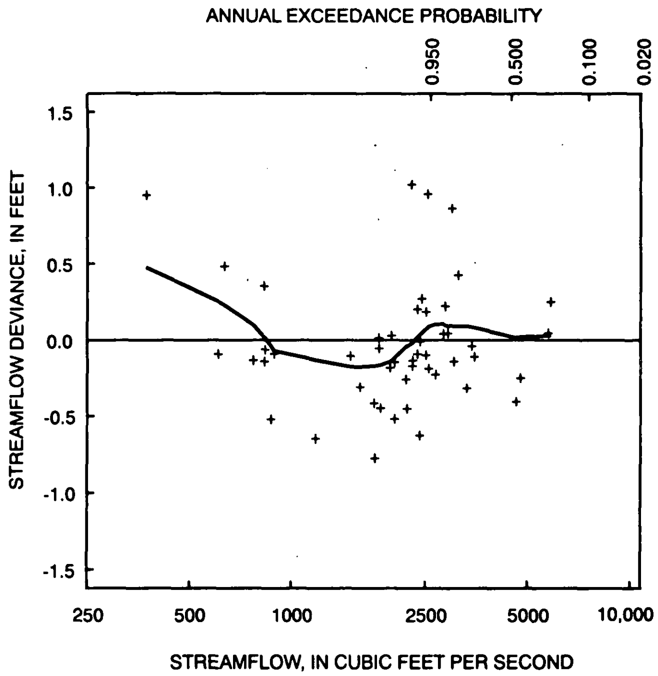

Figure 16. Relation between streambed deviance and streamflow at State Highway 89 over Kalamazoo River near Fennville, Mich.

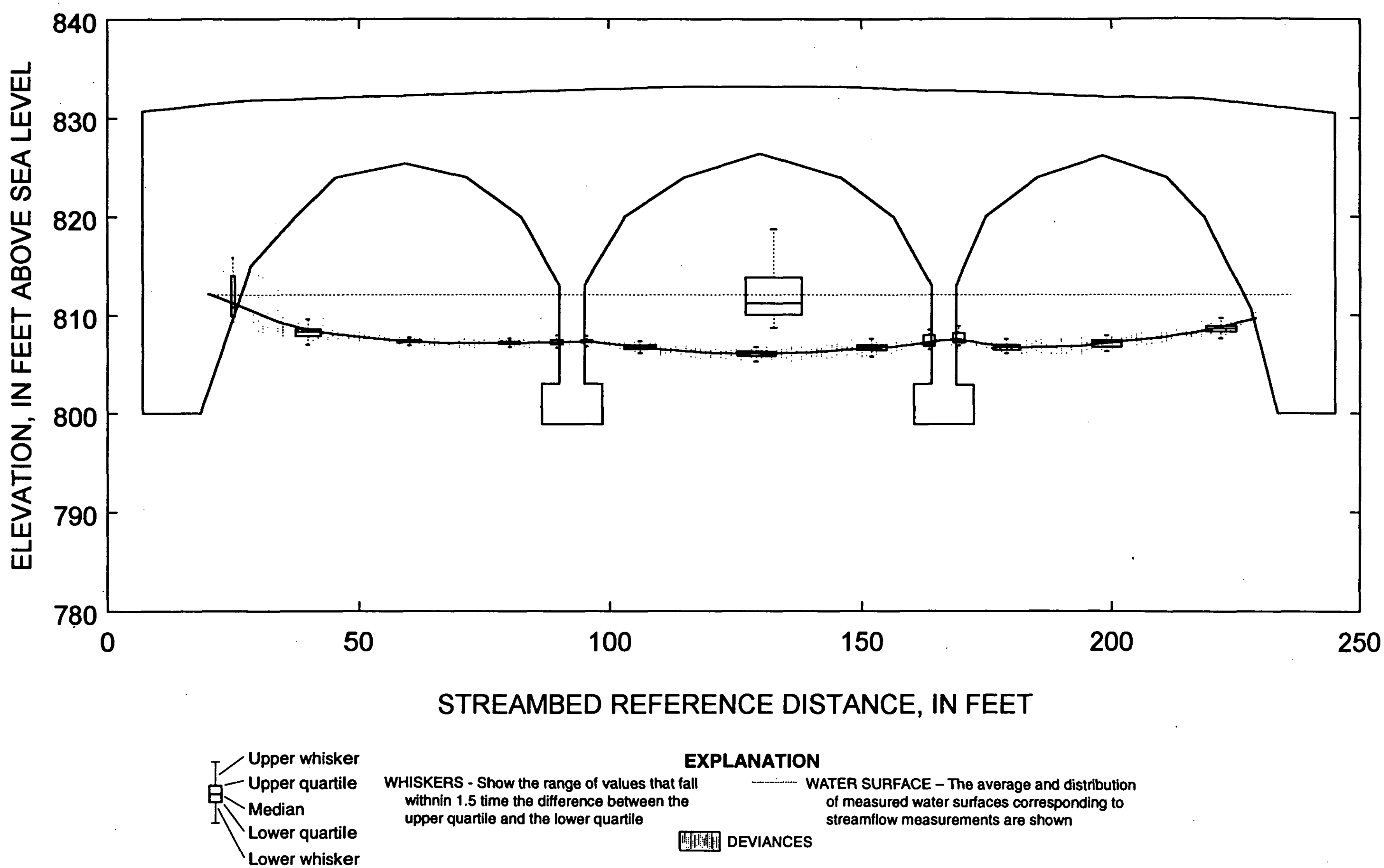

Figure 17. Normal streambed profile and local streambed variability at the downstream side of North Grand River Avenue over Grand River at Lansing, Mich.

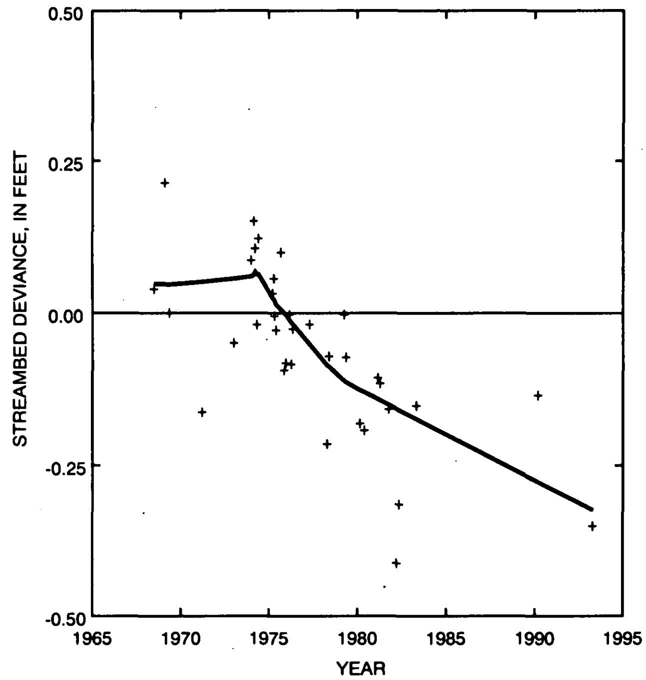

Figure 18. Trend in streambed deviance at the downstream side of North Grand River Avenue over Grand River at Lansing, Mich.

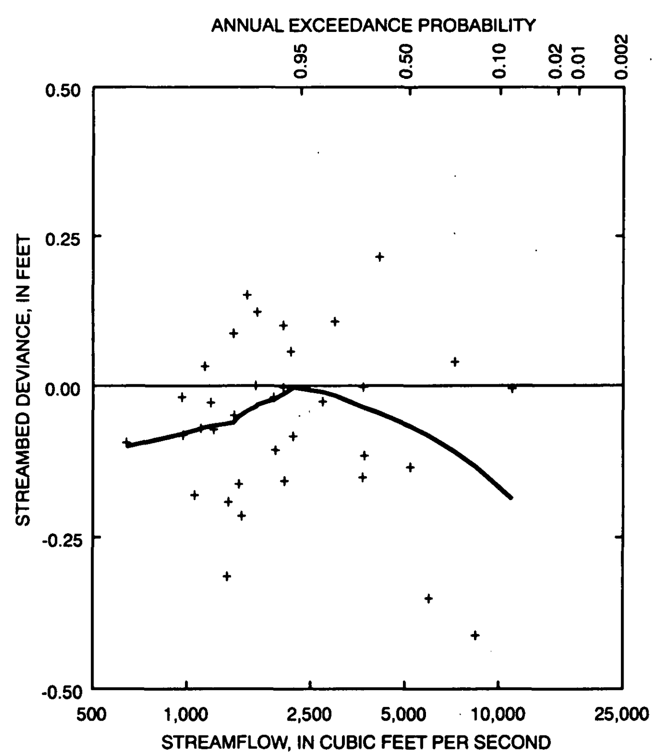

Figure 19. Relation between streambed deviance and streamflow at the downstream side of North Grand River Avenue over Grand River at Lansing, Mich.

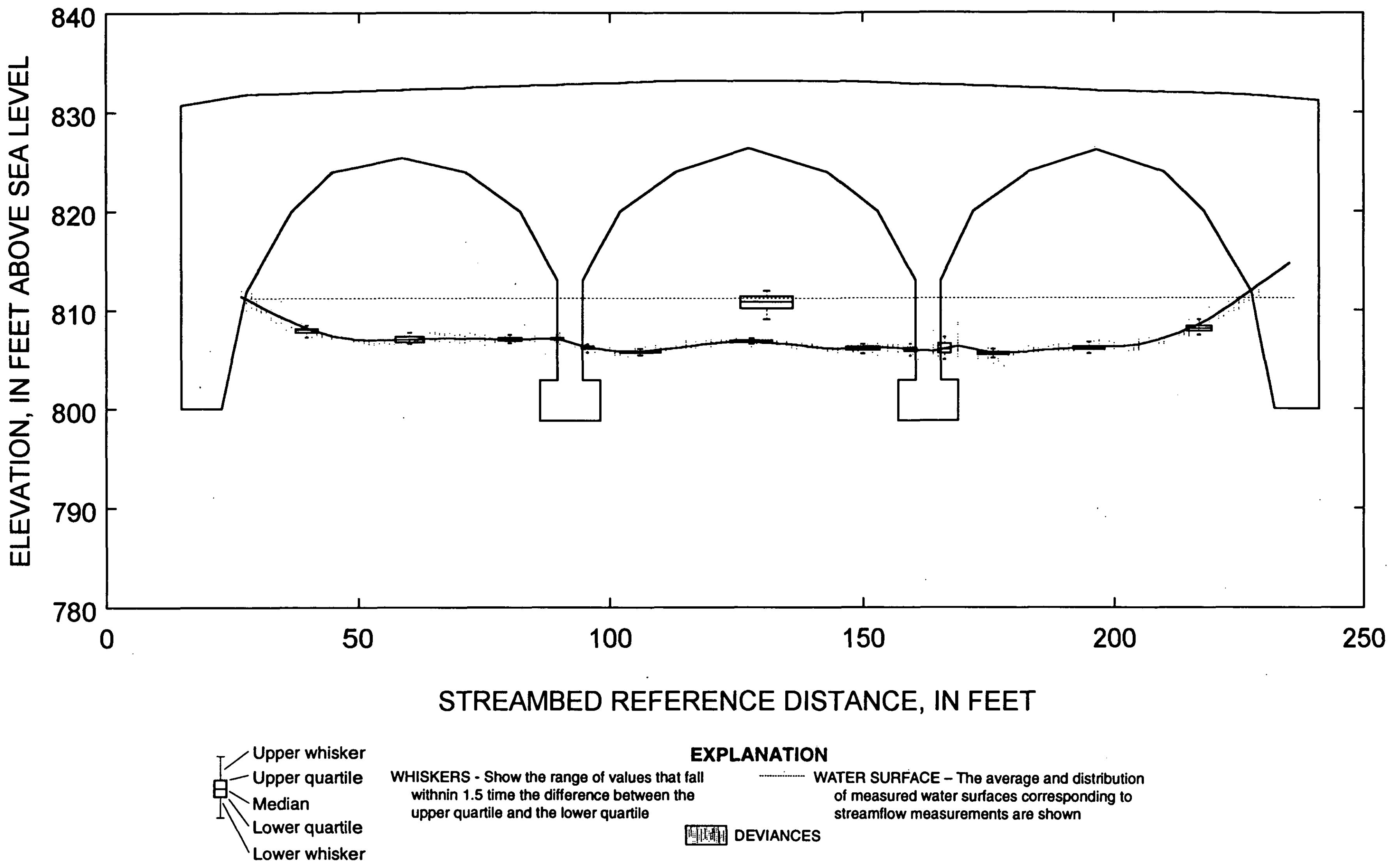

Figure 20. Normal streambed profile and local streambed variability at the upstream side of North Grand River Avenue at Grand River at Lansing, Mich.

No trend was apparent in the streambed deviances (fig. 21 and table 2); however, streambed deviances and depths of flow were negatively correlated (table 2). No relation between streambed deviance and streamflow (fig. 22) or velocity was detected (table 2). Variability of local deviances was similar below the left and right arches of the bridge, with slightly lower variability below the center arch.

State Highway 66 over Grand River at Ionia (04116000)

State Highway 66 bridge crosses Grand River in the southern part of the City of Ionia, Michigan, in Ionia County. Streamflow records were obtained at this site from March to June 1931 and from July 1951 to the present. Based on the available record, the mean streamflow is 2,070 ft^3/s, minimum daily flow, which occurred on July 16, 1977, was 109 ft^3/s, and maximum instantaneous flow, which occurred on April 1, 1960, was 21,500 ft^3/s (Blumer and others, 1996, p. 138). The gaging station, which is located on the left bank 15 ft downstream from the bridge, has a datum of 615.38 ft above sea level.

Up to a stage of about 623.4 ft, wading measurements are made at various sites about 0.5 mi downstream of the bridge; at higher stages streamflow is measured from the downstream side of the bridge. A normal streambed profile was computed on the basis of 1,310 soundings obtained from 50 streamflow measurements between July 7, 1975 and July 25, 1994 (fig. 23). Streamflow measurements used in developing the normal profile represented mean and maximum streamflows of 4,490 and 17,900 ft^3/s, mean and maximum velocities of 2.17 and 3.67 ft/s; and mean and maximum flow depths of 7.76 and 14.13 ft, respectively. At this gaging station, 17,900 ft^3/s is an 8.1-yr flood.

Deviances had a mean and standard deviation of -0.01and 0.16 ft, respectively, and ranged from -2.19 to 4.75 ft. Streambed deviances ranged from -0.30 to 0.34 ft; mean and standard deviations of these deviances was -0.0055 and 0.1649 ft, respectively. Trend analysis indicated that the streambed aggraded (table 2) about 0.5 ft between 1980 and 1995 (fig. 24). Also, streambed deviances were negatively correlated with depths of flow (table 2). No relation between streambed deviance and streamflow (fig. 25) or velocity was detected (table 2). Variability of local deviances was fairly uniform throughout the channel with slightly higher variability near the center of the channel.

Scottville Road over Pere Marquette River at Scottville (04122500)

Scottville Road bridge crosses Pere Marquette River in the southern part of the Village of Scottville, Michigan, in Mason County. Streamflow records have been obtained at a gaging stations at this site from August 1939 to the present. On the basis of these records, the mean streamflow is 709 ft^3/s, the minimum daily flow, which occurred on August 9, 1941, was 310 ft^3/s, and the maximum instantaneous flow, which occurred on September 13, 1986 was 6,440 ft^3/s (Blumer and others, 1996, p. 171). The gaging station, which is located on the right bank 20 ft upstream from Scottville Road bridge, has a datum of 597.66 ft above sea level.

Most direct streamflow measurements are made on the downstream side of Scottville Road bridge. Occasional wading measurements at stages below 597.66 ft are made 300-1,000 ft upstream from the gaging station. A normal streambed cross-sectional profile was computed for the downstream side of the bridge on the basis of 2,065 soundings obtained from 73 streamflow measurements between March 10, 1982 and July 22, 1992 (fig. 26). Streamflow measurements used in developing the normal profile represent mean and maximum streamflows of 1,027 and 6,440 ft^3/s, mean and maximum velocities of 1.40 and 4.23 ft/s; and mean and maximum flow depths of 5.56 and 12.02 ft, respectively. At this gaging station, 6,440 ft^3/s exceeds the 100-yr flood.

Two streamflow measurements document dramatic changes in streambed degradations during the maximum flood of record. The first measurement of 6,440 ft^3/s at the peak streamflow of the flood on September 13, 1986, was associated with a streambed degradation of 1.55 ft. Four days later, a second measurement of 2,610 ft^3/s indicated a streambed degradation of 4.06 ft. The lack of correspondence between the peak streamflow and the maximum channel degradation provides insight into the complexity of the scour process.

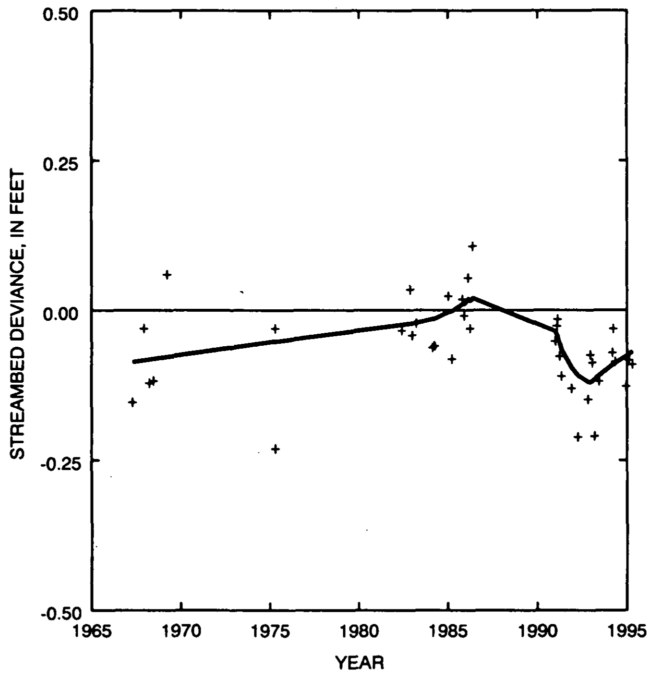

Figure 21. Trend in streambed deviance at the upstream side of North Grand River Avenue over Grand River in Lansing, Mich.

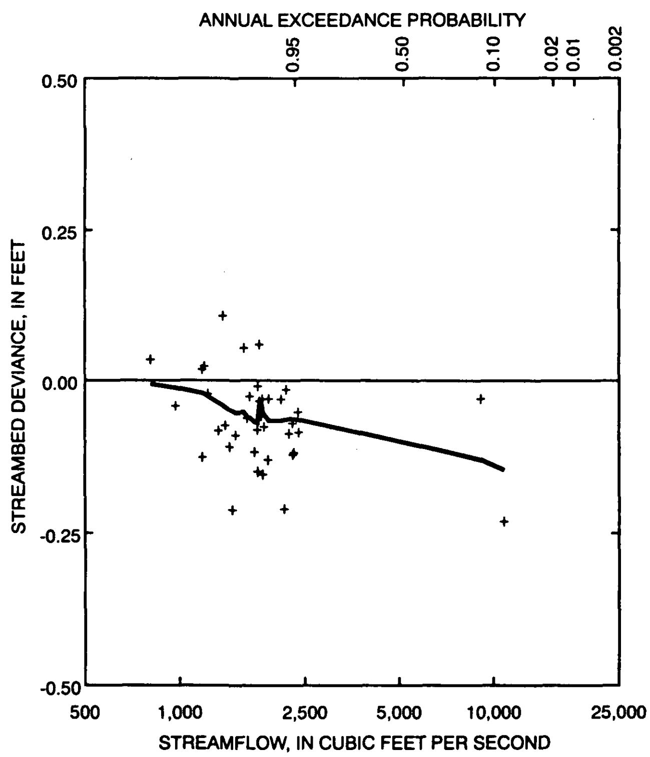

Figure 22. Relation between streambed deviance and streamflow at the upstream side of North Grand River Avenue over Grand River in Lansing, Mich.

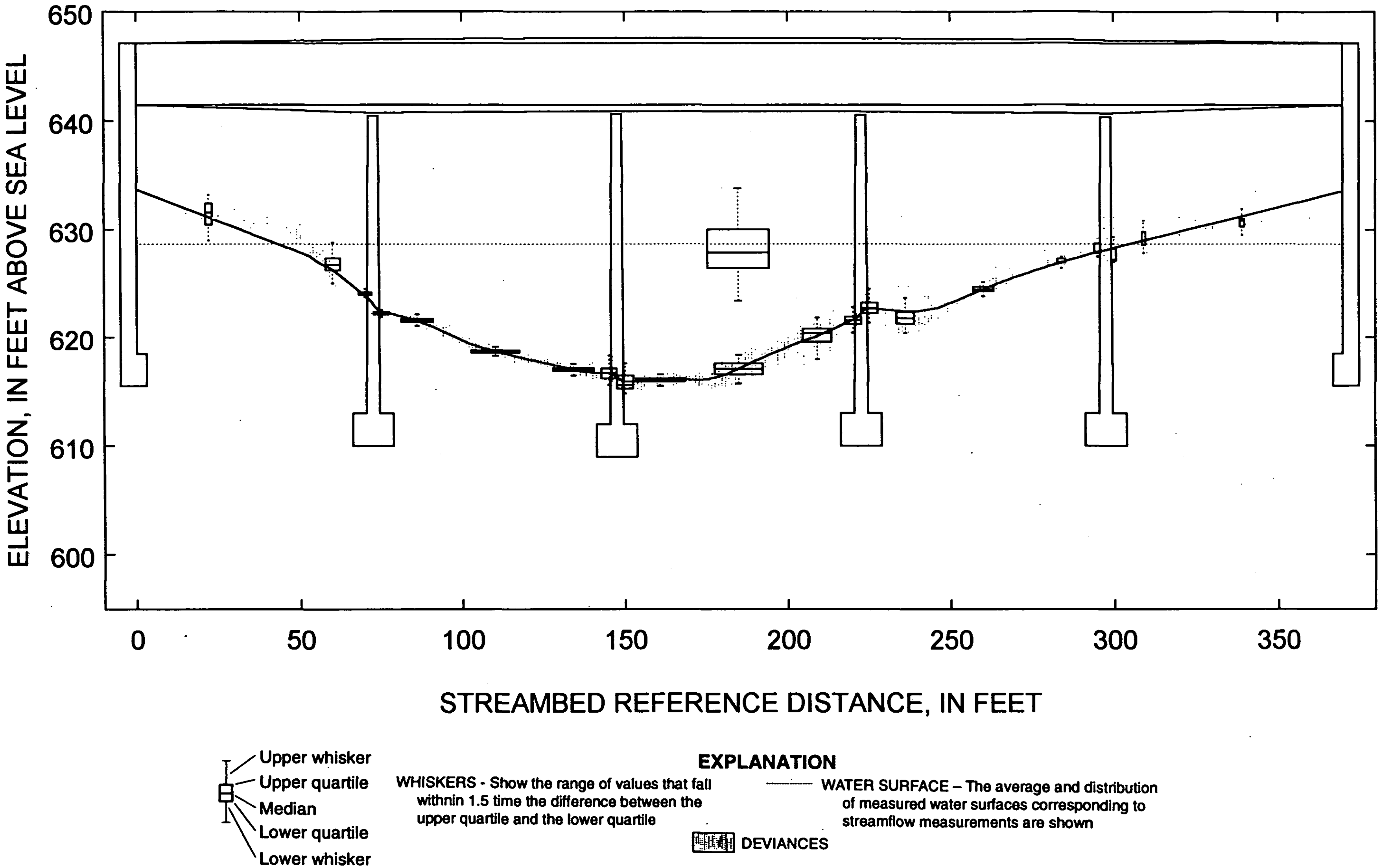

Figure 23. Normal streambed profile and local streambed variability at State Highway 66 over Grand River at Ionia, Mich.

