University of Minnesota
St. Anthony Falls Hydraulic Laboratory

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STABILITY OF THE CHANNEL OF THE MINNESOTA RIVER NEAR STATE BRIDGE NO. 93, MINNESOTA

by

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ABSTRACT

The Minnesota State Highway No. 93 bridge crosses the Minnesota River near the town of Le Sueur. The bridge is situated at the apex of a bend the outside of which impinges against the eastern river valley wall. Near Le Sueur, the Minnesota River is a meandering stream with actively migrating bends. The valley walls has helped stabilize the channel in the immediate vicinity of the bridge, where the channel has moved little in the course of a century.

Just upstream of the bridge is a reach consisting of several short bends, nowhere impinging against the valley walls, that are migrating downstream and outward at a relatively rapid rate near 9 ft/year (3 m/year). The western approach to the bridge was riprapped in order to thwart the downstream progression of a bend. As a result, the bend ravelled up against the riprap and cut itself off. The channel now impinges against the riprap at a ninety degree angle, and then flows along the base of the riprap to the bridge opening. A large scour hole exists at the point of impingement, where the approach is in danger of being washed out. In the future, successive bends can be expected to migrate into the riprap, until the channel breaches the western approach and abandons the bridge.

The Minnesota Department of Transportation is presently considering replacement of the bridge deck. The actively migrating bends in the reach in question preclude relocating the bridge away from its present stable location near the valley wall. A short channel relocation just upstream of the bridge can improve alignment. It can also mitigate the possibility of a natural cutoff causing the bridge to be abandoned.

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INTRODUCTION

In early, 1981, the Minnesota Department of Transportation commissioned the St. Anthony Falls Hydraulic Laboratory to conduct a study of the Minnesota River near the State Highway No. 93 bridge crossing. The area in question is shown in Fig. 1. As State Highway No. 93 heads westward from the town of Le Sueur, it must pass underneath a railroad bridge immediately before crossing the Minnesota River. Because of this the deck of the bridge is low and is subject to frequent inundation. During the flood of 1965, both the deck and approaches were under water, as shown in Fig. 2. One possibility under consideration by the Department of Transportation is relocation of the bridge elsewhere in the floodplain of the Minnesota River, allowing for the construction of a higher deck. This would also require a channel relocation.

The scope of the study is defined partially in the contract negotiated between the Minnesota Department of Transportation and the St. Anthony Falls Hydraulic Laboratory. "...a study of the stability of the channel of the Minnesota River near the State Highway No. 93 bridge crossing is to be undertaken. Both present conditions, and conditions induced by relocation and realignment of the channel, are to be studied... Analytical methods and case histories are to be utilized for the study;..."

A non-specific diagnostic approach to the problem is taken herein. A brief account of the hydraulic and geomorphic state of the channel and floodplain is provided. Historical records are used to examine trends of channel migration near the bridge, and to analyze the interaction between the channel and the bridge. Historical records are incorporated in a numerical model of channel migration to predict the consequences of: a) leaving the bridge and channel as is, b) moving the bridge and channel to a point near the center of the floodplain, and c) leaving the bridge as is, but providing a channel change upstream to prevent erosion of the western approach.

THE HYDRAULIC AND GEOMORPHIC SETTING

The Minnesota River originates at Big Stone Lake near the border of Minnesota and South Dakota. For most of its length, it flows in a fairly wide alluvial valley incised below the surrounding plains. From its source to Mankato it flows in a southeasterly direction, as shown in Fig. 3. At Mankato the river abruptly changes direction and flows northeasterly toward its confluence with the Mississippi River.

The State Highway No. 93 crossing near Le Sueur is located about halfway between Mankato and Jordan; the river is gaged at these latter two sites.

The river valley. Near the town of Le Sueur, the Minnesota River has roughly straight, parallel valley walls directed along a southwest-northeast axis (Fig. 1). The valley has a bottom width of about 4250 ft (1300 m) and is incised approximately 165 ft (50 m) below the surrounding plains. The valley shows no obvious terraces, and is entirely inundated during large floods (Fig. 2).

Borehole logs obtained from the Minnesota Geological Survey suggest that the valley is filled with deep alluvium and unconsolidated glacial till. The shale and sandstone bedrock is reached at an elevation of about 572 ft (174 m) above mean sea level, or about 168 ft (51 m) below a typical floodplain elevation of 740 ft (226 m). The downvalley slope is approximately 1.56×10^{-4} over a reach 11,650 ft (3550 m) in length, chosen to include the State Highway No. 93 bridge. The floodplain is divided about equally between forest and land in cultivation (Fig. 4).

Channel planform. In the reach in question, and indeed throughout most of the length from Mankato to the confluence with the Mississippi River, the Minnesota River is a classical meandering stream. The point bars show well-developed scroll bars, evidencing an orderly downstream progression of bends due to differential accretion and erosion. The progressional sequence of vegetation at the point bars typifies the colonization of newly created land associated with this type of migration. Oxbow lakes are common in the floodplain (Fig. 4); they provide evidence of relief of the accretionary buildup of sinuosity by means of the cutoff of sharp bends.

The bridge is located near the apex of a sharp bend that impinges against the east valley wall. Just upstream of this point are five short, fairly symmetrical bends. These bends are rather tightly spaced. Just upstream of them is a long, unusually straight reach that hugs the east valley wall for a distance of 2.4 miles (3.8 km). The next bend downstream of the bridge is quite long, with an apex that impinges against the west valley wall for a distance of 2300 ft (690 m).

The channel gives no evidence of recent aggradation or degradation relative to its floodplain, which is essentially the entire valley. The reach near the bridge thus appears to be in grade.

Channel bed and bank material. The channel bed is dominated by medium sand, although locally coarser and finer material are present. The channel banks and flood plain contain large amounts of silty fine sand. Although lenses of cohesive material could be observed in cutbanks recently exposed by erosion, cohesiveness does not appear to play a significant role in channel mechanics near the State Highway No. 93 bridge. A typical cutbank on the outside of a bend is shown in Fig. 5.

In February, 1981, the Minnesota Department of Transportation took extensive samples of bed material in the Minnesota River near the trunk Highway No. 169 bridge, located about 1.5 miles (2.4 km) downvalley of the State Highway No. 93 bridge (Fig. 1). Visual inspection indicated that Minnesota River bed material near the two bridges is similar. Three typical grain size distributions are shown in Fig. 6.

Hydrology. The reach of the Minnesota River near Le Sueur is not gaged. However, inferences as to hydrologic conditions can be made from the gaging stations at Mankato and Jordan (Fig. 3). Data for various flood flows are listed in Table 1; the information was compiled by the U.S. Geological Survey. The difference in discharge between Mankato and Jordan is not large, due to the lack of substantial tributaries in between. Thus, flood flows at the State Highway No. 93 bridge can be interpolated.

Rating curves were obtained for the gage sites at Mankato and Jordan; these allowed for estimation of bankfull flows. The estimates are given in Table 1. Bankfull flow seems to be realized once every three to four years, a range rather typical of alluvial streams in humid regions (Nixon, 1959).

Channel Geometry. The channel was surveyed and sounded on February 27, 1981, at a low discharge near 1200 cfs (34 cumecs). The locations of several cross sections near the State Highway No. 93 bridge are shown in Fig. 4. The cross sections are shown in Fig. 7.

In Fig. 7 cross sections 20 and 21 are, respectively, fairly typical of apexes and crossings in freely meandering streams. Cross sections 13 and 18, however, show abnormal scour. They are adjacent to points A and B on Fig. 4, which correspond to the two deepest points of scour of the surveyed reach. The implications of this scour are discussed below.

Cross-sectional data were used in conjunction with a topographical map of the area to estimate average bankfull geometry. Estimated values are shown in Table 2.

Forced scour holes near revetment. The maximum depths of water in the scour holes near at points A and B of Fig. 4 were 24 ft (7.3 m) and 27 ft (8.9 m), respectively, on the day of survey. In contrast to these values, average thalweg depth was about 10 ft (3.0 m) on the day of survey. It is apparent that these are points of extreme scour.

The cause of the scour is apparent from Fig. 4. Whenever flow is forced to impinge at a high angle of attack against an inerodible barrier, large scour can be expected. This is the case at both points A and B. At the latter point, this barrier was originally the west valley wall; today it is the revetted embankment of Trunk Highway No. 169.

This scour hole at point A is of more significance, due to its position adjacent to the riprapped western approach to State Bridge No. 93. The scour is in fact forced by the combination of the riprap and the high angle of impingement. The magnitude of the scour is masked by the fact that the river was at low flow when measurements were taken. At the flood flows that might endanger the bridge, the depth of scour can be expected to be significantly greater. It can be concluded that the western approach to the bridge is in danger of being eroded. The history of this problem is described subsequently.

TABLE 1. Various Flood Flows for the Minnesota River

Flow	Discharge at Mankato	Discharge at Jordan
	(cfs)	(cfs)
bankfull	24,000	20,000
2-year	14,000	17,000
5-year	30,000	34,000
10-year	44,000	49,000
25-year	65,000	710,000
50-year	84,000	91,000
100-year	105,000	115,000
200-year	130,000	140,000
1965	94,000	116,000
largest on record	110,000	116,000

TABLE 2. Average Parameters at Bankfull Flow

Water surface slope	S	0.000156	
Top-bank width	B	304 ft	(92.6 m)
Mean depth	H	13.3 ft	(4.1 m)
Discharge	Q	22,000 cfs	(623 cumecs)
Mean flow velocity	V	5.44 ft/s	(1.66 m/s)
Froude Number	F	0.26	

HISTORY OF THE CHANNEL PLANFORM

The present State Highway No. 93 bridge across the Minnesota River was built in 1923. The progress of channel migration before and after the construction of the bridge serves to illustrate a remarkable interaction. This interaction was documented with the use of aerial photographs and maps of the channel for the years 1873, 1928, 1940, 1957, 1968, 1977, and 1980. All photographs and maps were reduced to a common scale, using township lines to adjust for local distortion. It was so found that the 1928 map is highly inaccurate, often placing the channel well outside of a river valley that is thousands of years old. The 1873 map, on the other hand, displayed township lines that matched closely with those of a 1977 topographical map.

In Fig. 8, the 1873, 1940, 1957, 1968, and 1980 channels are shown for a reach centering on the State Highway No. 93 bridge. The bend at the bridge and the one immediately downstream impinge on the valley walls, which act to prevent further lateral erosion. The latter bend is also quite long. Both bends have migrated downstream rather slowly.

The situation upstream of the bridge is quite different. A series of short bends, nowhere impinging against the valley walls, have been rapidly migrating downstream and outward. As the bend just upstream of the bridge has migrated downstream, its downstream side has impinged on the line of riprap along the western approach to the bridge. Thus, although the downstream side was forced to cease migrating, the upstream side continued to move, causing the bend to fold up and sharpen. The sudden impingement of the channel against the riprap at the apex of this sharp bend likely led to the formation of a deep scour hole. Furthermore, the sharpness of the bend made it ripe for the formation of a chute cutoff, which indeed occurred between 1957 and 1968. It is this chute cutoff which has led to the present alignment, with the channel angled directly at the raprap; thus, the impingement and scour continues at a different location.

