UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

EFFECT OF BANK PROTECTION MEASURES, STEHEKIN RIVER, CHELAN COUNTY, WASHINGTON

By Leonard M. Nelson

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS, INCH-POUND TO METRIC

Multiply inch-pound units	By	To obtain SI units
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (ft^3/s)

Note: 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 "Mean Sea Level."

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ABSTRACT

An investigation of the lower Stehekin River was conducted to study the effects on flood elevations and velocities from four bank-protection and flood prevention measures that are being contemplated as a means of reducing erosional losses of river-bank property. These measures are: bank armoring, armored revetment levees, spur dikes, and redevelopment of old cutoff channels.

The banks at seven study sites could be armored without adverse effect on the flood velocities and elevations. The largest increases due to armoring--up to 1.6 feet per second in velocity and 1 foot in elevation--occurred in the vicinity of sites 5, 6, and 7 where the gradient of the river channel is about 50 feet per mile and the velocities are high to begin with (about 6 to 13 feet per second). The use of a levee in conjunction with armoring on the northeast bank from sites 5 to 7 would increase the velocities as much as 2.8 feet per second and increase the elevation as much as 1 foot, but it would also provide some flood protection to the east bank, which is frequently inundated.

Spur dikes were considered a practical alternative only at site 3, where reduced bank erosion may occur without aggravating flood inundation or erosion elsewhere. The rerouting of flood flow through an old cutoff channel near site 1 increased the velocity by 3.2 feet per second and the elevation by 1 foot for the 100-year flood; however, it would move floodwater away from residential property where bank erosion is a problem. The few other old channels that shortcut river bends where much erosion occurs are apparently already part of the channel during floods.

INTRODUCTION

This study was conducted for the National Park Service to determine the effect of flood elevations and water velocities from measures that are being contemplated to reduce bank erosion and flooding along the lower Stehekin River. Up to four different measures were studied at each of seven river sites where the National Park Service has indicated that bank erosion is a problem. The seven sites are located in the Lake Chelan National Recreational Area along a 7-mile reach of the Stehekin River upstream from its inlet into Lake Chelan (fig. 1). The area is located in north-central Washington about 90 miles northeast of Seattle. The effects on flood elevations and water velocities were determined for peak discharges corresponding to floods of 10-, 50-, and 100-year-recurrence intervals.

Along the 7-mile study reach, the Stehekin River meanders within a wide uneven flood plain that consists of alluvial gravel, cobbles, and boulders. The flood plain is covered largely by conifers with deciduous trees and underbrush, with the thickest growth along the river channel and its tributaries. Scattered summer vacation cabins and year-round homes are on the flood plain near the riverbanks with most of them near the river's mouth at Lake Chelan.

Along relatively straight stretches of the 7-mile study reach, the channel of the Stehekin River has a generally trapezoidal shape about 300 feet wide and 7 or 8 feet deep from the top of the banks. In river bends the channel has a triangular shape, with the greatest depth on the outside of the bend (about 10 or 12 feet from the top of the bank). Where bank erosion is a problem, it generally occurs on the outside of the river bends. One place where bank erosion is of major concern is the river bend identified as site number 1 in figure 1 and shown in the photograph in figure 2. Among the trees just to the right of the eroding bank in the photograph (center background) are a number of private cabins and homes that are losing property to bank erosion.

As bank erosion progresses, trees are undermined, eventually toppling into the river to form floating debris that often lodges somewhere in or along the channel. In some cases, as shown in the photograph in figure 3, extensive amounts of such debris can lodge on the outside of bends and provide a natural barrier against erosion. In other cases, particularly near the river's mouth, debris jams in the channel have caused the cutting of new channels and the abandonment of old channels.

Materials that form the stream channel are similar to material found on and underlying the flood plain. The roundedness that typifies alluvial origin and the generally large size of material that characterizes the high energy of the steep stream gradient are illustrated in figure 4. The gradient of the river channel varies from about 50 feet per mile at river mile 7 to about 10 feet per mile just upstream from the river's mouth.

Any particular protective measure can be selected for any one riverbank site just on the basis of its effect on flood elevation or water velocity at the site, but these should not be the only criteria for selection. Protection applied to one bank may be effective at that site, but may adversely affect the opposite bank or be detrimental farther downstream. In general, passive measures, such as armoring, will have less adverse impacts on opposite-bank or downstream sites than will aggressive measures that change the river course or channel geometry. In this study, the effects on flood elevation and velocity for each measure, applied one at a time to one site, are determined along the study reach. No combinations of measures were studied. The selection of the protection measures at the seven sites and the structural design of specific bank-protection measures are beyond the scope of this study.