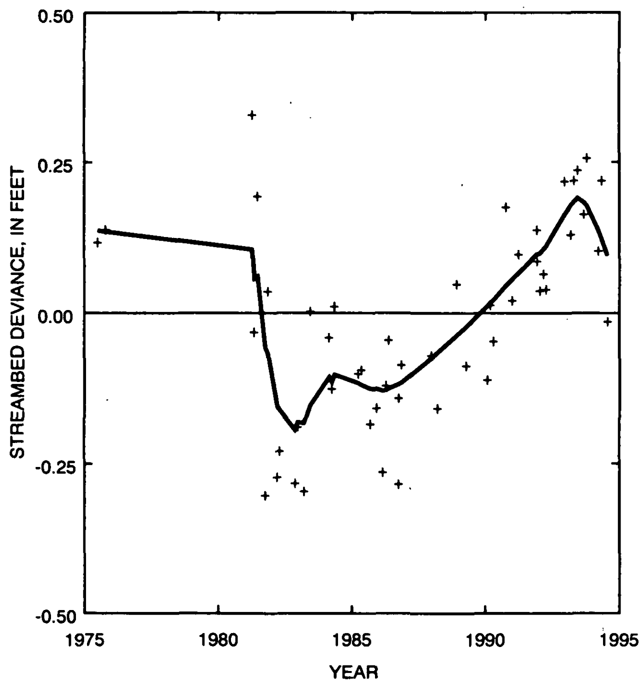

Figure 24. Trend in streambed deviance at State Highway 66 over Grand River at Ionia, Mich.

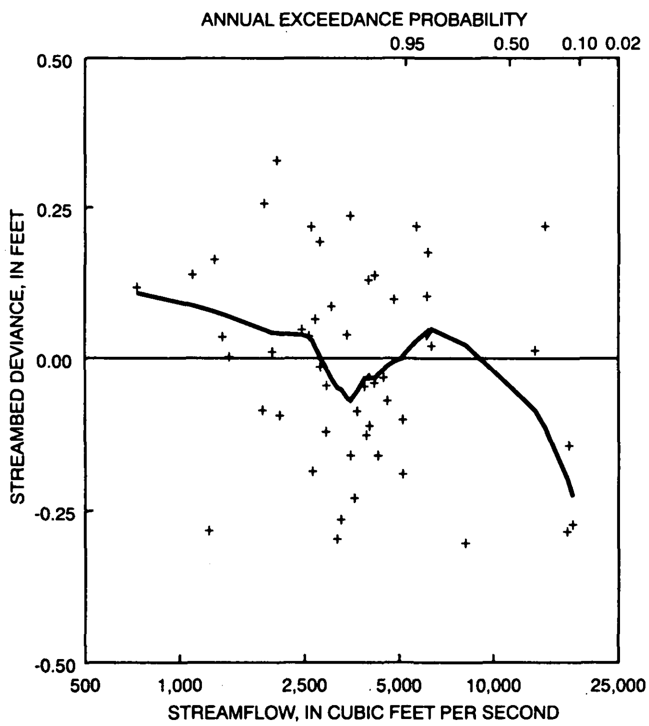

Figure 25. Relation between streambed deviance and streamflow at State Highway 66 over Grand River at Ionia, Mich.

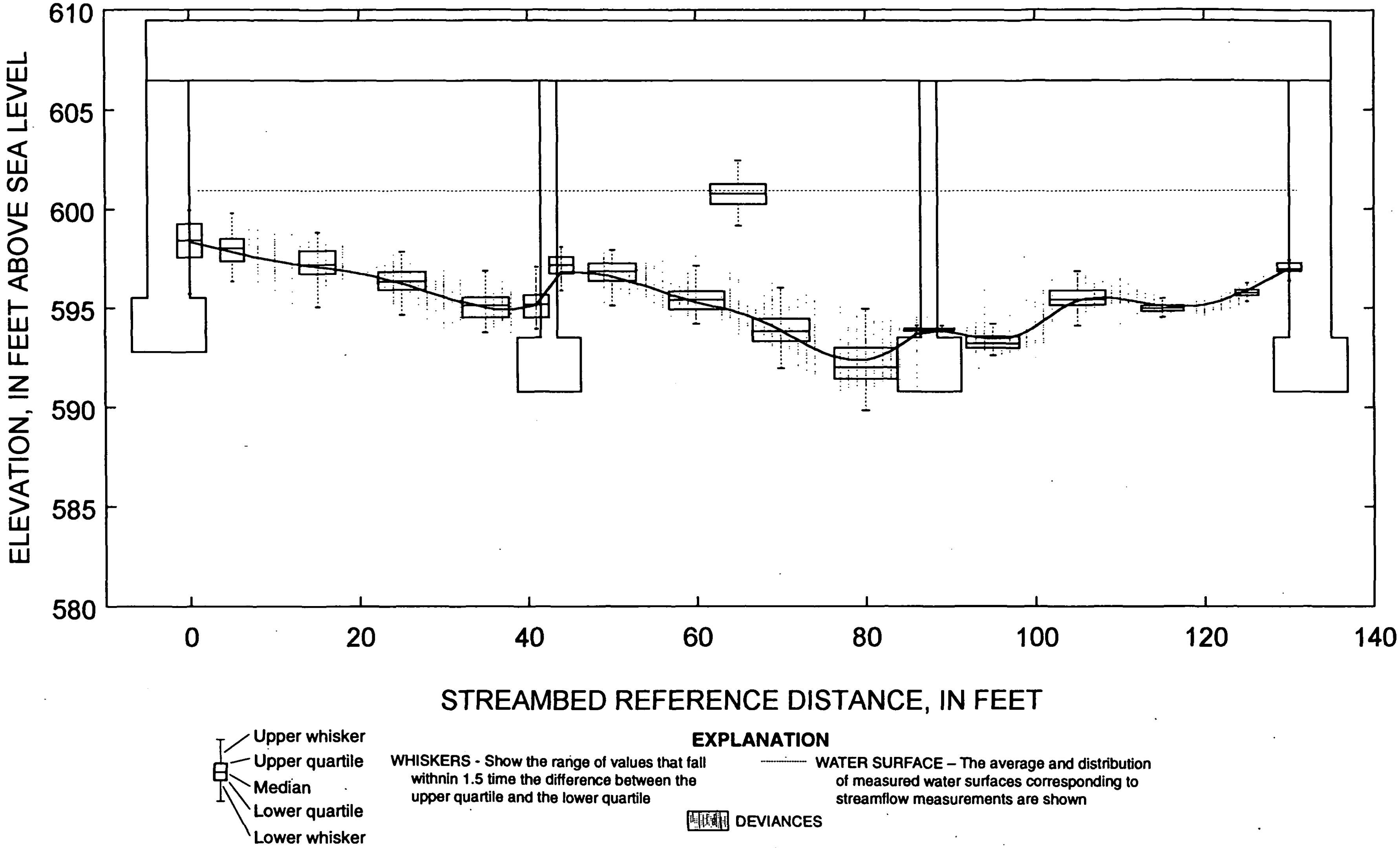

Figure 26. Normal streambed profile and local streambed variability at Scottville Road over Pere Marquette River at Scottville, Mich.

Deviances had a mean and standard deviation of -0.02 and 0.98 ft, respectively, and ranged from -8.55 to 2.97 ft. Streambed deviances ranged from -4.06 to 1.07 ft; the mean and standard deviation of these deviances was -0.0224 and 0.6441 ft, respectively. Trend analysis indicated that the channel degraded (fig. 27) during the period represented by the streamflow measurement (table 2). Also, streambed deviances were negatively correlated with flow depth (table 2). No consistent relation between streambed deviances and streamflow (fig. 28) or velocity were detected (table 2). Variability of local deviances was fairly uniform except near the right abutment where streambed elevations showed less variability. Soundings at the pier on the right side of the bridge apparently rest on the bridge footing.

State Highway 37 over Manistee River near Sherman (04124000)

State Highway 37 bridge crosses Manistee River 0.9 mi north of Sherman, Michigan in northwestern Wexford County. Streamflow records have been obtained at the site from July 1903 to May 1916, from October 1930 to September 1931, and from October 1933 to the present. On the basis of this record, the mean streamflow is about 1,067 ft^3/s; the minimum daily mean flow, which occurred on February 21, 1936, was 540 ft^3/s; and the maximum instantaneous flow, which occurred on March 25, 1913, was about 3,570 ft^3s (Blumer and others, 1996, p. 175). The gaging station, which is located on the right bank 50 ft downstream from the bridge on State Highway 37, has a datum of 804.24 ft above sea level.

Streamflow measurements at low-flow conditions (below a stage of 815.7 ft) are made by wading a section about 200 ft downstream from the bridge, subject to change due to scour near each bank (R.G. Nettleton, U.S. Geological Survey, written commun., 1991). All other measurements are made from the downstream side of the bridge. A normal cross-sectional profile of streambed elevations was computed on the basis of 1,870 soundings of channel depth from 69 streamflow measurements made between November 5, 1970, and December 1, 1992 (fig. 29). Streamflow measurements used in developing the normal profile represented mean and maximum streamflows of 1,494 and 3,240 ft^3/s, mean and maximum velocities of 2.32 and 3.15 ft/s; and mean and maximum flow depths of 5.70 and 9.37 ft, respectively. At this gaging station, 3,240 ft^3/s is a 21.8-yr flood.

Deviances had a mean and standard deviation of -0.005 and 0.47 ft, respectively, and ranged from -2.01 to 1.41 ft. Streambed deviances ranged from -0.90 to 0.39 ft; mean and standard deviations of these deviances were -0.0072 and 0.2429 ft, respectively. No trends were apparent in streambed deviances (fig. 30 and table 2). Streambed deviances were negatively (fig. 31) correlated with streamflow, velocities, and depths (table 2). Variability of local deviances was generally greatest midway between the piers in the main channel.

Fergus Road over Shiawassee River near Fergus (04145000)

Fergus Road bridge crosses Shiawassee River 1.2 mi east of the Village of Fergus, Michigan in south-central part of Saginaw County. The gaging station near this site was operated between October 1939 and September 1984 and again from October 1988 to September 1994. Based on the station record, mean streamflow was 451 ft^3/s; a maximum instantaneous flow of 7,500 ft^3/s occurred on Aug. 6, 1947; and a minimum daily mean flow of 29 ft^3/s occurred on August 8, 1966 (Blumer and others, 1993, p. 163). The gaging station, which was located on the right bank at the downstream side of the bridge on Fergus Road, had a datum of 585.80 ft above sea level.

During low and medium stages (below a stage of 588.6 ft), streamflow measurements were made at wading sections 300-500 ft downstream from the bridge. At higher stages, measurements were made at the downstream side of the bridge. Bridge measurement conditions were generally only fair, at best, due to frequent collection of debris on the bridge piers (T.A. Dewitt, U.S. Geological Survey, written commun., 1995). A normal cross-sectional profile of the streambed was computed on the basis of 1,418 depth soundings from 52 streamflow measurements obtained between October 31, 1972 and December 5, 1994 (fig. 32). Streamflow measurements used in developing the normal profile had mean and maximum streamflows of 1,117 and 7,340 ft^3/s, mean and maximum velocities of 1.66 and 2.96 ft/s; and mean and maximum flow depths of 4.44 and 11.53 ft, respectively. At this gaging station, 7,340 ft^3/s is a 27.4-yr flood.

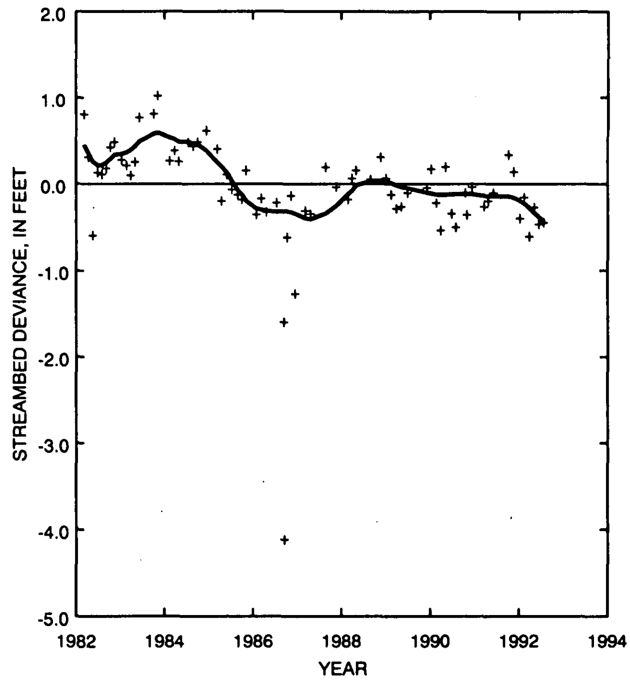

Figure 27. Trend in streambed deviance at Scottville Road over Pere Marquette River at Scottville, Mich.

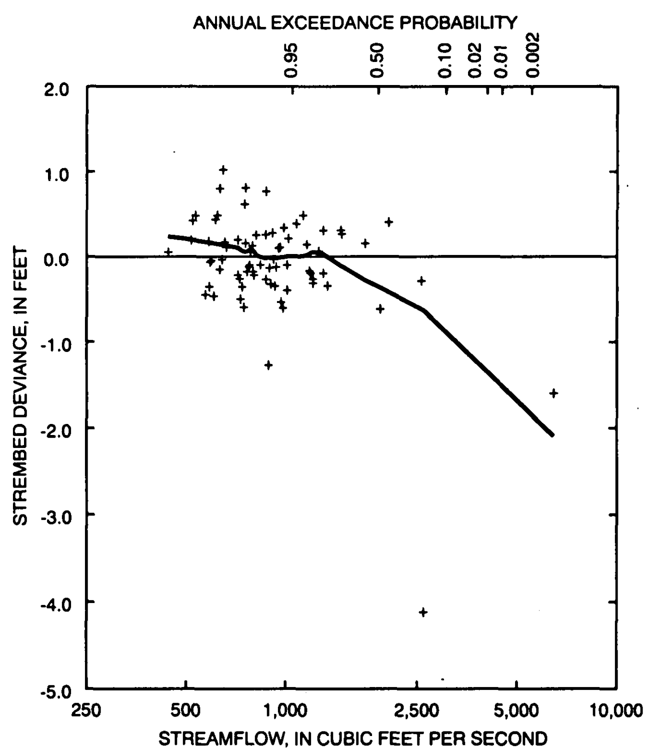

Figure 28. Relation between streambed deviance and streamflow at Scottville Road over Pere Marquette River at Scottville, Mich.

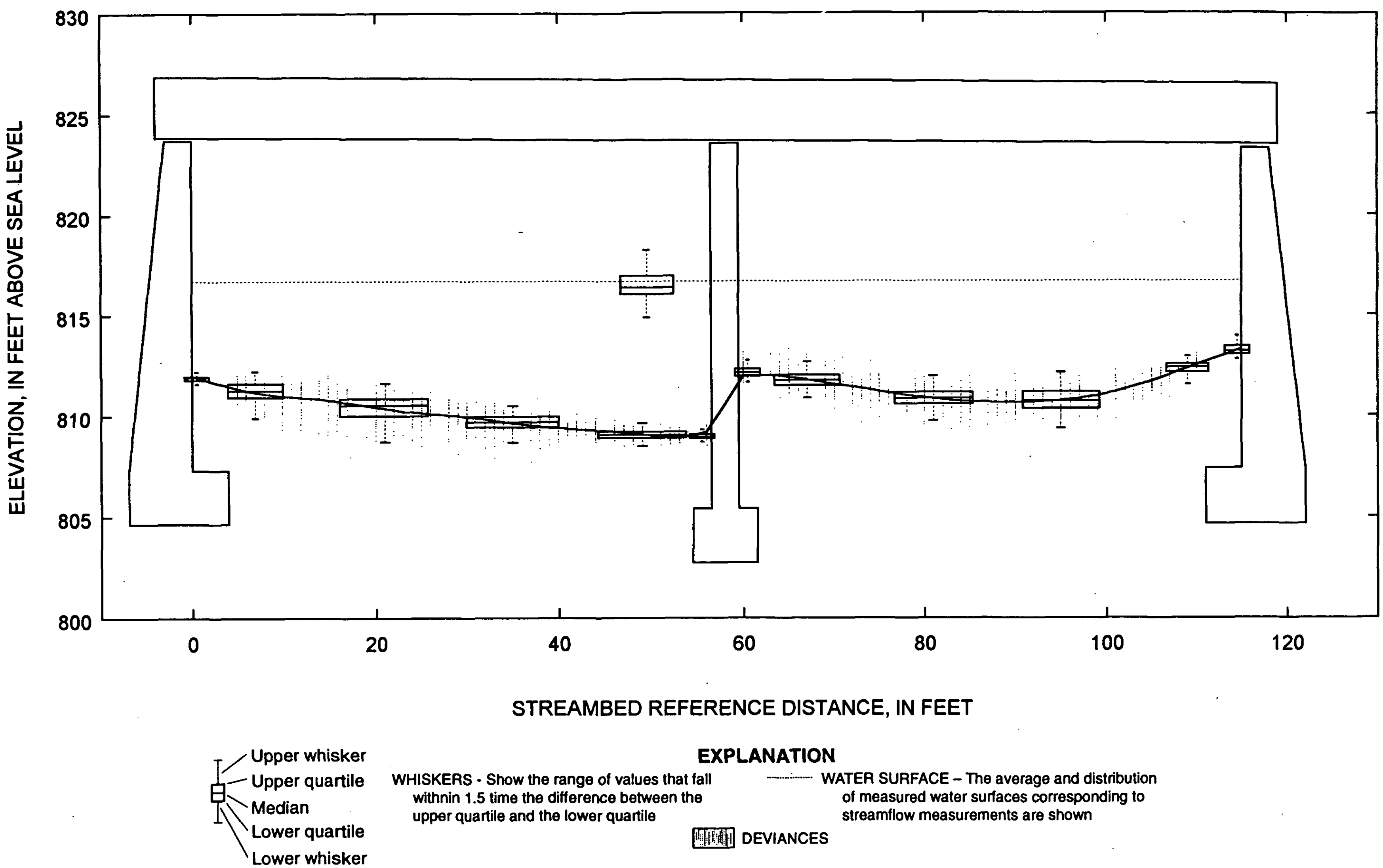

Figure 29. Normal streambed pro file and local streambed variability at State Highway 37 over Manistee River near Sherman, Mich.

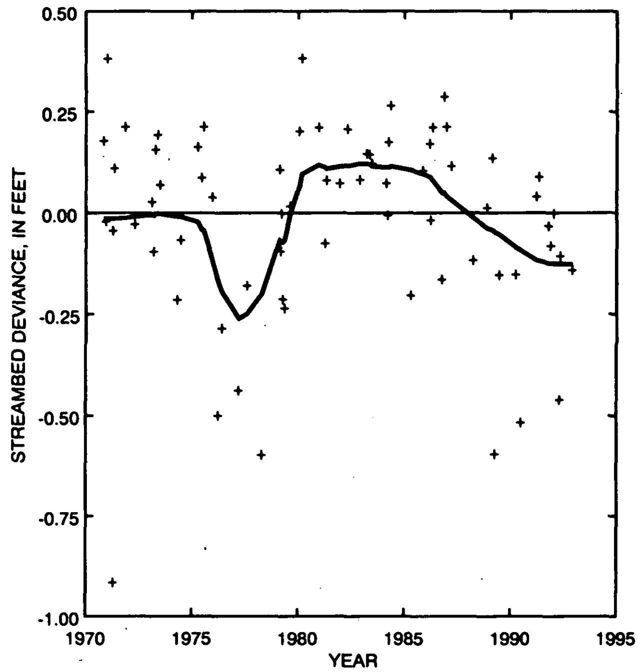

Figure 30. Trend in streambed deviance at State Highway 37 over Manistee River near Sherman, Mich.

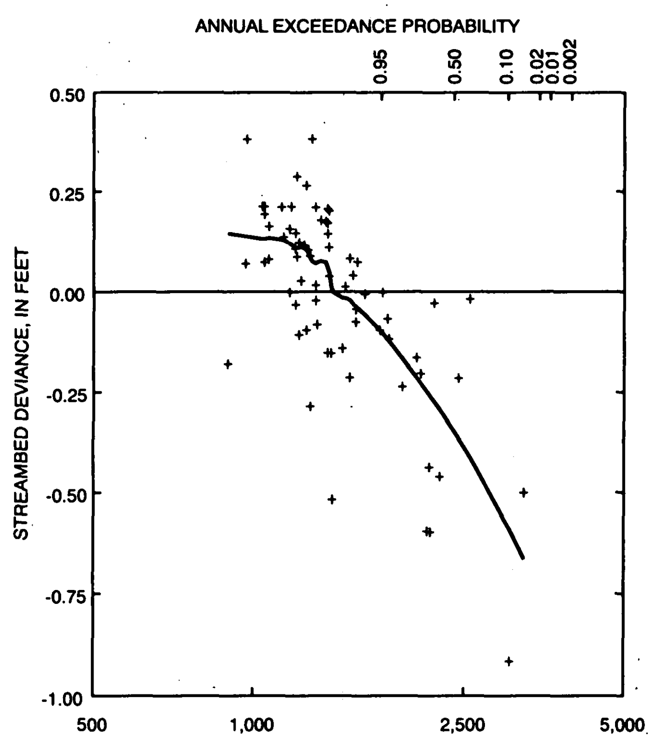

Figure 31. Relation between streamflow deviance and streamflow at State Highway 37 over Manistee River near Sherman, Mich.