The events on the upstream side of the bridge are part of a larger problem. The five bends presently immediately upstream of the bridge are short and tend to migrate downstream at the rather rapid rate of 9 ft/year (3 m/year). The line of riprap along the western approach effectively blocks that migration. This blockage causes the several bends upstream to migrate outward laterally rather than downstream. The result is a buildup of excess sinuosity which is eventually alleviated by chute cutoffs during periods of overbank flow. In addition to the one just upstream of the bridge, a similar cutoff occurred at the bend at point C in Fig. 4 between 1940 and 1957.

Thus, the fixed position of the bridge and western approach, although appropriate when constructed, are today incompatible with the channel. The channel would like to cross the highway at a point to the west of the bridge. Failure to accomplish this has led to "shock" and deep scour where the channel is abruptly forced from the point where it would like to cross the highway to the bridge. Blockage of downstream migration has led to sharpening of bends, buildup of sinuosity, and cutoffs. It is apparent that channel alignment upstream of the bridge is poor today, and can be expected to be poor in the future.

If the present state of affairs is allowed to continue, part of the western approach may be undermined by scour and washed out. In addition, during a large flood the channel may alleviate its excess sinuosity by cutting across the western approach and abandoning the bridge. Such a tendency is evidenced by a scour hole on the floodplain downstream of the western approach; it is marked as point S on Fig. 4.

It should be reiterated that the relative mobility of the short bends upstream of the bridge, which do not impinge against the valley wall, contrasts sharply with the relative stability of the long bend just downstream of the bridge, which does impinge against the valley wall for a considerable distance. The valley walls provide a stabilizing effect. This can be seen to a remarkable degree in Fig. 9, illustrating the reach immediately upstream of that shown in Fig. 8. The long, unusually straight channel seen therein has maintained its alignment for more than one hundred years by dint of its location along the east valley wall.

This historical fact of relative channel stability near valley walls has application to the present day bridge site. The bridge is also along the eastern valley wall, and thus occupies a relatively stable location. Thus, it may be more desirable to maintain the bridge site and relocate the channel upstream to improve alignment than to relocate the bridge closer to the floodplain center, where it would be subject to the unmitigated vagaries of channel migration.

GUIDELINES FOR CHANNEL RELOCATION

Two problems have been identified at the State Highway No. 93 bridge across the Minnesota River. They are the problem of inundation due to the low deck, and the blockage of meander migration along the western approach. The latter problem leads to excessive scour and the threat of a cutoff that would leave the bridge abandoned. Although the present study was motivated by the former of these, the inundation is probably more of a nuisance than a threat. The latter is more serious in nature.

A possible approach to the solution of either problem is channel relocation. Specifically, if the channel of the Minnesota River near the bridge could be relocated away from the east valley wall, it could be rebuilt with a higher deck elevation. A well chosen channel realignment upstream of the present bridge, with or without bridge relocation, could also alleviate the scour problem and the conflict between the meander pattern and the bridge.

The choosing of a channel relocation has traditionally been more art than science. A considerable body of literature suggests that straightening of long reaches of streams can lead to serious degradation upstream and aggradation downstream (Parker and Andres, 1976), and can also lead to ecological problems (Barclay, 1980). On the other hand, short cutoffs often occur in actively migrating natural streams; they provide a means for alleviating local excesses of sinuosity built up by gradual accretionary migration. These natural cutoffs produce only minor aggradation and degradation, and in sand bed streams do not have a marked effect on reaches upstream and downstream. It follows that isolated, short artificial cutoffs should not typically have deleterious effects on the reaches upstream and downstream. Some evidence for this is provided by many of the more than one hundred case histories of channel relocation, mostly near bridges, in Brice (1981).

Some criteria for the choosing of a channel relocation for the purpose of improving a bridge site can be summarized as follows.

1. The length of a relocated channel should be as short as possible. It is advisable to cut off single bends rather than a series of three or four bends, for example. Relocated channels are usually shorter than the original channel, and thus steeper. The local steepening includes degradation upstream and aggradation downstream, as is illustrated in Fig. 10 (Lane, 1946). As as rule of thumb, one can estimate the extent of these effects upstream and downstream of the relocated reach in terms of the length of the original reach truncated by the cutoff; aggradation and degradation should be felt two or three lengths downstream and upstream, respectively (Parker, 1978; Brice, 1974). The shorter the reach that is cut off, the more localized these effects become.

2. The relocated channel should be chosen to take advantage of natural stabilizing factors wherever possible, especially when a bridge is involved. These include valley walls, bedrock outcrops, and clay plugs. If the channel can be tied to these, its tendency to migrate can be diminished or eliminated (Joglekar, 1971).

3. In the absence of natural controls, straight relocations should be avoided. Gentle curvature typical of the reach in question should be provided. In a meandering channel bar formation is controlled by bends, and point bars cannot migrate any faster than the bends. In fairly straight channels, alternate bars form independently of curvature and migrate downstream much more rapidly than bends. As they migrate downstream, they induce bank erosion at points that cannot be predicted a priori. A typical example of this is shown in Fig. 11 (Lewin, 1976).

4. Consideration should be given to the state of the relocated reach ten to thirty years in the future. It is not cost effective to solve immediate problems at the expense of creating greater problems later.

In addition to the above criteria, it hardly needs to be mentioned that the specifics of each site should be considered.

PROGRAM DAIJA

In the case of the Minnesota River near the State Highway No. 93 bridge, it is clear from Figs. 8 and 9 that the design of any channel relocation must include consideration of channel migration. The history recorded in those figures can be used to obtain a qualitative prediction of the future natural migratory trends of a river. If the channel is relocated, however, no history exists from which to predict the future of the relocated reach. This dilemma could be circumvented by means of an understanding of the mechanics of channel migration, which are presumably the same for natural and relocated reaches. Specifically, a mechanistically well-founded computer model would be helpful.

In the case of river aggradation and degradation, such models have been available for several years; an example is the HEC-6 model (Thomas and Prasuhn, 1977). No such model has been available for planform migration because the equations governing the deformation of bends were not known. However, Ikeda, Parker, and Sawai (1981) and Parker, Sawai, and Ikeda (1982) have recently succeeded in delineating the necessary equations.

These equations were used to write a computer model of channel migration named DAIJA. A brief description of the model is given herein. A more detailed documentation manual will be issued as time permits.

Program DAIJA uses the St. Venant equations of shallow water flow in curved channels, and a consideration of scour produced by secondary currents in bends, to predict bank shear stress distribution. Bed topography is specifically tied to channel curvature; independent alternate bars are not allowed. In the program, it is assumed that erosion occurs along banks subjected to shear stresses that are higher than the ambient value for a reach, and that deposition occurs along banks subjected to comparatively low shear stress. The model maintains constant width; if one bank erodes, the opposite bank deposits.

The relation between the rate of bank erosion and bank shear stress involves a dimensionless erosion constant E_0. The parameter E_0 can only be determined by means of optimization, so as to cause the model to reproduce known channel history.

A constant flow discharge is used in the model. This is the source of some difficulty, as the actual channel is subjected to a range of discharges, from well below to well above bankfull. One important parameter is the dimensionless Chezy friction factor C, defined such that

$$U = C \sqrt{g\ HS}$$

where U and H are cross-sectionally averaged flow velocity and depth, g is the acceleration of gravity, and S is the down-channel slope of the energy grade line. In sand bed streams such as the Minnesota River, C varies strongly with flow conditions, being largest for low flows and smallest for high flows. The choice of a constant flow that on the average reproduces the migration of an average yearly hydrograph is complicated by this variation.

The most sensible arbitrary constant discharge one might use is the bankfull discharge; it was adopted for the present study. Since the value of C appropriate for reproducing past channel history likely differs from the value at bankfull flow, both C and E_o were made arbitrarily adjustable. The adjustment in C also allows for compensation for inaccuracies inherent in the basic equation.

Thus program DAIJA is calibrated for a given reach of a given river by adjusting C and E_o so as to reproduce previously observed channel migration over a period of ten to twenty years. The time span chosen for calibration must include only accretionary migration; no cutoffs should have taken place. However, once the model is calibrated, it can predict conditions ripe for cutoffs.

The present version of program DAIJA assumes a spatially constant value of E_o , so that floodplain erodibility is assumed to be constant. Fortunately, this does not appear to be inappropriate for the reach of the Minnesota River under consideration.

The model uses a fixed boundary condition upstream and a pinned boundary condition downstream. That is, channel position and planform angle are constant at the upstream end of the reach, and position is constant at the downstream end.

The particular method of solution of the equations used in DAIJA uses a set of Lagrangian "material" points imbedded in the channel. A spatial sweep first determines the sign and magnitude of the shear stress along one bank. A temporal sweep then moves each point normal to the channel by an amount proportional to the excess shear stress. This normal mapping is reminiscent of that employed by Hickin and Nanson (1975) to analyze migration data from the Beatton River, British Columbia. It may thus be called a "Hickin mapping"; it is schematized in Fig. 12.

MODELING OF MIGRATION OF THE PRESENT CHANNEL

The numerical model was calibrated using the reach shown in Fig. 13, and the time interval between 1968 and 1980. The downstream boundary condition is satisfied at the bridge. Although it was in theory possible to find an upstream reach that had not moved in over 100 years (Fig. 9), time constraints dictated that the upstream end of the calibration reach be at a point where in fact some migration had occurred between 1968 and 1980. This local migration cannot be predicted by the model; fortunately, it did not prove to be a serious impediment to calibration.

In Table 3, various observed and calibrated input parameters are tabulated. It is seen that the observed value of C is 2.3 times higher than the calibrated value at bankfull flow.

TABLE 3. Input Parameters

Observed	C	21.0
Calibrated	C	9.2
Calibrated	E_o	8.00×10^{-8}

It is seen in Fig. 13 that the agreement between calculated and observed channels in 1980 is good. Deviation at the upstream end is the expected result of not satisfying the fixed boundary condition. It is rather modest.

At the downstream end, the channel is against a line of riprap. The present version of DAIJA can simulate the immobility of a reach already against riprap, but cannot simulate a channel being rendered immobile in the future as it migrates into riprap. Thus, the predicted 1980 channel has tried to migrate around the end of the simulated riprap. This has not in fact occurred, because the actual riprap extends farther westward. However, the product of thwarted migration is a deep scour hole, which does exist at the spot in question.

Once calibrated, the model can be used to predict the future. The result of doing nothing except maintaining the simulated riprap, for the twelve years from 1980 to 1992, is shown in Fig. 14. In twelve years all bends migrate downstream toward the riprap except the one nearest to the bridge; blockage causes it to tighten so that it appears ripe for a chute cutoff. It is apparent that until the cutoff actually occurs, the present deep scour hole along the riprap will continue to threaten the western approach.

In addition, the sinuosity of the reach increases by a factor of ten per cent. This portends of a larger natural cutoff to relieve this buildup; such a cutoff might pass through the western approach and leave the bridge abandoned. The three natural cutoffs considered to be most likely to occur in the near future are illustrated in Fig. 1. Cutoff No. 1 is a long cutoff that passes along a floodway known to be utilized by the river. In particular, it passes along a scour hole just downstream of State Highway No. 93 that is known to have formed during the 1969 flood. Cutoff No. 2 is a shorter cutoff that would be realized if the river cut through at the present scour hole. Cutoff No. 3 would result from a chute cutoff of the bend nearest to the bridge, and would be in addition to a similar recent cutoff. Only cutoff No. 3 would not abandon the bridge.

