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June 1993

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Waterways Experiment
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Demonstration Erosion Control Project Monitoring Program

Fiscal Year 1992 Report

Volume VII: Appendix F
Model Study of Bendway Weirs as Bank Protection

by Thomas J. Pokrefke
Hydraulics Laboratory

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Waterways Experiment Station
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Final report

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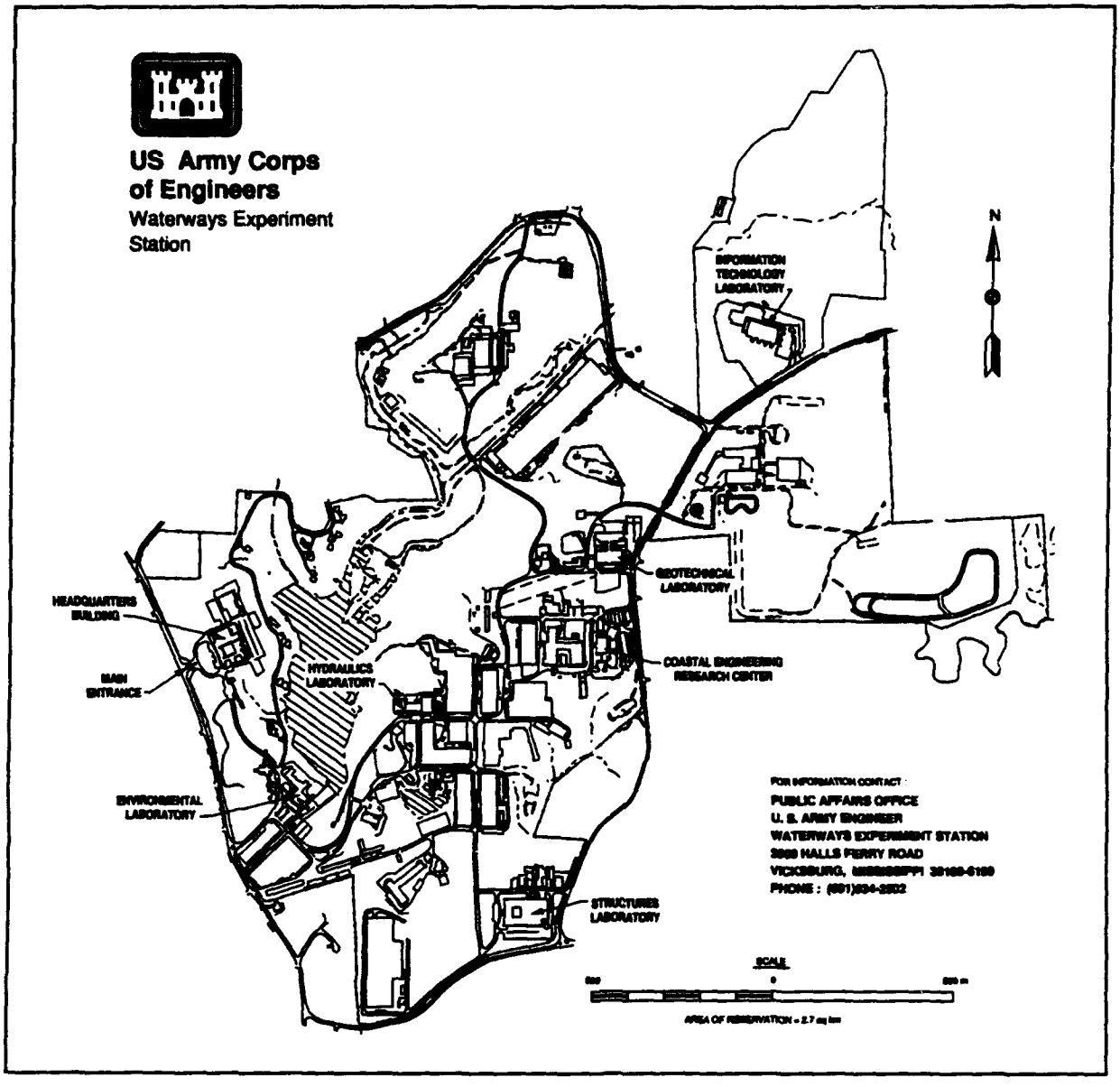

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Appendix F
Model Study of Bendway Weirs as Bank Protection

Introduction

Background

The Demonstration Erosion Control Project (DEC) is concerned with the channel response to stabilization measures within the numerous watersheds in the Yazoo River Basin in northern Mississippi. The Waterways Experiment Station (WES) has been tasked with the monitoring program for the DEC Project which has bank stability as one of the technical area activities. Within the DEC Project the types of bank protection used have become somewhat standard and are the typical type of stream protection widely used throughout the U.S. This includes hard points, longitudinal peaked stone dikes, and typical riprap bank protection. All of these approaches are essentially providing material along the bankline which the stream is incapable of moving during the anticipated flow events.

Purpose of study

Since the bank protection methods used on the DEC Project can, at times, become quite expensive, it was decided to conduct some physical model tests to develop a newer approach which would provide equal or better protection as existing methods at a lower cost to the project. That approach was focused on the use of bendway weirs.

Approach

The bendway weir concept had been developed on a WES movable-bed model study of the Mississippi River conducted for the U.S. Army Corps of Engineers, St. Louis District. Bendway weirs were developed to eliminate shoaling problems in the bends of navigable streams where the natural

point bar deposition on the inside of the bend encroached into the navigation channel and restricted the channel.

Results of those tests indicated that bendway weirs would not only widen the channel in a bend, but would also change the way water and sediment moved through the bend by increasing velocities on the inside (convex side) of the bend and lowering velocities on the outside (concave side) of the bend. Thus the resulting currents were more evenly distributed across the channel. The redistribution of the currents also allowed bed material to accumulate on the outside of the bend in the deep portion of the channel, which added stability to the revetted bank there. Tests also indicated that there may be an improvement in the navigation channel immediately downstream of the reach with bendway weirs. This change appeared to be a result of the redistribution of water and sediment in the bendway and how, with the weirs in place, it approached the downstream reach.

Since in those previous studies the weirs redistributed the movement of water and sediment through the bendways, it was decided to investigate for the DEC Project the use of such weirs to reduce the concentration of higher velocities on the outside of an unprotected bank and possibly accomplish some deposition of material on the outside of the bend. If this could be accomplished, then the potential for bank failure would be reduced. To conduct such a study required development of various physical modeling parameters since the study would address movement of both the bed and bank material. The composition of stream banks is highly variable from one stream to another and even from one location to another on the same stream. Therefore, the study conducted was not a model study of any particular DEC stream, but rather an investigation in a facility where both the bed and banks were composed of sand and were erodible when subjected to flow.

Development of Study Parameters

Prior to conducting any testing, various parameters had to be developed to allow eventual extrapolation of the results to the DEC Project. Since this was not a study of any particular DEC stream, it was felt that the study had to be similar to the DEC streams; therefore, WES and the U.S. Army Engineer District, Vicksburg (LMK) conducted a limited review of pertinent data from some of the DEC streams and set some parameters for this investigation. The DEC data indicated that several streams have a width-to-depth ratio of about 10; therefore, that value was used for the study. The planforms for Fannagusha, Harland, and Black Creeks were analyzed for radius of curvature and degree of bend. This analysis indicated that as in any natural stream there is a significant spread in the radii and degree of bend curvature with no one value for each being any more dominant than another value. However, radius of curvatures equal

to two and one-half times the top bank width and degree of curvature of 110 degrees occurred often enough to use in this study.

The initial channel planform and uniform channel cross-section installed in the model is shown on Plate 1. The elevations shown on the cross-section are relative to the study only and were established for ease of measurement during testing. The top bank was assumed to be at elevation 0 ft, and since the constructed channel depth was 1.5 ft, the channel invert was set at el -15 ft. This was a factor of 10 and eliminated the need to present all of the study data with decimal points. All horizontal measurements presented in this report are actual measurements without a factor of 10 adjustment. The bed and bank material used in the study was a fine grained sand with an almost uniform size distribution. The sand has a specific gravity of 2.65 and a size distribution with a D_{15} of 0.17 mm, a D_{50} of 0.23 mm, and a D_{85} of 0.30 mm. This particular facility has been used for movable-bed modeling of specific river reaches and was useful for this study since it has sufficient pump capacity and the study material (sand) is similar to what may be present in parts of the DEC Project.

Prior to testing, a stage hydrograph was developed to use on the study. Since this was not a study of a particular reach, no prototype data were available; therefore, a symmetrical stage hydrograph was developed (Plate 2), and the discharge was adjusted in the study reach until reasonable sand movement was obtained for all stages tested. The criteria used for evaluation of the sand movement was as the stage increased the movement of bed and bank material also increased. The amount of time each flow lasted was dependent on obtaining a reasonable amount of bank recession in a reasonable amount of time. The specific hydrographic information relative to the stages maintained is presented in Table 1.

Table 1
Hydrographic Information Used

Stage Elevation, ft	Percent of Bankfull Stage	Time, min	Percent of Time Equal to or Less than Stage
4.0	26.7	200	27.0
5.0	33.3	180	51.4
7.5	50.0	160	73.0
10.0	66.7	140	91.9
12.5	83.3	60	100.0

Note: Total running time of hydrograph 740 minutes or 12 hours and 20 minutes.

Since each reproduction of the hydrograph took two work days to complete, the model was maintained in a no-flow, flooded condition overnight near the stage elevation that operation began on the second day. This kept the hydrostatic pressure in the banklines from causing the banks to slough off overnight. It was obvious during the adjustment period that without following this procedure, the benches developed on the banklines during the individual stages tested would be eliminated and affect the study results.