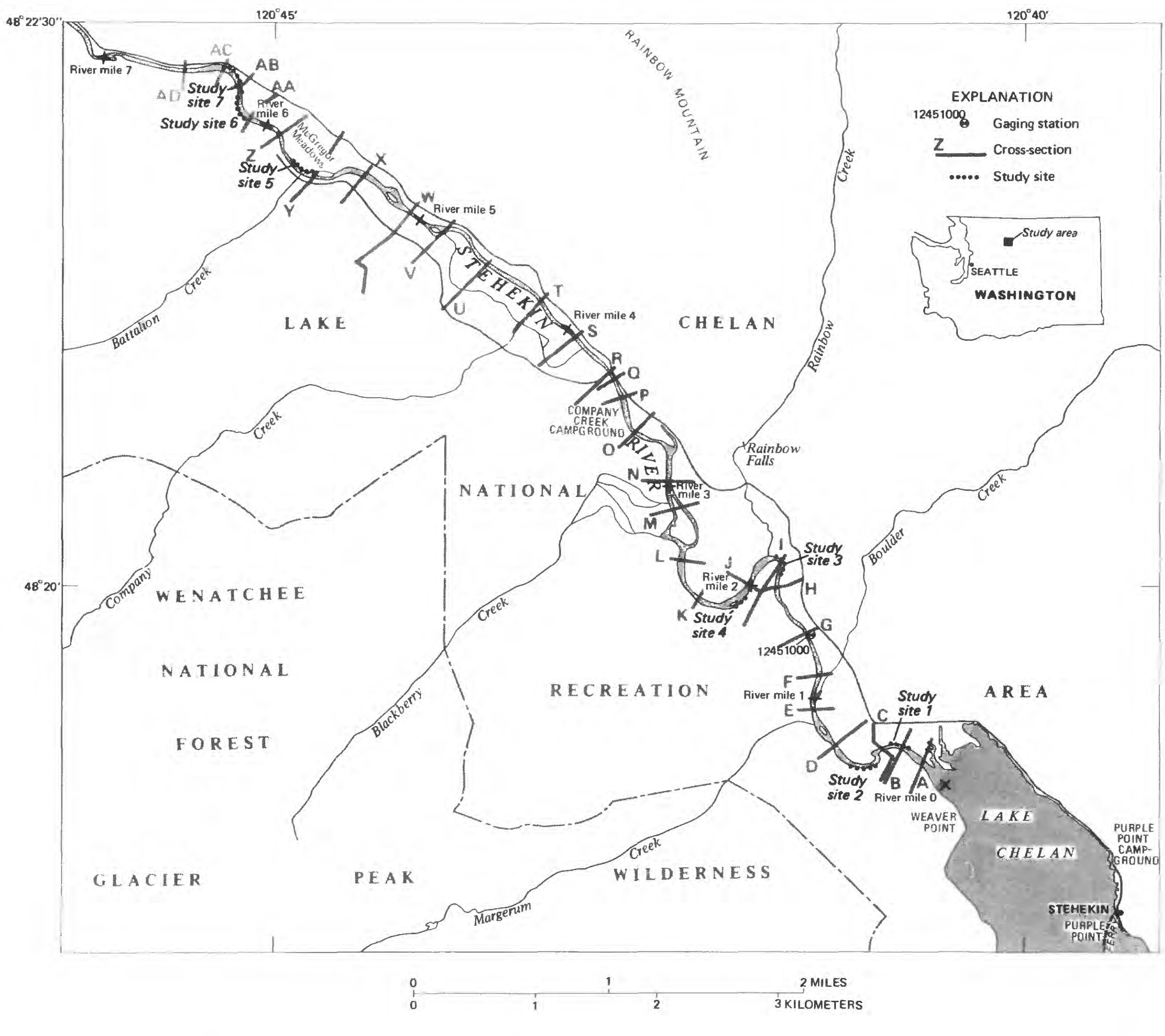

FIGURE 1. – Stehekin River study area, with locations of cross sections and study sites.

FIGURE 2. – View of eroding bank (center background), looking upstream of site 1.

FIGURE 3. – View looking downstream at the accumulation of natural debris protecting the outside of a river bend upstream of site 7.

FIGURE 4. – Example of streambed material found at water edge at cross section AC, typical of materials throughout the study reach.

BANK PROTECTION MEASURES STUDIED

The four types of protective measures included in this study are (1) bank armoring to the top of the existing bank; (2) armored revetment levees constructed to just above the elevation of a 100-year flood; (3) spur dikes constructed to an elevation equal to the top of bank or levee; and (4) the redevelopment of old cutoff channels that bypassed certain river bends. Not all of the four types are practical at each location, and only the practical measures were investigated.

The most commonly used method of dealing with the erosion of highway embankments by waves or high-velocity flow is to armor the embankments with more resistant material (State of California, 1970). This method is often applied to streambanks, is generally easy to repair, and is usually esthetically acceptable. Armoring can consist of different shapes, sizes, and amounts of material. For this study, it was assumed to consist of large, angular rock that would fill 10 feet of channel adjacent to the bank and would decrease the cross-sectional area. Armored revetment levees would be an extension of the armoring to the top of a levee high enough to contain flow within the channel. The thickness of rip-rap and placement within the channel were assumed to represent the maximum probable effect. Ten feet was chosen because the thickness of existing rip-rap pads ranges from 3 to 10 feet. Less than 10 feet of rip-rap, or placement of the rip-rap along an excavated bank, would cause less effect than indicated in this report. Because of the rough streambed, it was assumed that the rip-rap would not change the Mannings roughness coefficient for the over all channel.

Spur dikes are fingers of erosion-resistant material projecting into a river channel from a bank. They are used to deflect streamflow and reduce erosion by decreasing the velocity of the streamflow adjacent to the bank. In slowing the water velocity along the protected bank, they also increase the water-surface elevation, causing streamflow to deflect across the river toward the opposite bank. Of all the erosion-prevention measures, spur dikes may have the most detrimental effect on opposite-banks and downstream sections. In addition to deflecting flow, spur dikes also decrease the cross-sectional area of flow. In this study a spur dike was represented as a vertical bridge abutment extending normal to the bank across 0.1, 0.2, and 0.3 the width of the channel. The dike was used like an eccentric bridge opening. The height of the spur dike was made equal to that of the bank.

The redevelopment of old cutoff channels would represent an effort to move the main channel back to some former location where the erosion of riverbanks was not of concern. This alternative may be possible wherever the old channels exist, but the accomplishment may be difficult. In this study, it was assumed that the existing channel would be blocked, thus forcing the river to use an old channel which had been cleared of vegetation and would afford the river a route of least resistance. In most cases, this would shorten the river length by eliminating bends (and some cross sections), but would increase the river gradient and its velocities, possibly to an extent that bank erosion at some point downstream would be increased. Whatever caused the river to abandon the old channels could recur, however, and negate the effort of forcing the river into the old channels.

APPROACH

Seven study sites were selected by personnel from the National Park Service during a field reconnaissance in the summer of 1982. The sites are shown on figure 1 and detailed on figures 5, 6, and 7. The solid lines on figures 5 and 6 represent the boundaries of the river as of December 1975; for figure 7 they are for conditions of July 1978.

Boundaries based on aerial photographs from 1962 have been sketched in figures 5 and 6 to indicate the considerable erosion that has occurred relative to the conditions in 1975. The 1978 boundaries are also shown on figure 5. These changes are most pronounced from 1962 to 1975, particularly at sites 1, 2, 3, and 4. At these sites, some of the banks appear to have eroded 100 to 200 feet in length along bends. Much of the change probably occurred in June 1974 during the highest flow of the 1962 to 1975 period.

During the period 1975 to 1978, the annual peak discharges were much lower and changes in the river were much more subtle. Most notably, the river appears to have established a better defined channel during that period; however, that change might also have been a product in part of a debris-removal operation by the U.S. Corps of Engineers in 1975 in the most downstream 2 miles of the river.