In summary, then, the prognosis for the present channel is continued scour along the western approach, and intensified blockage of the meander pattern as more bends migrate into the riprap. Eventual relief via a natural cutoff may be expected. The cutoff may cause the channel to abandon the bridge.

MODELING OF RELOCATED CHANNELS

It would appear that the river can solve its present dilemma by means of a natural cutoff. A cutoff of the river's choosing, however, can hardly be depended upon to maintain the present bridge crossing, or to provide an advantageous future crossing. A well-chosen artificial relocation, however, could resolve both issues, at least for the next several decades.

Three channel relocations were considered; they correspond to the three natural cutoffs shown in Fig. 1. Alternative No. 1 has the advantage of following an existing path of flood flow concentration. It would also allow for a higher bridge deck. It has the disadvantage of being very long; it cuts off three bends. Because of its length, it is more likely to cause aggradation at the trunk Highway No. 169 bridge 1.5 miles (2.4 km) downvalley. This could in turn force channel migration, which would have deleterious effects on the bridge.

In addition, Alternative No. 1 would not allow for a bridge site anchored to either valley wall. Thus, the bridge site could easily be rendered incompatible in the future by future channel migration. Also, the proximity to the intersection of State Highway No. 93 and Trunk Highway No. 169 is also undesirable in a reach as prone to shifting as the present one. Due to these shortcomings, the alternative was not considered further.

Alternative No. 2 has the advantage of being short. It passes through the existing scour hole along the western approach, thus providing direct relief. The bridge would have to be relocated, but a higher deck could be constructed. The future bridge site would again not be subject to the stablizing effect of the valley walls. Alternative No. 3 is even shorter, and preserved the present stable bridge site. It would not allow for a higher deck. Both Alternatives Nos. 2 and 3 were chosen for modeling.

Assuming for simplicity that the relocations were constructed in 1980, predictions of the future of the channel planform in 1992 are provided in Figs. 15 and 16. The downstream ends of the reaches are assumed not to have moved; indeed these points have not moved in one hundred years. No riprap is assumed to have been placed anywhere. Both relocated channels have been provided with curvature to suppress alternate bars.

Alternative No 2, in Fig. 15, appears to be less desirable than Alternative No. 3 in Fig. 16. Already a bend is forming at the upstream end of the relocated channel, and as migration progresses laterally and downstream, the bridge may lose its good alignment.

On the other hand, in the case of Alternative No. 3, migration near the bridge appears in a predictable fashion, and at a rather modest rate even in the absence of riprap. It would appear to maintain good alignment for many years into the future. The bend immediately upstream of the relocated channel continues to migrate downstream but would likely not migrate into the western approach for another fifty years. Even this could be prevented by revetting the channel and holding point E of Fig. 16, which would force the bend in question to cut off well before migrating into the bridge approach.

In summary, it appears that Alternative No. 3 represents the best solution to the scour and blockage problems associated with the State Highway No. 93 bridge ascross the Minnesota River. This alternative does not help solve the problem of deck inundation; however, the solution to this problem requires relocation of the bridge away from the eastern valley wall, an undertaking that is not recommended.

A MINIMAL OPTION

The most immediate danger to the bridge site is the scour along the western approach. Some means of alleviating this should be considered even if the channel is not relocated. The scour hole is presently so deep that the riprap along the approach is in danger of being undermined at the toe. Thus, the addition of more riprap is not likely to provide much extra protection. A more effective solution would be obtained by altering the flow so as to prevent impingement directly against the riprap.

In Fig. 17, five short spurs have been placed near the critical point. These spurs should deflect the main thread of flow, and eventually the channel, away from the point of abrupt impingement. Thus, some relief from scour would be provided. These spur dikes would, however, neither alleviate the blockage nor help prevent an adverse cutoff.

The literature contains a variety of suggestions as to the design and placement of spur dikes. Five good sources of information are Brice et al. (1978), Pokrefke (1978), Neill (1973), Richardson and Simons (1974), and Joglekar (1971). In light of the fact that deposition is not expected between the spurs, and in light of the necessity of reducing scour as much as possible, impermeable rock spurs with an apron placed around the tips are recommended. The crest of the spur should be level and at approximate bankfull elevation (about 735 ft or 224 m above mean sea level). The length, angle, and spacing of the spur dikes in Fig. 18 have been chosen in accordance with recommendations in the literature. The tips of the spur dikes can be expected to be subjected to rather intense scour, and may have to be replaced after floods.

CONCLUSIONS AND RECOMMENDATIONS

In discussing the situation at the State Highway No. 93 bridge across the Minnesota River, it is necessary to dintinguish between the bridge itself and its western approach.

The bridge is located at the outside of a bend. However, the proximity of the bridge to the eastern valley wall has rendered it stable with respect to lateral erosion. Although the bend on which the western approach is located has migrated downstream, the river has occupied the location of the bridge for at least 105 years. On the other hand, the channel shows a rather rapid migration rate of about 9 ft/year (3 m/year) wherever the channel is away from valley walls. A bridge not anchored to the valley walls would be subjected to the vagaries of this migration, and could easily be rendered unsuitable in a decade or two without considerable maintenance. Thus reconstruction of the bridge, and relocation of the channel to a point nearer to the center of the floodplain, is not recommended. The bridge should stay where it is, even at the expense of a deck that is inundated from time to time.

Upstream of the bridge, bends have been increasing in sinuosity and migrating into the riprap of the western approach at a fairly rapid rate. The riprap has blocked migration, forcing cutoffs and a flow that impinges on the approach at a near right angle. This has resulted in a deep scour hole along the riprap. This scour may eventually lead to migration of the channel across the approach, with a possible cutoff so as to cause the river to abandon the bridge. The channel is presently poised for a cutoff somewhere due to the buildup of sinuosity.

A short channel relocation just upstream of the bridge, with no bridge relocation, could immediately eliminate the scour problem, partially relieve the buildup of sinuosity, provide a better hydraulic approach to the bridge, and eliminate the problem of bend blockage along the approach for at least the next two or three decades. The length of the reach so abandoned would be no longer than those typically abandoned by natural cutoffs. The effect of the relocation would not be expected to be felt any more than 1.3 miles (2.1 km) upstream and downstream of the relocated channel, and can be expected to be rather modest. In particular, no significant adverse effect would likely be felt at the Trunk Highway No. 169 bridge, 2.1 miles (3.4 km) downstream of the State Highway No. 93 bridge. Based on considerations of river behavior alone, the environmental effect of the relocation could hardly be distinguished from a natural cutoff.

The outside (east) bank of the relocated channel should be riprapped for a length of about 700 feet (210 m) upstream of the bridge as an extra measure of safety.

Local revetment of both banks at the upstream end of the relocated channel would eventually force cutoff of the bend immediately upstream. This would provide added protection against a natural long channel avulsion, and against another bend ravelling itself up at the western approach.

If a channel relocation is not considered feasible due to financial or other reasons, then at the very least attention should be paid to the existing scour hole along the western approach. The deepness of the scour hole would suggest that the addition of more riprap might not provide extra protection. However, fields of impermeable spur dikes would move the scour away from the approach, and help protect it.

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This report was typed by Patricia Swanson. Karl Wikstrom performed the photographic work, and the drafting was done by Bob Bulleigh.

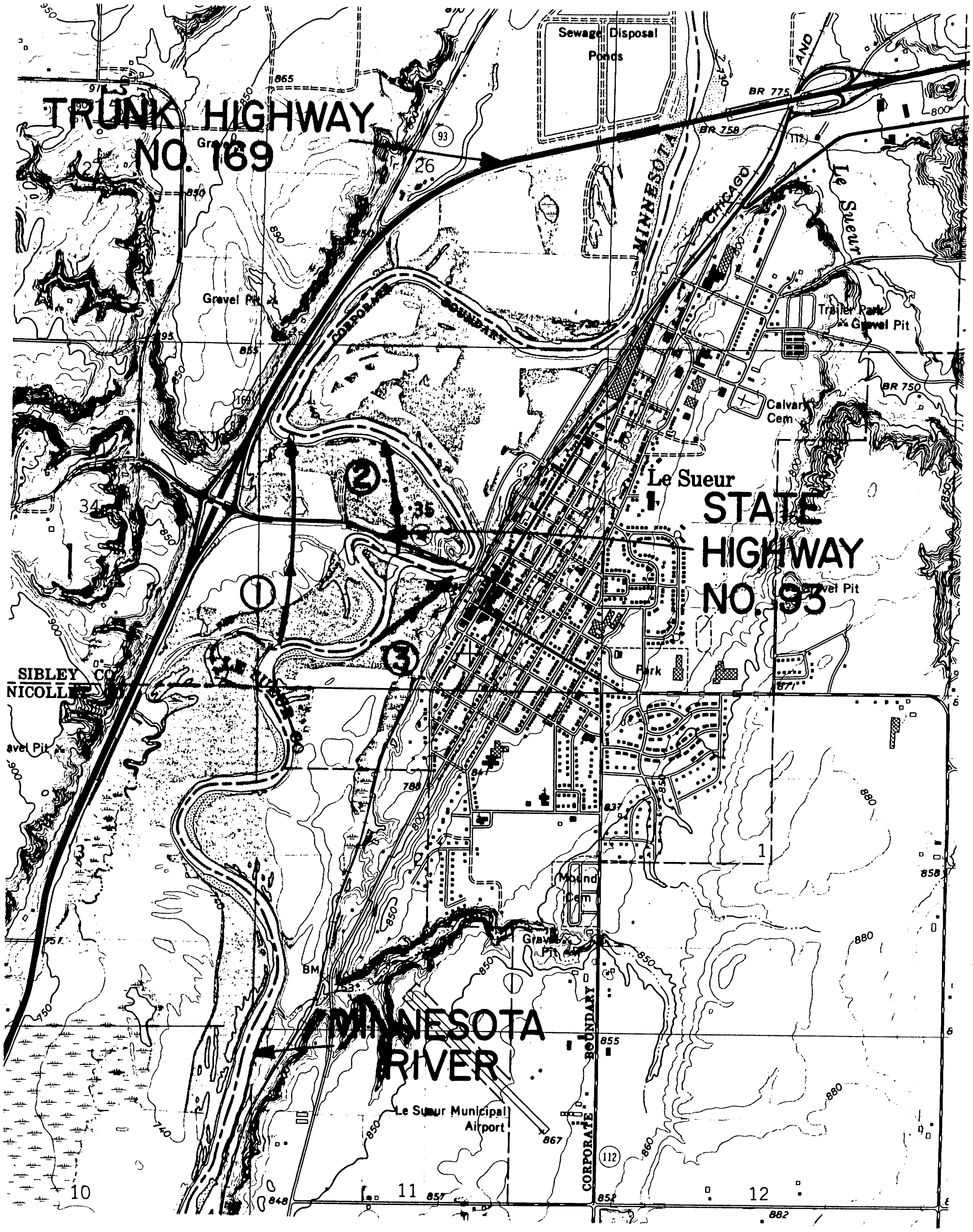


Fig. 1. Topographical map of the vicinity of the State Highway No. 93 bridge; taken from the U.S. Geological Survey topographical map of the LeSueur quandrangle. Notation is explained in the text.

