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# Design and Development of Bendway Weirs for the Dogtooth Bend Reach, Mississippi River

## Hydraulic Model Investigation

by *David L. Derrick, Thomas J. Pokrefke, Jr., Marden B. Boyd  
James P. Crutchfield, Raymond R. Henderson*

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Prepared for U.S. Army Engineer District, St. Louis

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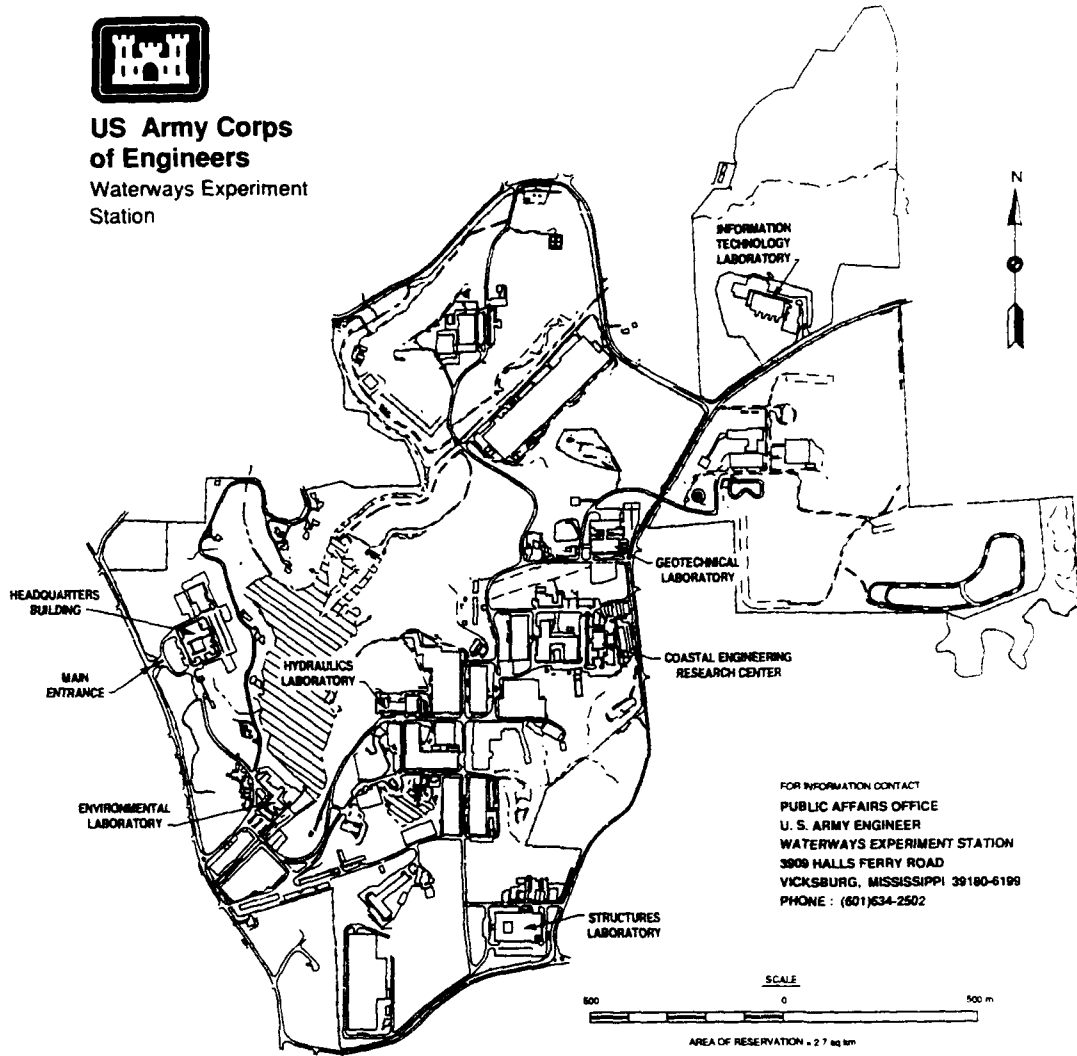
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# Preface

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The model investigation reported herein was conducted for the U.S. Army Engineer District, St. Louis (CELMS), in the Inland Waterways Research Facility of the Hydraulics Laboratory at the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. The Inland Waterways Research Facility is coordinated by the U.S. Army Engineer Division, Lower Mississippi Valley (CELMV), and jointly funded by CELMS and the U.S. Army Engineer Districts of Memphis, Vicksburg, and New Orleans to study troublesome reaches on the middle and lower Mississippi River.

This investigation was conducted during the period January 1984-January 1992 under the general supervision of Messrs. H. B. Simmons and F. A. Herrmann, Directors of the Hydraulics Laboratory, and R. A. Sager, Assistant Director of the Hydraulics Laboratory, and under the direct supervision of J. E. Glover and M. B. Boyd, Chiefs of the Waterways Division, Hydraulics Laboratory. The engineer in immediate charge of the investigation was Mr. D. L. Derrick, who was assisted by Messrs. J. P. Crutchfield and R. R. Henderson, all of the River Regulation Section, River Engineering Branch, Waterways Division. This report was prepared by Messrs. Derrick, Crutchfield, Boyd, Henderson, and Thomas J. Pokrefke, Chief, River Engineering Branch.

During the course of the model study, coordination was maintained between CELMS, CELMV, and WES through monthly progress reports, highly detailed monthly memorandums for record, telephone conversations, and interim test results consisting of maps, slides, photographs, and videotapes. Messrs. Robert D. Davinroy and Claude (Norman) Strauser of CELMS made frequent visits to WES to observe model tests, discuss test results, and coordinate the testing program. Visits to observe model tests and discuss test results were also made by Messrs. Charlie Elliott, Steve Ellis, and Max Lamb of CELMV. Messrs. Derrick, Crutchfield, and Henderson visited the prototype several times to observe river behavior, examine existing river training structures, and gather needed prototype data.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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# Conversion Factors, Non-SI to SI Units of Measurement

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Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	25.4	millimeters
miles (U.S. statute)	1.609344	kilometers
pounds (mass)	0.4535924	kilograms

# 1 Introduction

---

This report presents the results of a movable-bed model investigation concerned with the development of plans for the improvement of the Dogtooth Bend reach of the Mississippi River. Plans tested were proposed by the U.S. Army Engineer District, St. Louis, in collaboration with representatives of the U.S. Army Engineer Waterways Experiment Station (WES). The plans were designed to develop a stable navigation channel through the reach, specifically, to widen the navigation channel and improve high water flow patterns through Price's Landing Bend and the upper portion of Dogtooth Bend, and improve the navigation channel in the crossings immediately downstream of these bends. The Dogtooth Bend reach of the river was selected for this model study due to the multitude of acute problems within the reach. Also, two of the bends within the reach are geometrically similar to a number of other bends on the middle and lower Mississippi River. It is estimated that 16 bends on the open river portion of the middle Mississippi River and 65 to 80 on the lower Mississippi River at times experience inadequate navigation channel widths. Results from this model study will be analyzed and used in correcting problems in several of these bendways.

## Nomenclature and Definitions

Nomenclature and definitions used throughout this report are as follows. The terms *left bank* and *right bank* are referenced to downstream (i.e., left descending bank and right descending bank). The *channel* is the area enclosed within (deeper than) the zero contours. The *navigation channel* is the section of the river deeper than el -10<sup>1</sup>, and the *deepwater channel* is that part of the channel at el -30 and below. When features (lengths, heights, angles, etc.) of a series of dikes, weirs, or other river training structures are listed, the order of progression is always *upstream to downstream*. When river training structures are numbered, the order of progression is also always *upstream to downstream*. The term *normal* refers to an angle of 90 deg, i.e., *normal to the bank* is the same as *perpendicular to the bank*. *Model stability* or *bed stability* or *stable* is when the bed of the model displays no significant changes between two

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<sup>1</sup> Elevations (el) cited herein are in feet referenced to the Low-Water Reference Plane (LWRP).

successive runs. *Remolding the model* entails sculpting the bed of the model to the same elevations and contours as either a prototype survey or a previous model run. The *apex of a bend* is defined as the area close to the midpoint of the bend. At Price's Landing Bend this will encompass miles 30.6 to 29.8, and at Dogtooth Bend, miles 23.8 to 23.0. The phrase "*The model was returned to prototype specifications*" means that all river training structures from previous plans were removed and all structures remaining in the model meet prototype specifications. The *initial bed configuration* used for each plan will always be specified at or near the end of the plan description and is defined as the shape of the bed at the beginning of the test.

## History and Description of the Prototype

The Dogtooth Bend reach (Figure 1) of the middle Mississippi River extends from mile 39.6<sup>1</sup> (Thebes Gap) to mile 20.2 (Thompson Landing). In geologic time, the channel through Thebes Gap has been relatively stable as it is entrenched in solid rock. However, the remainder of the reach has meandered across the entire floodplain as shown by the ancient river courses indicated by the different cross-hatching patterns on the Mississippi River Meander Belt Map (Figure 2).

The study reach has undergone considerable channel stabilization work. Bank revetment using hand-placed cobblestones was initiated in the 1920's. Modern bank revetment incorporating 400-lb maximum weight<sup>2</sup> Graded Stone C placed upon a graded bank by dragline now covers approximately 20 miles of bank line within the study reach.

Dike construction has also had a long history with the first dikes consisting of screens floated by whiskey kegs. The idea was to slow the velocity of the water so that sediment would be deposited. The life of this type of dike was short, typically one year or less. Next, several different timber pile dike designs were employed; the earliest version used a single row of timbers with a wire screen attached to the upstream face. The most successful of the pile dike designs consisted of rows of pile clumps (a clump usually contained three timber piles driven close together and bound with wire rope) connected with horizontal stringers. Lumber screens were added to this design to encourage sediment deposition. Since the mid-1960's, Graded Stone A with a maximum 5,000-lb weight limit has been used exclusively for both dike construction and repair. Many of the old timber pile dikes have been repaired or completely filled in with this size rock.

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<sup>1</sup> River miles above mile zero, which is located at the confluence of the Ohio and Mississippi Rivers (near Cairo, IL).

<sup>2</sup> A table of factors for converting non-SI units of measurement to SI units is presented on page viii.

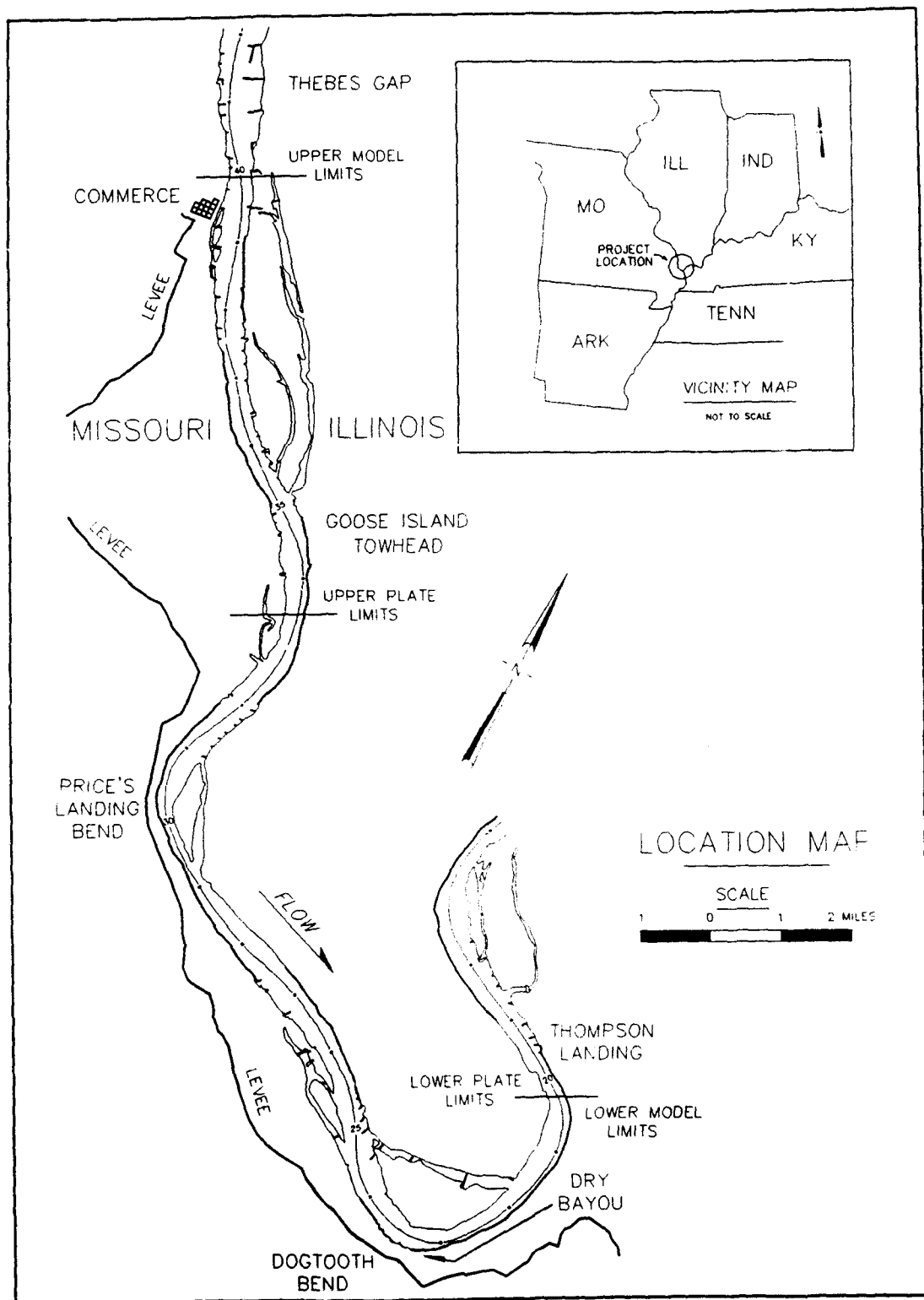


Figure 1. Dogtooth Bend Reach



Figure 2. Mississippi River Meander Belt Map

At the start of the model study the prototype contained 73 dikes, 8 under-water sills, and approximately 20 miles of bank revetment. The sills were installed in Price's Landing Bend in 1964 and 1965 to stabilize the toe of the existing bank revetment. An as-yet undetermined number of dikes and bend-way weirs will be designed and installed in the river to complete the Mississippi River Master Plan scheduled for completion in 2010. Some existing dikes on the outer bank of Dogtooth Bend will be removed.

Even with an abundance of river training structures in this reach, regular maintenance dredging is still required, mainly on the inside of the bends at the point bar and in the channel crossings immediately downstream of a bend. Figures provided by the St. Louis District show that for the reach of the middle Mississippi River between St. Louis, MO, and Cairo, IL, dredging costs in the bendways alone average \$4 to \$6 million annually, with an additional \$5 to \$6 million spent on dredging the crossings.

The Dogtooth Bend reach (Plate 1) is a sinuous section of river with numerous distinct bends separated by crossings of various lengths. Starting at the upstream end of the model at Thebes Gap (mile 39.6), the river is relatively straight for 3 miles with the navigation channel along the right descending bank. The navigation channel crosses from right to left and enters a gentle bend that curves toward the right. The river then is straight for 1 mile in which the channel crosses from left to right before entering Price's Landing Bend. This bendway curves to the left with the navigation channel along the right bank. Price's Landing Bend is composed of at least three smaller bends of various radii. The entire bend is 80 deg (miles 31.2 to 29.5) with an averaged radius of 7,900 ft. The navigation channel is deep but narrow in places. Below the bend the river is straight for approximately 2 miles (miles 29.5 to 27.5) with a poor (and at times nonexistent) right-to-left navigation channel crossing. The river then enters a large-radius right-hand bend. A 1-mile straight reach with a left-to-right crossing transpires before the river enters Dogtooth Bend (miles 24.7 to 22.8). This is a left-hand bend of 110 deg and a 5,900-ft average radius with a narrow, deep navigation channel located near the right (outer) bank. The river curves to the left downstream of the bend with a very narrow navigation channel along the right bank. The model terminates at mile 20.2 (Thompson Landing). Dogtooth Bend actually can be broken down into a pair of bends separated by a short straight stretch. In this report the upper section of the bend and the short straight section (miles 24.7 to 20.2) are referred to as Dogtooth Bend and Crossing. The lower section of Dogtooth Bend is outside (downstream of) the model limits.

## **Descriptions of Prototype Problems**

In this study three specific problem areas were targeted: inadequate navigation channel widths through two bends, adverse high-water flow patterns through these bends, and a narrow or nonexistent navigation channel in the crossings immediately downstream of the bends. These problems are discussed in the following paragraphs.



### **Constricted navigation channel through a bend**

At Price's Landing and Dogtooth Bends the point bar has encroached into the navigation channel. The narrowest section of the navigation channel is usually near the apex of the bend. This narrowed channel leads to the following problems: groundings of towboats on the point bar, inadequate navigation channel widths, delays to navigating towboats, and higher velocities, which cause accelerated deterioration of bendway bank protection structures and adversely impact navigation and safety.

From 1985 to 1988 an average of 20 bendway groundings were reported each year in the reach of river from St. Louis, MO, to Cairo, IL. Most involved barges running aground on the bendway point bars. These accidents endangered the safety of the towboat crews, threatened the integrity of the navigation channel, and halted or delayed traffic through the bendway until all grounded barges were freed.

The inadequate width of the navigation channel forces tows to flank (a series of skilled stopping and turning maneuvers) while navigating the bend at low and medium stages. Flanking delays the maneuvering tow and any other traffic waiting for the flanking tow to clear the bend. The St. Louis District<sup>1</sup> estimated that delays in bendways due to a constricted navigation channel on the middle Mississippi River between St. Louis, MO, and Cairo, IL, cost the navigation industry between \$13 and \$26 million annually, depending on river conditions. Between 81 and 96 bendways on the middle and lower Mississippi River at times experience inadequate navigation channel widths.

The higher velocities associated with a narrow navigation channel result in greater forces acting upon the bank protection structures. Repercussions of this include higher maintenance costs, and in some cases, a shorter life for the structure than initially anticipated. Also, higher velocities combined with the narrowed channel increase the risks associated with navigating through the bend.

### **Detrimental high-water flow patterns**

Currents concentrating on the outside bank of a bend have caused serious problems for both barge traffic and bank stabilization and protection structures. Higher velocities coupled with currents concentrating on the outside bank of the bend make navigation difficult and dangerous. In extreme cases these flows can threaten the integrity and stability of the bank and bendway itself. During a period of high water in 1983 the bank line and levee at Dry Bayou (mile 23.3, at the apex of Dogtooth Bend) failed. The resulting torrent formed a large, deep scour hole (commonly referred to as a blue hole) on the landward

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<sup>1</sup> Personal Communication, 1984, from Robert D. Davinroy, St. Louis District, to David L. Derrick, WES.

side of the levee and flowed over farmland for approximately 5 miles before re-entering the river. Damage to levees, bank protection structures, and farmland was significant. Left unchecked, the river could form a cutoff along this path, which would be catastrophic.

### **Inadequate crossings**

The crossings immediately downstream of Price's Landing and Dogtooth Bends both exhibit insufficient navigation channel depth and width, which seriously impede navigation and require frequent dredging. In the crossing downstream of Price's Landing Bend the traditional design solution of employing conventional dikes to further constrict and deepen the channel would be difficult to implement as the width of the river in this section is already roughly equal to the minimum contraction width. The minimum contraction width for the section of river in this study is set at 1,500 ft. No structures may be built that confine the river to a narrower width than this.

## **Environmental Considerations**

Many of the bendway point bars encroaching on the navigation channel of the river are inhabited by the least tern, a sea bird of the genus *Sterna*, a federally protected endangered species. A traditionally designed emergent dike system built across the secondary channel that separates the point bar from the mainland would allow natural predators (coyotes and feral dogs) easy access to the nests and eggs of the least tern. These dikes would also allow easier access for humans with recreational vehicles, who also threaten the least terns, their nests, and their habitat. According to the St. Louis District, these considerations played a major role in the ultimate design consideration for the development of river training structures for this study reach.

## **Purpose of the Model Study**

Several plans were proposed by the St. Louis District for the improvement and stabilization of the navigation channel in this reach. Due to the complex nature of the processes that shape alluvial rivers and the intricate three-dimensional flow through a bend, a three-dimensional analytical evaluation of the effects of the proposed plans would have been extremely difficult, expensive, and inconclusive. Accordingly, a hydraulic model study was undertaken to obtain some indication of the effectiveness of the various proposed river training structure plans.

## 2 The Model

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### Description

The movable-bed model used for this study reproduced to a horizontal scale of 1:400 and a vertical scale of 1:100 the reach of Mississippi River between miles 39.6 and 20.2, which is a sufficient section of the river above and below the problem area to study all proposed plans. The scales selected resulted in a distortion of the linear scale of 4.0, which is acceptable for a model of this type. Crushed, granulated coal with a specific gravity of 1.30 and median grain size of approximately 4 mm was used as the movable bed material. The bank lines and dikes were constructed of 3/4-in. crushed limestone sprinkled with cement. The model study was conducted at WES in the Inland Waterways Research Facility flume. Water to the flume was supplied by a 10-cfs pump in a recirculating system and measured with 12- by 6- and 6- by 3-in. venturi meters. Flow through the venturi meters was controlled by electric valves. Water-surface elevations in the flume were controlled by a vertical slide-type tailgate and measured using point gages.

### Model Verification

Before tests of improvement plans were undertaken, adjustments were made until the model reproduced, to a reasonable degree of accuracy, the changes that had occurred in the prototype. This process is referred to as model verification. The verification process establishes the discharge scales, the rate of introducing bed material for each flow reproduced, the supplemental slope required to produce movement of the bed material, the model operating techniques, and the accuracy to which the model reproduces prototype conditions.

Verification of the model was begun with the channel portion molded to the March 1977 prototype survey (Plate 1) and the overbank molded to conditions indicated by the 1966 and 1967 U.S. Geological Survey Quadrangle maps of the area. Please note that all plates in this report cover only miles 33.3 to 20.2, not the entire length of the model, which was miles 39.6 to 20.2 (see Figure 1 for plate and model limits). This was done to present the model

results at a scale large enough to discern important details within the areas of interest. The model was operated by reproducing the flows that occurred in the river during the period 1 October 1977 to 30 September 1978 (Plate 2). This operation was repeated and adjustments were made until the model reproduced, with reasonable accuracy, the essential characteristics of the reach and channel configurations indicated by the April 1983 prototype survey (Plate 3). The 1977-78 hydrograph (also referred to in this report as the average annual hydrograph) was chosen since it coincided with a complete river survey (March 1977) and also represented a fairly typical water year. The next complete study reach survey was the April 1983 survey, a flood year. To verify a model under these conditions is difficult, but this is an example of working with the data available.

Results of the final adjustment run indicated that the model reproduced the general characteristics of the prototype reach, and the verification was considered adequate for the purpose of the study. Comparison of the results of the final verification run (verification run 5, Plate 4) with the prototype survey of April 1983 (Plate 3) indicated that the model had a greater tendency to scour at dike 35.0 (R), the navigation channel was wider and shallower from miles 37.5 to 36.3 and miles 23.0 to 22.5, and was wider and deeper from miles 32.1 to 31.4. The model exhibited greater deposition than the prototype, narrowing the navigation channel from miles 31.0 to 30.6, miles 28.8 to 27.5, and miles 24.5 to 23.7. These differences and tendencies must be considered in any evaluation of test results of river training structure improvement plans.

The model verification was checked using the 1983 flood hydrograph (Plate 5) to ensure that the model would correctly reproduce a high-water event. After one run, folded screen wire was added to carefully selected areas of the model to regulate the overbank flow velocities. These velocities appeared to be higher in the model than would be expected in the prototype. The screen wire replicated tree lines and areas of dense underbrush. Aerial photographs were used to determine the position of the wire (the 1977-78 hydrograph has no flows that overtop the banks; therefore it is not affected by the addition of the overbank screen wire). Since the April 1983 prototype bed configuration (Plate 3) was surveyed during a period of high water, it was compared to the 1983 flood hydrograph, verification run 2, bed survey (Plate 6). The surveys were similar, indicating that the model did in fact reproduce this high-water event accurately. A more detailed description of the model verification process is presented in Franco.<sup>1</sup>

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<sup>1</sup> J.J. Franco. (1978). "Guidelines for the design, adjustment and operation of models for the study of river sedimentation problems," Instruction Report H-78-1 (includes Appendixes A-C), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

## 3 Tests and Results

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### Test Procedure

After verification, the model was run to stability using the average annual hydrograph (Plate 7). This base test (Plate 8, Base Test rerun, run 5) provided a basis with which the effects of the various river training structure improvement plans were compared. The average annual hydrograph used during the base test and in the testing of most plans was furnished by the St. Louis District.<sup>1</sup> This hydrograph was based on both historical records and mathematical model computations; it has few bank-full flows and no overbank flows.

A base test using the 1983 Mississippi River flood hydrograph (Plate 5) was also run. The flood hydrograph covered the period of time from 1 October 1982 to 30 September 1983. This test was used to determine the effect of flood flows on channel stability.

Each reproduction of the average annual or 1983 flood hydrograph is herein referred to as a run. Most of the tests of improvement plans or modifications were started with the bed configuration obtained at the end of the preceding test, or, where stated, the model was remolded to the bed configuration obtained after Base Test rerun, run 5. The bed of the model was surveyed and mapped at the end of each run. The stages at the end of each run were 13.5 ft and 10.0 ft for the average annual and 1983 flood hydrographs, respectively. Only final results or significant changes produced by each plan or modification are included in this report. In tests where interest was confined to a small area (Plans I, I-1, I-2, I-3, and Q), only changes within that area are discussed.

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<sup>1</sup> Personal Communication, 1984, from Robert D. Davinroy, St. Louis District, to David L. Derrick, WES.

## **Base Test Rerun, Average Annual Hydrograph**

### **Description**

A base test was conducted to allow the model to reach stability using the average annual hydrograph supplied by the St. Louis District. During the first prototype field trip, a large expanse of revetted bank line was observed that was not shown as revetted on the prototype maps (and consequently was not revetted in the model). Modifications were made to the model, and the base test was rerun. Model stability was reached after run 5 (Base Test rerun, run 5). The beginning bed configuration was the verification, run 5, survey. This base test supplied a stable bed configuration against which most subsequent river training structure improvement plans were compared.

### **Results**

After five runs using the average annual hydrograph (Base Test rerun, run 5, Plate 8), the model showed that a navigable channel (although narrow in places) at or below el -10 existed throughout the reach except in the crossings downstream of Price's Landing and Dogtooth Bends. The crossing below Price's Landing Bend was poorly aligned and displayed insufficient navigation depths between miles 28.8 and 27.6. The navigation channel downstream of Dogtooth Bend revealed insufficient depths and width from miles 22.2 to 21.5.

## **Base Test, 1983 Flood Hydrograph**

### **Description**

The model was subjected to two runs of the 1983 Mississippi River flood hydrograph (Plate 5) to obtain an indication of the stability of the channel during a high-water year. The beginning bed configuration for this test was the Base Test rerun, run 5 survey (Plate 8).

### **Results**

Results after two runs using the 1983 flood hydrograph were deemed satisfactory with few negative impacts from the flood flows. Some deterioration of the navigation channel in the crossing downstream of Price's Landing Bend was noted, but overall, results were similar to the Base Test rerun, run 5, survey.

## Introduction to River Training Structure Tests

The goal of the model tests was to arrive at a practical and cost-effective solution to the numerous problems (outlined in the "Descriptions of Prototype Problems" section) encountered in this reach of river. Since no physical model studies of bendways with similar problems had been performed, history was not a major influence in finding a practical solution. Therefore, many types of river training structures were tested and analyzed. If the purpose of a test was not specifically aimed at solving the prototype problems described previously, then the specific purpose of that test was stated in the plan description. Also, model results were always compared to the beginning bed configuration of the test unless clearly stated otherwise.

### Plan A

#### Description

Plan A consisted of six dikes at Price's Landing Bend and six dikes at Dogtooth Bend. All dikes were attached to the right descending bank and were level-crested with dikes 1 through 6 at el -4, dikes 7 and 8 at el -1, and dikes 9 through 12 at el 0. All dikes were built to a length of 600 ft, except dikes 3, 4, and 5, which were 300 ft long. Spacing between dikes varied. All dikes were angled 50 deg downstream of a line drawn perpendicular to the bank line at the bank end of the dike. The starting bed configuration was the Base Test rerun, run 2, 1983 flood hydrograph survey. This survey differs very little from the Base Test rerun, run 5, survey; therefore, to reduce costs and save time, the model was not remolded. The average annual hydrograph (Plate 7) was employed during Plan A and in all subsequent tests performed during the model study unless stated otherwise.

#### Results

Results of Plan A after two runs (Plate 9, again please note that the report plates cover only miles 33.3 to 20.2) indicated some scour in the deep-water channel at Price's Landing Bend and a reduction in width of the navigation channel at Dogtooth Bend. Overall, Plan A did not widen or improve the navigation channel through the reach. Also, this plan did not redirect currents from the outer bank toward the point bar. In fact, visual observations of confetti indicated that the Plan A dikes redirected the surface water currents toward the outer bank in both bends. This could be detrimental to navigation, and the increased hydraulic forces against the revetment could threaten the stability of the bank and might increase maintenance costs. This situation is particularly alarming at Dogtooth Bend due to the already high concentration of currents on the outer bank since these concentrated high-velocity currents were directly responsible for the bank failure at Dry Bayou during the 1983 flood.

## **Plan A-1**

### **Description**

Plan A-1 was the same as Plan A except that the dike elevations were changed. For Plan A-1, dikes 1 and 4 were at el -6, dikes 2 and 5 were at el -4, dikes 3 and 6 were at el -2, dikes 7 and 10 were at el -3, dikes 8 and 11 were at el -1, and dikes 9 and 12 were at el +1. All dikes were level-crested. The beginning bed configuration used was the Plan A, run 2, bed survey (Plate 9).

### **Results**

Comparing the second run of Plan A-1 (Plate 10) to the Plan A, run 2, survey revealed that the navigation channel at Price's Landing Bend had narrowed, while Dogtooth Bend remained stable, except for a slight widening of the navigation channel at mile 23.0.

## **Plan B**

### **Description**

Plan B included removal of Plan A-1 dikes 7, 8, and 9 and extending prototype dikes 25.0 (L) and 24.5 (L) at el 0 until the extensions intersected. The starting bed configuration was the Plan A-1, run 2, survey (Plate 10).

### **Results**

Results after the second run of Plan B, shown in Plate 11, indicated that the navigation channel at Price's Landing Bend continued to narrow slightly. At Dogtooth Bend a large, deep scour hole formed downstream of the intersection of dikes 25.0 (L) and 24.5 (L). The navigation channel narrowed in the vicinity of and for approximately 4,500 ft downstream of this scour hole. The navigation channel widened an average of 400 ft at the apex of the bend (miles 24.6 to 24.0), and surface water currents appeared slightly improved; however, overall test results were not deemed satisfactory.

## **Plan C**

### **Description**

Plan C was specifically designed to widen the navigation channel in the approach to Price's Landing Bend. This plan included installing two



600-ft-long, level-crested dikes (dikes 2-U and 1-U) on the right bank at el 0 upstream of Plan A dike 1. These dikes were angled 22 deg downstream of a line drawn perpendicular to the bank line at the bank end of the dike. Plan A dike 1 was raised to el 0. Plan A dikes 4, 5, 6, 10, 11, and 12 were removed. The Plan B, run 2, bed survey was used as the starting bed configuration (Plate 11).

## Results

After two runs on Plan C (Plate 12), a large, deep scour hole formed around the Plan C dikes and the navigation channel widened approximately 700 ft in that area. The flow split below Plan C dike 1-U, resulting in the formation of a 700-ft-wide half-mile-long center channel bar averaging el +5 in height. The navigation channel in this area narrowed from 960 to 240 ft. Flow that overtopped dikes 2-U and 1-U appeared to be directed into the bank. An average of 20 ft of scour occurred at the toe of the revetment through the remainder of the bend. Depths were insufficient for navigation at mile 30.9 and in the crossing downstream of Price's Landing Bend (miles 29.0 to 27.6). At Dogtooth Bend the navigation channel decreased in width by 200 ft from miles 23.6 to 23.2, whereupon the flow split, resulting in the formation of a midchannel bar that cut the effective navigation channel width from 900 to 120 ft from miles 22.7 to 22.4. The navigation channel narrowed slightly through the remainder of the model. Again, test results were considered unsatisfactory.

## Plan C-1

### Description

Plan C-1 involved shortening Plan C dikes 2-U and 1-U by 200 and 300 ft, respectively. A stone dike in the same location as prototype dike 24.3 (L) was installed with a length of 1,300 ft, the 1,000 ft nearest the bank level-crested at el +25 and the remainder sloping to el +14 at the river end. Prototype dike 24.3 (L), a deteriorated pile dike deemed ineffective by the St. Louis District, had never been installed in the model. Ranges 29 to 45 were remolded to the Plan B, run 2, bed survey (Plate 11). The remainder of the model used the Plan C, run 2, survey (Plate 12).

### Results

After two runs on Plan C-1 (Plate 13) a 400-ft-wide bar averaging +4 ft in elevation was formed from miles 31.0 to 30.5, resulting in a loss of the navigation channel in that area. Some channel improvement in the crossing downstream of Price's Landing Bend occurred. Except for minor changes, the remainder of the model was stable.

## Plan C-2

### Description

Plan C-2 included removing Plan C dike 1-U and shortening Plan C dike 2-U to a length of 240 ft. Dike 32.0 (R) was extended 200 ft riverward with a 600-ft L-head added at the river end of the extension. The dike extension and L-head were built level-crested at el +20. Ranges 29 to 45 were remolded to the Plan B, run 2, survey (Plate 11). The remainder of the model used the Plan C-1, run 2, bed configuration (Plate 13).

### Results

The navigation channel through Price's Landing Bend narrowed slightly during run 2 of Plan C-2 (Plate 14), with the point bar constricting the channel in the vicinity of weir 30.3 (R). The crossings downstream of both Price's Landing and Dogtooth Bends shoaled to the point where a stable and satisfactory navigation channel did not exist at either location.

## Plan D

### Description

For Plan D a 13,500-ft-long longitudinal dike (longitudinal dike No. 1), level-crested at el -18 ft, was installed approximately 200 ft riverward of the right bank revetment throughout the length of Dogtooth Bend (miles 24.6 to 22.2). Plan A-1 dikes 1, 2, and 3 and prototype dike 24.3 (L) were removed. Plan C dike 2-U was lengthened to 320 ft. Plan C dike 1-U was reinstalled at el 0, with a length of 150 ft. Dike 32.0 (R) was returned to prototype dimensions (Table 1). Dikes 22.3 (L) and 23.8 (L) (the secondary channel closure dikes at Dogtooth Bend) were raised to a level-crested el +17. The L-head on dike 35.1 (R) was uniformly lowered to el +17 at the downstream end to more accurately reflect prototype conditions. The model was remolded to the Base Test rerun, run 5, bed survey (Plate 8) prior to the initiation of the Plan D model runs.

### Results

After three runs of Plan D (Plate 15), the navigation channel at Price's Landing Bend widened between miles 31.0 and 29.8, except for some narrowing between miles 30.8 and 30.5, where a bar extended from the middle of the navigation channel to the point bar on the left. The zero contour to the left of the navigation channel remained stationary throughout the bend. Small midchannel bars with heights of el -6 and el -8 formed at miles 30.3 and 29.7, respectively. The downstream crossing improved slightly, resulting in a

narrow navigation channel along the right bank. The navigation channel in Dogtooth Bend between miles 24.5 and 22.3 narrowed 200 to 720 ft, except at mile 23.5, where it widened to 120 ft. Apparently the eight prototype short stub dikes on the outside of this bend created a great deal of turbulence, which in turn resulted in the navigation channel width obtained in the Base Test. When the long longitudinal dike was installed (negating the effects of the stub dikes), the smoother alignment resulted in a much narrower navigation channel.

## **Plan D-1**

### **Description**

For Plan D-1, Plan C dikes 2-U and 1-U were lengthened to 400 and 200 ft, respectively. The riverward 400 ft of dike 24.2 (L) was uniformly sloped from el +22 to el -5. The riverward 800 ft of dike 23.8 (L) was modified as follows: the crest elevation was sloped from el +22 to el 0 over a 200-ft length, then level-crested at el 0 for 400 ft, and finally sloped to el -5 at the river end. The starting bed configuration was the Plan D, run 3, bed survey (Plate 15).

### **Results**

Plan D-1, run 2 (Plate 16), results indicate flow entering Price's Landing Bend was redirected toward the left. This resulted in a bar formation (average height, el -4) that was attached to the right bank at mile 31.0 and extended across the navigation channel at mile 29.5. Deposition between miles 30.0 and 29.4 shoaled the navigation channel in that area. Only minor changes were observed at Dogtooth Bend. The navigation channel in the crossing downstream of Dogtooth Bend widened an average of 160 ft from miles 22.7 to 21.0.

## **Plan E**

### **Description**

For Plan E, Plan C dikes 2-U and 1-U were shortened to lengths of 200 and 100 ft, respectively. Dike 24.6 (R), the separate (detached) riverward section of dike 24.8 (R), and the 13,500-ft-long longitudinal dike from Plan D were removed. The extension of dike 24.5 (L) was raised to el +17, and the extension of dike 25.0 (L) was raised to el +17 where it intercepted dike 24.5 (L), and to el +20 where it tied into the original dike. The model was remolded to the Base Test rerun run 5 survey (Plate 8).

## Results

Results after two runs of Plan E (Plate 17) were unsatisfactory. The navigation channel widened 100 ft from miles 31.0 to 30.2, but was pinched down at mile 30.0, narrowing by approximately 160 ft. The downstream crossing was slightly improved between miles 28.8 and 28.0. The navigation channel decreased by between 120 and 560 ft throughout Dogtooth Bend (miles 24.7 to 22.1).

## Plan E-1

### Description

Plan E-1 included extending Plan C dikes 2-U and 1-U to lengths of 250 and 125 ft, respectively. The Plan E, run 2, bed survey (Plate 17) was employed as the initial bed configuration for testing of Plan E-1.

### Results

Results after two runs on Plan E-1 (Plate 18) indicated that the navigation channel increased in width an average of 200 ft between miles 31.2 and 28.2; however, midchannel bars formed at miles 31.0, 29.8, 29.6, and 28.6 (average bar elevations, -8, -7, -8, and -9, respectively) making navigation hazardous. The remainder of the model was relatively unchanged.

## Plan E-2

### Description

Plan E-2 included construction of dikes No. 1, 2, and 3 evenly spaced 1,600 ft apart (distance measured from river end to river end) along the left bank at Goose Island Towhead (miles 32.95, 32.70, and 32.35). The dikes were angled normal to the bank and level-crested at el +17 with lengths of 400, 600, and 200 ft, respectively. Observations (aided by confetti) during Plan E showed that flow entering Price's Landing Bend appeared divided. The Plan E-2 dikes were built in an area where the bank line was irregular. These dikes were designed to eliminate this irregularity (providing a more constant outer bank radius) and create a better aligned and more uniform flow field entering Price's Landing Bend.

Upstream of Dogtooth Bend a 4,000-ft-long curved dike was constructed, starting near the river end of dike 25.4 (L) and extending downstream until it intersected the end of the dike 24.5 (L) extension. The beginning bed configuration used was the Plan E-1, run 2, survey (Plate 18).

## Results

Plan E-2, run 2 (Plate 19), indicated that changes caused by the Goose Island Towhead dikes were minor. The existing midchannel bar at mile 31.0 became attached to the right bank. The effects of the 4,000-ft-long curved dike at mile 25 were largely confined to the immediate area. Scour was noted alongside and off the end of the dike and also on the opposite bank in the vicinity of dike 24.8 (L).

## Plan E-3

### Description

Plan E-3 included additional dikes No. 4, 5, and 6 along the left bank of Goose Island Towhead at miles 33.05, 32.85, and 32.50. All dikes were angled normal to the bank and level-crested at el +17. Lengths were 300, 460, and 500 ft, respectively. One dike was placed upstream of and the other two were placed between the Plan E-2 dikes, resulting in an even spacing of 800 ft between all six dikes in this field. This test was designed to ascertain the effects on channel development of reducing dike spacing by one-half (from 1,600 ft in Plan E-2 to 800 ft in Plan E-3). At Dogtooth Bend the right bank revetment was realigned and set back between miles 24.8 and 23.8. The setback distance was 800 ft at mile 24.8, and from there the revetment curved smoothly until it intersected the bank end of dike 23.8 (R). Testing was undertaken with the channel configuration that existed at the end of Plan E-2, Run 2 (Plate 19).

### Results

After completion of three runs of Plan E-3 (Plate 20), results indicate the point bar at mile 32.4 would experience considerable scour, widening the navigation channel by 700 ft. The navigation channel migrated 200 ft to the left between miles 31.9 and 31.3. A narrow portion of the midchannel bar remained at mile 31.0. The channel narrowed 200 ft at mile 30.3. Doubling the number of Goose Island Towhead dikes improved the navigation channel width and alignment in the immediate area. However, this plan did not improve the navigation channel in Price's Landing Bend. The crossing immediately downstream of Price's Landing Bend improved between miles 29.1 and 28.5, but the navigation channel was nonexistent at the lower end of the crossing (miles 28.3 to 27.7). At Dogtooth Bend the channel migrated to the setback revetment between miles 24.8 and 23.8. The remainder of the bend was unchanged. The channel alignment was smoother through the bend due to the realigned revetment, but navigation channel width was not improved.

## Plan E-4

### Description

The river end of dike 23.8 (L) was raised to el +20 and from there smoothly sloped to an existing el +30 at station +1764. A 1,500-ft-long L-head, level-crested at el +15 and angled 105 deg (measured clockwise from the main stem of the dike) was added to dike 23.8 (L). The Plan E-3, run 3, bed survey (Plate 20) was employed for the initiation of model tests.

### Results

After two runs on Plan E-4 (Plate 21), the midchannel bar at mile 31.0 disappeared. The channel increased in width an average of 400 ft between miles 30.6 and 30.2, but narrowed 160 ft between miles 30.0 and 29.5. A scour hole formed at the upper end of the dike 23.8 (L) L-head. The navigation channel narrowed 200 and 240 ft at miles 24.4 and 23.2, respectively, while the zero contour moved toward the navigation channel an average of 400 ft at these locations.

Comparison of Plan E-4, run 2, with the Base Test rerun run 5 survey showed some improvement in the navigation channel at Price's Landing Bend with an increased channel width of 200 and 240 ft at miles 30.8 and 30.2, respectively. However, sufficient navigation depths were not maintained in the crossing downstream of Price's Landing Bend, and the navigation channel at Dogtooth Bend (miles 24.7 to 22.4) narrowed between 1,000 and 120 ft, making this test unsuccessful.

## Plan F

### Description

Plan F included restoring dikes 24.2 (L) and 23.8 (L) to prototype specifications. Dike 24.6 (R), the detached (separate) riverward section of dike 24.8 (R), Plan C dikes 2-U and 1-U, all Plan E-2 dikes, all Plan E-3 dikes, and the setback revetment from Plan E-3 were removed. A 12,300-ft-long longitudinal dike (longitudinal dike No. 1) level-crested at el +30 except for one dip to el +23 was installed along the right side of the channel throughout Price's Landing Bend (miles 31.4 to 29.2). A 14,080-ft-long longitudinal dike (longitudinal dike No. 2) level-crested at el +30 was installed along the right side of the channel through Dogtooth Bend (miles 24.8 to 22.6). The longitudinal dike at Price's Landing Bend had 11 perpendicular dikes tying it to the right bank, and the longitudinal dike at Dogtooth Bend employed 14 tie-back dikes. All Plan F tie-back dikes were level-crested at el +30. The model was remolded to the Base Test rerun run 5 bed survey (Plate 8) prior to the initiation of the Plan F runs.

## Results

Three runs of Plan F (Plate 22) were completed. Because of longitudinal dike No. 1, the navigation channel through Price's Landing Bend was smooth and well aligned. However, the navigation channel width was basically unchanged, except for a 320-ft increase in width from miles 30.0 to 29.6. Scour occurred between miles 28.8 and 27.7, resulting in a wide and fairly well aligned navigation channel in the downstream crossing. Confetti observations showed that surface water currents on the outside of Price's Landing Bend were aligned with the longitudinal dike. However, the currents in the center and toward the inside of the bend crossed over quickly and were concentrated on the outside bank of the bend by the time the apex of the bend was reached. The navigation channel narrowed an average of 440 ft throughout Dogtooth Bend (miles 24.3 to 22.3). Channel alignment through the bend was slightly improved due to the smooth radius of longitudinal dike No. 2. The downstream crossing widened an average of 300 ft between miles 22.3 and 21.0. In summation, while some desirable results were achieved, implementing this plan in the prototype would be very expensive.

## Plan F-1

### Description

Plan F-1 included building four very long dikes (dikes No. 1-4) with lengths of 5,960, 6,600, 6,680, and 6,360 ft on the left bank at Price's Landing Bend and five long dikes (dikes No. 5-9) with lengths of 2,640, 3,400, 4,000, 4,360 and 4,300 ft on the left bank at Dogtooth Bend. The Plan F-1 dikes were designed to contract the river to a width of 1,500 ft (measured from el 0 at the end of the dike to el 0 on the opposite bank). All nine Plan F-1 dikes were angled normal to flow and had 500-ft-long L-heads attached at the stream end. The L-heads were angled parallel to the flow. All nine Plan F-1 dikes tied into the left bank main-line levee, closed off all secondary channels, extended well onto the point bar, and were level-crested at el +39. This height would cause all river flow below el +39 to be forced into the main channel of the river. The beginning bed survey used was Plan F, Run 3 (Plate 22).

### Results

After two runs on Plan F-1 (Plate 23) the model displayed no major changes at Price's Landing Bend. At Dogtooth Bend scour was observed off the ends of the two upstream L-head dikes and the navigation channel widened an average of 200 ft throughout the bend (miles 24.6 to 21.8). Again, as in Plan F, this plan would be very costly to implement.

## **Plan F-1, 1983 Flood Hydrograph**

### **Description**

Since the Plan F-1 dikes could possibly prove more effective during high flows, the decision was made to test this plan using the 1983 flood hydrograph. The Plan F-1, run 2, bed survey (Plate 23) was employed as the starting bed configuration.

### **Results**

Except for a slight widening at the apex of Price's Landing Bend, no navigation channel improvements were realized after one repetition of the 1983 flood hydrograph on Plan F-1 (Plate 24).

## **Introduction to Plan F-2**

Preliminary tests involving Iowa vane dikes (with assistance from Dr. Jacob Odgaard of Iowa State University, Cedar Rapids, IA) were conducted in two bendways of an available WES physical movable-bed model for possible inclusion of Iowa vanes in the Dogtooth Bend testing program. Results were disappointing; therefore, no further action was taken.

Based on studies previously conducted at WES investigating dike parameters such as angle, it was felt that a series of upstream angled weirs submerged in the deepest portion of the navigation channel with a crest elevation low enough to allow river traffic to pass over unimpeded might improve the navigation channel. It was felt that flow overtopping the weir could possibly be redirected at an angle perpendicular to the crest of the weir.

## **Plan F-2**

### **Description**

Plan F-2 included building seven weirs (bendway weirs 1-7) tied to longitudinal dike No. 1 at Price's Landing Bend and five weirs (bendway weirs 8-12) tied to longitudinal dike No. 2 at Dogtooth Bend. All weirs were level-crested at el -15, evenly spaced 1,500 ft apart (unless stated otherwise, all weir spacing in this report was measured between the midpoints of adjoining weirs), and angled 30 deg upstream of a line drawn perpendicular to the longitudinal dike at the point where the weir tied into the longitudinal dike. The maximum weir height was determined by adding the required channel draft (9 ft) to an allowance for ice buildup on the bottom of the tows during cold weather plus an appropriate factor of safety, for a total of 15 ft (el -15).



Weir length was determined by the weir height. For this plan the weirs spanned the distance from the el -15 contour on the inside of the bend to the point where the weirs tied into the longitudinal dike. The weirs at Price's Landing Bend were built between miles 31.4 and 29.6 at lengths of 820, 830, 920, 990, 1,130, 1,230, and 840 ft. The weirs at Dogtooth Bend were built in the area from miles 23.8 to 22.8 with lengths of 820, 990, 1,240, 1,420, and 1,180 ft. The beginning bed configuration was the Plan F-1, 1983 flood hydrograph, run 1, survey (Plate 24).

## Results

Plan F-2, run 2 (Plate 25), displayed an improved navigation channel through Price's Landing bendway. This channel widened an average of 200 ft from miles 31.1 to 29.3 with the zero contour moving to the left an average of 250 ft between miles 30.5 and 29.5. Except at mile 27.8 where the average bed elevation was -9 ft, the navigation channel through the downstream crossing was wide, deep, and well aligned. The navigation channel through Dogtooth Bend narrowed 180 ft from miles 24.5 to 24.2, widened 240 ft from miles 24.2 to 23.7, narrowed 120 ft from miles 23.7 to 23.6, widened 180 ft from miles 23.6 to 23.4, and narrowed 280 ft between miles 23.4 and 23.0. Improvement was noted in the crossing downstream of Dogtooth Bend where the channel was up to 200 ft wider at two locations (miles 22.5 and 21.8). Results of Plan F-2 indicated that weirs could improve conditions in the reach. Therefore, a comprehensive testing program using bendway weirs was undertaken.

## Plan G

### Description

Plan G included returning all dikes to prototype specifications and building 18 weirs angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. In both bends where weirs were placed, the outer bank did not have a constant radius. To help in orienting the weirs uniformly relative to each other, a constant outer bank radius of curvature was calculated and used to lay out the weir angle. All weirs were attached to the right bank, were level-crested at el -15, and were evenly spaced 1,400 ft apart. Nine weirs were positioned in the Price's Landing Bend navigation channel (miles 31.4 to 29.3) at lengths of 810, 1,080, 960, 1,000, 1,220, 1,060, 860, 1,240, and 1,380 ft, and nine weirs were positioned in the Dogtooth Bend navigation channel (miles 24.3 to 22.5) at lengths of 1,520, 1,440, 1,060, 1,160, 1,280, 1,440, 1,400, 1,560, and 1,520 ft. As in Plan F-2, weir height was again based on the required channel depth, with an additional allowance for ice buildup on the barges plus an appropriate factor of safety. Weir length was a function of weir height. In Plan G the weir spanned the distance between the el -15 contour on the outside bank of the bend and the el -15

contour on the inside of the bend. The model was remolded to the Base Test rerun run 5 bed configuration (Plate 8) prior to the installation of the plan and the initiation of model testing.

## Results

Results of Plan G, run 3 (Plate 26), indicated an increase in the navigation channel width at Price's Landing Bend of 240 ft between miles 31.2 and 30.5, and 320 ft between miles 30.1 and 29.7. The navigation channel narrowed 160 ft from miles 30.5 to 30.1. The crossing downstream of Price's Landing Bend experienced scour over a considerable area, resulting in an exceptionally wide and well-aligned navigation channel with an average width of 1,300 ft between miles 29.5 and 26.4.

At Dogtooth Bend the navigation channel widened an average of 280 ft near the apex of the bend (miles 23.7 to 23.3), and between 160 and 950 ft from miles 22.2 to 20.9. The navigation channel decreased in width an average of 320 ft between miles 24.7 and 24.2, 200 ft at mile 23.8, and 240 ft between miles 23.2 and 22.2. These changes resulted in a fairly smooth, wide, and well-aligned navigation channel throughout the bendway and downstream crossing (average width of 1,060 ft between miles 24.8 and 20.9). The channel (defined as the distance between the zero contours) widened 280 ft from miles 23.7 to 23.2 and miles 21.7 to 20.9. The channel narrowed an average of 320 ft both upstream and downstream of dike 24.2 (L) and narrowed an average of 280 ft from miles 23.1 to 21.8.

## Plan G-1

### Description

Plan G-1 was the same as Plan G with the exception of Plan G weirs 14 and 15, which were shortened to lengths of 1,200 and 1,000 ft, respectively, and reangled to 15 and 10 deg, respectively, upstream of a line drawn perpendicular to the bank line at the bank end of the weir. This plan was designed to allow Plan G-1 weirs 14 and 15 to more effectively redirect currents toward the point bar to widen the navigation channel in the area. Plan G-1 model tests were begun using the Plan G run 3 bed configuration.

### Results

The navigation channel narrowed 160 ft in the area of Plan G-1 weirs 14 and 15 (miles 23.3 to 23.0) making this test unsuccessful. Also, some deterioration was noted in the crossing downstream of Price's Landing Bend where the navigation channel decreased in width an average of 240 ft between miles 22.6 and 20.9.