Tests and Results

Base test

Description. Since this study was general in nature, there was no typical verification of a prototype situation. The procedures discussed above were used to achieve reasonable sediment movement, and the channel configuration at the end of that test was considered as an establishment of base conditions. The initial condition for the base test was the channel configuration shown in Plate 1. The test was conducted using the stepped hydrograph (Plate 2) and during the tests, six-tenth depth spot (point) velocities were taken half-way down the right bank slope, at the toe of the right and left banks, and near the centerline of the channel. These velocities were taken on the beginning and ending 5-ft stages and on the 12.5-ft crest.

Results. The results of the base test are presented on Plates 3 and 4. The ending channel configuration (Plate 3) indicated that very little right bank recession took place in the upstream portion of the study, but about Range 17 some recession was initiated until its maximum recession of about 2 ft occurred along the right bank around Range 31. There was essentially no change in the channel invert elevation with the ending survey indicating elevations of -14 and -16-ft. The only exception was where the material scoured from the right bank upstream of Range 31 and tended to deposit along the slope toe downstream of Range 31. In this area there was a slight tendency to develop a crossing and have the thalweg of the channel move from the right to the left. The point velocities (Plate 4) indicated that the velocities were initially fairly uniform and that they remained that way through the crest of the hydrograph to the ending 5-ft stage. Although there were some variations in individual quantities during the test, no significant velocity changes were observed.

Plan 1

Description. For Plan 1 the bendway weir configuration shown in Figure 1 was installed into the study reach. Several of the parameters for the plan were based on the top bank width of the study channel. This was done to make the study results applicable to the DEC Project. The plan

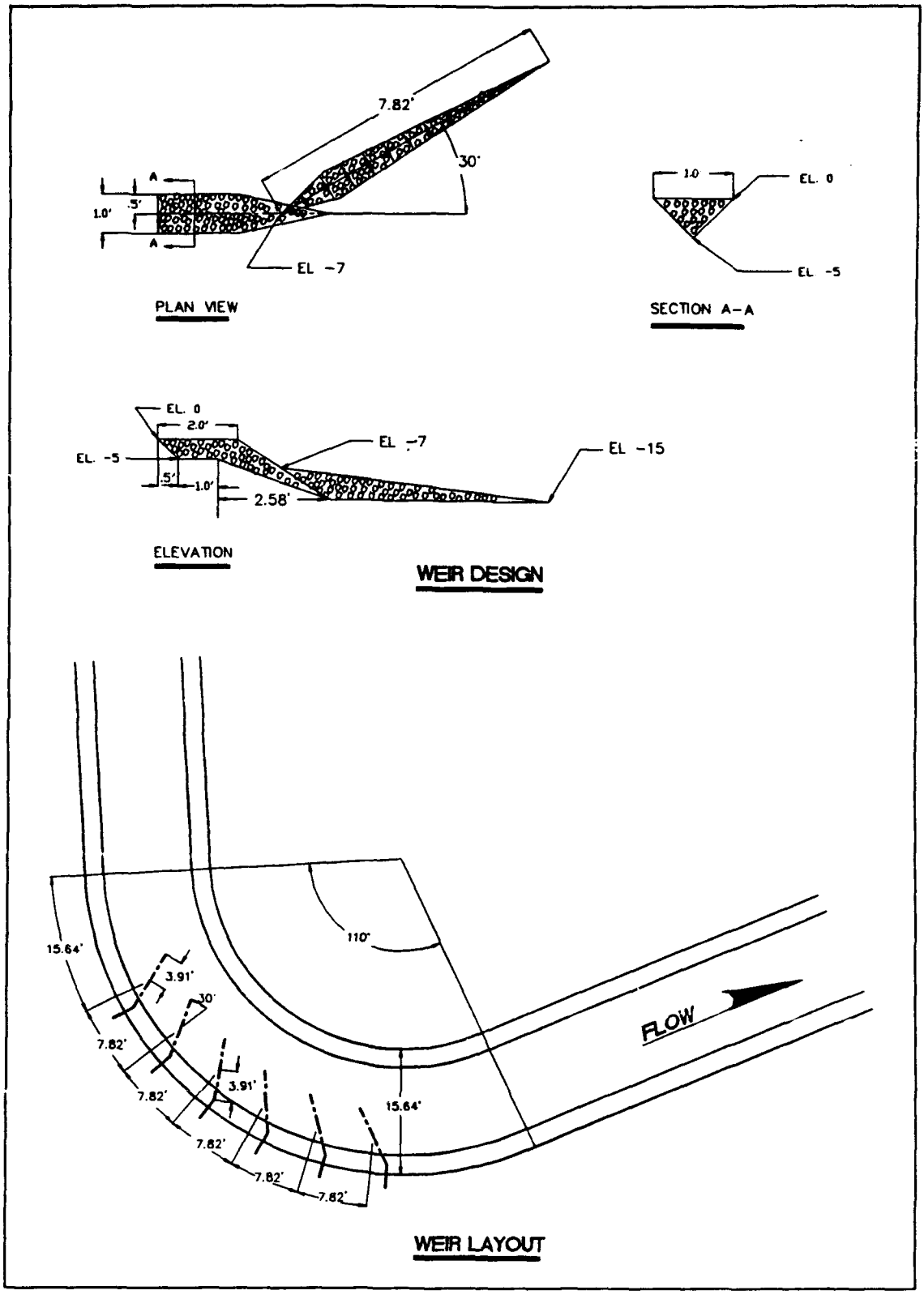


Figure 1. Test 1 weir layout and design

was comprised of six weirs spaced 7.82 ft apart (spacing equal to one-half top bank width) with the most upstream weir located 15.64 ft downstream of the point of curvature of the bend (equal to the top bank width). The weirs were angled upstream 30 degrees to a line perpendicular to the bankline at the weir root. The weir root or key into the bank was similar to the method that LMK presently uses on hard points. The elevation of the weir where it intersected the bank was -7 ft (approximately mid-bank elevation) with the stream end of the weir at the channel invert of el. -15 ft. This produced a weir section which was particularly thin on the stream end; however, it was felt that such a design may provide a degree of armoring as scour occurred and reduced the attack on the stream end of the weir. The stone used to construct the weirs had a D_{50} of about three-eighths inch. Prior to installation of the weirs and initiation of testing, the channel bed was remolded to the initial bed configuration (Plate 1).

Results. The bed configuration at the end of the hydrograph (Plate 2) is presented on Plate 5. The results indicated that there was essentially no bank recession to Range 25. Downstream of that point the bank recession was reduced, with the maximum of 1.5 ft occurring at Range 33. Compared to the base test the bank recession at Range 31 was reduced from 2 ft to about 6 inches. Scour as great as 5 ft occurred at the stream end of the weirs; however, the left bank of the bendway also scoured somewhat indicating that the weir length was probably too great. This conclusion was supported by the point velocities taken during the test (Plate 6). The weirs were effective in redirecting the currents from the outside toward the inside of the bend; however, the magnitude of those velocities was increased to over 2 fps in some instances and toward the inside bank.

As a first test on the use of bendway weirs to reduce bankline recession, it was felt that this test was very successful. It was obvious that some additional design and enhancement was necessary and possible, but the amount of testing time available was limited. From Test 1 it was apparent that the length of weirs could be reduced, a greater stone section was required on the stream end of the weir since a small amount of end scour significantly reduced the length of the weir as the stone was launched, and additional weirs would help the bank recession in the straight reach downstream of the bend. Although not as apparent as some of the above observations, it seemed that the spacing could be increased without an adverse effect on the weir field performance. However, it was decided that the spacing used would be maintained and no additional weirs would be added to the field. This was based on conducting as many tests as possible changing only weir length and height. It was hoped that additional tests could be conducted at a later date to investigate some of the other variables.

Plan 2

Description. Plan 2 was the same as Plan 1 except the weir length was reduced to 5.86 ft (three-eighths of top bank width) and the weir height

was modified (Figure 2). The intersection of the weir with the bankline remained at el -7 ft with a 1.5 ft transition to el -11 ft. From that point the weir sloped to a stream end elevation of -13 ft with the stone on its natural angle of repose to the channel invert of el -15 ft. Prior to installation of the weirs and initiation of testing, the channel bed was remolded to the initial bed configuration (Plate 1).

Results. Results of Plan 2 tests are presented on Plates 7 and 8. Test results indicated that essentially no bankline recession occurred upstream of Range 25. The maximum bank recession of about 1.5 ft occurred around Range 33 with about 1.0 ft of recession at Range 31. The maximum scour at the stream end of the weirs was to el -18 ft, and the recession of the inside of the bend was significantly reduced when compared to Plan 1 test results. Due to the increase in the weir section at the bankline there was a tendency to increase the deposition of material at the toe of the bank slope within the weir field. Point velocities (Plate 8) indicated that the weirs continued to have a significant effect on the currents by redirecting the higher velocities from the outside of the bend and toward the inside of the bend. However this tendency was somewhat reduced with a decrease in the maximum velocity due to the decrease in weir length when compared to Plan 1 (compare Plates 6 and 8).

Plan 3

Tests with Plans 1 and 2 were concerned with the application of the bendway weir concept on bankline recession; however, no data were available on the effectiveness of those type structures compared to existing bank protection measures used by LMK on the DEC Project. Therefore, it was decided that a test of the LMK hard point design presently used would be evaluated in the study to provide such a comparison. This also provided some information relative to bendway weir design in that one could consider the hard point design would be equivalent to a bendway weir of zero length.

Description. A portion of the plans and specification drawings used by LMK for hard points is presented in Figure 3. This was the particular design used in the study to compare the effectiveness of bendway weirs verses a typical hard point design. The hard point field consisted of six structures in the same locations in the bendway where the weirs had been tested. Prior to construction and testing of the hard points, the channel was remolded to the initial configuration (Plate 1).