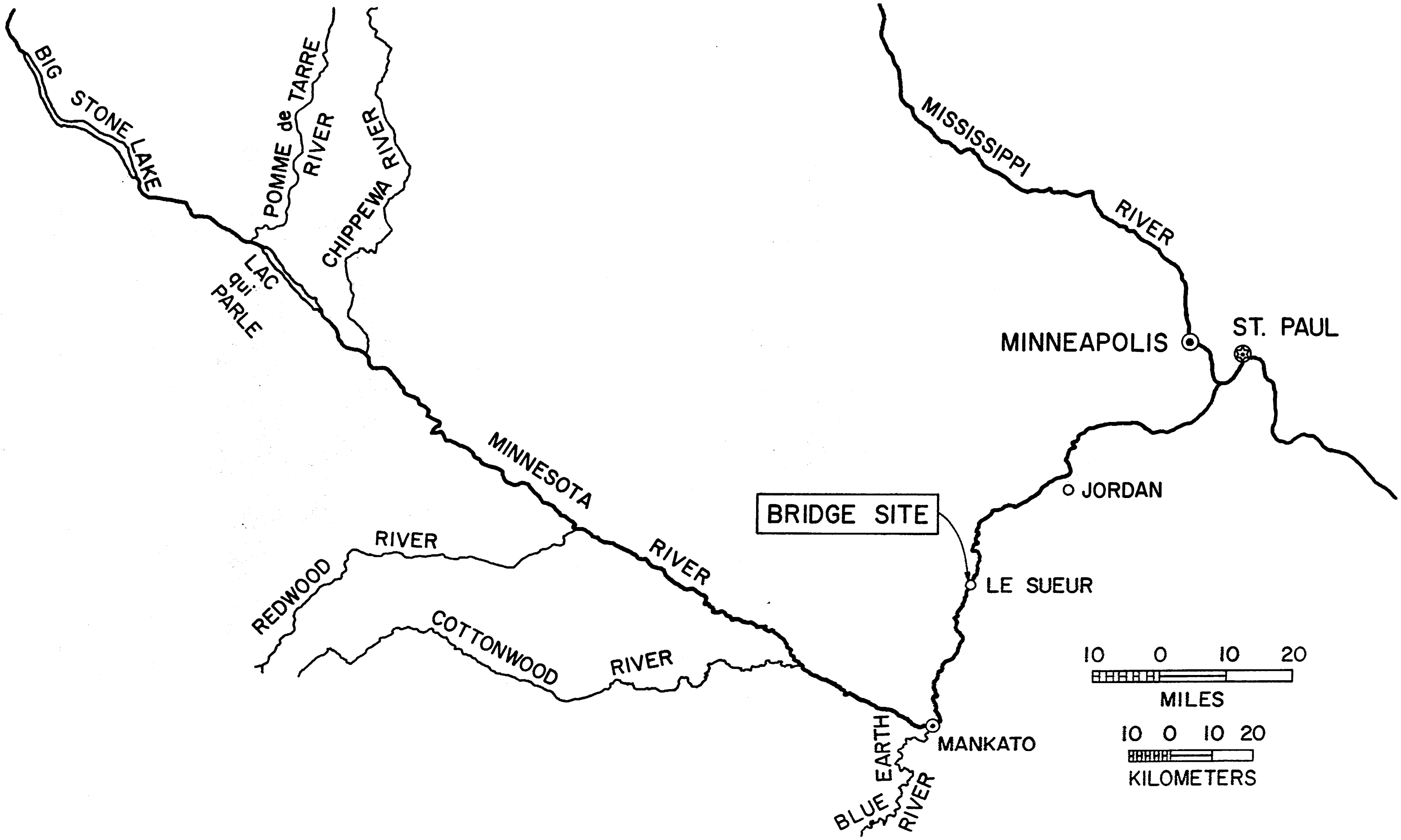


Fig. 3. Map of the Minnesota River basin.

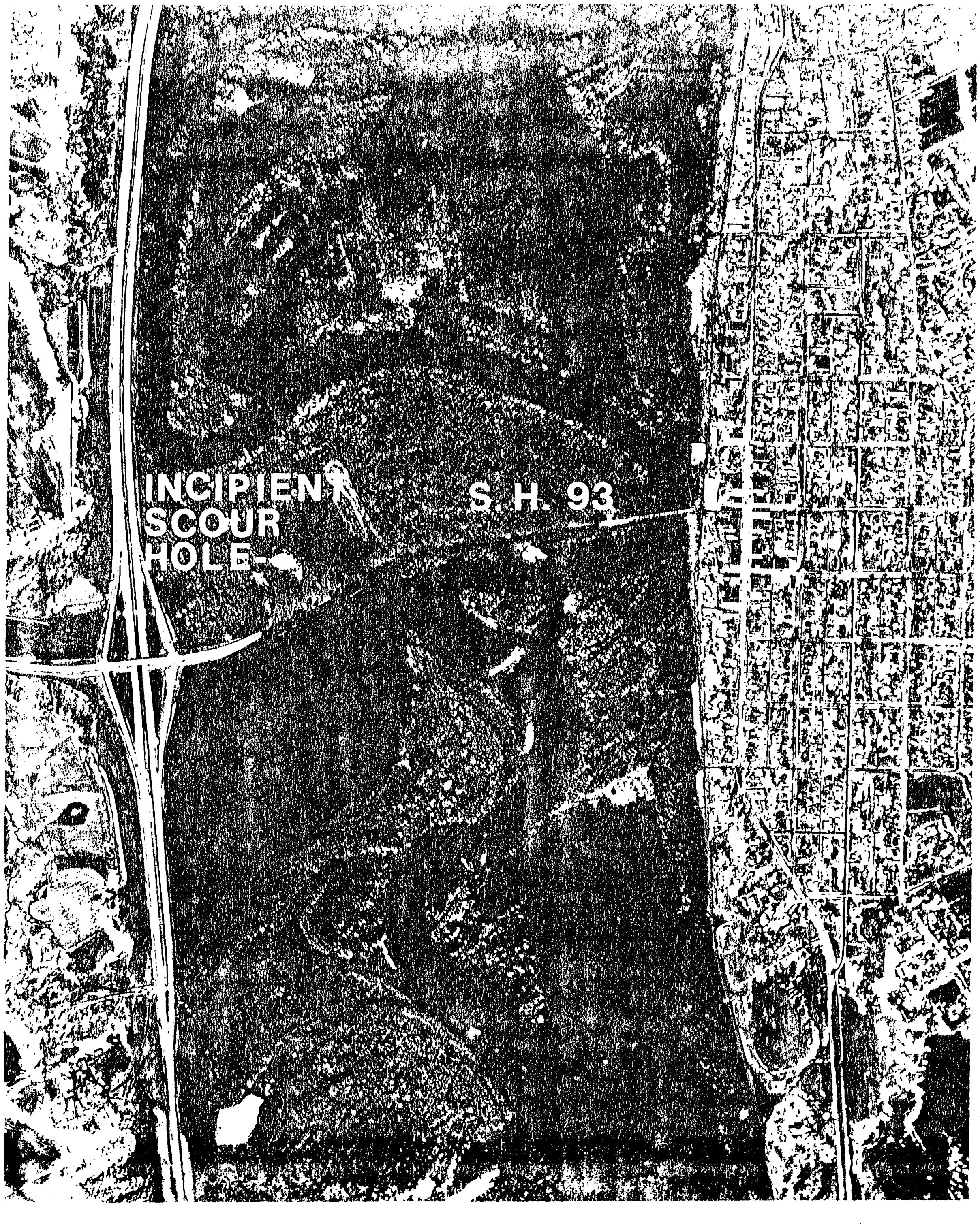


Fig. 2. The Minnesota River and floodplain, 1965 flood in the vicinity of the State Highway No. 93 bridge.

Fig. 4. The Highway No. 93 bridge site in 1980.

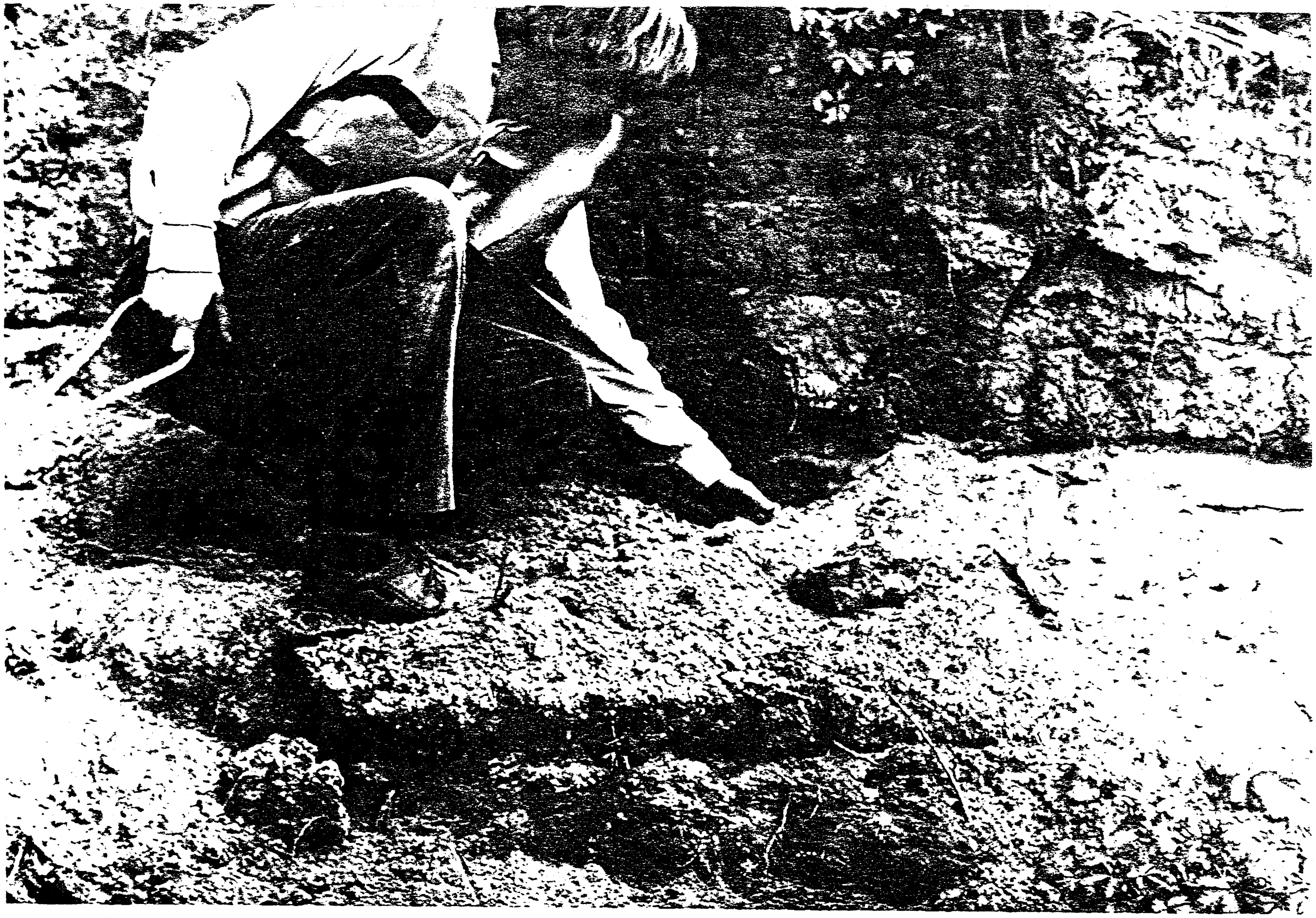
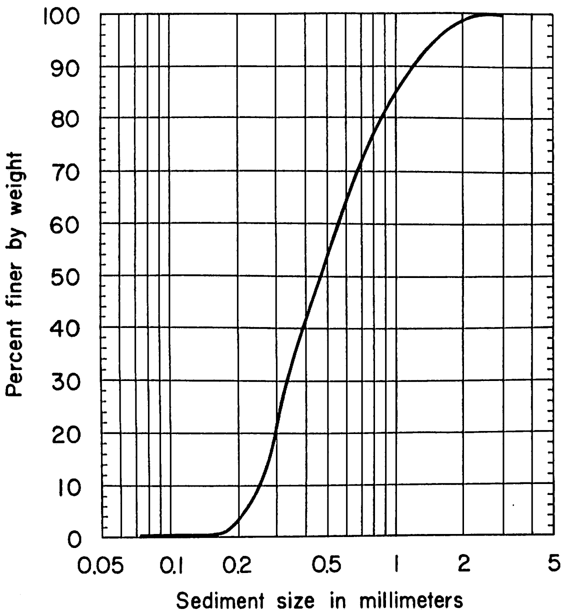
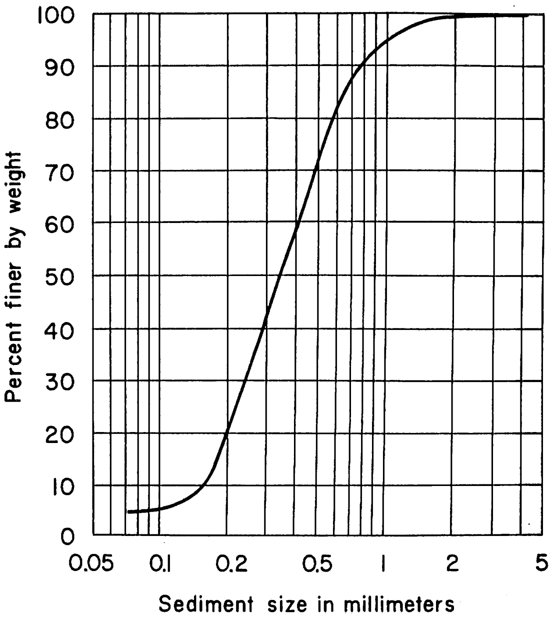