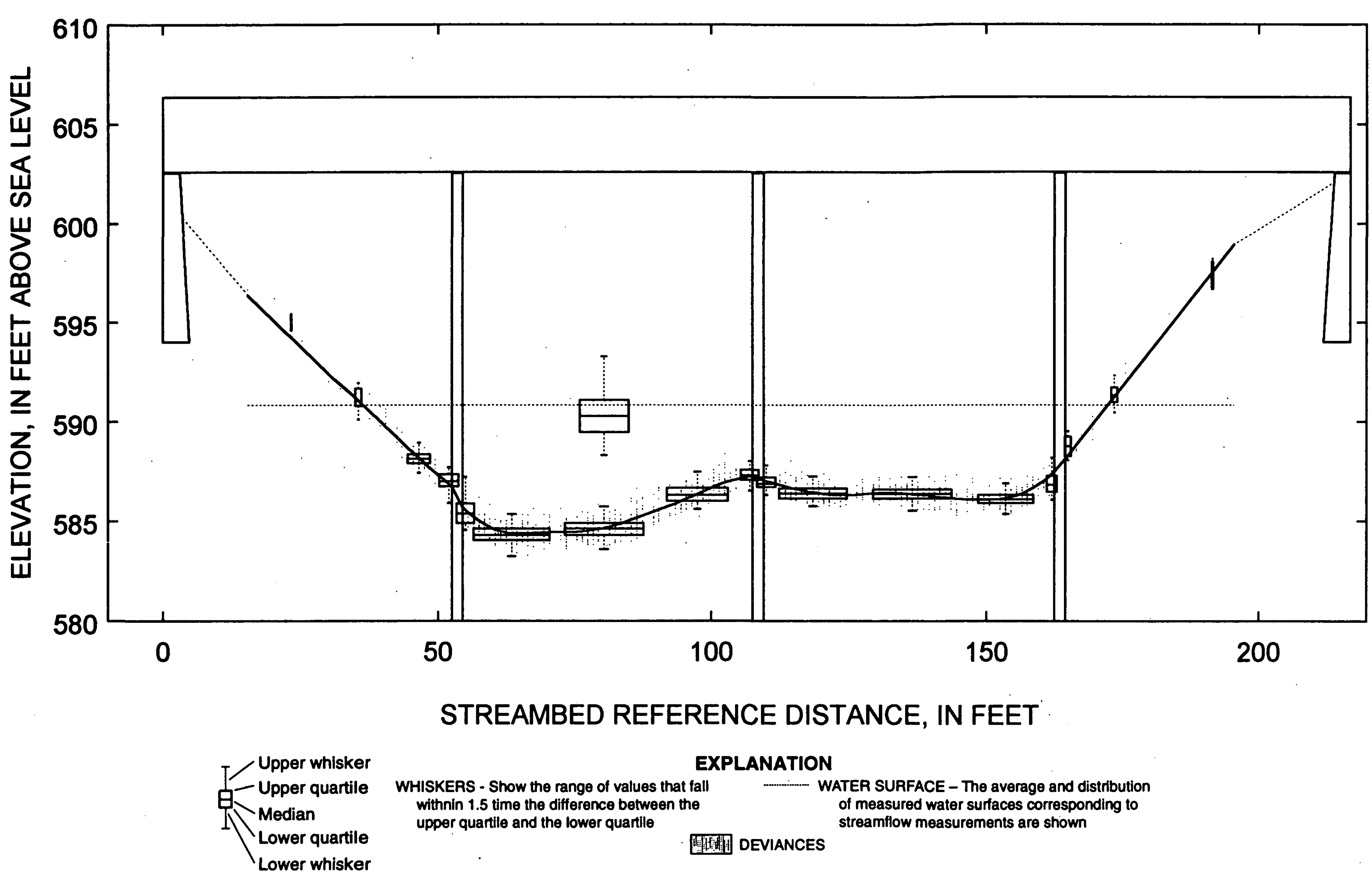

Figure 32. Normal streambed profile and local streambed variability at Fergus Road over Shiawassee River near Fergus, Mich.

Deviances had a mean and standard deviation of -0.02 and 0.44 ft, respectively, and ranged from -1.31 to 1.79 ft. Streambed deviances ranged from -0.48 to 0.66 ft and had a mean and standard deviation of -0.03 and 0.22 ft respectively. Trend analysis indicates that deviances were declining (fig. 33) during the period represented by the measurements (table 2). No significant relation was detected between streambed deviances and streamflow (fig. 34), velocity, or depth (table 2). Variability of local deviances was fairly uniform with the channel.

State Highway 13 over Flint River near Fosters (04149000)

State Highway 13 bridge crosses Flint River 2 mi west of the Village of Fosters, Michigan in the central part of Saginaw County. The gaging station near this site was operated from October 1939 to September 1984 and from October 1987 to September 1992. During this period, the mean streamflow was 758 ft^3/s; a maximum instantaneous flow of 19,000 ft^3/s occurred on April 7, 1947; and a minimum daily mean flow of 28 ft^3/s occurred on August 6, 1941 (Blumer and others, 1994, p. 171). The gaging station, which was located on the left bank of the stream about 20 ft downstream from the bridge on State Highway 13, had a datum of 582.22 ft above sea level.

Low and medium flow conditions (up to a stage of 584.7 ft) were commonly measured by wading a section about 300 ft upstream from the gaging station; higher flows were measured from the downstream side of the bridge on State Highway 13. A normal cross-sectional profile of the streambed was computed from 1,599 soundings from 61 measurements between March 29, 1972 and August 3, 1992 (fig. 35). Streamflow measurements used in developing the normal profile had mean and maximum streamflows of 2,878 and 9,450 ft^3/s, mean and maximum velocities of 2.70 and 3.31 ft/s; and mean and maximum flow depths of 6.47 and 12.63 ft, respectively. At this gaging station, 9,450 ft^3/s is a 6.5-yr flood.

Deviances had a mean and standard deviation of -0.008 and 0.83 ft, respectively, and ranged from -4.17 to 8.86 ft. Streambed deviances ranged from -0.61 to 0.84 ft and had a mean of 0.00 and a standard deviation of 0.29 ft, respectively. Trend analysis indicates that streambed deviance decreased (fig. 36) during the period represented by the measurements (table 2). Streambed deviance was positively associated with streamflow (fig. 37) and depth; no correlation was detected between streambed deviance and velocity (table 2). Variability of local deviances was greatest between the left abutment and the left pier; however this variability is associated with changes in streambed form caused by channel improvement and protection measures in the vicinity of the bridge near the piers and abutments.

State Highway 46 over Saginaw River at Saginaw (04157000)

State Highway 46 (Rust Avenue) bridge crosses Saginaw River in the City of Saginaw, Michigan in the north-central part of Saginaw County. Due to low stream gradients, a slope rating is used to compute daily mean streamflow greater than 10,000 ft^3/s at the nearby gaging station. When flow is below 10,000 ft^3/s (about 90 percent of the time), transient-flow conditions caused by wind and seiche action from Saginaw Bay invalidate the slope-rating and so only daily mean streamflows greater than 10,000 ft^3/s are generally published. The gaging station, which is located on the right bank 1,000 ft downstream from State Highway 46 in Saginaw, has a datum of 565.05 ft above the International Great Lakes datum. An auxiliary station is located about 20 mi downstream from the base station in Essexville, Michigan.

Peak flow measurements began on Saginaw River in 1904; continuous streamflow monitoring occurred from December 1942 to September 1991 and from October 1994 to the present. The maximum measured streamflow of 68,000 ft^3/s occurred on March 30, 1904 (Blumer and others, 1996, p. 210). Flow reversals have been observed throughout the river. All streamflow measurements are made on the downstream side of State Highway 46. A normal cross-sectional profile of the streambed was computed from 2,059 soundings from 67 streamflow measurements obtained between September 17, 1981 and April 22, 1993 (fig. 38). Streamflow measurements used in developing the normal profile had mean and maximum streamflows of 12,213 and 52,800 ft^3/s, mean and maximum velocities of 1.62 and 4.55 ft/s; and mean and maximum flow depths of 12.55 and 20.00 ft, respectively. At this gaging station, 52,800 ft^3/s is a 15.0-yr flood.

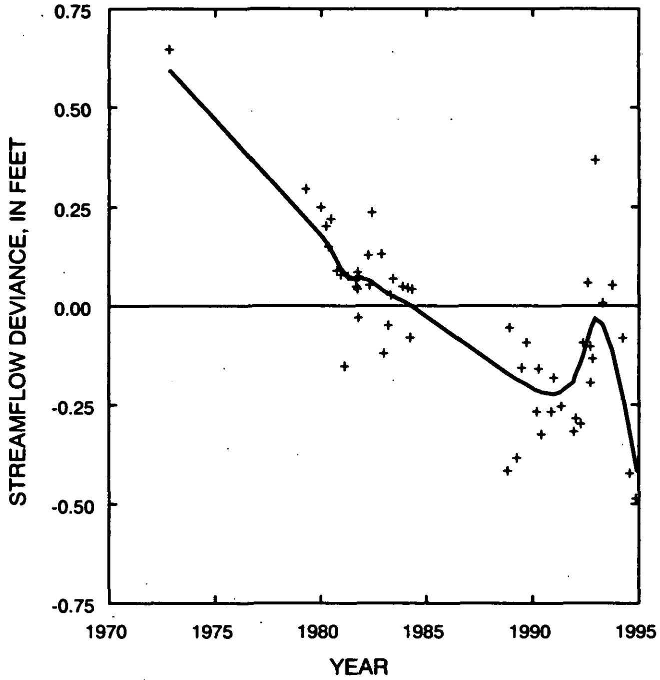

Figure 33. Trend in streambed deviance at Fergus Road over Shiawassee River near Fergus, Mich.

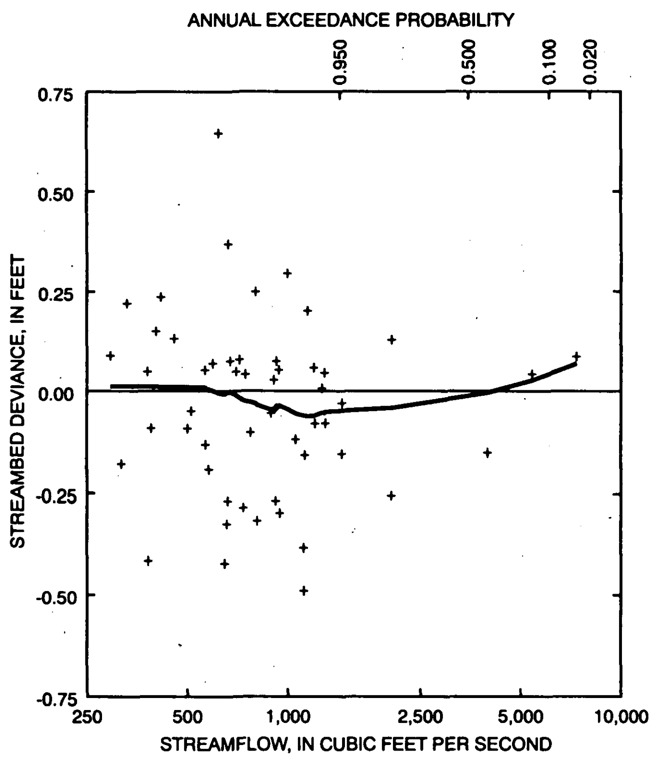

Figure 34. Relation between streambed deviance and streamflow at Fergus Road over Shiawassee River near Fergus, Mich.

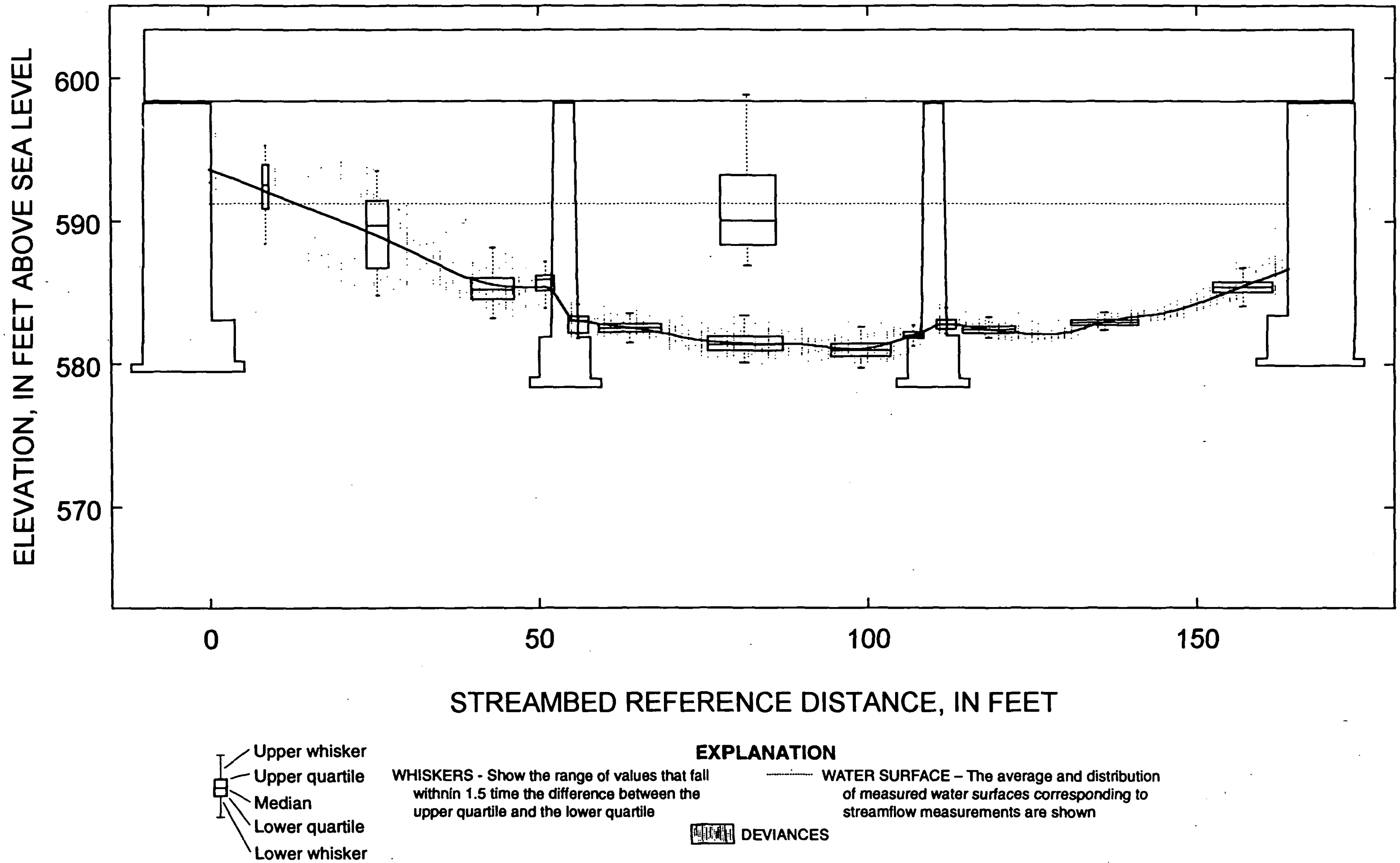

Figure 35. Normal streambed profile and local streambed variability at State Highway 13 over Flint River near Fosters, Mich.

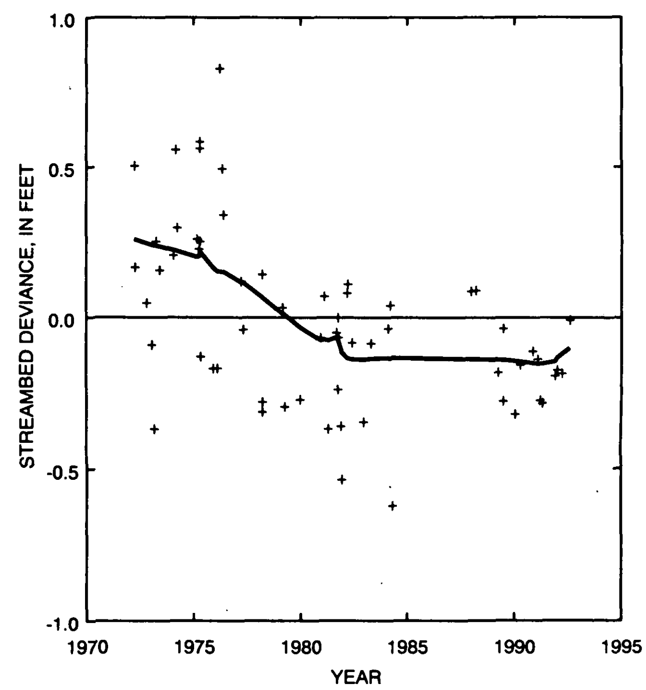

Figure 36. Trend in streambed deviance at State Highway 13 over Flint River near Fosters, Mich.

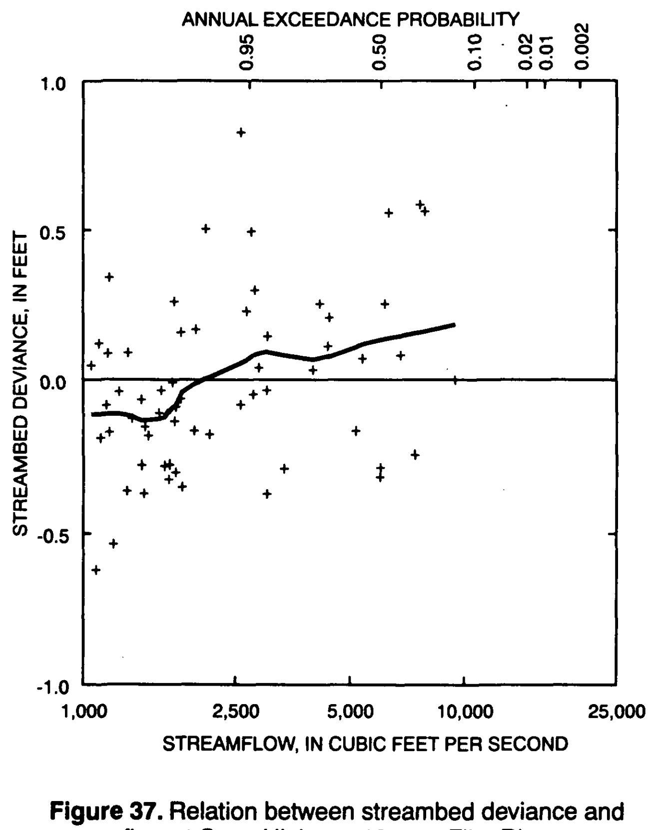

Figure 37. Relation between streambed deviance and streamflow at State Highway 13 over Flint River near Fosters, Mich.

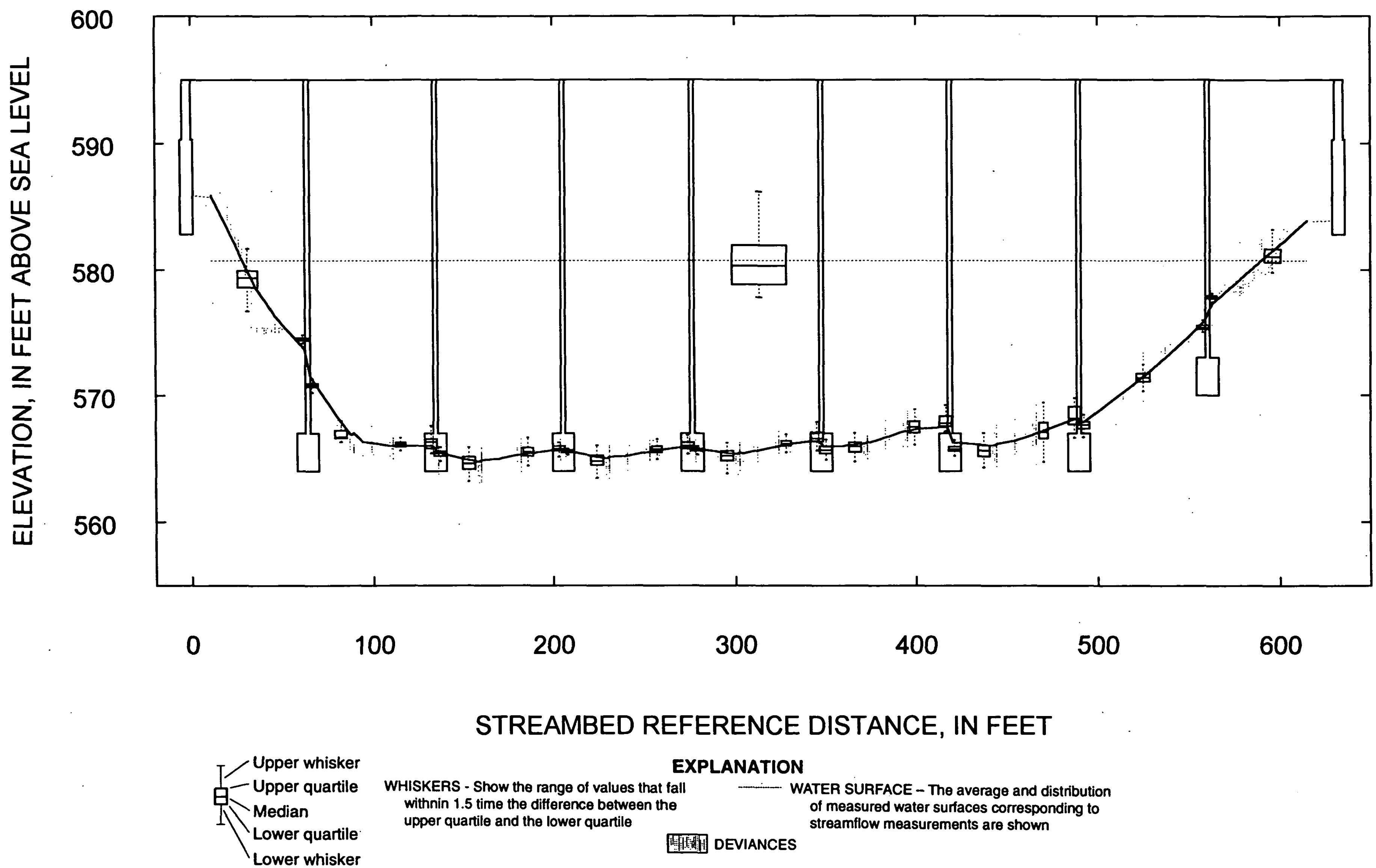

Figure 38. Normal streambed profile and local streambed variability at State Highway 46 over Saginaw River at Saginaw, Mich.

Deviances had a mean and standard deviation of -0.10 and 0.70 ft, respectively, and ranged from -3.84 to 5.82 ft. Streambed deviances ranged from -0.58 to 0.77 ft and had a mean and -0.08 ft and a standard deviation of 0.23 ft. Trend analysis indicates that streambed deviances were increasing (fig. 39) during the period of data collection (table 2). Streambed deviance and streamflow (fig. 40), velocity, and depth were uncorrelated (table 2). Variability of local deviances was uniform within the channel.

Moravian Drive over Clinton River at Mount Clemens (04165500)

Moravian Drive bridge crosses Clinton River 0.5 mi west of the City of Mount Clemens, Michigan in southeastern Macomb County. The gaging station near this site has been operated from May 1934 to the present. During this period, the mean streamflow was 557 ft^3/s; the maximum instantaneous flow of 21,200 ft^3/s occurred on April 6, 1947; and the minimum daily flow of 25 ft^3/s occurred on August 24, 1934 (Blumer and others, 1996, p. 228). The gaging station, which is situated on the left bank at the downstream side of Moravian Drive bridge, has a datum of 570.43 ft above sea level. The bridge opening at State Highway 97, 0.6 mi downstream (east) of Moravian Drive may be effective as partial or complete control during high water (D.V. Eagle, U.S. Geological Survey, written commun., 1988). An auxiliary station is located 2.0 mi downstream from the gaging station at State Highway 3 (Gratiot Avenue).

Below a stage of 575.4 ft, streamflow measurements are commonly made by wading a cross section 400 ft downstream from the Moravian Drive bridge; above this stage, streamflow measurements are made from the downstream side of the bridge. A normal cross-sectional profile of the streambed was computed on the basis of 1,562 soundings from 62 streamflow measurements made between November 19, 1970 and August 16, 1994 (fig. 41). Streamflow measurements used in developing the normal profile had mean and maximum streamflows of 1,416 and 8,480 ft^3/s, mean and maximum velocities of 1.87 and 4.74 ft/s; and mean and maximum flow depths of 5.38 and 10.47 ft, respectively. At this gaging station, 8,480 ft^3/s is a 3.9-yr flood.

Deviances had a mean and standard deviation of -0.006 and 0.56 ft, respectively, and ranged from -2.03 to 4.09 ft. Streambed deviances ranged from -0.31 to 0.28 ft and had a mean of -0.04 ft and a standard deviation of 0.14 ft. No consistent trend is apparent in streambed deviances (fig. 42) or in the relation between streambed deviance and streamflow (fig. 43), velocity, or depth (table 2). Variability of the local deviances was fairly uniform within the channel, although some increased variability is apparent on the left side of the left most pier.