## Plan G-2

### Description

Plan G-2 included returning all weirs to Plan G specifications and adding seven additional weirs to the model. Three weirs were placed in the Price's Landing Bend, spaced midway between Plan G weirs 4 and 5, 5 and 6, and 6 and 7, at lengths of 1,200, 1,160, and 980 ft, respectively. Four weirs were placed in Dogtooth Bend, midway between Plan G weirs 13 and 14, 14 and 15, 15 and 16, and 16 and 17, at lengths of 1,200, 1,440, 1,440, and 1,560 ft, respectively. This effectively reduced the weir spacing to 700 ft in the areas where weirs were added. All Plan G-2 weirs were level-crested at el -15 and angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. Plan G-2 was designed to widen the navigation channel at its narrowest point in the bend (near the apex) by doubling the weir density in that area. The entire model was remolded to the Plan G, run 3, bed survey (Plate 26).

### Results

Comparing Run 6 of Plan G-2 (Plate 27) to the Plan G, run 3, survey showed that the navigation channel at the apex of Price's Landing Bend (miles 30.6 to 29.8) widened between 160 and 480 ft, and at Dogtooth Bend increased an average of 300 ft between miles 23.5 and 22.4. The navigation channel through the remainder of the bend remained the same except for a slight narrowing at the lower end of the downstream crossing. Plan G-2 was deemed successful as both the channel (zero contour) and the navigation channel widened through both bends in the areas where weirs were added.

A comparison of Plan G-2, run 6 (Plate 27), with the Base Test rerun run 5 (Plate 8) shows the improvement throughout the reach to be nothing short of remarkable. The navigation channel through Price's Landing Bend widened an average of 380 ft from miles 31.8 to 28.5 (except for a 160-ft reduction in width between miles 29.6 and 29.1), and the downstream crossing experienced widespread scour. This resulted in a smooth, wide, well-aligned channel with an average width of 1,260 ft throughout the entire bendway and downstream crossing (miles 31.8 to 27.8). The narrowest points of the navigation channel in the bend and crossing were 1,020 ft and 840 ft, at miles 30.9 and 27.8, respectively. The average width of the navigation channel through the apex of the bend (miles 30.6 to 29.8) was 1,360 ft with the narrowest point measuring 1,110 ft at mile 30.4. An average of 15 ft of sediment was deposited on the toe of the revetment on the right side of the navigation channel at Price's Landing Bend (miles 30.8 to 29.6), bringing the bottom elevation in this area up to an average el -27 (compared to an average el -42 in Base Test rerun run 5).

At Dogtooth Bend and the immediate downstream crossing, the navigation channel widened an average of 200 ft between miles 24.7 and 23.7, widened an average of 360 ft from miles 23.7 to 23.4, decreased in width an average of 320 ft between miles 23.0 and 22.2, then dramatically widened 800 ft from miles 22.2 to 21.6. The resulting navigation channel was smooth, wide, and well-aligned with an average width of 1,180 ft in the bend (miles 24.8 to 22.5) and 900 ft in the downstream crossing (miles 22.5 to 20.9). Narrowest points of the navigation channel in the bend and crossing were 840 and 640 ft at miles 22.6 and 21.4, respectively. The average width through the apex of the bend (miles 23.8 to 23.0) was 1,180 ft with the narrowest point at mile 23.8 (960 ft). An average of 14 ft of sediment was deposited on the toe of the revetment along the right side of the navigation channel between miles 24.4 and 22.0, bringing that area up to an average elevation of -28. An average of 30 ft of sediment was deposited on the toe of the right bank revetment between miles 23.9 and 22.8.

Comparison of Plan G-2, run 1 (Plate 28), with Plan G-2, run 6 (Plate 27), indicated that *almost all* of the channel improvement realized in Plan G-2 occurred during the first hydrograph. Through Price's Landing Bend and the downstream crossing, the navigation channel widths and depths and the amount of deposition on the toe of the outside bank revetment were very similar. At Dogtooth Bend the only major differences were that for run 1 25 ft of sediment was deposited on the toe of the bendway revetment (compared to 30 ft in run 6) and the navigation channel was 320 ft narrower at mile 23.7 and 280 ft narrower between miles 22.4 and 21.6.

Plan G-2 successfully addressed and resolved all problems discussed for this study reach in the section, "Description of Prototype Problems." Six distinct hydraulic improvements were obtained using bendway weirs in Plan G-2:

- a. The navigation channel through the bend was wider (especially so at the apex).
- b. Deposition occurred at the toe of the revetment on the outside of the bend, which helps to stabilize the bank.
- c. The navigation channel in the crossing downstream of the bend was deeper and wider.
- d. The navigation channel through the bend and immediate downstream crossing was better aligned.
- e. Observed surface water velocities were more uniform across any bendway cross section.
- f. Flow patterns in the bends were generally parallel with the banks and did not concentrate on the outer bank of the bend.

There was no evidence of unacceptable scour in the immediate vicinity of the weirs. These improvements were observed in both Price's Landing and Dogtooth Bends.

In a typical unimproved bend (without bendway weirs), surface water currents tend to move from the inside of the bend toward the outside, concentrating the currents on the outer bank of the bend. This did not occur during Plan G-2. Observations aided by 1/2-in.-square paper confetti indicated that the detrimental flow patterns normally observed in an unimproved bend had been beneficially redirected by the bendway weirs. The surface water currents were uniformly distributed (parallel with the banks) through the bendway eliminating the concentration of flow on the outside of the bend. Again, relying on confetti, velocities appeared to be fairly evenly distributed across any bendway cross section. These redirected currents should be expected to reduce or possibly eliminate scour on bank protection structures, thus lessening the likelihood of bank line failure during high-water events. The improved flow patterns, coupled with the increases in navigation channel width through the bends and crossings, would improve navigation and increase the margin of safety associated with this reach. Furthermore, these improvements could greatly reduce or eliminate the costly delays the towing industry has experienced due to the narrow navigation channel. The need for tows to flank (a series of start and stop maneuvers) during low and medium stages should be minimized. Flanking slows the maneuvering tow, which in turn delays any upstream or downstream traffic waiting for the flanking tow to clear the bend. These delays have proven costly to the towing industry (annual losses are estimated at \$13 to \$26 million, dependent on river conditions, for the Mississippi River between St. Louis, MO, and Cairo, IL).

### **Environmental impacts of bendway weirs**

According to Ragland, it is a commonly held belief among aquatic biologists that there is negligible aquatic life in the deepest sections of the Mississippi River.<sup>1</sup> While no studies have been carried out to support this belief (due mainly to the difficulty or impossibility of accurate sampling at great depths), the combined factors of shifting bed forms, high velocities, and lack of light would appear to support this hypothesis. The prototype navigation channel at both Price's Landing and Dogtooth Bends fits this description (as depths of el -60 or more are commonly encountered). The bendway weirs in Plan G-2 reshaped the bendway cross section from the typical deep inverted triangle found in revetted bendways into a wider, shallower trapezoid. This altered cross section should result in an increased usable aquatic habitat area for both fish and benthic invertebrates. According to Shechan, the stone bendway weir itself increases habitat diversity within the navigation channel and

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<sup>1</sup> Personal Communication, 2 June 1992, from Daniel Ragland, St. Louis District, to David L. Derrick, WES.

provides cover and protection for small fishes.<sup>1</sup> Furthermore, the stone used to construct the weir provides a firm and stable substrate to which benthic invertebrates can attach themselves and grow. Benthic invertebrates are bottom-dwelling insects (mayflies, caddis flies, stoneflies) that make up the major portion of the food supply for fish. In the Mississippi River there is not much plant production due to the extreme turbidity of the water. In fact, most plant and organic matter found in the river is derived from runoff or transported into the river by wind. A study by the St. Louis District of four bendways (two with bendway weirs, two without) to determine fish density and distribution (cataloging fish length, number of fish, species, etc.) was proposed for 1992, but results were not available at the time this report was prepared. In conclusion, the reshaped channel and the bendway weir itself positively impact the environment and could, in time, translate into increased quantities of aquatic life. Also, St. Louis District personnel feel that this new channel geometry is closer to the natural shape of the river channel, i.e., the shape of the river before revetment was introduced into the Mississippi riverine environment.

The uniform surface velocities across any given bendway cross section after bendway weir installation will have some effects on some species of fish. Dr. Sheehan states that to determine if the effects are beneficial or detrimental would require further study, but the increased velocities near the inside of the bend should be beneficial in transporting increased amounts of food to organisms in that area, thus changing it into a "truer riverine habitat."<sup>1</sup> Also, there is an upper velocity threshold (as yet undefined) that once exceeded greatly inhibits aquatic life and growth. The reduction of the high velocities near the outer bank of the bend after bendway weir installation could prove beneficial in this respect.

Since the weirs are submerged in the deepest section of the river, the major negative environmental consequence associated with emergent dikes (the gradual changing of aquatic habitat areas into terrestrial habitat) is avoided. In a traditional dike field the areas between the dikes are designed to fill with sediment. Over time the sediment continues to build higher and higher. Eventually these areas emerge above the waterline during low flows. Now this area is no longer aquatic habitat; it has become land, if only for a short time, which of course is not suitable for aquatic creatures.

The point bars at Dogtooth and Price's Landing Bends are inhabited by the least tern, a sea bird of the genus *Sterna*, a federally protected endangered species. Threats to the least tern include coyotes and feral dogs eating eggs and young birds and the activities of man (camping, hiking, the use of all-terrain vehicles, dike construction and repair, etc.) destroying nests and nesting

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<sup>1</sup> Personal Communication, 2 June 1992, from Dr. Robert Sheehan, Associate Professor at the Fisheries Research Laboratories of Southern Illinois University, Carbondale, IL, to David L. Derrick, WES.

areas. According to Smith and Renken,<sup>1</sup> the least tern requires a sand island or sand bar that is not connected to the mainland. Eighty-seven percent of the nesting sites studied were built on either fine or coarse sand. The nesting area must be above water at least 90 to 100 days (from approximately 15 May to 31 August) for the terns to successfully hatch their eggs. Usually the least tern nests near the center of the island as long as there is little or no tree cover. These areas are usually at a higher elevation than the surrounding sand bar and consequently are exposed first after the spring high water. Early-nesting least terns produce more young and experience greater daily survival rates than late nesters. Some terns do nest near the water's edge; but if the river rises, then the nest is lost. A traditional dike system that would close off the secondary channel by connecting the point bar to the mainland could result in damage to least tern habitat during construction and could also allow easier access for animals of prey and humans. Since the bendway weirs are submerged and are not located near the point bars, none of these problems are associated with them. In fact, the weirs should have little negative impact on the least tern. Also, any reshaping of the point bar due to forces generated by the bendway weirs should not greatly impact the least tern as these changes occur slowly over time and are limited to those areas of the point bar near the water's edge.

The improvement in the navigation channel through the bends and in the crossings downstream of the bends as demonstrated in Plan G-2 should result in a decrease in maintenance dredging. Less dredging means that less dredged material will need to be disposed of. With stricter and stricter environmental regulations being enacted that regulate dredged material and suitable dredged material disposal sites, this is an important consideration for the present and the future. Also, less dredging translates into a significant cost savings for the Corps.

### **Aesthetic considerations**

The bendway weirs in Plan G-2 were built level-crested at el -15. This elevation gives reasonable assurance that the weirs will be completely submerged at all times during all river stages. Since they cannot be seen, the natural scenic beauty of the river is undisturbed.

## **Introduction To Plans G-3 Through R**

Plan G-2 was the most successful test performed in the model up to this point. The St. Louis District was interested in optimizing this plan to its fullest extent. Toward that end, bendway weir geometry, height, length, angle, and constructibility were explored.

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<sup>1</sup> John W. Smith and Rochelle B. Renken. (1991). "Least tern nesting habitat in the Mississippi River Valley adjacent to Missouri," *Journal of Field Ornithology* 62(4), 497-504.

## Plan G-3

### Description

Plan G-3 was the same as Plan G-2 except a weir connecting the stream ends of Plan G-2 weirs 21 and 8 was added at Price's Landing Bend and a weir connecting the stream ends of Plan G-2 weirs 13, 22, 14, and intersecting weir 12 at a point 300 ft from its stream end was added at Dogtooth Bend. Plan G-2 weir 7 was lengthened to intersect this connecting weir. Both connecting weirs and the weir extension were level-crested at el -15. The weirs in Plan G-3 were designed to redirect currents that had caused deep scour holes at the ends of some weirs by aiming these currents toward the point bar with the desired result of a wider navigation channel in the area. The beginning bed configuration was the Plan G-2 run 6 bed survey (Plate 27).

### Results

At the conclusion of two runs of Plan G-3 some changes were noted in both bendways, but an overall improvement in navigation channel width and alignment was not observed.

## Plan G-4

### Description

Plan G-4 included removal of the Plan G-3 connecting weir at Price's Landing Bend and constructing a new interconnecting weir starting 440 ft from the stream end of Plan G-2 weir 20, crossing Plan G-2 weir 6 at a point 360 ft from its stream end, connecting to Plan G-2 weir 21 approximately 280 ft from its stream end, intersecting 280 ft from the stream end of Plan G-2 weir 7, and terminating at a point 320 ft from the stream end of Plan G-2 weir 8. Also, a connecting weir was added at Dogtooth Bend starting 320 ft from the stream end of Plan G-2 weir 14, crossing Plan G-2 weir 23 at a point 360 ft from the stream end, connecting 400 ft from the stream end of Plan G-2 weir 15, and ending 280 ft from the stream end of Plan G-2 weir 24. All connecting weirs were level-crested at el -15. The purpose of Plan G-4 was the same as that of Plan G-3. The starting bed configuration was the Plan G-3, run 2, survey.

### Results

After two runs on Plan G-4 (Plate 29), the navigation channel at Price's Landing Bend decreased in width an average of 240 ft in the area of the Plan G-4 weirs (miles 30.3 to 29.5). At Dogtooth Bend the navigation channel narrowed an average of 120 ft from miles 24.5 to 23.7, remained stable in the



area of the Plan G-4 weirs, and widened an average of 200 ft from miles 22.8 to 22.0.

Comparing Plan G-4, run 2 (Plate 29), to the Plan G-2, run 6, survey (Plate 27) showed the navigation channel at Price's Landing Bend narrowed an average of 320 ft in the vicinity of the Plan G-4 weirs (miles 30.6 to 29.7). At Dogtooth Bend the navigation channel decreased in width 200 ft between miles 24.4 and 23.4, widened 280 ft from miles 23.3 to 23.1, widened 200 ft between miles 22.8 and 22.0, and narrowed 240 ft from miles 21.9 to 21.2. Plan G-4 was not considered successful.

## **Introduction to Plans H and H-1**

Plans H and H-1 were run to determine the effects of sloped versus level-crested weirs. A direct comparison of the results of the previous plans determined whether level-crested or sloped bendway weirs were to be employed in the remaining model tests.

## **Plan H**

### **Description**

The model was returned to prototype specifications. Eight weirs were installed, four between miles 30.7 and 29.9 (Price's Landing Bend) and four between miles 23.9 and 22.8 (Dogtooth Bend). The weirs sloped from el -18 at the bank end to elevations of -22, -22, -25, -23, -21, -24, -26, and -26, with lengths of 480, 680, 1,040, 680, 320, 920, 1,200, and 1,320 ft, respectively. Spacing was uneven with 2,560 ft between weirs 1 and 2; 2,000 ft between weirs 2 and 3; 2,160 ft between weirs 3 and 4; 2,080 ft between weirs 5 and 6; 2,000 ft between weirs 6 and 7; and 2,720 ft between weirs 7 and 8. All weirs were angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. All weirs tied to the right bank revetment. The model was remolded to the Base Test rerun run 5 bed survey (Plate 8).

### **Results**

Four runs on Plan H (Plate 30) showed a 200-ft increase in navigation channel width from miles 31.0 to 30.5, a 240-ft increase between miles 30.4 and 30.0, and a 240-ft decrease in width from miles 30.0 to 29.0. The crossing downstream of Price's Landing Bend was unchanged except for some scour at mile 28.0. Dogtooth Bend displayed a 280-ft decrease in navigation channel width between miles 24.1 and 23.7, a 200-ft increase in width from miles 23.7 to 23.3, and a decrease in width of between 200 and 640 ft between miles 23.3 and 22.2. The downstream crossing widened 600 ft from miles

22.2 to 21.5. These changes resulted in a navigation channel that was wide and well aligned throughout the crossing.

## Plan H-1

### Description

Plan H-1 was the same as Plan H with the exception that all Plan H weirs were raised to a level-crested el -18. Weir lengths were the same as in Plan H. The Plan H, run 4, bed survey was used to begin the Plan H-1 tests.

### Results

Two runs on Plan H-1 (Plate 31) showed a slightly improved and much better aligned navigation channel through the bend and crossing at Price's Landing Bend. The navigation channel exhibited modest improvement through *Dogtooth Bend* and the immediate downstream crossing. The Plan H-1 results indicated that in these tests a level-crested weir design was superior to a sloped weir design as the navigation channel displayed improvement in all tested bendways and crossings.

## Introduction to Plans I Through I-3

Plans I through I-3 were designed to provide guidance to the St. Louis District on the most economical and hydraulically efficient construction sequence by which to build the *Plan G-2 bendway weirs*. In *Plan I* a single weir was constructed in each bendway. After completion of two hydrographs, another weir was added adjacent to the first weir in whichever area (either upstream or downstream) the highest rate of deposition occurred. This test sequence was repeated until a definite trend was established as to whether the weir fields should be built in an *upstream or downstream progression*. An important difference to note between this series of plans and *Plan G-2* is that all weirs in *Plan I* were level-crested at el -18 instead of the el -15 used in *Plan G-2*. Therefore, many of the plan descriptions state that a weir was positioned the same as a specific weir in an earlier plan but the length is shorter due to the *decrease in height*.

The amount of deposition that occurs where a weir is to be built is important from a cost savings standpoint because the lower third of a weir or dike is usually the most expensive portion to build as it is considerably wider, thereby requiring large quantities of stone to build. Therefore, a relatively small difference in bed elevation can at times result in a significant cost savings. Note: The "Results" sections of Plans I through I-3 will concentrate only on the areas in the immediate vicinity of the plan weirs.

## **Plan I**

### **Description**

For this plan the model was returned to prototype specifications. A weir the same length, angle, and position as Plan G-2 weir 4 was installed at Price's Landing Bend. A 750-ft-long weir was built in the same location as Plan G-2 weir 14 at Dogtooth Bend. Both weirs were level-crested at el -18 and angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. The model was remolded to the Base Test rerun run 5 survey (Plate 8), except for the secondary channel at Price's Landing Bend, which was remolded to the April 1983 prototype survey.

### **Results**

Run 2 of Plan I showed that deposition downstream of both Plan I weirs was greater than the amount of deposition upstream of the weirs. Therefore, in Plan I-1 one weir was built downstream of each Plan I weir.

## **Plan I-1**

### **Description**

Plan G-2 weir 19 and a 390-ft-long weir positioned the same as Plan G-2 weir 8 were installed in Price's Landing Bend. Weirs with lengths of 440 and 630 ft were installed in Dogtooth Bend in the same positions as Plan G-2 weir 11 and Plan G-2 weir 23, respectively. All Plan I-1 weirs were level-crested at el -18 and angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. The two weirs built in the shallow sections of the bends were designed to determine if significant amounts of sediment could be captured by a single weir in an area with little depth. The beginning bed configuration used was the Plan I, run 2, survey.

### **Results**

After two runs on Plan I-1, the bed was stable upstream of the two adjacent weirs at Price's Landing Bend while downstream 33 ft of sediment was deposited in the area where the next downstream weir would be located. Thus, for Plan I-2 a weir was installed downstream of these weirs. There was little bed elevation change near the weir placed at the lower end of Price's Landing Bend. Likewise, there was little bed elevation change in the vicinity of the weir at the upper end of Dogtooth Bend. In the area immediately upstream of the two adjacent weirs at Dogtooth Bend some deposition occurred while immediately downstream scour was noted. Consequently, for Plan I-2 a weir was installed upstream of the two adjacent weirs at Dogtooth Bend.

## Plan I-2

### Description

Plan I-2 was the same as Plan I-1 except weirs 1,000 ft long, positioned the same as Plan G-2 weir 5 (Price's Landing Bend) and Plan G-2 weir 22 (Dogtooth Bend) were installed in the model. Both were level-crested at el -18 and angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. The starting bed configuration was the Plan I-1, run 2, survey.

### Results

After two runs on Plan I-2, scour occurred upstream of the weir field at Price's Landing Bend with deposition occurring downstream. In Plan I-3 one weir was added at Price's Landing Bend downstream of the weir field. At Dogtooth Bend deposition occurred above and below the Plan I-2 weirs, with 8 ft upstream and 30 ft downstream. Therefore, for Plan I-3 a weir was installed immediately downstream of the Plan I-2 weirs.

## Plan I-3

### Description

Plan I-3 was the same as Plan I-2 but with additional weirs installed in the same locations as Plan G-2 weir 20 (Price's Landing Bend) and Plan G-2 weir 15 (Dogtooth Bend). Weir lengths were 1,040 ft and 760 ft, respectively. Both weirs were level-crested at el -18. The beginning bed survey employed was the Plan I-2, run 2, bed configuration.

### Results

After two runs on Plan I-3 (Plate 32), Price's Landing Bend displayed a stable deepwater channel upstream of the weirs and deposition immediately downstream. At Dogtooth Bend the deepwater channel scoured upstream of the weirs and was stable relative to depth, but widened at the end and immediately downstream of the Plan I-3 weir. This widening was viewed as a positive achievement, since longer, more effective weirs could then be built.

Plans I through I-3 indicated that from both the hydraulic and cost analysis standpoints bendway weirs in this reach should be built in an upstream to downstream progression.

## **Plan J**

### **Description**

Plan J was the same as Plan G-2 with the exception that the weirs were installed level-crested at el -18 (making most shorter than, and in a few cases extremely shorter than, the Plan G-2 weirs). Plan G-2 weirs 8, 9, 10, and 18 were not installed due to insufficient depths for construction. The ten weirs at Price's Landing Bend had lengths of 580, 560, 660, 740, 940, 940, 920, 820, 700, and 480 ft. The 11 weirs at Dogtooth Bend had lengths of 480, 620, 980, 1,200, 1,040, 1,000, 980, 1,120, 1,280, 1,360, and 1,320 ft. The St. Louis District was interested in the amount of channel improvement possible with the weirs constructed at el -18. This elevation would provide an increased depth for navigation, which was a concern after the severe drought and near-record low stages experienced on the river in 1988 and 1989. The model was remolded to the Base Test rerun run 5 bed survey (Plate 8) prior to initiation of the Plan J runs.

### **Results**

After four runs on Plan J (Plate 33), the navigation channel at Price's Landing Bend narrowed 640 ft between miles 30.8 and 30.0, resulting in a navigation channel width of only 160 ft. Flow redirected by the shortened weirs appeared to be overwhelmed by the large amount of flow unaffected by the weirs. This test implied that weir length and the width of water the weir influences relative to the overall width of the river at the location of the weir are of critical importance. At Dogtooth Bend the navigation channel widened an average of 320 ft from miles 23.7 to 23.3, narrowed an average of 280 ft between miles 23.3 and 22.2, then widened 480 ft from miles 22.2 to 21.7.

## **Plan J-1**

### **Description**

Plan J-1 was the same as Plan J with the exception that the two upstream weirs at Price's Landing Bend were extended 520 and 640 ft, respectively, and the second and third upstream weirs at Dogtooth Bend were extended 160 and 420 ft, respectively. All weir extensions were level-crested at el -18. This plan was designed to determine the effects on the navigation channel of extending some of the weirs through scour holes formed at the ends of the weirs during the Plan J tests. The Plan J Run 4 bed survey (Plate 33) was employed as the beginning bed survey.

## Results

Two runs on Plan J-1 (Plate 34) indicated a much improved and better aligned navigation channel through Price's Landing Bend with increases in width of between 680 and 200 ft from miles 31.1 to 30.1. The average width of the navigation channel through the bend was 920 ft. Observations aided by confetti indicated some crossing of the center channel surface water currents toward the outer bank. Flow near the inside of the bend generally stayed toward the inside of the bend. The crossing downstream of Price's Landing Bend was poorly defined with insufficient navigation depths between miles 28.0 and 27.7. No significant improvements were noted in the navigation channel in the area of the extended weirs at Dogtooth Bend.

## Plan K

### Description

Plan K was the same as Plan J-1 except that dike 23.5 (R) was removed. During Plan J-1 a small bar had formed that was attached to the right bank at mile 23.5 and extended downstream approximately 1,000 ft at an angle of 30 deg to the bank. Plan K was designed to determine if the dike immediately upstream of the bar (dike 23.5 (R)) had caused the bar to form. A bar in this location (attached to the outer bank of a sharp bend) would be hazardous to navigation. The starting bed condition was the Plan J-1, run 2, survey.

### Results

After one run on Plan K, the bar at mile 23.5 was scoured away. The results of Plan K indicate that dike 23.5 (R) was responsible for this unusual bar formation.

## Plan L

### Description

Plan L was the same as Plan K except the short dikes (referred to as "stub dikes" by the St. Louis District) on the outer bank of Dogtooth Bend (dikes 23.7 (R), 23.4 (R), 23.2 (R), 23.1 (R), and 23.0 (R)) were removed. This test was designed to determine what effects the stub dikes had on the width of the navigation channel. Miles 24.3 through 20.2 were remolded to the Base Test rerun run 5 bed survey. Miles 39.6 through 24.3 employed the Plan K, run 1, bed configuration.

## **Results**

Results after one run on Plan L showed the navigation channel at Dogtooth Bend narrowed an average of 160 ft between miles 23.5 and 22.2. From these results it can be concluded that the turbulence around the stub dikes does increase the navigation channel width at Dogtooth Bend.

## **Plan L-1**

### **Description**

Plan L weirs 9, 10, and 17 were extended 400, 400, and 200 ft, respectively. The beginning bed condition used was the Plan L, run 1, survey.

### **Results**

Two runs on Plan L-1 (Plate 35) indicated that the navigation channel narrowed in all areas where weirs were lengthened. In all cases the narrowing reduced an anomaly (the section of navigation channel that narrowed was still at least as wide as the adjacent upstream and downstream sections of navigation channel). Therefore, navigation would not appear to be adversely affected.

## **Conclusions from Tests with Bendway Weirs at el -15 Versus el -18**

Comparison of the best results obtained with weirs at el -18 (Plan K, run 1) with the best test results involving weirs at el -15 (Plan G-2, run 6) showed an average channel width of 930 ft through Price's Landing Bend in Plan K, run 1, while Plan G-2, run 6, had an average channel width of 1,630 ft (700 ft wider). The crossing downstream of Price's Landing Bend was wider (average width 1,180 ft) and better aligned in Plan G-2 than in Plan K (where it was poorly defined and shallower). The navigation channel through Dogtooth Bend was similar in both tests. The crossing downstream of Dogtooth Bend was considerably wider (average width of 900 ft versus 560 ft, a 340-ft improvement) and better aligned in Plan G-2. After weighing all evidence, it was decided to discontinue testing of weirs constructed at el -18 and resume tests using weirs at el -15.

## **Plan M**

### **Description**

Plan M was designed to determine the effects of extending bendway weirs through the scour holes formed at the river ends of the weirs during one repetition of the average annual hydrograph. The model was returned to prototype specifications, and 25 weirs were installed to Plan G-2 specifications. The model was remolded to the Plan G-2, run 1, bed configuration (Plate 28). Plan G-2 weirs 2, 3, 5, 8, 10, 16, 17, and 18 were extended to meet the inside bend el -15 ft contour from Plan G-2, Run 1.

### **Results**

This paragraph compares Plan M, Run 5 (Plate 36), and Plan G-2, Run 6 (Plate 27). After five runs on Plan M the navigation channel through Price's Landing Bend narrowed an average of 160 ft from miles 31.0 to 30.1 and 320 ft between miles 29.8 and 29.0. The downstream crossing navigation channel narrowed an average of 160 ft between miles 28.4 and 27.3. At Dogtooth Bend the navigation channel decreased in width an average of 240 ft from miles 24.8 to 23.6 and 450 ft in the area of the lengthened weirs (miles 23.6 to 23.3). The navigation channel widened 200 ft between miles 22.8 and 22.4, but narrowed an average of 160 ft in the downstream crossing (miles 22.0 to 20.9). Observations of confetti showed smooth and well-aligned surface water currents with no crossing or concentration of flow toward the outer bank at either Price's Landing or Dogtooth Bends.

Based on the results of Plans L-1 and M, extending the weirs could result in narrower navigation channels near the extended weirs and in some instances in other areas of the bends and crossings.

## **Introduction to Plans N, O, and R**

Note: Plan R has been grouped with Plans N and O due to the similarity of the plans being tested. Therefore, in this report Plans P and Q will immediately follow the Plan R results. Plans N, O, and R examined the effects of weir angle on channel improvement. Angles of 45 deg upstream (Plan N), 35 deg upstream (Plan O), and 25 deg upstream (Plan R) were tested. Combining information from these three tests with the results of Plan G-2 (weirs angled 30 deg upstream) should provide sufficient data to determine the most hydraulically efficient (optimum) weir angle or "window" of weir angles.



## Plan N

### Description

Plan N included removing the Plan M weirs from Dogtooth Bend and installing nine weirs in the bend angled 45 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir in that bend. The bank ends of all Plan N weirs were in the same locations as the bank ends of the Plan G weirs. The weirs were 1,500 ft long (except weir 18 which was 1,900 ft long), evenly spaced 1,400 ft apart (measured from *bank end to bank end*), and level-crested at el -15. The prototype stub dikes on the outside of Dogtooth Bend (dikes 23.7 (R), 23.5 (R), 23.4 (R), 23.2 (R), 23.1 (R), and 23.0 (R)) were removed. The model was remolded to the Base Test rerun run 5 bed survey (Plate 8).

### Results

Results after two runs on Plan N (Plate 37) indicated the navigation channel had narrowed between 120 and 640 ft throughout Dogtooth Bend (miles 24.8 to 22.2). The navigation channel widened 600 ft at mile 22.0, resulting in a well-aligned, 750-ft-wide navigation channel in the downstream crossing. This test was considered unsuccessful as the navigation channel through Dogtooth Bend narrowed considerably.

## Plan O

### Description

All Plan N weirs were removed from the model. Using the same weir spacing as Plan G-2, 25 weirs were installed in the model at an angle 35 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. All weirs were level-crested at el -15 with lengths of 1,000, 1,180, 980, 1,040, 1,100, 1,180, 1,180, 1,140, 1,080, 840, 1,140, and 1,220 ft at Price's Landing Bend and lengths of 1,900, 1,520, 1,080, 1,120, 1,340, 1,440, 1,400, 1,580, 1,500, 1,420, 1,580, 1,650, and 1,560 ft at Dogtooth Bend. The model was remolded to the Base Test rerun run 5 bed configuration (Plate 8) prior to the initiation of the Plan O runs.

### Results

After six runs on Plan O (Plate 38) the navigation channel at Price's Landing Bend was basically unchanged between miles 32.0 and 30.4, widened 400 ft from miles 30.4 to 29.7, then narrowed 320 ft between miles 29.7 and 29.0. An average of 16 ft of sediment was deposited on the toe of the outside bank revetment between miles 30.8 and 29.6, bringing the average bottom

elevation in this area to -26. The crossing downstream of Price's Landing Bend experienced improvement between miles 29.0 and 28.0; however, from there downstream sufficient navigation depths were not available (miles 28.0 to 27.7). Confetti tracers indicated that the inner bank and the center of channel surface water currents slowly crossed to and concentrated on the outer bank just downstream of the apex of the bend. At Dogtooth Bend the navigation channel narrowed an average of 120 ft from miles 23.5 to 22.2, then widened 600 ft at mile 22.0. Twenty-three feet of sediment was deposited on the toe of the revetment on the outside bank between miles 23.9 and 22.8, bringing the average bottom elevation in this area to -33. Confetti indicated the inside and center channel surface water currents moved toward the outer bank downstream of the apex of the bend and remained near the bank throughout the downstream crossing.

In Plan O, run 6, the navigation channel through Price's Landing and Dogtooth Bends was not as wide, as uniform, or as well aligned as in Plan G-2, run 6. Also, the navigation channel through both downstream crossings was deeper, wider, and better aligned in Plan G-2, run 6. Comparing Plan O to Plan G-2 demonstrates that Plan G-2 would provide the best return per dollar spent as the weirs in Plan O would be more expensive to build (because they are longer). The overall results of Plan G-2 showed that for this reach, weirs angled 30 deg upstream were more hydraulically efficient than the 35-deg upstream-angled weirs of Plan O. It appeared from the significant differences in test results that weir angle is an extremely critical parameter.

## **Plan R**

### **Description**

The model was returned to prototype specifications. Using the weir spacing of Plan G-2, 25 weirs were installed at an angle 25 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. All weirs were level-crested at el -15 with lengths of 880, 970, 880, 880, 1,040, 1,060, 1,000, 960, 910, 760, 1,160, and 1,180 ft at Price's Landing Bend and lengths of 1,440, 1,380, 960, 1,080, 1,180, 1,200, 1,240, 1,360, 1,260, 1,320, 1,380, 1,400, and 1,480 ft at Dogtooth Bend. The model was remolded to the Base Test rerun run 5 bed survey (Plate 8).

### **Results**

At the end of six runs on Plan R (Plate 39), the navigation channel at Price's Landing Bend narrowed an average of 160 ft from miles 30.7 to 30.5 and widened an average of 340 ft from miles 30.5 to 29.7. An average of 14 ft of sediment was deposited on the toe of the outside bank revetment between miles 30.8 and 29.6, bringing the average bed elevation in this area up to -28. The downstream crossing was greatly improved with a navigation channel averaging 1,180 ft in width. At Dogtooth Bend the navigation channel

narrowed between 80 and 720 ft (average decrease in width, 350 ft) throughout the bend (miles 24.8 to 22.2). Twenty-one feet of sediment was deposited on the toe of the outer bank revetment between miles 23.9 and 22.8, bringing this area up to an average bed elevation of -35. The crossing downstream of Dogtooth Bend was improved with an average increase in width of 500 ft between miles 22.2 and 21.5. Observations of confetti indicated the inside and midchannel surface water currents slowly crossed toward the outside bank in the area downstream of the apex of the curve in both bends.

## Conclusions from Tests of Different Bendway Weir Angles

Comparison of Plans G-2, O, and R (bendway weirs angled 30, 35, and 25 deg upstream, respectively) showed Plan G-2 to be markedly superior to the other plans tested. Plan N, with weirs angled 45 deg upstream, was not included in this comparison due to the poor results obtained. The following tabulation summarizes the comparison of these plans:

Location	Comparison of Plans		
	Plan G-2, Run 6	Plan O, Run 6	Plan R, Run 6
	30-Deg Angle	35-Deg Angle	25-Deg Angle
<b>Average Navigation Channel Width, ft</b>			
Price's Landing			
Bend, Miles 31.5-29.5	1,325	1,070	1,025
Crossing, Miles 29.5-27.5	1,030	980	1,030
Dogtooth			
Bend, Miles 24.5-22.5	1,100	1,060	820
Crossing, Miles 22.5-21.0	830	610	810
<b>Sediment Deposit, ft</b>			
Price's Landing	15	16	14
Bend, Miles 30.8-29.6			
Dogtooth Bend,	30	23	21
Miles 23.9-22.8			

These test results indicate that in these particular bends weir angle is extremely important, with the best overall results obtained using bendway weirs angled at 30 deg. Poorer results were realized with angles just 5 deg from the optimum.

## Plan P

### Description

All Plan O weirs were removed. A series of seven unevenly spaced, 400-ft-long dikes, level-crested at el +10, were installed along the right (outer) bank of Dogtooth Bend between miles 23.7 and 22.9. These seven dikes were angled slightly downstream (between 15 and 20 deg) and each had a bendway weir attached at the river end. The weirs were level-crested at el -15, with lengths of 920, 1,240, 1,360, 960, 880, 960, and 1,160 ft, respectively, and were angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the *dike*. The prototype L-head stub dikes on the outside bank of Dogtooth Bend (dikes 23.8 (R) and 23.3 (R)) were removed. The model was remolded to the Base Test rerun run 5 bed survey. This test was designed to determine if it would be beneficial to attach bendway weirs to existing downstream-angled dikes attached to the outer bank of a bend.

### Results

After two runs on Plan P (Plate 40) the navigation channel through Dogtooth Bend and the downstream crossing narrowed 600 ft from miles 23.9 to 23.7, widened between 240 and 720 ft from miles 23.7 to 22.8, narrowed an average of 320 ft from miles 22.7 to 22.2, and widened 800 ft at mile 22.0. Observations of confetti indicated that the turbulence between the two upstream plan dikes caused a division of flow, with concentrated flow along the bank and also along a line connecting the intersection points of the weirs and stub dikes. This division of flow could adversely affect navigation and bank stability. This test showed that bendway weirs should not be attached to existing downstream-angled dikes located on the outer bank of Dogtooth Bend.

## Plan Q

### Description

Plan Q is the same as Plan P except that two chevrons were built in the entrance to the secondary channel at Price's Landing Bend. The chevrons were blunt-nosed, 400 ft long, 170 ft wide near the nose, and 300 ft wide at the tail (which was open). They were spaced approximately 300 ft apart and were angled so that the right leg was perpendicular to flow entering the channel and the left leg was parallel to the thalweg of the secondary channel. The chevrons were designed to partially block flow entering the secondary channel. The purpose of this test was to determine whether the environmental quality of the river in the area of the chevrons would be enhanced. Based on data obtained from chevron tests in the St. Louis Harbor movable-bed model it was expected that blunt-nosed chevrons would cause local scour at the nose, along the outside of the legs, and within the interior of the chevron. Also, a sandbar

usually formed downstream of the open end of the chevron. This varied bottom relief is termed "diversity of habitat" by environmentalists. It can result in an enlarged aquatic habitat area, which in turn usually leads to an increase in aquatic life. Besides these local effects, no other changes were expected from this plan. The beginning bed survey employed was Run 2 of Plan P.

### **Results**

After two runs of the average annual hydrograph on Plan Q, the only change observed in the area of interest (the area near the chevrons) was 4 ft of scour at the blunt nose and down the outside of the right leg of the upstream chevron. The aquatic habitat area was not increased significantly, and there was little variation in the bottom relief.

## **Plan Q, 1983 Flood Hydrograph**

### **Description**

Since the Plan Q chevrons were built on a relatively high bar, the decision was made to run a flood hydrograph to ascertain the effectiveness of the chevrons during a high-water event. The beginning bed configuration used was the Plan Q, run 2, survey.

### **Results**

One run on Plan Q with the 1983 flood hydrograph (Plate 41) revealed 7 and 5 ft of deposition off the blunt nose and down the outside of the right leg, respectively, of the upstream chevron. Also, 23 ft of scour occurred along the left side of the left leg with 7 ft of scour inside and just slightly downstream of the open end of the chevron. This chevron appeared to act as a normal dike in this test. No changes were noted in the area of the downstream chevron. The Plan Q tests indicated the anticipated beneficial results anticipated would not be achieved.

## 4 Discussion of Results and Conclusions

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### Interpretation of Model Results

In any analysis and evaluation of the results of this study, the limitations of the model should be considered based on the model verification, the base test, hydrographs used, and the condition of the model bed at the time that a plan or modification to a plan was installed. Comparison of the final model verification run (verification run 5, Plate 4) with the prototype survey of April 1983 (Plate 3) indicated that the model had a greater tendency to scour at dike 35.0 (R). The navigation channel was wider and shallower from miles 37.5 to 36.3 and miles 23.0 to 22.5, and wider and deeper from miles 32.1 to 31.4. The model exhibited greater deposition than the prototype between miles 31.0 to 30.6, miles 28.8 to 27.5, and miles 24.5 to 23.7, narrowing the navigation channel in these areas.

These tendencies should be considered in the evaluation of the model results. Tests of improvement plans (Plans A through R) should be based only on those changes caused by the plans compared to results reproduced in the model during the base test (Base Test rerun run 5). It should also be considered that the model does not reproduce the movement of material in suspension, and that the bank lines were fixed, with no attempt made to reproduce the degree of erodibility of the banks and sandbars. All dikes and weirs were also fixed with no attempt made to model any structure deterioration or failure. Also to be considered are the average annual and 1983 flood hydrographs used for the testing of plans, which could be considerably different from what actually occurs in the river in the future, and the fact that all model surveys were taken after a low-water period.

All model tests involving weirs were performed in a bendway with the outer bank line of the bend *revetted*. No assumptions or extrapolations based on the results of this model study should be made regarding performance of bendway weirs in an *unrevetted* bend. Information on the design and test results of a very limited series of tests of bendway weirs in an *unrevetted*

bendway can be found in Pokrefke.<sup>1</sup> Also, model tests have not been performed with bendway weirs in a *pool* section of the river; therefore, weir performance under those conditions is yet to be determined.

## Summary of Results and Conclusions

The following definitions, results, and general indications were developed from the model study:

- a. Analysis of the results of Plans A through F-1 indicated that while many types of river training structures were tested, none were successful in significantly reducing the prototype problems (outlined in the section "Descriptions of Prototype Problems") encountered in this reach of river.
- b. Visual observations aided by floating confetti indicated that dikes angled downstream (Plans A through E-4) redirected the surface water currents toward the outer bank of the bend. This would adversely affect navigation, and the increased hydraulic forces on the revetment could threaten the integrity and stability of the bank and would likely result in increased maintenance costs. This increased pressure on the outer bank is of particular concern at Dogtooth Bend where there is already a high natural concentration of currents. These concentrated high-velocity currents were a major factor in the bank failure at Dry Bayou during a high-water event in 1983.
- c. Compared to all other plans tested in the model, Plan G-2 was the best at solving the complex multitude of problems associated with this study reach. Results after six runs demonstrated that the bendway weirs of Plan G-2 were the most effective in improving the alignment and widening the navigation channel through the bends and downstream crossings; constructively redistributing flow patterns; depositing significant amounts of sediment on the toe of the outside bank revetment; redistributing velocities in a more uniform manner; and improving the navigation channel in the crossing downstream of the bend.
- d. A bendway weir is defined as a rock structure located in the navigation channel of a bend, ideally angled 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. In cases where the outer bank of the bend does not have a constant radius, one should be calculated and employed when laying out weir position (this allows the bendway weirs within a field to act as a coherent unit). The bendway weir is level-crested at an elevation low enough to allow

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<sup>1</sup> Thomas J. Pokrefke. (1993). "Demonstration Erosion Control Project Monitoring Program, Fiscal Year 1992 Report; Volume VII: Appendix F, Model study of bendway weirs as bank protection," Technical Report HL-93-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

normal river traffic to pass over the weir unimpeded. The bendway weir must be of adequate height and length to intercept a large enough percentage of flow at the river cross section where the weir is located to produce the following six hydraulic improvements: a wider navigation channel through the bend, deposition at the toe of the revetment on the outside of the bend, more uniform flow velocities at any bend cross section, surface water currents that do not concentrate on the outside bank of the bend, an improved navigation channel in the crossing downstream of the bend, and an improved alignment of the navigation channel throughout the bend and downstream crossing.

- e. In addition to the hydraulic improvements outlined in the preceding paragraph, the following environmental benefits of properly placed and angled bendway weirs could be realized: water quality should not be adversely affected as the weirs are deeply submerged 100 percent of the time; the stone bendway weir itself creates diversity of habitat within the channel, provides cover and protection for small fishes, and creates a firm, stable substrate to which benthic invertebrates can attach themselves and flourish; and the cross-sectional shape of the bendway channel is changed from a deep triangle to a wider, shallower trapezoid, thus improving and increasing the usable aquatic habitat area (studies have shown that few fish live in the deepest sections of the Mississippi River). The weirs should have a minimal impact on the least tern, a federally protected endangered species of sea bird that inhabits the bendway point bars. Since the weirs will be submerged in the deepest section of the river at all times, the major negative environmental consequence associated with emergent dikes (the gradual conversion of aquatic habitat areas to terrestrial habitat due to deposition within the dike field) will be avoided. Also, the improvements in the navigation channel through the bends and downstream crossings should result in less maintenance dredging, which would result in a decrease in dredged material. With stricter environmental regulations being enacted this is very important now, and will become even more so in the future. In conclusion, since the weirs have less impact on the environment than traditional river training structures, the future could see more widespread use.
- f. Model tests analyzing weir angle (Plan G-2, weirs angled 30 deg upstream; Plan N, 45 deg upstream; Plan O, 35 deg upstream; and Plan R, 25 deg upstream) indicated that bendway weirs angled 30 deg upstream were the most effective in solving the navigation problems in this model reach (a detailed comparison of the results of these tests is presented in the section "Conclusions from Tests of Different Bendway Weir Angles"). Results of the 25- and 35-deg angled plans demonstrated that weir angle is an extremely important parameter. With only a 5-deg difference in angle, the results from these tests showed the weirs to be less effective than the 30-deg angled weirs of Plan G-2.
- g. While an entire series of tests involving weir heights and lengths was



not performed, the poor results of Plan J demonstrated that the length of the weirs, the angle of flow entering the weir field, and the width of water the weir influences relative to the overall width of the river at the location of the weir (percentage of flow captured) are of critical importance. These parameters have not been thoroughly investigated; therefore, the reader is hereby cautioned to determine their effect and importance on any proposed bendway weir design.

- h.* Various tests were performed with weirs constructed at el -18 and -15. Since during this study weir length was always a function of weir height, a direct comparison involving two identical plans with weirs at different heights was not conducted. However, comparing the best test results employing weirs at el -15 (Plan G-2, run 6) with the best test results involving weirs at el -18 (Plan K, run 1) showed the weirs at el -15 to be much more effective (a detailed comparison is contained in the section "Plan L").
- i.* Using the basic design parameters of Plan G-2, bendway weirs have been constructed in the prototype (the river) at Dogtooth Bend (1989 and 1990), and Price's Landing Bend (1991). Detailed weir theory, design, construction methods, and prototype performance at the Dogtooth Bend location are contained in the publication "Bendway Weir Design Manual."<sup>1</sup> Furthermore, as stated in the first paragraph of this report, results of this model were analyzed and used as a guide to design bendway weirs for two troublesome reaches of river not included in this study. On the middle Mississippi River in 1992, eight weirs were installed at Cape Rock Bend (mile 54), and nine weirs were installed at Red Rock (mile 94).
- j.* Response from the towing industry regarding the improvements in navigation due to prototype installation of bendway weirs at these four sites on the middle Mississippi River has been enthusiastic. "This is the best thing to happen on the river in a hundred years," said Andy Cannava of the American Commercial Barge Line, a regular user of the study reach of the river.

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<sup>1</sup> Robert D. Davinroy. n.d. "Bendway weir design manual," U.S. Army Engineer District, St. Louis, St. Louis, MO.

**Table 1  
Prototype Dike and Weir Elevations**

Dike Designation	Distance	Elevation ft LWRP	Dike Designation	Distance	Elevation ft LWRP
Left Bank			Right Bank		
39.6 (L)	0	+23	39.4 (R)	0	+18
	200	+20		230	+15
	800	+19		390	-1
	900	+15		475	-19
	960	0		550	-19
		1040	-39	39.1 (R)	0
L-Head	810	+20		60	+18
	1010	+12		400	+18
	1310	+14		460	0
	1710	+17	38.9 (R)	0	+24
	1910	+12		210	+15
	2050	+14		500	-7
	2410	+20		550	-10
	2830	+20	38.6 (R)	0	+22
3160	+22	70		+14	
3210	+24	360		+5	
38.3 (L)	0	+27		490	+10
	60	+23		550	+3
	100	+20	38.4 (R)	0	+29
	230	+20		310	+23
	290	+19		590	+18
		760		+18	
38.0 (L)	0	+32		910	+16
	310	+19	38.2 (R)	0	+15
	520	+5		280	+13
	580	-10		390	+2
	650	-17		420	-15
		450		-15	
37.5 (L)	0	+22	38.0 (R)	0	+21
	360	+20			
37.2 (L)	0	+22			

(Sheet 1 of 7)

Notes: All dikes are listed in an upstream to downstream progression. Dikes are designated by river miles.  
All distances are in feet measured from the bank end of the dike.  
All elevations are in feet referenced to the LWRP.