Results. Results of the test of hard points (Test 3) are presented on Plates 9 and 10. Results based on the channel configuration (Plate 9) indicated that the hard points were effective in virtually eliminating bank recession in the bendway within the hard point field. Through the bendway there was slight scour near the stream end of each hard point, but that scour did not appear to cause any bankline instability. Once the flow exited the bendway however, the effects of the hard points did not extend

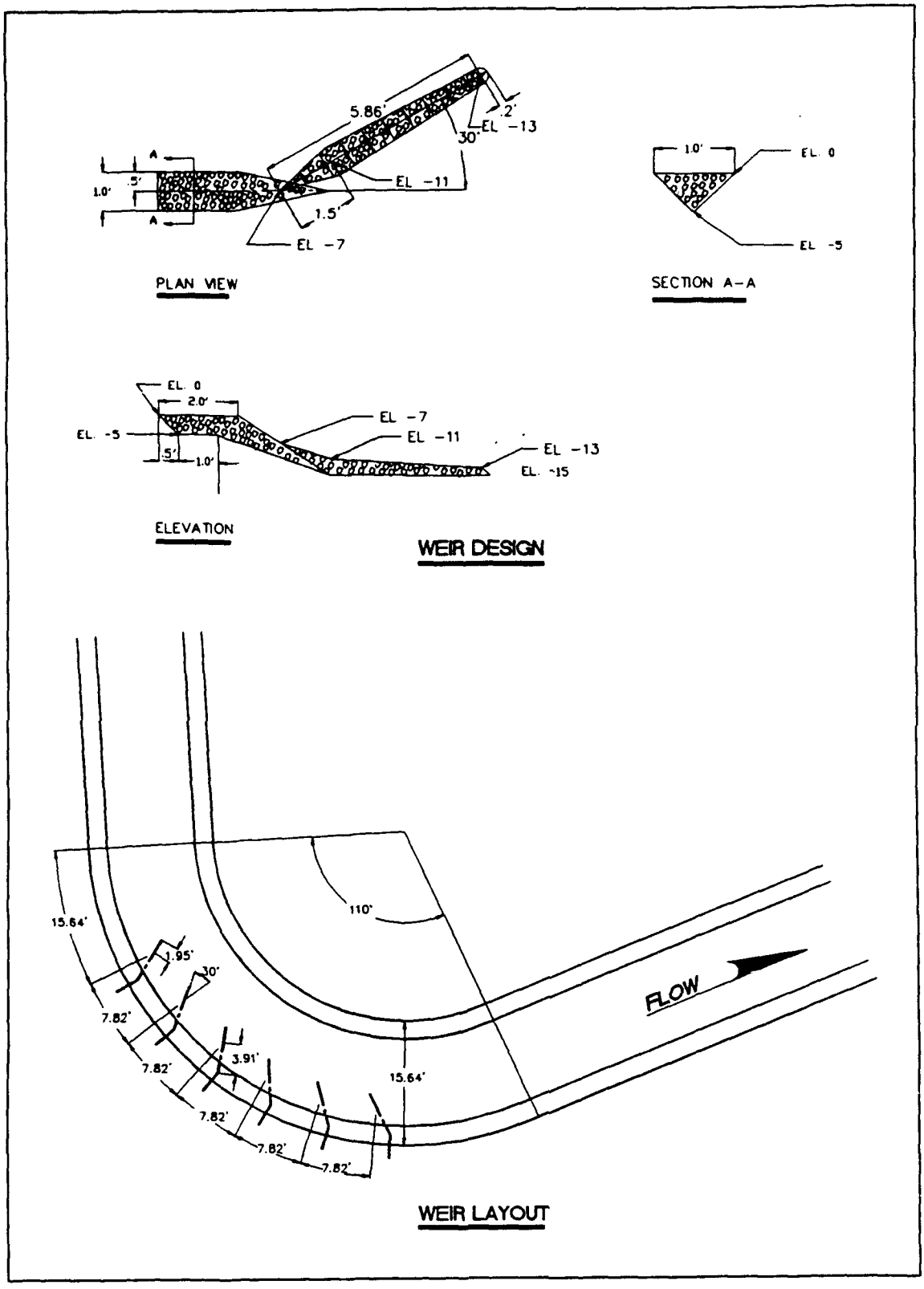
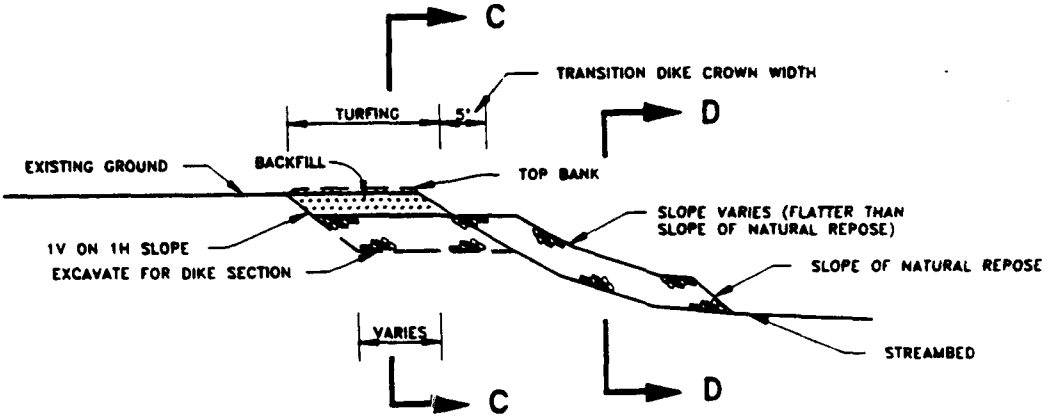
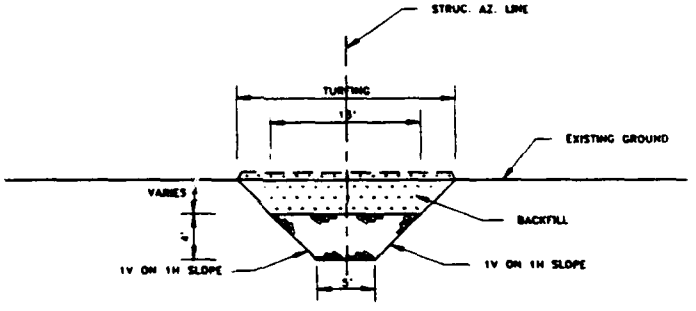


Figure 2. Test 2 weir layout and design



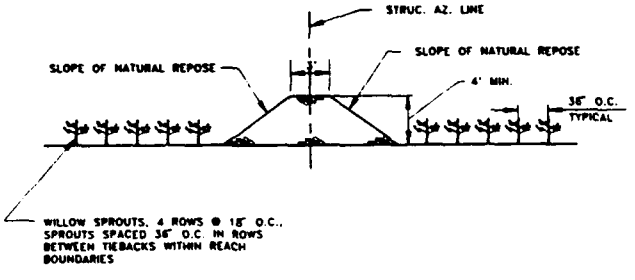
PROFILE

WHERE DIKE TIES INTO HIGH TOP BANK AND EXISTING BANK SLOPE IS FLATTER THAN SLOPE OF NATURAL REPOSE OF STONE.



SECTION C - C

WHERE TIEBACK TIES INTO LOW TOP BANK, TOP OF STONE WILL BE FLUSH WITH EXISTING GROUND AND NO BACKFILL WILL BE REQUIRED.



SECTION D - D

Figure 3. Plan 3, hard point design

downstream, which had been the case with the bendway weirs. To Range 27 there was no bank recession, but from that point downstream the bank recession rate increased. The maximum recession of about 2.2 ft occurred near Range 32 and the recession at Range 31 was about 1.5 ft. Point velocities taken during the test (Plate 10) indicated that the hard points had a greater effect on the low flows (5 ft stages) than on the high flow (12.5 ft stage) when compared to the base test. The effect of the hard points on the currents was not as dramatic as what had occurred with the bendway weirs. In the case of the hard points, the maximum velocities as the bend was exited tended to be on the right descending bank, while with the bendway weirs the maximum velocities were near the center of the channel (compare Plate 10 with Plates 6 and 8).

Discussion of Results and Conclusions

Comparison of test results

Since this was not a study of a specific reach within the DEC Project, the results must be analyzed relative to the different plans tested to provide the benefits of the various alternatives. Due to the size of the study channel and the need to present data over the entire study reach, the previously presented channel configuration maps did not provide a detailed picture of the results. To appreciate the magnitude of the bank recession and plan effectiveness, cross-sections were plotted for three study ranges (Ranges 19, 24, and 31). Those ranges were selected because Range 19 was approximately midway through the bend, Range 24 was near the end of the bendway, and Range 31 was the maximum point of bankline recession during the base tests. The cross-sections (looking downstream) from the right top bank (el 0 ft) to about the centerline of the channel are presented on Plate 11.

Results indicated that at Range 19 the top bank receded approximately 1.6 ft during the base test with little or no recession on Tests 1 through 3. At Range 24 results indicated top bank recession of approximately 1.6 ft during the base test and progressively less recession as the bendway protection structures were lengthened. That is, the LMK hard points (Test 3) had more erosion than Test 2 weirs, which had more erosion than Test 1 weirs. At Range 31 the maximum recession of 2.0 ft occurred during the base test with the continued trend of progressively less recession as the bendway protection structures were lengthened. The minimum recession with Plan 1 was about 0.8 ft; therefore, there was significant improvement in the scour reduction downstream of the bendway as a result of bendway weirs. It should be noted that Range 31 is located about 30 ft downstream of the most downstream weir; therefore, the effects of the weirs in redistributing the flow through and out of the bendway extended almost two channel widths (31.28 ft) downstream.

Limitation of study results

The study conducted was not on a specific stream within the DEC Project, although it is anticipated that the results obtained will be applied to appropriate DEC streams as a test of the bendway weir concept for bank protection. That application will be closely monitored and evaluated as the channel or channels adjust to the bendway weirs. Modeling or studying bank recession phenomenon is qualitative at best since the performance of any improvement plan in the prototype will be dependent on the composition of the stream banks relative to the specific soil types present in the banks. This study was conducted with banks of fine-grained sand which had little or no cohesiveness. In that sense the results should be somewhat conservative since most natural stream banks have some cohesiveness. All testing was conducted with one repetition of the discharge and stage hydrograph; therefore, the channel configuration and bank recession may be somewhat different if several repetitions of the hydrograph would have been conducted. Since no sediment was introduced to the study reach during the hydrograph, stable long term conditions were not evaluated in the study.