Summary of Streambed Deviance Analyses

Data from historical streamflow measurements were used to assess the vertical stability of the streambed at 13 sites in Michigan. Results of these assessments indicate that the range in deviances was less than 5 ft at 3 sites and less than 10 ft at 7 additional sites. The range in deviances exceeded 10 ft at State Highway 89 over Kalamazoo River near Fennville (near streamflow gaging station number 04108500) (12.76 ft), Scottville Road over Pere Marquette River at Scottville (04122500) (11.52 ft), and State Highway 13 over Flint River near Fosters (04149000) (13.03 ft). The range in streambed deviances was less than 1 ft at 6 sites and less than 2 ft at 6 additional sites. The maximum range in streambed deviances (5.15 ft) occurred at Scottville Road over Pere Marquette River at Scottville (04122500).

Significant trends ($p<0.05$) were detected in streambed deviances at 10 sites (North Grand River Avenue over Grand River at Lansing, Michigan is included as one of these sites because a trend was detected on the downstream side of the bridge, even though no trend was detected on the upstream side of the bridge); no trends were detected at 3 sites. Of the trends detected, 7 indicated that the channel was degrading and 3 indicated that the channel was aggrading. Although statistically significant, the magnitude of the trends was generally small (less than 0.5 ft of deviation from the normal profile during the period represented by the measurements).

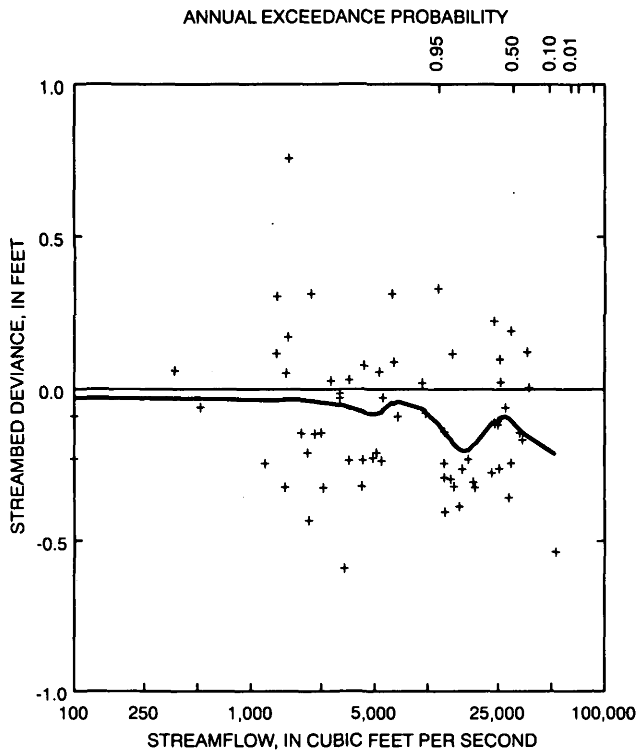

Figure 39. Trend in streambed deviance at State Highway 46 over Saginaw River at Saginaw, Mich.

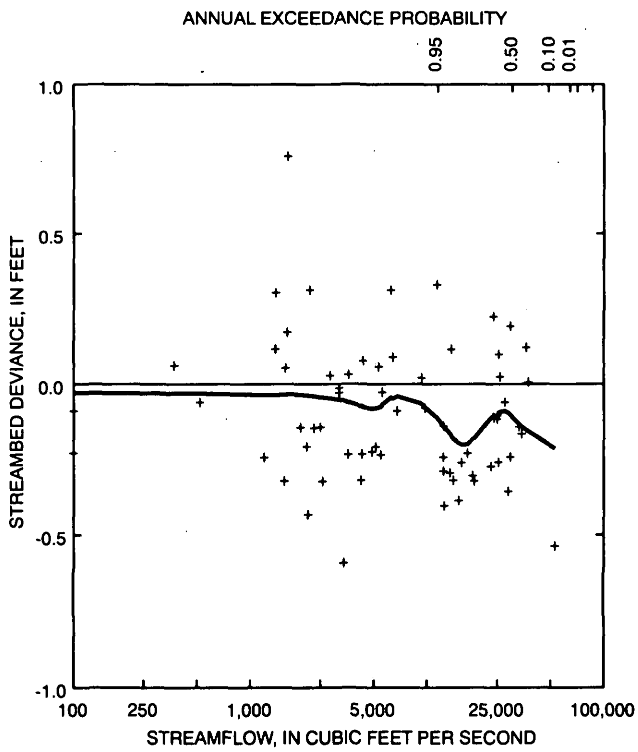

Figure 40. Relation between streambed deviance and streamflow at State Highway 46 over Saginaw River at Saginaw, Mich.

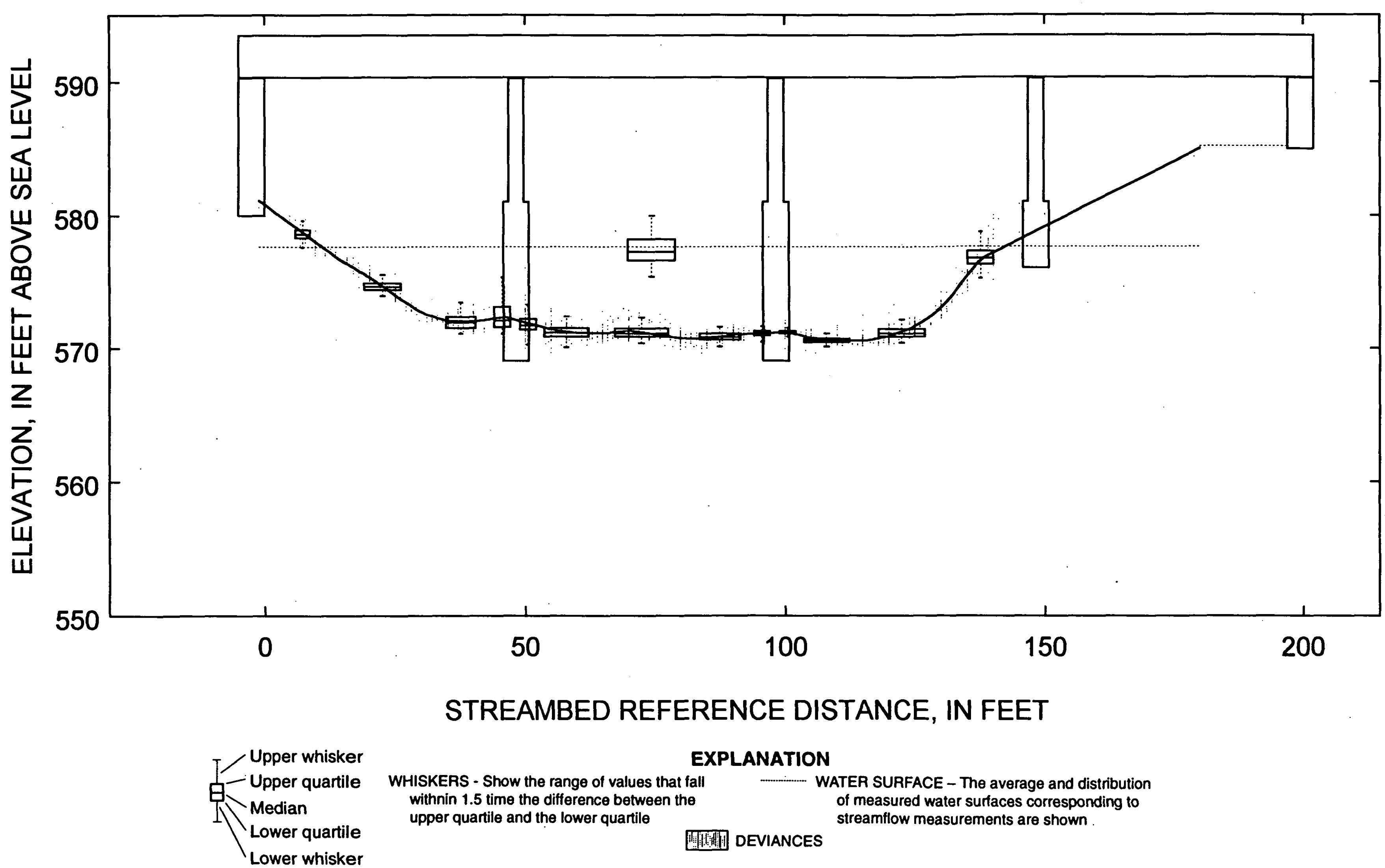

Figure 41. Normal streambed profile and local streambed variability at Moravian Drive over Clinton River at Mount Clemens, Mich.

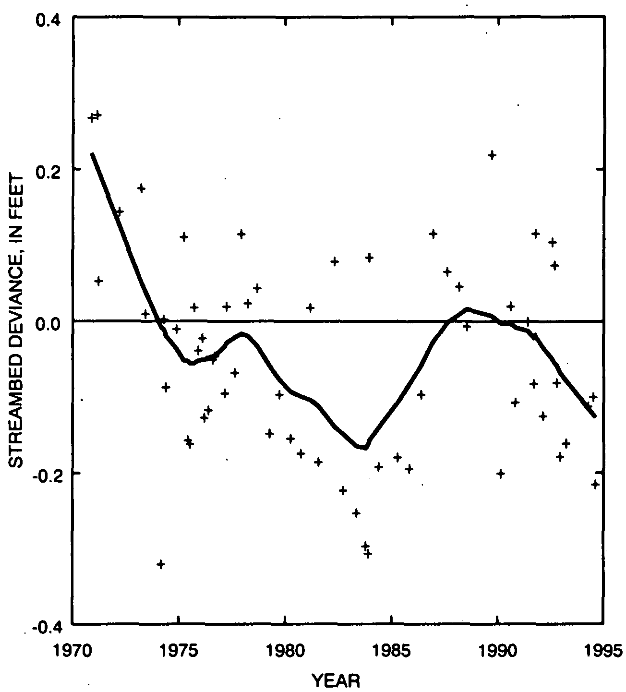

Figure 42. Trend streambed deviance at Moravian Drive over Clinton River at Mount Clemens, Mich.

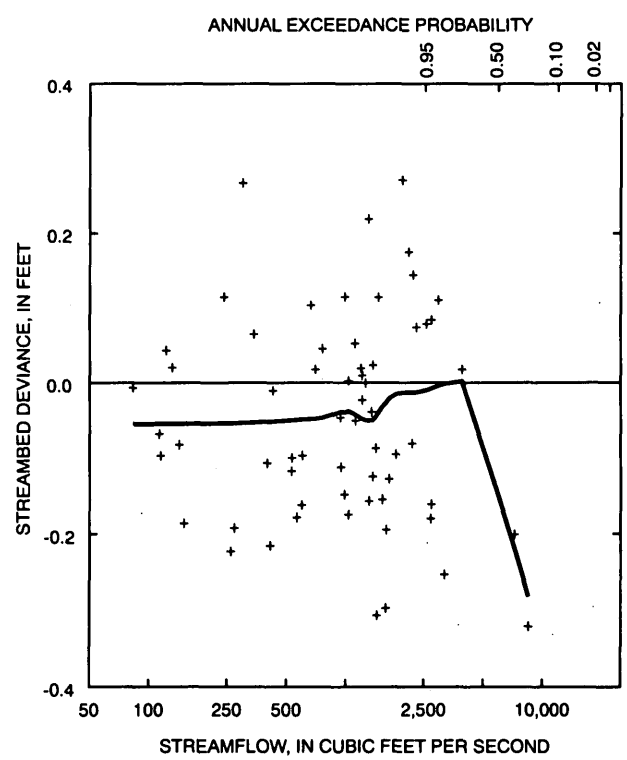

Figure 43. Relation between streambed deviance and streamflow at Moravian Drive over Clinton River at Mount Clemens, Mich.

Spearman correlation coefficients were computed to describe the monotonic relation between streambed deviance and streamflow, flow velocity, and flow depth. Streambed deviance was significantly associated with streamflow at only four sites. The empirical relation between streambed deviance and streamflow is ambiguous because two of these sites showed positive correlations with streambed deviance and two showed negative correlations. Two significant correlations were detected between streambed deviance and flow velocity. These correlations also present ambiguous empirical relations because one of these correlations was positive and one was negative. Significant correlations between streambed deviance and flow depth were detected at six sites. Of these significant correlations, five were negative, indicating that higher flow depths would likely be associated with lower streambed elevations.

Paired box plots show the local deviances grouped across measurements in the main channel and measurements near piers for each site investigated (fig. 44). Inspection of the box plots indicate negligible consistent difference between local deviances in the main channel and local deviances adjacent to piers. A Wilcoxon Signed-Rank Test (Conover, 1980, p. 280) was used to determine whether the range of local deviances near piers was statistically greater than the range of deviances in the main channel. In testing, the 1-percent trimmed range was used to eliminate any bias due to a larger number of soundings in the main channel than near piers. Results of the paired comparisons indicated that local variability adjacent to piers is not greater than the local variability in the main channel ($p = 0.9552$).

CHARACTERIZATION OF HISTORICAL SCOUR CONDITIONS FROM GEOPHYSICAL SURVEY INFORMATION

Four of the 13 study sites were surveyed with ground-penetrating radar (GPR) and (or) a tuned transducer. Survey data were inspected for evidence of refilled scour holes by examining patterns in the images of streambed-sediment deposits. At each site, transects were completed within the main-channel upstream and downstream from the bridge, along the sides of the piers, and at selected locations between the piers. Geophysical methods used are described in detail by Gorin and Haeni (1989).

Survey Methods

Ground-Penetrating Radar

GPR surveys were conducted with 50-mHz (megahertz, one megahertz is one million cycles per second), 100-mHz, and 300-mHz antennas that transmit and receive electromagnetic pulses in the radar band of frequencies. These pulses are transmitted through the water column and into the streambed sediments. Pulses are reflected from the streambed and subsurface interfaces due to differences in electromagnetic properties of the materials. Reflected pulses are received at an antenna, and the two-way travel time is measured. GPR does not work well in water with a specific conductance greater than 1,000 μS/cm (Placzek and Haeni, 1995) because the transmitted signal is attenuated within the water column.

For this study, the velocity of the pulse used for water was 0.11 ft/ns (feet per nanosecond) and for saturated sediments was 0.18 ft/ns. These velocities were used to estimate depths to subsurface interfaces. In shallow channels, the antenna was maneuvered around the piers and across the channel by wading. At locations too deep to wade, the antenna was attached to a boat.

Tuned Transducer

The tuned transducer was used with a 14-kHz (kilohertz) transducer to send and receive an acoustic signal. The acoustic signal is reflected from subsurface interfaces, where acoustic impedances change. In this study, the average velocity of sound through both water and the bed sediments was assumed to be 5,000 ft/s (feet per second). Transducers require water depths of 3 ft or more.

The transducer was suspended alongside a boat 6 to 12 in. below the water surface. The boat was maneuvered around the piers, across the channel, and at selected locations between the piers.

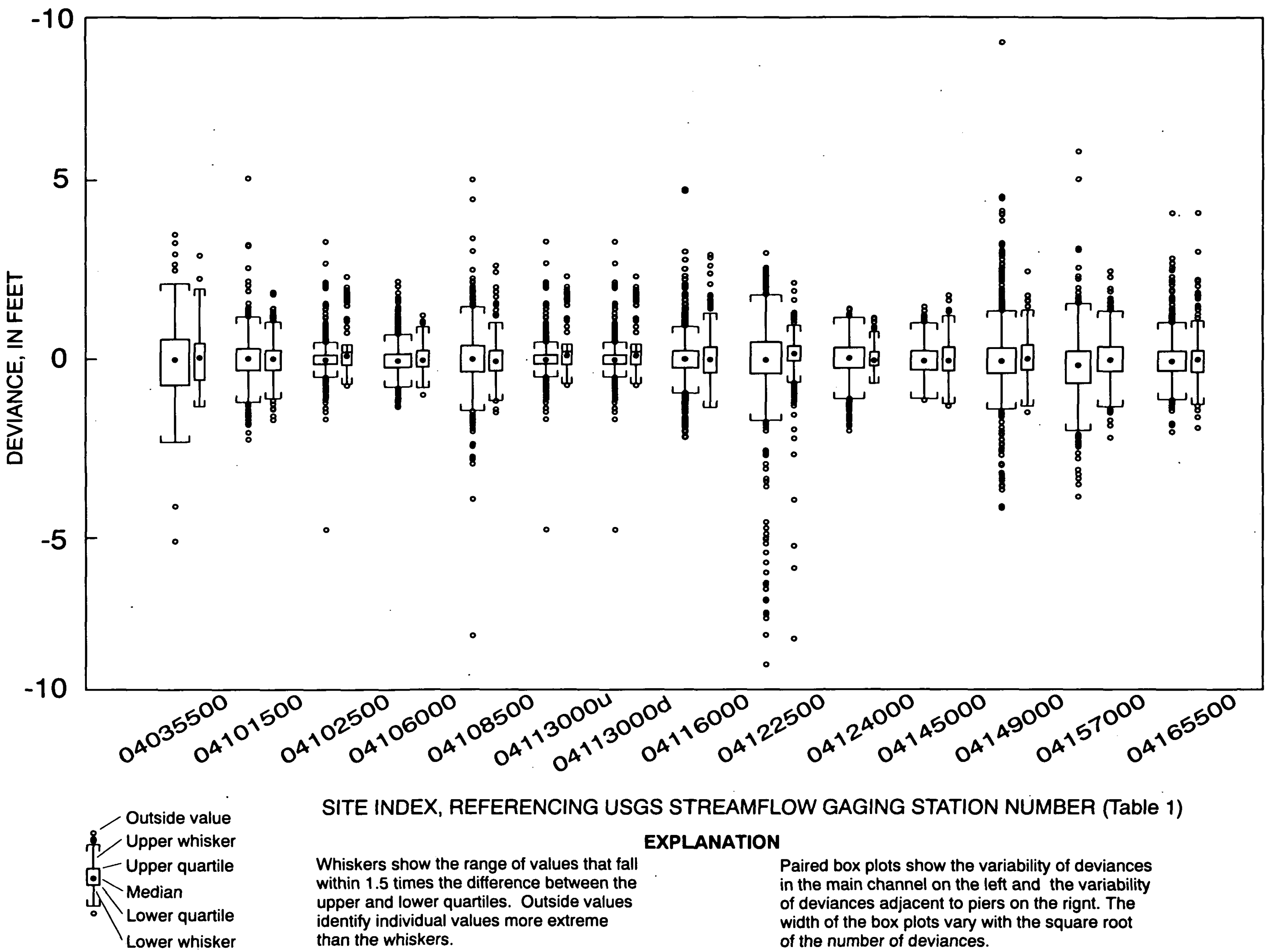

Figure 44. Variability of deviances in the main channel and deviances adjacent to piers at selected sites in Michigan.

Scour Conditions at Study Sites

State Highway 89 over Kalamazoo River near Fennville (04108500)

The bridge opening at State Highway 89 over Kalamazoo River near Fennville, Michigan was surveyed by use of GPR and the tuned transducer. GPR produced an acceptable record in shallow waters. The signal was attenuated in water depths greater than about 6 ft, however, and the record was sometimes limited to a trace of the streambed. Stream conductivities average about 550 µS/cm at this site.

An interface was detected on an east-west transect 15 ft downstream from the bridge. On the basis of field observations and analysis of a core collected during the geophysical survey, this interface was interpreted as a refilled scour hole. A portion of this reflector starts about 10 ft west (left, looking downstream) of the center pier (fig. 14) and extends to a point 15 ft east (right) of the second pier from the left.

The tuned transducer penetrated to a depth of about 3 ft. Shallow areas (1 to 2 ft) of scour and refill were interpreted from the survey. No evidence of deep scouring was indicated. The foundation for this structure consists of a footing set on piling. Soil-boring logs provided by the Michigan Department of Transportation, show that the bed material within the zone of penetration is predominately sand and fine to medium gravel. The geophysical record indicates some debris on the streambed and buried within the top layer of sediments.

North Grand River Avenue over Grand River at Lansing (04113000)

The bridge opening at North Grand River Avenue over Grand River in Lansing, Michigan was surveyed by use of the GPR. In shallow water, the signal penetrated about 4 ft into the streambed. In deeper water (greater than 4 ft) the signal was attenuated in the water column. The geophysical record indicates debris at some locations on the streambed and point reflectors, indicating some cobbles and (or) boulders are present at this site. No soil-boring logs were available. The foundation for this structure is a spread footing set on natural material.

State Highway 66 over Grand River at Ionia (04116000)

The bridge opening at State Highway 66 over Grand River at Ionia, Michigan was surveyed by use of the tuned transducer. The maximum penetration of the signal was about 4 ft. The record indicates scattered debris along the streambed and within the water column. The soil borings from the Highway Plans indicate 4.6 to 5.4 ft of sand and gravel over a thin layer of blue clay. Point reflectors are evident, indicating some scattered bolder or cobble-size material are present on the surface of the bed.

Tuned transducer data from a transect along the direction of flow between the second and third piers from the left (fig. 23) were interpreted as showing from 1 to 2 ft of scour, with refilling on the downstream side of the bridge. The scour surface is thought to start a few feet under the bridge and extends about 30 ft downstream. This may represent a small amount of contraction scour that has refilled. Only shallow spots of scour and refilling are visible in this record; no deep scour and deposition are indicated. The foundation for this structure is a spread footing set on natural material.

Scottville Road over Pere Marquette River at Scottville (04122500)

The bridge opening at Scottville Road over Pere Marquette River at Scottville, Michigan was surveyed by use of the GPR. The signal was attenuated in the water column, thus resulting in a limited amount of interpretable record. Except for the shallow-water part of the channel, the record consists of a trace of the streambed. The record was not sufficient to determine the extent of any scour that has refilled. The foundation for this structure is footings set on pilings. The soil boring logs from the highway plans indicate the bed material in the main channel consists of clay with traces of sand and gravel.

Summary of Geophysical Survey Results

GPR signals were rapidly attenuated in the water column because of the high specific conductance of the water. In water deeper than about 6 ft, the signal strength was not sufficient to penetrate the subbottom and the record sometimes consisted of only a reflection from the streambed. In shallow water (less than that 6 ft deep) the signal penetrated up to 7 ft into the sediment. The data were sometimes obscured by the effects of side echo, debris, point reflectors, and multiple reflections. The results of the GPR indicate this equipment can be used to investigate shallow streams to locate evidence of scour that has refilled. The best results are obtained when the material deposited into a scour hole has different physical properties than the surrounding bed material.

The tuned transducer was usable in water deeper than 4 ft. The data were sometimes obscured by the effects of side echo, debris, point reflections from cobbles and boulders, and multiple reflections. In shallow water, the ringing of the signal distorts the record and makes the interpretation difficult. On the basis of work completed in Indiana (Miller and Wilson, 1996), the use of the 3.5 to 7-kHz. transducer is thought to be capable of providing deeper penetration while only slightly reducing the resolution of the record. With deeper penetration, the results would be enhanced. This equipment can be used to investigate deeper streams to locate evidence of scour that has refilled.

ESTIMATION OF SCOUR POTENTIAL ON THE BASIS OF SEMI-THEORETICAL EQUATIONS

Semi-theoretical equations were used to estimate scour potential for the same 13 bridge sites where historical streambed stability was assessed on the basis of streamflow measurement data. These equations have been well documented in the literature (Richardson and others, 1993). Therefore, only a brief overview of the application of these equations is presented below, followed by a description of the results of the application of the equation to the study sites.

Application of Equations

Scour-potential estimates were computed by application of equations documented by Richardson and others (1993). Four potential components of scour potential were evaluated in this report: (1) long-term aggradation or degradation of the streambed, (2) contraction scour, (3) pier scour, and (4) abutment scour. A description of these four components and methods for estimation are described below.

Potential long-term aggradation and degradation of the streambed were evaluated on the basis of trends in the streambed elevation described in the previous section. None of the selected sites had consistent trend components greater than 0.5 ft. These magnitudes of trend components are considered insufficient to significantly affect total scour-potential estimates. Thus, the normal channel profile was used as the set of elevations to which contraction and local scour-potential estimates were referenced.