Thirty cross sections of the river from its mouth upstream to river mile 7 were used in the step-backwater computation. Data for 23 of those nearest the lake inlet were obtained from a survey conducted in about 1975 for the Chelan County flood insurance study (Federal Emergency Management Agency, 1980). The remaining seven were surveyed by the U.S. Geological Survey between river miles 5 and 7 during September 1982. A resurvey to update the 23 previous cross sections to 1982 conditions was beyond the scope of this study. All elevations are in the National Geodetic Vertical Datum of 1929 (NGVD). The identification system used for the new cross sections is a continuation of that used in the flood insurance study.

Flood elevations and mean water velocities were determined at each cross section for flood discharges of 10-, 50-, and 100-year recurrence intervals by using a U.S. Geological Survey step-backwater computer program (Shearman, 1976). This program utilizes data for river cross-section geometry and elevation, channel slope between cross sections, and Mannings roughness coefficient to balance the energy equation for a constant water discharge along a reach of river. The mean velocities are the mean of all velocities in each cross section, including those on the flood plain.

The step-backwater program was used first to establish the flood elevations and velocities that characterized the river in 1975 without any changes, assuming that data for the seven new cross sections were estimates of conditions in 1975. The starting water-surface elevation at Lake Chelan was obtained from the flood insurance study (normal elevation is 1,098 feet). The water-surface elevations determined from the step-backwater program are nearly identical with those given in the flood insurance study for the river reach covered by that study, and were used as reference elevations for evaluating the effects of erosion-prevention measures included in this study. A profile of flood elevations corresponding to a 100-year flood in the unmodified channel is given in figure 8. Flood elevations and velocities for 10-, 50-, and 100-year floods in the natural channel are listed in table 1 for each cross section. To evaluate the effects of a particular erosion-prevention measure at any one of the seven study sites, the geometry and hydraulic friction for cross sections, and the distance between cross sections at the site were changed in accord with requirements of the prevention measure, and then the step-backwater program was reapplied over the entire 7-mile reach to compute new flood elevations and velocities.

Because the information could be of value in selecting an erosion-prevention measure, a flood-boundary map for a 100-year flood in the unmodified river channel was prepared to extend the flood insurance study map from river mile 5 to river mile 7 (fig. 9). It was prepared by locating the points where flood elevations from the 100-year flood profile to intercept elevation contours on a U.S. Geological Survey quadrangle map. The map was checked by field observation. This map joins that shown in community-panel number 530015 0300 A of the flood insurance study (Federal Emergency Management Agency, 1980).

The flood discharges used in this study were taken from the Chelan County Flood Insurance Study (Federal Emergency Management Agency, 1980), and are based on 47 years of record at the stream gaging station on the Stehekin River (U.S. Geological Survey station number 12451000), which has been operated for more than 60 years (1910-15; 1926-84) by the U.S. Geological Survey at a location 1.4 miles upstream from Lake Chelan. The highest discharge of record is 18,900 ft^3/s on May 29, 1948 (U.S. Geological Survey, 1982). Discharges at selected sites are listed below.

	Drainage area (square miles)	10-year peak discharge (cubic feet per second)	50-year peak discharge (cubic feet per second)	100-year peak discharge (cubic feet per second)
At mouth	344	14,400	17,900	19,200
At cross section "J"	308	13,200	16,500	17,700
At cross section "U"	277	12,200	15,200	16,300

Note: a 100-year peak discharge has a 1-percent chance of occurring in any one year, a 50-year peak discharge has a 2-percent chance of occurring in any one year, and a 10-year peak discharge has a 10-percent chance of occurring in any one year.

Peak discharges were checked against the results of a 1979 U.S. Geological Survey log-Pearson III frequency analysis of 58 years of annual peak discharges at the gaging station. From that analysis the 10-year discharge was 14,100 ft^3/s, the 50-year was 17,900 ft^3/s, and the 100-year was 19,500 ft^3/s. These values are not sufficiently different from the discharges listed above to warrant any changes to the frequency-distribution analyses.