Table 1 (Continued)						
Dike Designation	Distance	Elevation ft LWRP	Dike Designation	Distance	Elevation ft LWRP	
Left Bank			Right Bank			
37.2 (L) (Continued)	70	+20	38.0 (R) (Continued)	170	+20	
	380	+16		300	+4	
	440	+8		450	-16	
37.1 (L)	0	+32	37.8 (R)	0	+14	
	100	+22		370	+10	
	240	+9		480	-1	
36.7 (L)	0	+32	37.6 (R)	0	+20	
	40	+23		130	+20	
	100	+22		320	+8	
	230	+10	430	+3		
	240	+9				
36.5 (L)	0	+29	35.1 (R)	0	+28	
	260	+19		100	+23	
	350	+4		L-Head	400	+22
	375	0		1000	+22	
36.2 (L)	0	+25	35.0 (R)	0	+26	
	350	+12		200	+10	
	625	+4	34.8 (R)	0	+28	
	760	0		230	+20	
35.9 (L)	0	+28		310	+15	
	450	+20		400	+8	
	575	+5		450	-7	
35.7 (L)	0	+25	34.1 (R)	0	+30	
	270	+20		100	+23	
	330	+7		400	+22	
	430	+7		780	+21	
	500	+14		870	+10	
35.5 (L)	0	+23		1075	+1	
	350	+19	33.3 (R)	0	+24	
	400	0		300	+24	
		480		+23		
35.0 (L)	0	+29		560	+20	
	100	+24				

**Table 1 (Continued)**

Dike Designation	Distance	Elevation ft LWRP	Dike Designation	Distance	Elevation ft LWRP	
Left Bank			Right Bank			
35.0 (L) Continued	500	+19	33.3 (R) (Continued)	600	+13	
	800	+18		640	+13	
L-Head	1020	+9	32.6 (R)	0	+21	
	1360	+9		360	+21	
32.2 (L)	0	+22		600	+18	
	210	+6		820	+17	
32.0 (L)	0	+26		930	+8	
	150	+15		1140	+7	
	270	+12		1220	+1	
	480	+10		32.2 (R)	0	+23
	590	+7			180	+19
31.8 (L)	0	+26		270	+15	
	200	+16		600	+3	
	420	0		650	+3	
31.7 (L)	0	+20	32.0 (R)	0	+26	
	100	+16		100	+24	
	250	+8	L-Head	260	+12	
	310	+10		360	+12	
31.6 (L)	0	+23	<b>Sill</b>			
	180	+19	<b>Designation</b>	<b>Distance</b>	<b>Elevation</b>	
	300	+14	30.5 (R)	0	-18	
	400	+13		300	-24	
	520	-11	30.4 (R)	0	-18	
31.4 (L)	0	+25		160	-21	
	200	+15		320	-24	
	300	+13	30.3 (R)	0	-18	
	380	0		160	-21	
31.2 (L)	0	+21	30.2 (R)	320	-24	
	220	+17		0	-18	
	430	+6		200	-22	
	450	+6	400	-26		
			30.0 (R)	0	-18	

**Table 1 (Continued)**

Dike Designation	Distance	Elevation ft LWRP	Dike Designation	Distance	Elevation ft LWRP
<b>Left Bank</b>			<b>Right Bank</b>		
31.1 (L)	0	+32	30.0 (R)	150	-21
	75	+19	(Continued)	300	-24
	420	+15	29.8 (R)	0	-18
	490	+10		210	-22
	730	+6		470	-27
	820	+1	29.6 (R)	0	-18
28.0 (L)	0	+14		260	-23
	300	+14		510	-28
27.5 (L)	0	+24	29.4 (R)	0	-18
	200	+24		280	-23
L-Head	400	+14		510	-27
	600	+8	<b>Dike Designation    Distance    Elevation</b>		
27.2 (L)	0	+26	27.6 (R)	0	+26
	150	+26		130	+26
	320	+18		290	+21
	450	+18		350	+21
26.85 (L)	0	+27	27.3 (R)	0	+16
	110	+27	L-Head	500	+16
	230	+17		600	+21
	350	+17		750	+21
25.4 (L)	0	+33	27.0 (R)	0	+20
	30	+31		170	+20
	100	+20		400	+17
	150	+13		450	+17
25.3 (L)	0	+36	26.9 (R)	0	+19
	100	+24		180	+19
	250	+13		400	+13
25.2 (L)	0	+32		590	+3
	100	+24		650	+3
	320	+12	26.7 (R)	0	+26

**Table 1 (Continued)**

Dike Designation	Distance	Elevation ft LWRP	Dike Designation	Distance	Elevation ft LWRP
Left Bank			Right Bank		
25.0 (L)	0	+32	26.7 (R)	200	+26
L-Head	490	+20	(Continued)	680	+17
	570	+13	L-Head	800	+9
24.9 (L)	0	+35		1450	+9
	50	+29	26.4 (R)	0	+20
	250	+20		200	+20
	415	+12		450	+14
24.5 (L)	0	+36	L-Head	500	+13
	50	+23		730	+8
	250	+16		790	+8
	500	+17	26.1 (R)	0	+20
	600	+13		1030	+20
24.4 (L)	0	+36		1430	+10
	75	+11		1500	+10
	150	+22	25.5 (R)	0	+26
	400	+29		100	+26
	450	+9		350	+14
	500	+23		490	-1
	600	+20		550	-1
	690	+13	25.3 (R)	0	+26
24.2 (L)	0	+39		75	+26
	50	+30		400	+16
	120	+30		500	+16
	200	+27	24.8 (R)	0	+21
	700	+21	(Landward section of two-part dike)	150	+21
	750	+17		240	+14
	900	+17		450	+14
	1000	+14		530	+21
23.8 (L)	0	+18	24.8 (R)	0	+19
			(Riverward section)		


**Table 1 (Continued)**

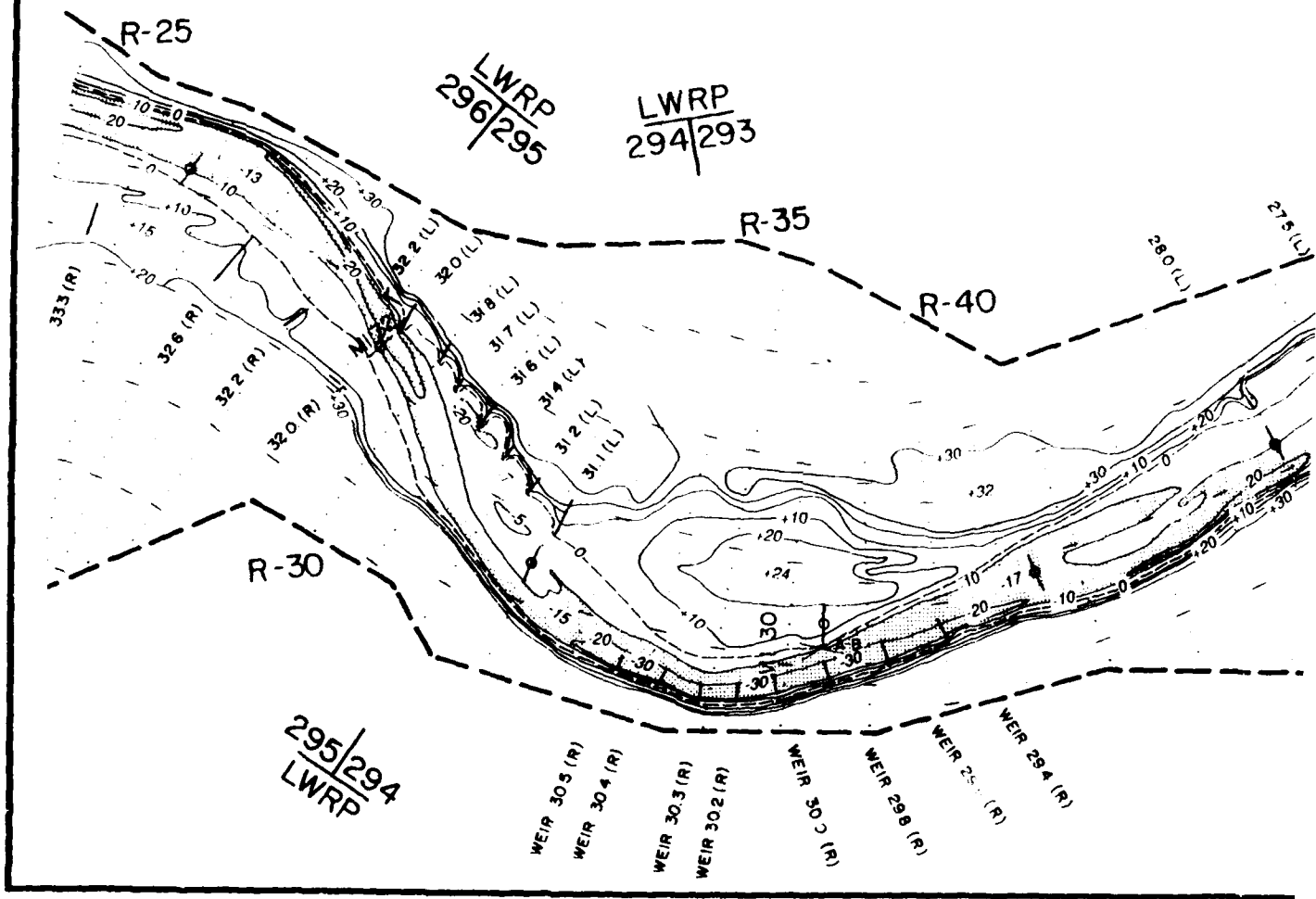
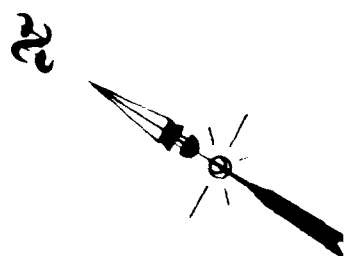
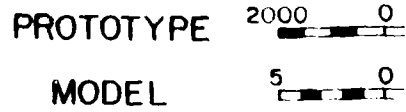
Dike Designation	Distance	Elevation ft LWRP	Dike Designation	Distance	Elevation ft LWRP
Left Bank			Right Bank		
23.8 (L) (Continued)	100	+21	24.8 (R) (Continued)	100	+19
	1475	+22		200	+13
	1500	+30	24.6 (R)	0	+22
	2125	+32		150	+22
	2200	+24		280	+13
	2300	+24		340	+13
	2325	+30	23.8 (R) L-Head	0	+39
	2650	+33		90	+23
	2675	+25		700	0
	2900	+15		730	-15
	3075	+13	23.7 (R)	0	+32
	3100	+19		310	-4
	3200	+14	23.5 (R)	0	+14
	3300	+25		100	-6
3500	+30	300		-18	
22.3 (L)	0	+36	23.4 (R)	0	+29
	175	+13		180	-1
	200	-7		270	-29
	300	-7		330	-24
	330	+21	23.3 (R) L-Head	0	+26
	500	+15		80	+14
	750	+17		200	+6
	800	+20		290	-8
	1000	+25	23.2 (R)	0	+13
	1075	+39		150	+3
1240	+39	290		-10	
21.9 (L)	0	+36	23.1 (R)	0	+13
	35	+25		110	-12
	175	+19		180	-22
	400	+18	23.0 (R)	0	+12
	500	+22		90	-9
	600	+22		200	-9

<b>Table 1 (Concluded)</b>					
<b>Dike Designation</b>	<b>Distance</b>	<b>Elevation ft LWRP</b>	<b>Dike Designation</b>	<b>Distance</b>	<b>Elevation ft LWRP</b>
<b>Left Bank</b>			<b>Right Bank</b>		
21.9 (L) (Continued)	725	+20			
	750	+14			
21.1 (L)	0	+36			
	180	+26			
	485	+15			
	520	+14			
20.5 (L)	0	+29			
	100	+29			
	590	+14			



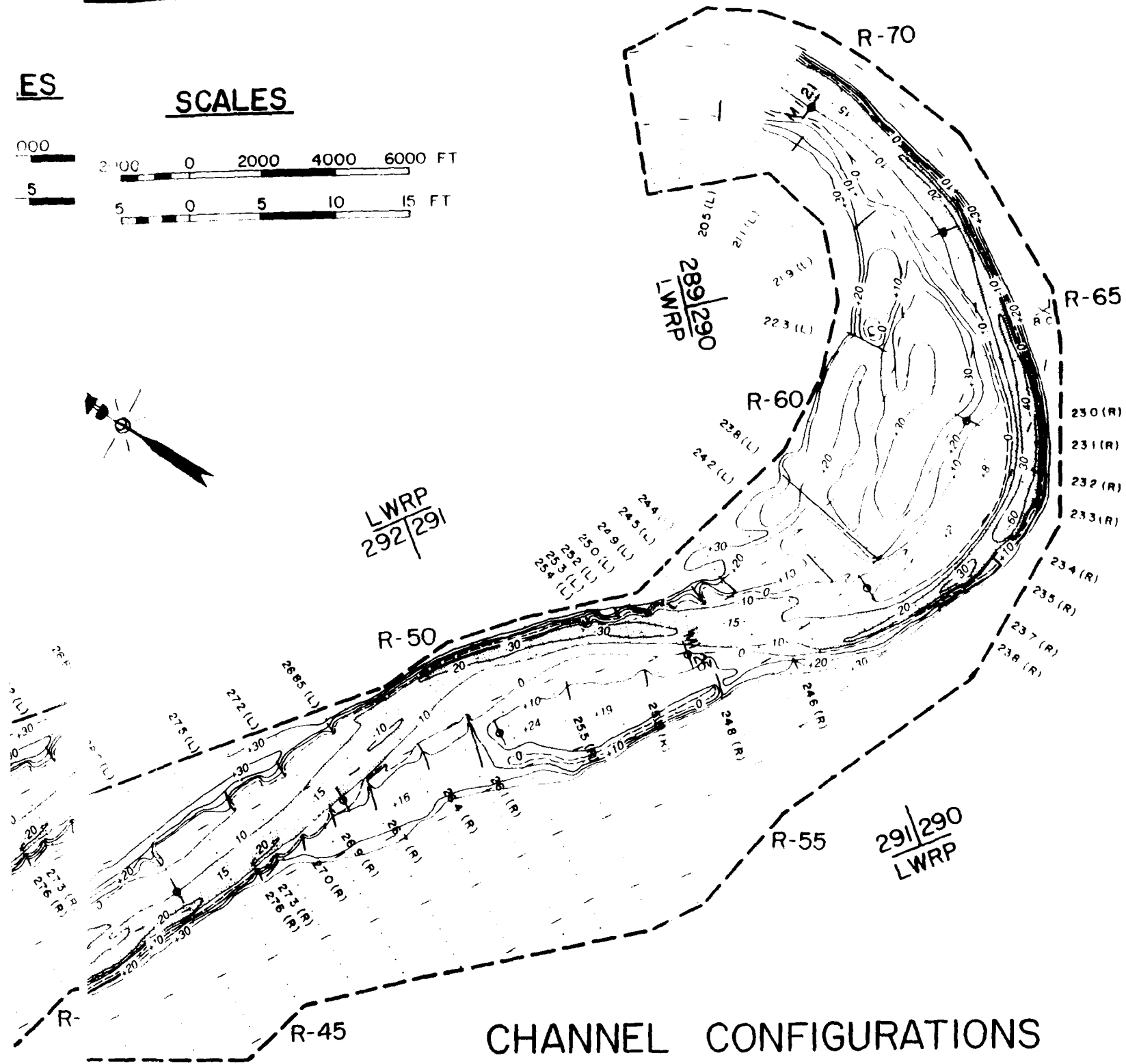
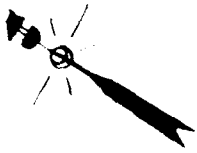
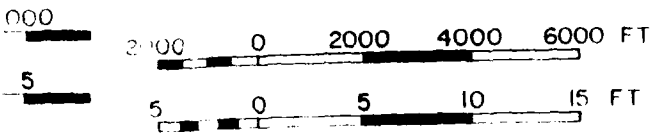
### LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



ES

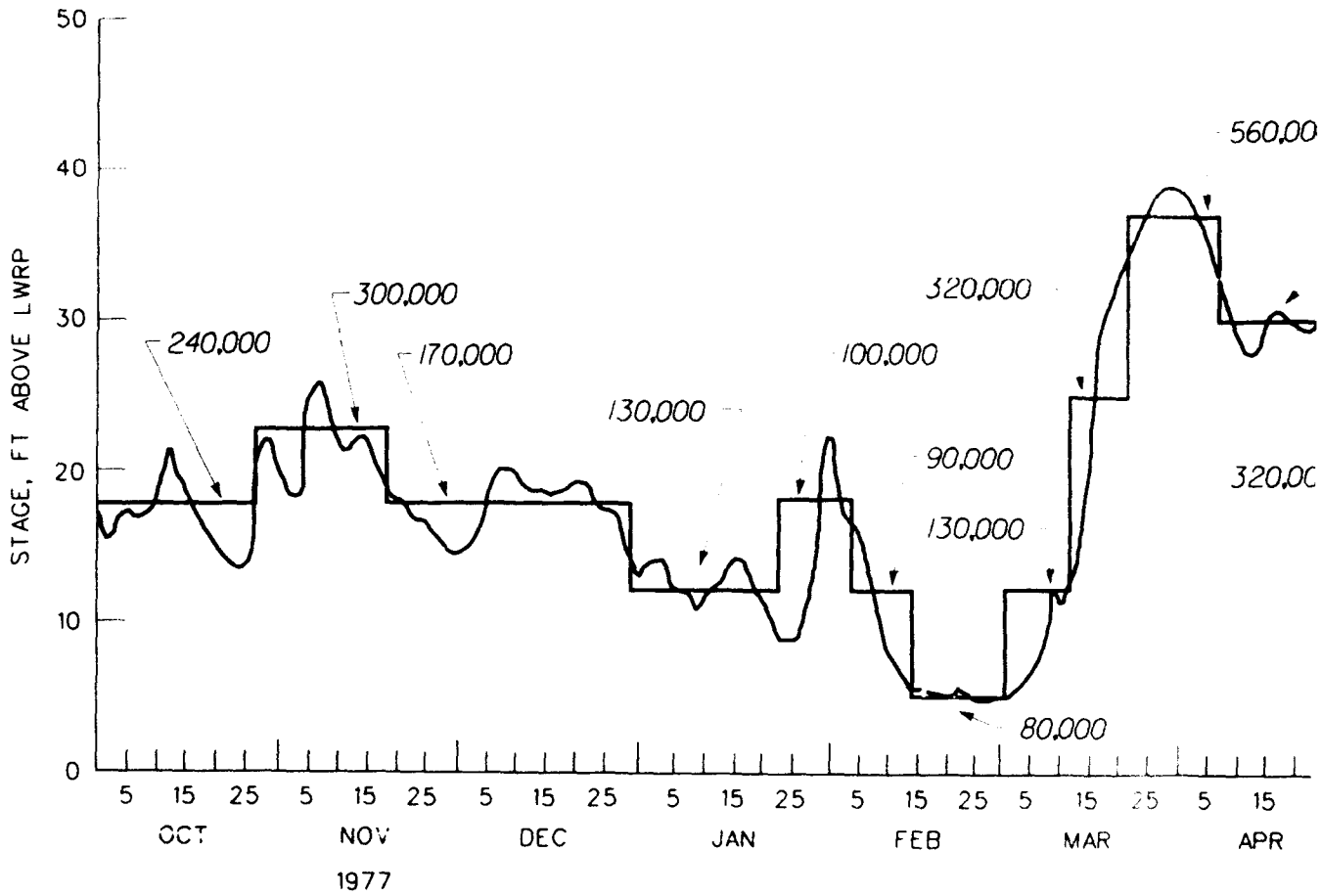
SCALES



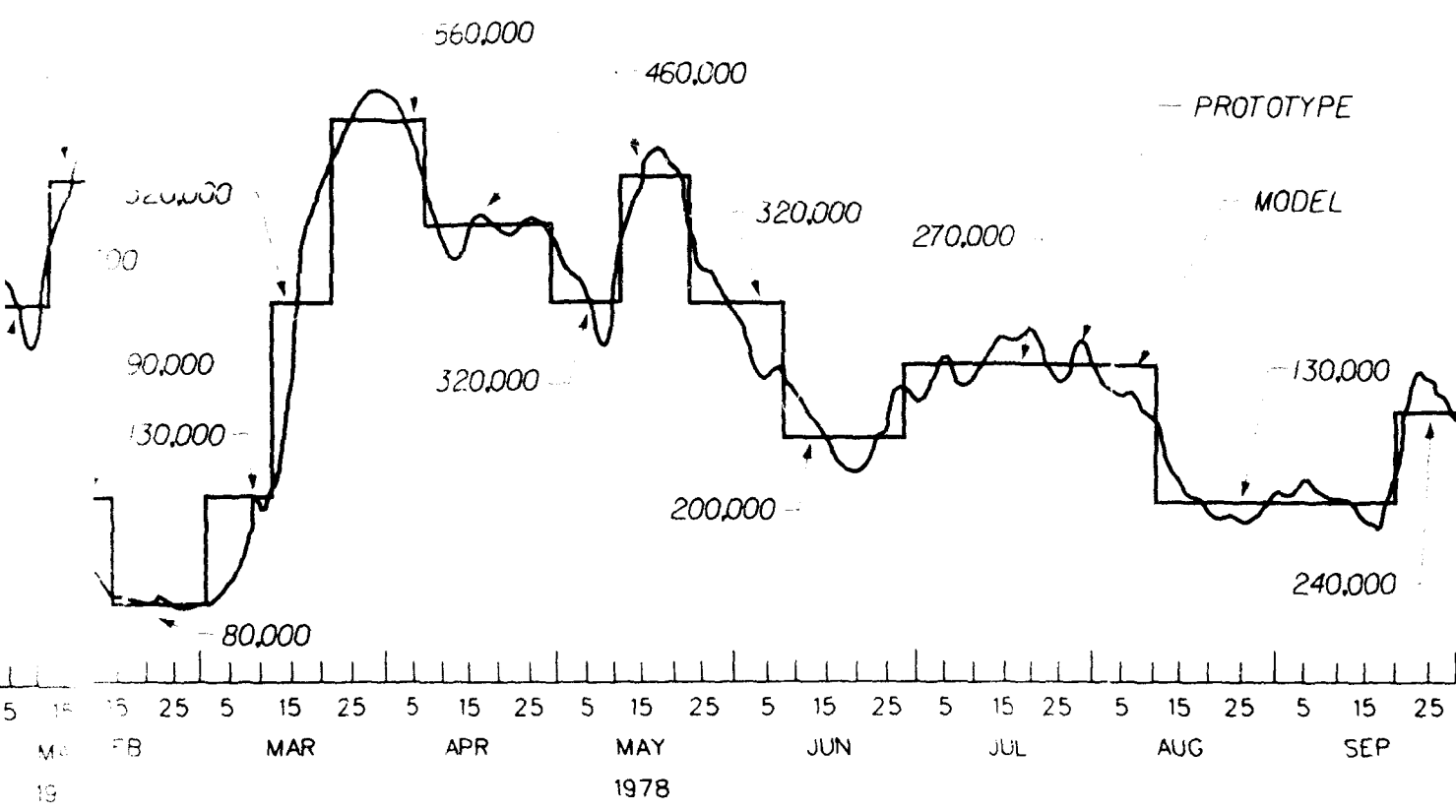
CHANNEL CONFIGURATIONS  
 PROTOTYPE - MARCH 1977

293/292  
LWRP

293/292  
LWRP






NOTE: VALUES SHOWN ON HYDROGRAPH  
ARE THE PROTOTYPE DISCHARGES IN CFS.

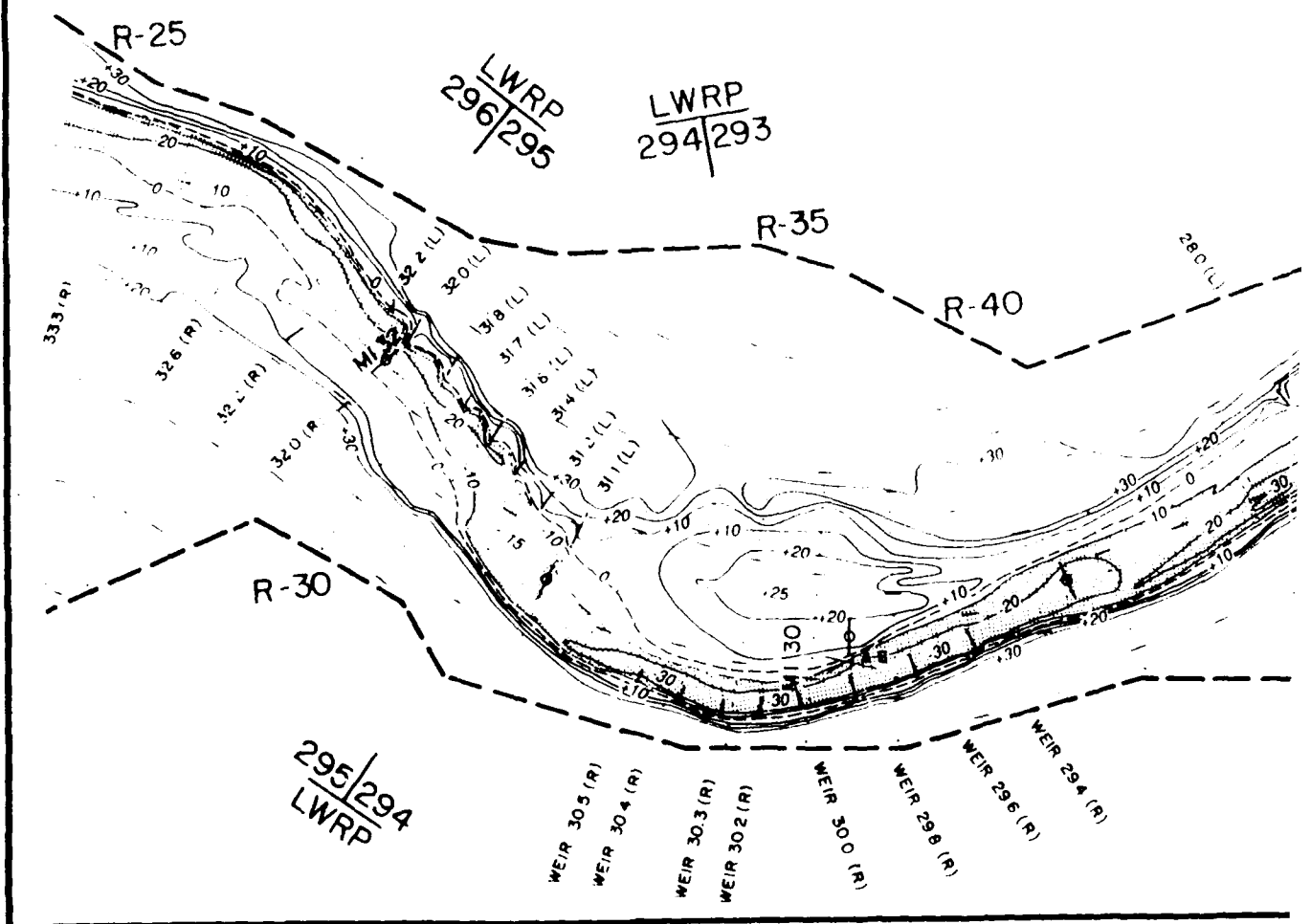
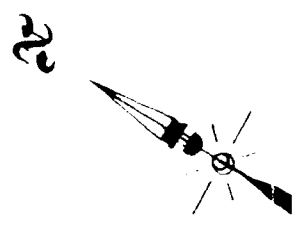


VERIFICATION HYDROGRAPH

# LEGEND

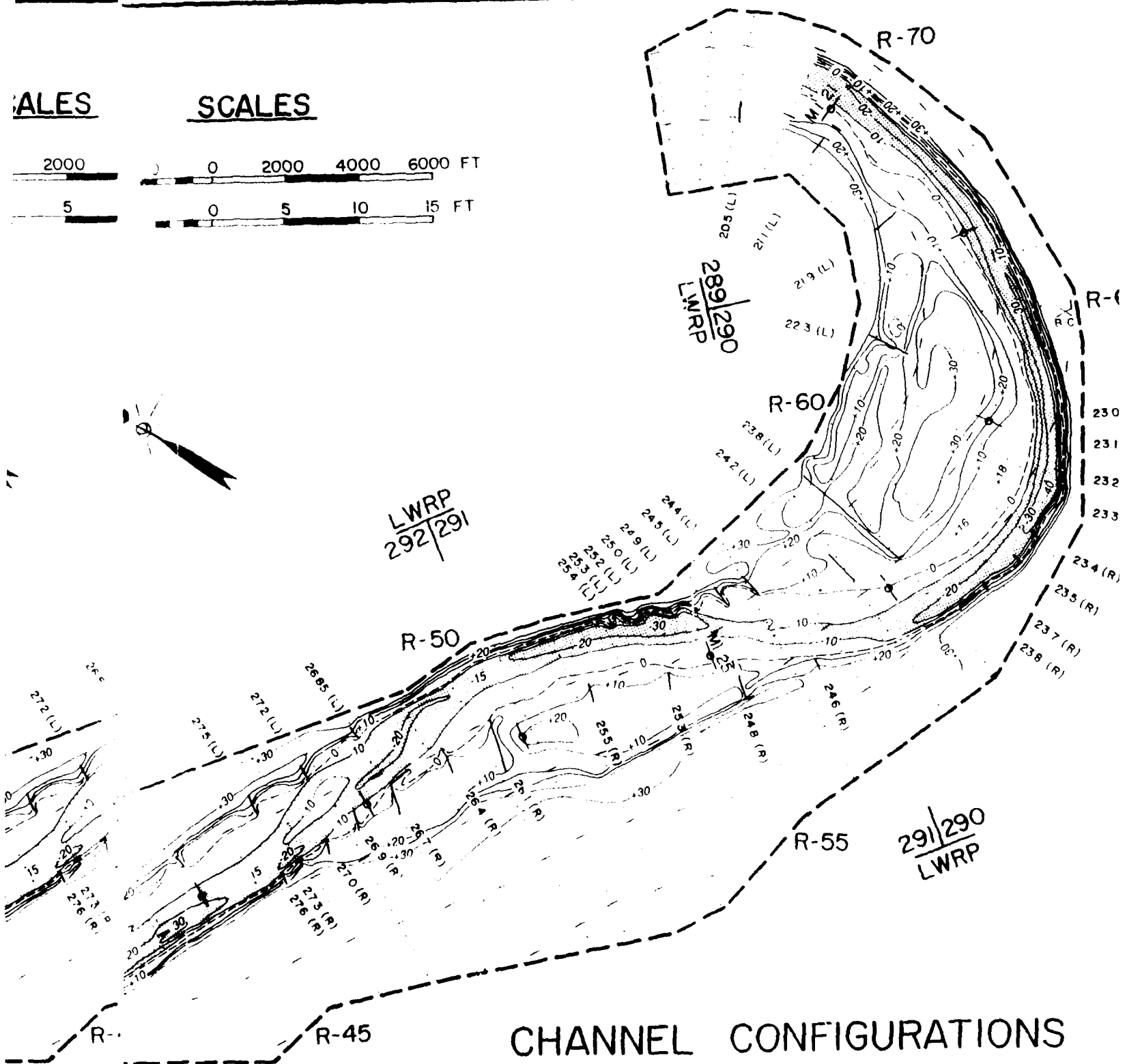
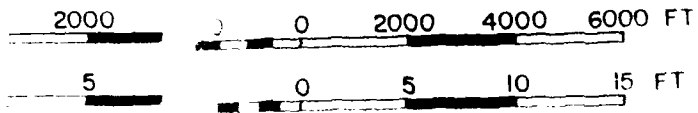
-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE  2000  
 MODEL  5



SALES

SCALES



# CHANNEL CONFIGURATIONS

## PROTOTYPE - APRIL 1983

293/290  
LWR

293/292  
LWRP

291/290  
LWRP

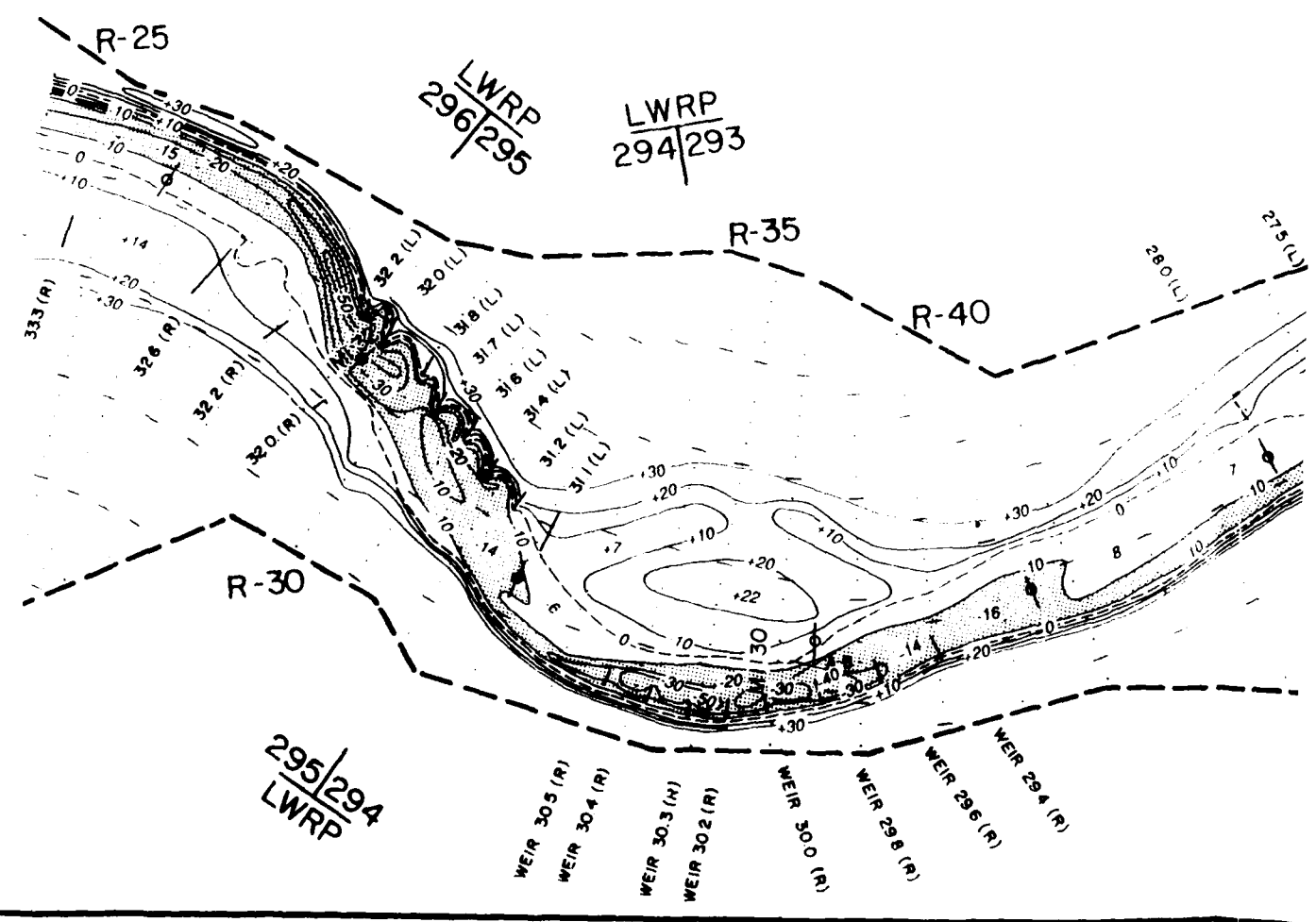
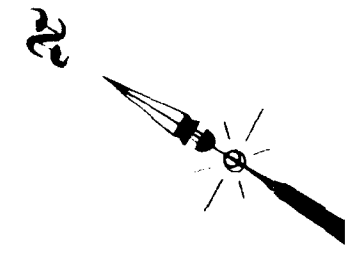
## LEGEND

- 10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

S

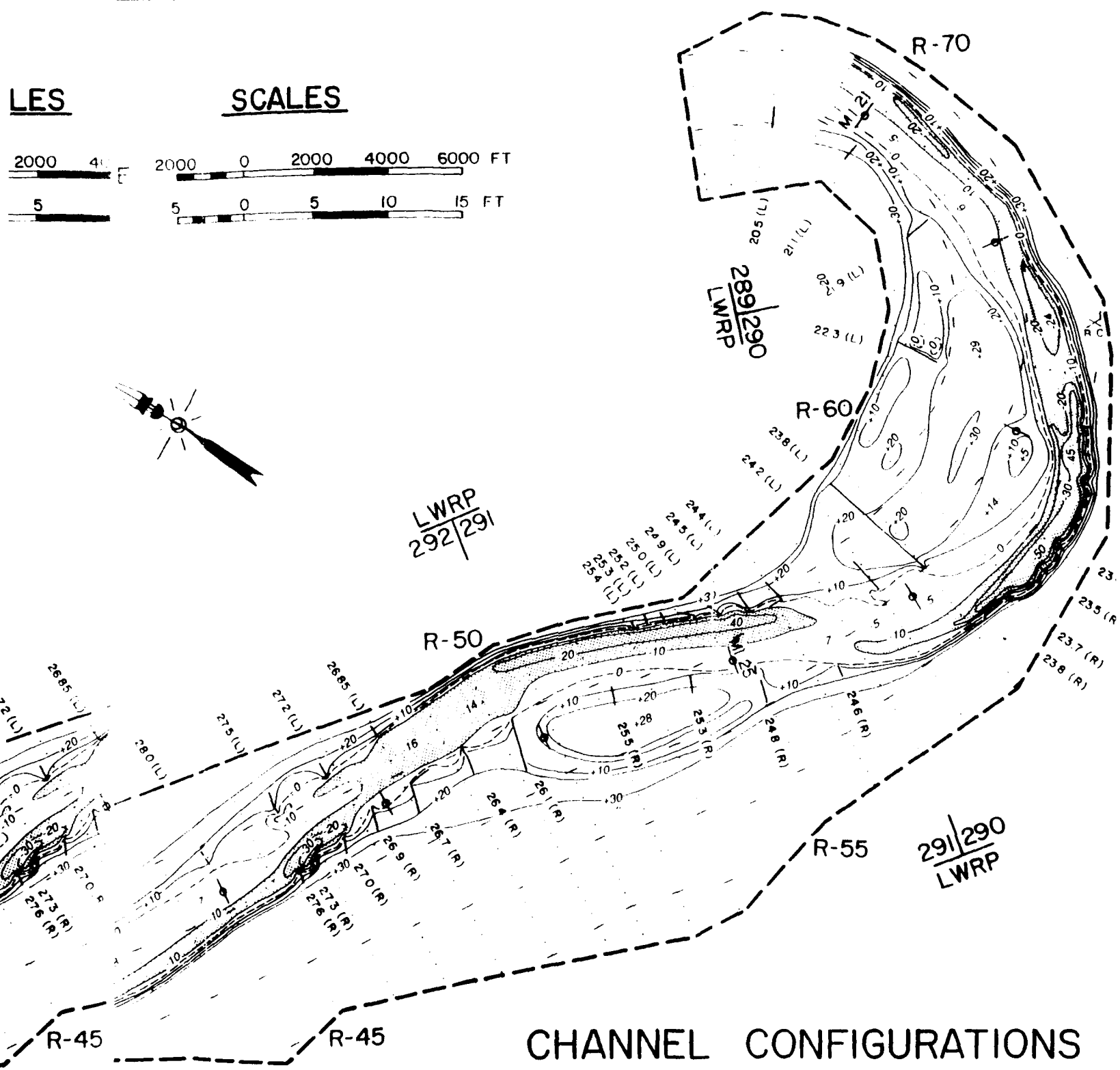
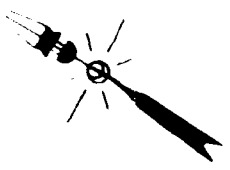
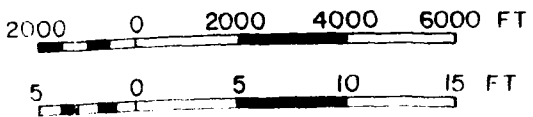
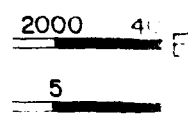
PROTOTYPE  2000 C

MODEL  5 C



LES

SCALES

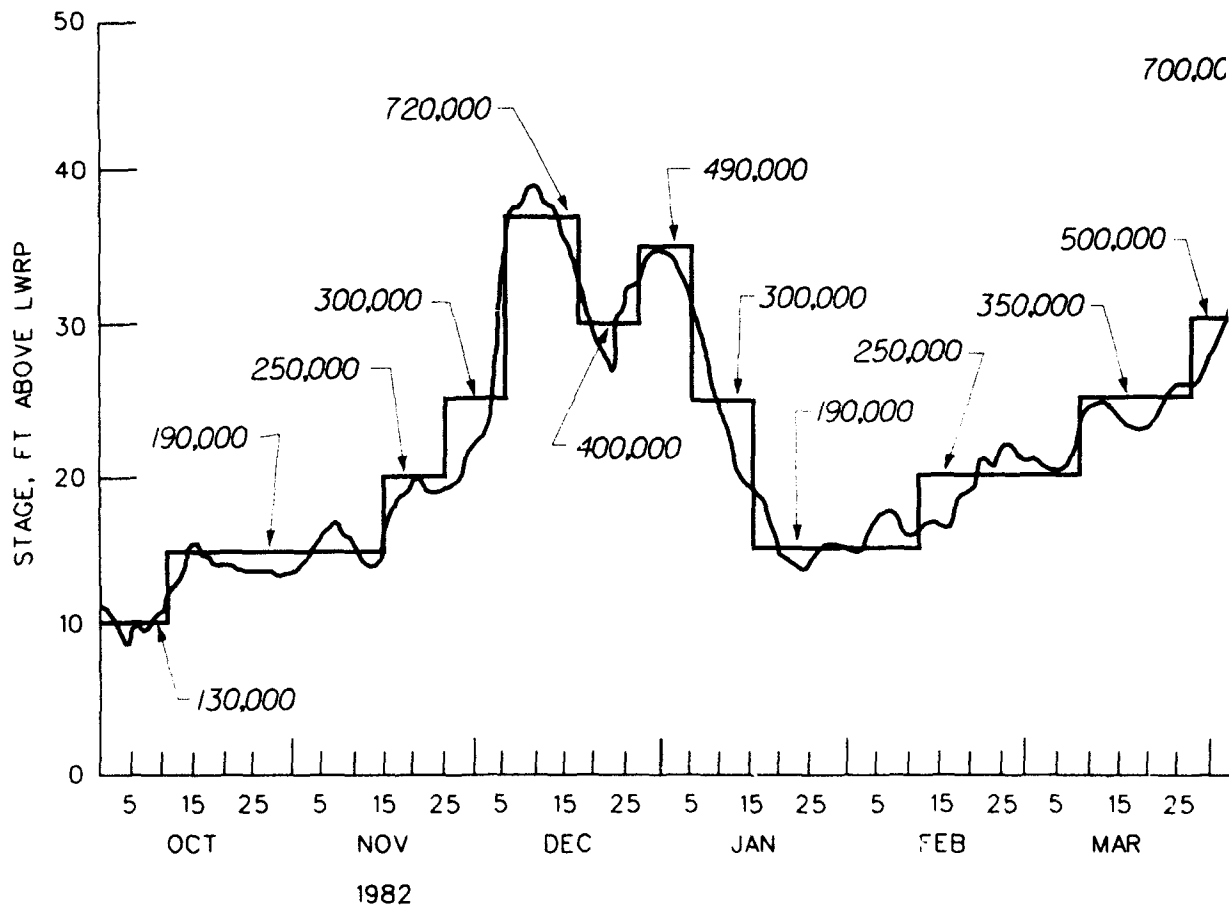


# CHANNEL CONFIGURATIONS VERIFICATION RUN 5

293/292  
LWRP

293/292  
LWRP

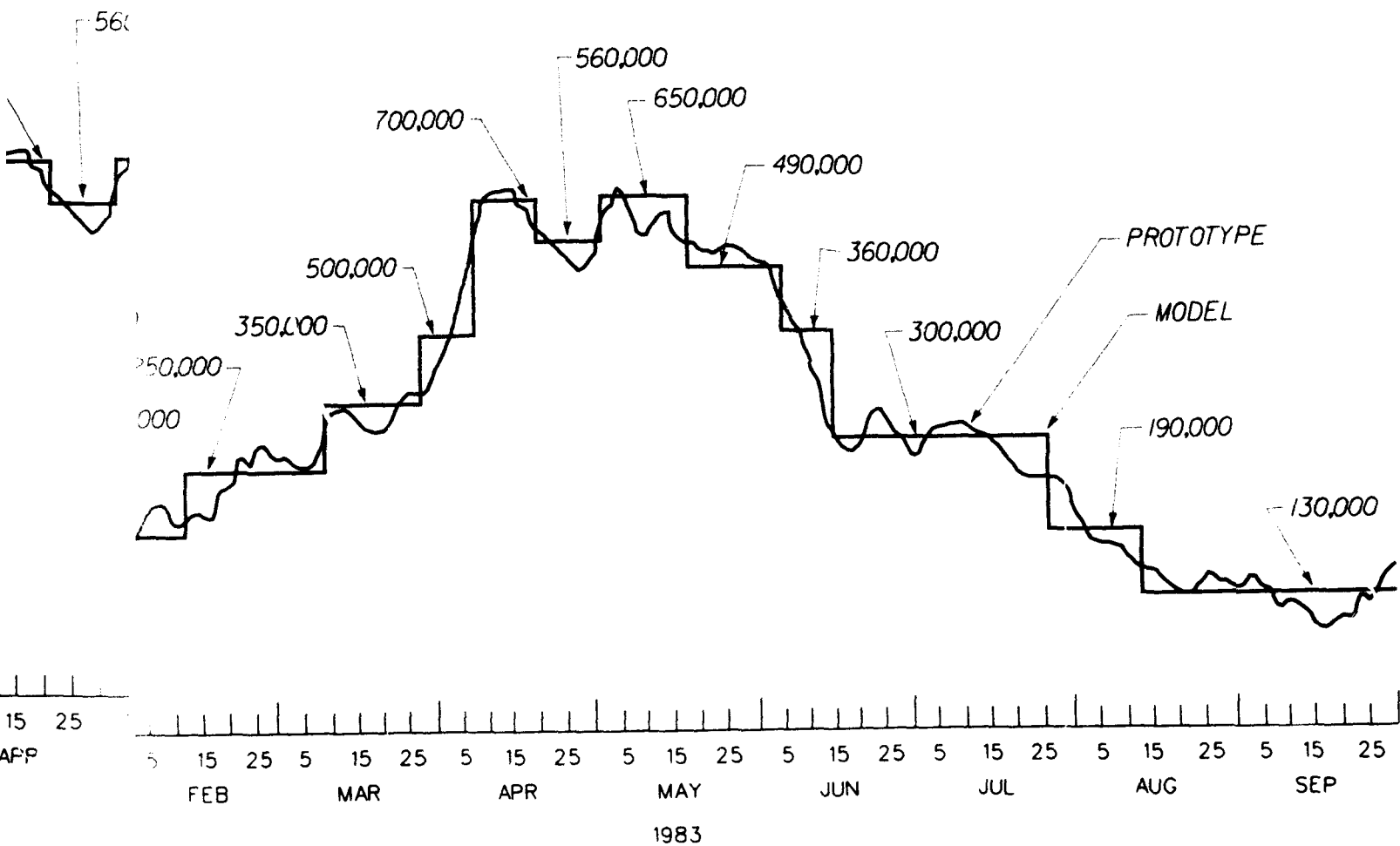




NOTE: VALUES SHOWN ON HYDROGRAPH ARE THE PROTOTYPE DISCHARGES IN CFS.


5



R)  
U)  
R)  
U)

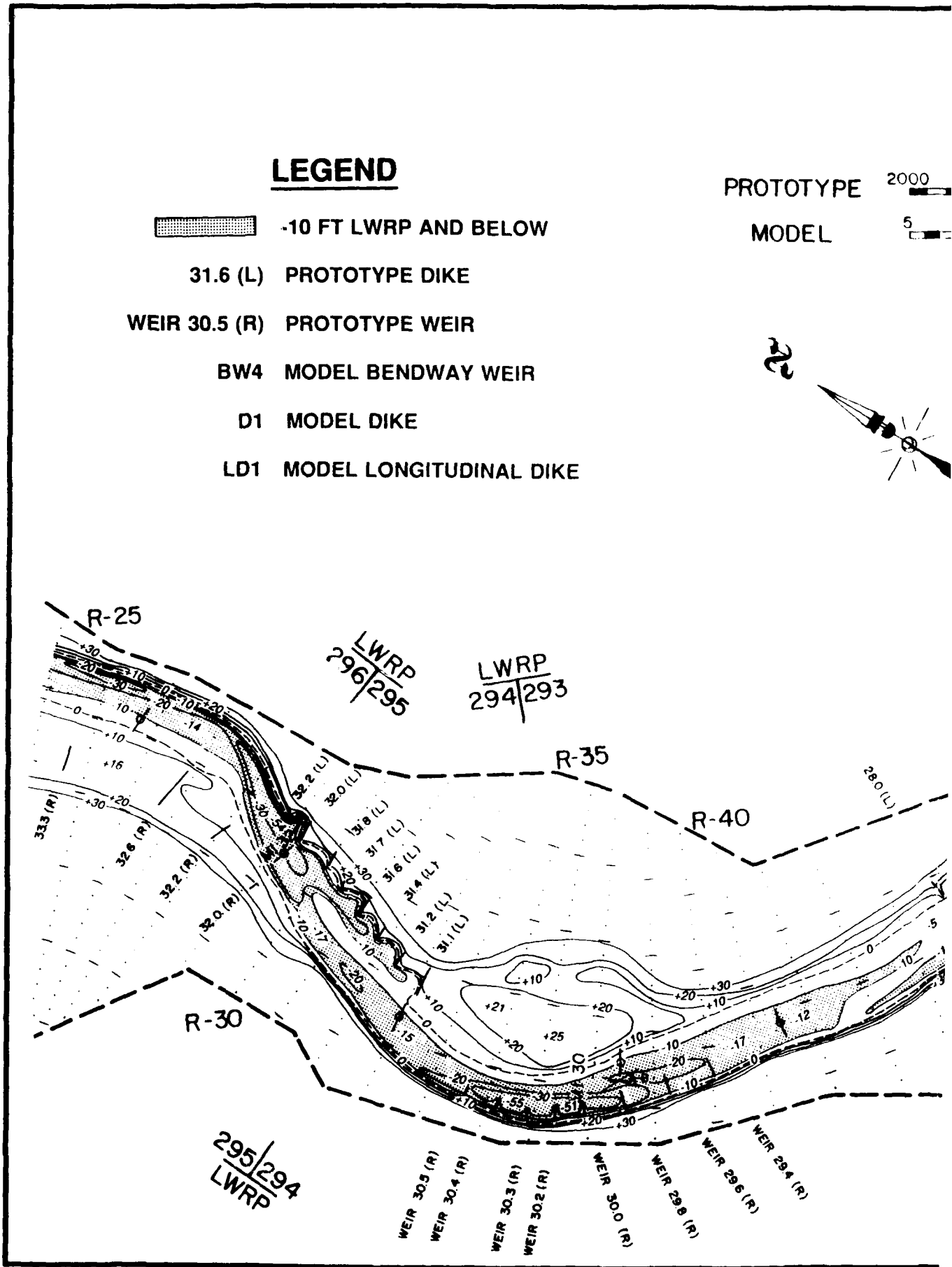
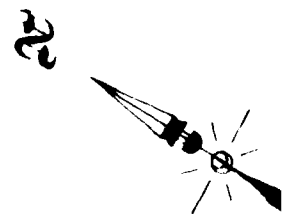


FLOOD HYDROGRAPH - 1983 PROTOTYPE

# LEGEND

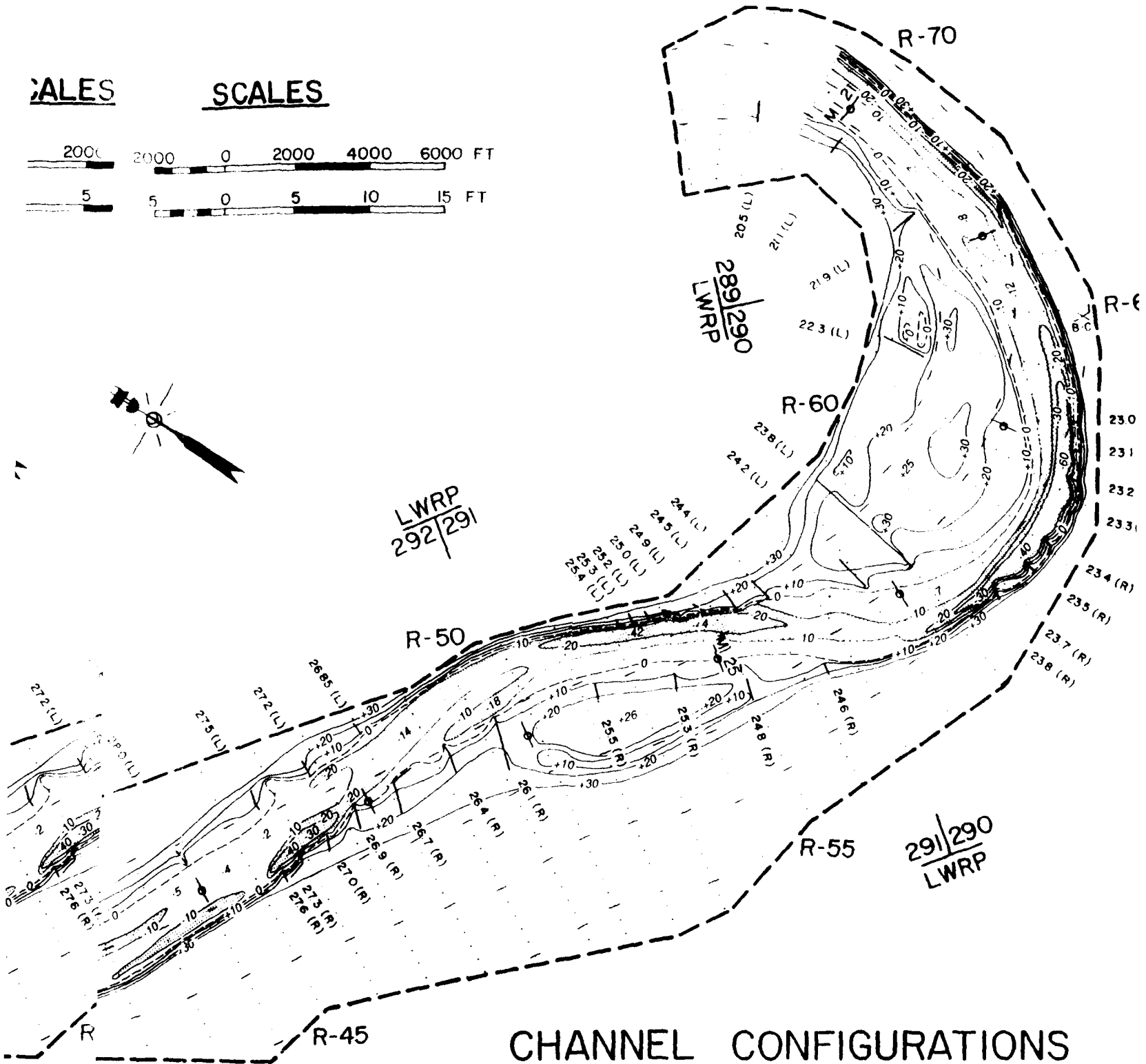
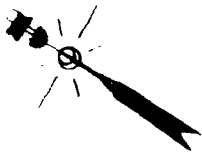
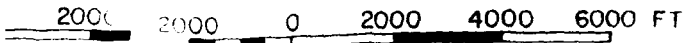
-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE  2000  
 MODEL  5



SALES

SCALES

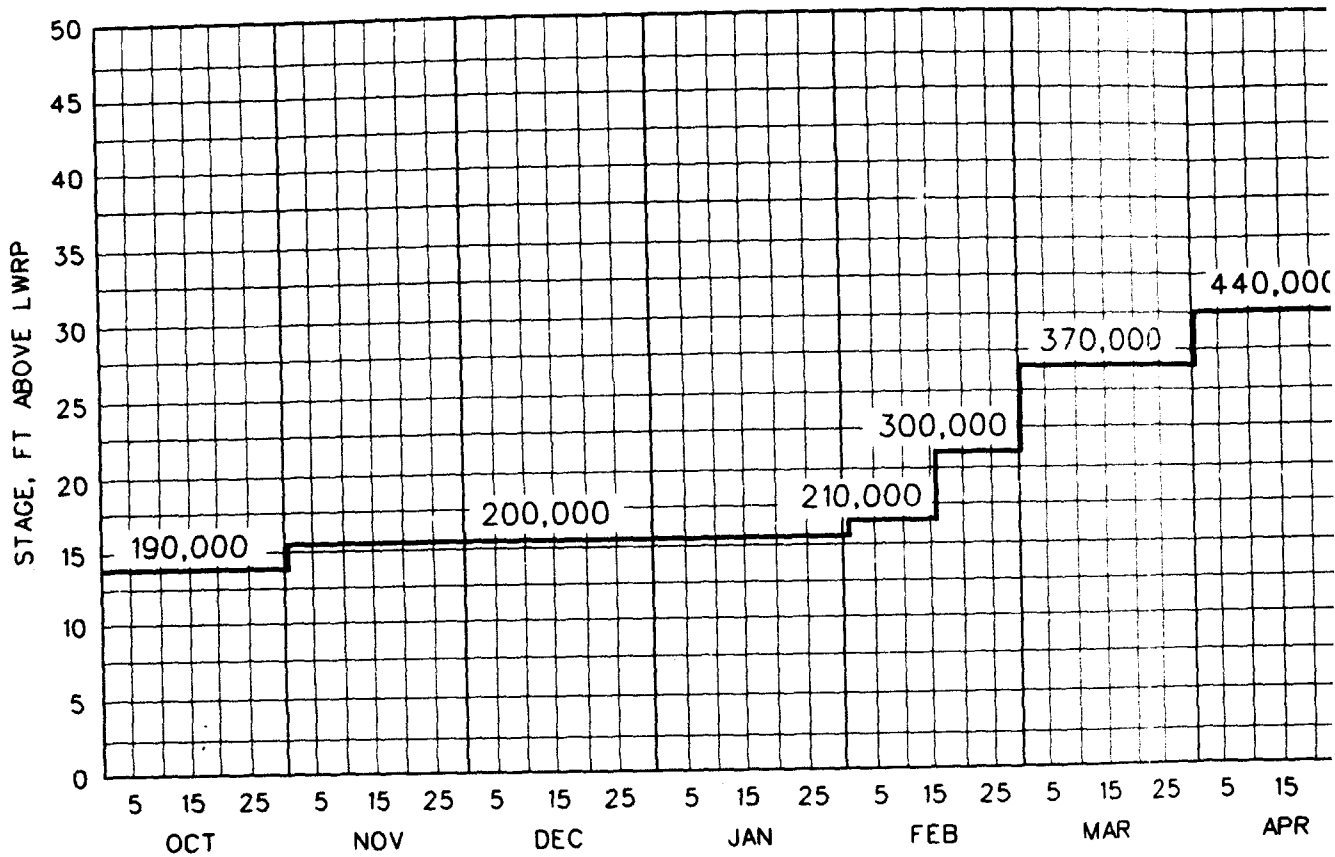


# CHANNEL CONFIGURATIONS

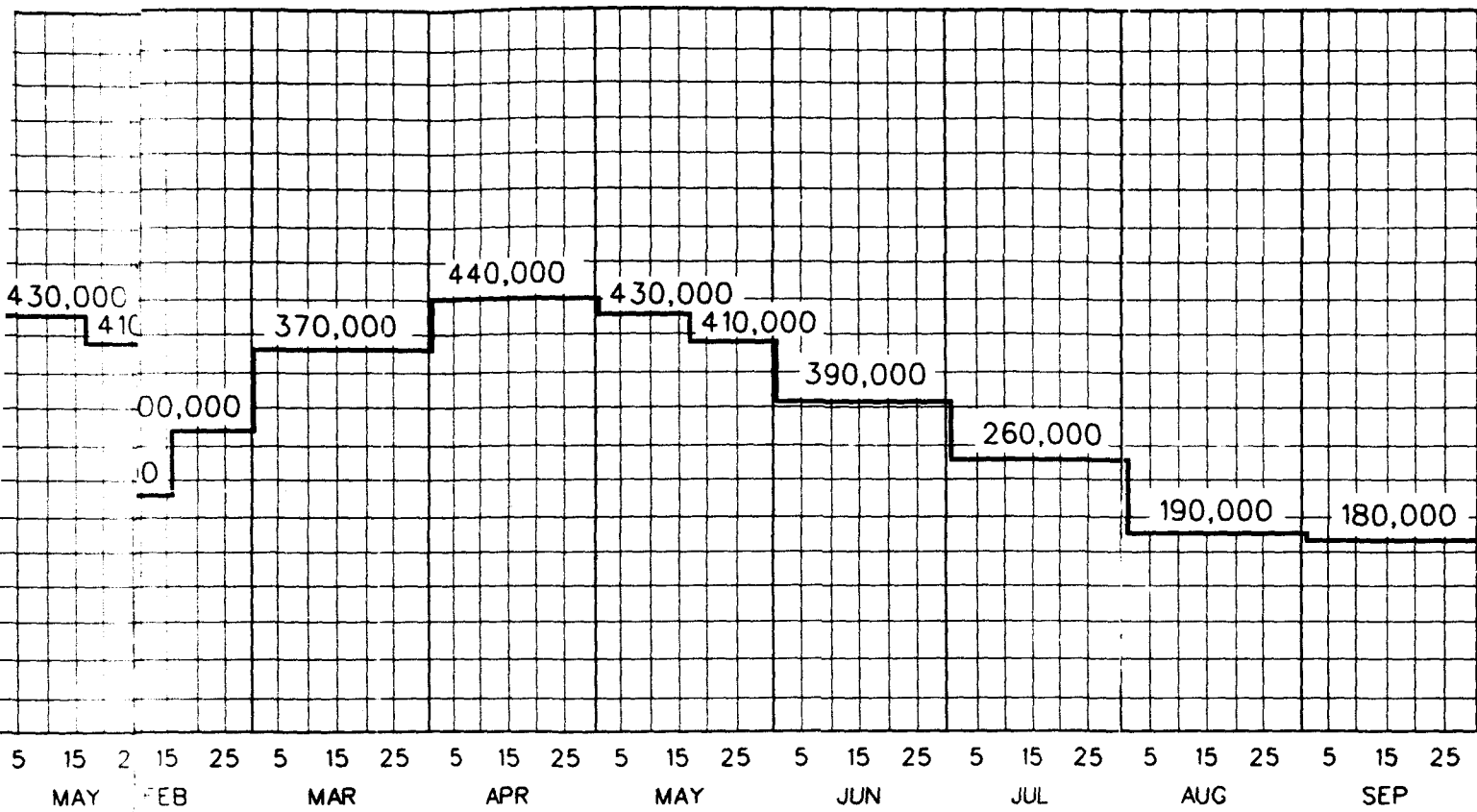
VERIFICATION RUN 2  
1983 FLOOD HYDROGRAPH

293/292  
LWRP

293/292  
LWRP



NOTE: VALUES SHOWN ON HYDROGRAPH  
ARE THE PROTOTYPE DISCHARGES IN CFS.