Contraction scour occurs when the flow area of a stream is reduced either by a bridge or by a natural contraction. This decrease in flow area is associated with an increase in the mean velocity and an increase in scour potential in the contraction. Two forms of contraction scour are recognized depending upon the competence of bed sediment materials in the approach section (Richardson and others, 1993, p. 9). Live-bed scour occurs when streambed sediment is transported from the approach section into the contracted section. Clear-water scour occurs when sediment transport from the approach section to the contraction section is negligible. Richardson and others (1993, p. 31) provide equations for estimating the magnitudes of contraction scour potential and criteria to determine which type of contraction scour is likely to occur.

Local scour occurs as a result of the formation of vortices near the base of piers and abutments (Richardson and others, 1993, p. 13). Factors that affect scour potential at piers and abutments include width of the pier, streamflow intercepted by the abutment and returned to the main channel, length of the pier if skewed to the flow, depth of flow, velocity of flow in the approach section, and size and gradation of bed materials, among other factors (Richardson, 1993, p. 14). Richardson and others (1993, p. 39) recommend the Colorado State University (CSU) equation for computing scour potential near piers.

Two equations were evaluated to estimate the magnitude of scour potential near abutments: Froehlich's equation and the HIRE equation (Richardson and others, 1990). Froehlich's equation was derived from dimensional analysis and regression analysis of available laboratory data (Richardson and others, 1993, p. 47). The HIRE equation was developed from Corps of Engineers field data of scour at the ends of spurs in the Mississippi (Richardson and others, 1993, p. 50). Criteria are provided to help determine whether the Froehlich equation or the HIRE equation (Richardson and others, 1993, p. 67) is applicable for particular field conditions. In this report, when both Froehlich's equation and the HIRE equation met the applicability criteria, the abutment scour estimate closest to the pier scour estimate was selected for consistency of local scour estimates. Total scour potential was computed as the sum of contraction scour potential and local scour potential near piers and abutments.

Application of the scour-potential equations requires site-specific information about flood-flow-frequency characteristics of the stream, hydraulic characteristics of the bridge opening and channel, and particle size characteristics of bed-sediment materials. Scour potentials were computed for flow conditions corresponding to the 100-yr flood.[7] Flood frequency characteristics were obtained from existing reports, such as flood insurance studies, describing the magnitude of the 100-yr recurrence interval floods. Where existing reports were unavailable or where considerable hydrologic information had been collected near the bridge site since the publication of a report, the WRC[8] guidelines for flood frequency analysis were followed to estimate the 100-yr flood magnitude.

Hydraulic data on bridge geometry and channel configuration were obtained from existing sources, including flood studies, bridge design plans, and topographic maps. Where necessary, field inspections were made and limited supplementary field data were collected. Hydraulic characteristics needed in scour computations were determined by use of WSPRO, a step-backwater analysis model (Shearman, 1990).

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[7]The 100-yr flood refers to the streamflow rate that has only a 1 percent chance of being exceeded each year. Thus over a long period of time, the mean rate of occurrence for a flood of this magnitude is once in 100 years. The probability of a flood in the current year is not a function of the length of time since the previous flood.

[8]WRC indicates the Water Resources Council (1982) guidelines used in the frequency analysis of the annual flood series. Results of this analysis are used in determining flood flow frequency.

The median diameter of bed-sediment material is used in the computation of scour potential (Richardson and others, 1993, p. 35). Information on the particle sizes of bed-sediment materials were interpreted from available logs of borings near bridge sites commonly drilled prior to bridge construction. In general, the logs indicated considerable vertical variability in material characteristics and some horizontal variability. Information from logs was supplemented with written descriptions of streambed materials from the station description at USGS streamflow gaging stations.

Estimation of Scour Potential

U.S. Highway 45 over Middle Branch Ontonagon River near Rockland (04035500)

U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Michigan is supported by two piers that divide the 384 ft long bridge into three spans. The length of the spans between abutments and piers is 120 ft and the length of the span between piers is 144 ft. Piers are sharp-nosed with a maximum width of 3 ft. Piers are aligned approximately parallel to streamflow at an angle of 35 degrees from normal to the plane formed by the bridge opening. Pier length in the direction of flow is 48 ft. Abutments are spill through with an embankment slope of 2:1 (2 ft horizontal transverse to 1 ft vertical displacement).

The channel is straight for about 600 ft upstream (east) and 1,700 ft downstream from the gaging station. Both banks are high, not likely to be overflowed by the 100-yr flood, and are heavily wooded. Logs of soil borings obtained by Michigan State Highway Department (MSHD) in 1955 indicate that channel sediments are composed of coarse sand and fine gravel overlying medium to coarse sand, silt, clay, and gravel. Records from USGS gaging station 04035500 confirm that the streambed consists of clay, sand, gravel, and stones and that some shifting of the hydraulic control of streamflow occurs because of the sandy characteristics of the streambed (J.C. Knudsen, U.S. Geological Survey, written commun., 1993). The median particle diameter used to compute scour potential was 2 mm (a very coarse sand).

Table 3. Scour potential of the 100-yr flood at U.S. Highway 45 bridge over Middle Branch Ontonagon River near Rockland, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	21,200
Water-surface elevation at downstream side of bridge opening (feet above sea level)	682.44
Water-surface elevation at the approach section (feet above sea level)	682.61
Flow velocity on downstream side of bridge opening (feet per second)	5.40
Flow velocity in the approach section (feet per second)	5.25
Contraction scour depth (feet), clear-water conditions	0.00
Pier scour depth (feet)	6.67
Abutment scour depth (feet)	
Left abutment, Froehlich's equation	11.10
Right abutment, Froehlich's equation	11.94

The magnitude of the 100-yr flood (table 3) was estimated on the basis of a flood-frequency analysis of 52 peak annual flows obtained between 1942 to 1993 at the gaging station. The WRC estimate of the 100-yr flood corresponds closely to 100-yr flood magnitude of 21,000 ft^3/s used in a hydraulic analysis of the bridge structure (Bruce Menerey, Michigan Department of Environmental Quality (MDEQ), written commun., 1995).

Channel and bridge geometry data for the step-backwater analysis were based on existing data from a similar computer model developed for the reach in 1981 (Bruce Menerey, MDEQ, written commun., 1995) and bridge-design plans. The starting water-surface elevation for the model was adjusted so that computed elevation near the gaging station was consistent with the stage-streamflow relation at the gaging station. Scour-potential estimates indicate that erosion of bed sediment near the footings of piers and abutments is possible during the 100-yr flood (fig. 45).

Broadway Street over St. Joseph River at Niles (04101500)

Broadway Street over St. Joseph River at Niles, Michigan is supported by four piers that divide the 300 ft long bridge into five 60-ft sections. Piers are sharp-nosed with a maximum width of 2.7 ft. Piers are aligned parallel to streamflow and normal to the plane formed by the bridge opening; pier length in the direction of flow is 43 ft. A sloping embankment adjoins the vertical abutments; vertical wingwalls extend from the abutments at a 45 degree angle on both the upstream and downstream sides of the bridge.

The channel curves gently to the right 700 ft downstream and gently to the left 1,200 ft upstream from the base station. Both banks are high and not subject to overflow. The streambed is composed of sand and gravel (C.R. Whited, U.S. Geological Survey, written commun., 1994). On the basis of this description and field inspection, the median particle diameter used in scour computations was estimated as 2 mm.

The magnitude of the 100-yr flood used for scour computations (table 4) was based on flood magnitude reported in the flood insurance study for the City of Niles, Michigan (Federal Emergency Management Agency, 1987). This flood flow frequency compare closely with the WRC estimate for the 100-yr flood of 21,600 ft^3/s, which is based on 64 annual peaks obtained between 1931 and 1994 at USGS gaging station 04101500.

Channel and bridge geometry data for the model were based on data from a similar backwater model used in the flood insurance study (Bruce Menerey, MDEQ, written commun., 1995) and data available from bridge-design plans (Neil Coulston, City of Niles, Michigan, written commun., 1996). The starting water-surface elevation for the model was adjusted so that the computed elevation near the gaging station was consistent with the stage-streamflow relation at the base station. Scour-potential estimates indicate that erosion of bed sediment materials near the footings of piers and abutments is possible during floods equalling or exceeding the magnitude of the 100-yr flood (fig. 46).

Table 4. Scour potential of the 100-yr flood at Broadway Street bridge over St. Joseph River at Niles, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	22,000
Water-surface elevation at the downstream side of bridge opening (feet, above sea level)	649.16
Water-surface elevation in the approach section (feet, above sea level)	649.25
Mean flow velocity in the bridge opening (feet per second)	5.00
Mean flow velocity in the approach section (feet per second)	4.21
Contraction scour depth (feet), clear-water conditions	0.70
Pier scour depth (feet)	5.72
Abutment-scour depth (feet)	
Left abutment, Froehlich equation	12.72
Right abutment, Froehlich equation	11.14

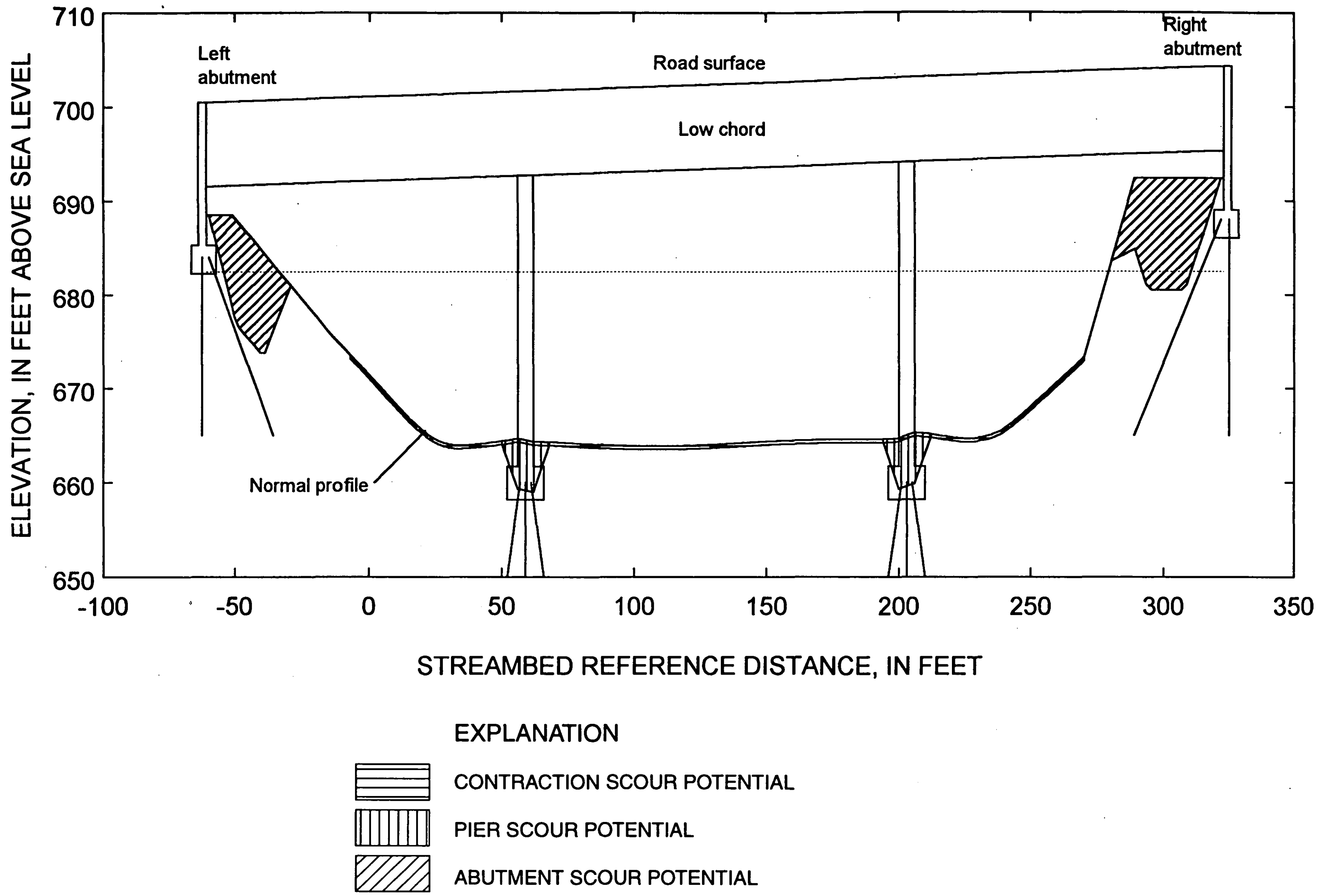

Figure 45. Estimated scour potential associated with the 100-yr flood at U.S. Highway 45 over Middle Branch Ontonagon River near Rockland, Mich.

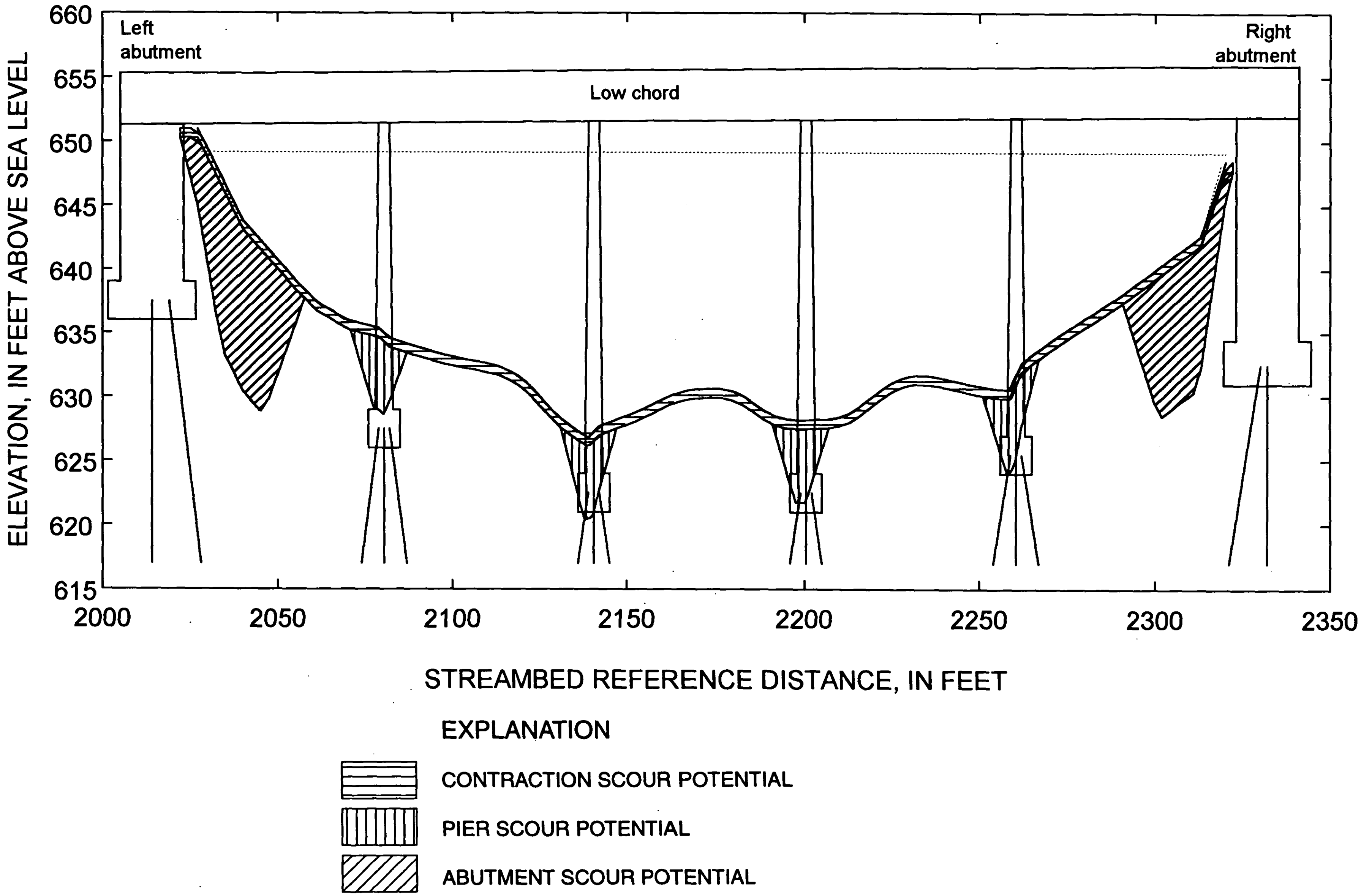

Figure 46. Estimated scour potential associated with the 100-yr flood at Broadway Street over St. Joseph River at Niles, Mich.

Coloma Road over Paw Paw River at Riverside (04102500)

Coloma Road over Paw Paw River at Riverside, Michigan is supported by two piers that divide the 154.5 ft long bridge into two 48.5 ft spans between the piers and abutments and a 57.5 ft span between piers. Concrete piers are round-nosed with a maximum width of 2.5 ft. Piers are aligned parallel to streamflow at an angle of 16 degrees from a plane normal to the bridge opening. Pier length in the direction of flow is 66.5 ft. A sloping embankment adjoins the vertical abutments; vertical wingwalls extend from the abutments at a 45 degree angle on both the upstream and downstream sides of the bridge.

The channel meanders in a low, marshy flood plain. Both banks are low and wooded and overflow on the right bank occurs at streamflows lower than the mean annual flood. The channel is straight for 300 ft north (upstream) of the gaging station and 100 ft downstream from the gaging station. Logs of borings by Berrien County Road Commission in 1965 indicate that bed sediments are composed of very loose silty sand with shells, peat, and fine silty sand. Records at gaging station 04102500 indicate that the channel and streambed are composed of clay and mud (C.R. Whited, U.S. Geological Survey, written commun., 1994). On the basis of logs of borings and field inspection, the median particle diameter used in scour computations was 0.06 mm (a coarse silt).

The magnitude of the 100-yr flood used in scour computations (table 5) was based on the flood magnitude used in the flood insurance study (Federal Emergency Management Agency, 1977). The WRC estimate of the 100-yr flood of 4,080 ft^3/s was based on 44 annual peaks obtained from 1952 and 1994 and a historical peak in 1947 at gaging station 04102500.

Channel and bridge geometry data for the step-backwater model were based on bridge design plans, USGS 7.5 minute topographic maps, and field-data collection. The starting water-surface elevation for the model was adjusted so that the computed elevation near the gaging station was consistent with the high-flow stage-streamflow relation at the gaging station. Scour-potential estimates indicate that undermining of the pile cap of piers and abutments is possible during floods equalling or exceeding the magnitude of the 100-yr flood (fig. 47).

River Street over Kalamazoo River at Comstock (04106000)

River Street over Kalamazoo River at Comstock, Michigan is supported by two piers that divide the146 ft long bridge into two 48 ft spans between abutments and piers and a 50 ft span between piers. Concrete piers are sharp-nosed with a maximum width of 4.25 ft near the footing and 3.0 ft near the low chord of the bridge. Piers are aligned parallel to streamflow and normal to the plane formed by the bridge opening; pier length in the direction of flow is 58 ft. A sloping 2:1 embankment rises to the vertical abutments.

The channel bends gently in the vicinity of River Street before bifurcating 800 ft west (downstream) of the bridge. Logs of borings near the bridge piers by MSHD in 1939 indicate that sediments in the channel are composed of 20 ft or more of stony sand and gravel. The station description for gaging station 04106000 also indicates that the streambed is composed of sand and gravel (R.L. LeuVoy, U.S. Geological Survey, written commun., 1992). The median particle diameter used in scour computations was 2 mm (a very coarse sand).

The magnitude of the 100-yr flood used for scour computations (table 6) was based on flood magnitude used in the flood insurance study for the Township of Comstock, Kalamazoo County, Michigan (Federal Emergency Management Agency, 1982). For comparison, flood-flow frequency was also analyzed by use of 57 annual peaks obtained between 1933 and 1994 at gaging station 04106000. The WRC estimate for the 100-yr flood was 7,080 ft^3/s, which is consistent with the value used in the 1982 flood insurance study.

Channel and bridge geometry data for the step-backwater model was based on bridge design plans, USGS 7.5 minute topographic maps, and field-data collection. The starting water-surface elevation for the model was adjusted so that the computed elevation near the gaging station was consistent with the high-flow stage-streamflow relation at the gaging station. Scour-potential estimates indicate that undermining of the footings of piers and abutments is possible during floods equalling or exceeding the magnitude of the 100-yr flood (fig. 48).

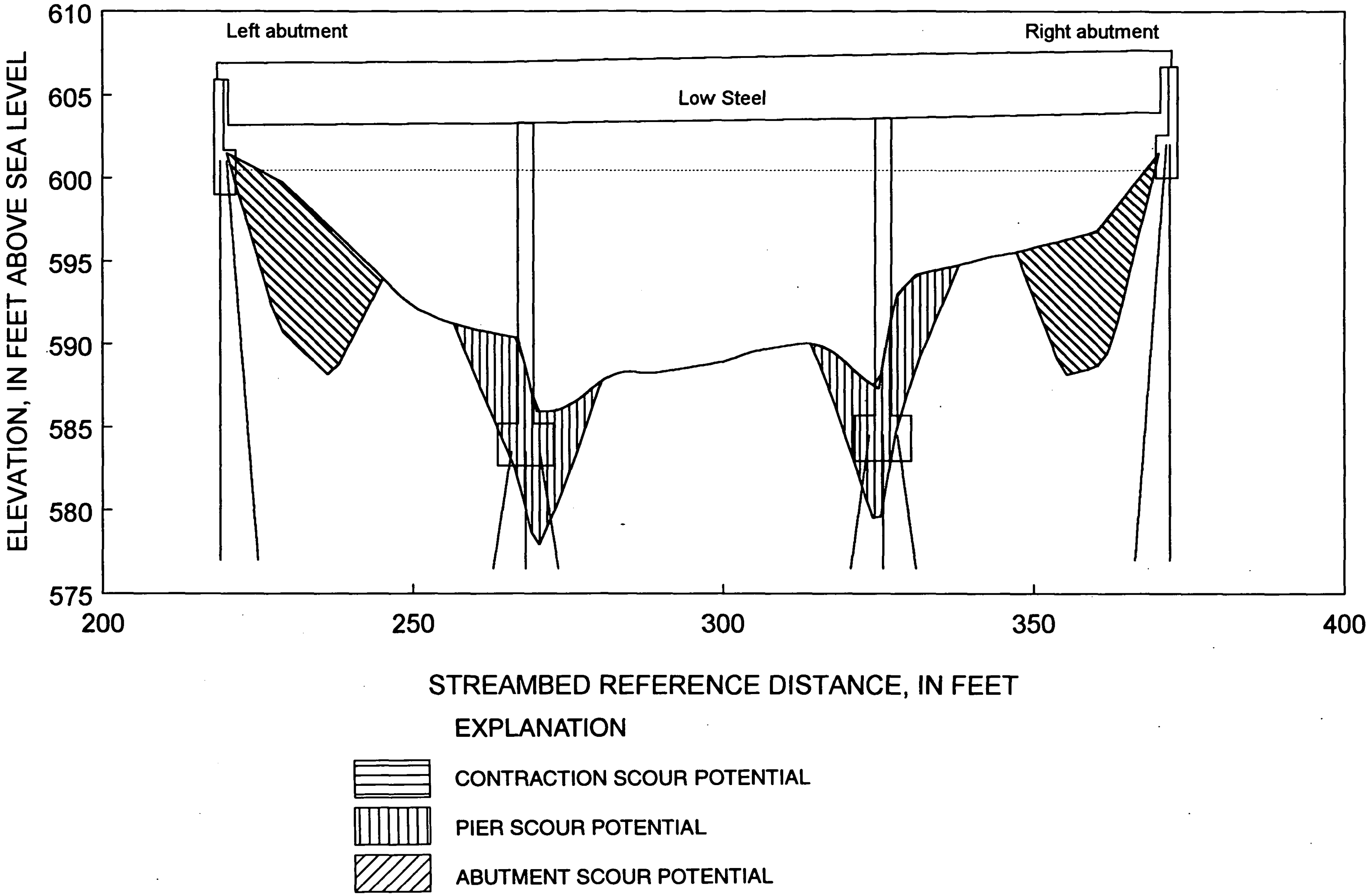

Figure 47. Estimated scour potential associated with the 100-yr flood at Coloma Road over Paw Paw River at Riverside, Mich.