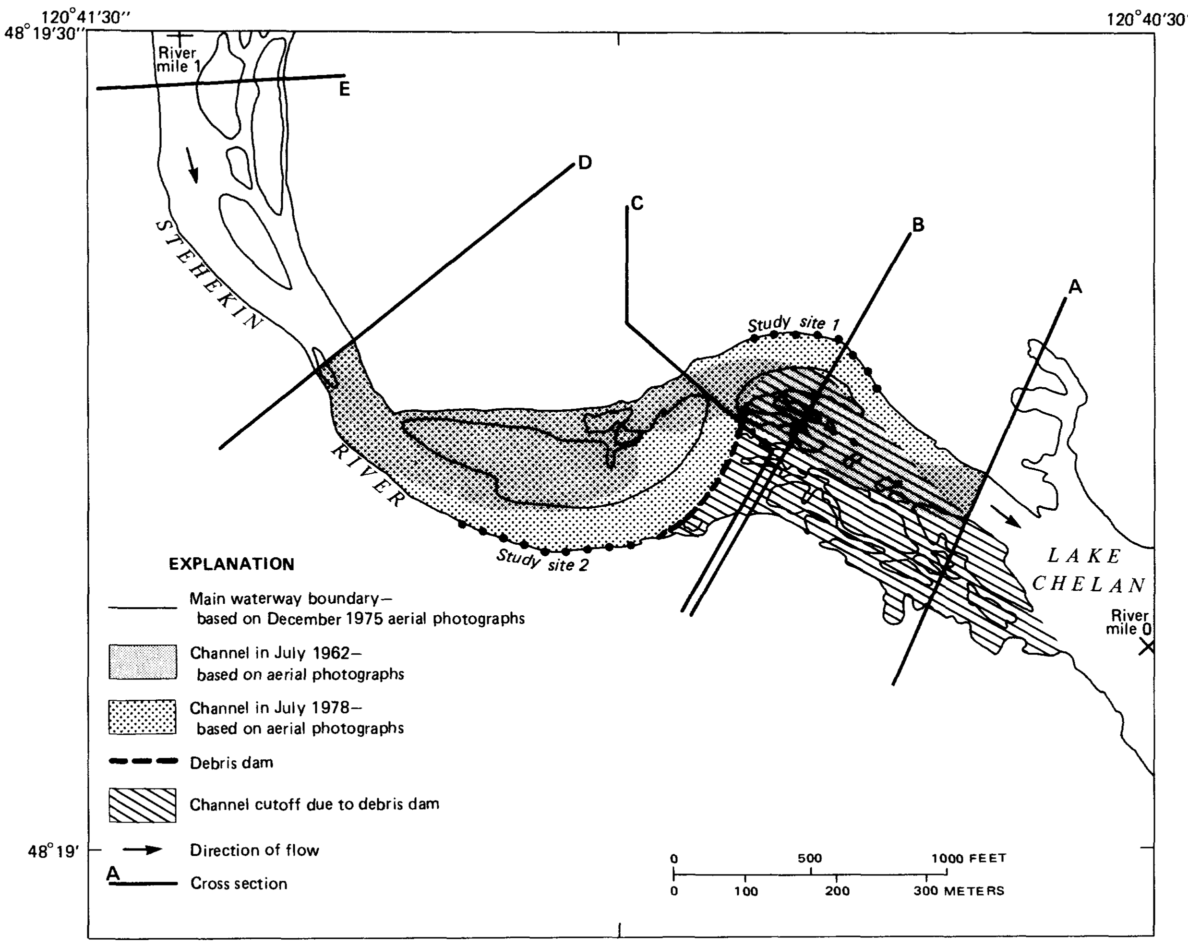

FIGURE 5. – Channel changes at Stehekin River sites 1 and 2 (from Federal Emergency Management Agency, 1980).

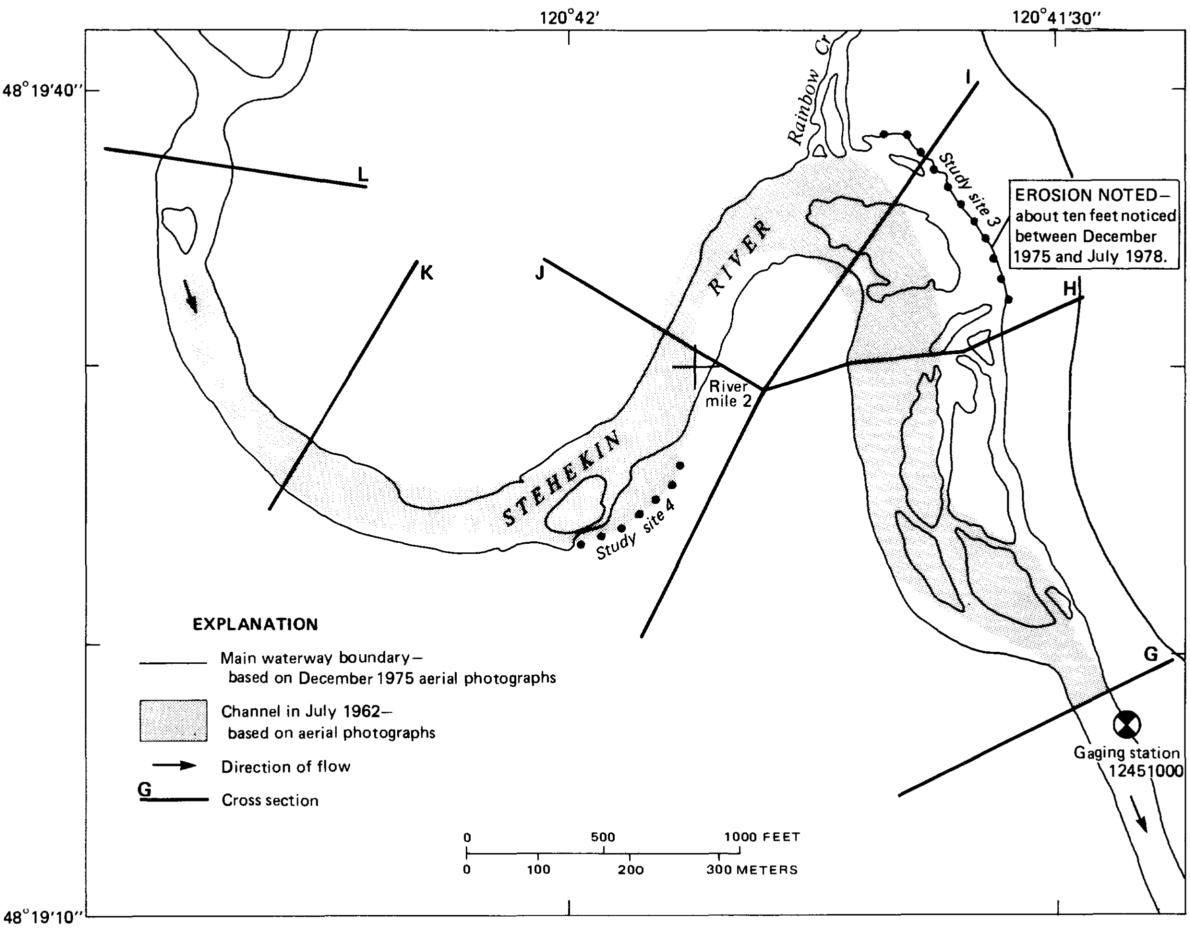

FIGURE 6. – Channel changes at Stehekin River sites 3 and 4 (from Federal Emergency Management Agency, 1980).