AVERAGE ANNUAL HYDROGRAPH

SC

### LEGEND

 -10 FT LWRP AND BELOW

31.6 (L) PROTOTYPE DIKE

WEIR 30.5 (R) PROTOTYPE WEIR

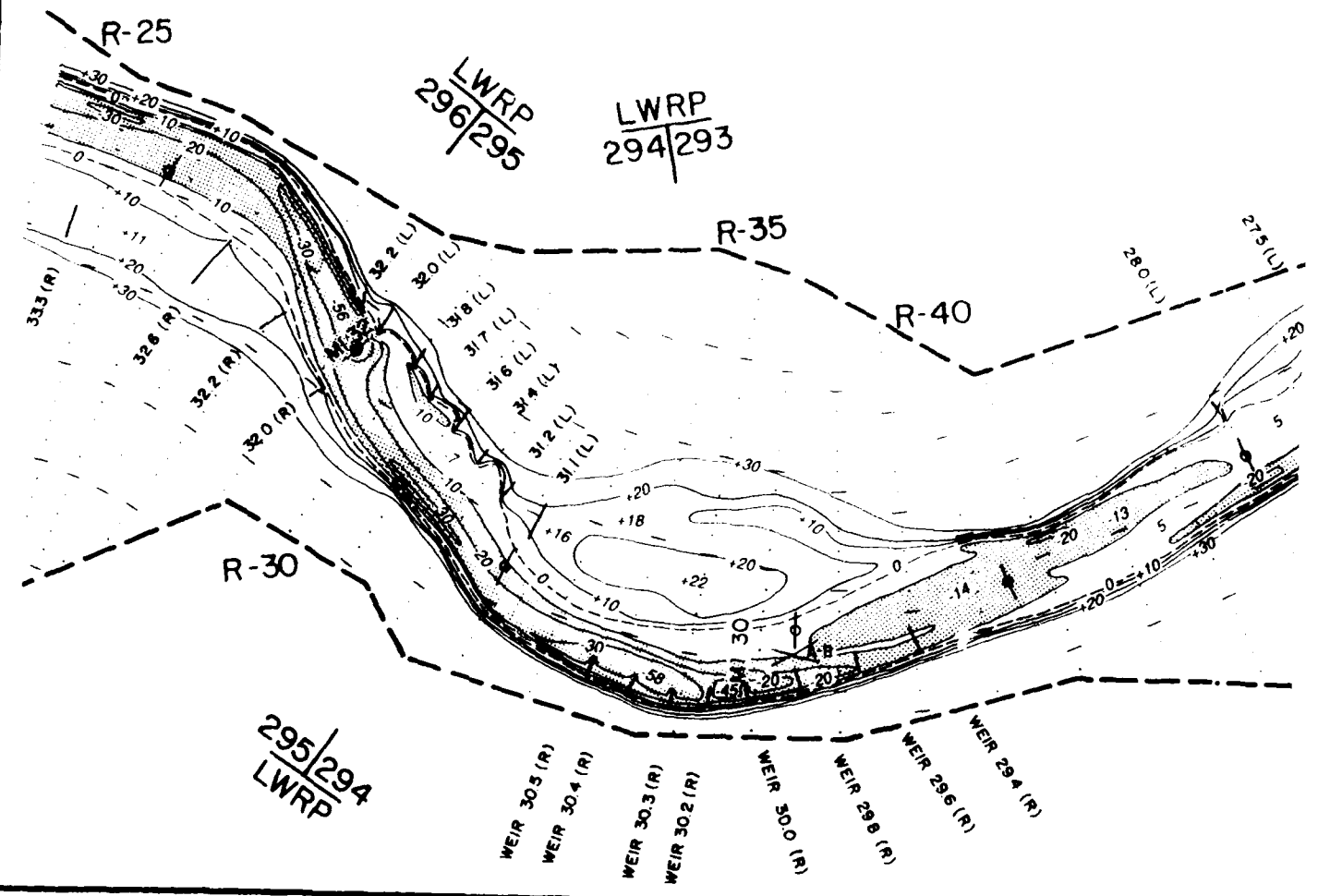
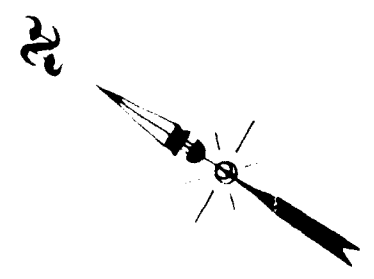
BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

LD1 MODEL LONGITUDINAL DIKE

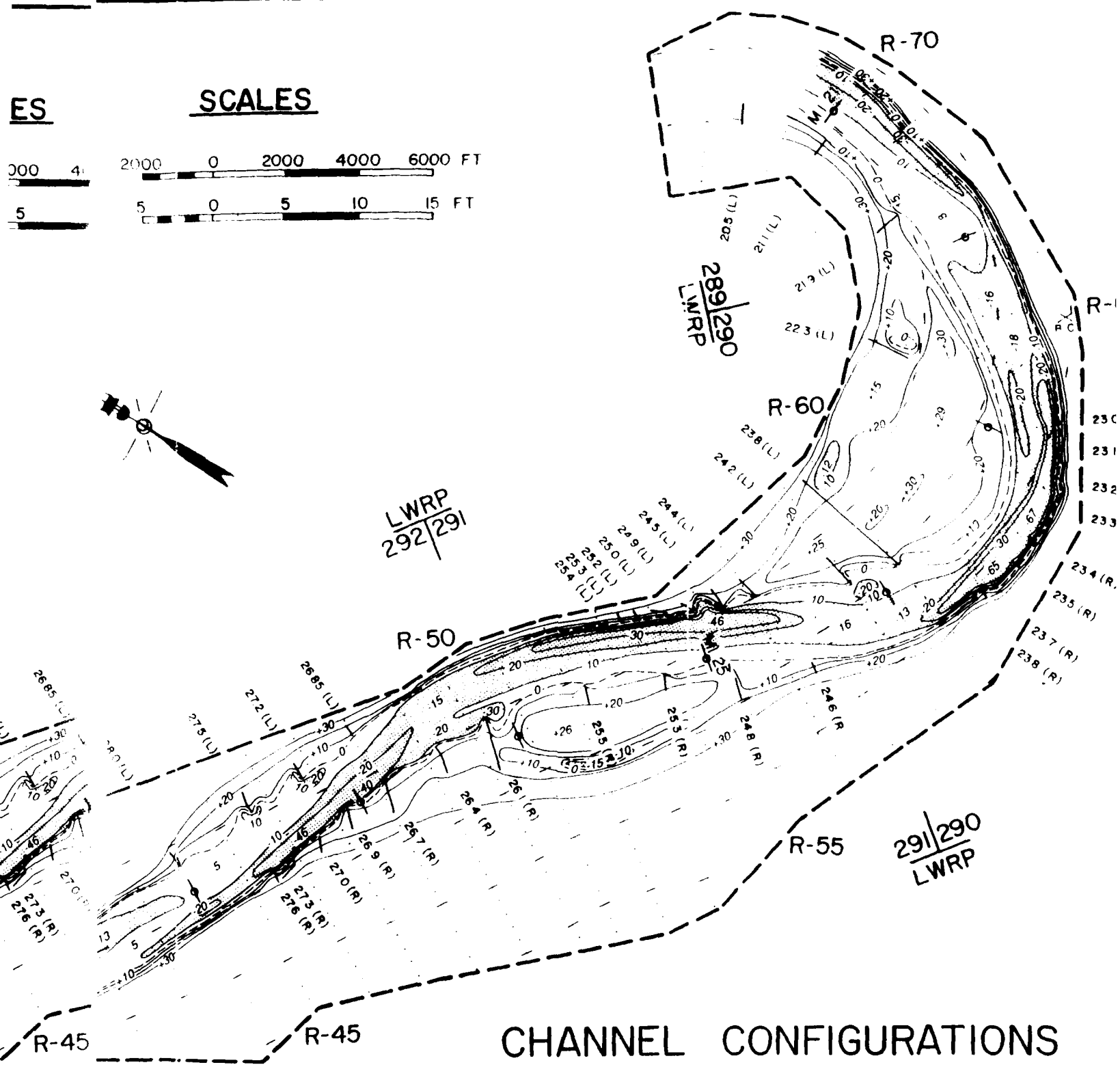
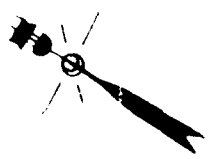
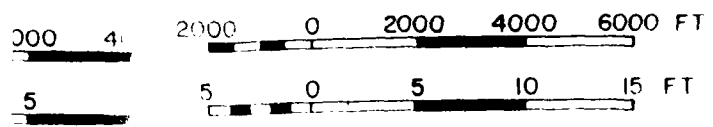
PROTOTYPE  2000 0

MODEL  5 0



ES

SCALES




CHANNEL CONFIGURATIONS  
 BASE TEST RERUN RUN 5

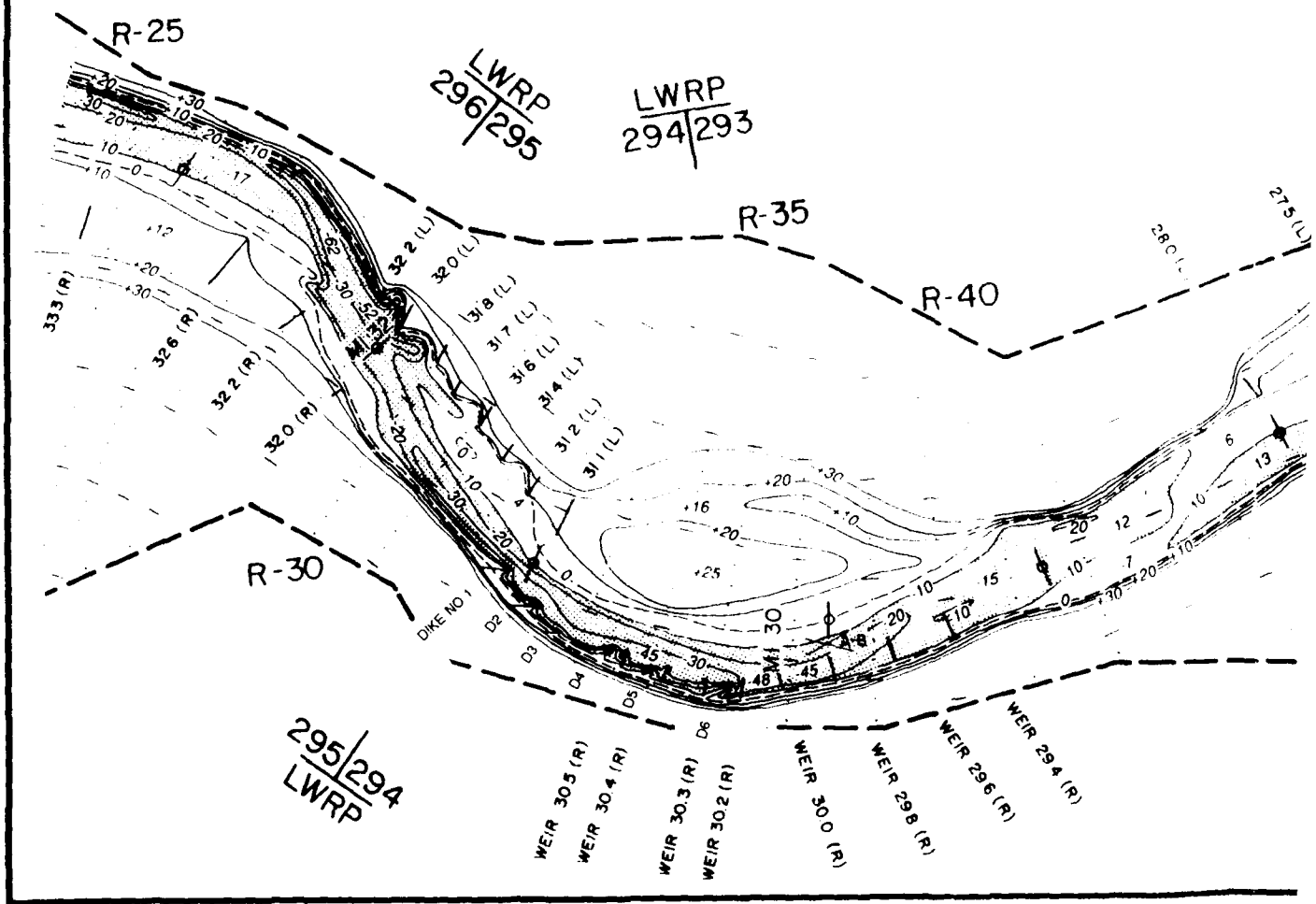
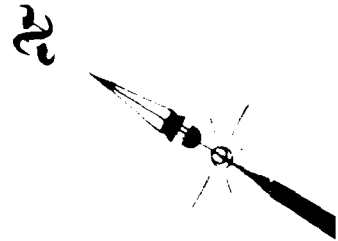
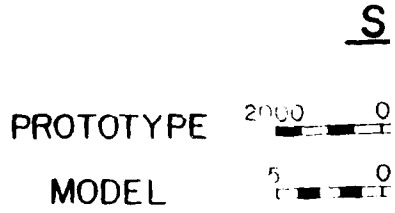
293/292  
 LWRP

293/292  
 LWRP



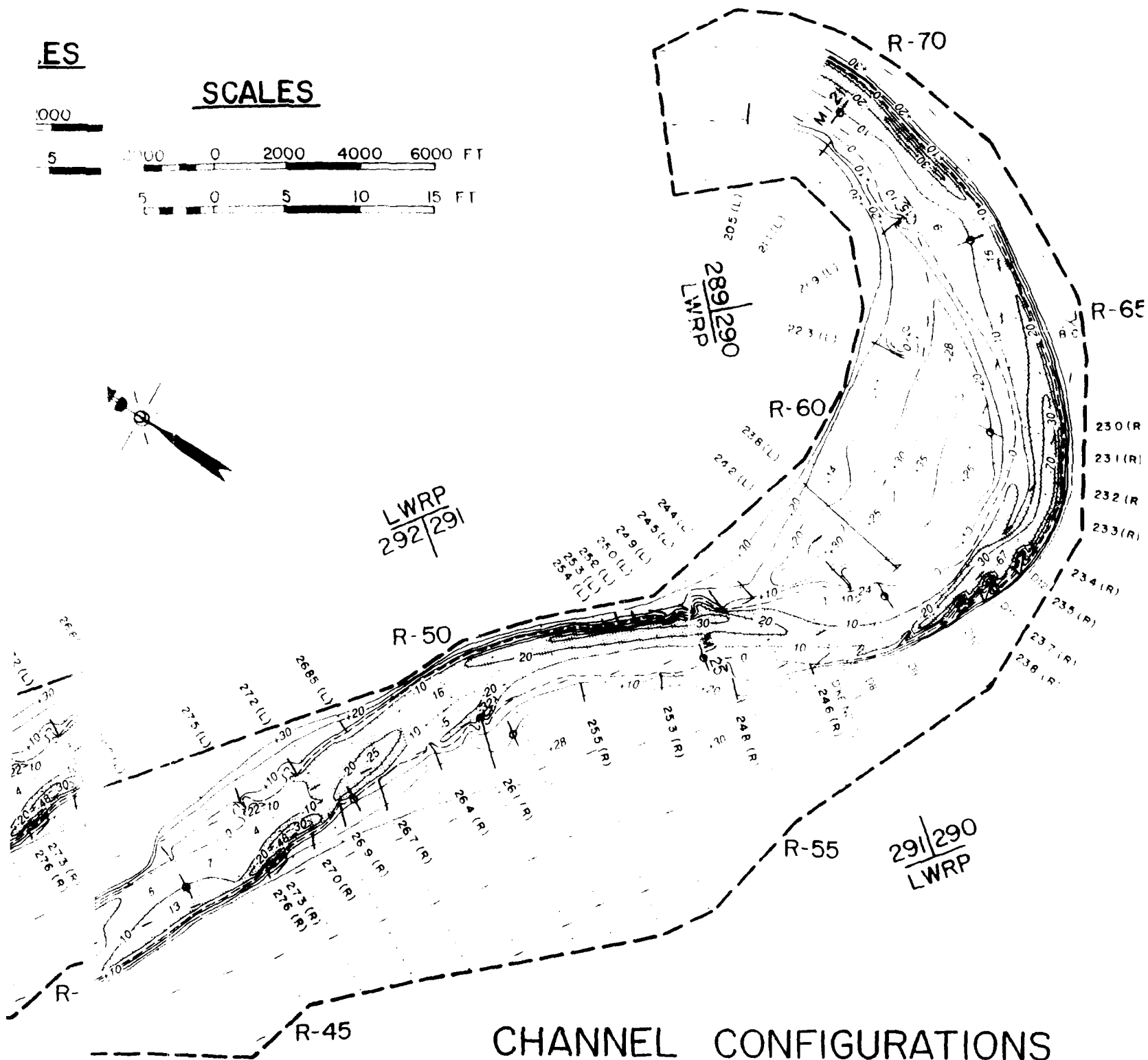
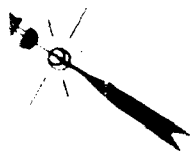
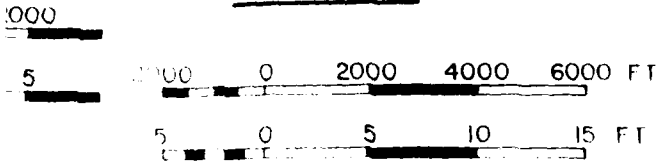
# LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



ES

SCALES



CHANNEL CONFIGURATIONS

PLAN A RUN 2

293/292  
LWRP

293/292  
LWRP

# LEGEND

 -10 FT LWRP AND BELOW


31.6 (L) PROTOTYPE DIKE

WEIR 30.5 (R) PROTOTYPE WEIR

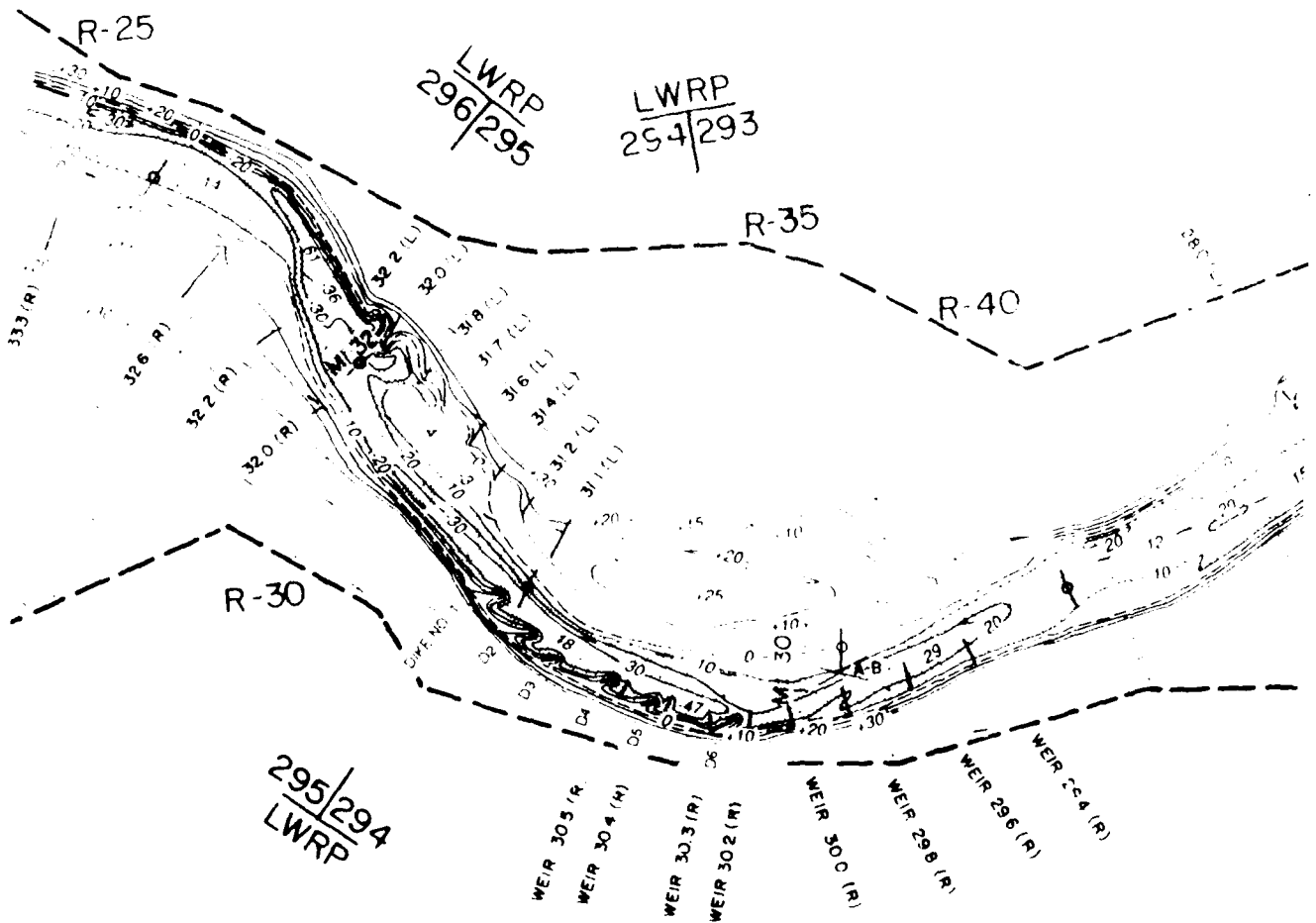
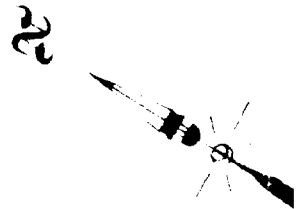
BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

LD1 MODEL LONGITUDINAL DIKE

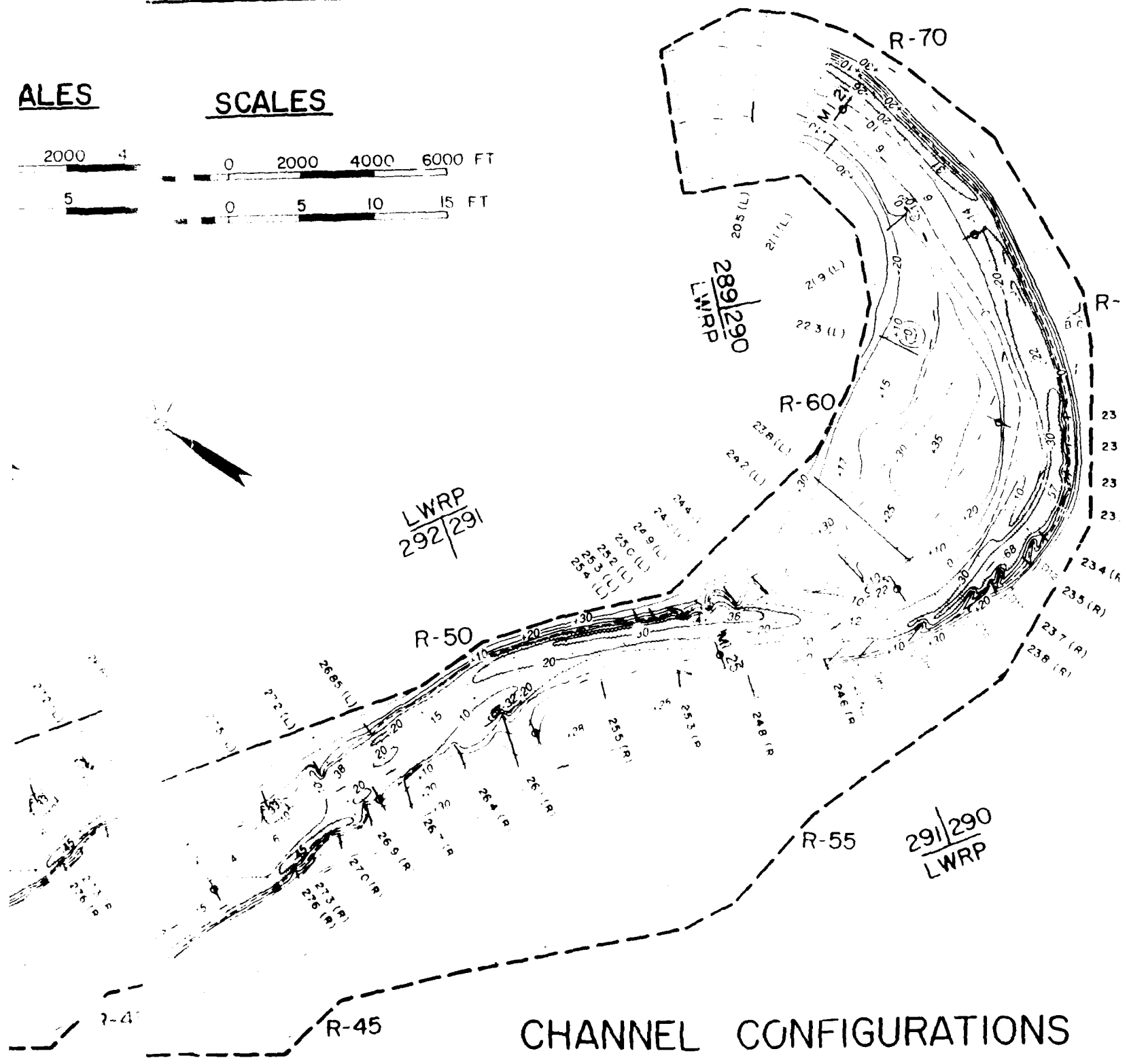
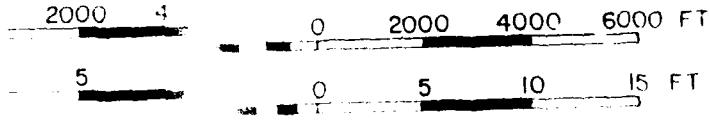
PROTOTYPE  2000

MODEL  5



ALES

SCALES



CHANNEL CONFIGURATIONS  
PLAN A-1 RUN 2

293/292  
LWRP

293/292  
LWRP

# LEGEND



-10 FT LWRP AND BELOW

31.6 (L) PROTOTYPE DIKE

WEIR 30.5 (R) PROTOTYPE WEIR

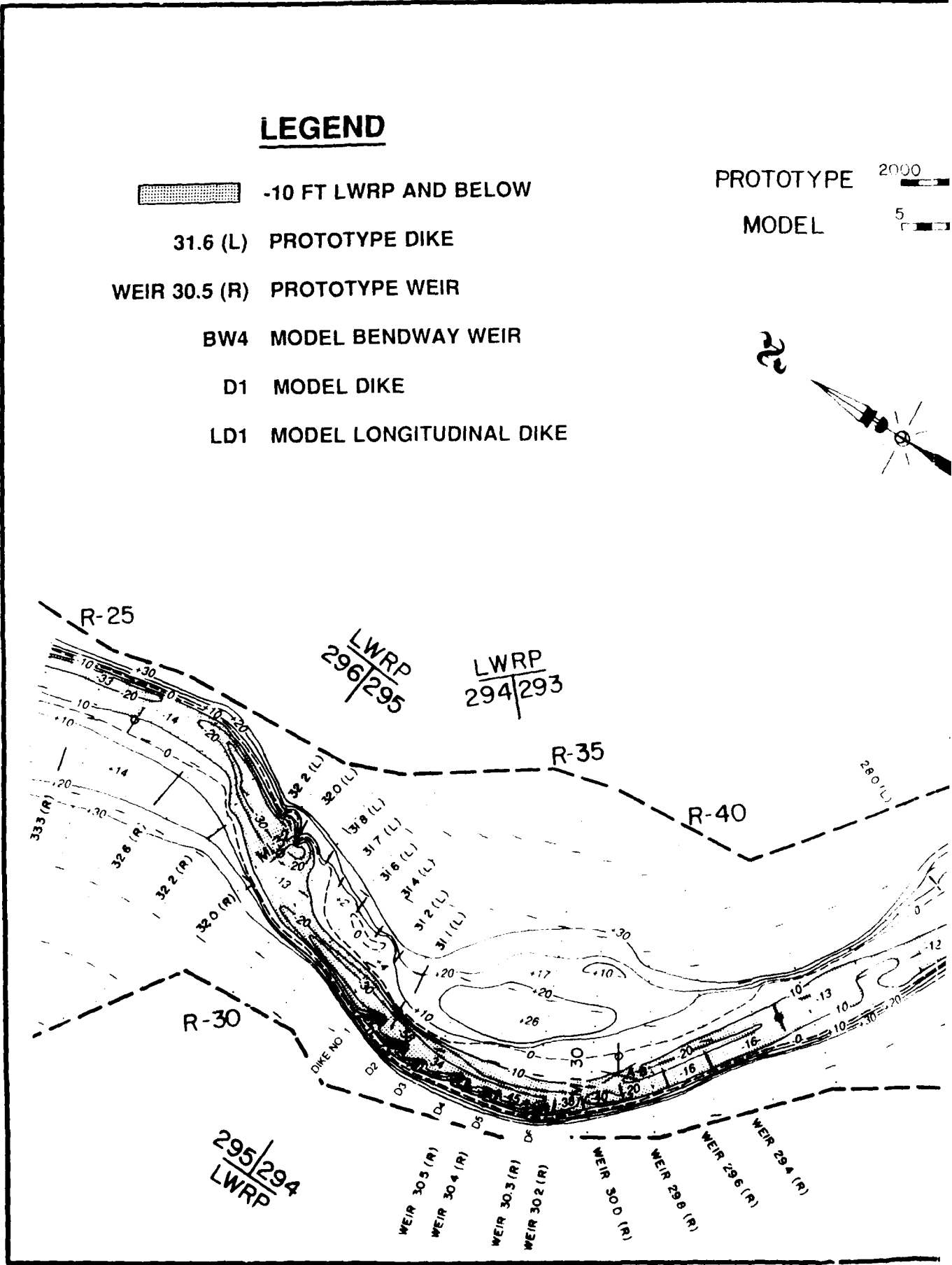
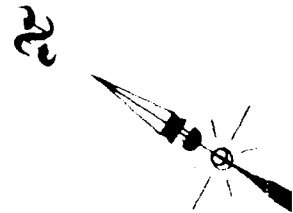
BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

LD1 MODEL LONGITUDINAL DIKE

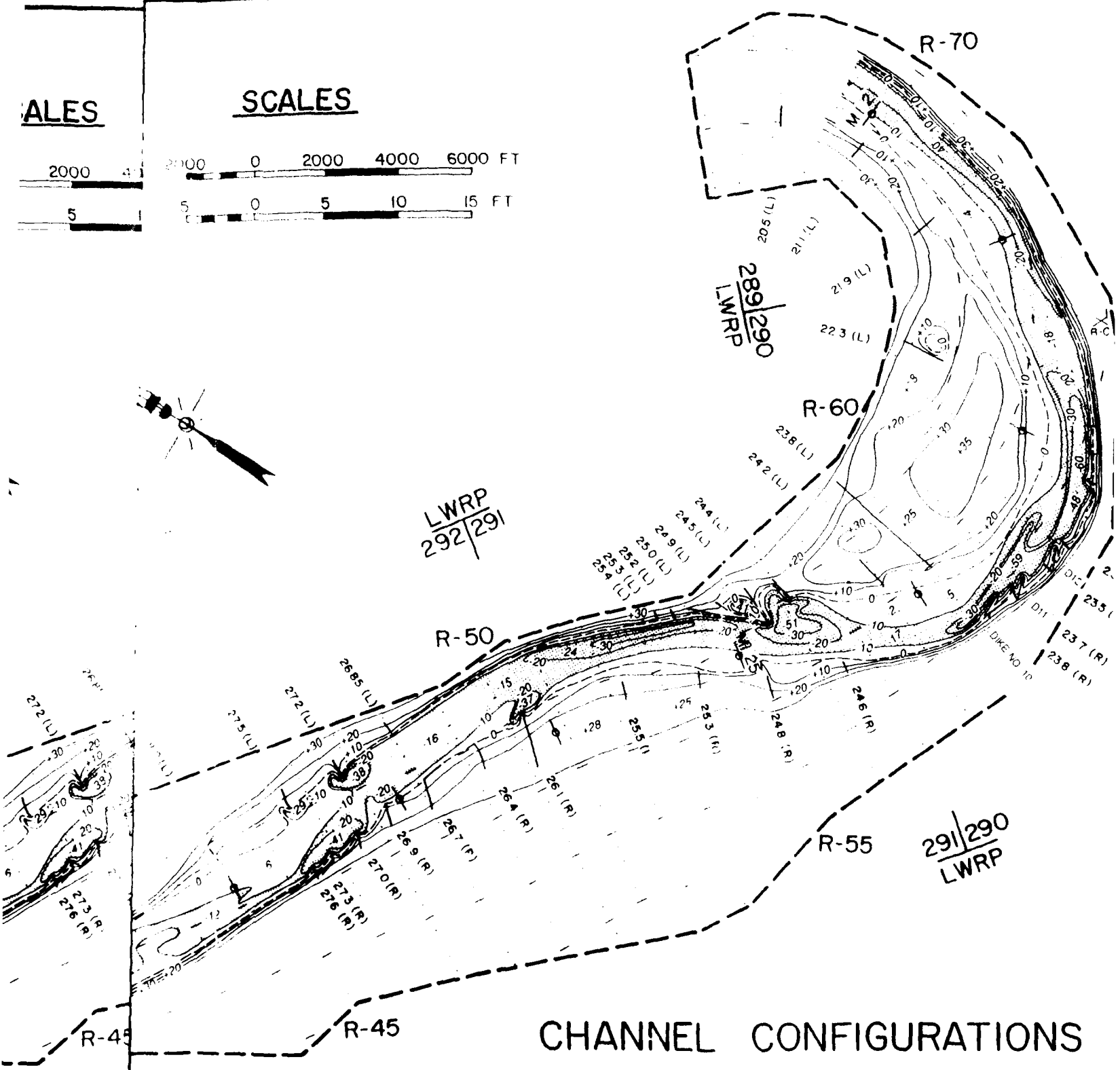
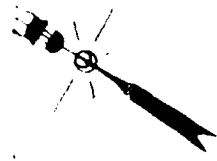
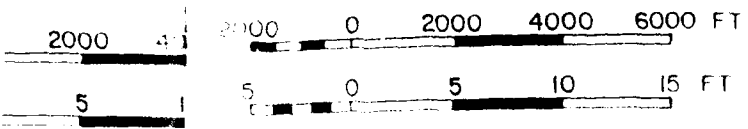
PROTOTYPE 2000

MODEL 5



MALES

SCALES



# CHANNEL CONFIGURATIONS

PLAN B RUN 2

293/292  
LWRP

293/292  
LWRP

291/290  
LWRP

292/291  
LWRP

289/290  
LWRP

# LEGEND



-10 FT LWRP AND BELOW

31.6 (L) PROTOTYPE DIKE

WEIR 30.5 (R) PROTOTYPE WEIR

BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

LD1 MODEL LONGITUDINAL DIKE

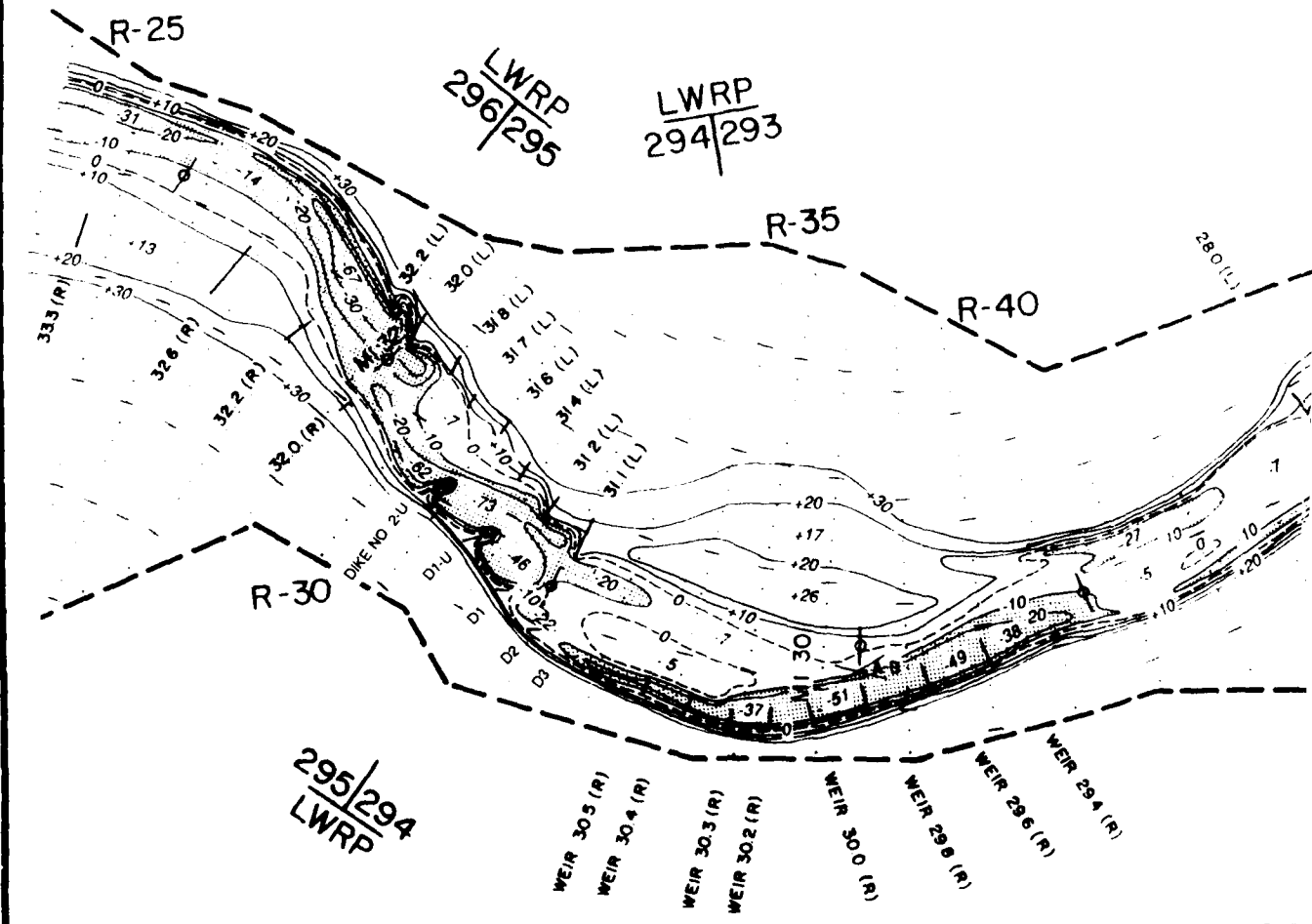
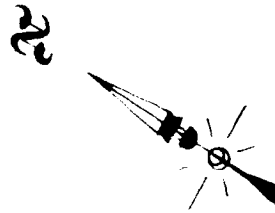
PROTOTYPE

2000



MODEL

5



5

(R)

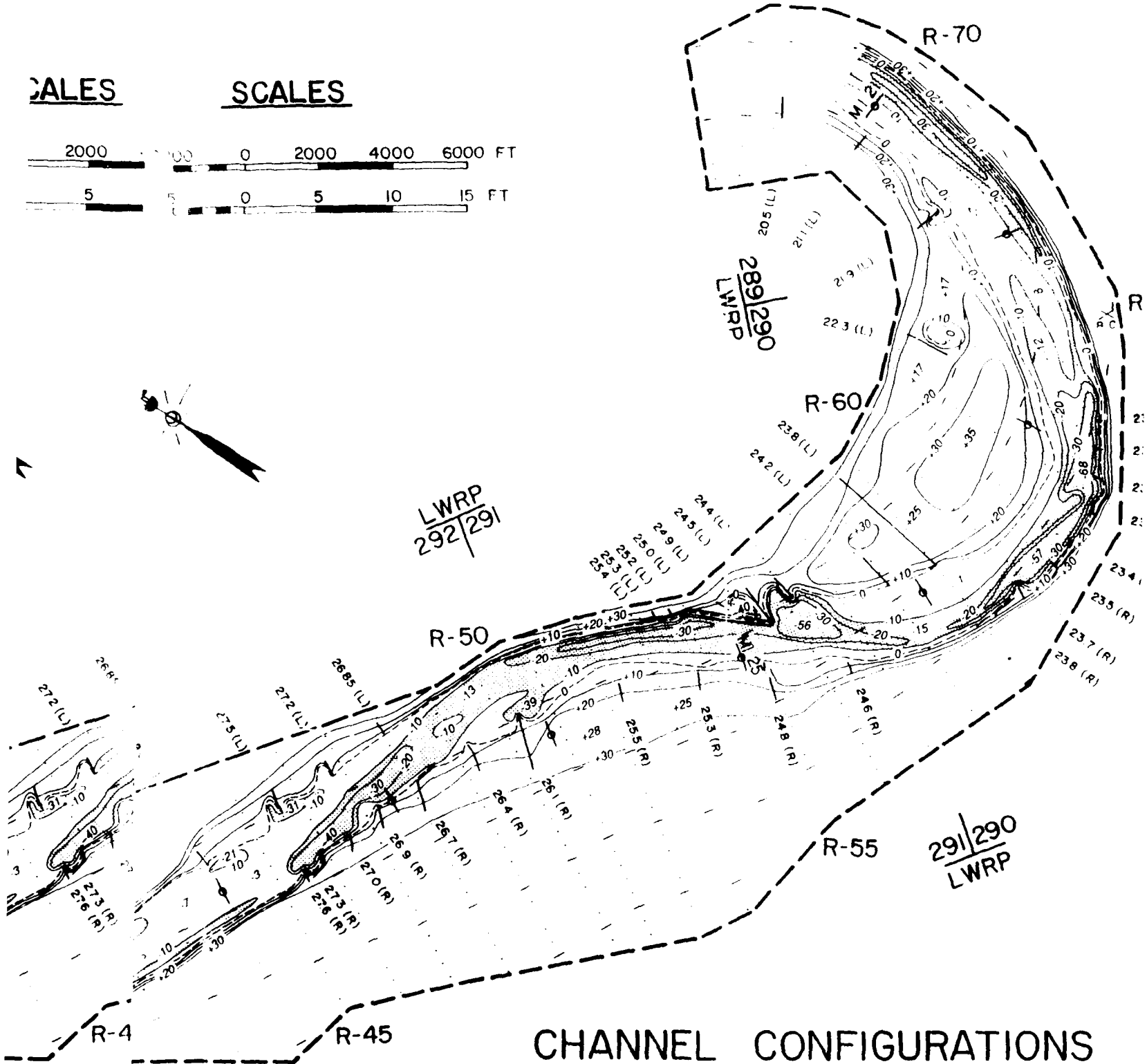
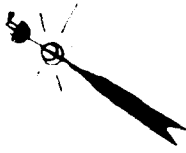
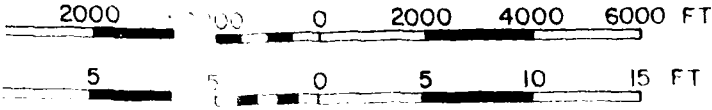
(R)

(R)

(R)

SCALES

SCALES



# CHANNEL CONFIGURATIONS

## PLAN C RUN 2

293/297  
LWRP

293/292  
LWRP


289/290  
LWRP



LWRP  
292/291

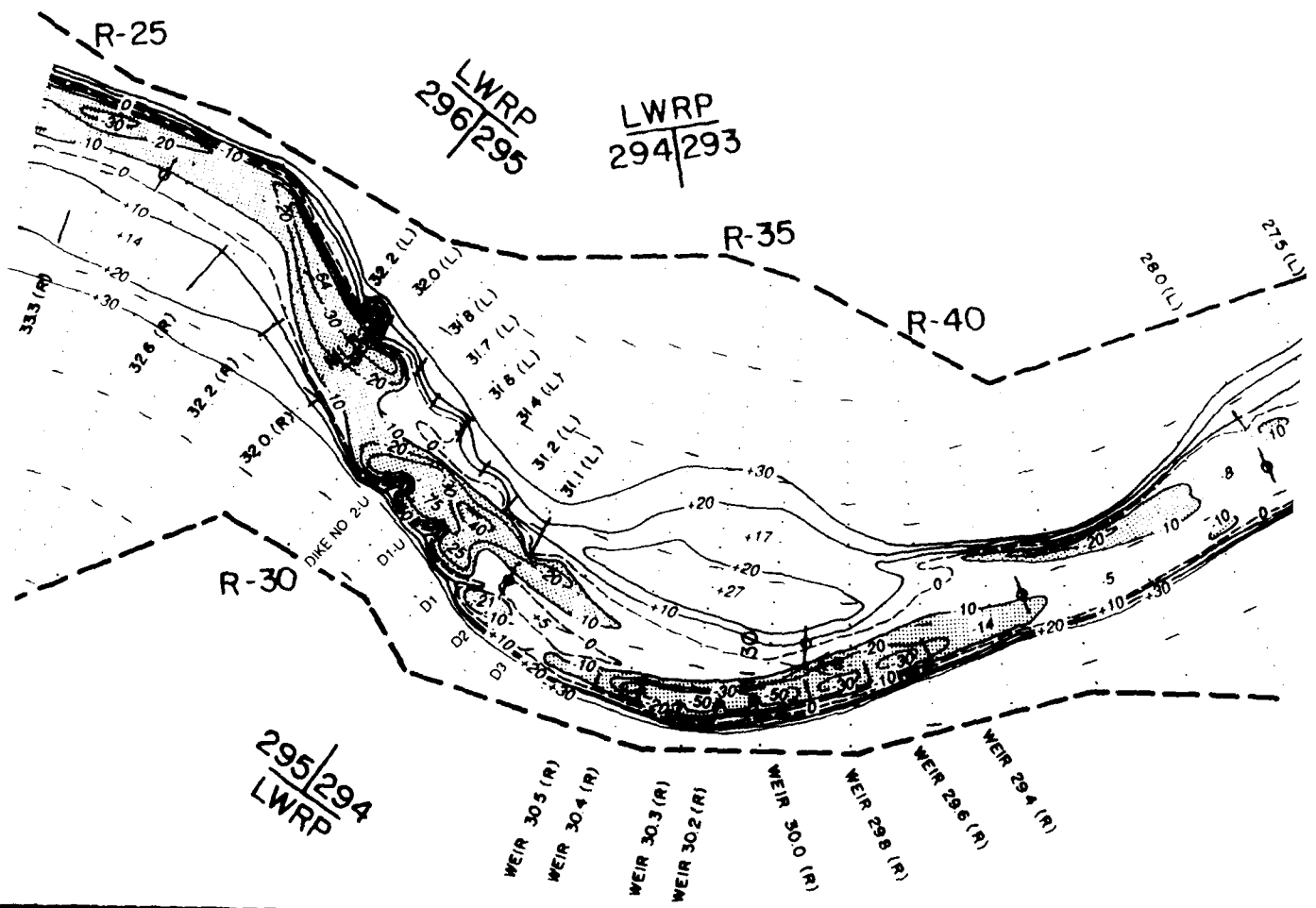
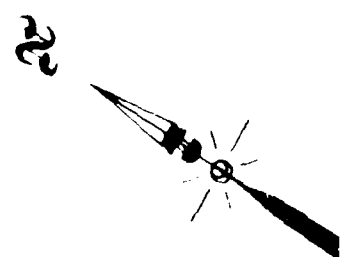
291/290  
LWRP