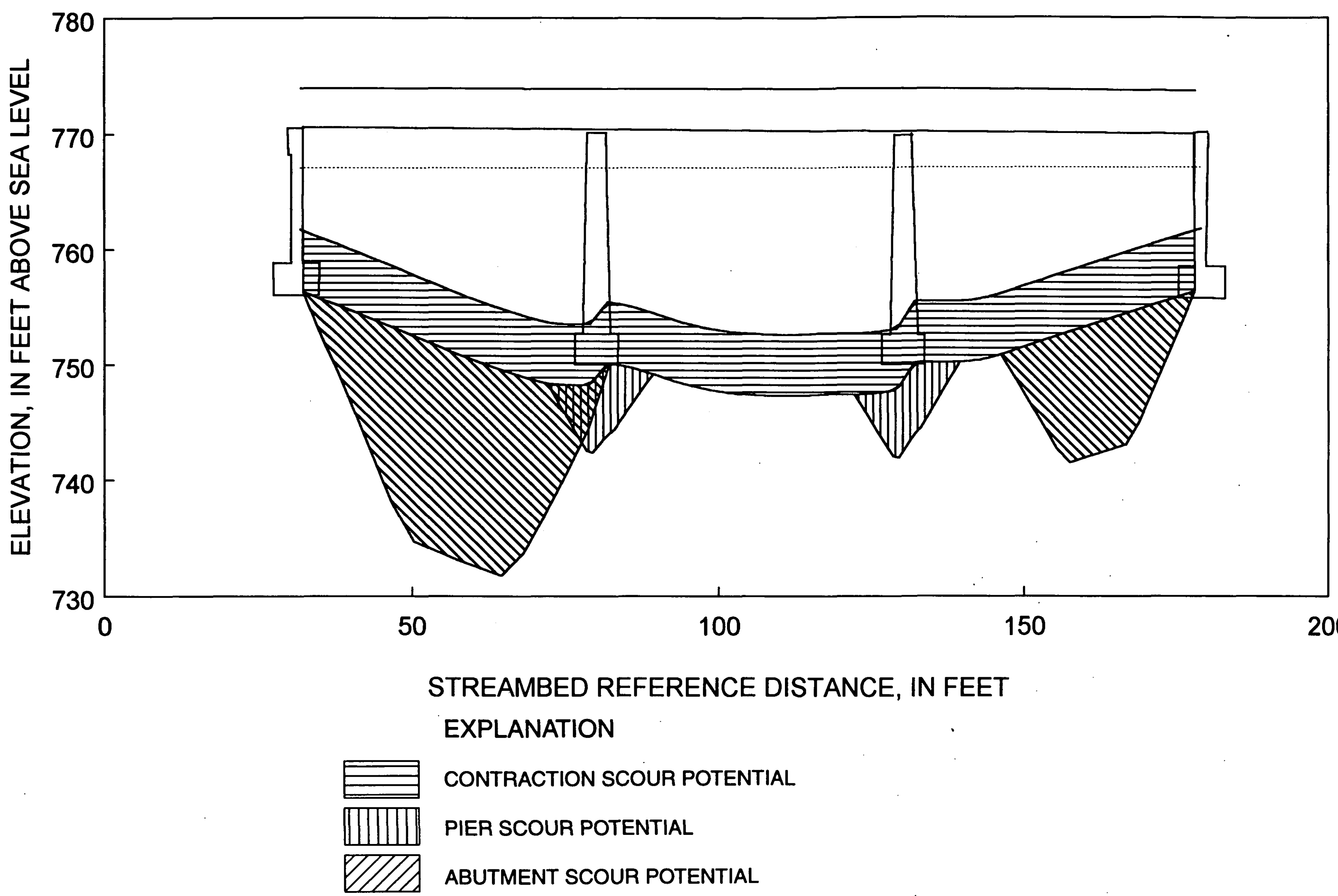

Figure 48. Estimated scour potential associated with the 100-yr flood at River Street over Kalamazoo River at Comstock, Mich.

Table 5. Scour potential of the 100-yr flood at Coloma Road bridge over Paw Paw River at Riverside, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	4,100
Water-surface elevation at downstream side of bridge (feet above sea level)	600.47
Water-surface elevation at the approach section (feet above sea level)	600.55
Mean flow velocity at downstream side of bridge (feet per second)	3.70
Mean flow velocity at the approach section (feet per second)	4.90
Contraction-scour depth (feet), live-bed equation	0.00
Pier scour depth (feet)	8.51
Abutment-scour depth (feet)	
Left abutment, HIRE equation	9.00
Right abutment, HIRE equation	8.17

Table 6. Scour potential of the 100-yr flood at River Street bridge at Kalamazoo River at Comstock, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	6,770
Water-surface elevation at downstream side of bridge (feet above sea level)	767.09
Water-surface elevation at the approach section (feet above sea level)	767.37
Mean flow velocity at downstream side of bridge (feet per second)	2.86
Mean flow velocity at the approach section (feet per second)	2.40
Contraction-scour depth (feet), clear-water conditions	5.30
Pier scour depth (feet)	6.14
Abutment-scour depth (feet)	
Left abutment, HIRE equation	17.78
Right abutment, Froehlich's equation	8.17

State Highway 89 over Kalamazoo River near Fennville (04108500)

State Highway 89 over Kalamazoo River near Fennville, Michigan is supported by five piers that divide the 357 ft long bridge into two 58.5 ft spans between abutments and piers and four 60 ft spans between piers. Concrete piers are round-nosed with a width of 3 ft. Piers and abutments are aligned parallel to streamflow and normal to the plane formed by the bridge opening. Pier length in the direction of flow is 35 ft. The streambed rises to the vertical abutments and 12 ft, 90 degree wingwalls.

The channel is straight for 300 ft upstream and downstream of the gaging station. Both banks are wooded and overflow at medium high stages greater than 597.5 ft above sea level. Logs of test borings by MSHD in 1948 indicate that the streambed is composed of about 1 ft of silt overlying 12 ft of medium sand and fine gravel. The station description for gaging station 04108500 (R.L. LeuVoy, U.S. Geological Survey, written commun., 1990) and field observation also indicates that the streambed is composed of sand. The median particle diameter used in scour potential computations was 0.375 mm (a medium sand).

The magnitude of the 100-yr flood used in the scour computations (table 7) was computed on the basis of 63 annual peak flows at USGS gaging station 04108500 obtained between 1929 and 1993. WRC guidelines were used in the flood-frequency analysis.

Channel and bridge geometry input data for the model were based on USGS 7.5 minute topographic maps and field-data collection. The starting water-surface elevation for the model was adjusted so that computed elevation near the gaging station was consistent with the extended high-flow stage-streamflow relation at the gaging station. Scour-potential estimates indicate that undermining of the footings of piers and abutments is possible during floods equalling or exceeding the magnitude of the 100-yr flood (fig. 49).

Table 7. Scour potential of the 100-yr flood at State Highway 89 bridge over Kalamazoo River near Fennville, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	12,300
Water-surface elevation at downstream side of bridge (feet above sea level)	601.68
Water-surface elevation at the approach section (feet above sea level)	601.75
Mean flow velocity at downstream side of bridge (feet per second)	3.09
Mean flow velocity at the approach section (feet per second)	3.08
Contraction-scour depth (feet), live-bed conditions	0.39
Pier scour depth (feet)	6.20
Abutment-scour depth (feet)	
Left abutment, HIRE equation	13.97
Right abutment, Froehlich's equation	9.68

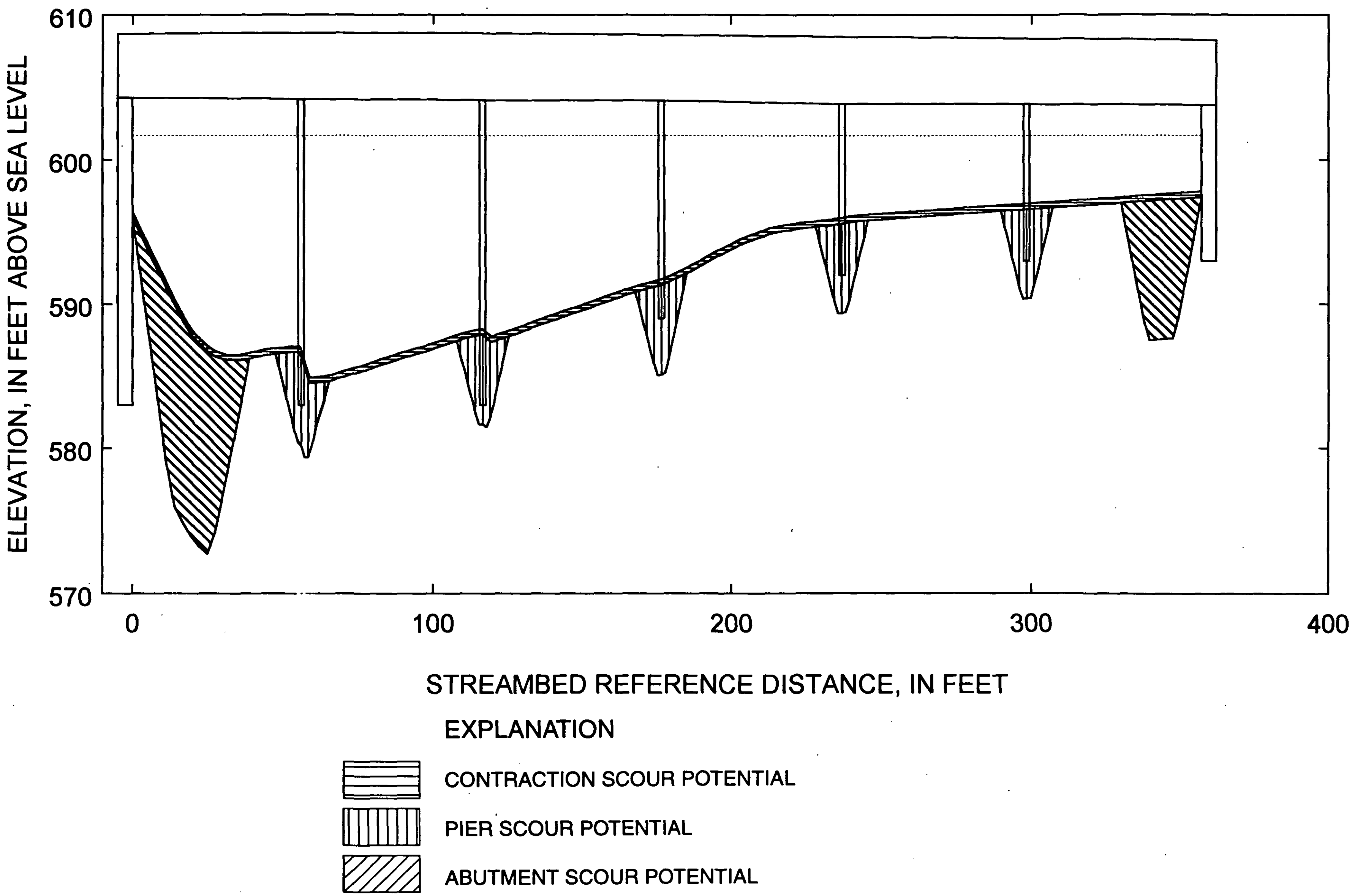

Figure 49. Estimated scour potential associated with the 100-yr flood at State Highway 89 over Kalamazoo River near Fennville, Mich.

North Grand River Avenue over Grand River at Lansing (04113000)

North Grand River Avenue over Grand River in Lansing, Michigan is a concrete arch bridge supported by two piers. The 200 ft long bridge is subdivided into three arches. The north and south arches have a maximum width of about 62 ft; the center arch spans 66 ft. Concrete piers are round-nosed with a minimum width of 5 ft. Piers and abutments are aligned parallel to streamflow and normal to the plane formed by the bridge opening; pier length in the direction of flow is 40 ft. The streambed rises to the arches that form the abutments.

The channel is straight for 1,000 ft east (downstream) of the gaging station and curves gently to the north upstream of the gaging station. Both banks are high and not subject to overflow. The station description for gaging station 04113000 (R.L. LeuVoy, U.S. Geological Survey, written commun., 1995) and field observation indicates that the streambed is composed of sand, gravel, boulders, and urban debris. The median particle diameter used in scour computations was estimated as 32 mm (fine gravel).

The 100-yr flood flow used in the scour potential calculations (table 8) was based on the value reported in the 1978 flood insurance study for the City of Lansing, Michigan. For comparison, WRC estimates of the 100-yr flood is 18,000 ft^3/s, based on 94 annual peaks obtained at USGS gaging station 04113000 between 1901 and 1995.

Channel and bridge geometry input data for the model was based on the flood insurance study of the City of Lansing, Michigan (Bruce Menerey, MDEQ, written commun., 1996). The starting water-surface elevation for the model was adjusted so that computed elevation near the gaging station was consistent with the extended high-flow stage-streamflow relation at the gaging station. Scour-potential estimates indicate that local scour could effect pier and abutment stability during periods when flows equal or exceed the magnitude of the 100-yr flood (fig. 50).

Table 8. Scour potential of the 100-yr flood at North Grand River Avenue bridge over Grand River in Lansing, Mich.

Attribute	Estimate
Total streamflow (cubic feet per second)	19,400
Streamflow through the bridge opening (cubic feet per second)	18,750
Streamflow over the road (cubic feet per second)	650
Water-surface elevation at downstream side of bridge (feet above sea level)	825.06
Water-surface elevation at the approach section (feet above sea level)	826.23
Mean flow velocity at downstream side of bridge (feet per second)	4.98
Mean flow velocity at the approach section (feet per second)	2.88
Contraction-scour depth (feet), clear-water conditions	0.00
Pier scour depth (feet)	9.41
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	30.29
Right abutment, Froehlich's equation	18.11

State Highway 66 over Grand River at Ionia (04116000)

State Highway 66 over Grand River at Ionia, Michigan is supported by four piers that divide the 370 ft long bridge into two 72.5 ft spans between abutments and piers and three 75 ft spans between piers. Concrete piers are round-nosed and taper from a maximum width of 4.1 ft near the footings to 3.0 ft near the low chord of the bridge. Piers and abutments are aligned parallel to streamflow and normal to the plane formed by the bridge opening; pier length in the direction of flow is 65 ft. The streambed rises to the vertical abutments and wingwalls set 90 degrees to the abutments.

The channel is straight for about 3,000 ft northeast (upstream) of the gaging station and bends sharply to the right (north) downstream of the gaging station. Both banks are wooded and overflow at medium-high stages (greater than 597.5 ft above sea level). Logs of borings obtained by MDOT in 1947 indicate that the streambed is composed of about 5 ft of sand and gravel overlying blue clay. The station description for gaging station 04116000 (R.L. LeuVoy, U.S. Geological Survey, written commun., 1990) indicates that the streambed is composed of clay and gravel. The median particle diameter used in scour computations was 2 mm (very coarse sand).

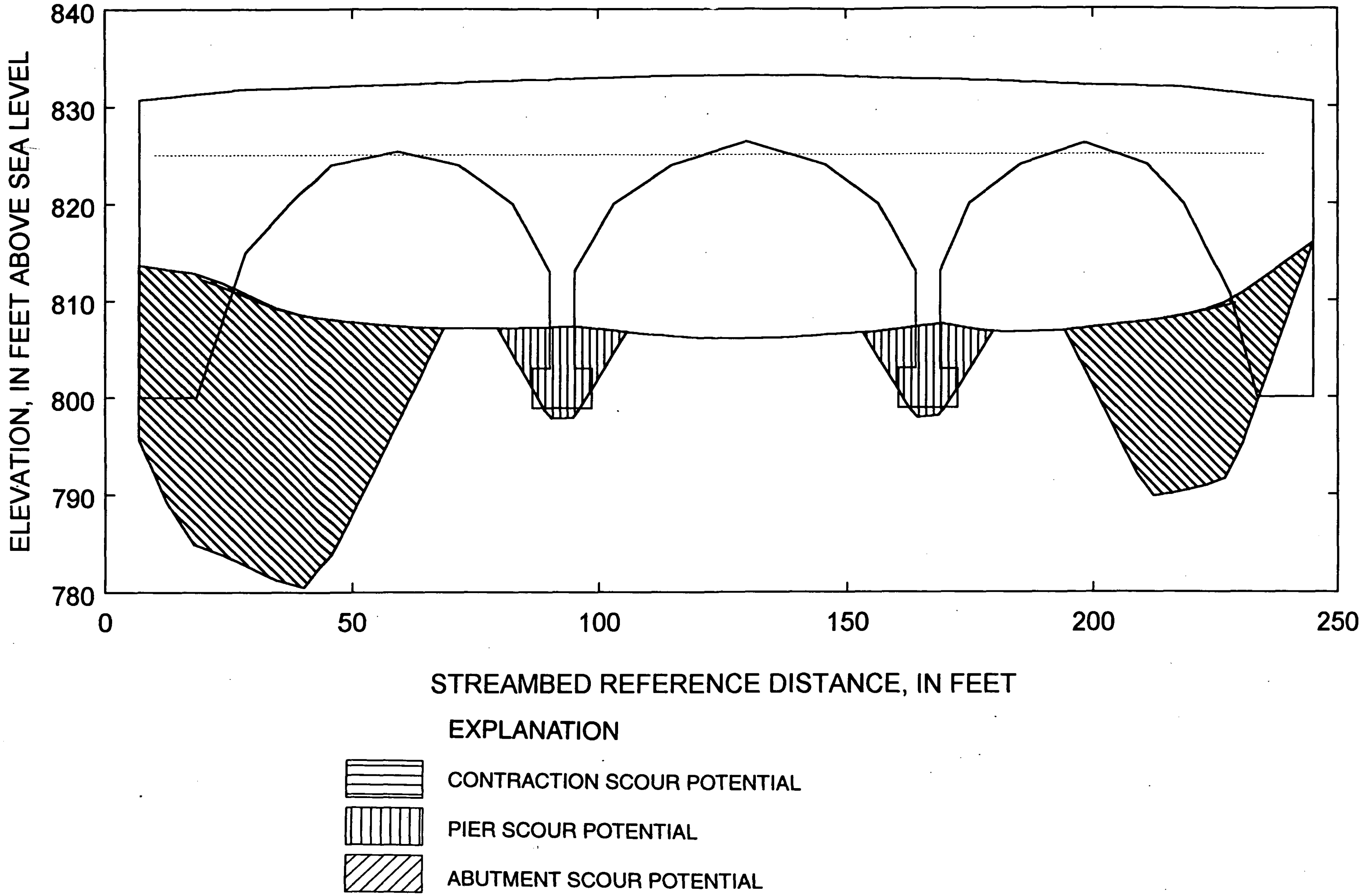

Figure 50. Estimated scour potential associated with the 100-yr flood at North Grand River Avenue over Grand River in Lansing, Mich.

The magnitude of the 100-yr flood used in the scour computation (table 9) was the 100-yr flood flow used in the flood insurance study for the City of Ionia, Michigan (Federal Emergency Management Agency, 1983). The flood insurance study used 39,000 ft^3/s for the 100-yr flood, which was considerably higher than WRC estimate based on the systematic record. The WRC estimate of the 100-yr flood, computed by use of 47 annual peak flows obtained between 1949 and 1995 at gaging station 04116000, was 26,900 ft^3/s. Although historical flood information may help resolve the differences between the two sets of estimates, in this report the scour potential was assessed on the basis of a 100-yr flood of 39,000 ft^3/s.

Channel and bridge geometry data for the model was based on USGS 7.5 minute topographic maps, bridge site plans, and field-data collection. The starting water-surface elevation for the model was adjusted so that the computed elevation near the gaging station was consistent with the elevation used in the flood insurance study. Scour-potential estimates indicate that undermining of the footings of piers and abutments is possible during floods equalling or exceeding the magnitude of the 100-yr flood (fig. 51).

Scottville Road over Pere Marquette River at Scottville (04122500)

Scottville Road over Pere Marquette River at Scottville, Michigan is supported by two piers that evenly divide the 135 ft long bridge into three 45-ft spans. The bridge crosses the stream at an angle of 35 degrees; however the piers and abutments are aligned parallel to streamflow. Concrete piers are sharp-nosed with a maximum width of 3 ft and a length of 42 ft. Abutments are vertical; embankments have a 2:1 (horizontal to vertical) side slope. The bridge is 31 ft wide.

The channel is straight for about 30 ft upstream and 500 ft downstream. Both banks are heavily wooded and brush covered. Overbank areas are low-lying and subject to overflow at stages above 601.2 ft above sea level. Logs of borings by MSHD in 1940 indicate that the streambed is composed of 20 ft of clay with traces of sand and gravel. Gaging station records indicate that the streambed is composed of sand, gravel, and some large rocks (R.G. Nettleton, U.S. Geological Survey, written commun., 1991). The median particle diameter used in scour potential computations was 2 mm (very coarse sand).

The magnitude of the 100-yr flood was based on the WRC estimate computed by use of 55 systematic annual peak flows obtained between 1940 and 1994 (table 10). No historic peaks outside the period of data collection were available.

Channel and bridge geometry data for the step-backwater model were based on an existing step-backwater model (Bruce Menerey, MDEQ, written commun., 1996). USGS 7.5 minute topographic maps and bridge site plans provided supplemental data. The starting water-surface elevations for the model was adjusted so that the computed elevation near the gaging station was consistent with the elevation used in the flood insurance study. Scour-potential estimates indicate that undermining of the footings of piers and abutments is possible during floods equalling or exceeding the magnitude of the 100-yr flood (fig. 52).