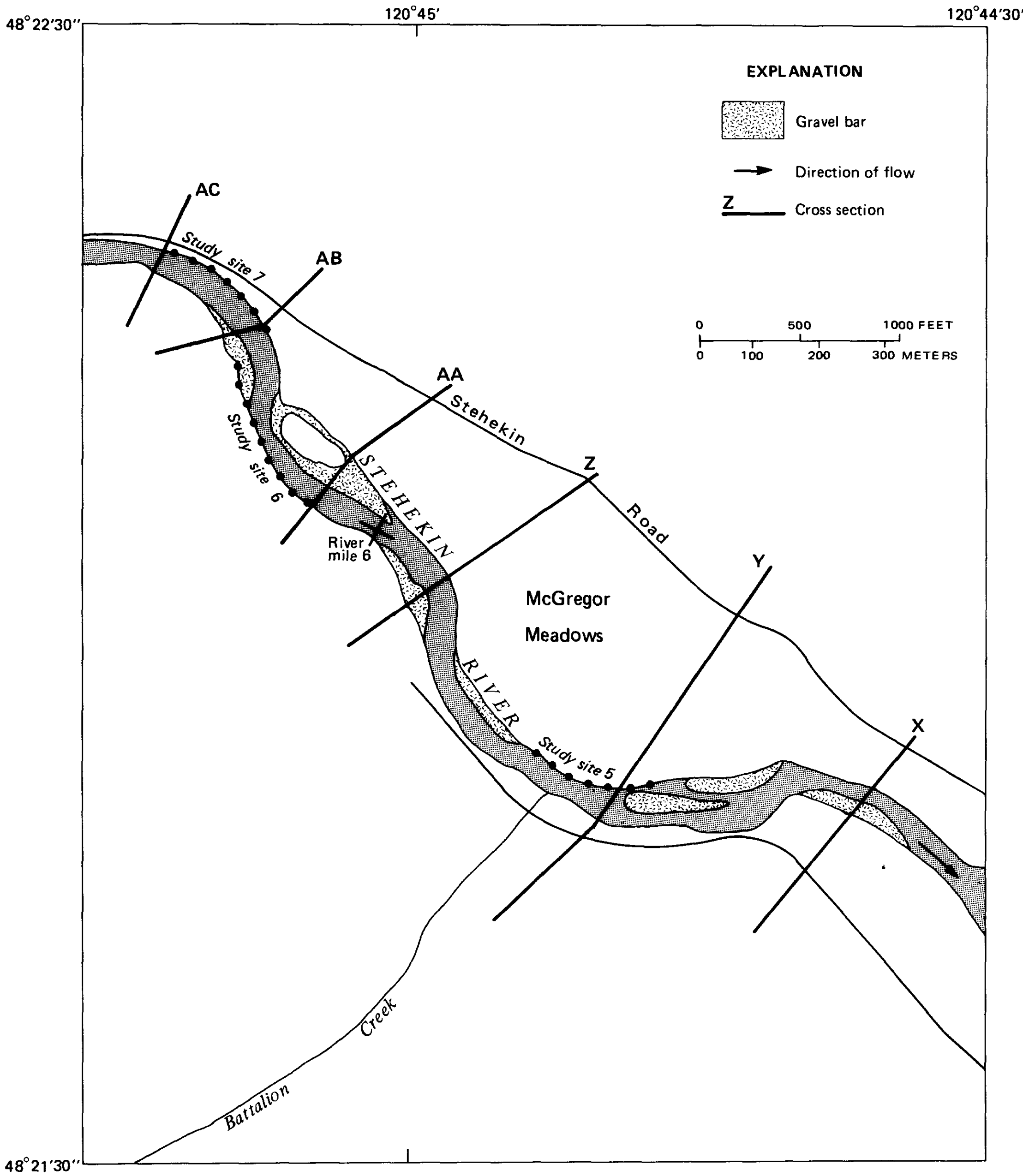

FIGURE 7. – The July 1978 channel configuration of the Stehekin River at sites 5, 6, and 7 (from aerial photographs).

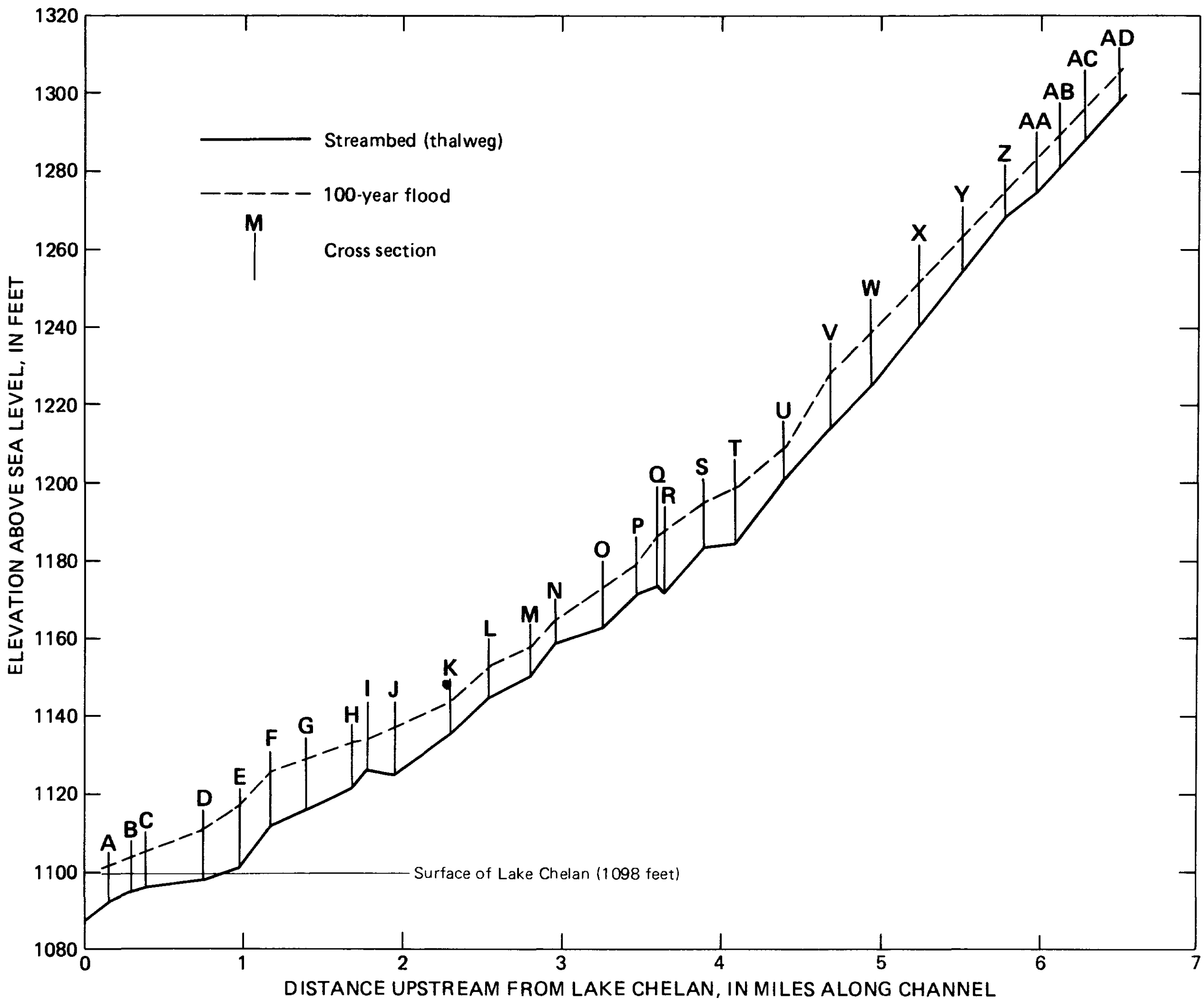

FIGURE 8. – Profile of the 100-year flood on the Stehekin River. Elevations for the 10-year and 50-year floods (see table 1) nearly coincide with the 100-year flood.