# LEGEND

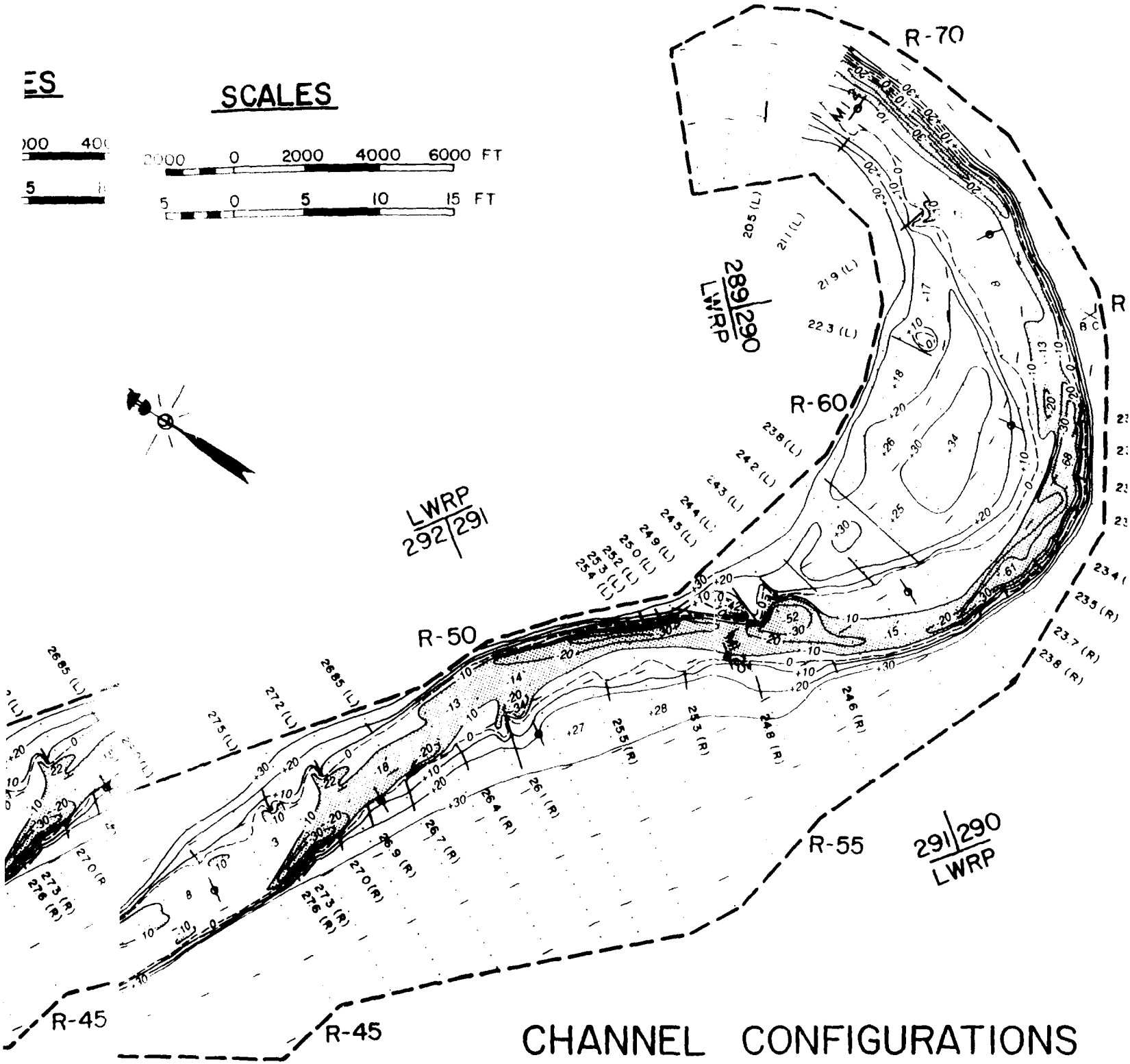
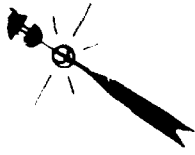
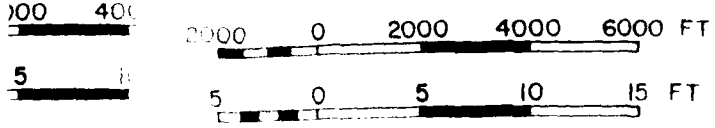
-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE  2000  
 MODEL  5



ES

# SCALES




## CHANNEL CONFIGURATIONS



PLAN C-1 RUN 2

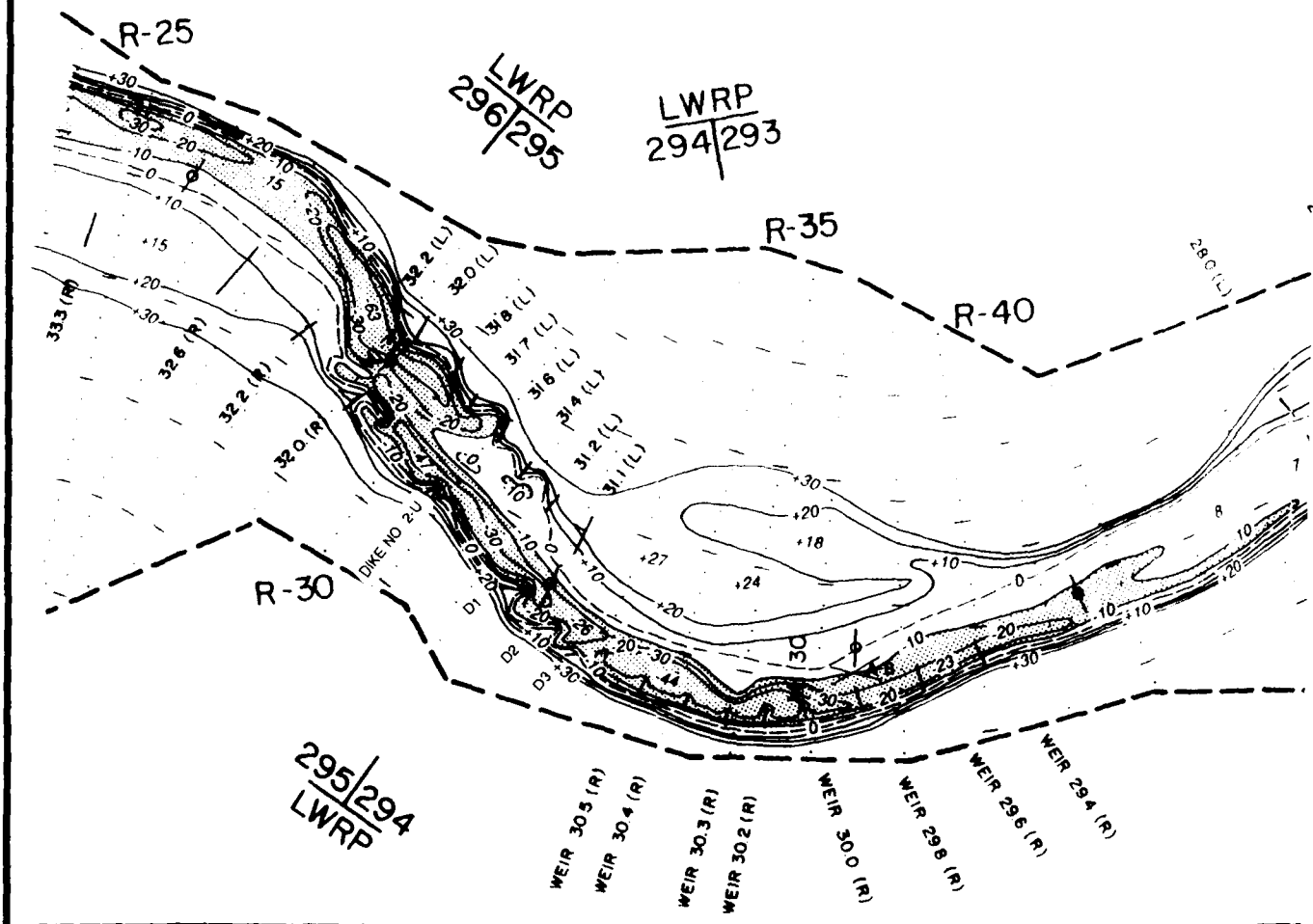
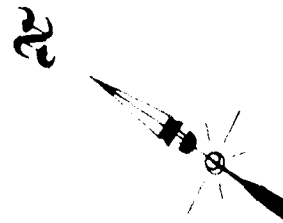
293/292  
LWRP

293/292  
LWRP

# LEGEND

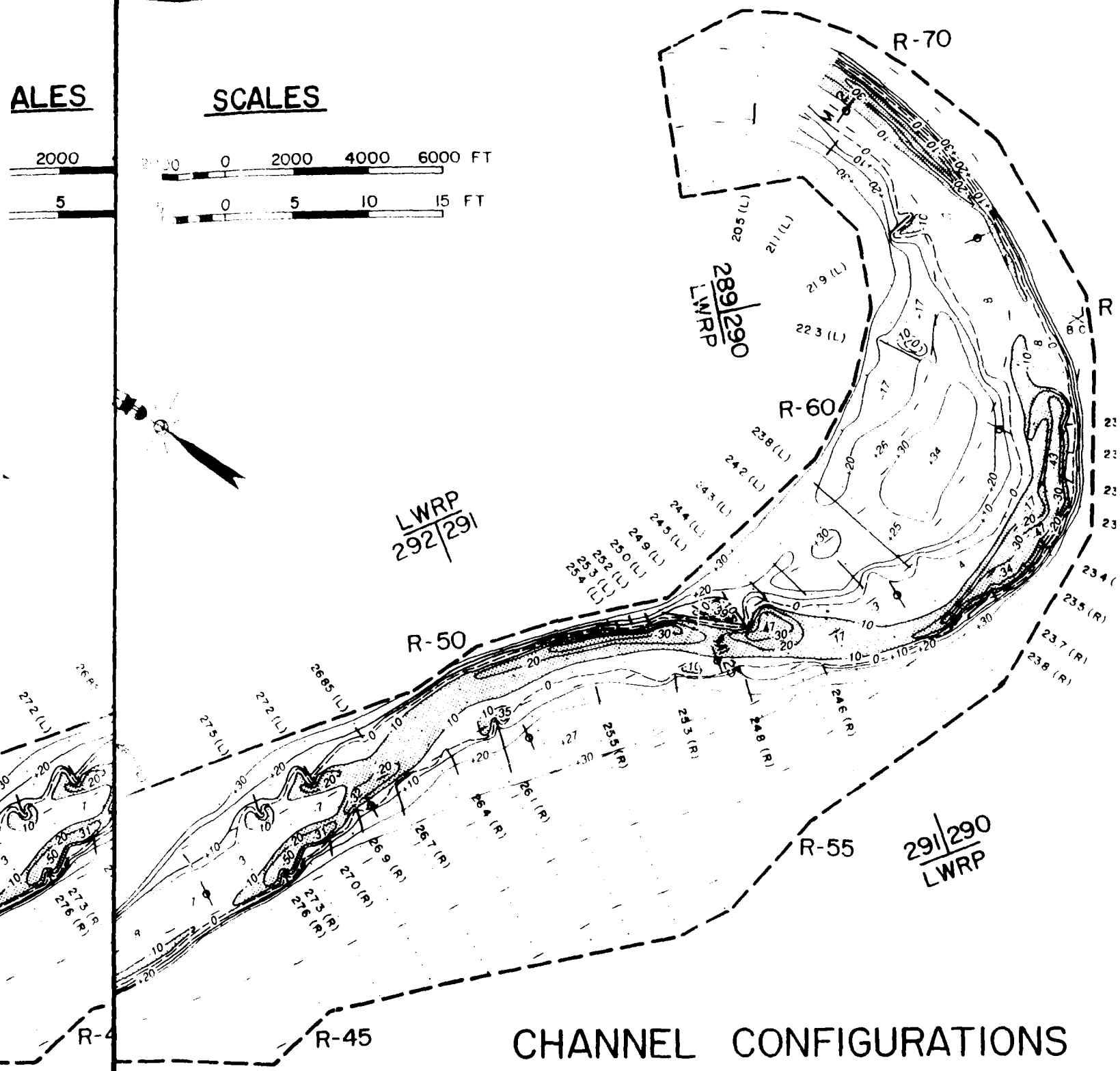
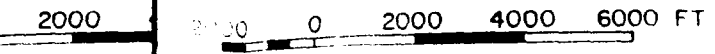
-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE  2:100  
 MODEL  5



ALES

SCALES



# CHANNEL CONFIGURATIONS

## PLAN C-2 RUN 2

293/29  
LWRP

293/292  
LWRP

# LEGEND



-10 FT LWRP AND BELOW

31.6 (L) PROTOTYPE DIKE

WEIR 30.5 (R) PROTOTYPE WEIR

BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

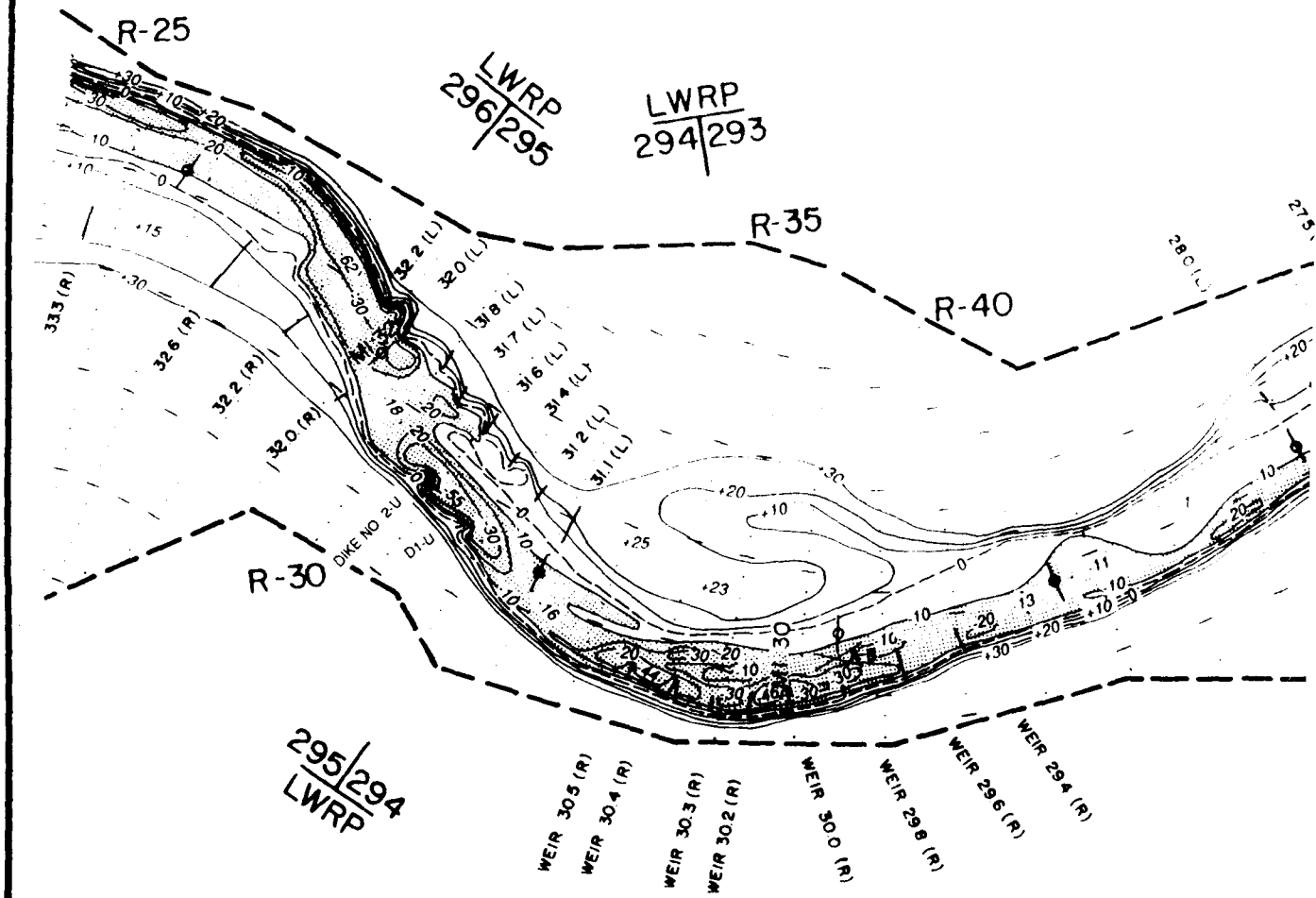
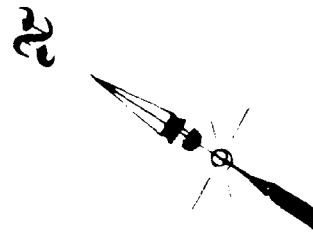
LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE

2000

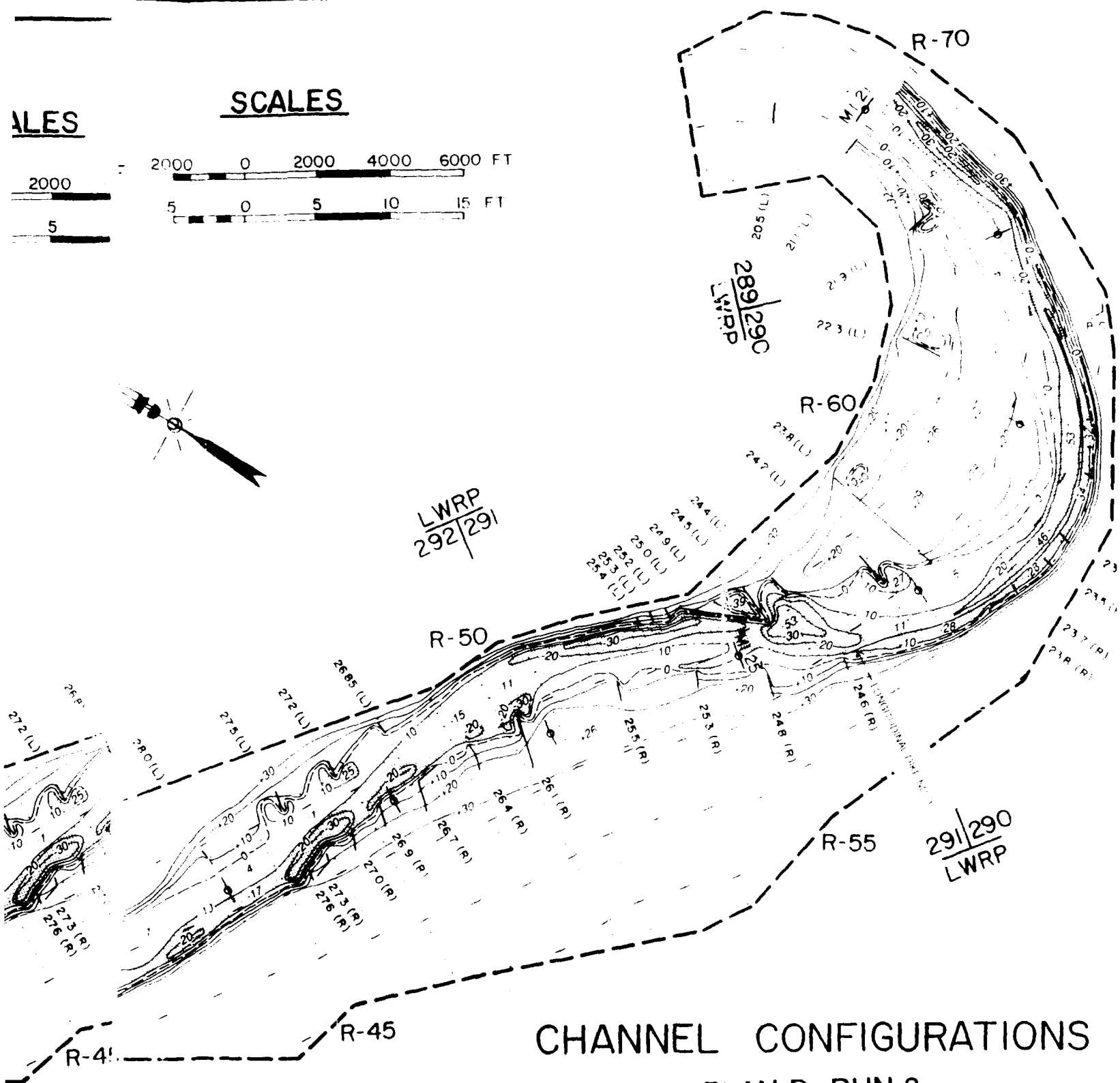
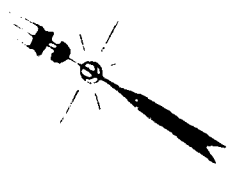
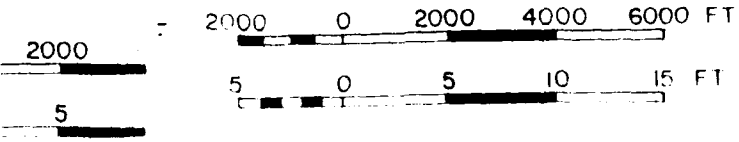
MODEL

5



SCALES

SCALES



# CHANNEL CONFIGURATIONS PLAN D RUN 3

293/292  
LWRP

293/292  
LWRP

291/290  
LWRP

LWRP  
292/291

LWRP  
289/290

# LEGEND



-10 FT LWRP AND BELOW

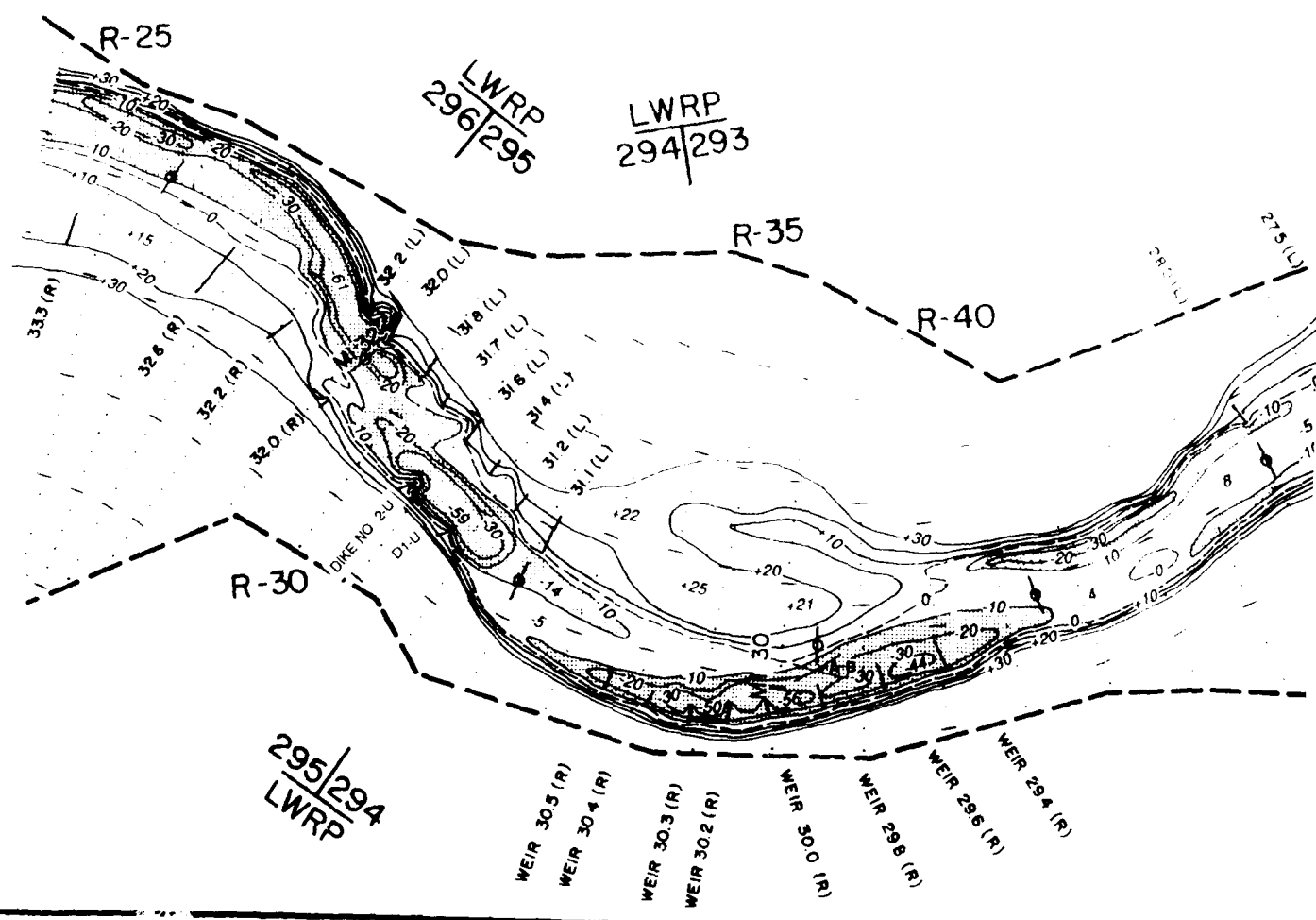
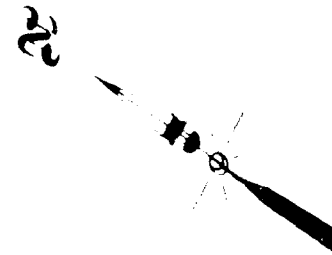
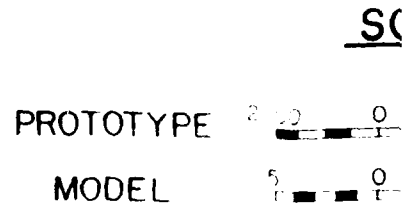
31.6 (L) PROTOTYPE DIKE

WEIR 30.5 (R) PROTOTYPE WEIR

BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

LD1 MODEL LONGITUDINAL DIKE



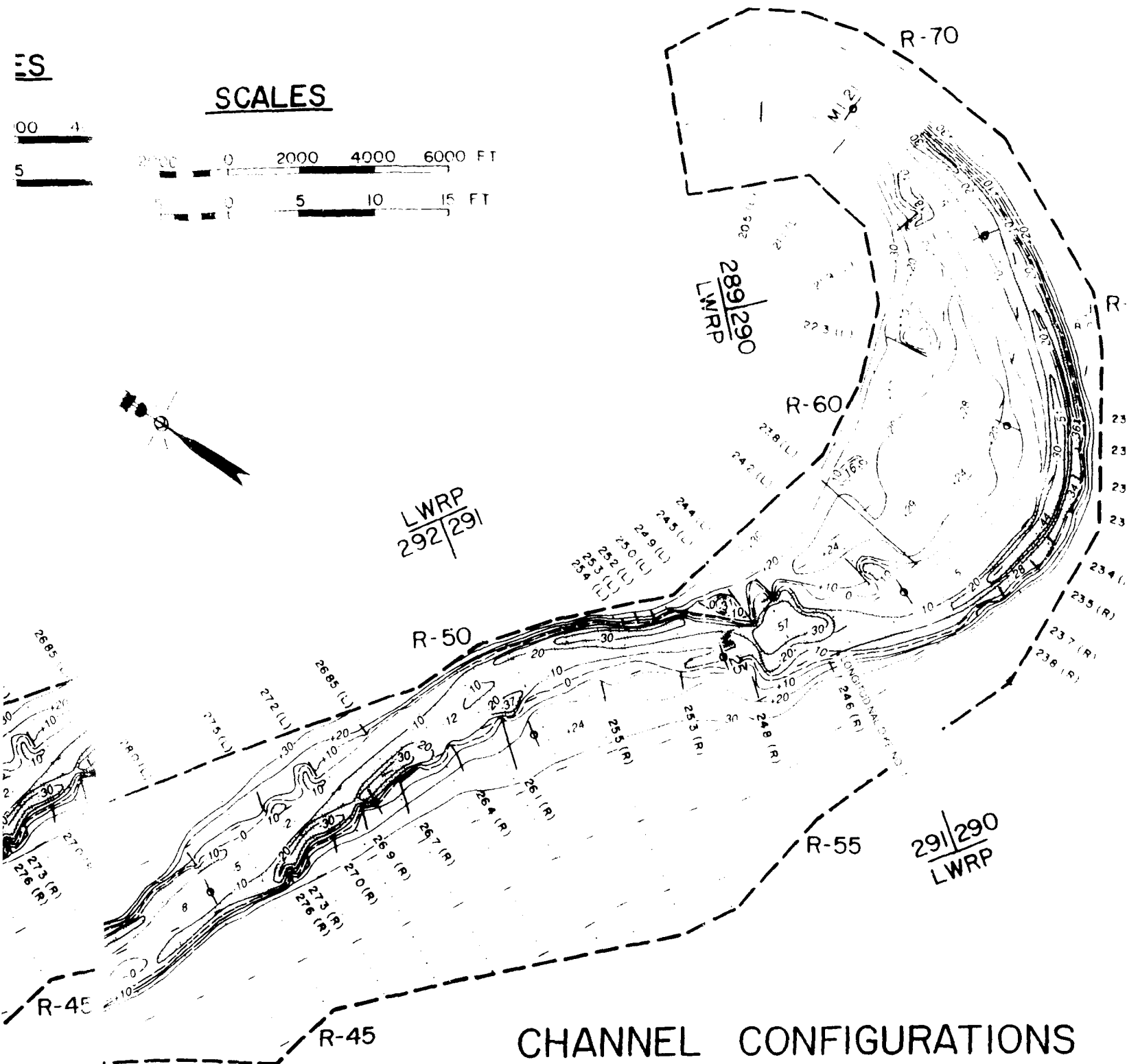
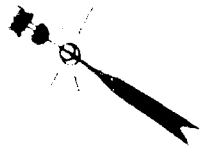
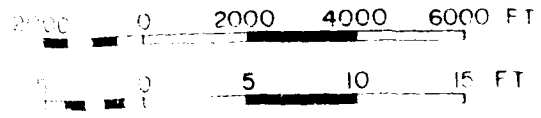
5  
(R)  
(R)  
(R)  
(R)

15

ES

SCALES

00 4  
5



CHANNEL CONFIGURATIONS  
 PLAN D-1 RUN 2


293/292  
LWRP

293/292  
LWRP



SCALE

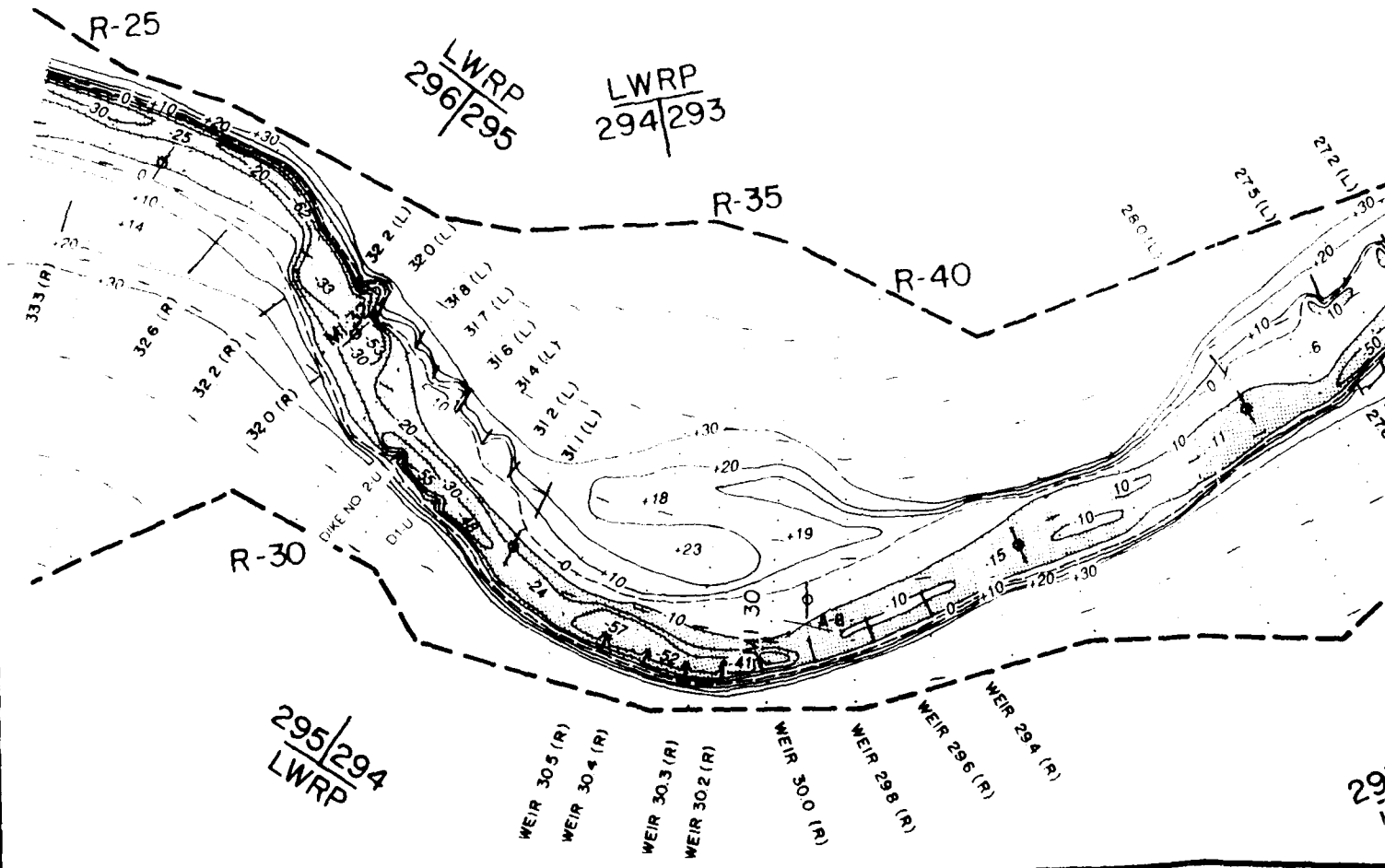
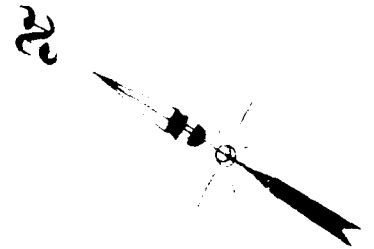
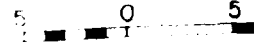
**LEGEND**

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

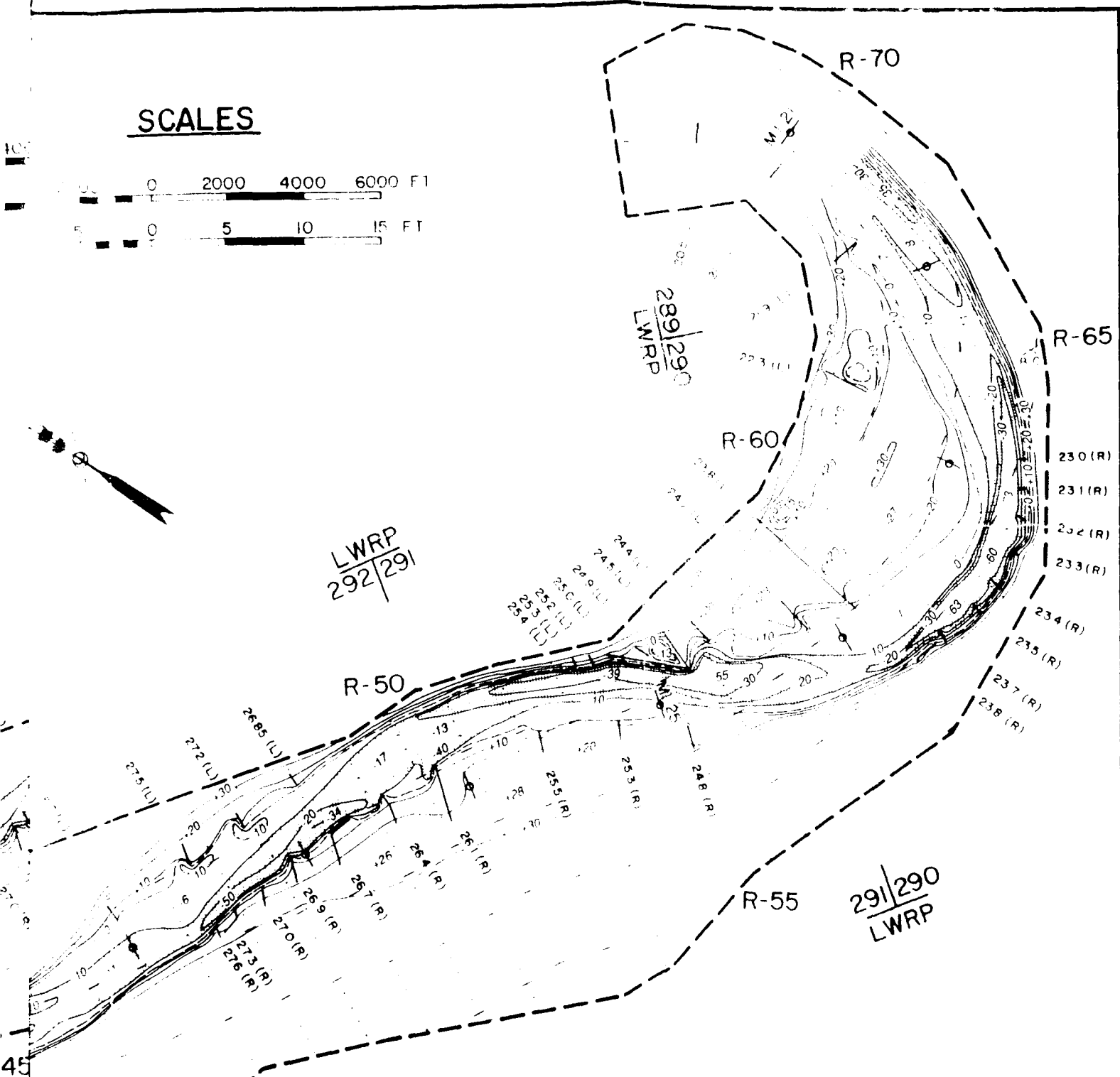
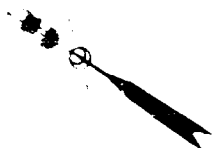
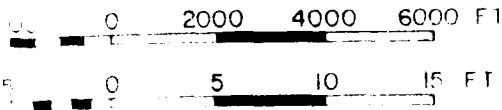
PROTOTYPE



MODEL



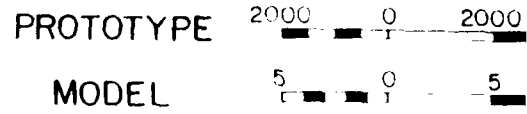
SCALES




CHANNEL CONFIGURATIONS  
PLAN E RUN 2

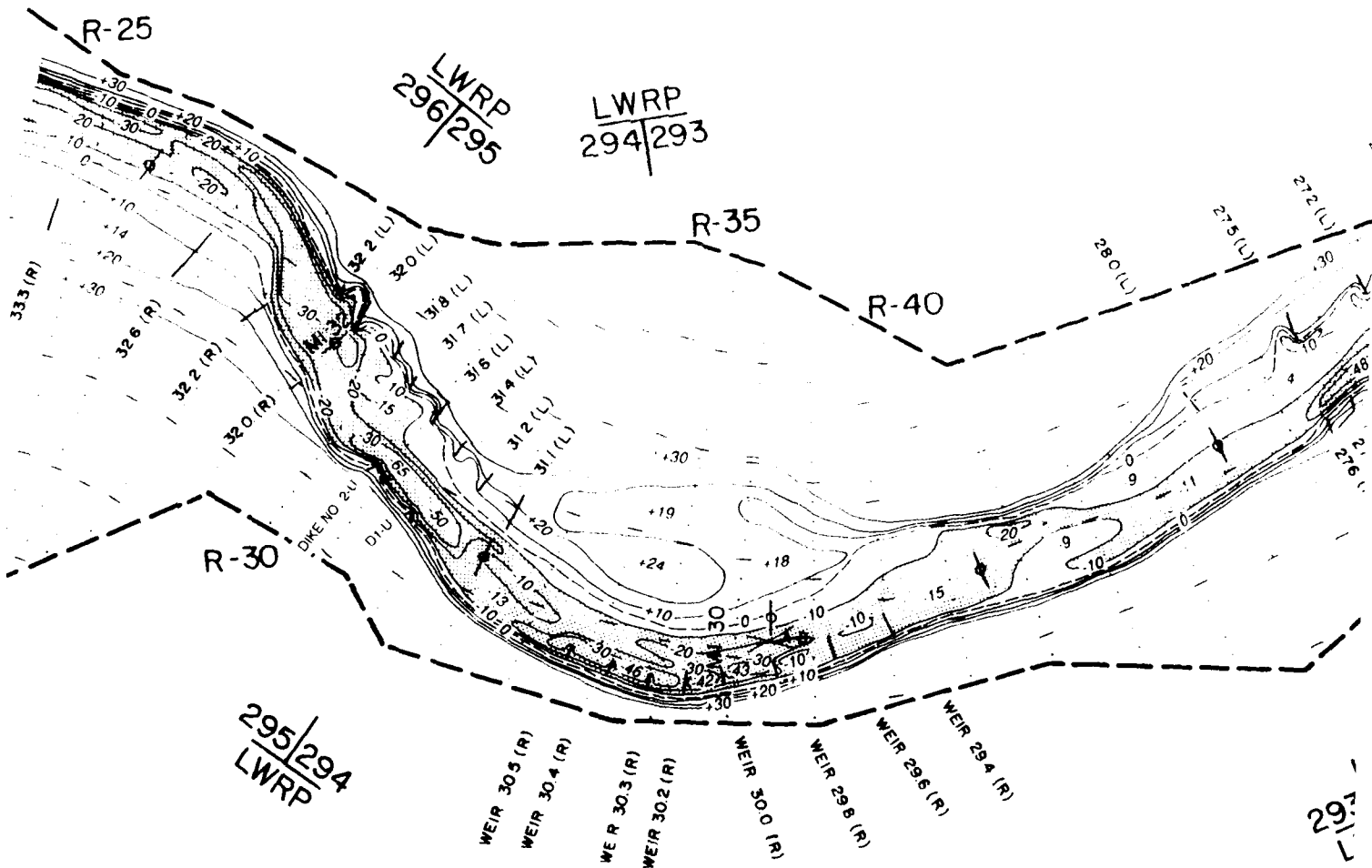
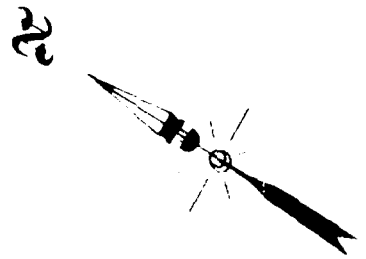
293/292  
LWRP

**SCALES**

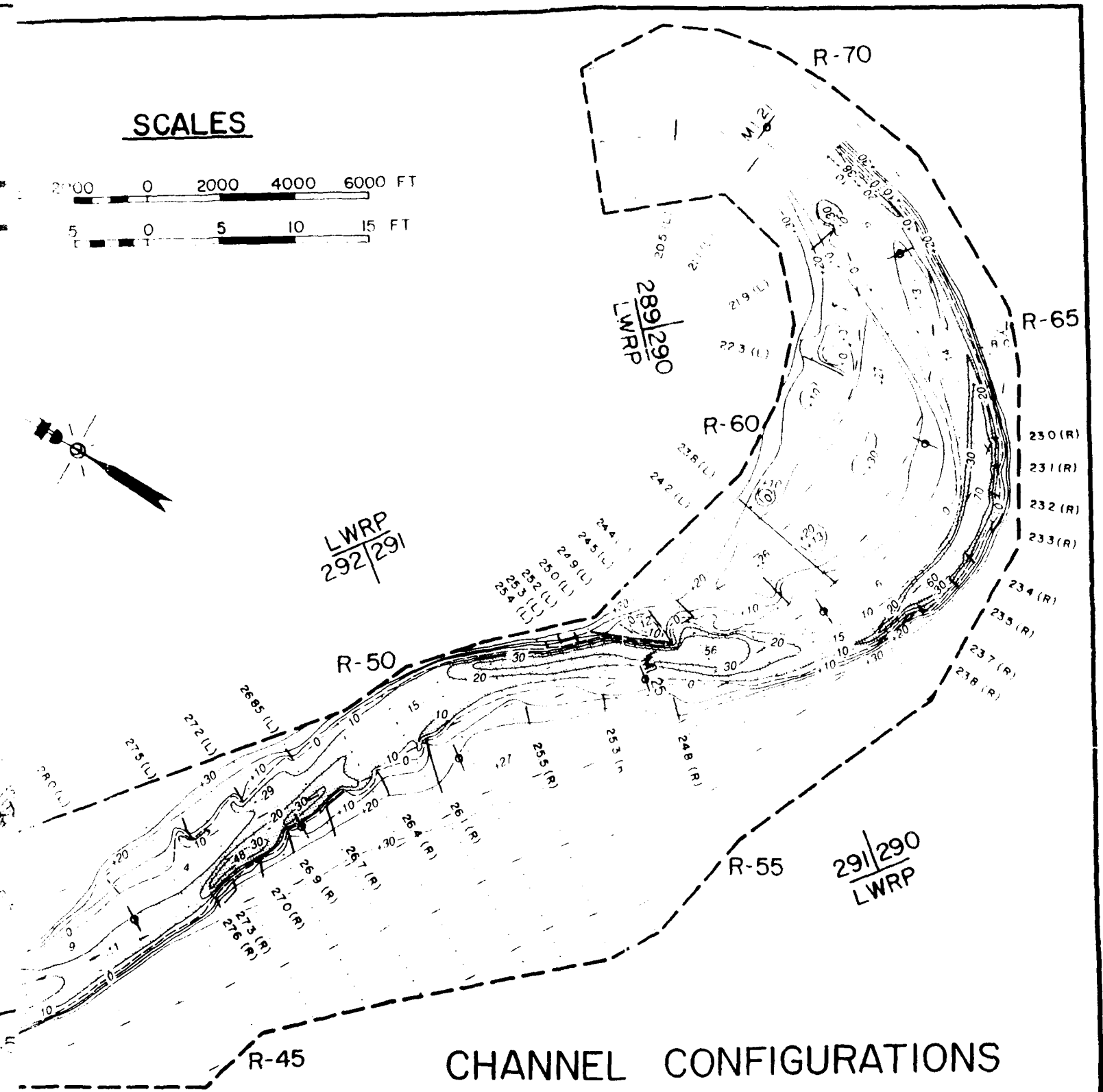
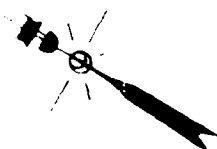
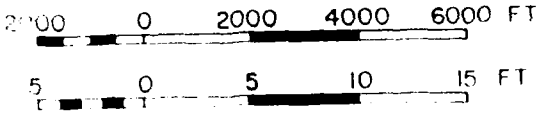


**LEGEND**

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



**SCALES**




**CHANNEL CONFIGURATIONS**


PLAN E-1 RUN 2

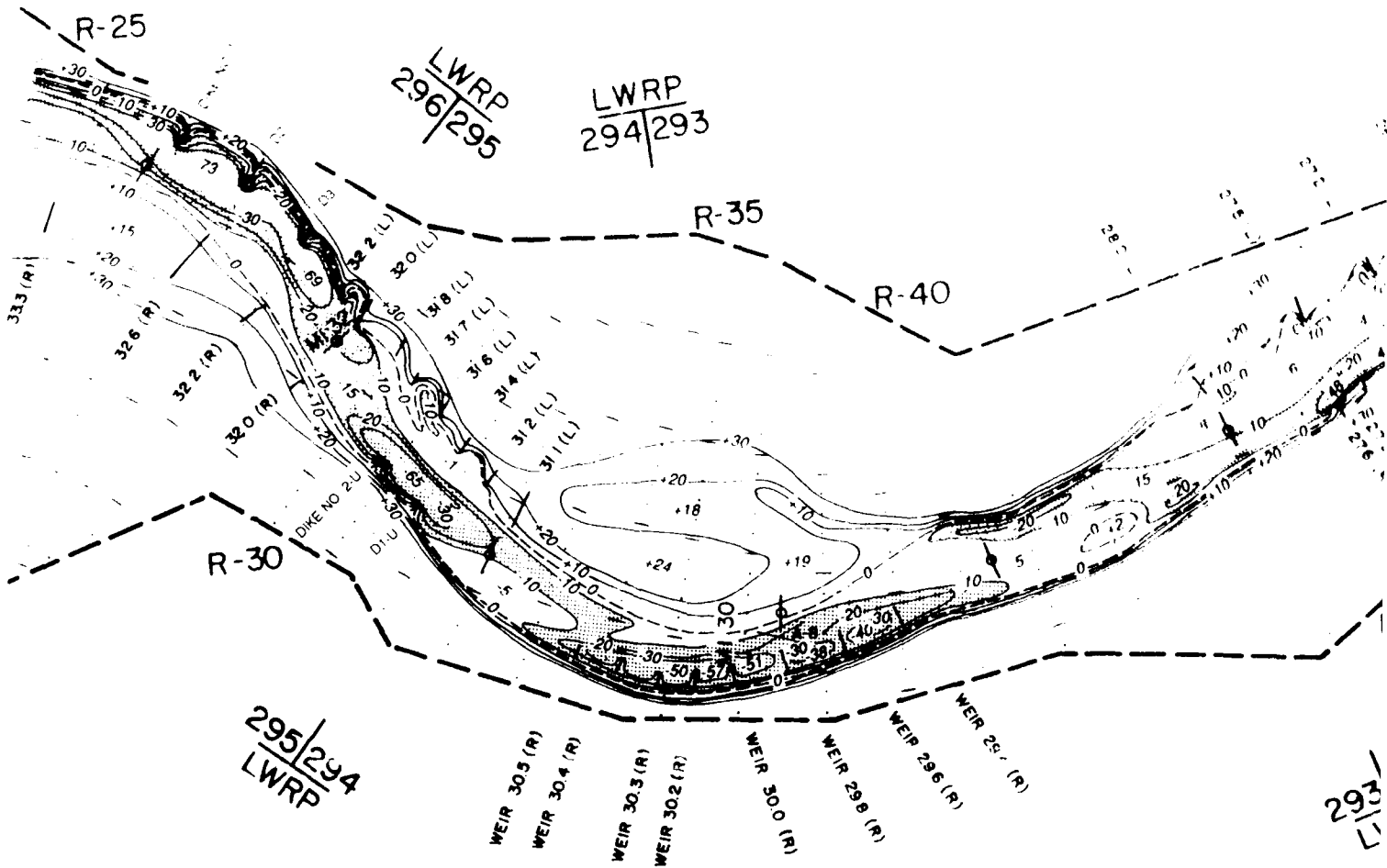
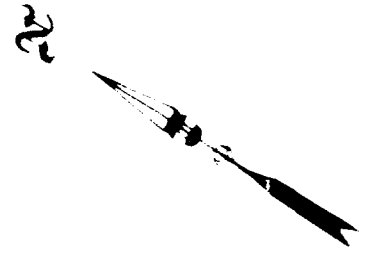
293/292  
LWRP