This study was a limited study conducted for the DEC Project to evaluate the use of bendway weirs for bankline protection. Due to limited funding and time constraints, only a few options were studied. However, enough was learned from this study to make a reasonable application for a "field demonstration" of the bendway weir concept provided that all involved parties realize the limited nature of the study.

Summary of results and conclusions

The following results and conclusions were developed during the study:

a. Within the bendway Plans 1, 2, and 3 provided essentially equal protection of the bank from recession.

b. Downstream of the bend Plan 1 provided more bank protection than Plan 2, which provided more bank protection than Plan 3 (LMK hard points).

c. The bendway weirs in Plan 1 were too long and caused scour on the inside of the bendway.

d. The bendway weirs in Plans 1 and 2 were effective in realigning the flow and moving the higher velocity currents from the bankline and toward the center of the channel.

e. The longest bendway weir length (Plan 1) produced the maximum amount of stream end scour. Environmentally this additional scour could be attractive relative to habitat diversity.

f. Plan 3 (LMK hard points) provided protection in the hard point field, but that protection did not extend downstream of the field.

g. Although not tested, study results suggest that the addition of bendway weirs downstream of the field tested would provide additional resistance to bank recession in the straight reach downstream of the bend.

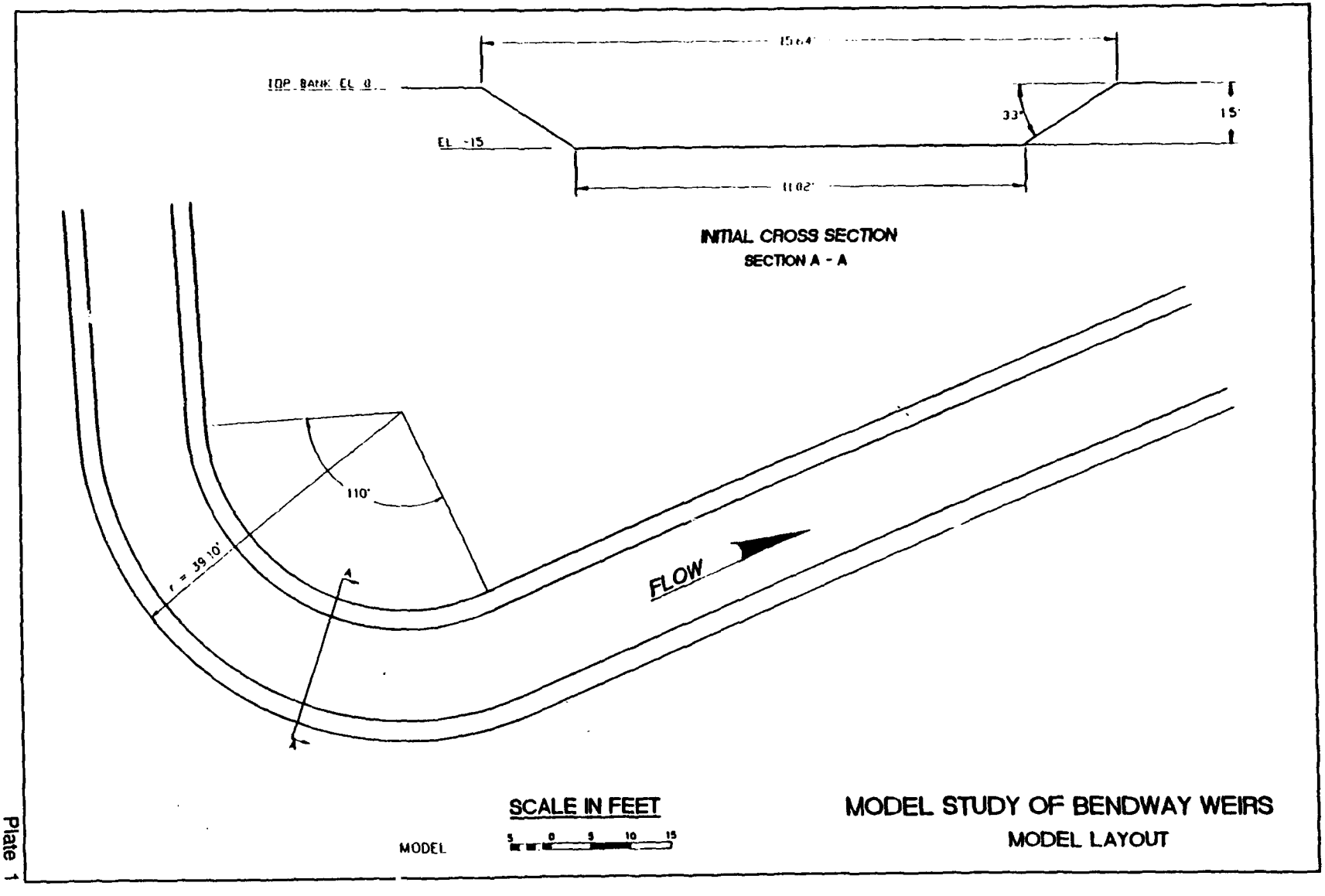
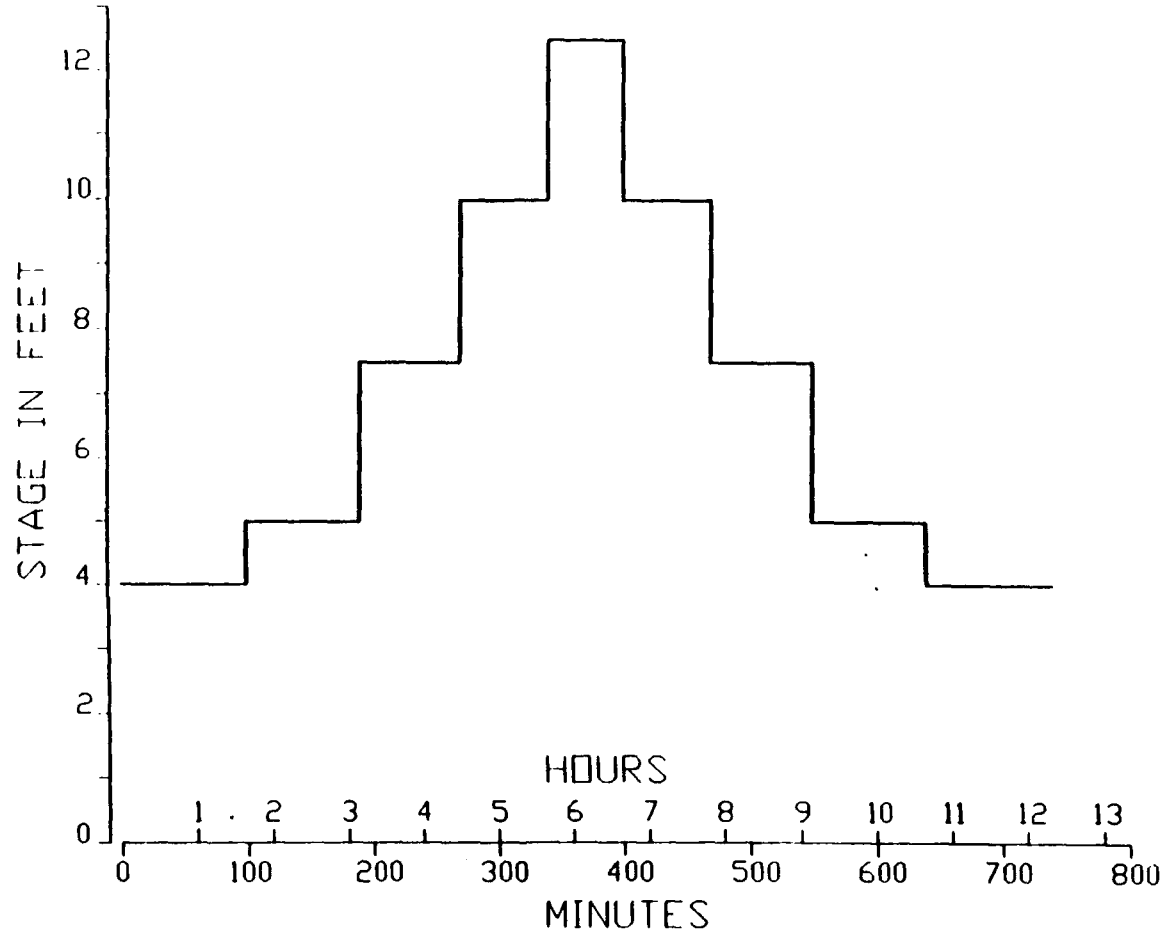

TOP BANK EL 0
EL -15
33°
15'
INITIAL CROSS SECTION
SECTION A - A
110°
r = 39.10'
A
A
FLOW
SCALE IN FEET
MODEL
5 0 5 10 15
MODEL STUDY OF BENDWAY WEIRS
MODEL LAYOUT