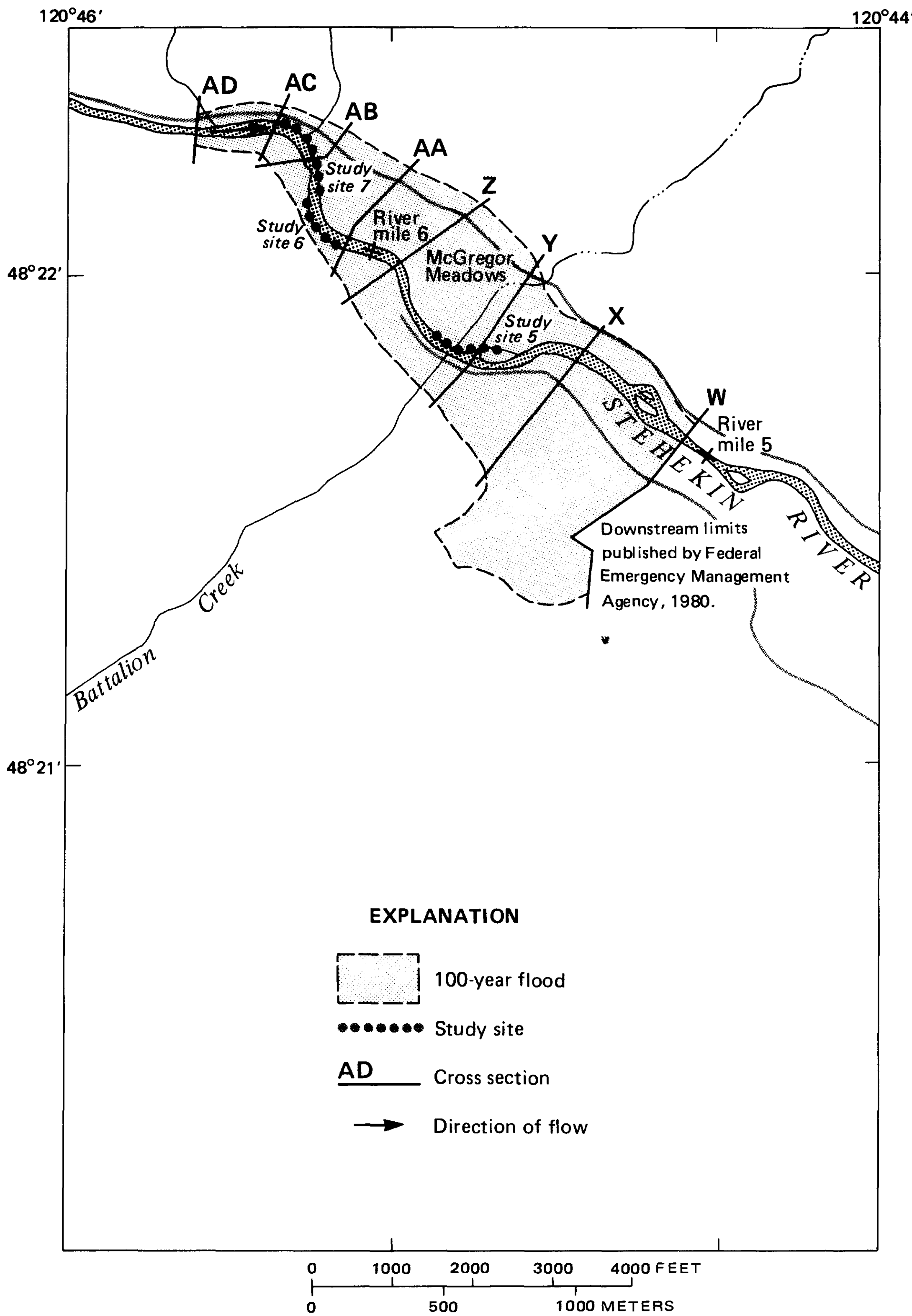

FIGURE 9. – Extension of Stehekin River 100-year flood boundary, published by Federal Emergency Management Agency, 1980.

TABLE 1.--Mean velocities and water-surface elevations for 10-, 50-, and 100-year floods in the Stehekin River from river mile 0 to 6.5 without any channel or bank changes

[Elevations are rounded to the nearest foot]

Cross-section identification	Distance upstream from mouth (miles)	Streambed Thalweg elevation (feet)	Mean flood velocity (feet per second)			Flood elevation (feet)		
			10-year	50-year	100-year	10-year	50-year	100-year
A	0.15	1,092	4.7	4.1	3.9	1,102	1,103	1,103
B	.29	1,095	3.6	3.7	3.8	1,104	1,105	1,105
C	.38	1,096	4.1	4.5	4.6	1,106	1,106	1,106
D	.75	1,098	6.0	6.2	6.3	1,111	1,112	1,112
E	.97	1,101	5.7	6.2	6.4	1,118	1,119	1,119
F	1.16	1,112	7.2	6.4	6.2	1,122	1,123	1,123
G	1.39	1,116	5.4	5.9	6.0	1,128	1,129	1,129
H	1.68	1,122	4.1	3.6	3.5	1,131	1,132	1,133
I	1.78	1,126	4.1	3.7	3.6	1,133	1,134	1,134
J	1.95	1,125	2.0	2.2	2.2	1,136	1,136	1,137
K	2.29	1,135	12.4	13.3	13.6	1,142	1,143	1,143
L	2.53	1,144	4.5	4.6	4.7	1,151	1,152	1,152
M	2.80	1,150	6.0	6.1	6.1	1,157	1,157	1,157
N	2.97	1,158	6.2	6.1	6.1	1,164	1,164	1,164
O	3.26	1,162	2.0	2.0	2.1	1,171	1,172	1,172
P	3.47	1,171	8.1	9.7	10.4	1,177	1,178	1,178
Q	3.60	1,173	5.8	4.6	4.3	1,184	1,185	1,185
R	3.64	1,171	4.2	4.4	4.4	1,185	1,186	1,186
S	3.88	1,176	2.2	2.3	2.4	1,189	1,190	1,190
T	4.09	1,183	4.7	5.0	5.0	1,194	1,194	1,194
U	4.40	1,200	8.2	8.7	8.9	1,207	1,208	1,208
V	4.69	1,215	4.0	4.2	4.2	1,226	1,227	1,227
W	4.95	1,224	3.4	3.6	3.6	1,236	1,236	1,237
X	5.24	1,239	6.9	7.0	7.1	1,250	1,250	1,251
Y	5.51	1,253	6.3	6.1	6.1	1,261	1,262	1,262
Z	5.78	1,267	6.4	5.6	5.6	1,274	1,274	1,274
AA	5.98	1,273	4.0	4.3	4.4	1,281	1,281	1,281
AB	6.12	1,279	9.8	9.8	10.0	1,286	1,287	1,287
AC	6.28	1,287	6.3	6.7	6.9	1,294	1,295	1,295
AD	6.50	1,296	12.5	13.3	13.5	1,303	1,304	1,304

EFFECT OF BANK PROTECTION MEASURES AT SEVEN SITES

For the hydraulic analysis at site 1 the bank was first assumed to be armored in combination with a levee on the left bank to retain the water in the channel. This changed the velocities and elevations only slightly at site 1 and had no effect upstream from site 1.