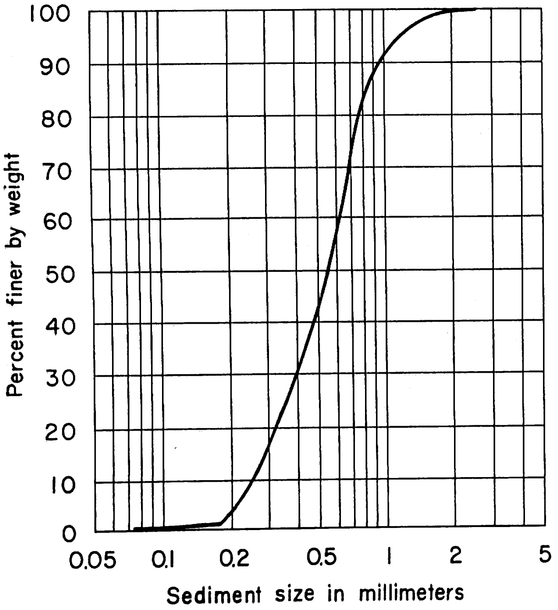
Fig. 5. A cut bank on the outside of the second bend upstream of the State Highway No. 93 bridge.



(a)

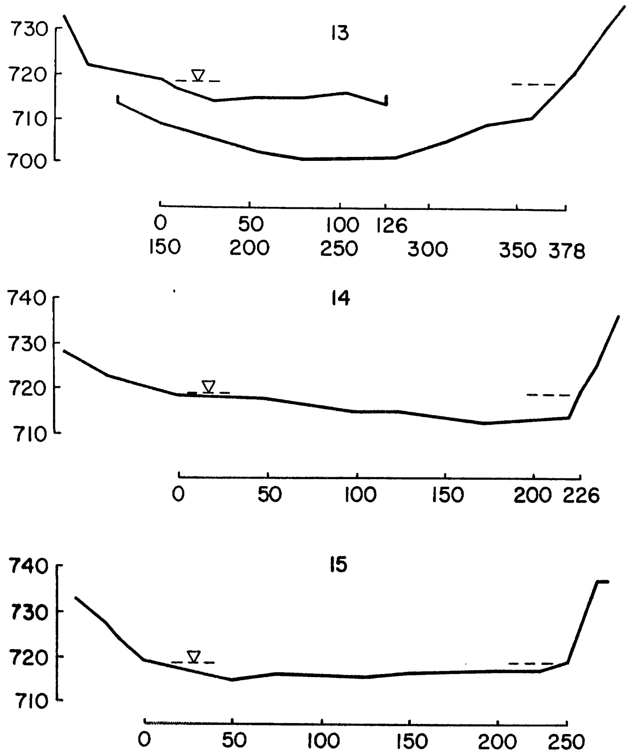


(b)

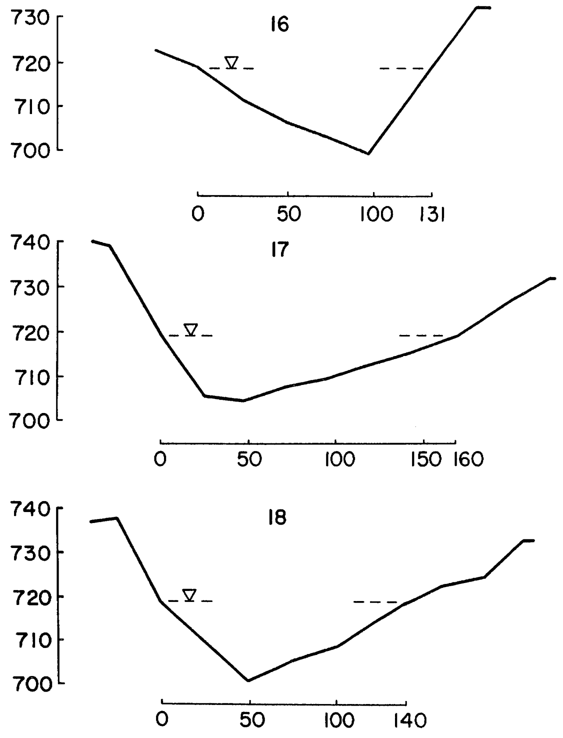


(c)

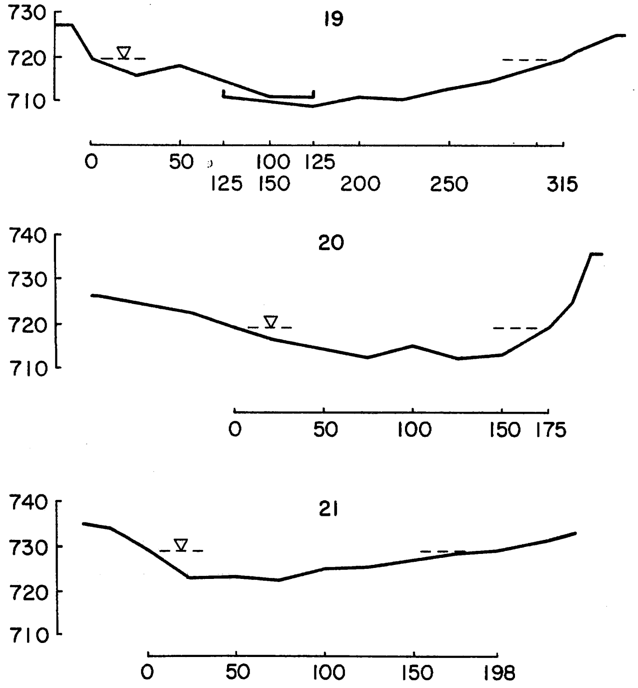
Fig. 6. Three typical size distributions of bed material in the Minnesota River near the Trunk Highway No. 169 bridge.



(a) Cross sections 13, 14, and 15.



(b) Cross sections 16, 17, and 18.



(c) Cross sections 19, 20, and 21

Fig. 7. Channel cross sections as surveyed on February 27, 1981. Locations are shown on Fig. 4.

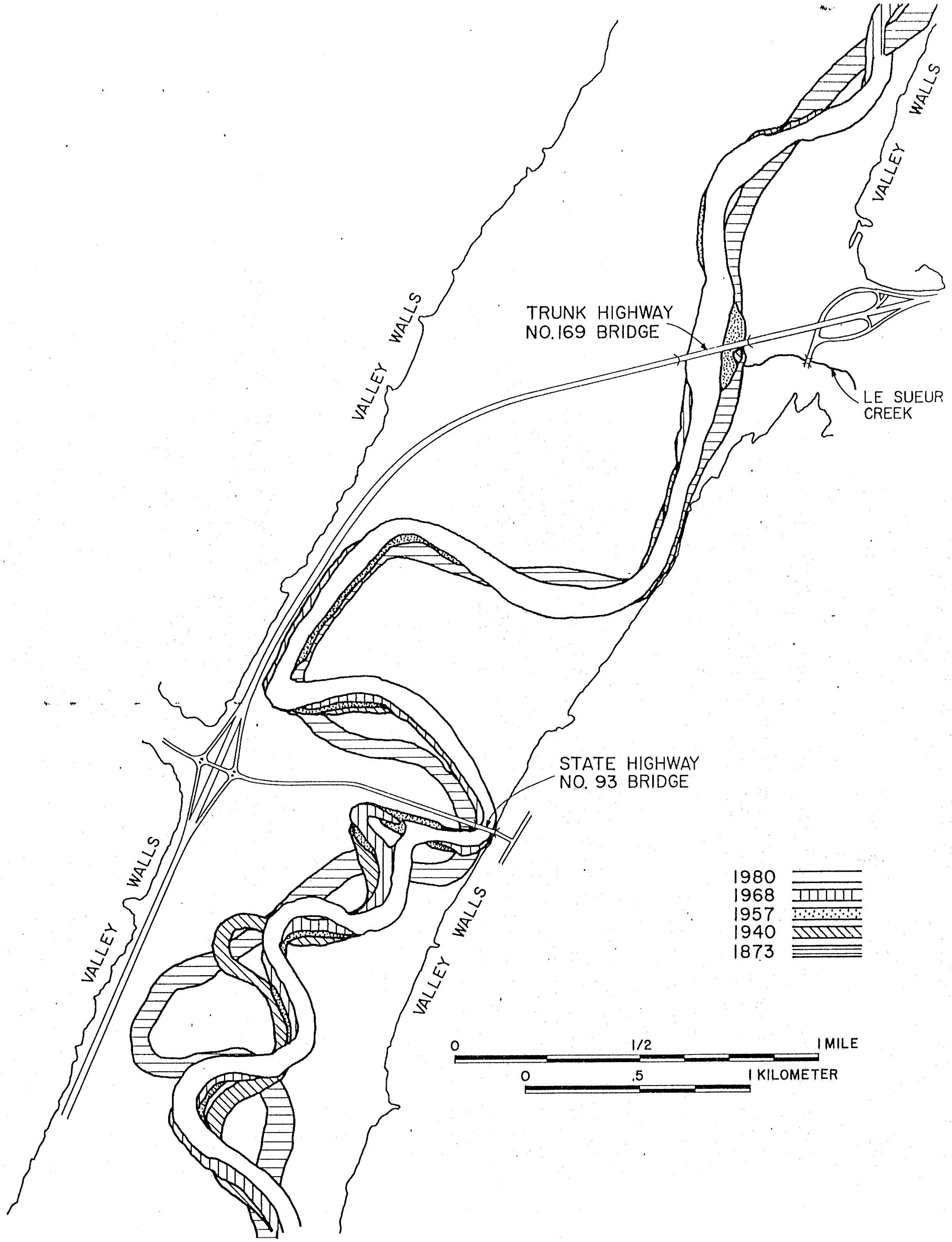


Fig. 8. The 1873, 1940, 1957, 1968, and 1980 channels of the Minnesota River near the State Highway No. 93 bridge.