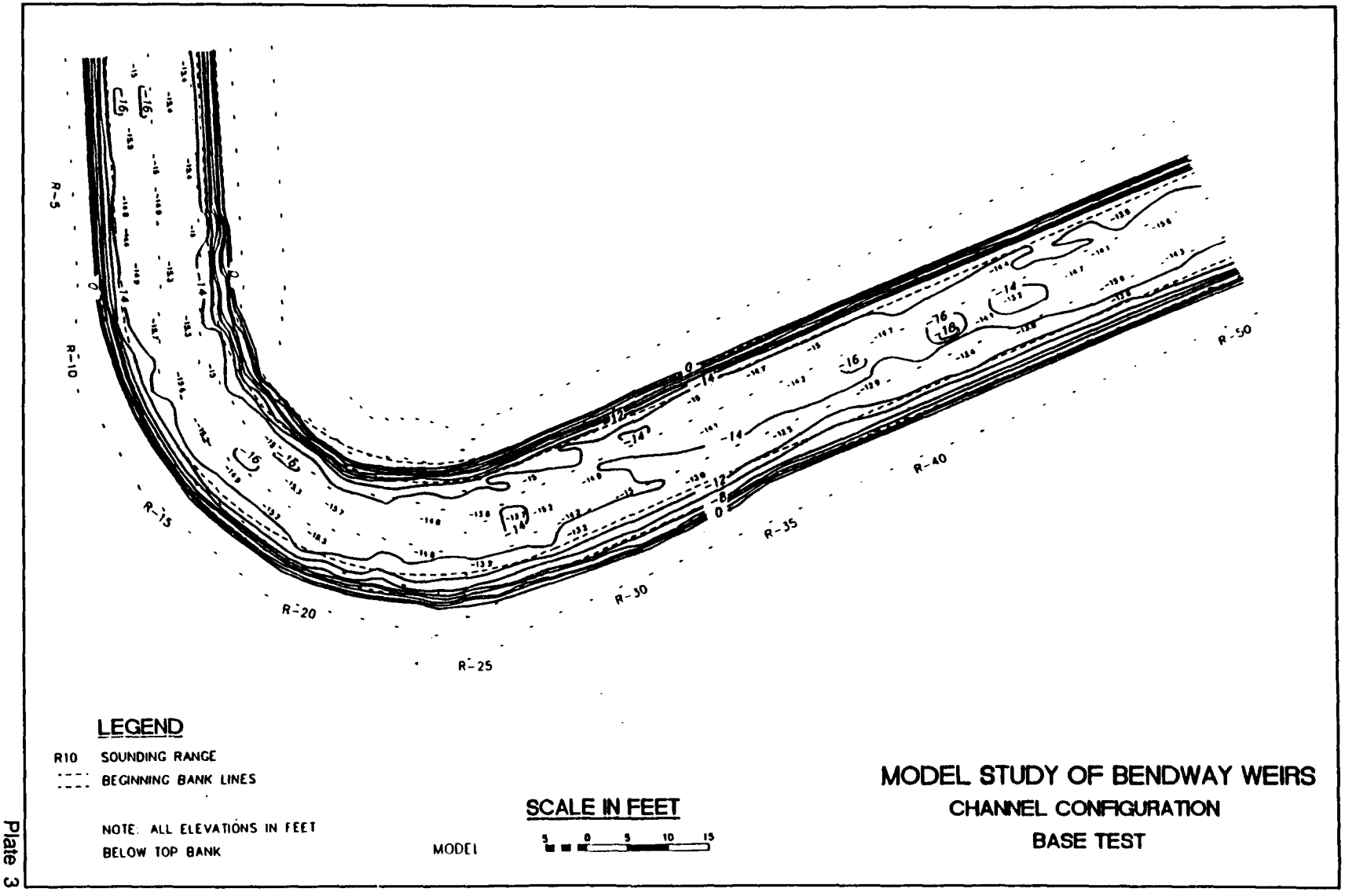
Plate 1

Plate 2



MODEL STUDY OF BENDWAY WEIRS

TESTING HYDROGRAPH



LEGEND

R10 SOUNDING RANGE

BEGINNING BANK LINES

NOTE: ALL ELEVATIONS IN FEET
BELOW TOP BANK

MODEL

SCALE IN FEET

5 0 5 10 15

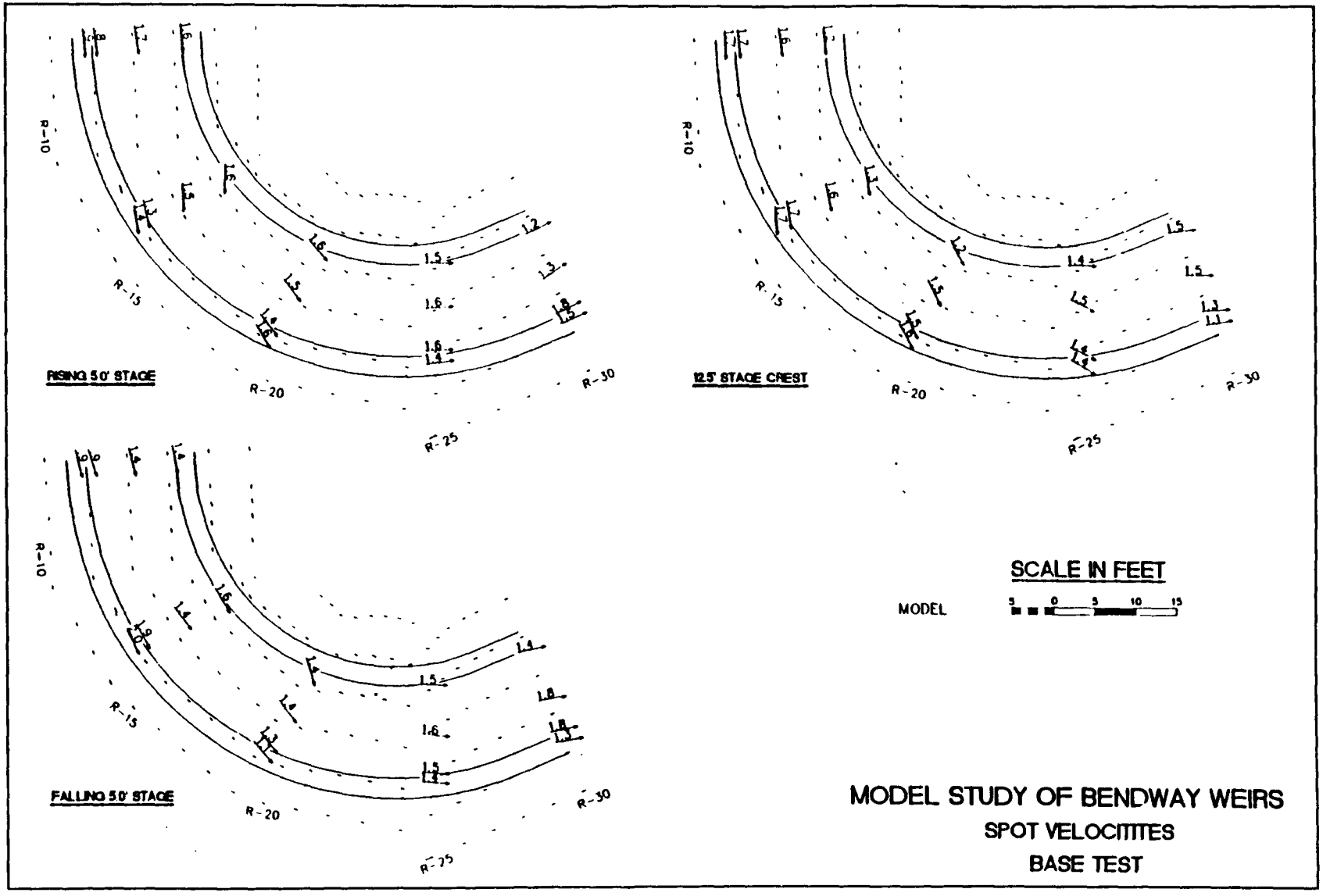
MODEL STUDY OF BENDWAY WEIRS

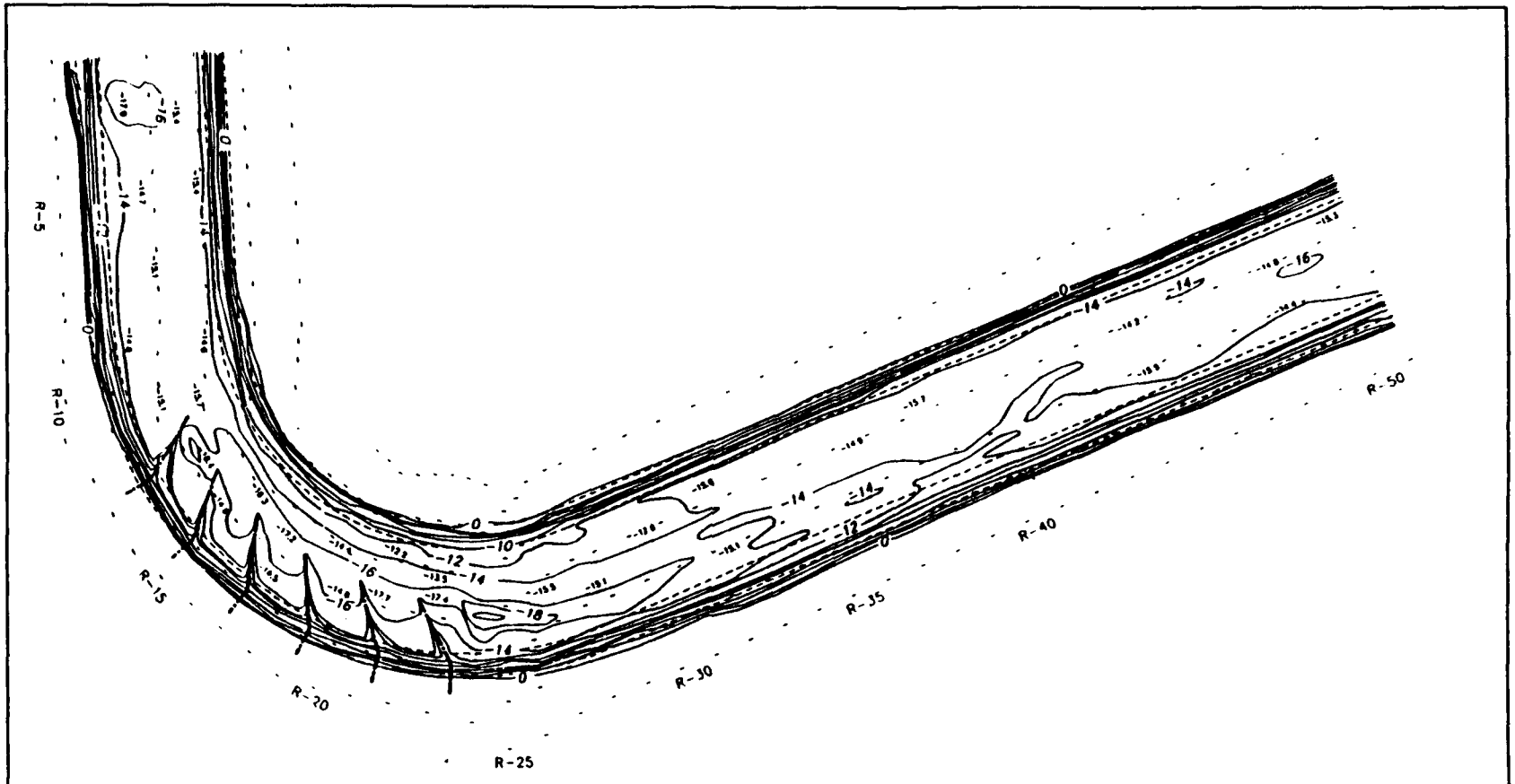
CHANNEL CONFIGURATION

BASE TEST

Plate 3

Plate 4


RISING 5.0' STAGE
12.5' STAGE CREST
FALLING 5.0' STAGE
R-10
R-15
R-20
R-25
R-30
SCALE IN FEET
MODEL
5 0 5 10 15
MODEL STUDY OF BENDWAY WEIRS
SPOT VELOCITITES
BASE TEST