Spur dikes were investigated next at site 1. Because the existing channel is narrow there, a spur dike of 0.1 channel width would extend into the channel about the same distance as armoring; therefore, it was not evaluated. A spur dike of 0.2 the width of the channel width was simulated at cross section B, which is located at site 1 (fig. 5). This spur dike caused maximum increase in mean velocity of 1.0 foot per second and an increase in elevation of 1 foot for the 100-year peak discharge (table 2). Because an increase in velocity of 1.0 foot per second was considered a reasonable limiting value, a 0.3 width spur dike was not investigated.

The erosion caused by flow directed toward the north bank between cross sections B and C at site 1 (fig. 5) could possibly be eliminated by rerouting the flow through the old cutoff channel at cross section B. The large debris dam blocking the upstream end of the old channel and the overgrown vegetation in the old channel would need to be removed and the existing open channel closed in order to reroute the flow. Routing the entire flow through this channel, which is smaller than the existing channel, caused a velocity increase of 3.2 feet per second and an elevation increase of 1 foot at cross section B (table 2). At cross section D the velocity decreased 0.9 foot per second and elevation increased 1 foot. Changes further upstream were insignificant. If the old cutoff channel were to be opened and the existing open channel were to remain open, some of the flood flow would be diverted away from site 1, which would likely reduce flood velocities and elevations, but the investigation of this condition was not within the scope of this study.

At site 2 armoring could possibly protect the banks from erosion; a levee was not considered because of the high southwest bank. Because the channel is wide at site 2, the use of bank armoring would increase flood velocities and elevations only slightly. Spur dikes at site 2 were considered to be detrimental because the dikes would likely deflect the flow more towards site 1; thus, they were not studied. There is no cutoff channel at site 2. At flood stages there is one wide channel; the island is inundated.

At sites 3 and 4 the 100-year flood elevation is below the top of the bank. Therefore, levees are not a useful alternative and were not studied. Because of the extremely large channel areas at sites 3 and 4, armoring would have only a slight effect on the velocities and elevations. Spur dikes were not examined for site 4 because they would likely deflect flow more towards site 3. However, the effects of 0.3-channel-width spur dikes on the east bank at cross sections H and I were investigated. The effects were apparent for all peak discharges, but were greatest for the 10-year peak discharge. For that discharge, the two spur dikes caused an increase in velocity of 0.8 foot per second at cross section H and decreases of 1.5 feet per second at cross section I and 0.5 foot per second at cross section J. Flood elevations were increased 1 foot at cross sections H and J and 2 feet at cross section I. By deflecting the flow away from site 3 and reducing the velocity at cross sections I and J, these spur dikes could possibly return the channel location to that which existed in 1962 (fig. 6). The comparison of the mean velocities and elevations with and without spur dikes is given in table 3.

At site 5, because the flow of water is being directed towards the opposite bank by the alignment of the upstream channel, little erosion is occurring except around some debris lodged against trees. Spur dikes at site 5 offer no advantage not already present.

Sites 6 and 7 are on the outside of a river bend (fig. 7). At site 6 some erosion is evident, but at site 7 the accumulation of debris is essentially armoring the riverbank (fig. 3). As indicated in table 4, the use of armor at any of these sites causes little change in flood velocities and elevations, except at cross section AA where some increases would occur.

At site 6, spur dikes could offer some protection from erosion, but would deflect flow toward the east bank, which is already subject to overtopping during large floods. The use of spur dikes at site 7 was not investigated because it would deflect the flow more towards site 6 and likely increase erosion there. In addition, the high velocities in the river approach to site 7 would likely make spur dikes short-lived. The velocities are near critical at cross sections AB and AD (tables 1 and 4). The near critical velocities suggest high erosional power.

The effects of a levee was investigated in combination with bank armoring along the east bank of the river extending from cross sections AD to Y and includes sites 5, 6, and 7 (fig. 1). A levee along that bank could offer some protection to the east-side floodplain (fig. 9) from inundation by river floods, but flooding probably would still occur locally from the small tributary streams. The levee could cause velocities to increase by up to 2.8 feet per second and elevations to increase as much as 1 foot (table 4). The increased velocities in this reach could cause erosion to accelerate at places along the west bank if the west bank was not armored.

TABLE 2.--Comparison of mean velocities and elevations for 10-, 50-, and 100-year floods at cross sections near sites 1 and 2, for flow through present channel (a), through an old cutoff channel (b), and with a spur dike (c)
[Elevations are rounded to the nearest foot]

Cross section	10-year flood						50-year flood					
	Mean velocity (feet per second)			Elevation (feet)			Mean velocity (feet per second)			Elevation (feet)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
A	4.7	5.3	4.7	1,102	1,102	1,102	4.1	5.4	4.1	1,103	1,103	1,103
B	3.6	6.4	4.2	1,104	1,105	1,105	3.7	6.9	4.6	1,105	1,105	1,105
C	4.1	(d)	3.8	1,106	(d)	1,106	4.5	(d)	4.1	1,106	(d)	1,107
D	6.0	5.2	6.4	1,111	1,112	1,111	6.2	5.3	6.6	1,112	1,113	1,112
E	5.7	6.0	5.6	1,118	1,117	1,118	6.2	6.4	6.1	1,119	1,118	1,119
F	7.2	7.0	7.3	1,122	1,122	1,122	6.4	6.3	6.4	1,123	1,123	1,123
G	5.4	5.4	5.4	1,128	1,128	1,128	5.9	5.9	5.9	1,129	1,129	1,129