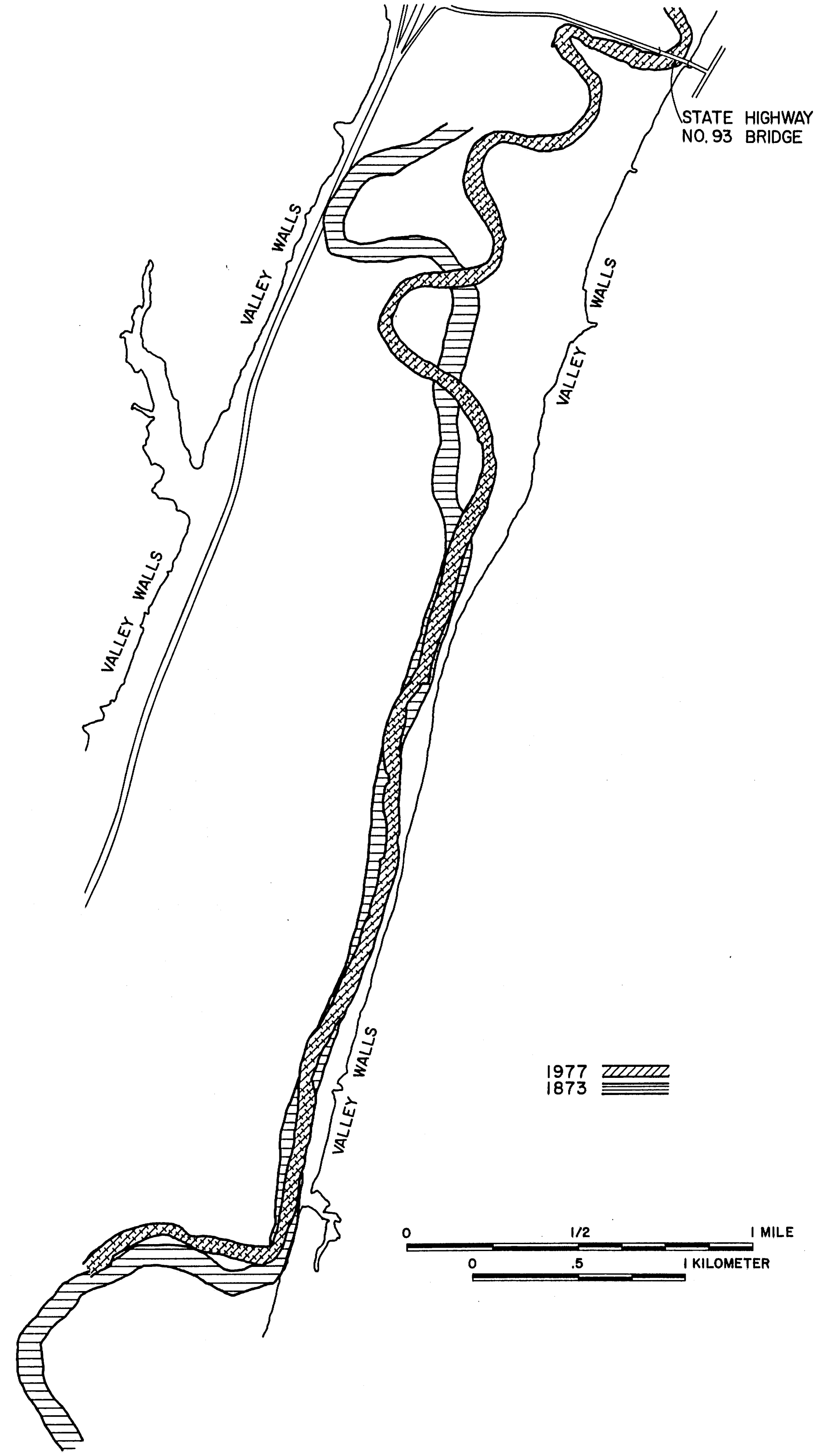


Fig. 9. The 1873 and 1977 channels of the Minnesota River immediately upstream of the reach shown in Fig. 8.

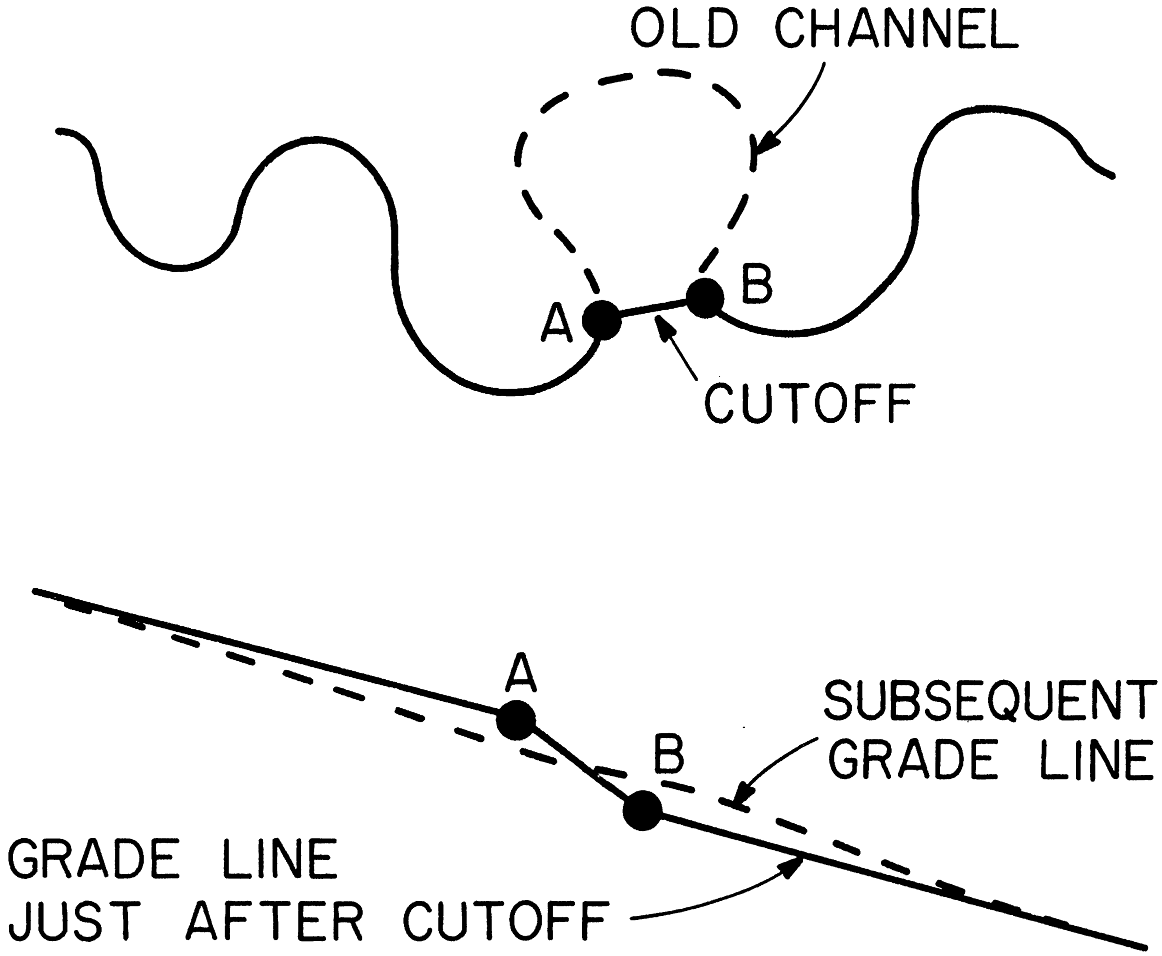


Fig. 10. Schematization of aggradation and degration near a cutoff.

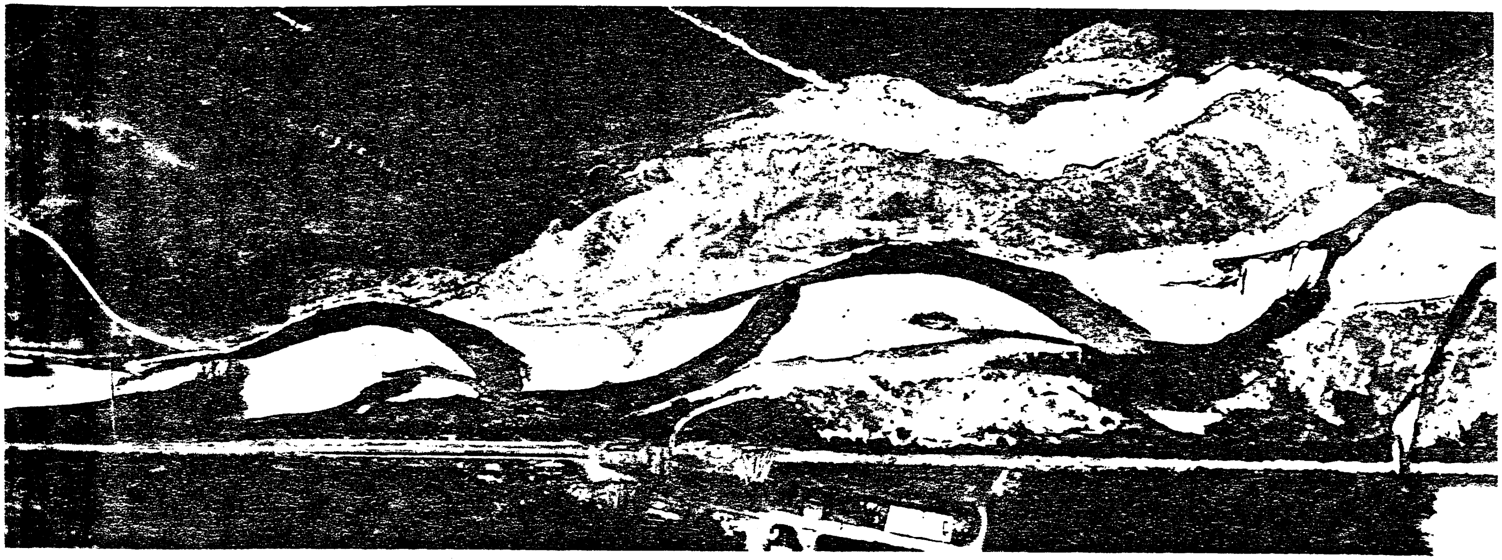


Fig. 11. The channel of the Ystwyth River, Wales, U.K., several months after realignment in a straight pattern. Alternate bars have formed, migrated downstream, and caused bank erosion. The original meandering pattern has begun to reassert itself. (Courtesy J. Lewin)