Table 9. Scour potential of the 100-yr flood at State Highway 66 bridge over Grand River at Ionia, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	39,000
Water-surface elevation at downstream side of bridge (feet above sea level)	645.00
Water-surface elevation at the approach section (feet above sea level)	645.92
Mean flow velocity at downstream side of bridge (feet per second)	2.54
Mean flow velocity at the approach section (feet per second)	2.21
Contraction-scour depth (feet), live-bed conditions	5.30
Pier scour depth (feet)	9.44
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	22.73
Right abutment, HIRE equation	26.78

Table 10. Scour potential of the 100-yr flood at Scottville Road bridge over Pere Marquette River at Scottville, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	4,490
Water-surface elevation at downstream side of bridge (feet above sea level)	604.24
Water-surface elevation at the approach section (feet above sea level)	604.60
Mean flow velocity at downstream side of bridge (feet per second)	1.58
Mean flow velocity at the approach section (feet per second)	1.31
Contraction-scour depth (feet), clear-water conditions	4.65
Pier scour depth (feet)	5.53
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	10.93
Right abutment, Froehlich's equation	8.37

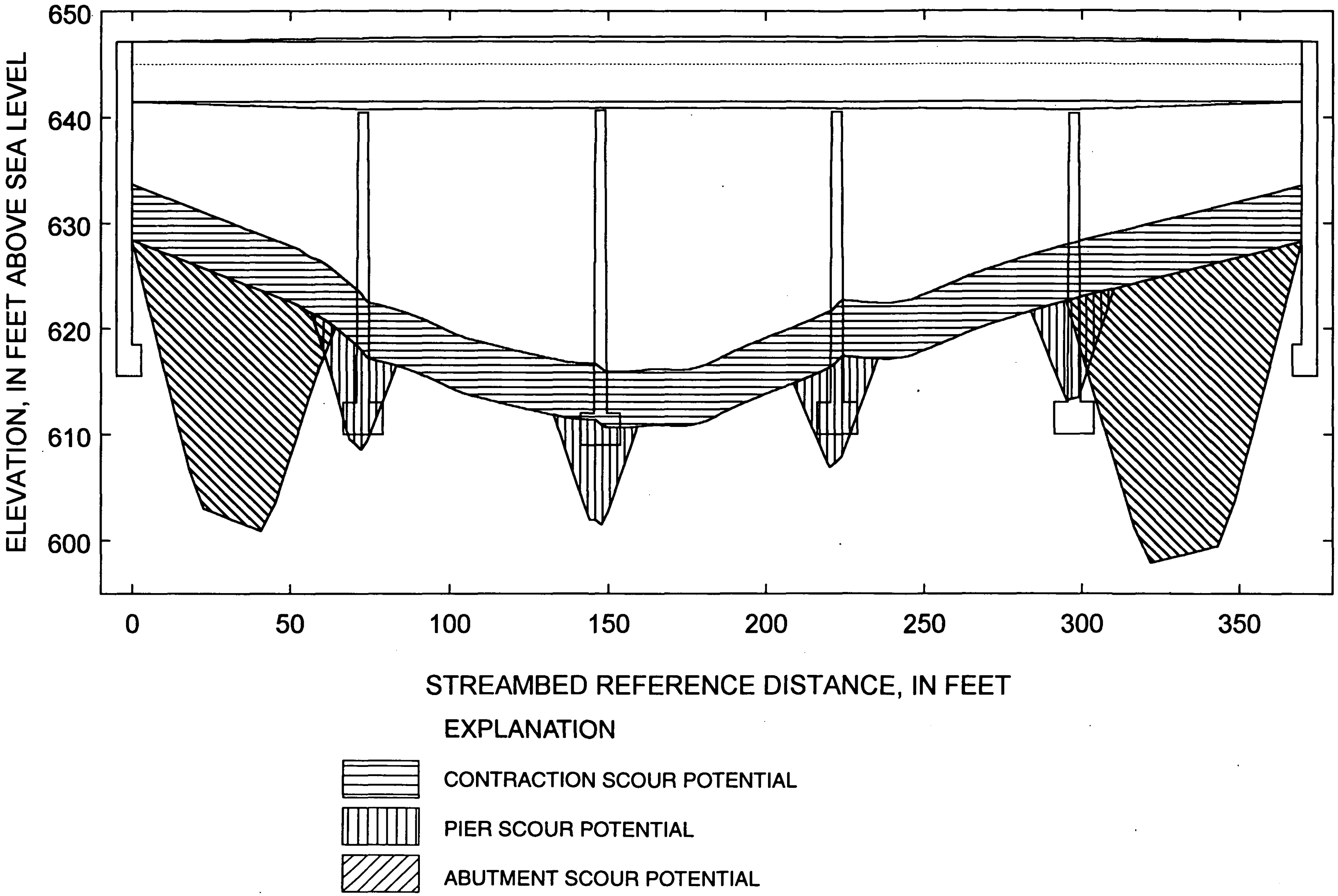

Figure 51. Estimated scour potential associated with the 100-yr flood at State Highway 66 over Grand River at Ionia, Mich. (Depiction of footings for abutments and piers is based on 1947 bridge design plans by MSHD.)

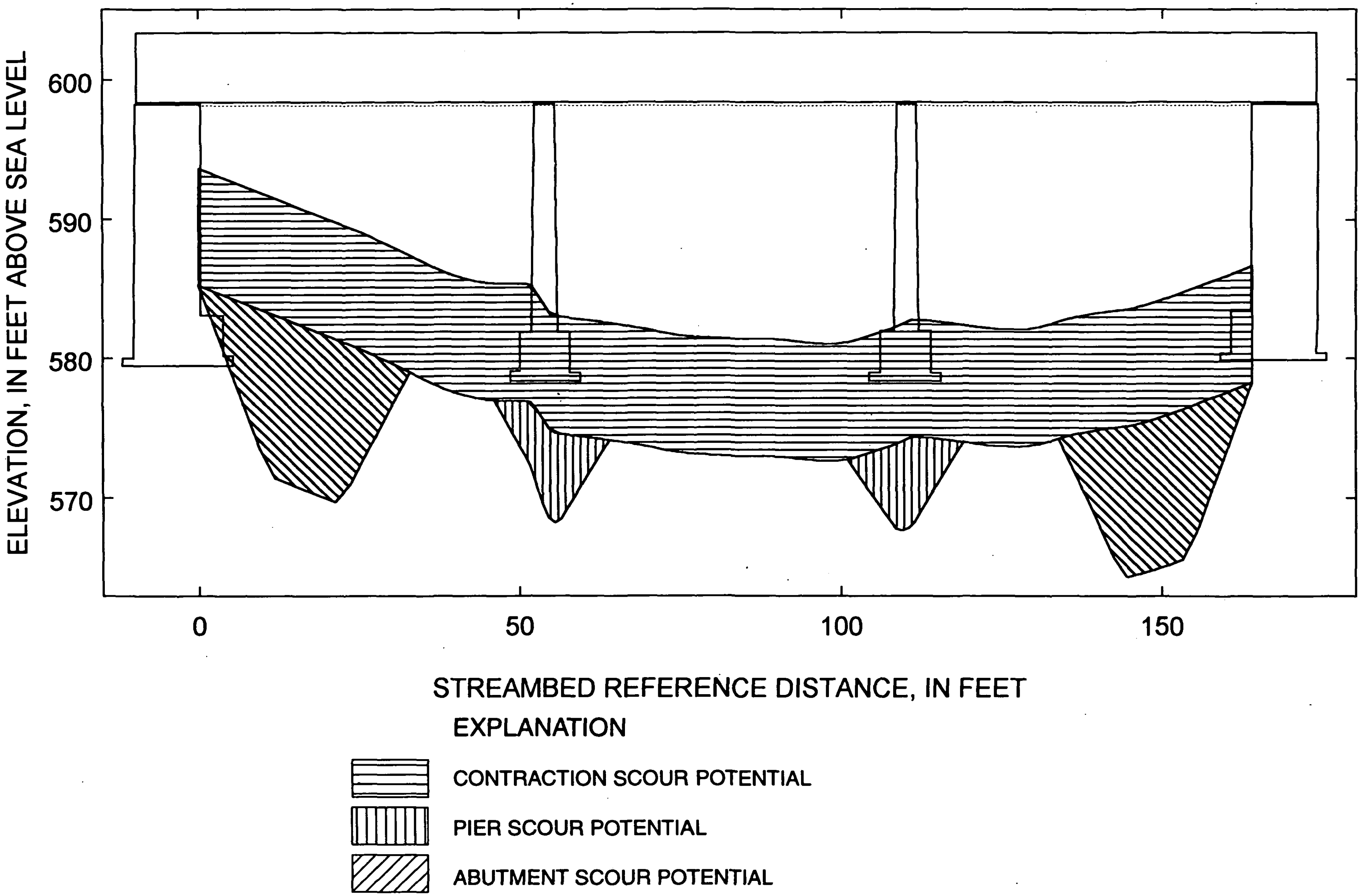

Figure 52. Estimated scour potential associated with the 100-yr flood at Scottville Road over Pere Marquette River at Scottville, Mich.

State Highway 37 over Manistee River near Sherman (04124000)

State Highway 37 across Manistee River near Sherman, Michigan is supported by one pier that divides the 115 ft long bridge into two equal spans of 57.5 ft. The bridge crosses the stream at an angle of 19 degrees, however the pier and abutments are aligned parallel to streamflow. The concrete round-nosed pier is 4 ft wide and 46 ft long. Abutments are vertical and embankments are sloping at a 2:1 ratio. The bridge width is 42 ft.

The channel is straight for 200 ft upstream and 400 ft downstream from the bridge. Low-lying areas on the south (left) bank are flooded above stages of 818.4 ft, areas on the north (right) bank are flooded above stages of 817.4 ft above sea level. Logs of borings by the MDOT in 1994 indicate that the streambed consists of a 2 ft sand and gravel layer overlying clay with traces of sand and gravel. Gaging station records indicate that the streambed is composed of sand and fine gravel (Bert Nettleton, U.S. Geological Survey, written commun., 1991). The median particle size of streambed materials used in scour potential computations was 2.0 mm (very coarse sand).

Table 11. Scour potential of the 100-yr flood at State Highway 37 bridge over Manistee River near Sherman, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	3,620
Water-surface elevation at downstream side of bridge (feet above sea level)	820.97
Water-surface elevation at the approach section (feet above sea level)	821.03
Mean flow velocity at downstream side of bridge (feet per second)	2.63
Mean flow velocity at the approach section (feet per second)	2.61
Contraction-scour depth (feet), clear-water conditions	(1)
Pier scour depth (feet)	6.44
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	7.32
Right abutment, Froehlich's equation	8.20

[1]Negative values indicated.

The magnitude of the 100-yr flood used in the scour potential computations (table 11) was the WRC estimate computed on the basis of 74 annual peak streamflow values obtained between 1904 and 1994 at USGS gaging station 04124000. A step-backwater model was developed on the basis of bridge site plans, gaging stations records, and topographic maps. The starting water-surface elevation for the step-backwater model was adjusted for consistency with the rating maintained at the gaging station. Results of scour potential calculations indicate that significant scour near the abutments may occur with the 100-yr flood (fig. 53).

Fergus Road over Shiawassee River near Fergus (04145000)

Fergus Road across Shiawassee River near Fergus, Michigan is supported by three piers that divide the 220 ft long bridge into four equal spans of 55 ft. The bridge crosses the stream at an angle of 40 degrees, however piers and abutments are aligned parallel to streamflow. Piers are formed from 12-in. steel *H* piling that is estimated to be about 40 ft long. Abutments and embankments are sloping at a 2:1 angle. The bridge width is 30 ft.

The channel is fairly straight for about 1,500 ft upstream and bends to the left about 500 ft downstream from the bridge. The banks are steeply diked. Some trees and brush adjoin the banks near the edge of water but the growth is relatively sparse beyond the top of the banks. Debris frequently accumulates on the bridge piers. Both banks overflow at stages above 596 to 599 ft above sea level, depending on the conditions of the dikes. The streambed is composed of sand and mud and is susceptible to scour during high water (T.A. Dewitt, U.S. Geological Survey, written commun., 1995). Logs of borings from Saginaw County Road Commission in 1955 indicate that streambed deposits include 4 ft of sand and silt with traces of wood and organic materials overlying silty blue clay. The median particle diameter of streambed materials used in scour computations was 0.5 mm (a medium sand).

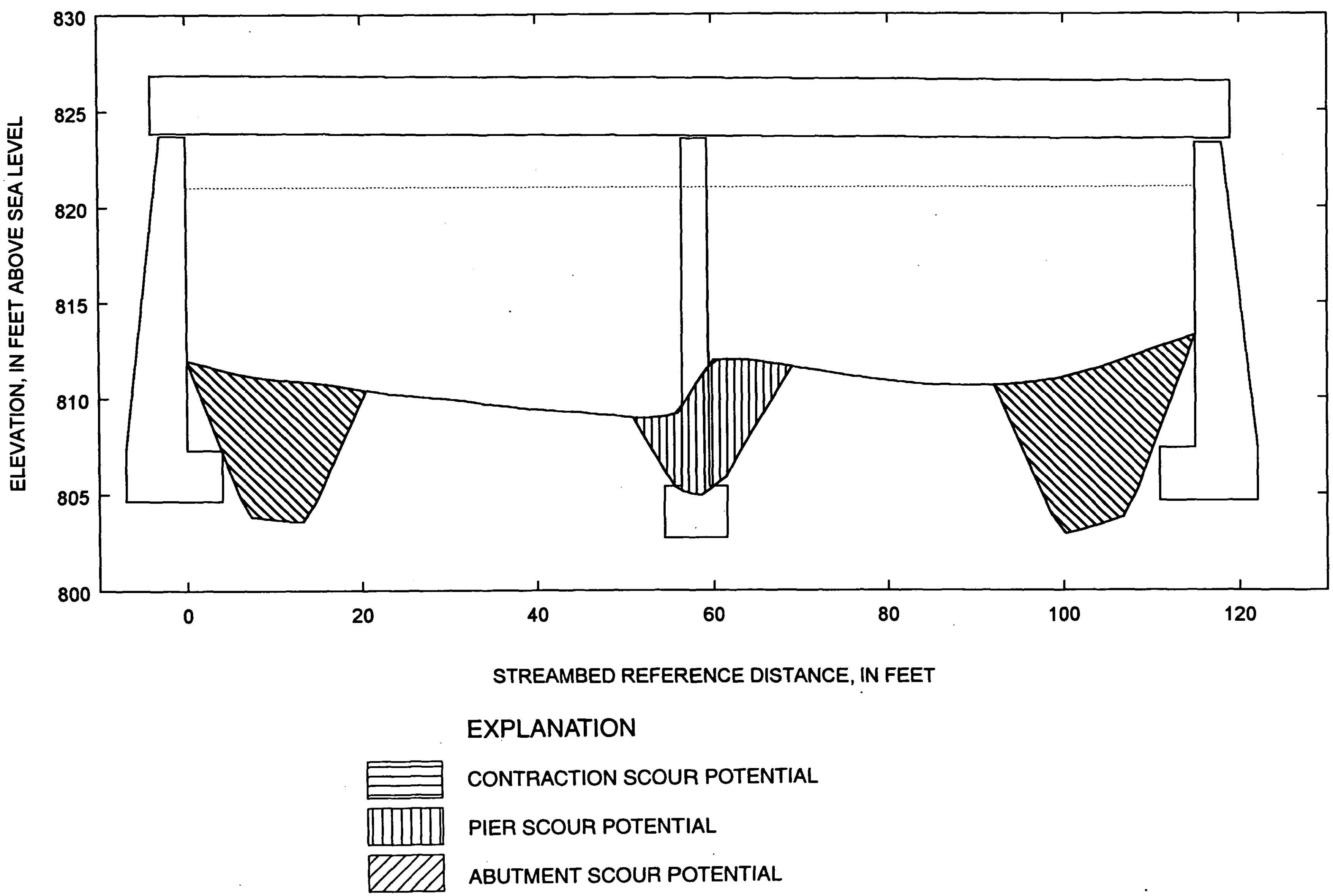

Figure 53. Estimated scour potential associated with the 100-yr flood at State Highway 37 over Manistee River near Sherman, Mich.

The magnitude of the 100-yr flood used in the scour potential computations (table 12) was determined on the basis of 51 annual peak streamflow values obtained between 1940 and 1994 at gaging station 04145000. A step-backwater model was developed to compute hydraulic conditions for the 100-yr flood on the basis of bridge site plans, gaging station records, topographic maps, and field survey data.
Possible failures of the dikes creates additional uncertainty in computed water-surface elevations at this site. The starting water-surface elevation for the step-backwater model was adjusted for consistency with the rating maintained at the gaging station. Results of scour potential calculations are shown in table 12 and fig. 54.

Table 12. Scour potential of the 100-yr flood at Fergus Road bridge over Shiawassee River near Fergus, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	8,840
Water-surface elevation at downstream side of bridge (feet, above sea level)	601.68
Water-surface elevation at the approach section (feet, above sea level)	601.78
Mean flow velocity at downstream side of bridge (feet per second)	4.57
Mean flow velocity at the approach section (feet per second)	4.54
Contraction-scour depth (feet), live-bed conditions	0.00
Pier scour depth (feet)	3.40
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	0.00
Right abutment, Froehlich's equation	0.00

State Highway 13 over Flint River near Fosters (04149000)

State Highway 13 over Flint River near Fosters, Michigan is supported by two piers that divide the 165 ft long bridge into three 55 ft long spans. The bridge crosses the river normal to streamflow. Concrete piers are sharp-nosed with a mean width of 3.5 ft and a length of 43 ft. Vertical abutments meet 2:1 sloping ground at an elevation of 591.65 ft. The bridge width is about 40 ft.

The channel is straight for more than 1,200 ft downstream of the bridge. Banks are diked and not subject to overflow except in extreme high stages. About 300 ft upstream from the bridge, the channel bends sharply to the south. Dikes upstream of the gaging station overflow during extreme high water, causing flow to spill into Birch Run, 400 ft north of the Flint River at State Highway 13. The channel is mostly mud and sand with much imbedded and submerged debris. Some channel reconstruction work was done at the bridge site to alleviate high-water overflow problems (P.J. Klimek, U.S. Geological Survey, written commun., 1991). Logs of borings by MSHD in 1940 indicate that below the stream bottom, streambed materials consist of about 3 ft of sand and gravel overlying a marly aquatic peat. The median particle diameter used in scour potential calculations was 0.5 mm (a medium sand).

The magnitude of the 100-yr flood used in scour potential calculations (table 13) was based on 50 annual peak streamflow values obtained between 1940 and 1992 at gaging station 04149000. A step-backwater model was developed to compute hydraulic conditions for the 100-yr flood on the basis of bridge site plans, gaging station records, topographic maps, and field survey data. Possible failures of the dikes creates additional uncertainty in computed water-surface elevations at this site. The starting water-surface elevation for the step-backwater model was adjusted for consistency with the rating maintained at the gaging station. Results of water-surface profile and scour potential calculations indicate that significant scour is possible during a 100-yr flood event (table 13 and fig. 55).

Table 13. Scour potential of the 100-yr flood at State Highway 13 over Flint River near Fosters, Mich.

Attribute	Estimate
Total streamflow (cubic feet per second)	16,200
Streamflow in Flint River at State Highway 13 (cubic feet per second)	10,300
Streamflow in Birch Run at State Highway 13 (cubic feet per second)	1,900
Road overflow at State Highway 13 north of Birch Run (cubic feet per second)	4,000
Water-surface elevation at downstream side of bridge (feet above sea level)	598.15
Water-surface elevation at the approach section (feet above sea level)	598.57
Mean flow velocity at downstream side of State Highway 13 bridge (feet per second)	4.92
Mean flow velocity at the approach section (feet per second)	0.88
Contraction-scour depth (feet), live-bed conditions	8.42
Pier scour depth (feet)	6.42
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	11.72
Right abutment, Froehlich's equation	10.79

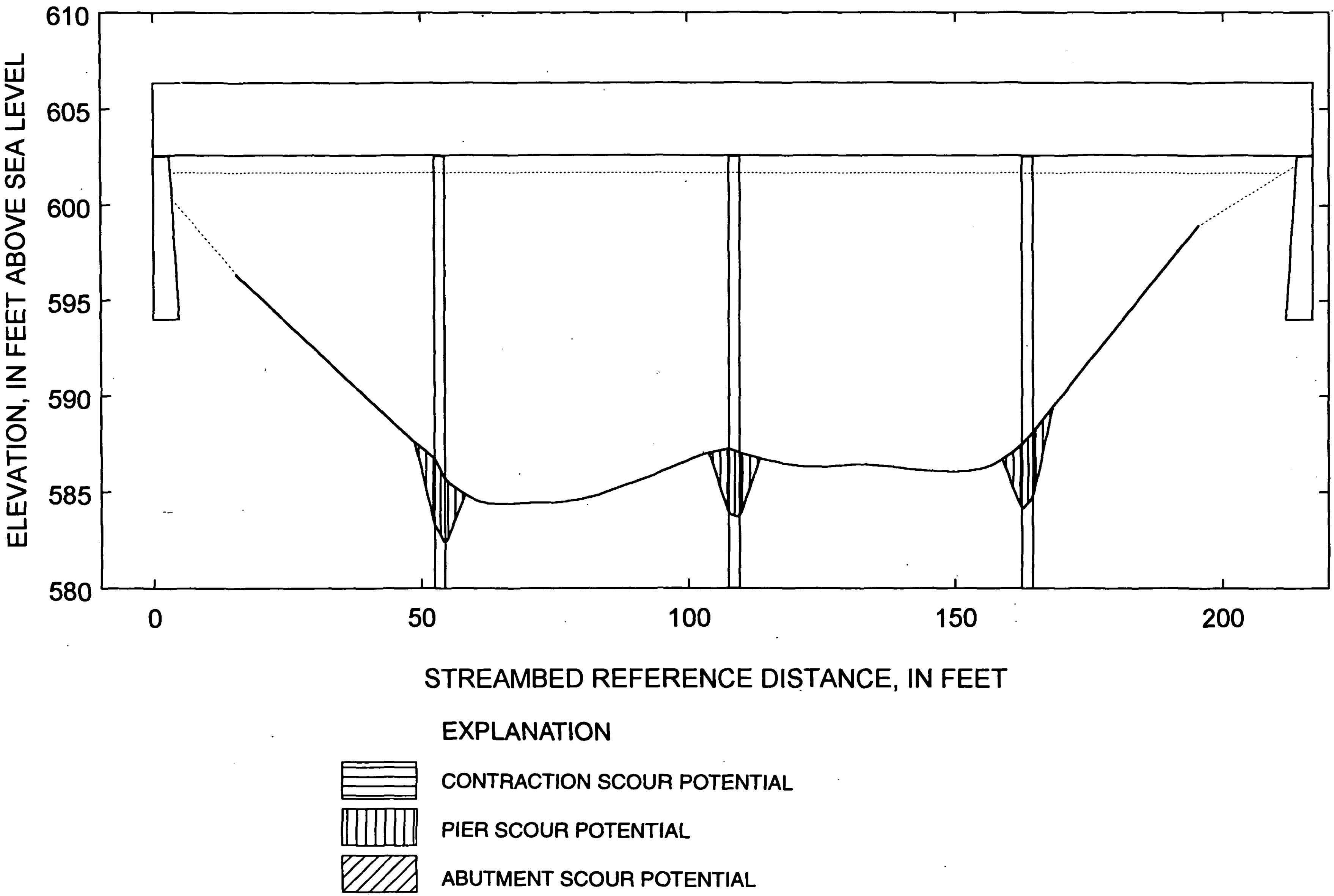

Figure 54. Estimated scour potential associated with the 100-yr flood at Fergus Road over Shiawassee River near Fergus, Mich.