LEGEND

R-10 SOUNDING RANGE

BEGINNING BANK LINES

WEIR

NOTE: ALL ELEVATIONS IN FEET BELOW TOP BANK

SCALE IN FEET

MODEL 5 0 5 10 15

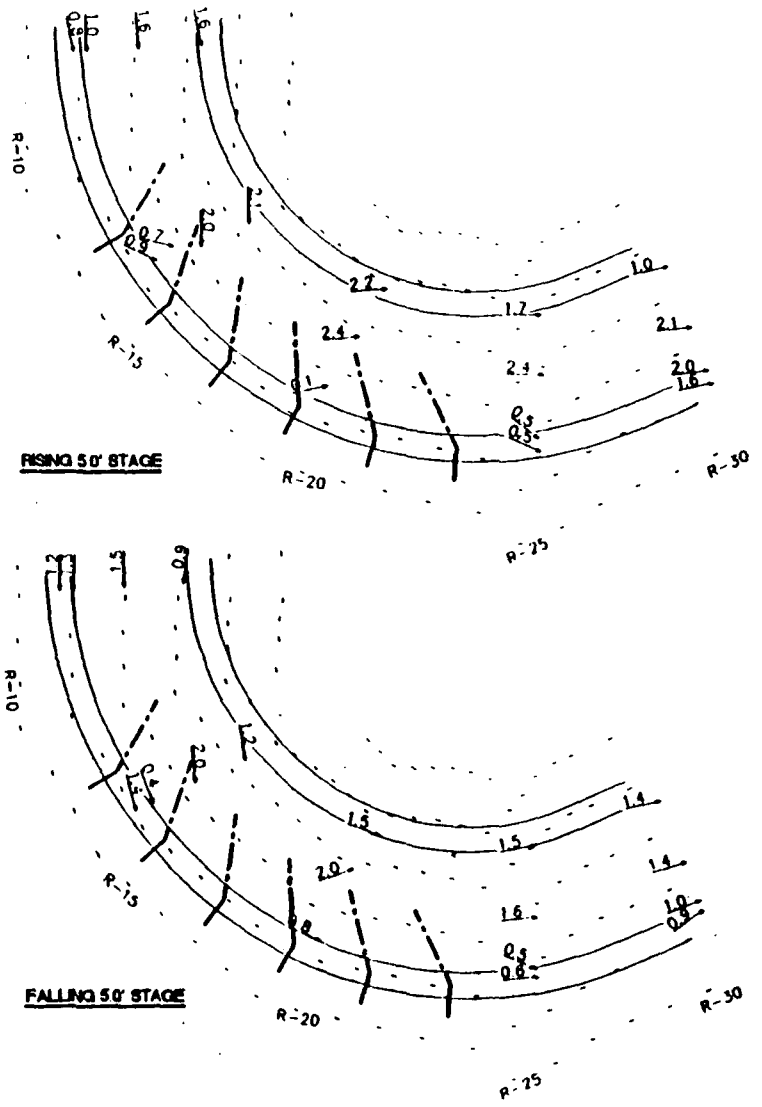
MODEL STUDY OF BENDWAY WEIRS

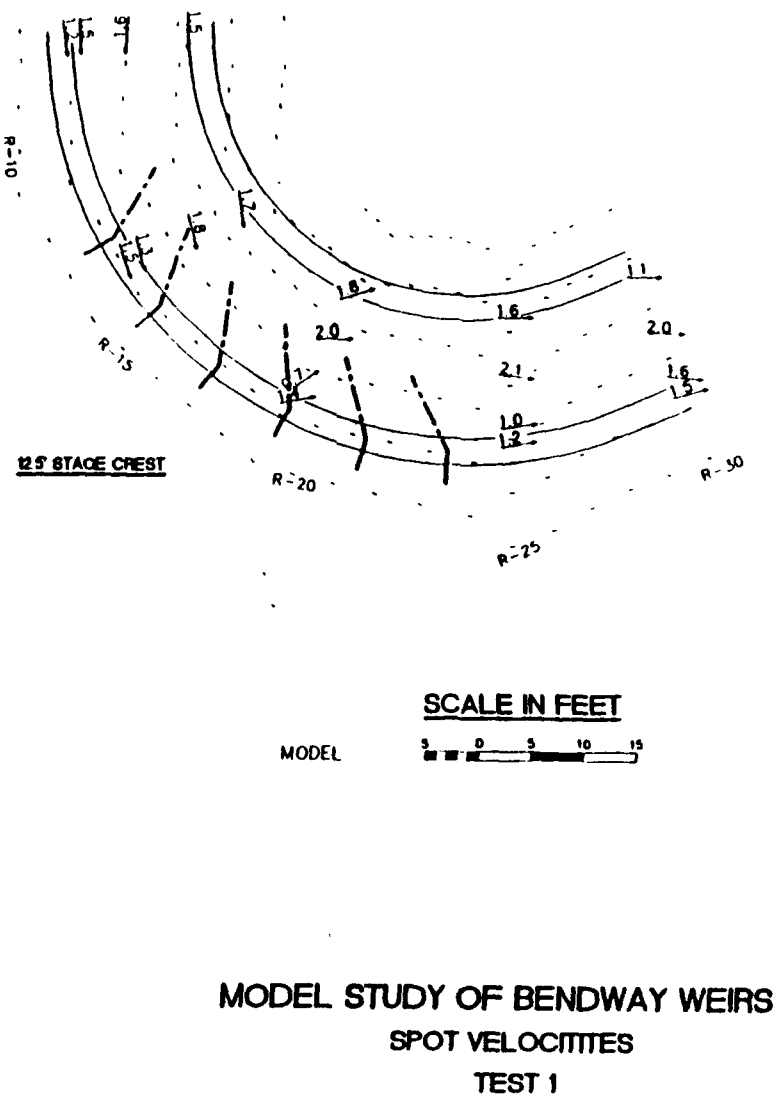
CHANNEL CONFIGURATION

TEST 1

Plate 5

Plate 6





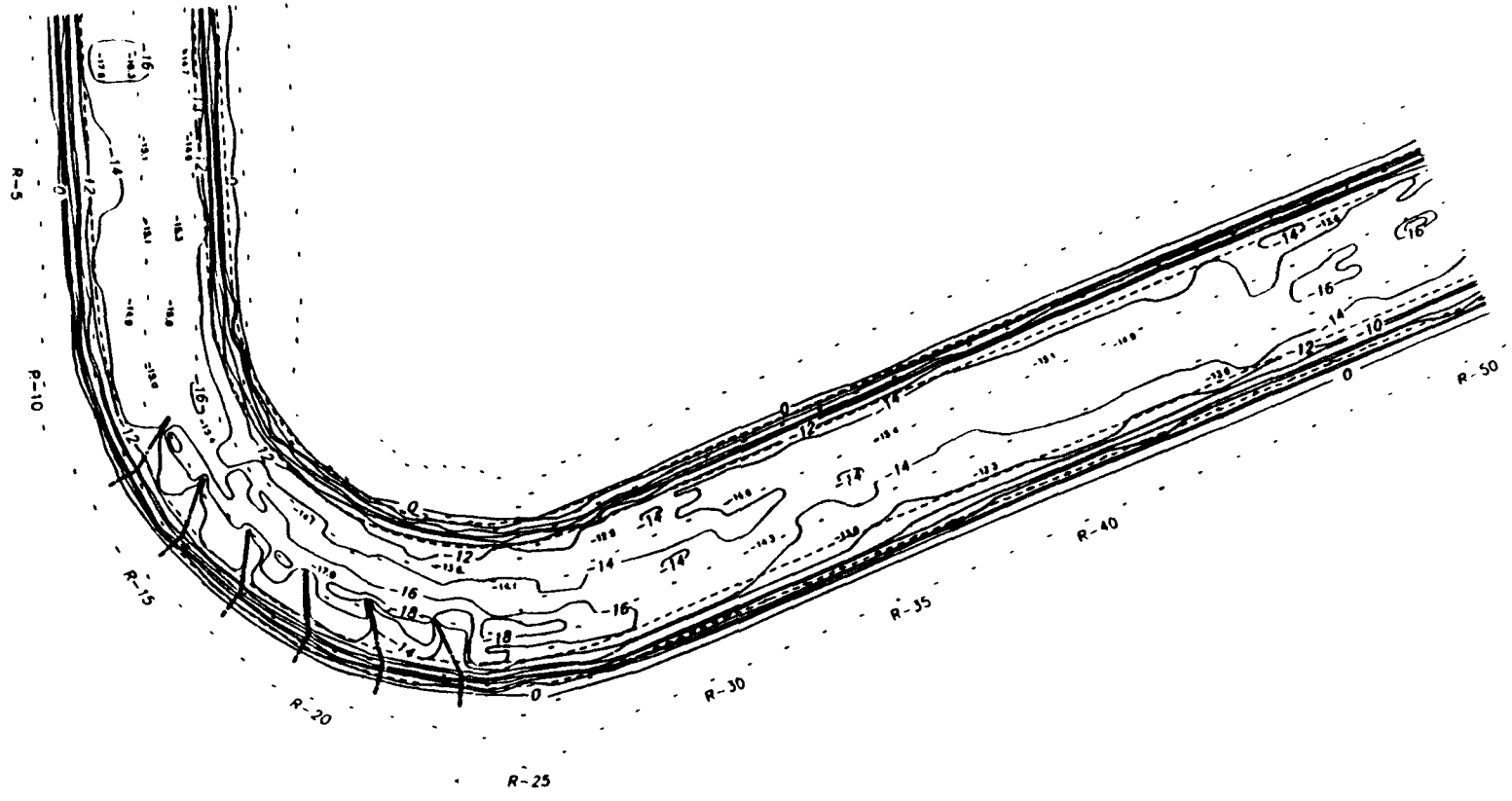
SCALE IN FEET

MODEL 5 0 5 10 15

MODEL STUDY OF BENDWAY WEIRS

SPOT VELOCITTES

TEST 1



LEGEND

R-10 SOUNDING RANGE

BEGINNING BANK LINES

WEIR

NOTE: ALL ELEVATIONS IN FEET BELOW TOP BANK

MODEL

SCALE IN FEET

5 0 5 10 15

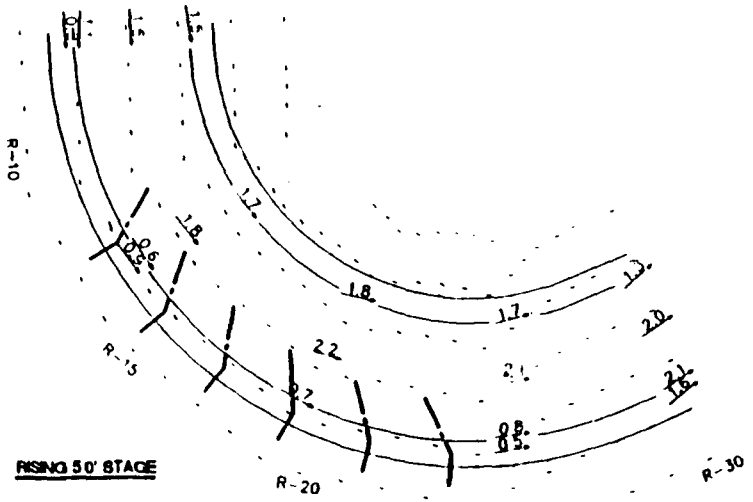
MODEL STUDY OF BENDWAY WEIRS

CHANNEL CONFIGURATION

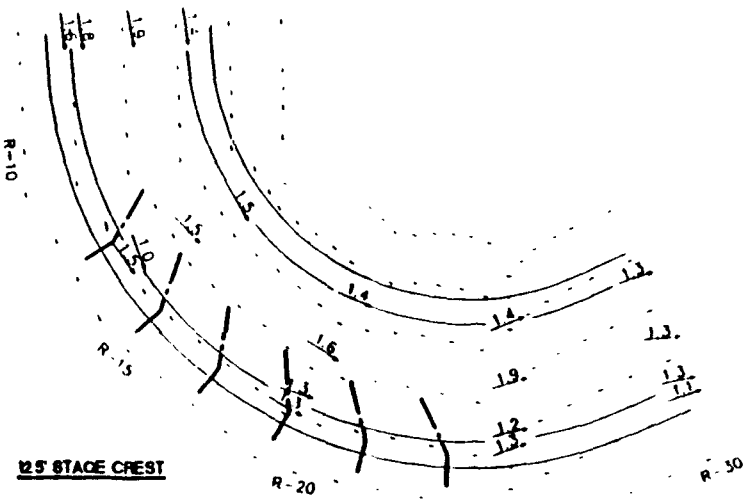
TEST 2

Plate 7

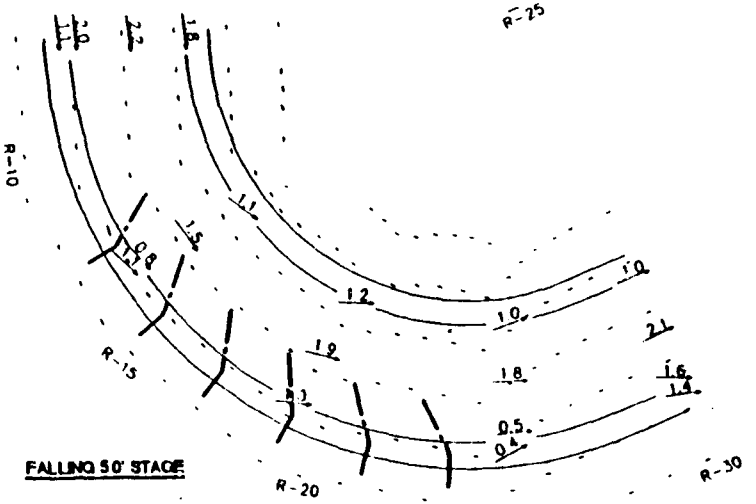
Plate 8



RISING 5.0' STAGE



12.5' STAGE CREST



FALLING 5.0' STAGE

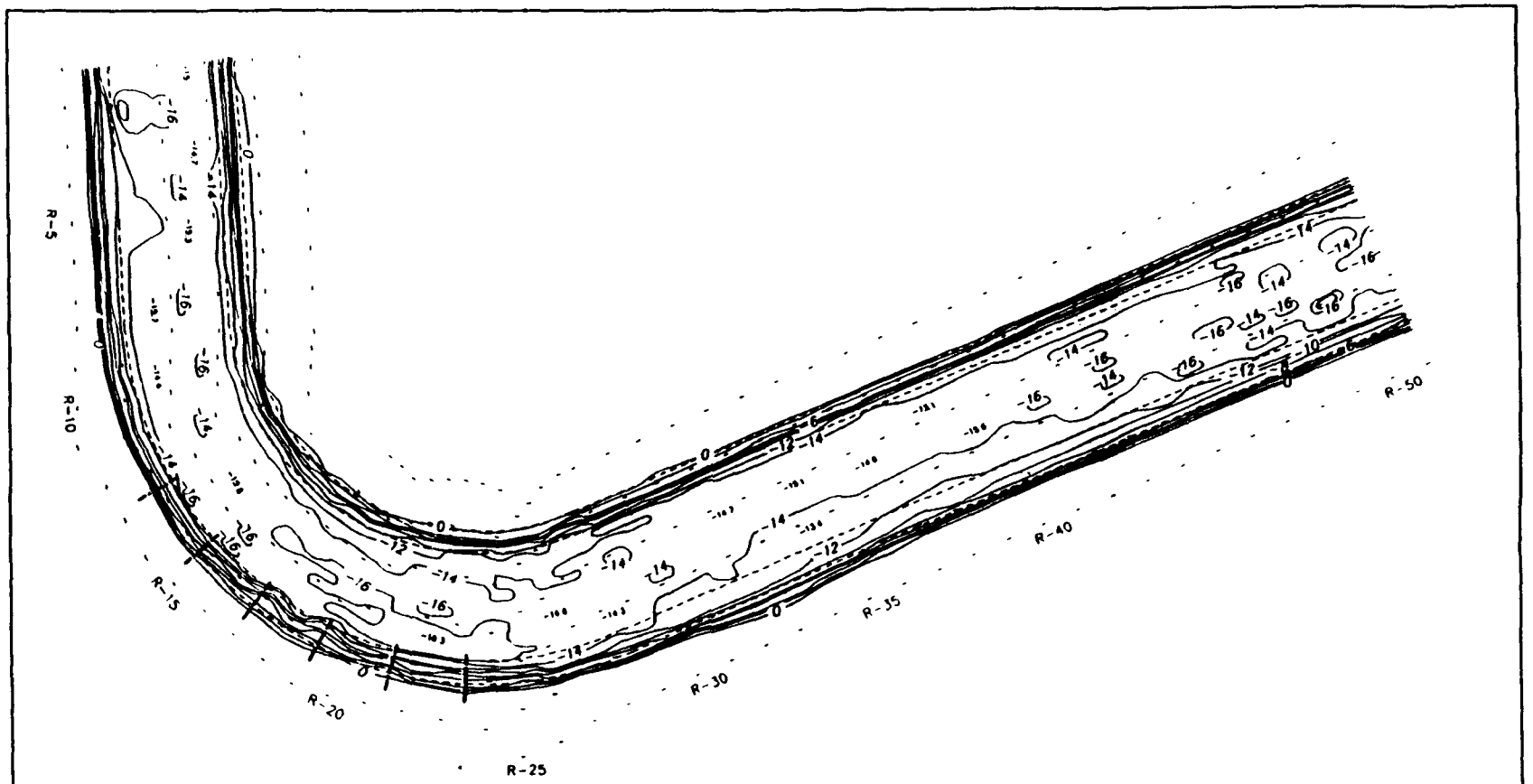
SCALE IN FEET

MODEL 5 0 5 10 15

MODEL STUDY OF BENDWAY WEIRS

SPOT VELOCITITES

TEST 2



LEGEND

R-10 SOUNDING RANGE

BEGINNING BANK LINES

WEIR

NOTE. ALL ELEVATIONS IN FEET BELOW TOP BANK

MODEL

SCALE IN FEET

5 0 5 10 15

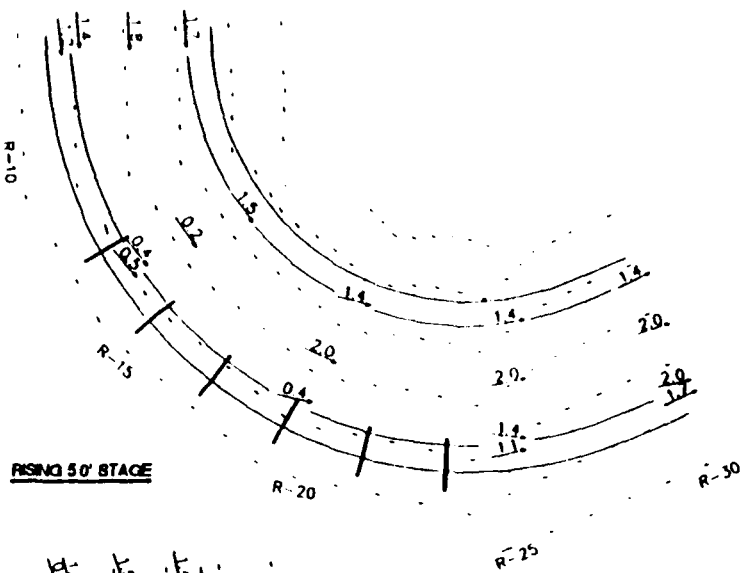
MODEL STUDY OF BENDWAY WEIRS