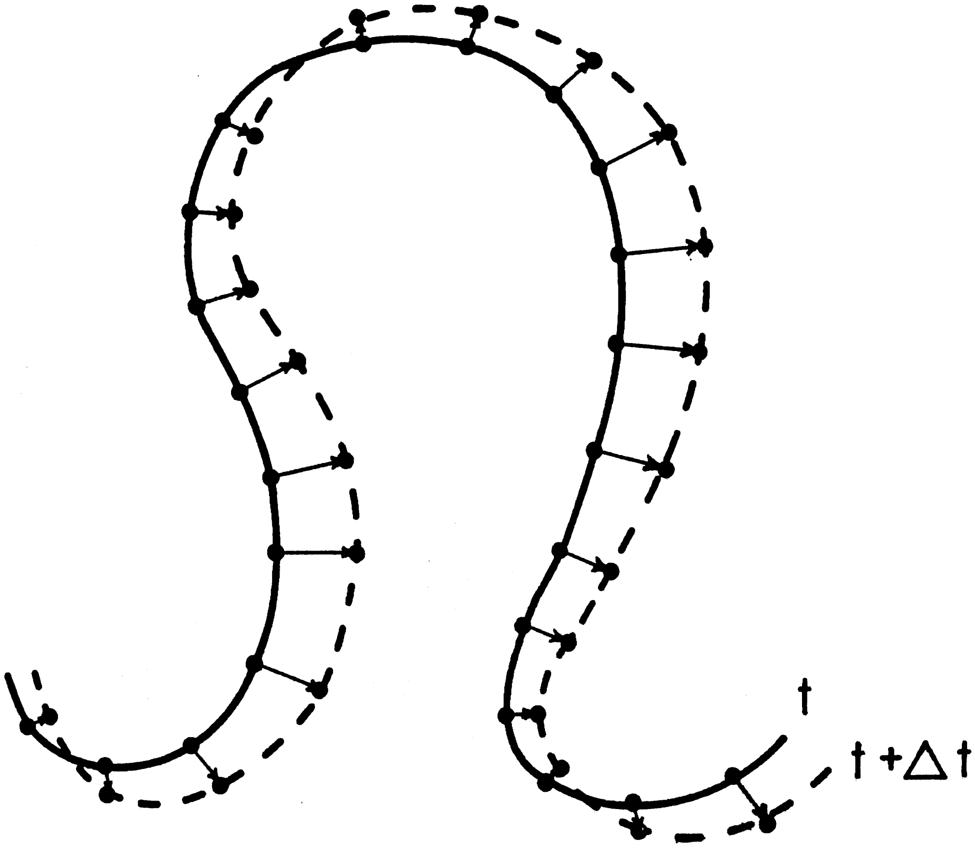


Fig. 12. Schematization of solution by Hickin mapping. In a single time step, each "material" point is moved as a vector, the direction of which is normal to the channel, and the magnitude of which is proportional to the excess shear bank stress.

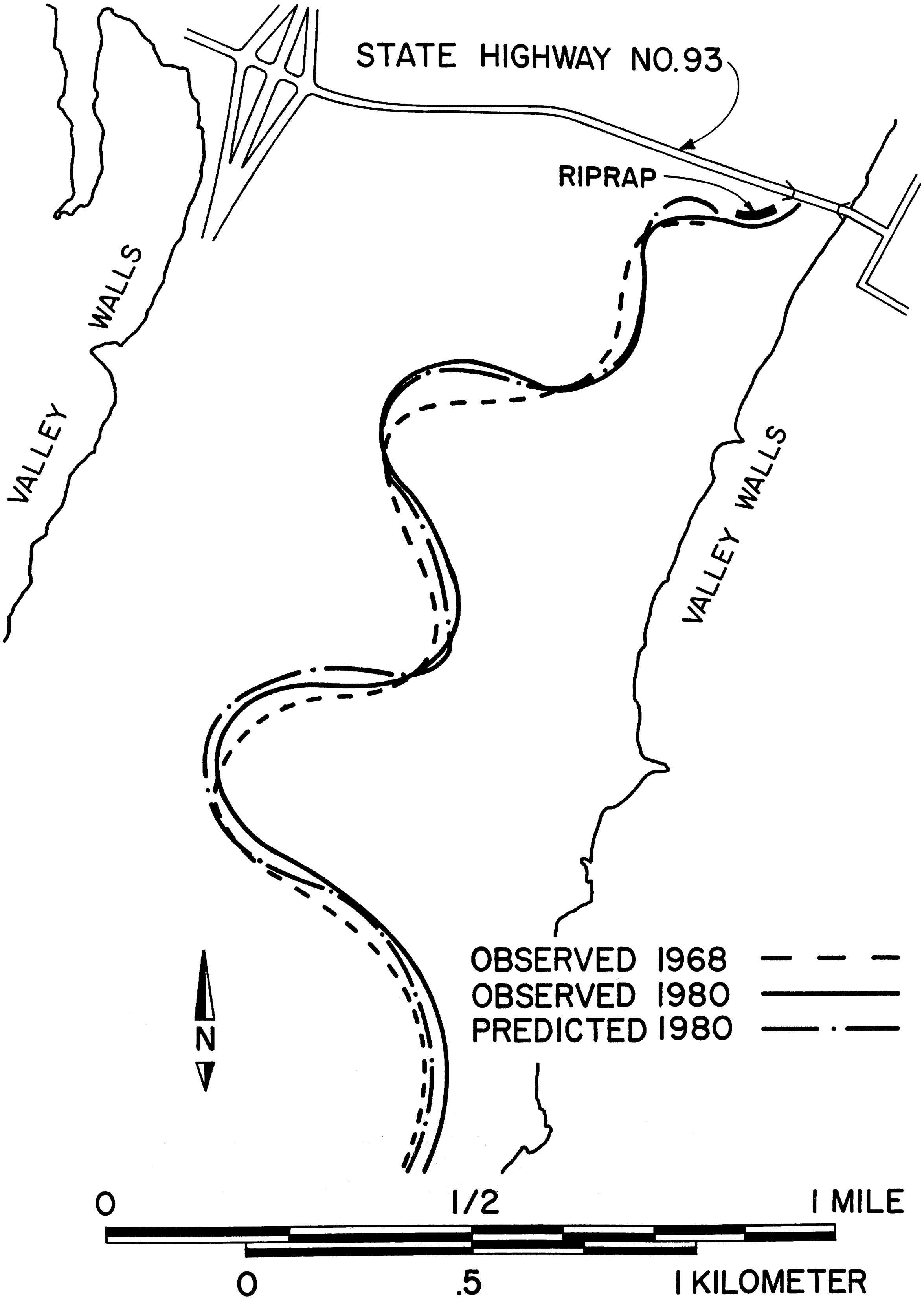


Fig. 13. Results of calibration from 1968 to 1980. The lines denote the position of the channel centerline.

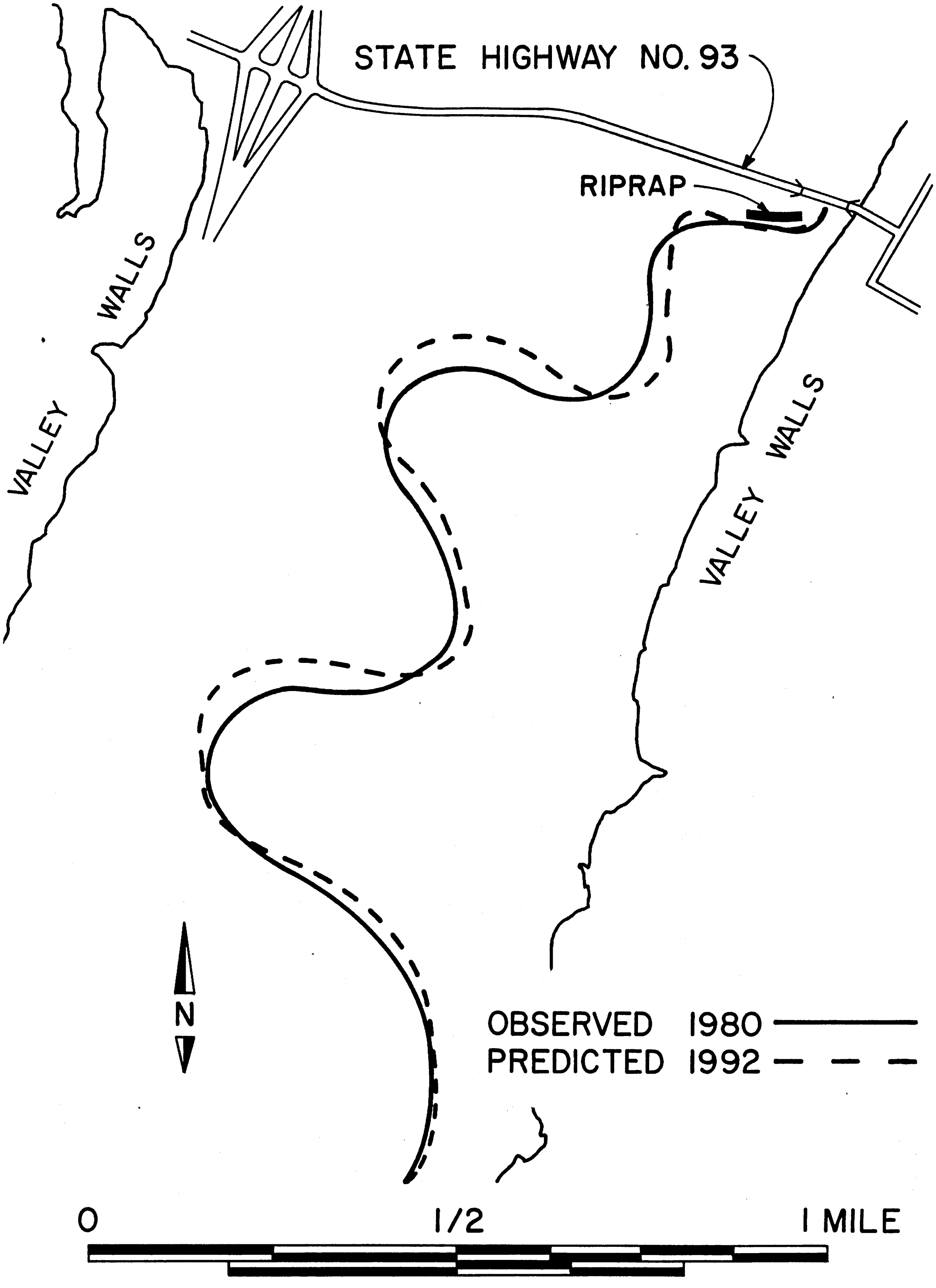


Fig. 14. Prediction from 1980 to 1992 under the assumption that only the simulated riprap is maintained.