SCALES

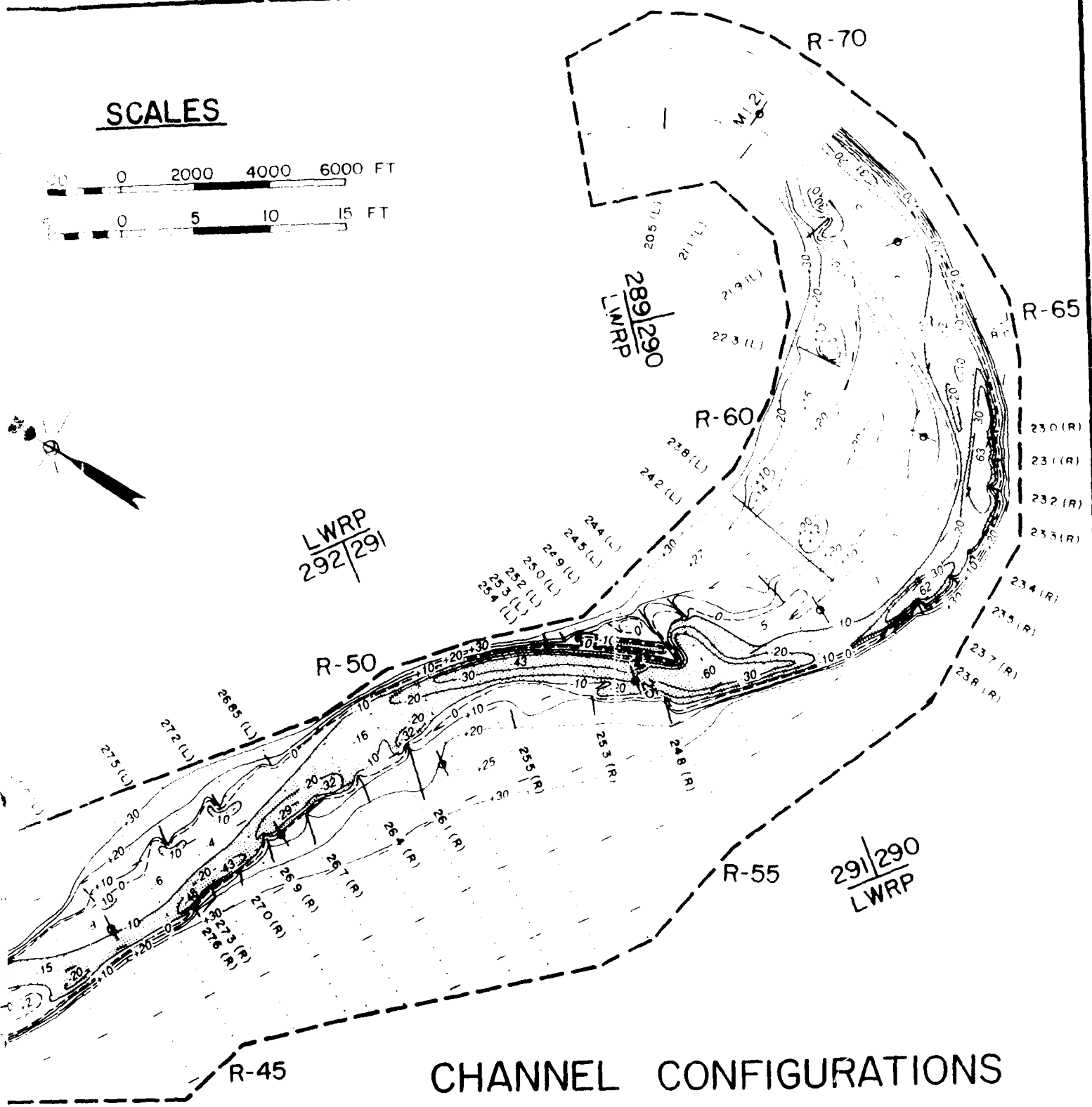
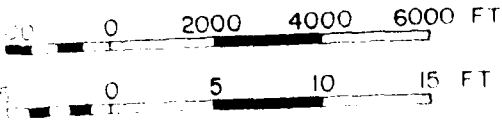
LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE  MODEL 



SCALES



CHANNEL CONFIGURATIONS  
PLAN E-2 RUN 2

293/292  
LWRP

SCALES

LEGEND

 -10 FT LWRP AND BELOW


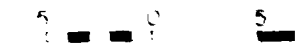
31.6 (L) PROTOTYPE DIKE

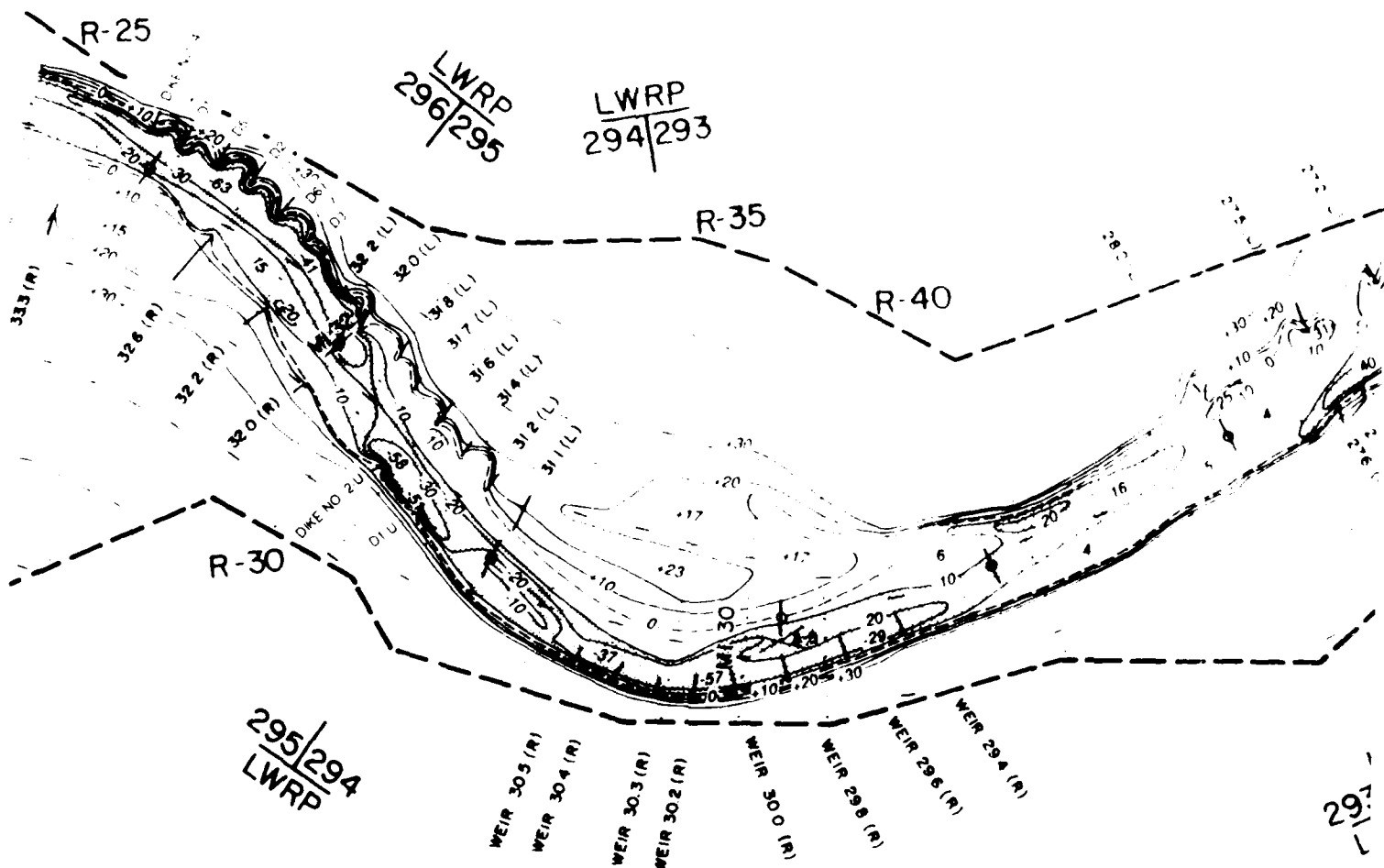
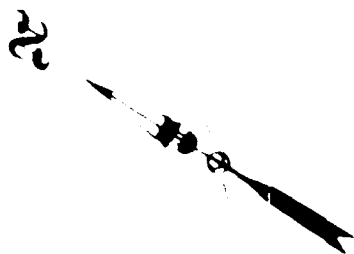
WEIR 30.5 (R) PROTOTYPE WEIR

BW4 MODEL BENDWAY WEIR

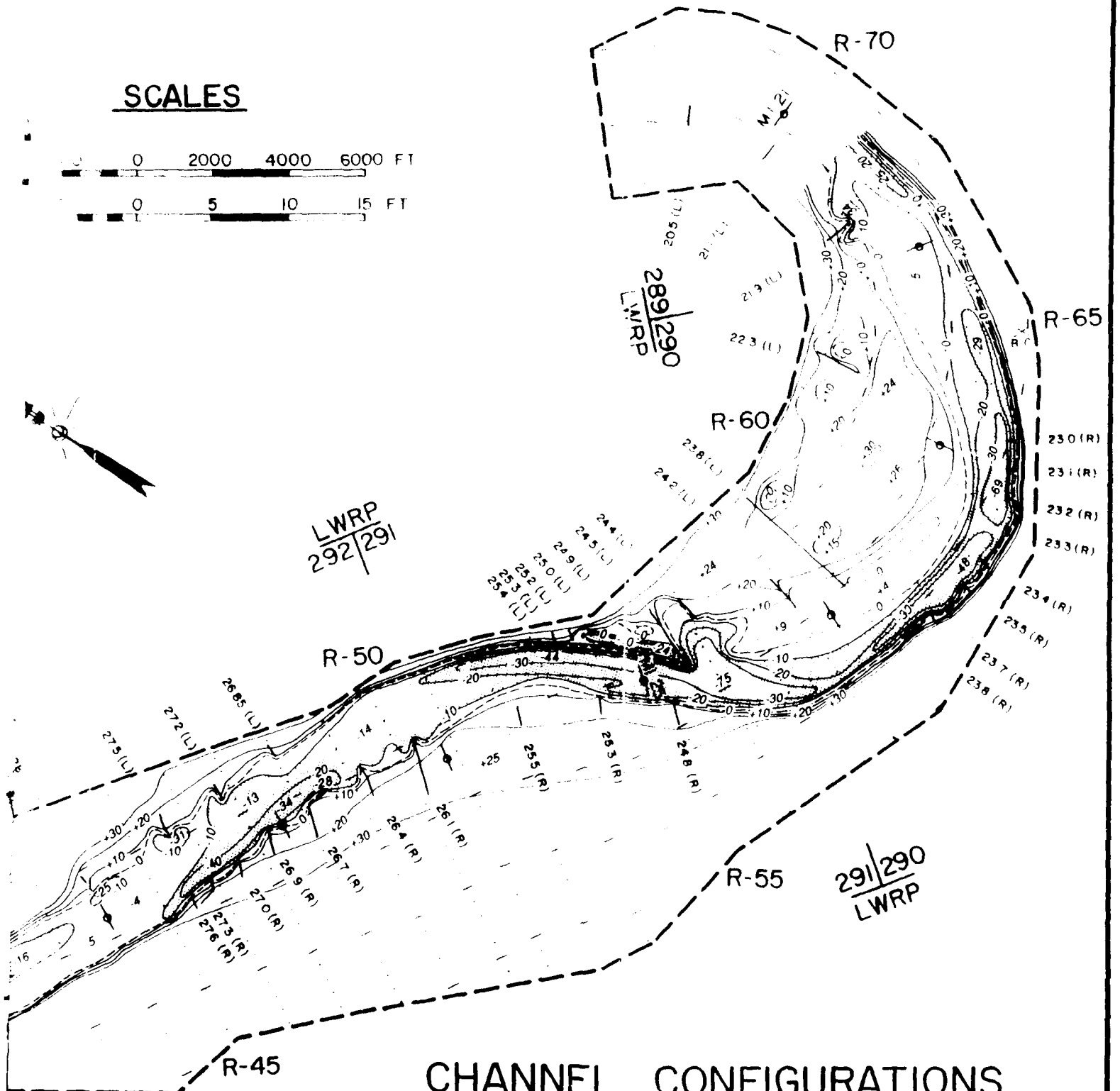
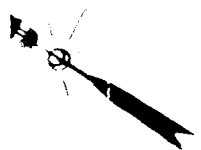
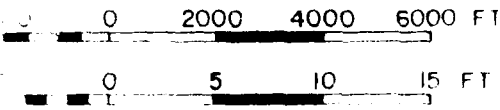
D1 MODEL DIKE

LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE  3000  
 MODEL  5



SCALES



CHANNEL CONFIGURATIONS  
PLAN E-3 RUN 3

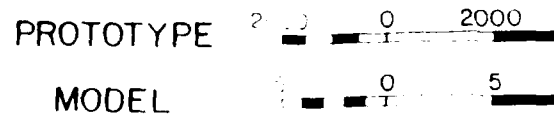
293/292  
LWRP

291/290  
LWRP


289/290  
LWRP

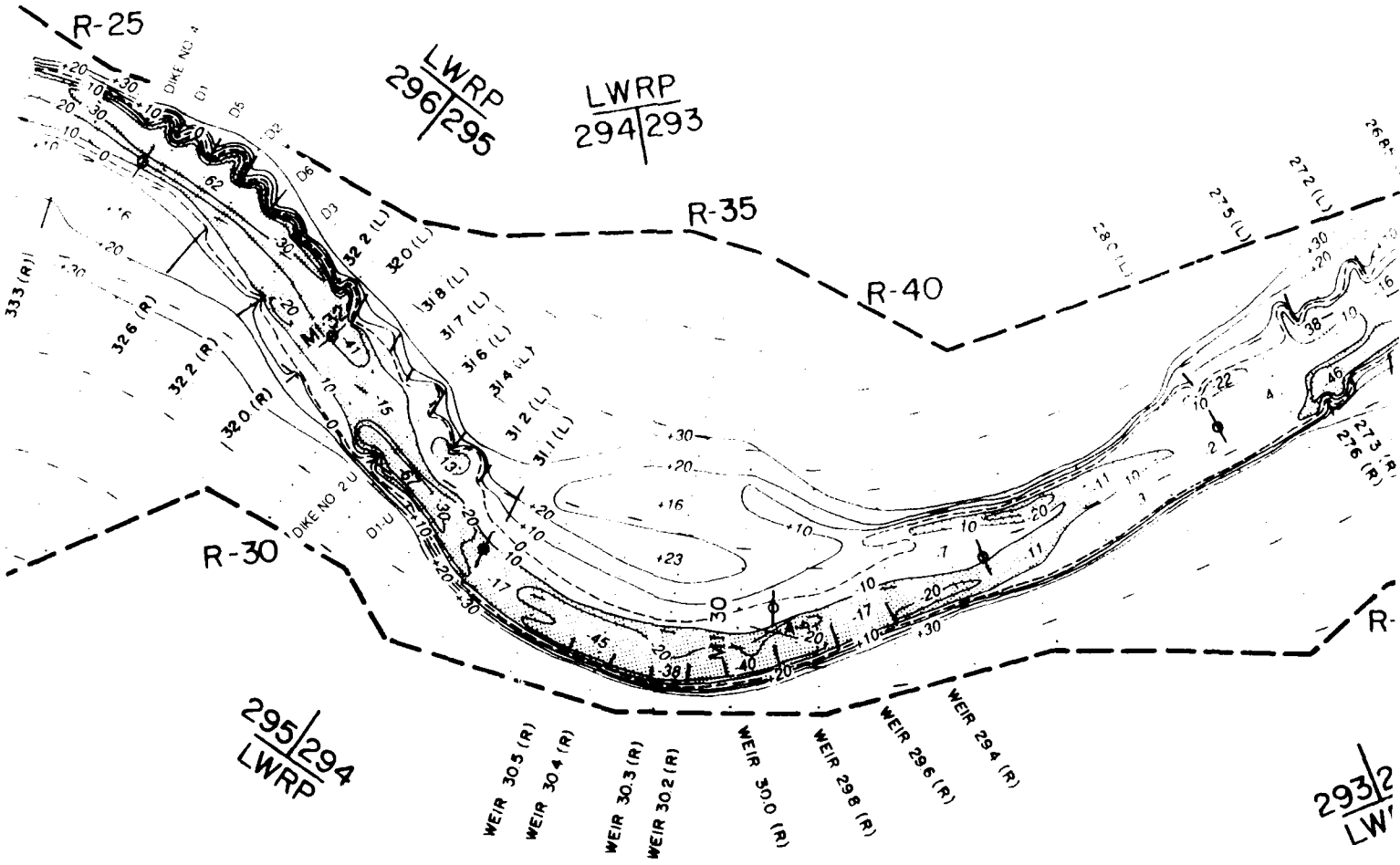
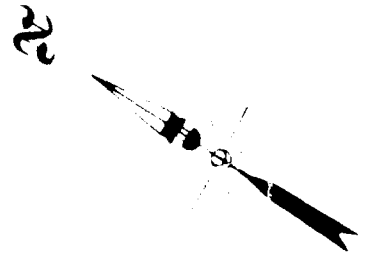


**SCALES**

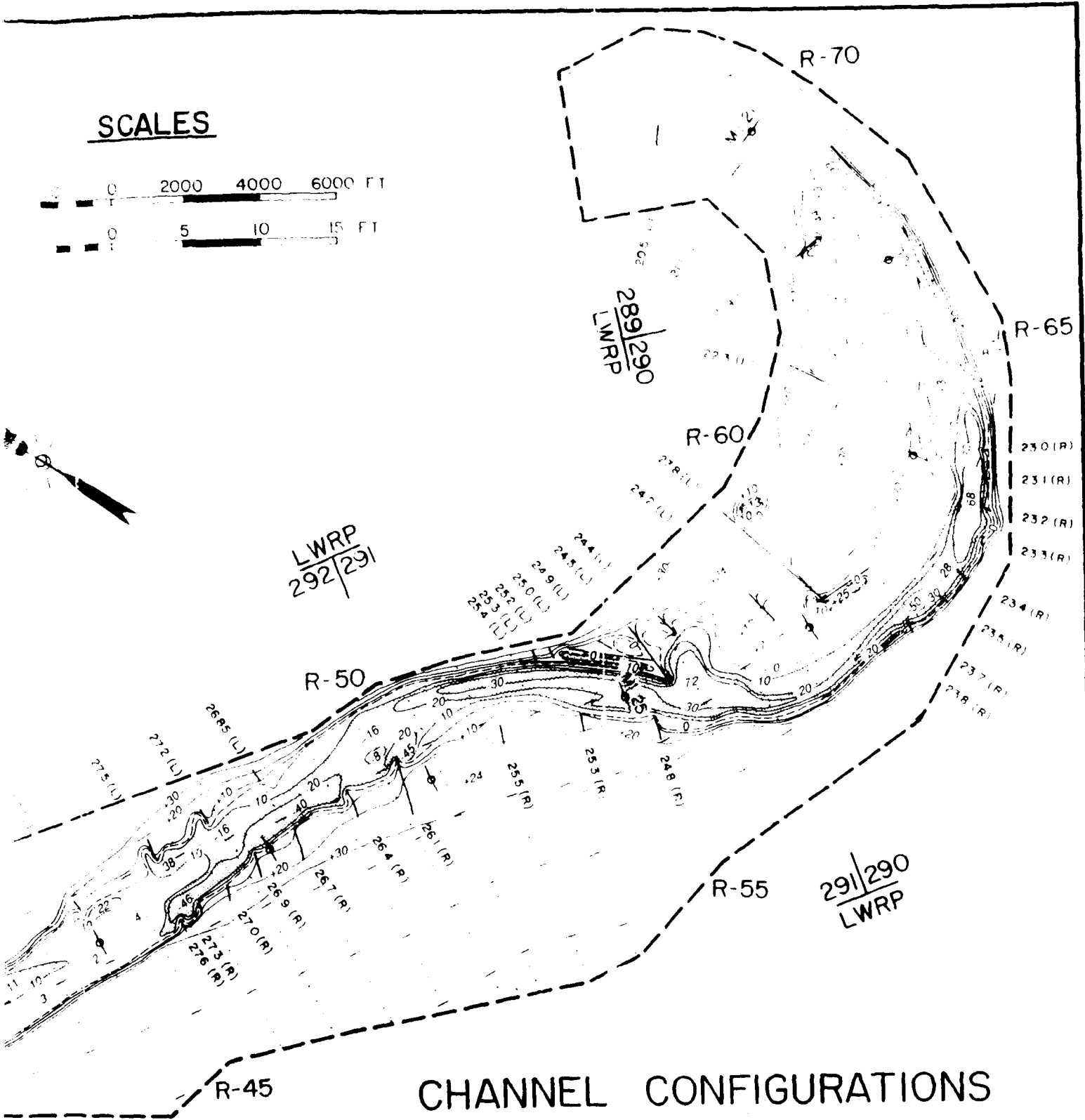
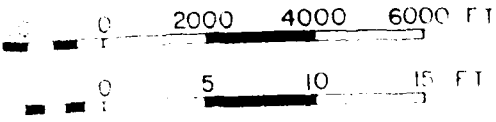


**LEGEND**

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



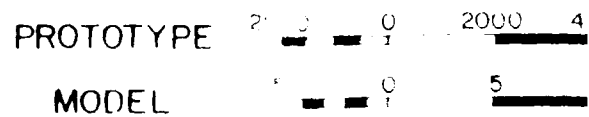
**SCALES**




**CHANNEL CONFIGURATIONS  
PLAN E-4 RUN 2**

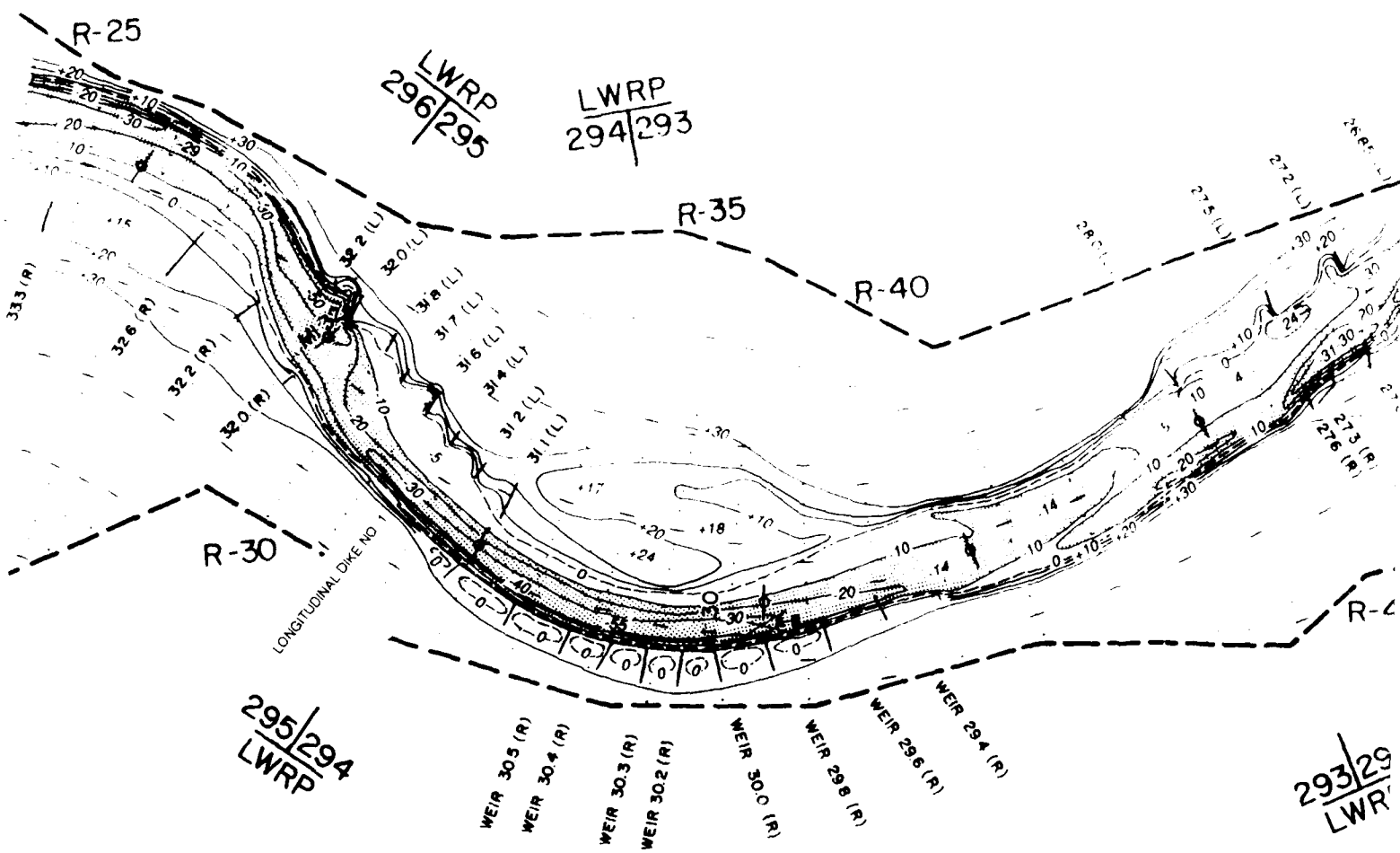
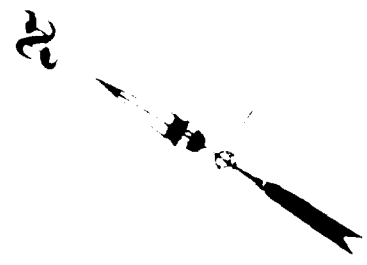
LWRP  
293/292

SCALES

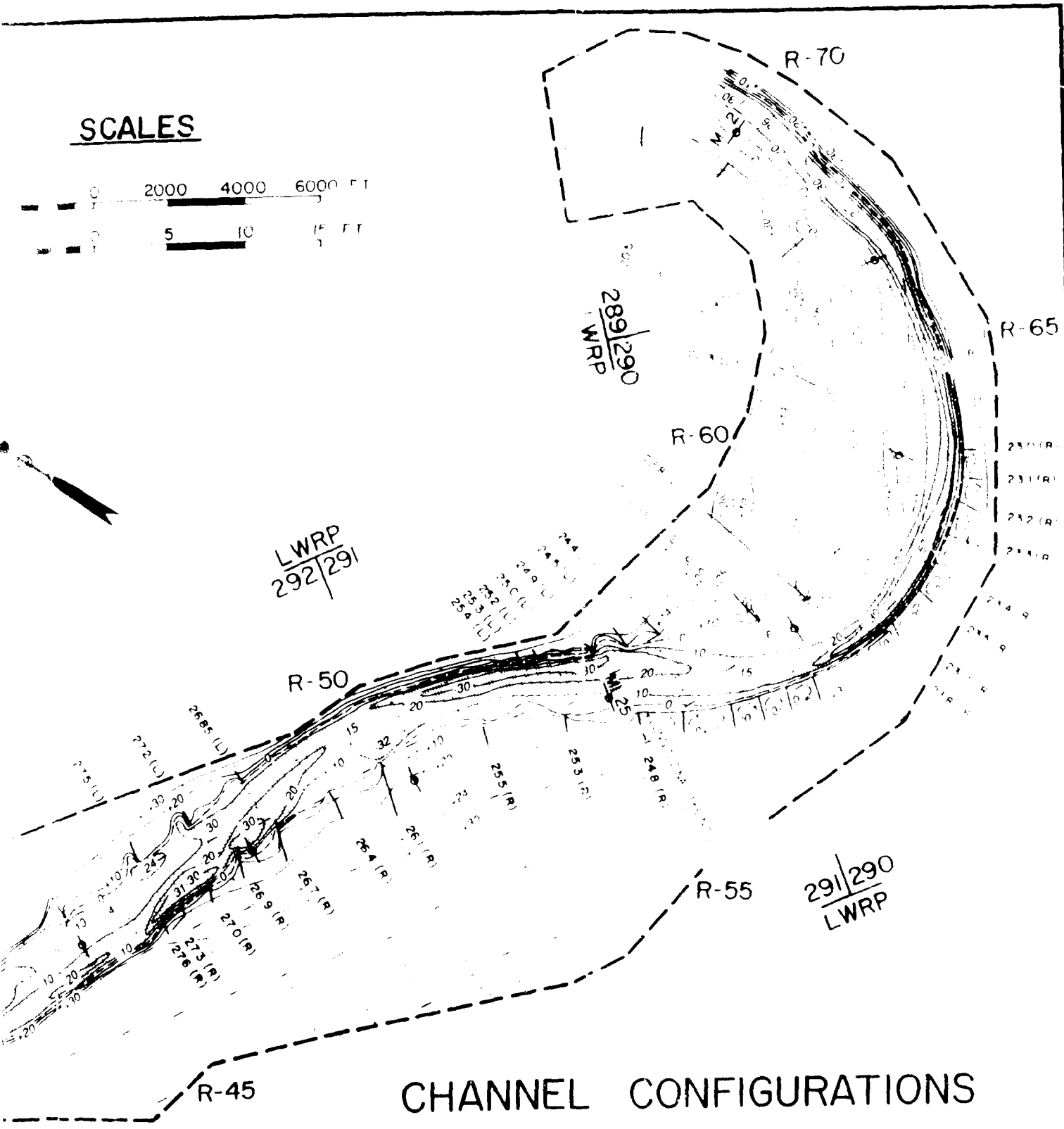
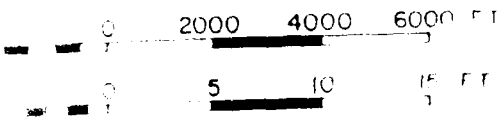


LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONG TUDINAL DIKE



**SCALES**



**CHANNEL CONFIGURATIONS  
PLAN F RUN 3**

293/292  
LWRP

SCALE

LEGEND

 -10 FT LWRP AND BELOW

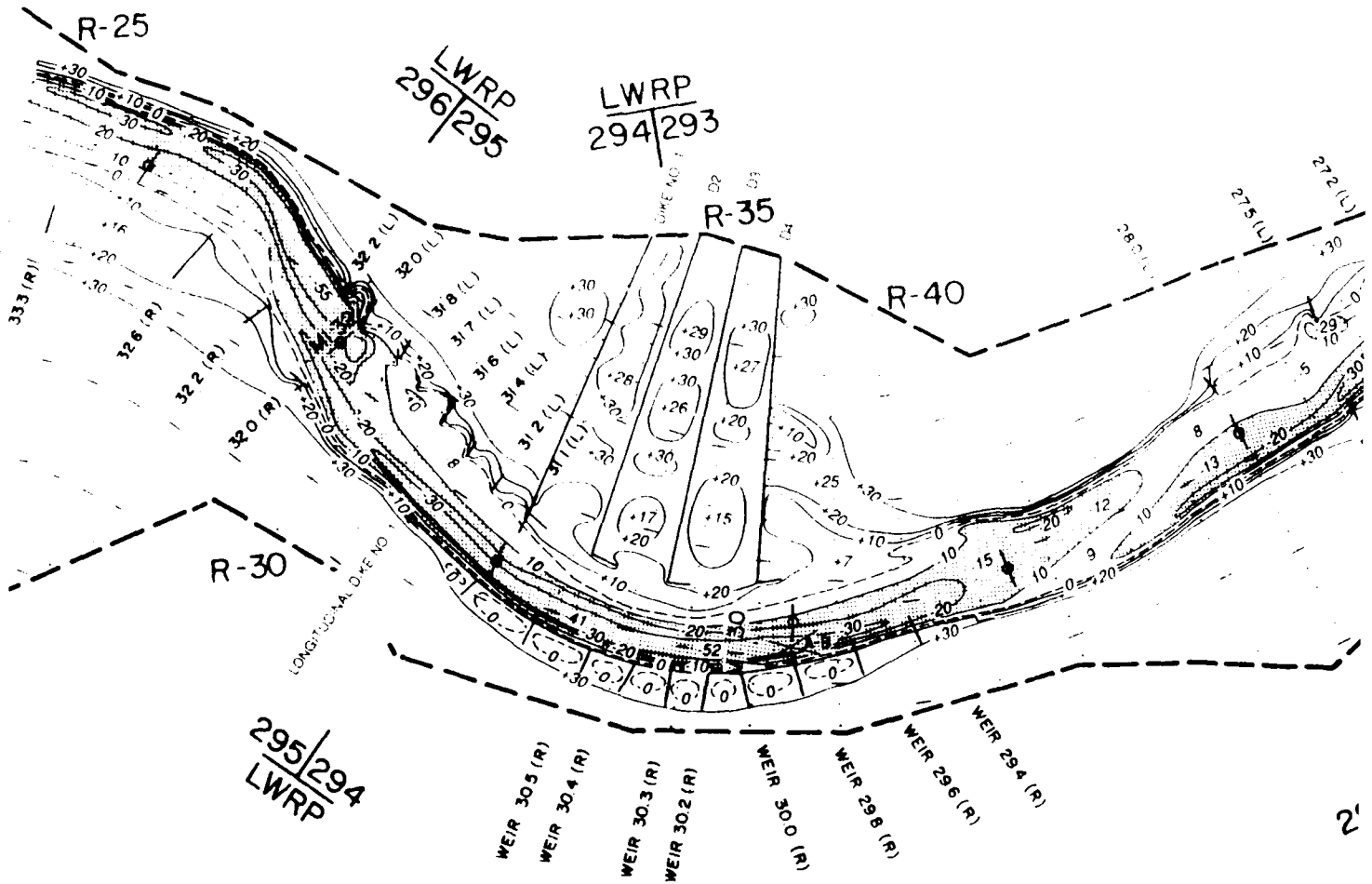
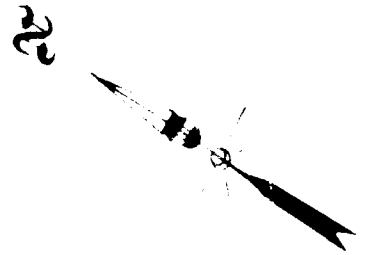
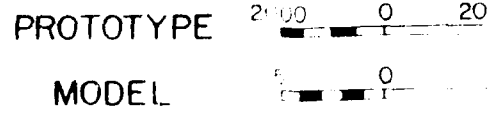
31.6 (L) PROTOTYPE DIKE

WEIR 30.5 (R) PROTOTYPE WEIR

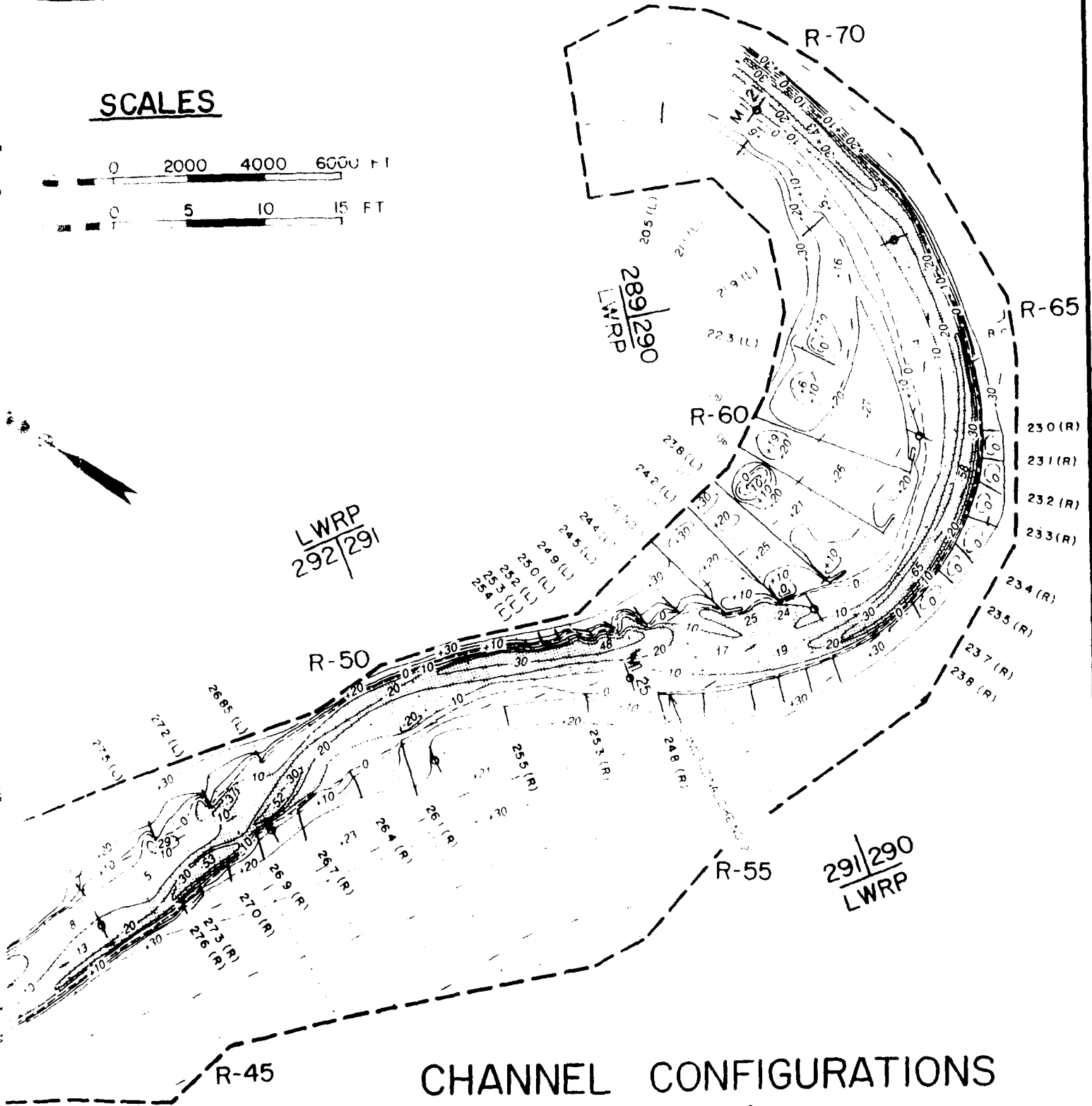
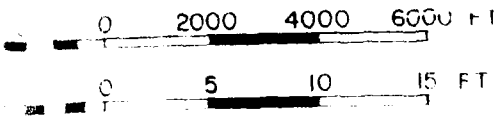
BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

LD1 MODEL LONGITUDINAL DIKE




SCALES

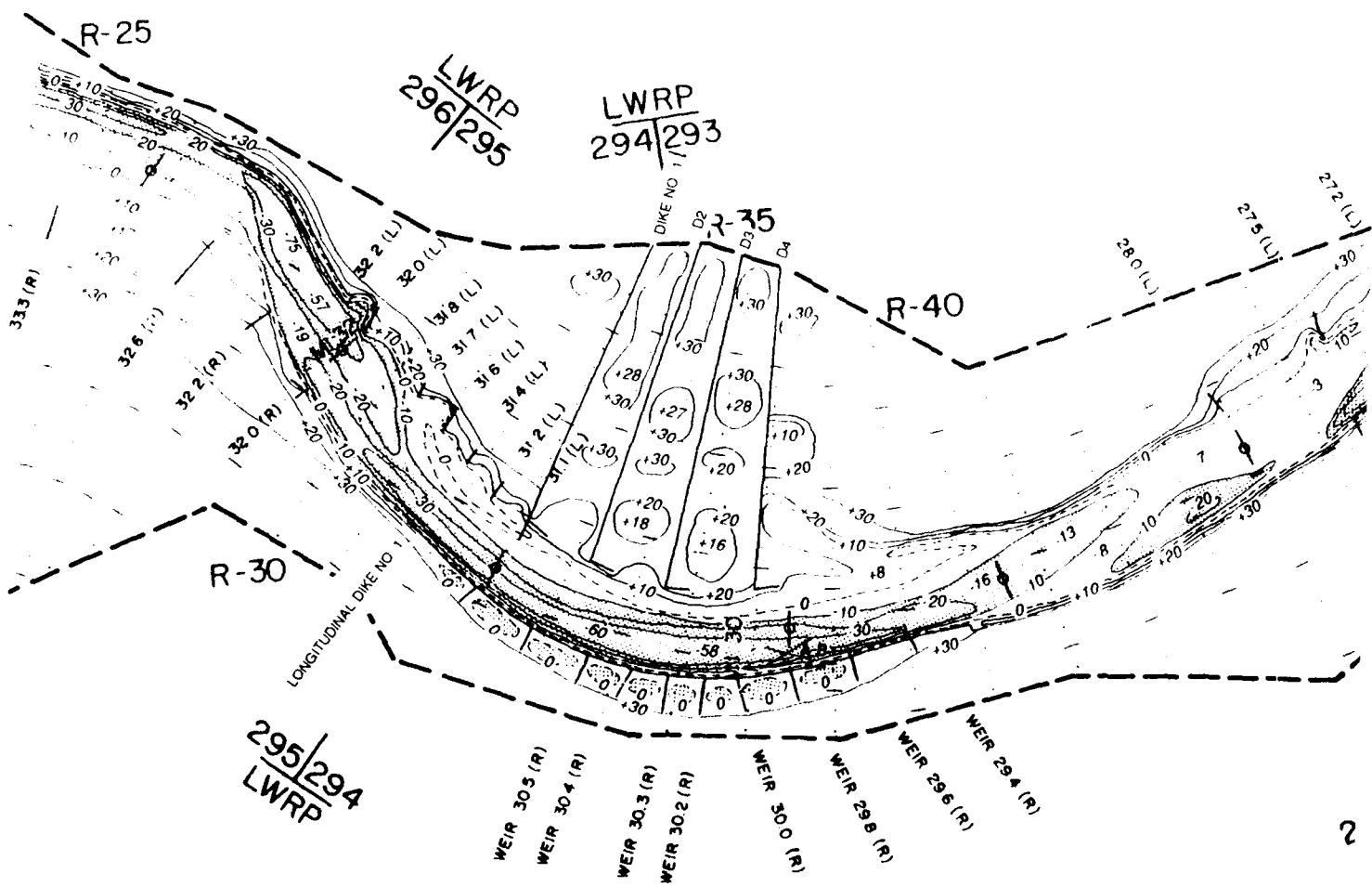
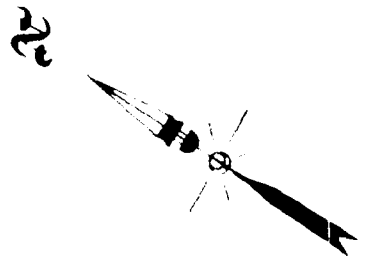
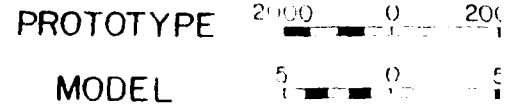


CHANNEL CONFIGURATIONS  
PLAN F-1 RUN 2

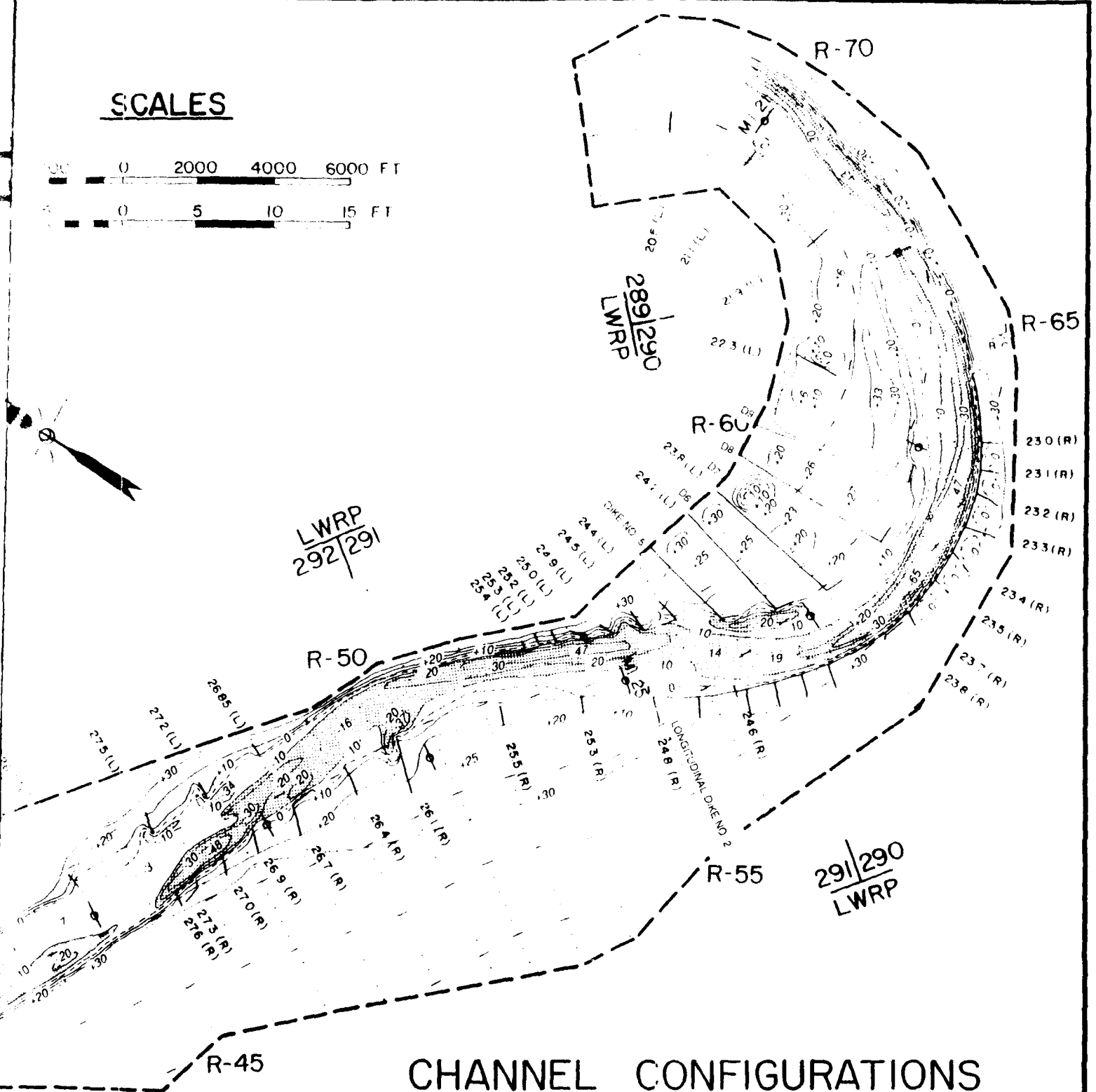
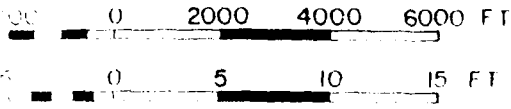
SCALE

LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



SCALES



CHANNEL CONFIGURATIONS  
PLAN F-1 RUN 1  
1983 FLOOD HYDROGRAPH



SCALE

LEGEND

 -10 FT LWRP AND BELOW

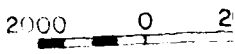
31.6 (L) PROTOTYPE DIKE

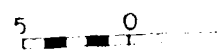
WEIR 30.5 (R) PROTOTYPE WEIR

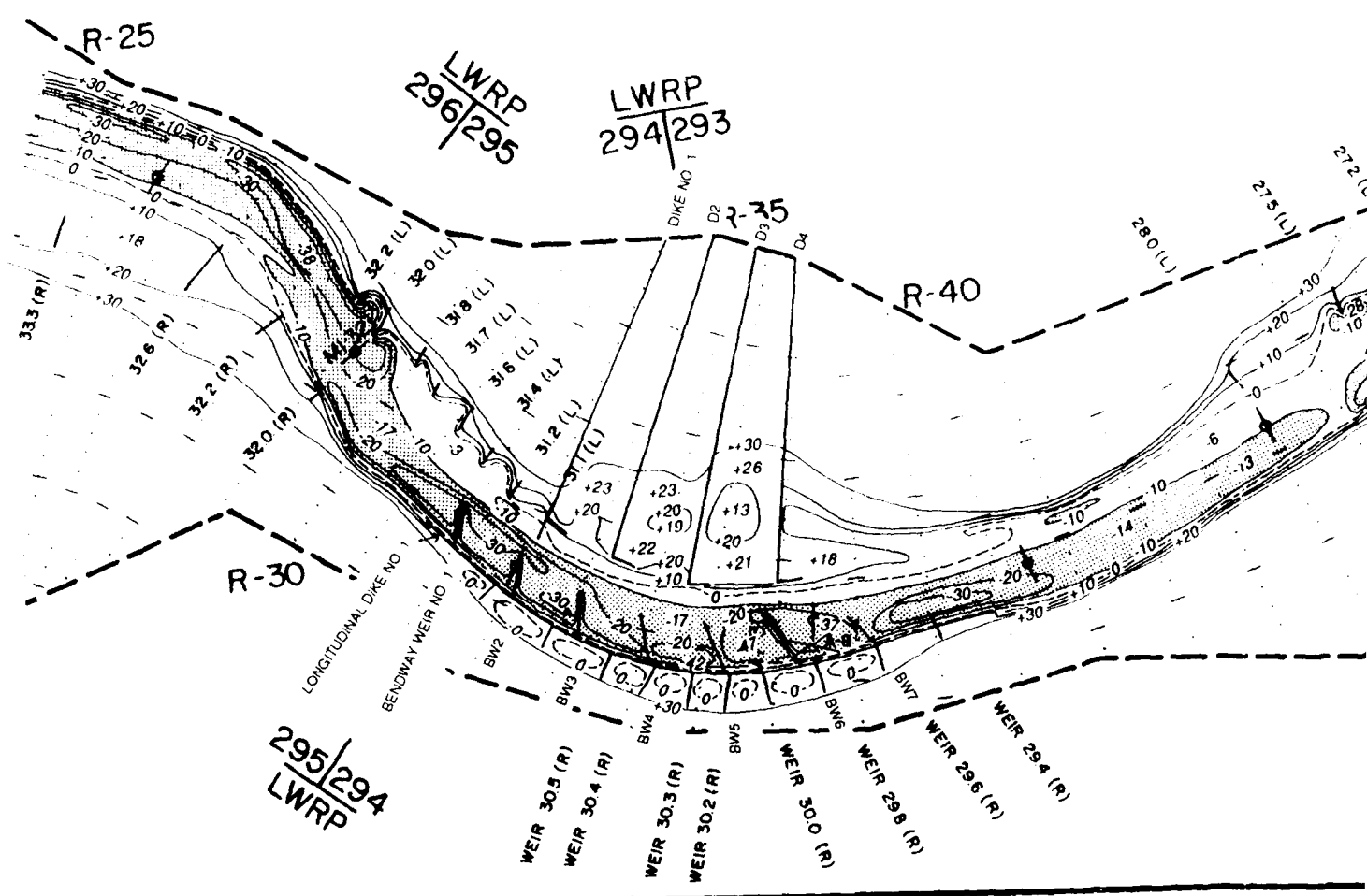
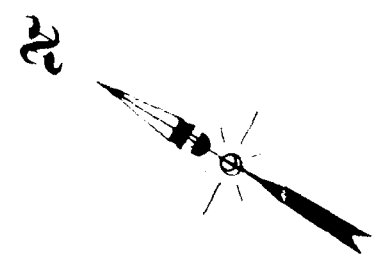
BW4 MODEL BENDWAY WEIR