Cross section	100-year flood					
	Mean velocity (feet per second)			Elevation (feet)		
	(a)	(b)	(c)	(a)	(b)	(c)
A	3.9	5.5	3.9	1,103	1,103	1,103
B	3.8	7.0	4.8	1,105	1,105	1,105
C	4.6	(d)	4.2	1,106	(d)	1,107
D	6.3	5.4	6.6	1,112	1,113	1,112
E	6.4	6.6	6.2	1,119	1,119	1,119
F	6.2	6.1	6.2	1,123	1,123	1,123
G	6.0	6.0	6.0	1,129	1,129	1,129

TABLE 3.--Comparison of mean velocities and elevations for 10-, 50-, and 100-year floods at cross sections near sites 3 and 4, for present channel (a) versus a channel with spur dikes (b) on the east bank at sections H and I
[Elevations are rounded to the nearest foot]

Cross section	10-year flood				50-year flood				100-year flood			
	Mean velocity (feet per second)		Elevation (feet)		Mean velocity (feet per second)		Elevation (feet)		Mean velocity (feet per second)		Elevation (feet)	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
G	5.4	5.4	1,128	1,128	5.9	5.9	1,129	1,129	6.0	6.0	1,129	1,129
H	4.1	4.9	1,131	1,132	3.6	4.2	1,132	1,133	3.5	4.0	1,133	1,133
I	4.1	2.6	1,133	1,135	3.7	2.7	1,134	1,135	3.6	2.7	1,134	1,136
J	2.0	1.5	1,136	1,137	2.2	1.6	1,136	1,137	2.2	1.7	1,137	1,138
K	12.4	12.4	1,142	1,142	13.3	13.3	1,143	1,143	13.6	13.6	1,143	1,143
L	4.5	4.5	1,151	1,151	4.6	4.6	1,152	1,152	4.7	4.7	1,152	1,152

TABLE 4.--Comparison of mean velocities and elevations for 10-, 50-, and 100-year floods at cross sections near sites 5, 6, and 7 for the present channel (a), a channel with armoring (b), and levees (c)

[Elevations are rounded to the nearest foot]

Cross section	10-year flood: Mean velocity (feet per second)			10-year flood: Elevation (feet)			50-year flood: Mean velocity (feet per second)			50-year flood: Elevation (feet)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
Y	6.3	6.3	7.8	1,261	1,261	1,262	6.1	6.1	7.8	1,262	1,262	1,263
Z	6.4	6.3	8.4	1,274	1,274	1,274	5.6	5.5	8.4	1,274	1,275	1,275
AA	4.0	5.6	6.5	1,281	1,281	1,281	4.3	5.9	7.0	1,281	1,282	1,282
AB	9.8	9.1	9.7	1,286	1,286	1,286	9.8	9.2	9.7	1,287	1,287	1,287
AC	6.3	6.6	6.7	1,294	1,294	1,294	6.7	7.1	7.4	1,295	1,295	1,295
AD	12.5	12.5	12.5	1,303	1,303	1,303	13.3	13.3	13.3	1,304	1,304	1,304

100-year flood

Cross section	Mean velocity (feet per second)			Elevation (feet)		
	(a)	(b)	(c)	(a)	(b)	(c)
Y	6.1	6.1	8.0	1,262	1,262	1,263
Z	5.6	5.6	8.4	1,274	1,274	1,275
AA	4.4	5.9	7.2	1,281	1,282	1,282
AB	10.0	9.5	9.9	1,287	1,287	1,287
AC	6.9	7.2	7.7	1,295	1,295	1,295
AD	13.5	13.5	13.5	1,304	1,304	1,304

SUMMARY

The effects on flood velocities and elevations of one to four contemplated types of protective measures were investigated at seven sites identified for study by the National Park Service along the lower Stehekin River. The effect on flood velocity and elevation that could be caused by bank armoring was determined by assuming that 10 feet of channel adjacent to the eroding bank would be filled by rock to the top of the bank, and that the armoring would increase hydraulic roughness to some extent. The effect from armored revetment levees was determined by assuming that the levee would be high enough to contain the 100-year flood in the channel and would be used in combination with armored banks. The effect of spur dikes was determined by representing a spur dike as a vertical bridge abutment extending out from one bank or the other at a cross section and computing flow velocity and elevation as though the channel passed through an eccentric bridge opening. The redevelopment of old cutoff channels was investigated by closing the existing open channel and routing the flow through the cutoff channel. Investigations of combinations of alternatives at different sites were beyond the scope of this study.

All of the study sites are important to some local residents, but the floodplain at site 1 is more developed and is probably most important to the greatest number of residents. At site 1, simple armoring was not investigated because the bank is too low for that to be effective for both erosion prevention and flood protection, but any of the other alternative prevention measures except a spur dike should be effective. An armored levee produced little change in velocities or elevation. A spur dike at cross section B would possibly reduce erosion, but it would also increase the local flood elevation. While diversion into the old cutoff channel also increased flood elevations, it is removed some distance from the inhabited area and whatever means were used to block the existing open channel could be set high enough to prevent flooding. At site 2, the high bank precludes a need for levees, and spur dikes would change the flow direction to adversely affect site 1, so neither levees nor spur dikes were investigated. Armoring the banks at this site could possibly protect them against erosion and would only slightly increase flood velocities and elevations. There is no cutoff channel at site 2.

At sites 3 and 4 the high banks preclude the need for levees. Because of the wide channel with large capacity at site 3, spur dikes and armoring could be effective alternatives. Armoring would not greatly increase the flood velocities or elevations, and although spur dikes would, floods would still be contained in the channel. At site 4 spur dikes would deflect the flow more towards site 3. This condition, along with the absence of cutoff channels at sites 3 and 4, limits the viable erosion-prevention measures to armoring as the only practical alternative at site 4. There the flood velocities and elevation would be increased only slightly by armoring.

The stream gradient is steep--about 50 feet per mile--at sites 5, 6, and 7, which causes flow to be rapid at or near critical depth with high velocities. Spur dikes here would likely increase velocities and would be difficult to maintain. Bank armor would produce only small increases in flood velocities and elevations and is a viable measure, but it would not reduce the flood inundation that occurs on the eastern floodplain. At sites 5, 6, and 7 the use of armor and a levee along the east bank to prevent overflow would increase flood velocities and elevations somewhat, but may be a practical option if the armor can withstand the velocities. The selection of the protection measures at the seven sites and the structural design of specific bank-protection measures is beyond the scope of this study.

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