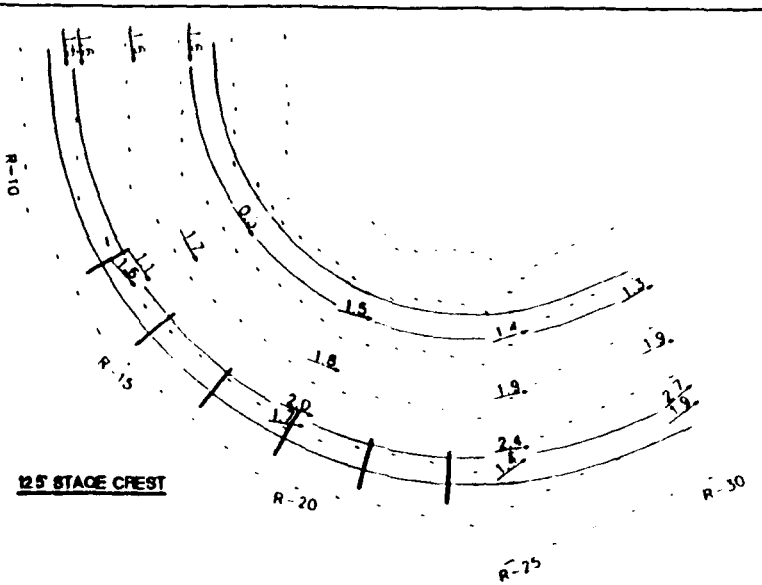
CHANNEL CONFIGURATION

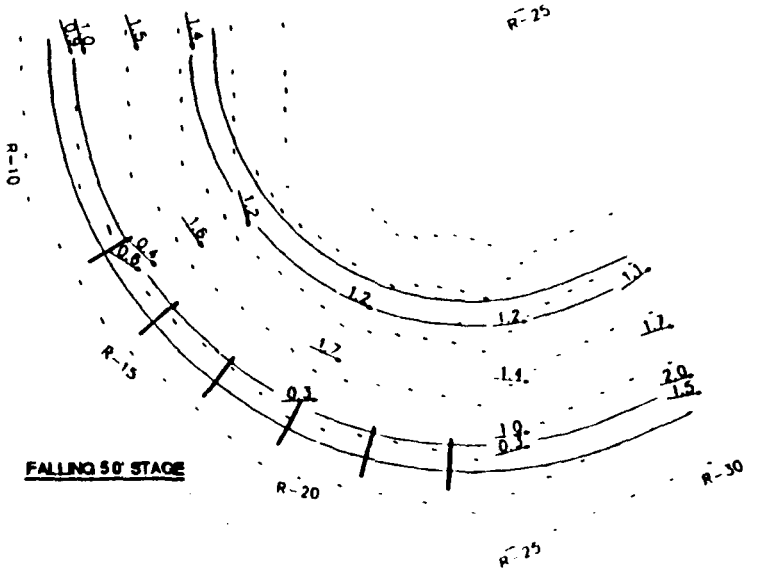
TEST 3

Plate 9

Plate 10

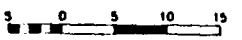






SCALE IN FEET

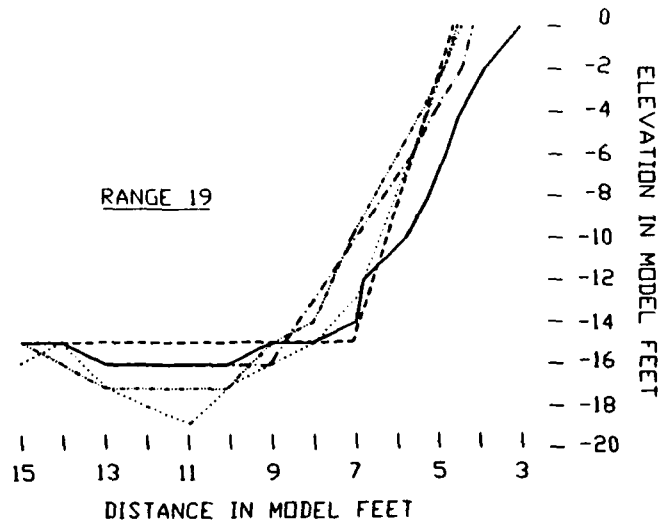
MODEL

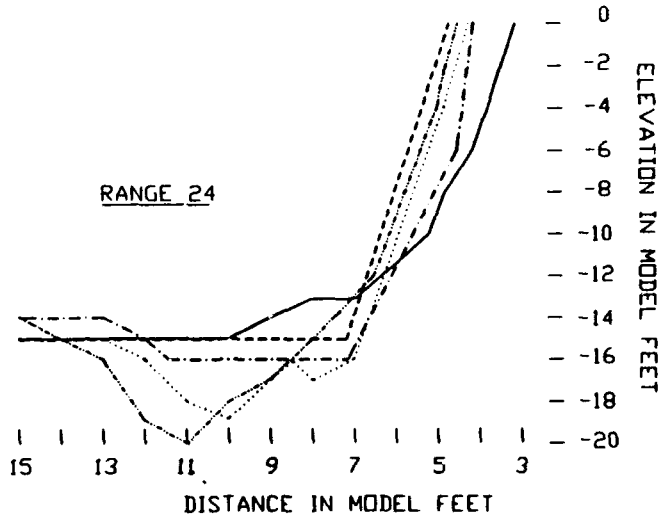


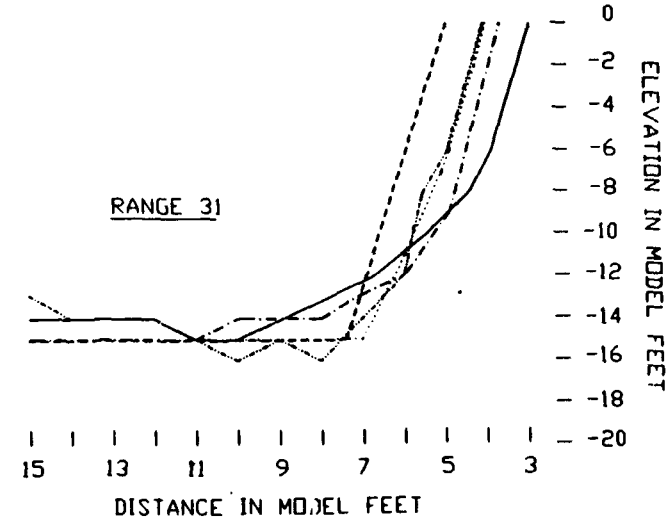
MODEL STUDY OF BENDWAY WEIRS

SPOT VELOCITITES

TEST 3







LEGEND

- INITIAL CONDITIONS
- BASE
- LMK HARD POINTS
- TEST 1
- TEST 2

MODEL STUDY OF BENDWAY WEIRS

CHANNEL CROSS SECTIONS

Plate 11

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

The purpose of monitoring the Demonstration Erosion Control (DEC) Project is to evaluate and document watershed response to the implemented DEC Project. Documentation of watershed responses to DEC Project features will allow the participating agencies a unique opportunity to determine the effectiveness of existing design guidance for erosion and flood control in small watersheds. The monitoring program includes 11 technical areas: stream gaging, data collection and data management, hydraulic performance of structures, channel response, hydrology, upland watersheds, reservoir sedimentation, environmental aspects, bank stability, design tools, and technology transfer.

This appendix discusses the bendway weir concept, which had been developed previously for application on the Mississippi River to eliminate shoaling problems for navigation in bendways, caused by the natural point bar deposition on the inside of bends encroaching into the navigation channel. From those previous investigations on navigation problems, it was learned that bendway weirs would not only widen the channel in a bend, but would also change the way water and sediment move through the bend. The bendway weirs

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increased velocities on the inside (convex side) of the bend and lowered velocities on the outside (concave side) of the bend. The purpose of this model study was to evaluate the potential of bendway weirs as a cost-effective alternative for stabilizing alluvial stream bends of the type seen in the DEC Project. The study was limited in scope, with only a few options being tested. However, enough was learned from this study to make a reasonable application for a "field demonstration" of the bendway weir concept in a DEC watershed.