D1 MODEL DIKE

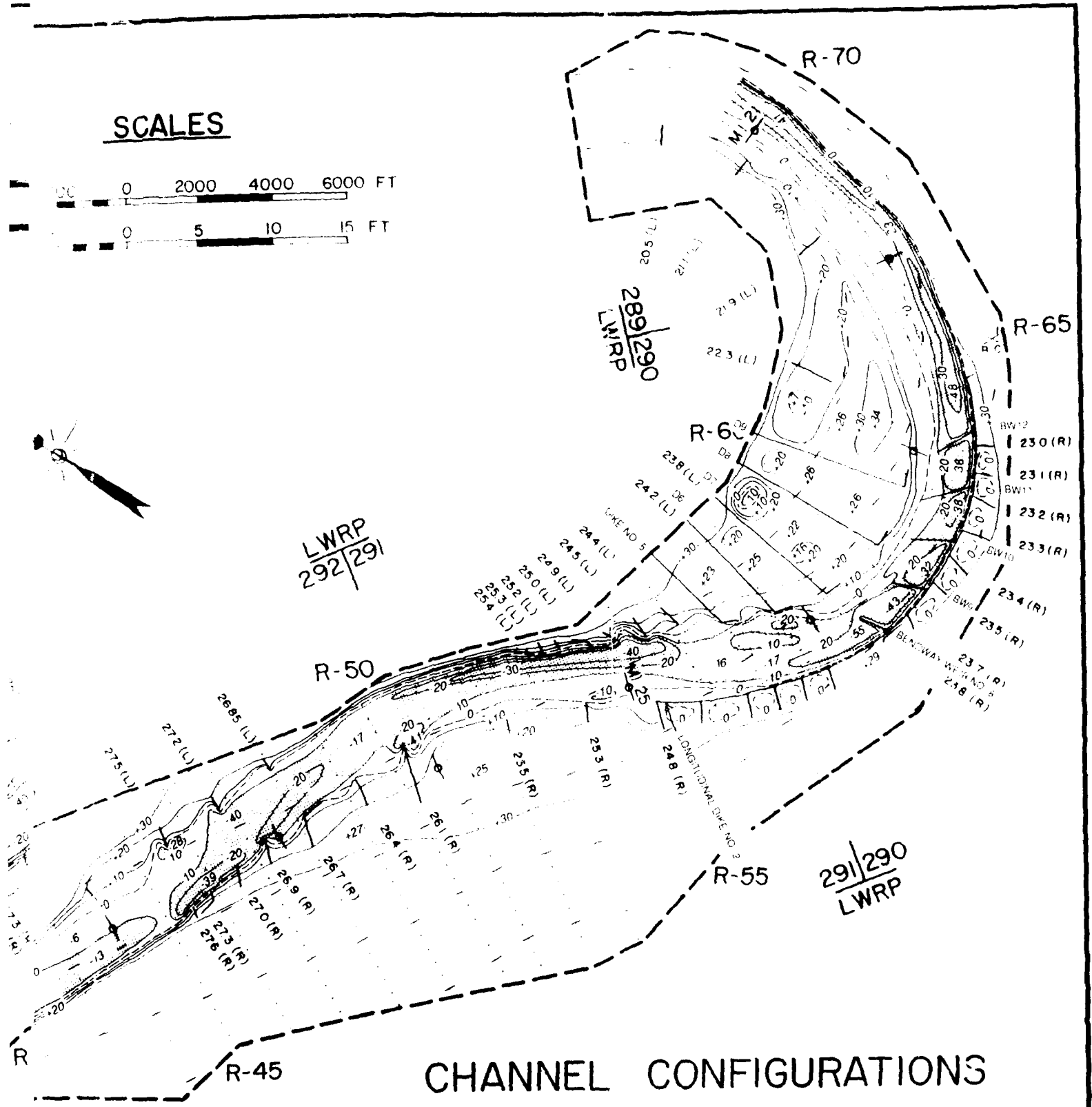
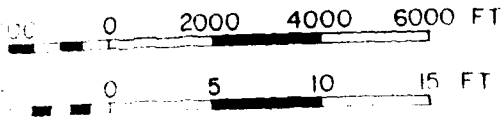
LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE 

MODEL 



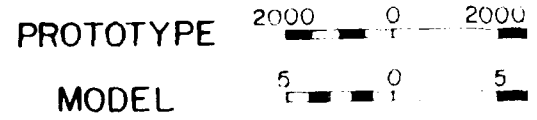
SCALES




CHANNEL CONFIGURATIONS  
PLAN F-2 RUN 2

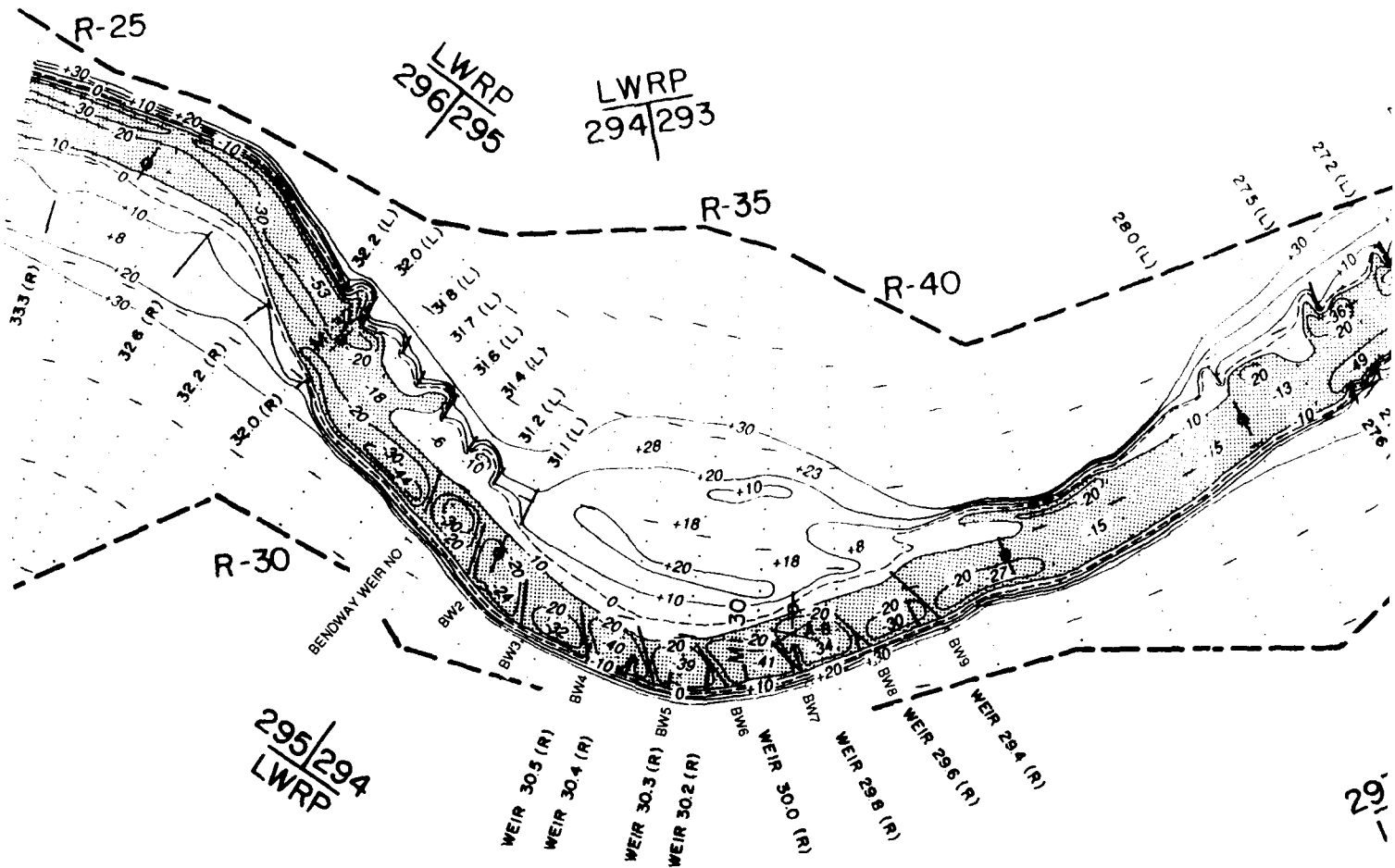
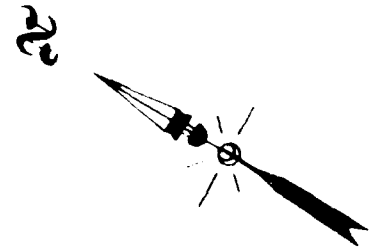
5/2  
W  
293/292  
LWRP

SCALES

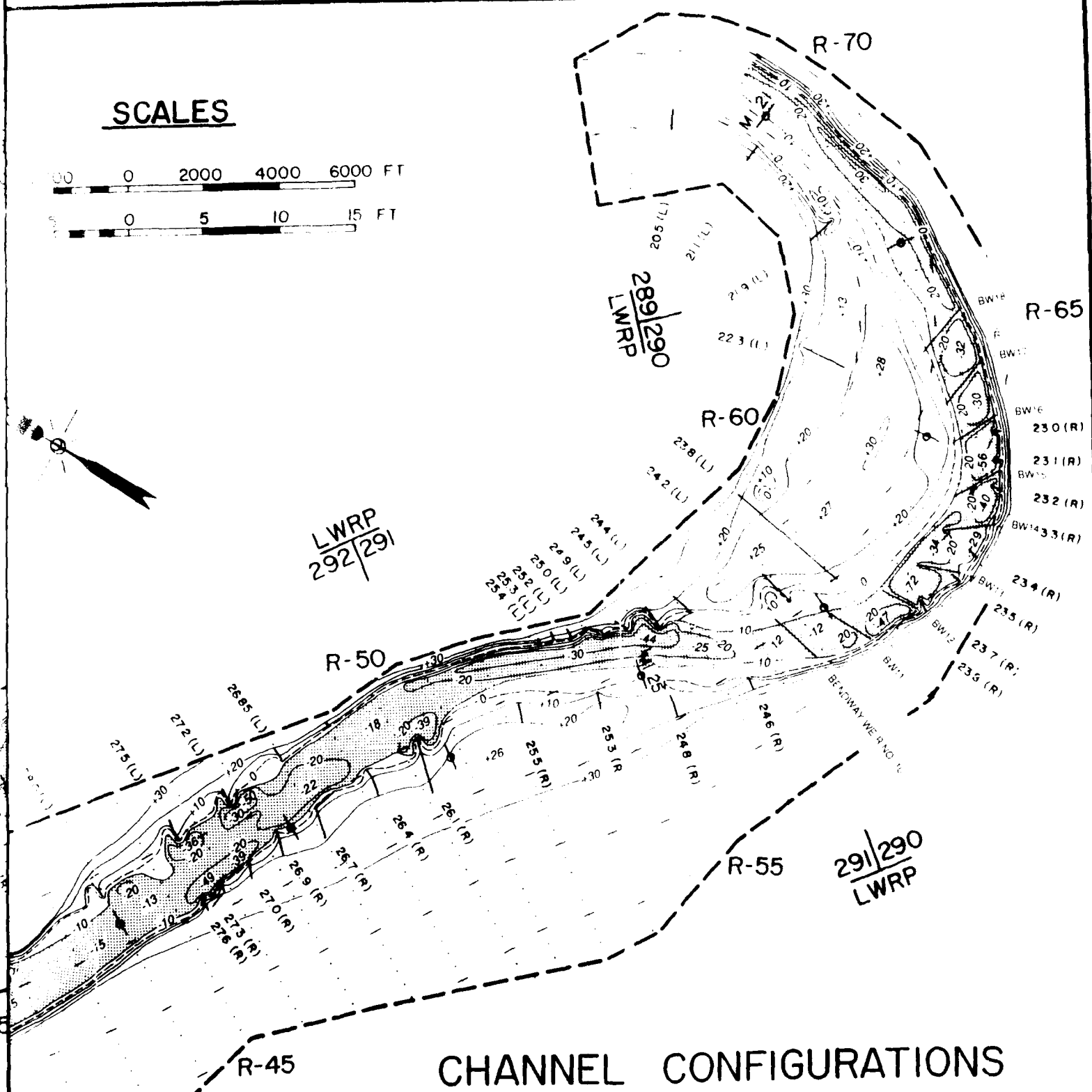
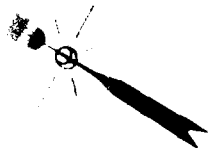
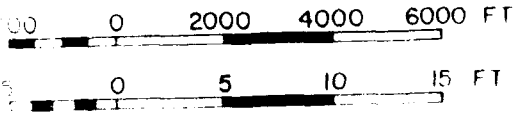


LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

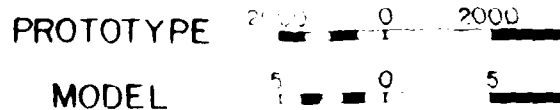


# SCALES




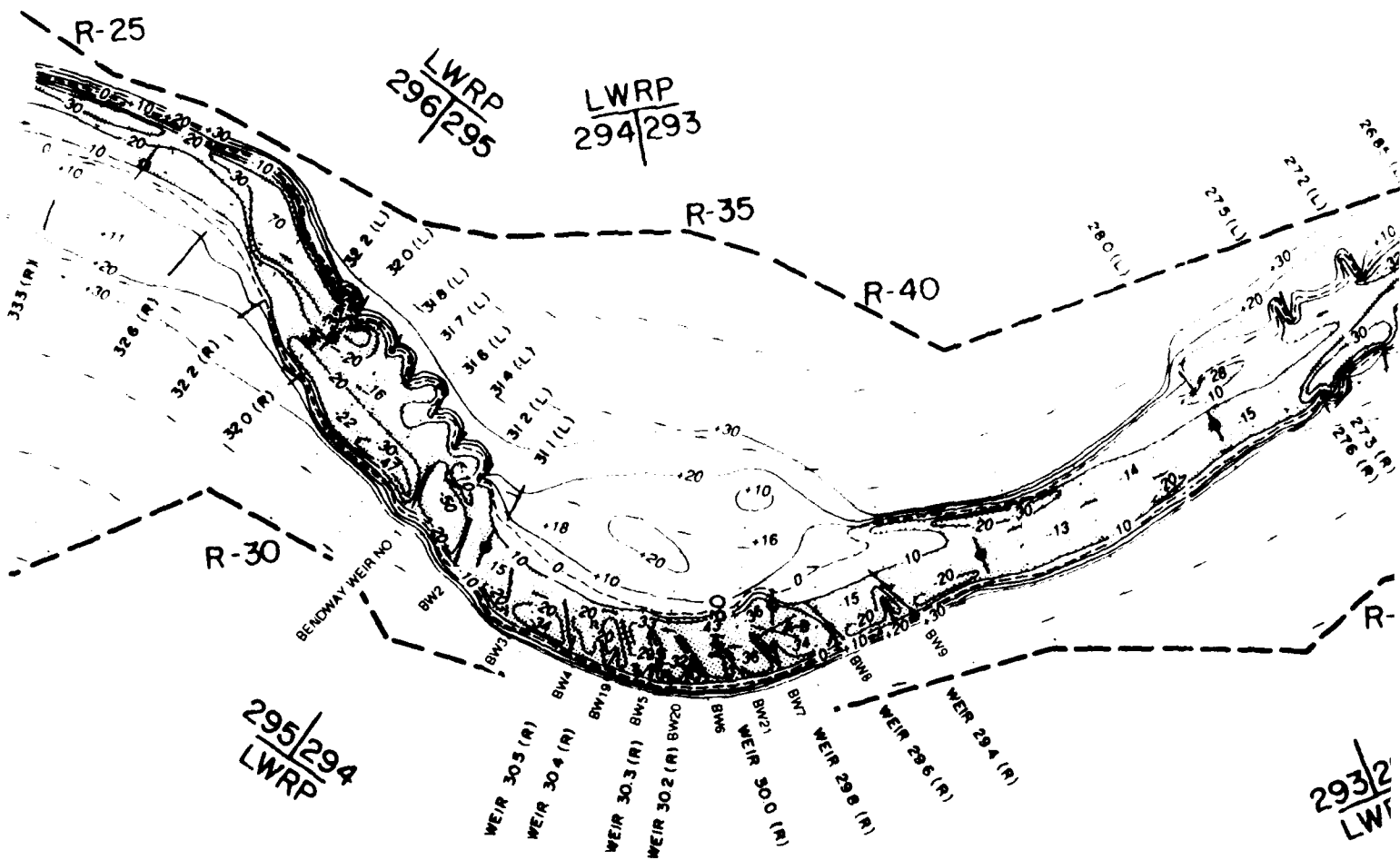
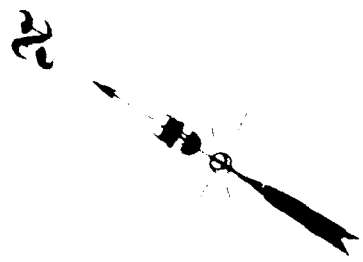
## CHANNEL CONFIGURATIONS PLAN G RUN 3

# SCALES

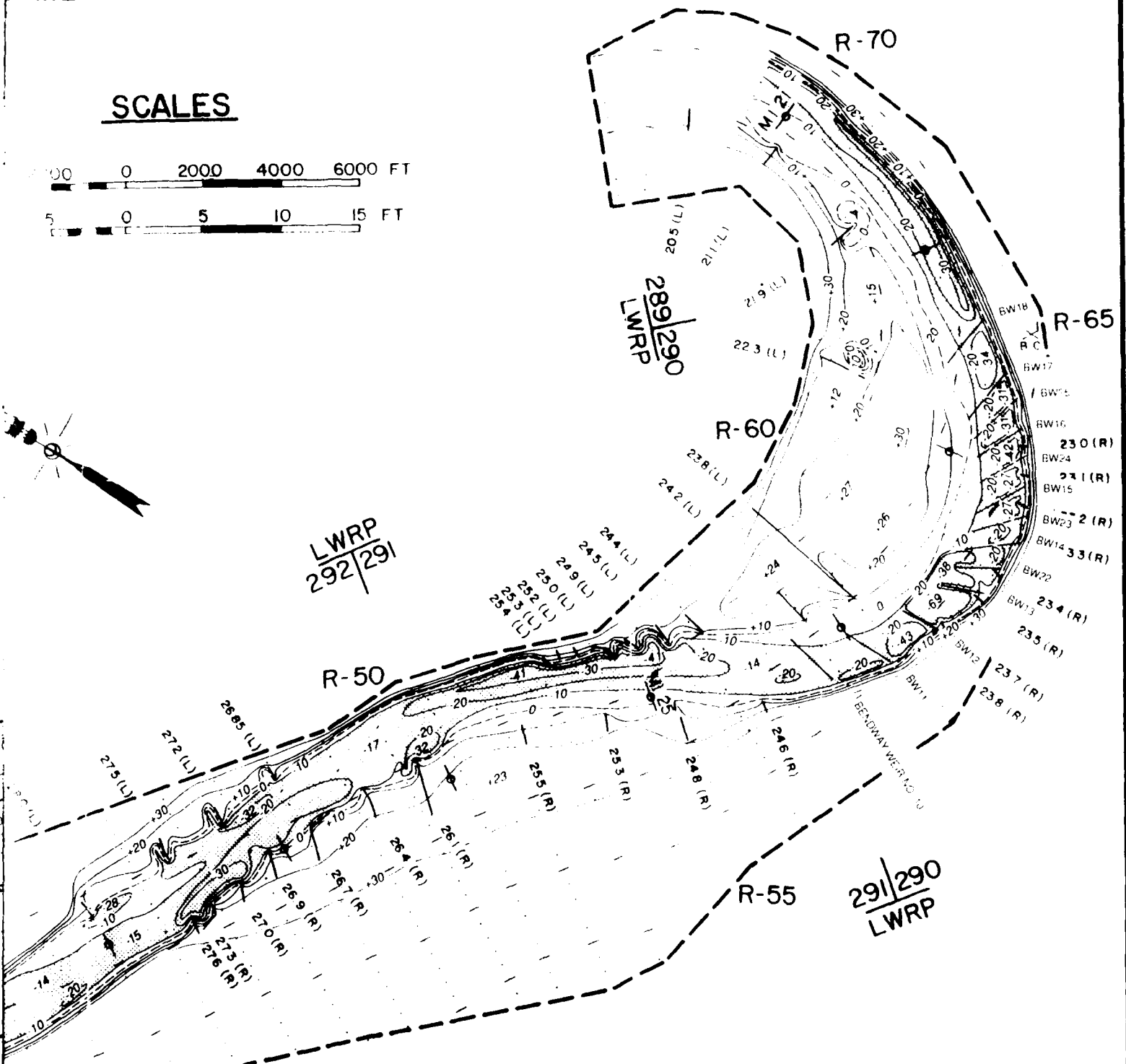
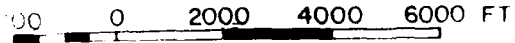


## LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



**SCALES**



**CHANNEL CONFIGURATIONS**


PLAN G-2 RUN 6

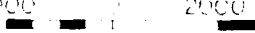
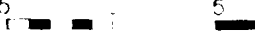
293/292  
LWRP

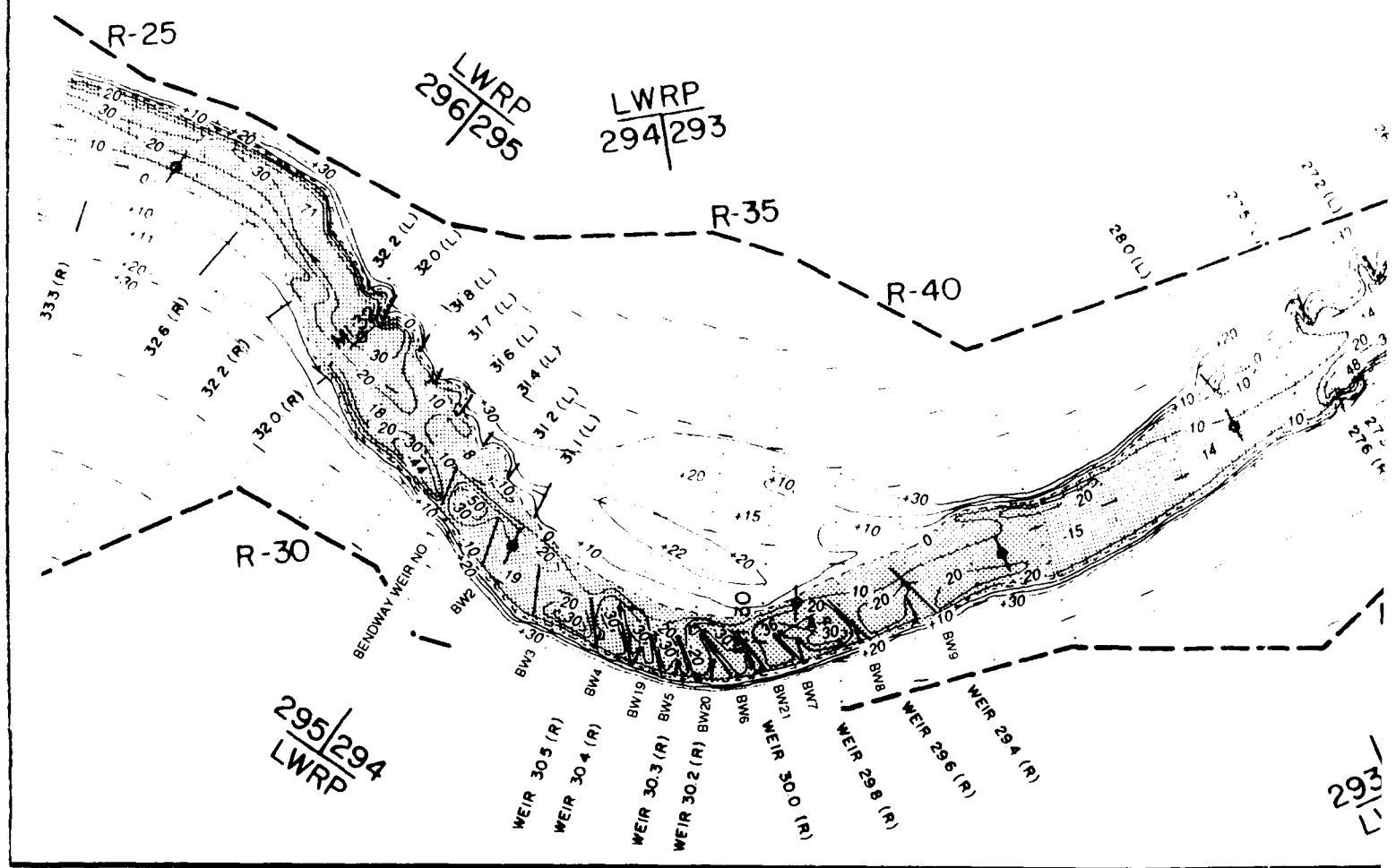
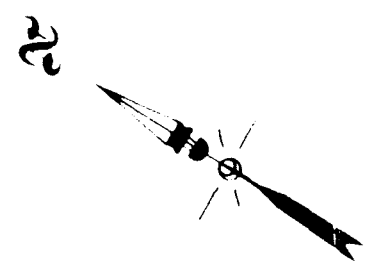
291/290  
LWRP

SCALES

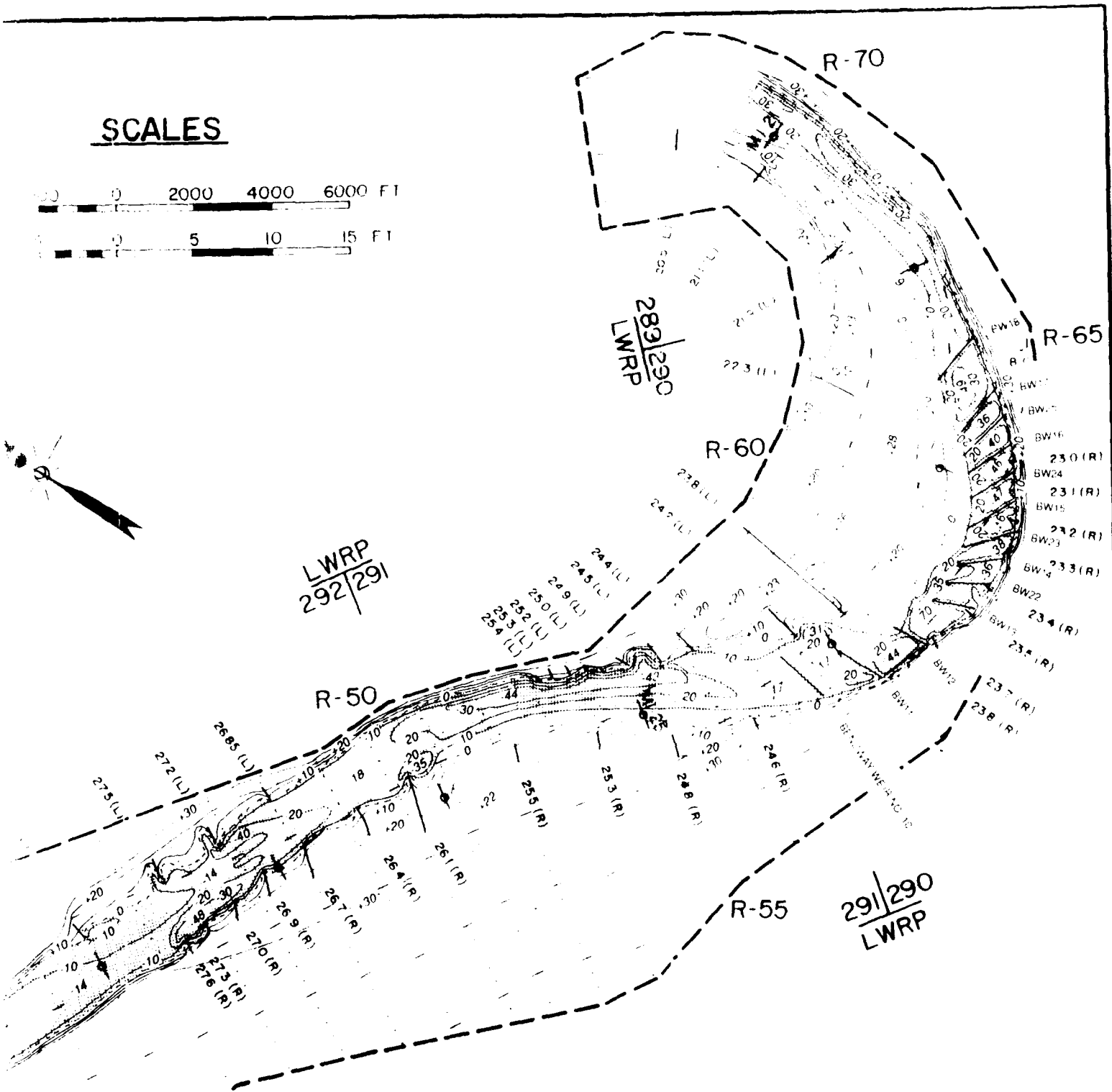
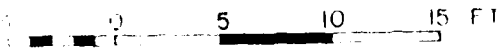
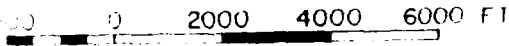
LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

PROTOTYPE  $\frac{2000}{1}$   2000  
 MODEL  $\frac{5}{1}$   5



SCALES




CHANNEL CONFIGURATIONS  
PLAN G-2 RUN 1

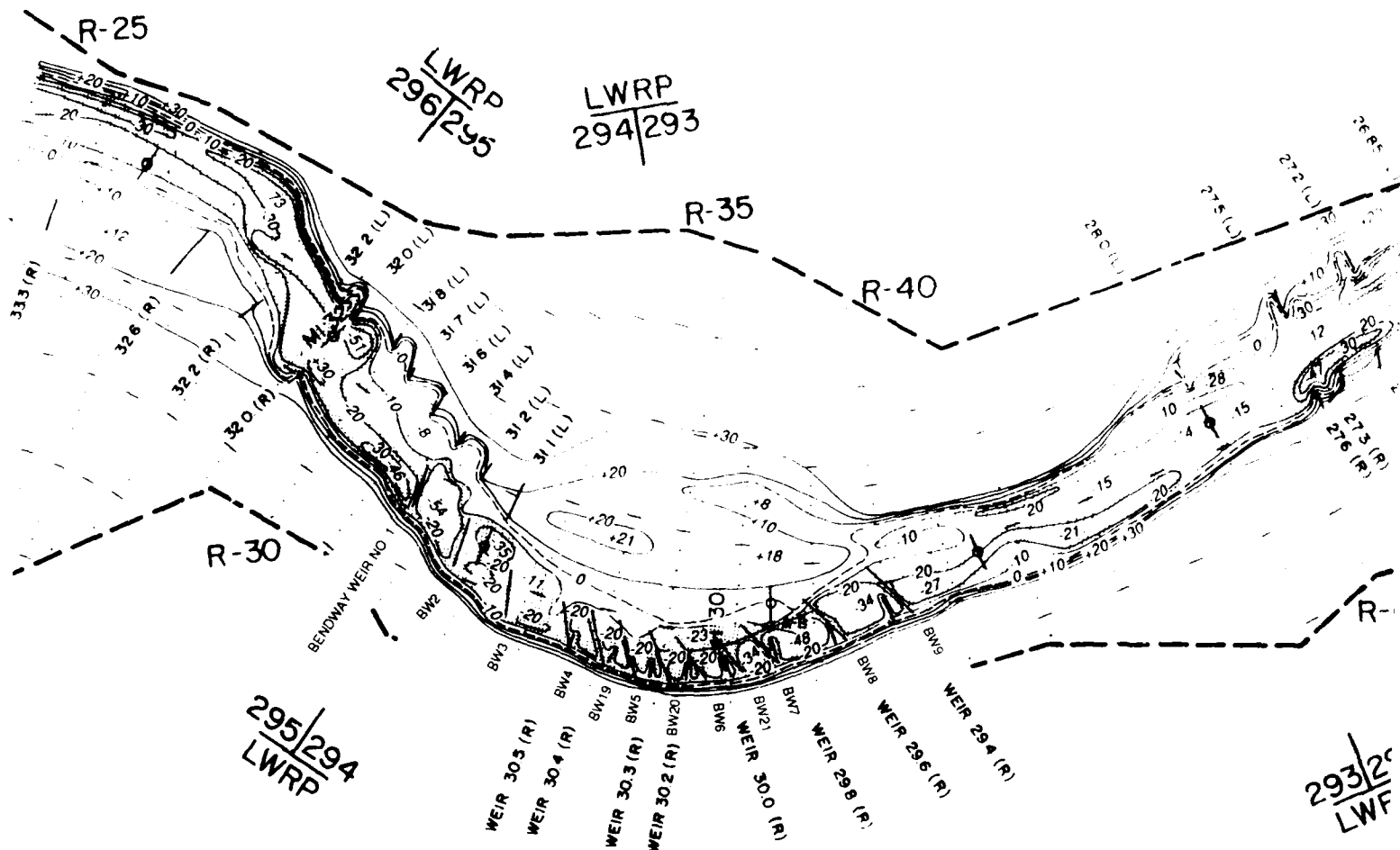
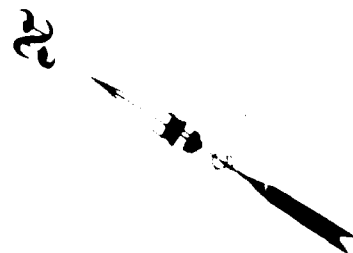
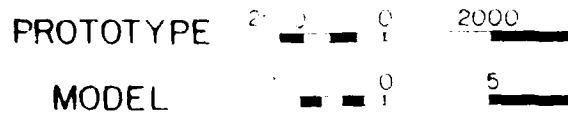
293/292  
LWRP



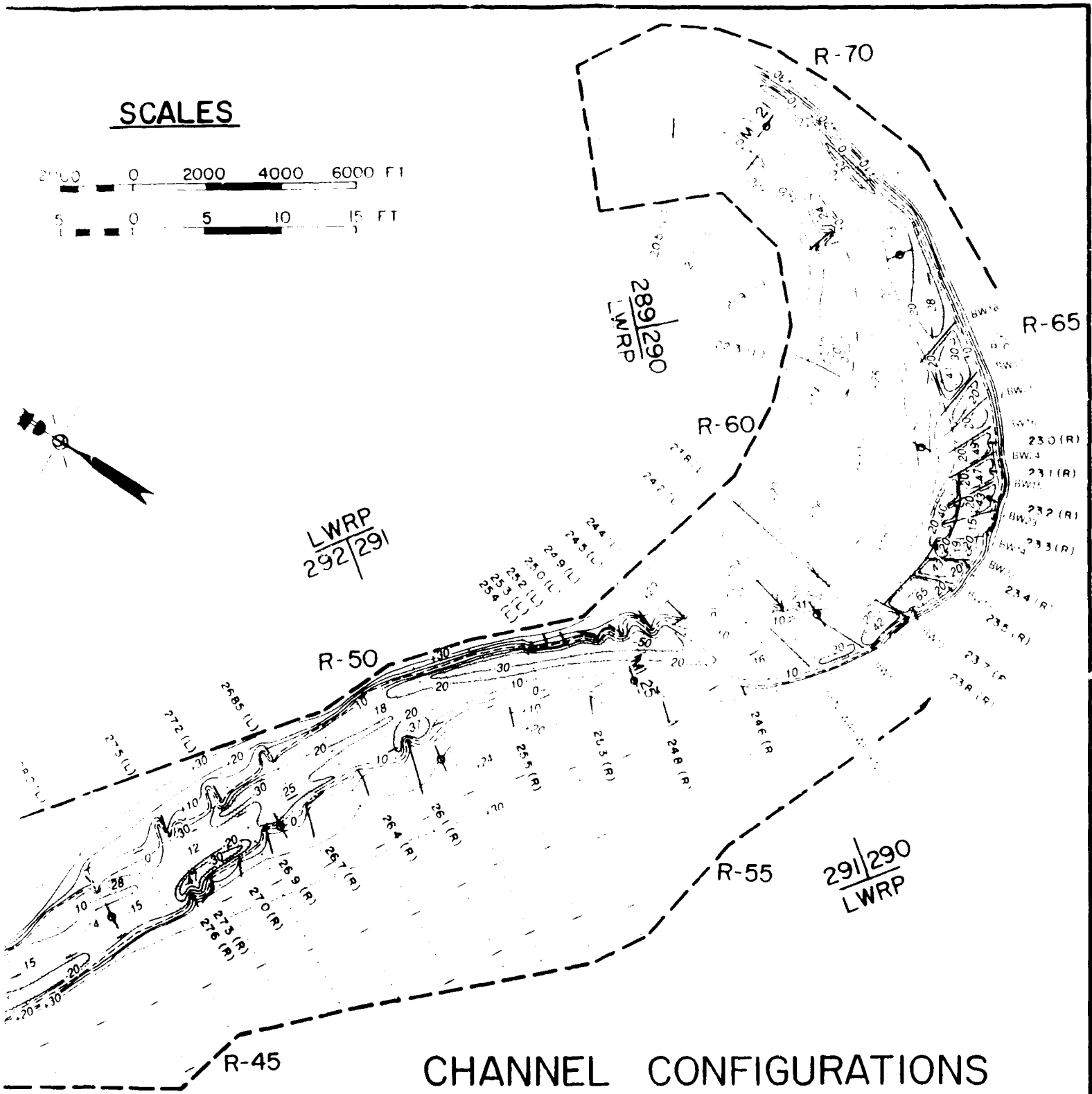
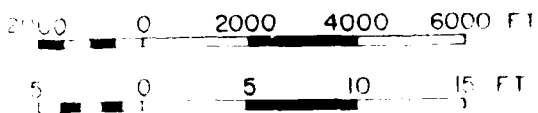
# SCALES

# LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



SCALES




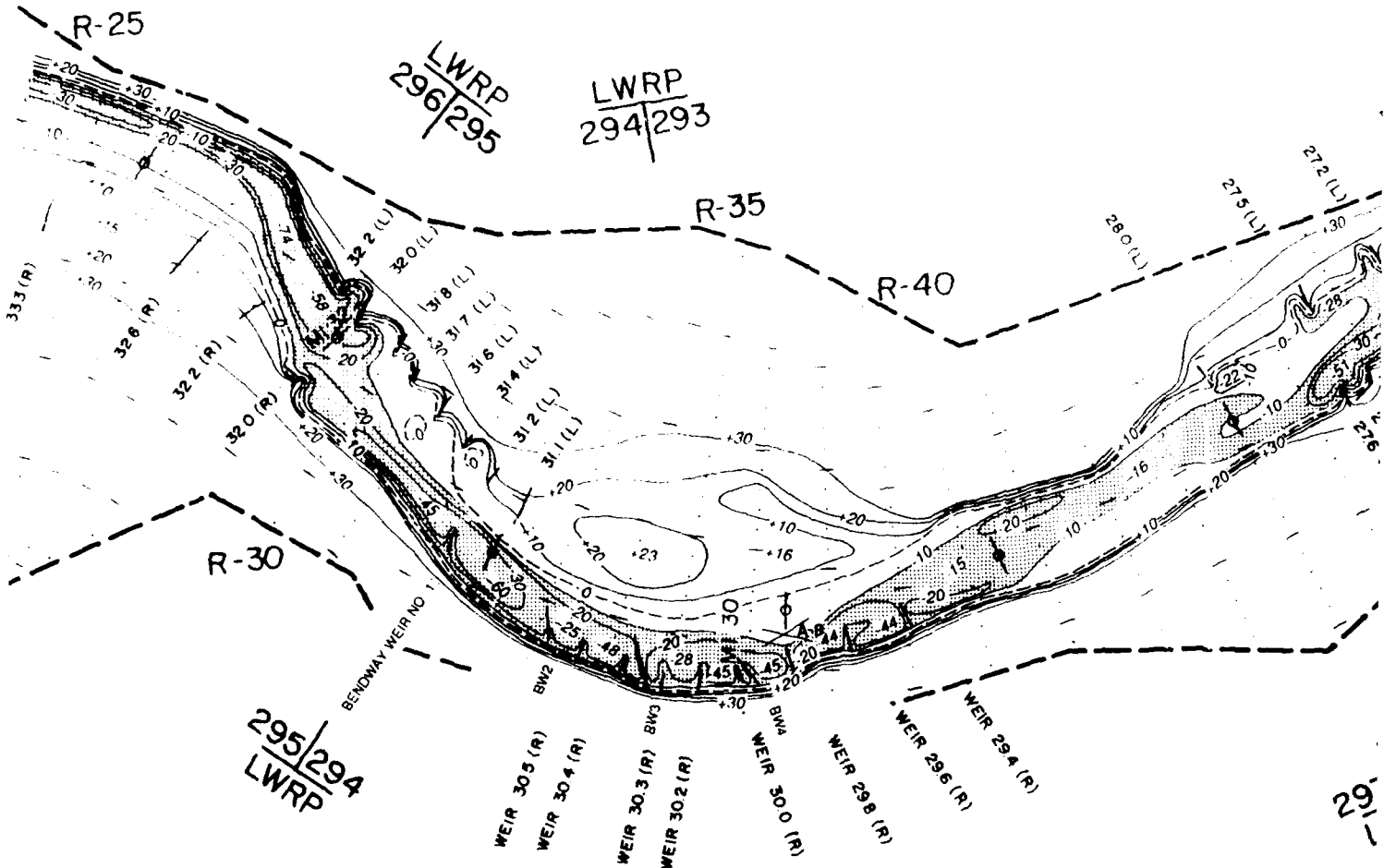
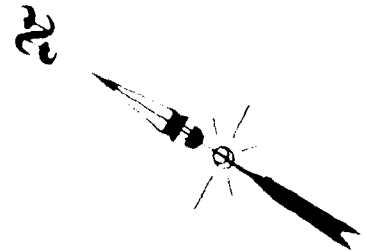
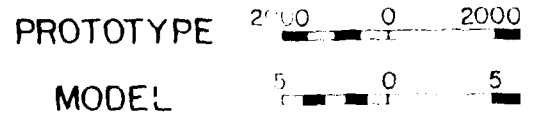
CHANNEL CONFIGURATIONS  
PLAN G-4 RUN 2

293/292  
LWRP

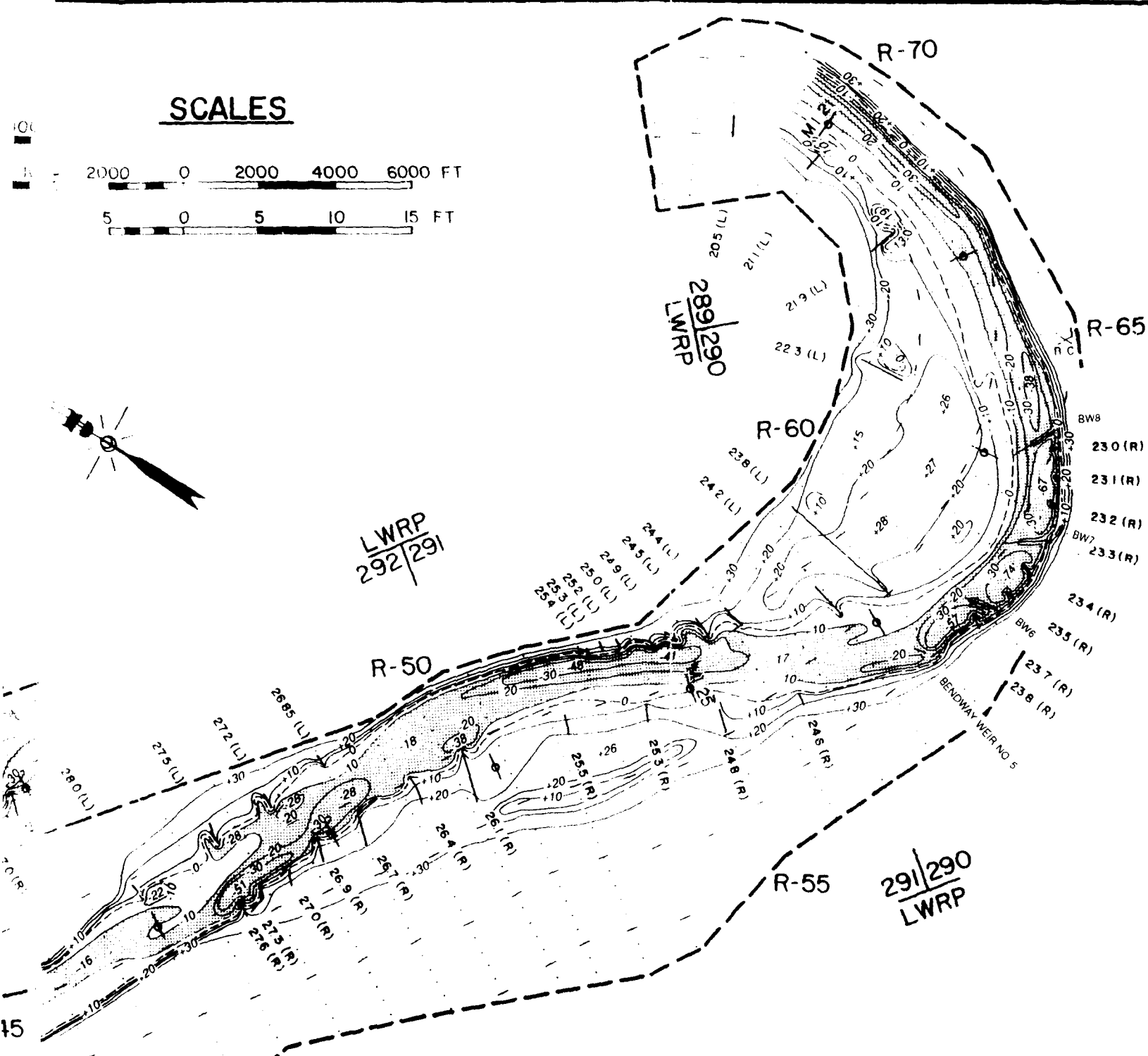
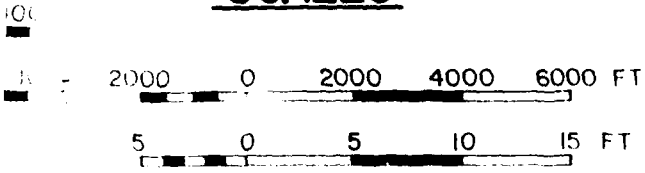
SCALES

LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE




SCALES

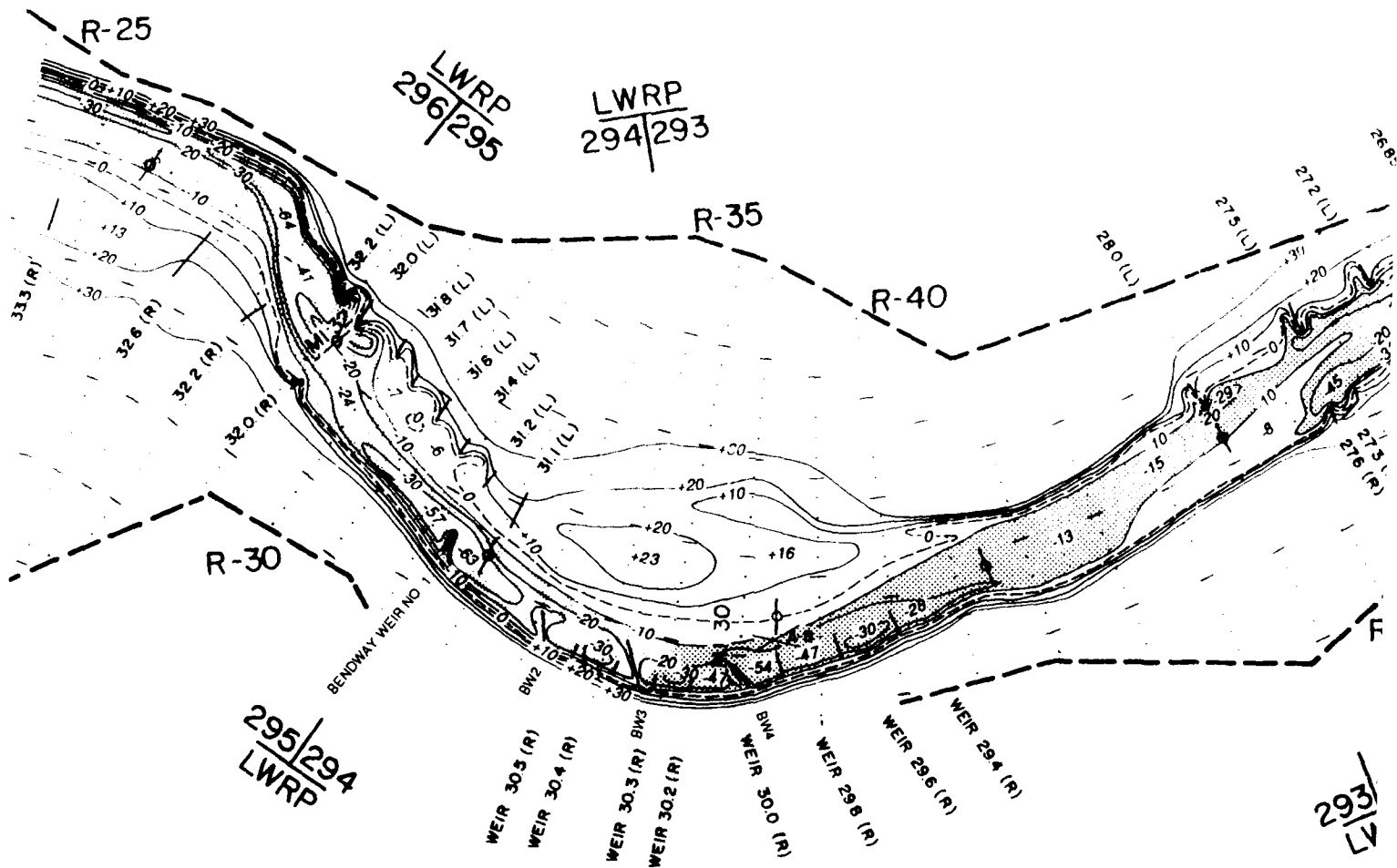
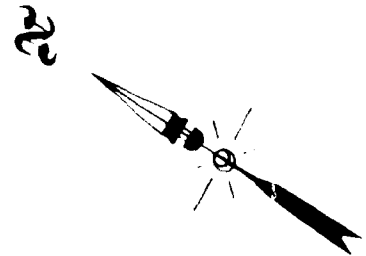
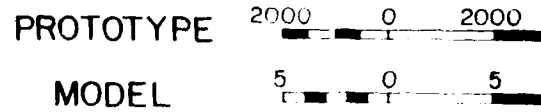


CHANNEL CONFIGURATIONS  
PLAN H RUN 4

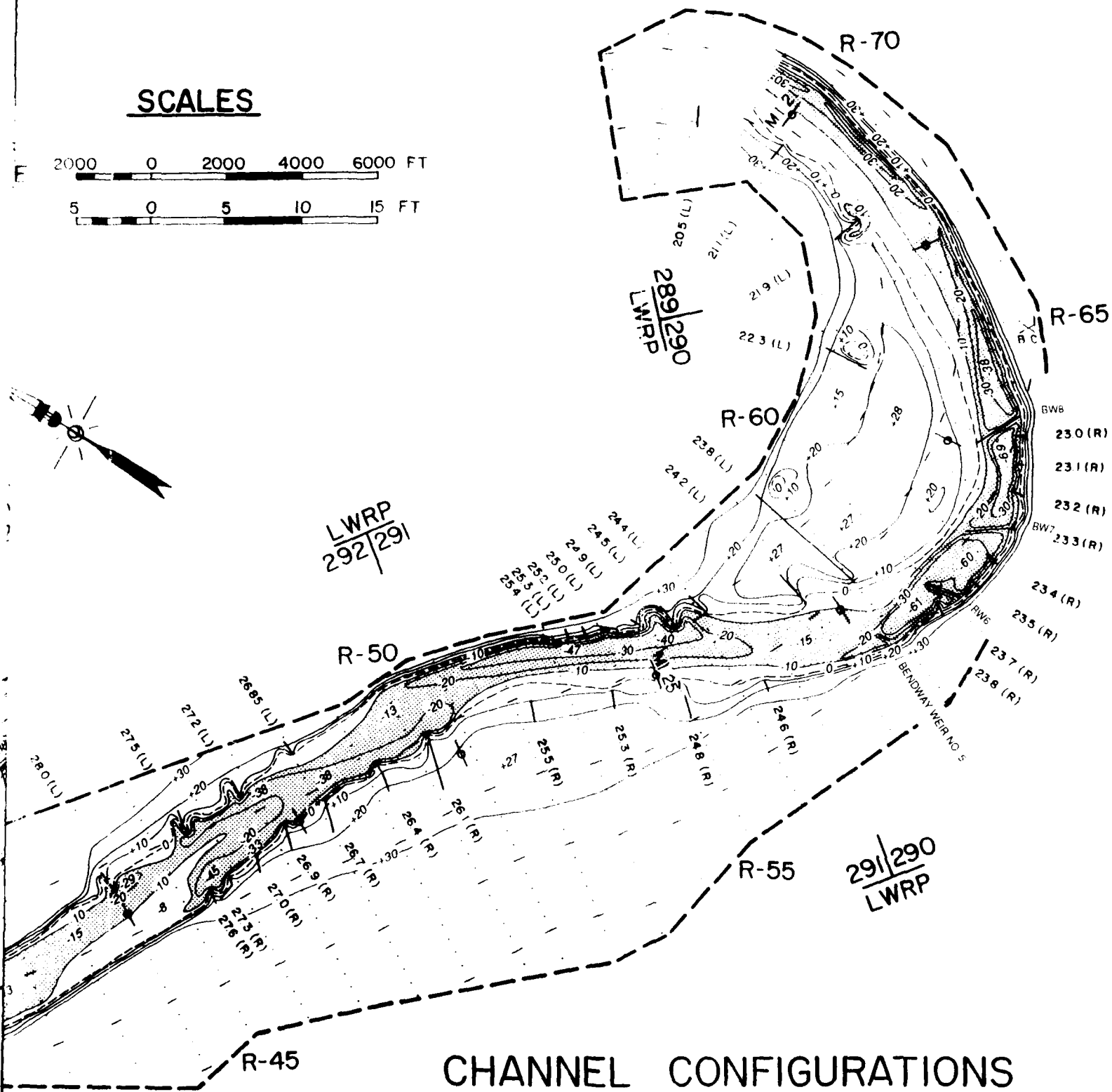
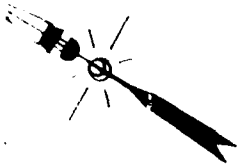
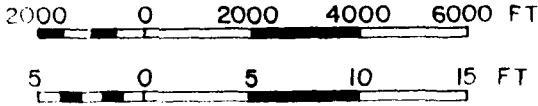
# LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