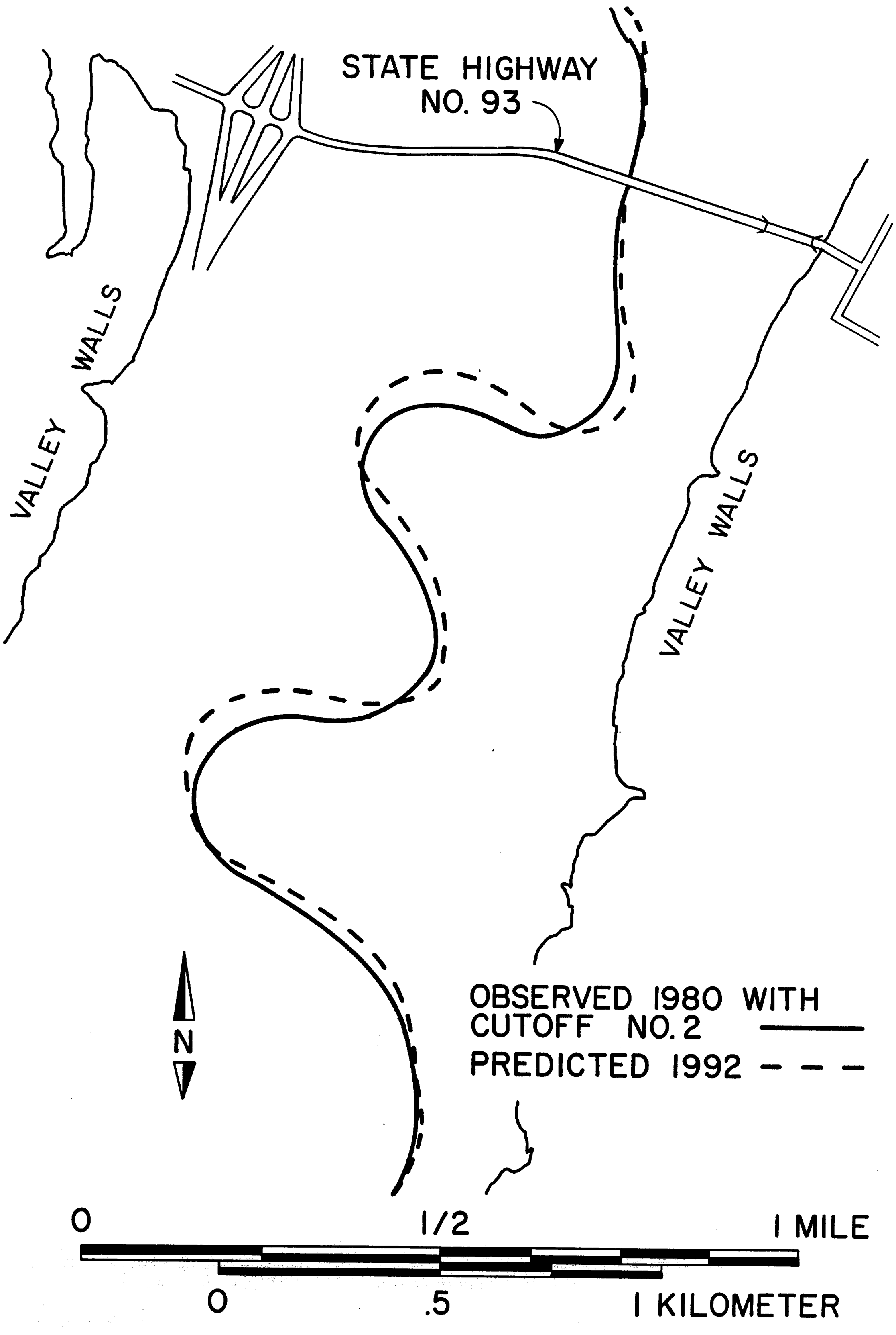


Fig. 15. Prediction of the channel migration from 1980 to 1992 assuming the channel was relocated in 1980 according to alternative 2.

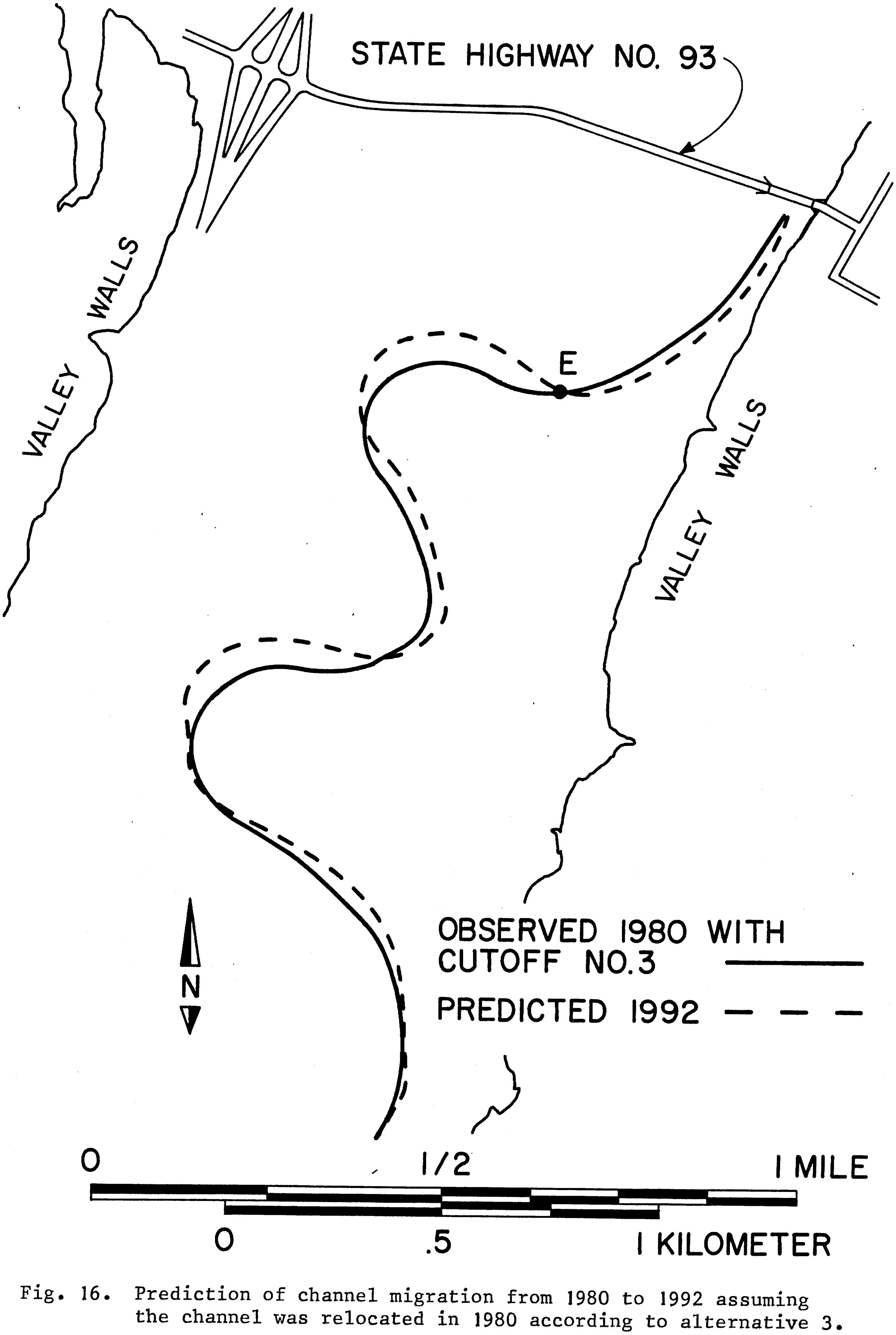


Fig. 16. Prediction of channel migration from 1980 to 1992 assuming the channel was relocated in 1980 according to alternative 3.

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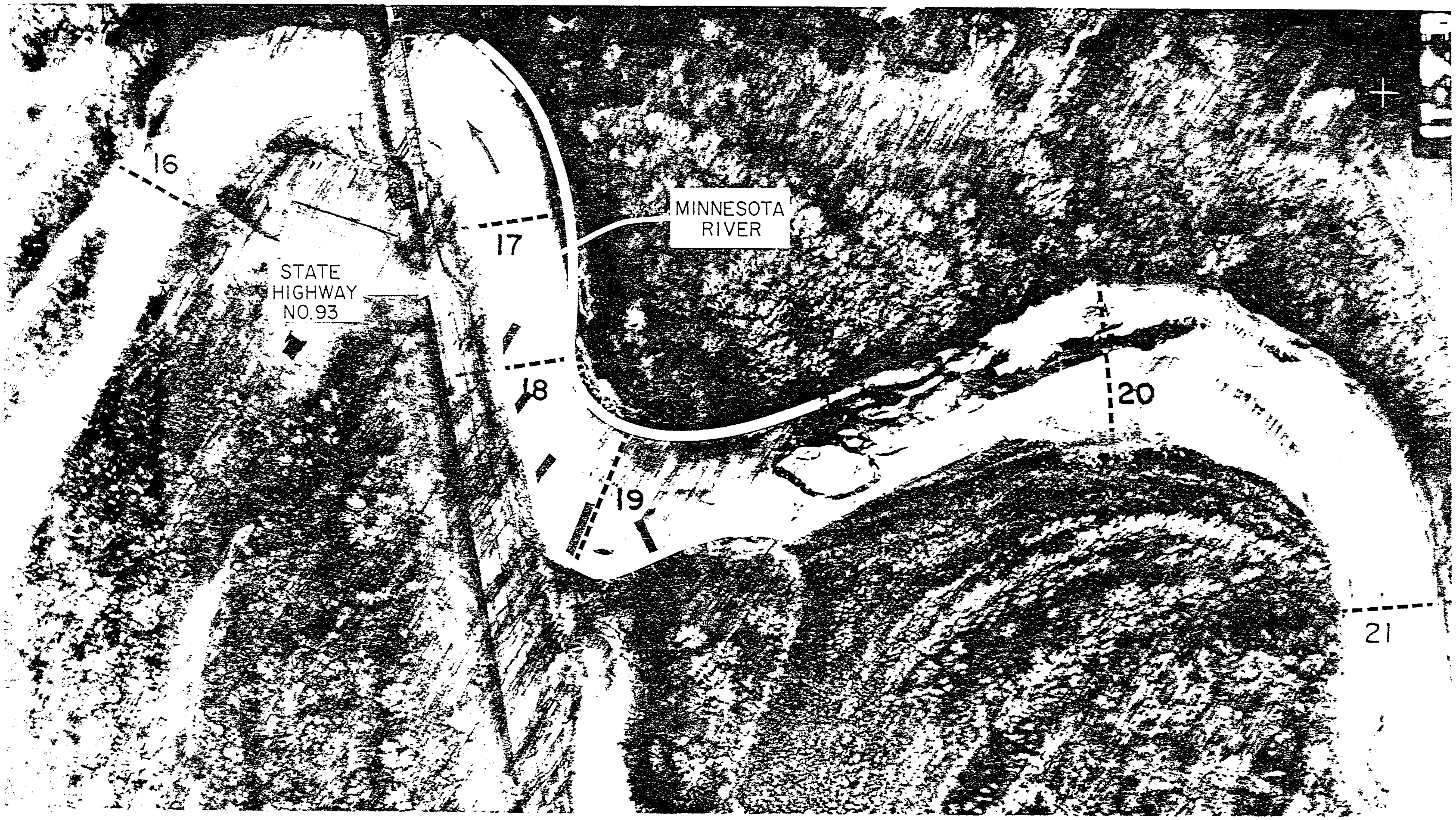

Fig. 17. Suggested placing of spur dikes as a minimal option. The banks have been outlined for clarity.

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