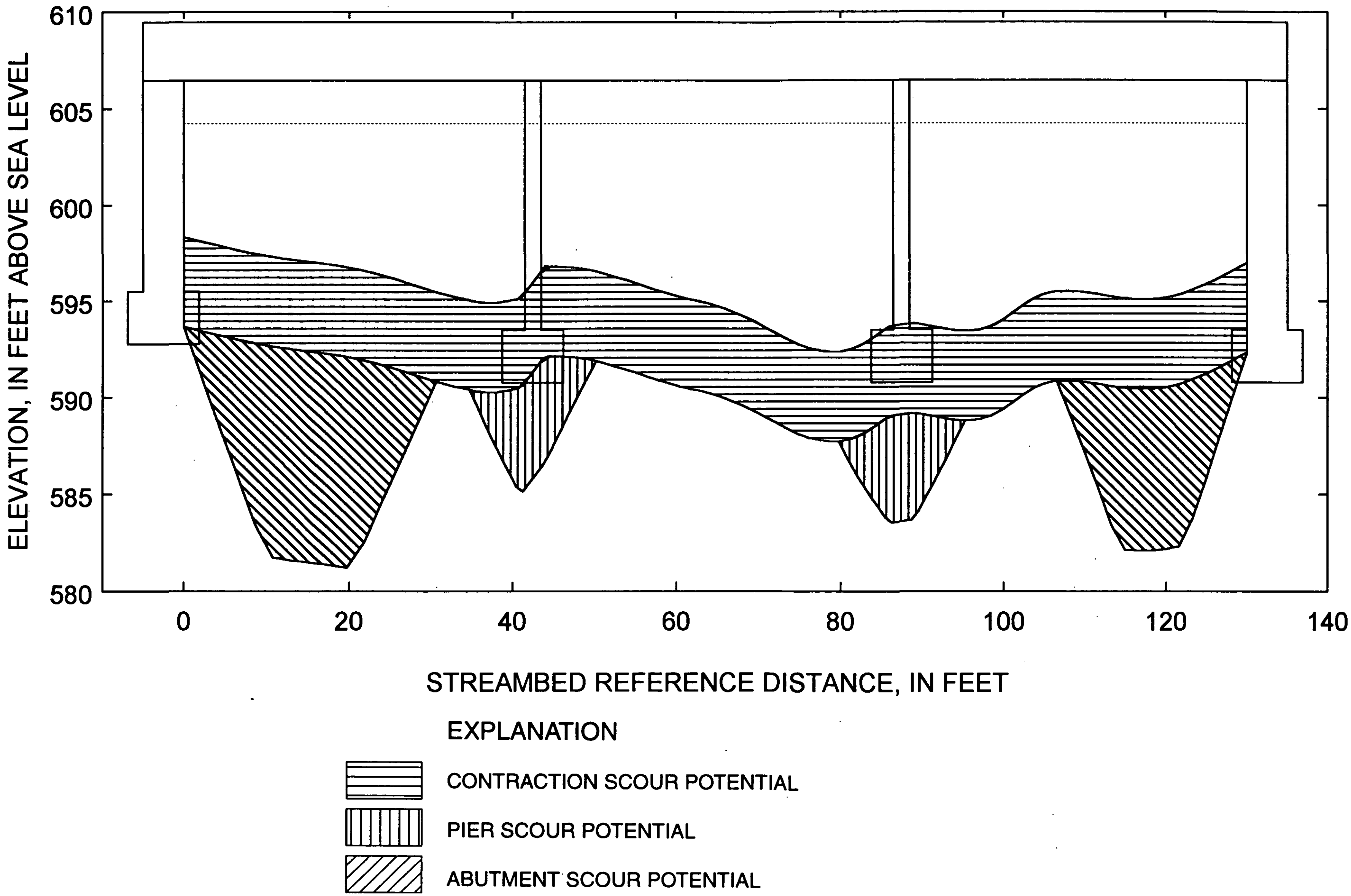

Figure 55. Estimated scour potential associated with the 100-yr flood at State Highway 13 over Flint River near Fosters, Mich.

State Highway 46 over Saginaw River at Saginaw (04157000)

State Highway 46 over Saginaw River at Saginaw, Michigan is supported by eight piers that divide the 630 ft long bridge into nine spans.The lengths of the seven spans between piers is 71.0 ft and the length of the two spans between the piers and abutments is 66.5 ft. The concrete piers are sharp-nosed with a width of 3.0 ft and a length of 74 ft. The bridge crosses the stream normal to the direction of flow. The width of the bridge is 71 ft.

The channel has little curvature near State Highway 46 bridge. Logs of borings from MDOT in 1954 indicate that streambed materials are composed of 2-3 ft of medium and coarse grained sand mixed with bark and organic silt overlying soft blue clay. The median diameter sediment particle used in scour computations was 0.5 mm (medium to coarse grained sand).

The magnitude of the 100-yr flood (table 14) was determined from the flood insurance study for the City of Saginaw, Michigan (Federal Emergency Management Agency, 1983). For comparison, flood-flow frequencies were computed on the basis of 74 peak annual streamflow values obtained between 1901 and 1994 and supplemented with historical information beginning in 1873. The WRC estimate for the 100-yr flood was 71,100 ft^3/s. The step-backwater model used to help compute scour potential was based on the step-backwater model used in the flood insurance study (Bruce Menerey, MDEQ, written commun., 1996). Summary results of water-surface profile and scour potential calculations indicate that significant scour near bridge piers and abutments is possible during a 100-yr flood event (table 14 and fig. 56).

Table 14. Scour potential of the 100-yr flood at State Highway 46 bridge over Saginaw River at Saginaw, Mich.

Attribute	Estimate
Streamflow (cubic feet per second)	68,000
Water-surface elevation at downstream side of bridge (feet above sea level)	592.72
Water-surface elevation at the approach section (feet above sea level)	592.78
Mean flow velocity at downstream side of bridge (feet per second)	4.95
Mean flow velocity at the approach section (feet per second)	4.56
Contraction-scour depth (feet), live-bed conditions	0.21
Pier scour depth (feet)	5.48
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	9.88
Right abutment, Froehlich's equation	16.48

Moravian Drive over Clinton River at Mount Clemens (04165500)

Moravian Drive over Clinton River at Mount Clemens, Michigan is supported by 3 piers that divide the 200 ft long bridge into four 50-ft spans. The concrete piers are square-nosed, 46 ft long and 4 ft wide. The bridge crosses the stream at an 18 degree angle from normal to the bridge opening; piers and abutments are aligned parallel to the direction of streamflow. The bridge is 32 ft wide.

The channel is fairly uniform and straight between the base and auxiliary stations. Stream banks are fairly high and not subject to overflow except during high water conditions. Logs of borings from Macomb County Road Commission in 1929 indicate that streambed materials consist of 4-5 ft of grey water sand overlying hard sandy blue clay. Records at gaging station 04165500 indicate that the streambed is composed of sand, gravel, and clay and is fairly permanent (D.V. Eagle, U.S. Geological Survey, written commun., 1988). Vegetal growth occurs during some summers. The median diameter sediment particle used in scour computations was 2 mm (a very coarse sand).

The magnitude of the 100-yr flood (table 15) was based on the flood insurance study for the Township of Clinton, Macomb County, Michigan (Federal Emergency Management Agency, 1992).

Table 15. Scour potential of the 100-yr flood at Moravian Drive bridge over Clinton River at Mount Clemens, Michigan

Attribute	Estimate
Streamflow (cubic feet per second)	21,300
Water-surface elevation at downstream side of bridge (feet above sea level)	592.11
Water-surface elevation at the approach section (feet above sea level)	593.63
Mean flow velocity at downstream side of bridge (feet per second)	8.39
Mean flow velocity at the approach section (feet per second)	2.88
Contraction-scour depth (feet), live-bed conditions	5.18
Pier scour depth (feet)	10.0
Abutment-scour depth (feet)	
Left abutment, Froehlich's equation	17.0
Right abutment, Froehlich's equation	11.2

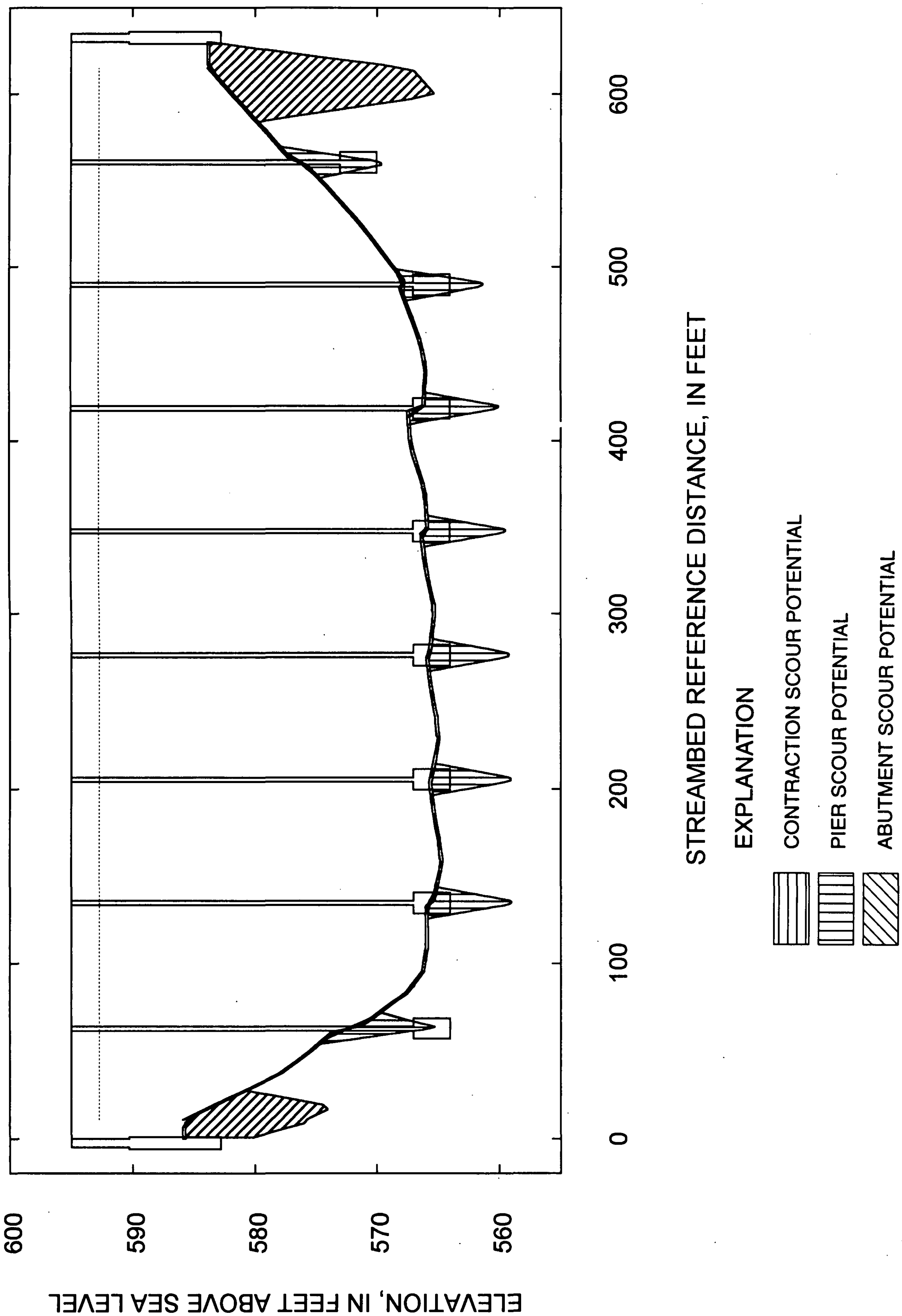

Figure 56. Estimated scour potential associated with the 100-yr flood at State Highway 46 over Saginaw River at Saginaw, Mich.

For comparison, flood-flow frequency was computed on the basis of 60 peak annual flows obtained at gaging station 04165500 between 1935 and 1994. Results from WRC computations indicate that the 100-yr flood is 21,900 ft^3/s. The step-backwater model used to compute properties for scour computations was based on the step-backwater model used in the flood insurance study (Bruce Menerey, written commun., 1994). Summary results of water-surface profile and scour potential calculations indicate significant scour potential associated with the 100-yr flood (table 15 and fig. 57).

RELATION OF STREAMBED STABILITY TO SCOUR POTENTIAL

Deviances provide a measure of the stability of the streambed. Thus, sites with a large range of streambed or local deviances are considered less stable than sites with a small range of streambed or local deviances. Comparisons between measures of streambed stability and estimates of scour potential are used to assess the consistency of empirical data with scour potential computed by use of semi-theoretical equations and procedures recommended by the Federal Highway Administration (Richardson and others, 1993).

A positive correlation between the range of streambed deviances and contraction-scour potential is a necessary condition for establishing consistency between the empirical measures and the semi-theoretical equations. The likely range of streambed deviances, however, also increases with the number of measurements compiled for each site. To eliminate this effect, the (one percent) trimmed range of streambed deviances was used rather than the full range (the maximum minus the minimum streambed deviance) for comparison. Finally, values of both trimmed ranges and scour potentials were converted to ranks so that the detection of correlation was not limited to a linear relation, but included any monotonic form.

Results of a Spearman's rank correlation test (Conover, 1980, p. 252) indicate that no significant correlation exists (*rho* = 0.0481, *p*-value = 0.8752) between the trimmed ranges in streambed deviances and contraction-scour potentials computed for 100-yr flood conditions. Thus, the empirical measure of streambed stability formed by the streambed deviances are not considered consistent with contraction-scour-potential estimates.

The consistency of empirical measures of local stability with the recommended procedure of computing total scour potential near piers as the sum of contraction scour plus local pier scour was also assessed. Among the 13 selected sites, the average and standard deviation of contraction scour potential associated with the 100-yr flood is 2.32and 2.98 ft respectively; the average and standard deviations of local pier scour potential is 6.87 and 1.92 ft, respectively. Thus using recommended procedures, the total scour potential adjacent to piers is about four times as large as scour potential in the main channel. Comparison of the ranges of local deviances adjacent to piers and ranges in the main channel (fig. 44) indicate that there is no significant difference. Therefore, the empirical measures of local streambed stability are not consistent with the recommended procedure for computing total scour potential near piers by adding contraction scour to local pier scour estimates.

This lack of consistency between empirical measures of streambed stability and results obtained by use of recommended equations and procedures may indicate a limitation of the recommended methods for hydrogeologic conditions in Michigan. More likely, failure to detect a correlation between streambed stability at low flood magnitudes and scour potential for high (100-yr) flood magnitudes may be expected if the relation between scour and streamflow is highly nonlinear. Empirical evidence for this nonlinearity is evident at Scottville Road over Pere Marquette River at Scottville (fig. 28). At this site, streamflow shows little consistent relation to streambed deviance for flows less than 2,500 ft^3/s. Thus, projecting the large streambed deviances associated with the two measurements at flows greater than 2,500 ft^3/s (that occurred near an event that exceeded the 100-yr flood) would not have been possible on the basis of information from the lower flows.

For the 13 sites investigated, measurements selected for the analysis included maximum flows that were generally less than the 50-yr flood event. The median recurrence interval of maximum flows was 12.6 yr; six sites had maximum measured flows less than the 10-yr flood event. Thus, available measurements may not have been made at high enough flows to allow quantification of nonlinear effects or project scour conditions associated with large floods.

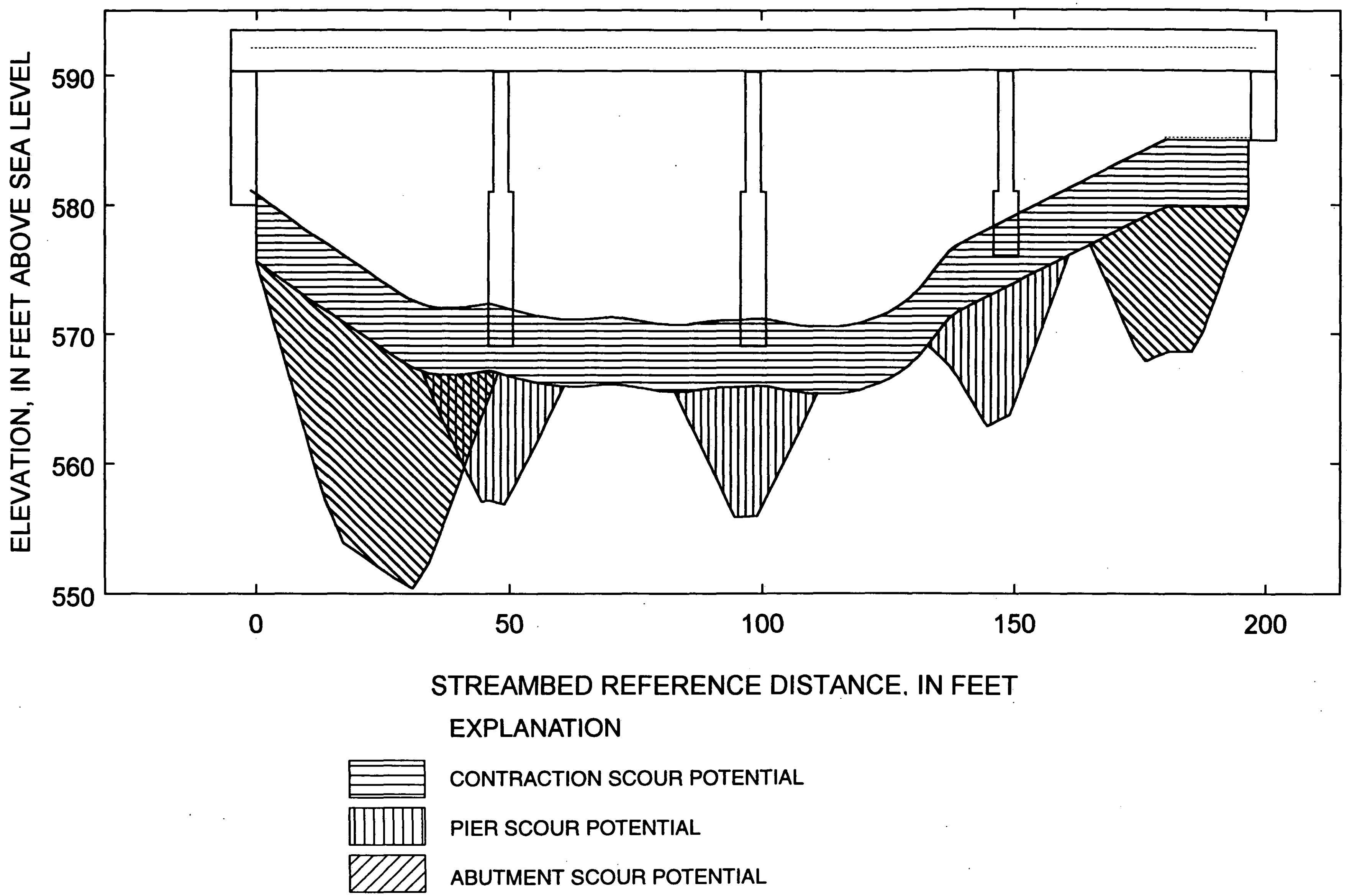

Figure 57. Estimated scour potential associated with the 100-yr flood at Moravian Drive over Clinton River at Mount Clemens, Mich.

SUMMARY AND CONCLUSIONS

Thirteen bridges that cross streams near U.S. Geological Survey gaging stations were selected for analysis of streambed stability and scour potential in Michigan. Forty or more historical streamflow measurements were analyzed at each site to characterize streambed stability. Data from 773 streamflow measurements were compiled, including 20,471 individual streambed soundings obtained between 1959 and 1995. Streambed elevations were compiled at each site to define a normal streambed profile across the bridge opening during the period spanned by the measurements. Differences between the normal profile elevation and individual soundings were referred to as deviances. Average deviances over the entire bridge opening for individual streamflow measurements were referred to as streambed deviances; average deviances within a subsection of the streambed, compiled over all measurements, were referred to as local deviances.

Analysis of deviances indicate significant variability in streambed stability among the 13 sites investigated. The downstream side of the Scottville Road bridge crossing Pere Marquette River at Scottville, Michigan showed the greatest variability. Deviances ranged from -8.55 to 2.97 ft; streambed deviances ranged from -4.06 to 1.07 ft. Deviances on the upstream-side of the bridge opening at North Grand River Avenue over Grand River in Lansing, Michigan showed the least variability. Deviances ranged from -2.11 to 6.26 ft; streambed deviances ranged from -0.22 to 0.11 ft.

Significant trends ($p<0.05$) were detected in streambed deviances at 10 sites, no trends were detected at 3 sites. Of the trends detected, 7 indicated that streambed elevations were degrading and 3 indicated that the channel was aggrading. Although statistically significant, the magnitudes of the trends were generally small (less than 0.5 ft of deviation from the normal profile during the period represented by the measurements). Streambed deviance and streamflow were uncorrelated at 9 sites; two sites had positive correlations and two sites had negative correlations. Two significant correlations were detected between streambed deviance and velocity; of these correlations, one was positive and one was negative. Significant correlations between streambed deviance and flow depth were detected at six sites. Of these significant correlations, five were negative indicating that higher flow depths would likely be associated with lower streambed elevations. The lack of consistency in the signs of the correlation coefficients prevents a generalization of the relationship between streambed deviances and streamflow, velocity, and depth.

Paired box plots show the local deviances grouped across measurements in the main channel and measurements near piers for each site investigated (fig. 44). Inspection of the box plots indicate little consistent difference between local deviances in the main channel and local deviances adjacent to piers. A Wilcoxon Signed-Rank Test (Conover, 1980, p. 280) was used to determine whether the range of local deviances near piers was statistically greater than the range of deviances in the main channel. In testing, the 1-percent trimmed range was used to eliminate any bias due to a larger number of soundings in the main channel than near piers. Results of the paired comparisons indicated that local variability adjacent to piers is not greater than the local variability in the main channel ($p = 0.9552$).

Geophysical data were obtained near bridge openings at four selected sites. GPR data were obtained with floating 50-, 100-, and 300-mHz antenna at three sites; a tuned 14-kHz transducer was used at two sites. In these applications, much of the geophysical signals were absorbed in the water column, penetration into the streambed was limited. Interference from debris, side echo, point and multiple reflectors further complicated efforts to interpret the attenuated signal. Evidence of historical scour conditions were detected in some locations.

Potential scour associated with a 100-yr flood was computed by use of equations and procedures recommended for nationwide use by the Federal Highway Administration. Contraction scour-potential estimates ranged from 0 to 8.42 ft; local scour potential near piers ranged from 3.4 to 10.0 ft, and local scour potential near abutments ranged from 0 to 30.3 ft. Total scour potential adjacent to piers, which is computed by adding contraction scour to local scour, was about 4 times as large as scour potential estimates in the main channel (areas unaffected by local scour).

No significant correlations were detected between scour-potential estimates and measures of channel stability from historical streamflow measurements. Thus, the available empirical data does not confirm the applicability of the contraction-scour potential equations for use in Michigan. Furthermore, data from streamflow measurements indicate that streambed stability near piers is similar to streambed stability in the main channel. Thus there is no empirical evidence to confirm the applicability of the procedure recommended by the Federal Highway Administration of adding contraction scour to local scour to estimate total scour potential adjacent to piers.

The inconsistency between measures of streambed stability and scour-potential estimates may indicate that the equations and procedures used to compute scour potential are not applicable without modification to hydrogeologic conditions in Michigan. Several other factors, however, are more likely to explain this lack of consistency. Primarily, the scour-potential equations describe a nonlinear relation between streamflow and scour potential. Field evidence for this nonlinearity is available from analysis of data at Scottville Road over Pere Marquette River at Scottville, Michigan. At this site, streambed deviance and streamflow showed little correlation at flows less than 2,500 ft^3/s. During a flood event with a peak discharge of 6,440 ft^3/s, which exceeded the 100-yr flood, negative streambed deviances of 1.55 ft and 4.06 ft were measured. These large streambed deviances could not have been projected on the basis of the relation between streambed deviance and streamflow at flows less than 2,500 ft^3/s.

Maximum streamflows compiled from measurement data generally had recurrence intervals of 12.6-yr or less. These flow magnitudes may not have been sufficient to generate scour conditions comparable to those for which the Federal Highway Administration equations and procedures were designed to predict scour potential. Other factors that may have contributed to the failure to detect correlation between streambed deviances and scour potential include the limited number of sites evaluated and the location of measurements on the downstream side of the bridge opening, rather than on the upstream side of the bridge opening where scour conditions may be more severe. Additional study of bridge scour conditions in Michigan is needed to confirm the applicability of the semi-theoretical bridge scour-potential equations for use in Michigan's hydrogeologic conditions.

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