# SCALES



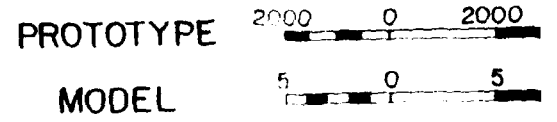
**SCALES**




**CHANNEL CONFIGURATIONS  
PLAN H-1 RUN 2**

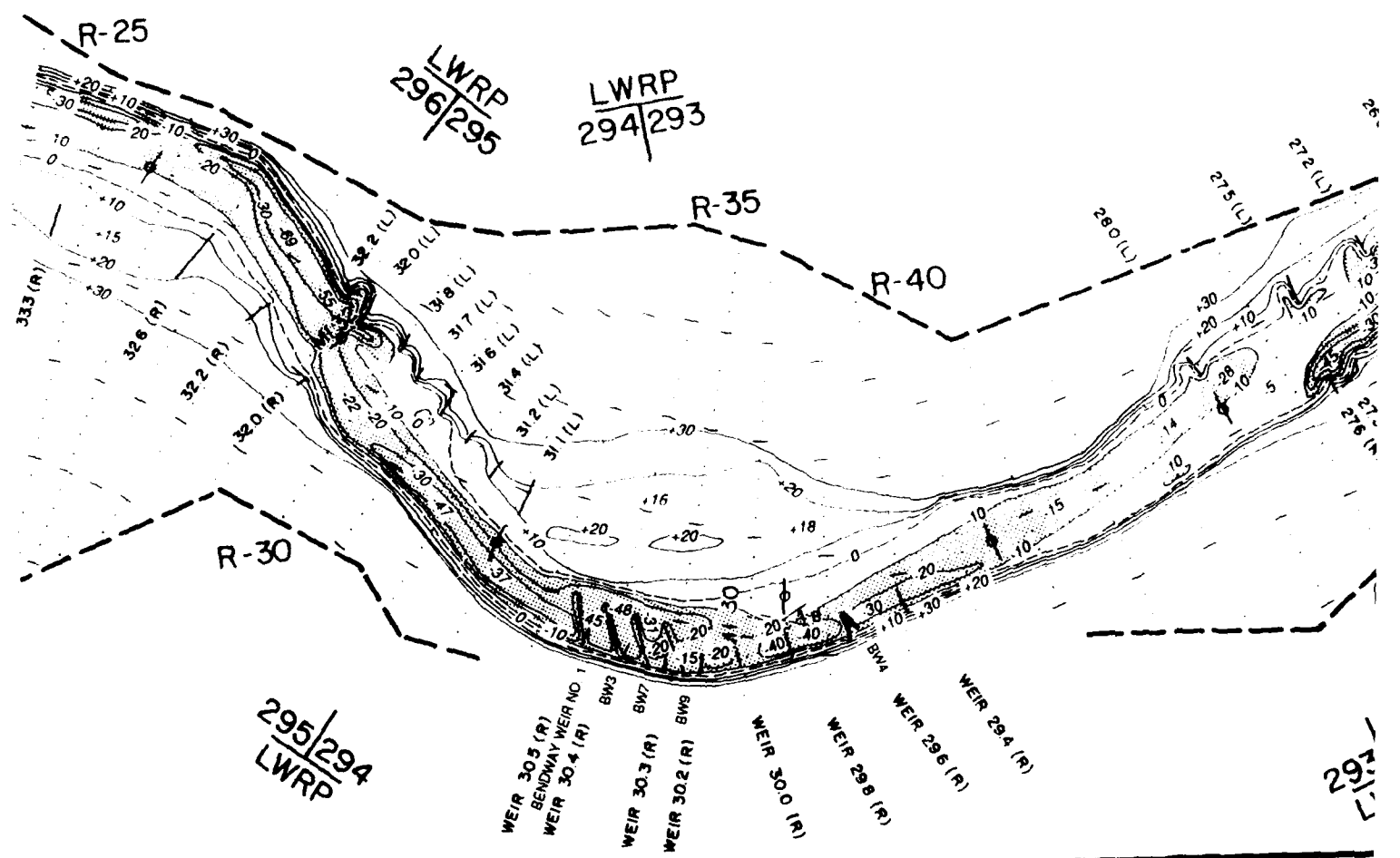
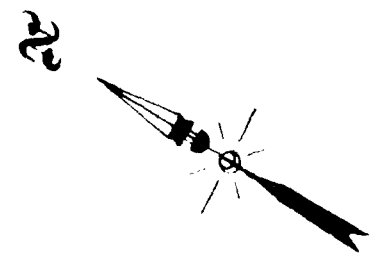
293/292  
LWRP

**SCALES**

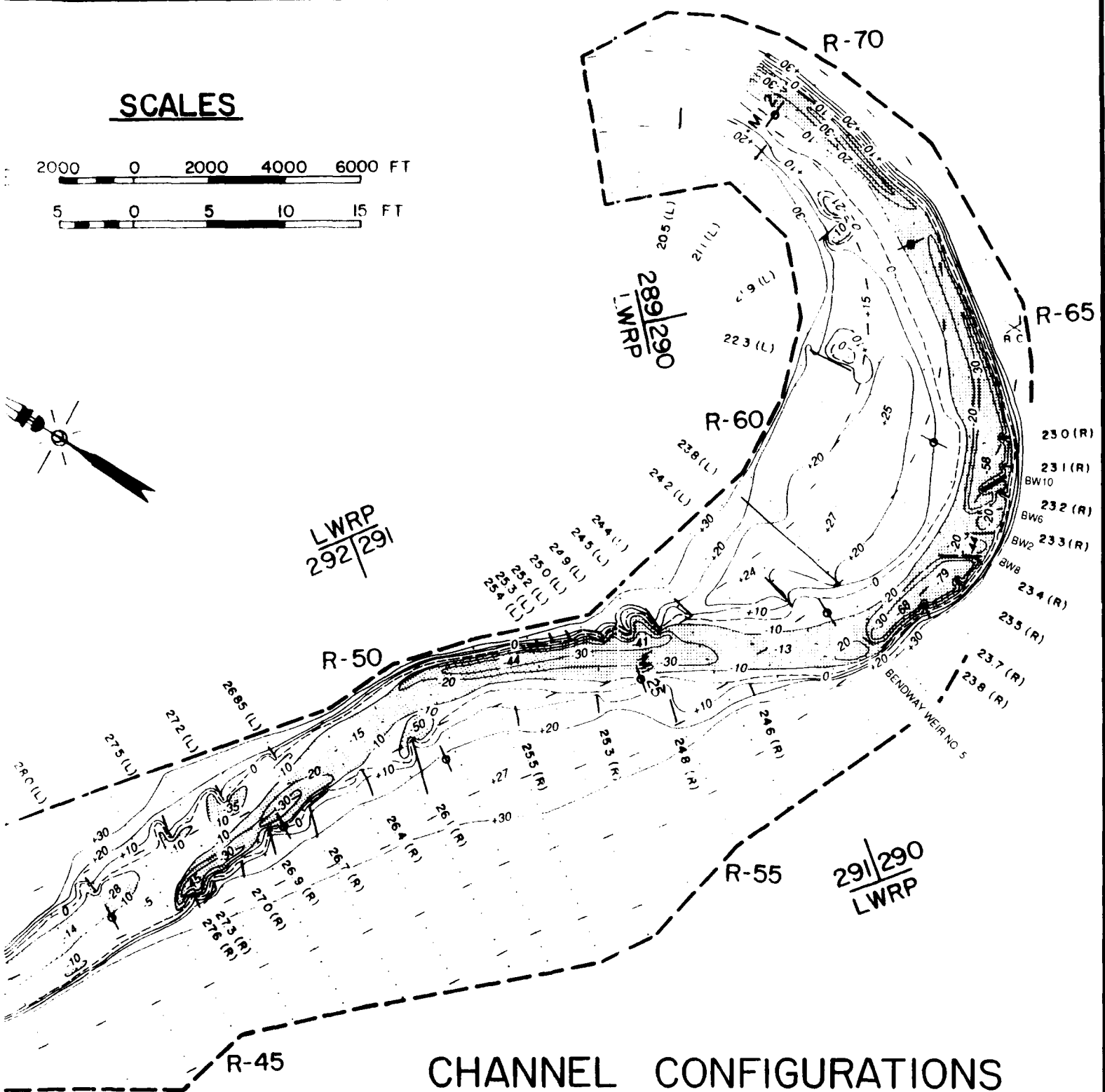
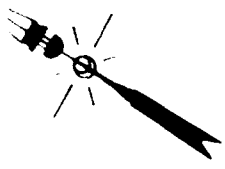
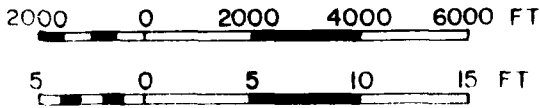


**LEGEND**

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



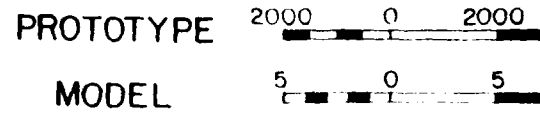
**SCALES**




**CHANNEL CONFIGURATIONS  
PLAN I-3 RUN 2**

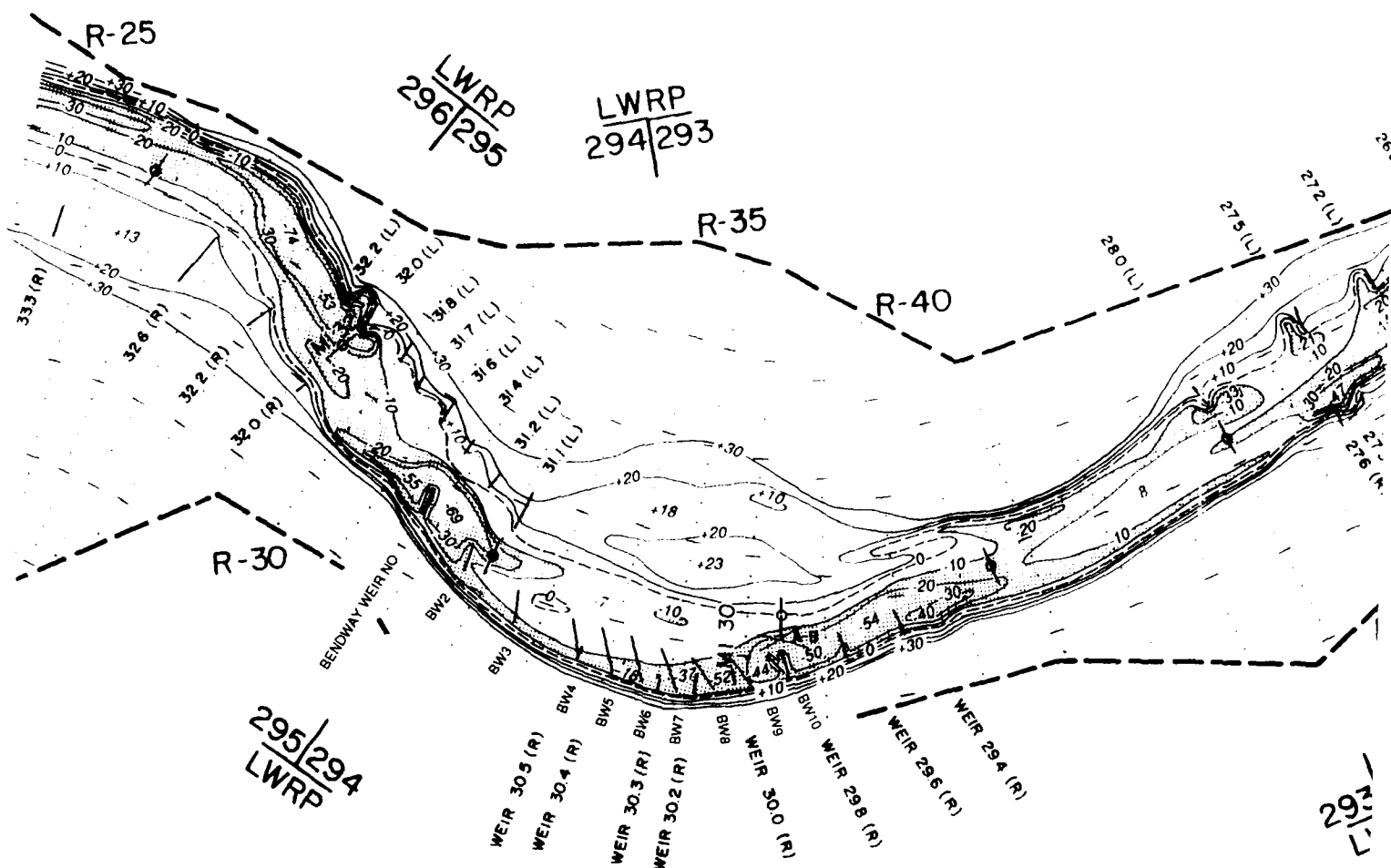
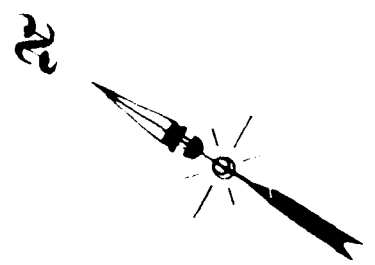


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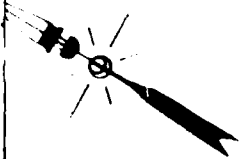
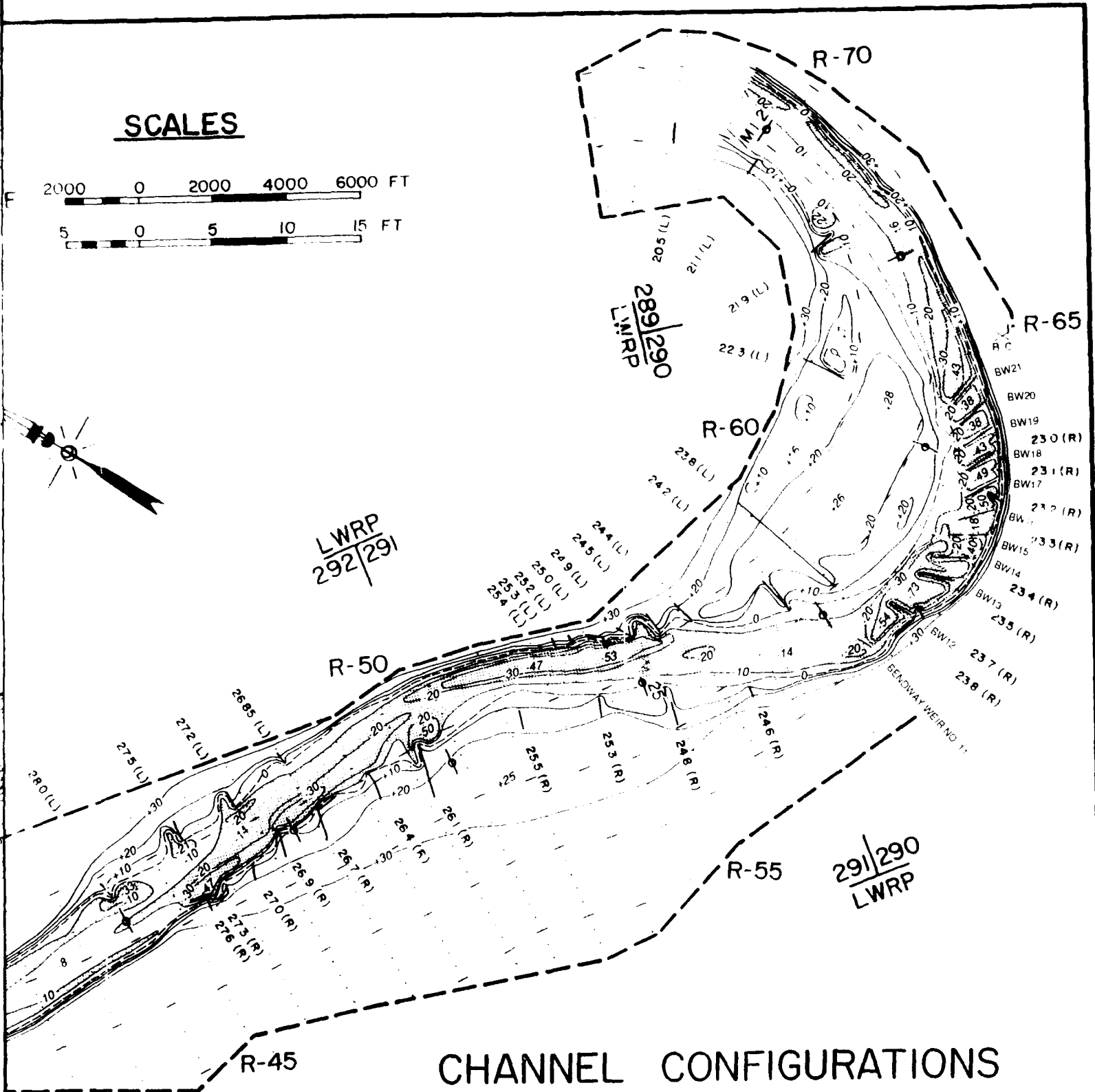
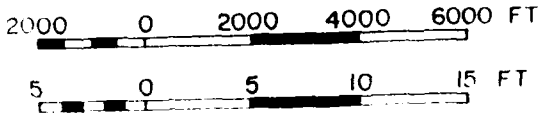


**LEGEND**

-  -10 FT LWRP AND BELOW
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- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



**SCALES**




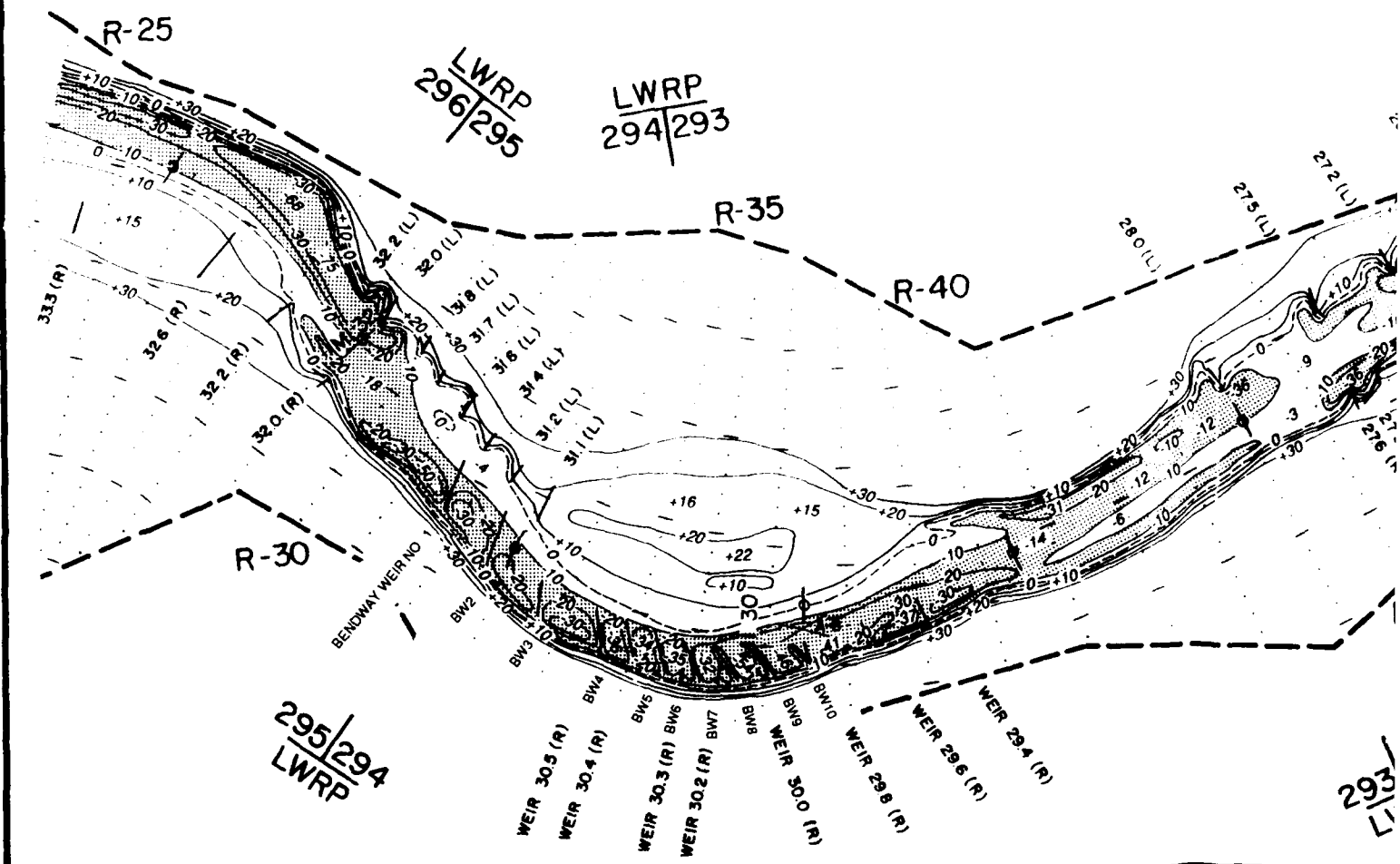
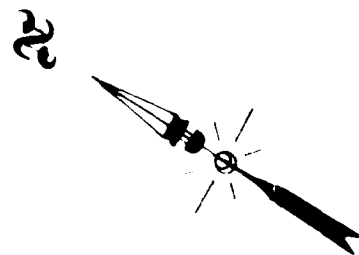
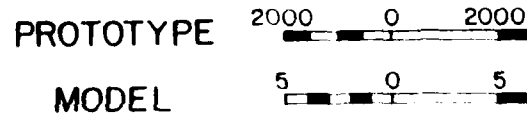
**CHANNEL CONFIGURATIONS  
PLAN J RUN 4**

**293/292  
LWRP**

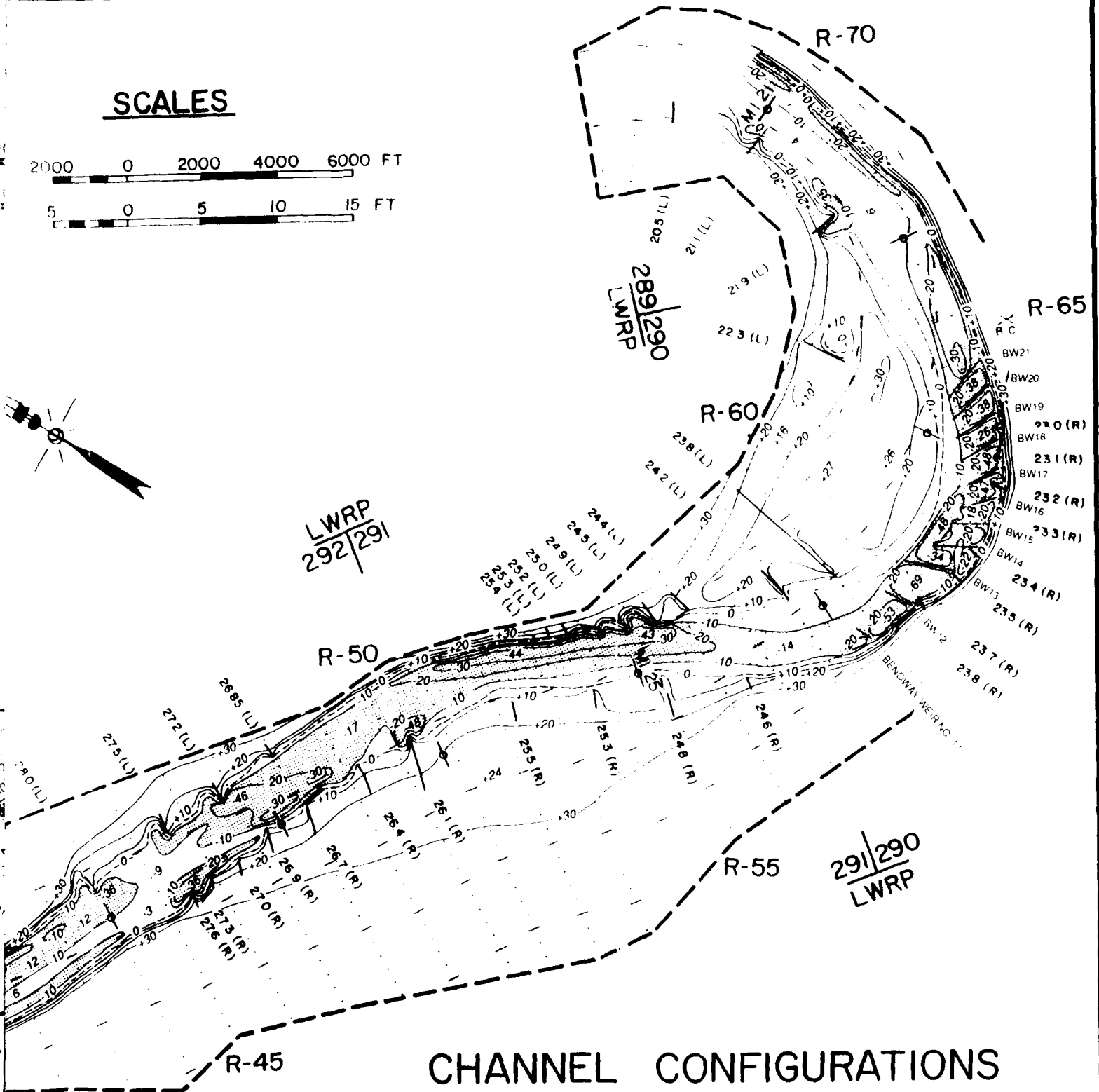
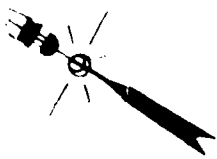
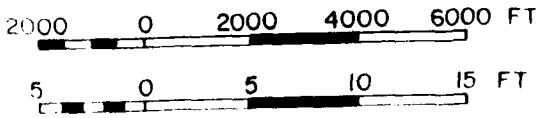
**SCALES**

**LEGEND**

-  -10 FT LWRP AND BELOW
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- WEIR 30.5 (R) PROTOTYPE WEIR
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- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

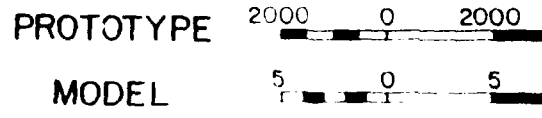


**SCALES**




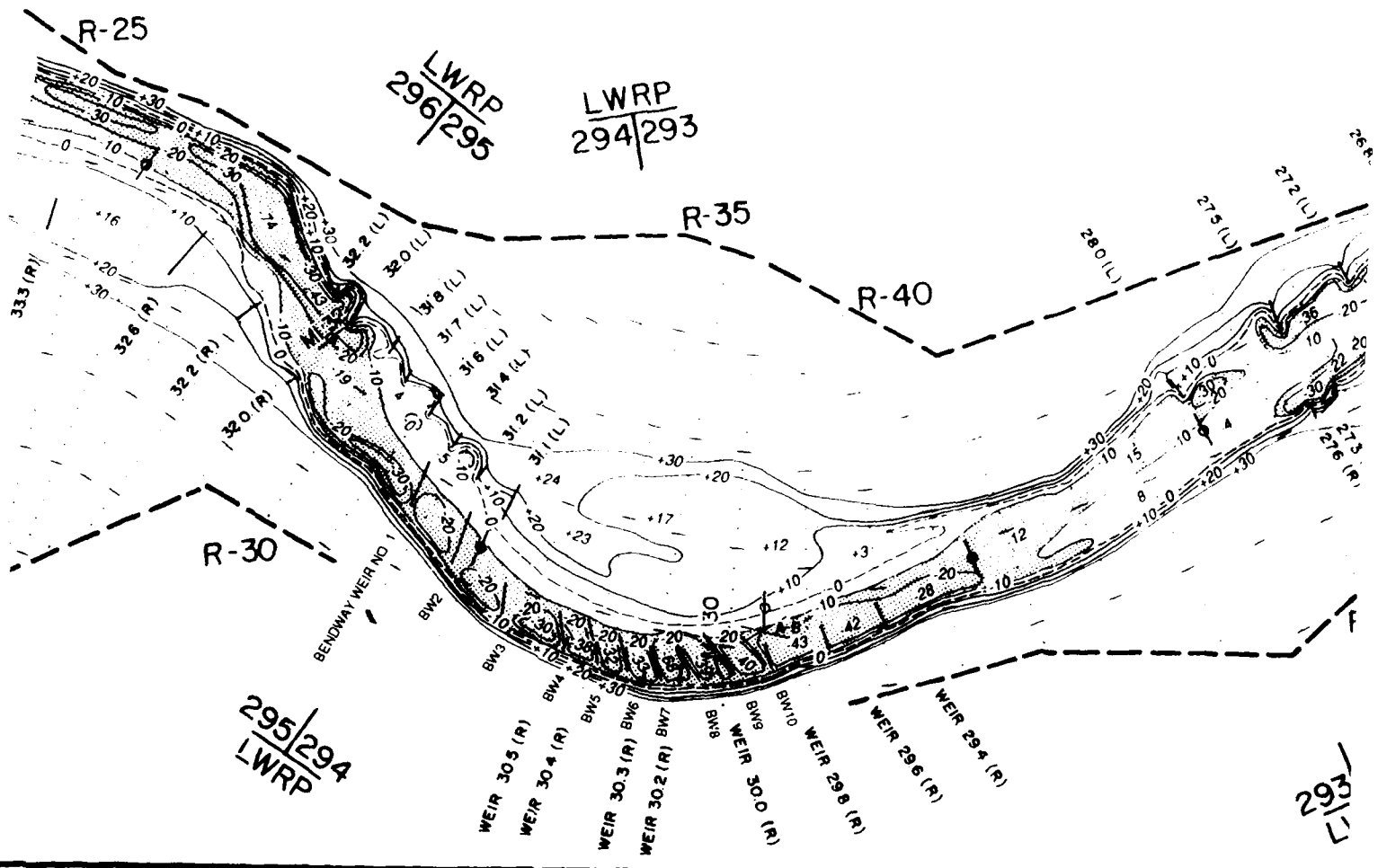
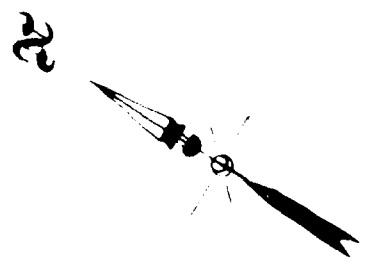
**CHANNEL CONFIGURATIONS  
PLAN J-1 RUN 2**

SCALES



LEGEND

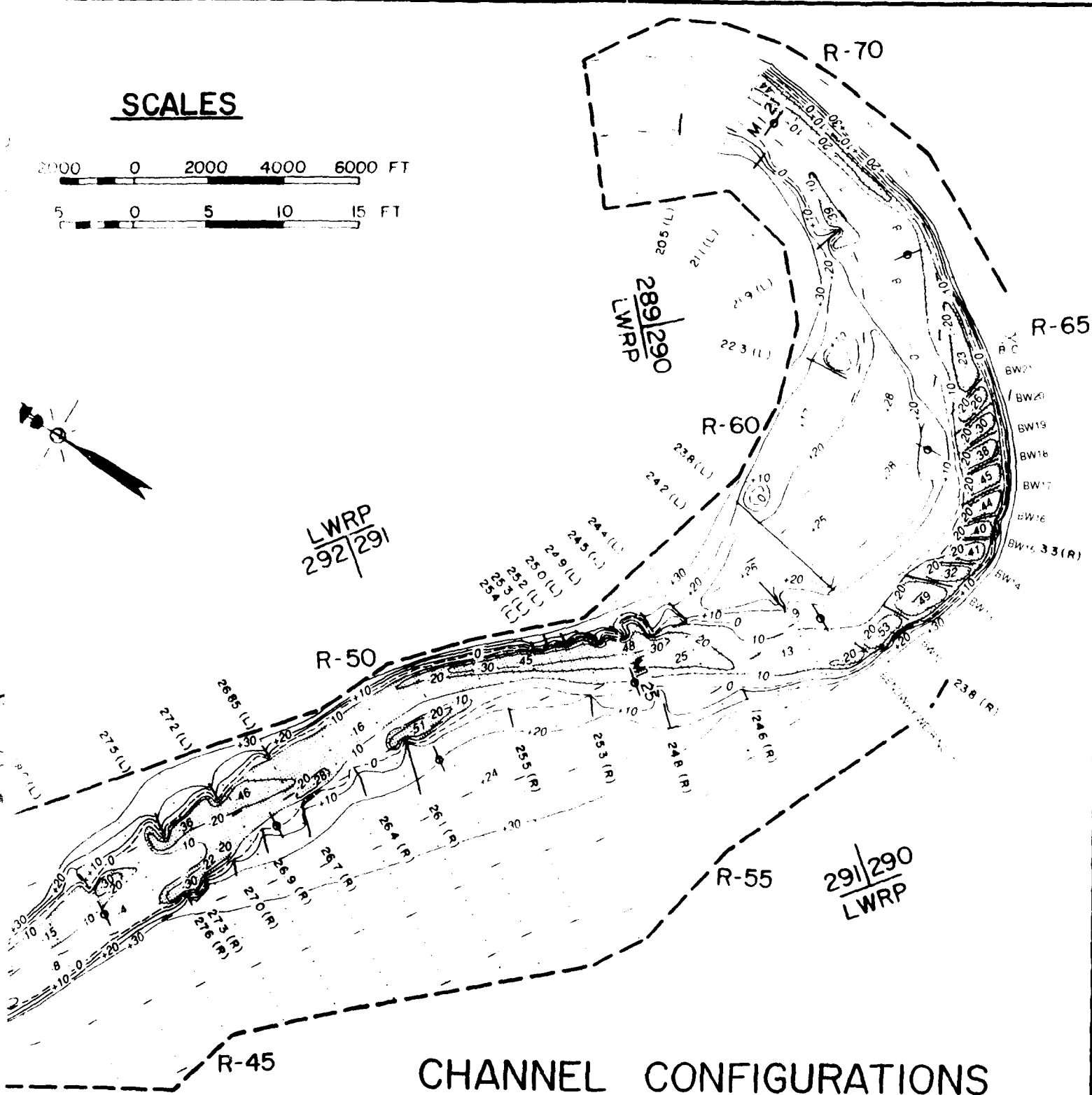
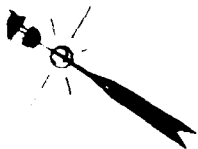
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- WEIR 30.5 (R) PROTOTYPE WEIR
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- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



# SCALES

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5 0 5 10 15 FT

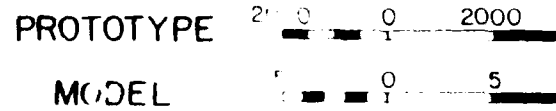


## CHANNEL CONFIGURATIONS


PLAN L-1 RUN 2

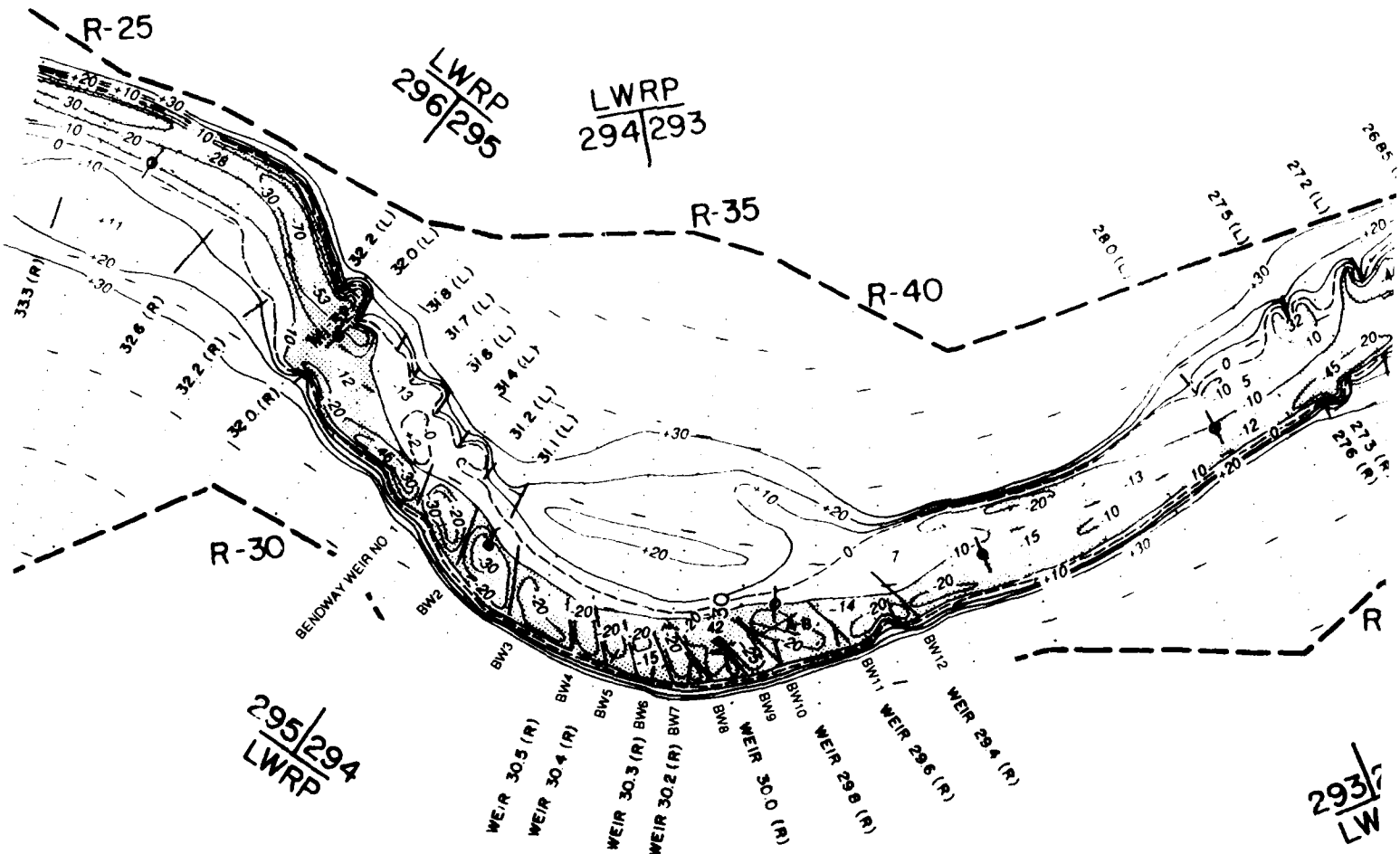
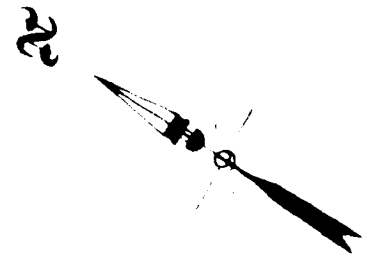
293/292  
LWRP

SCALES

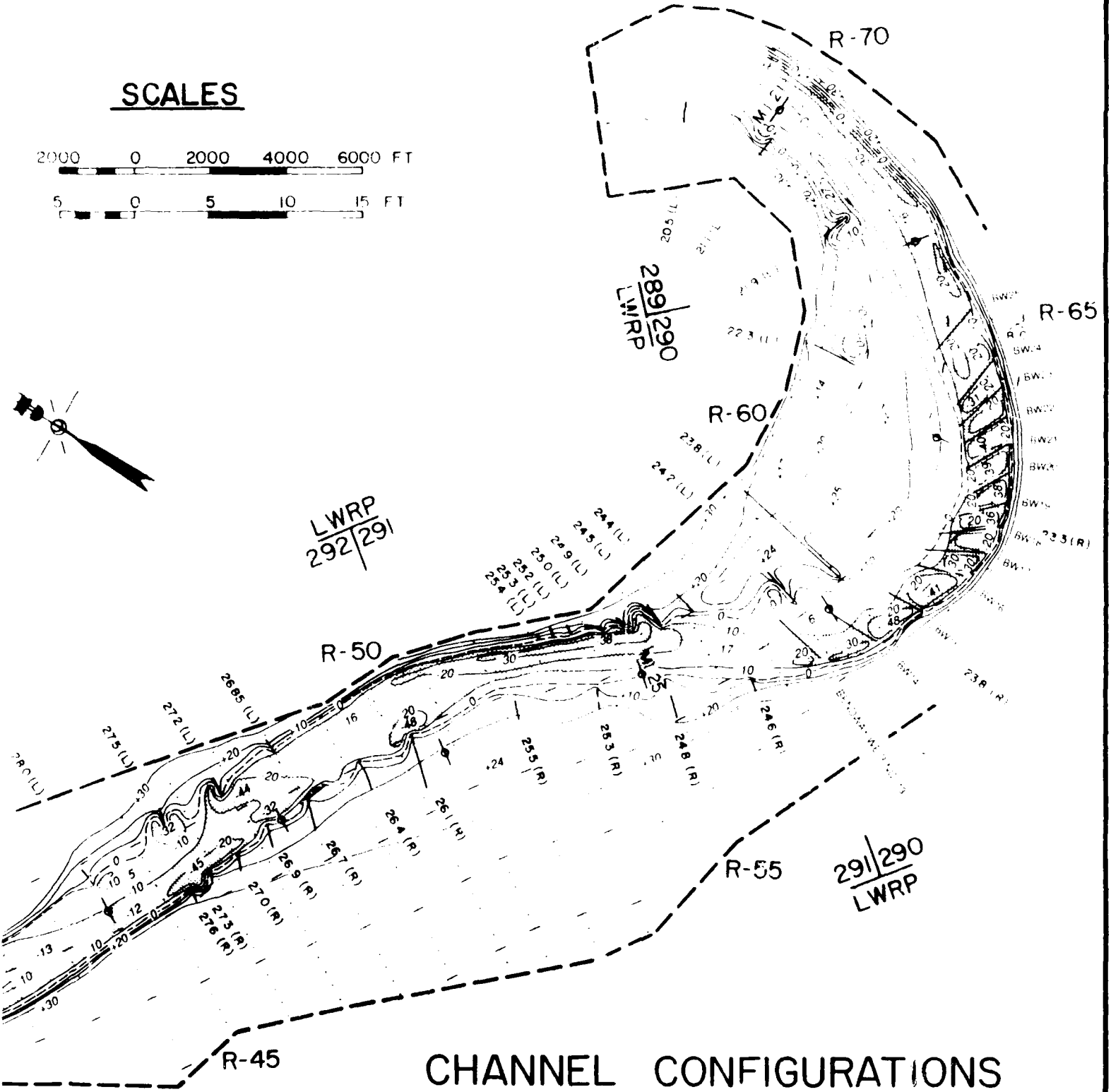
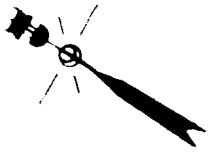
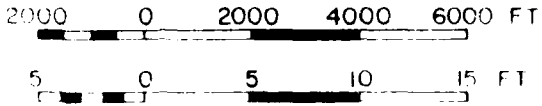


LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



**SCALES**




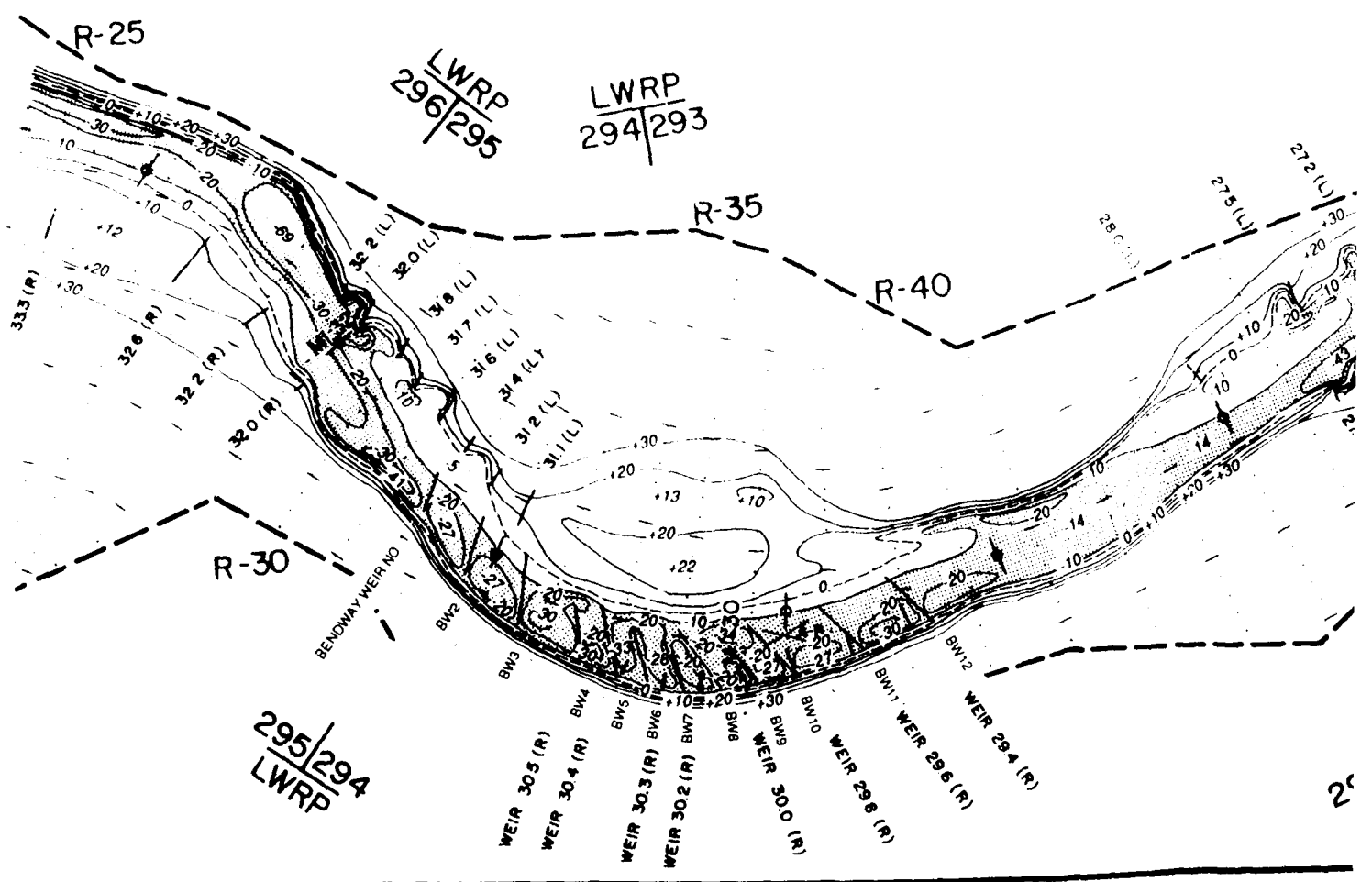
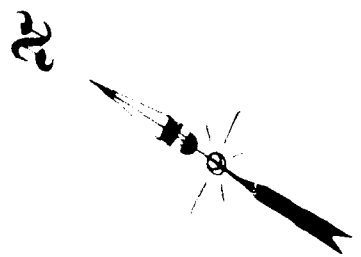
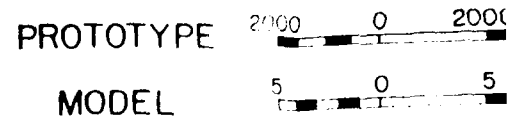
**CHANNEL CONFIGURATIONS  
PLAN M RUN 5**



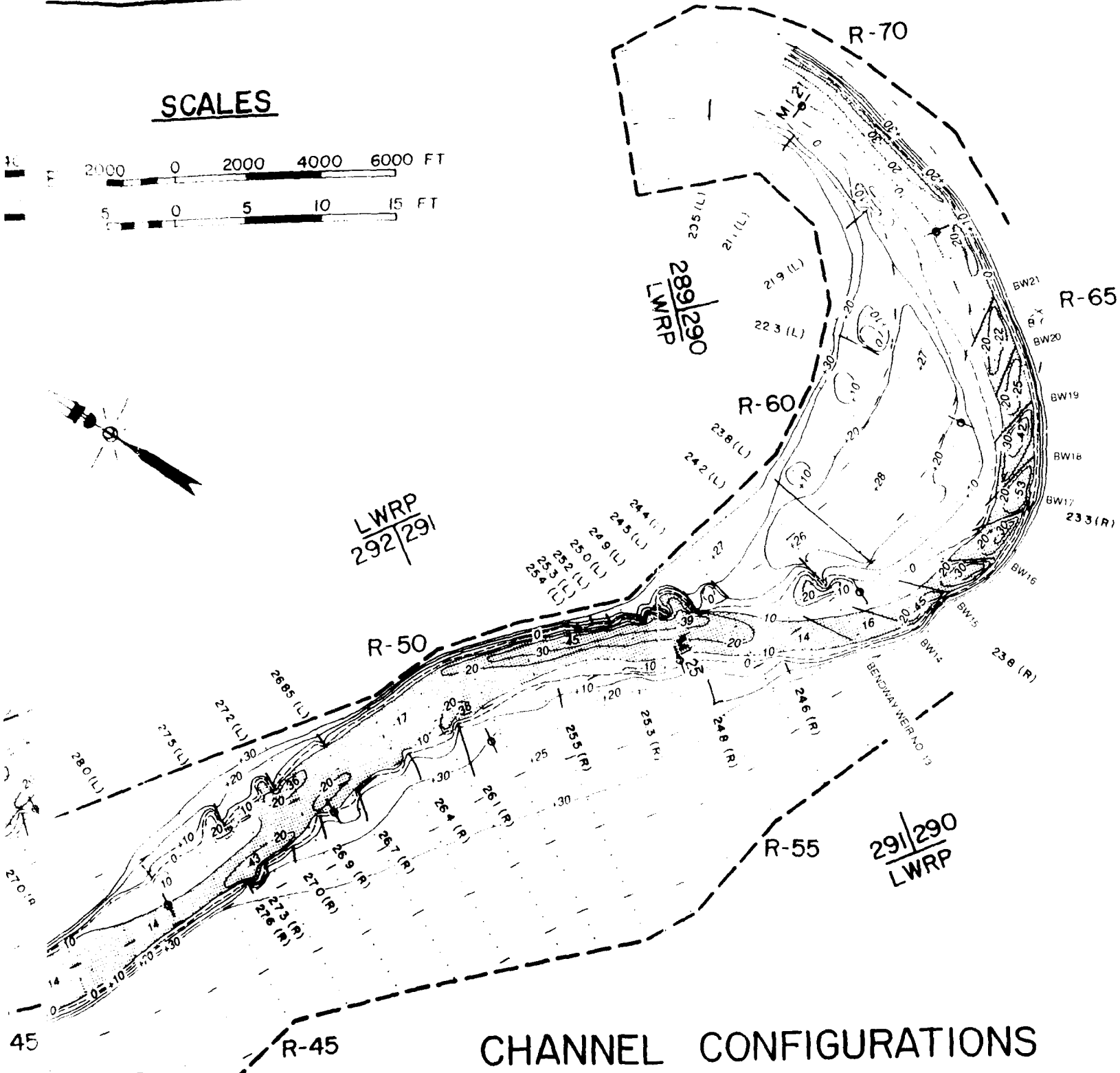
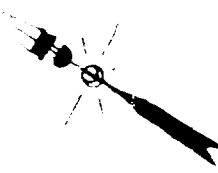
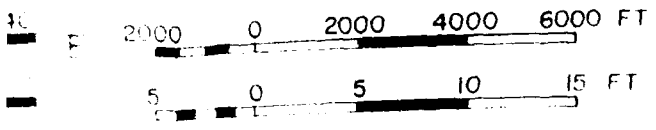
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LEGEND

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- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



SCALES




CHANNEL CONFIGURATIONS  
PLAN N RUN 2

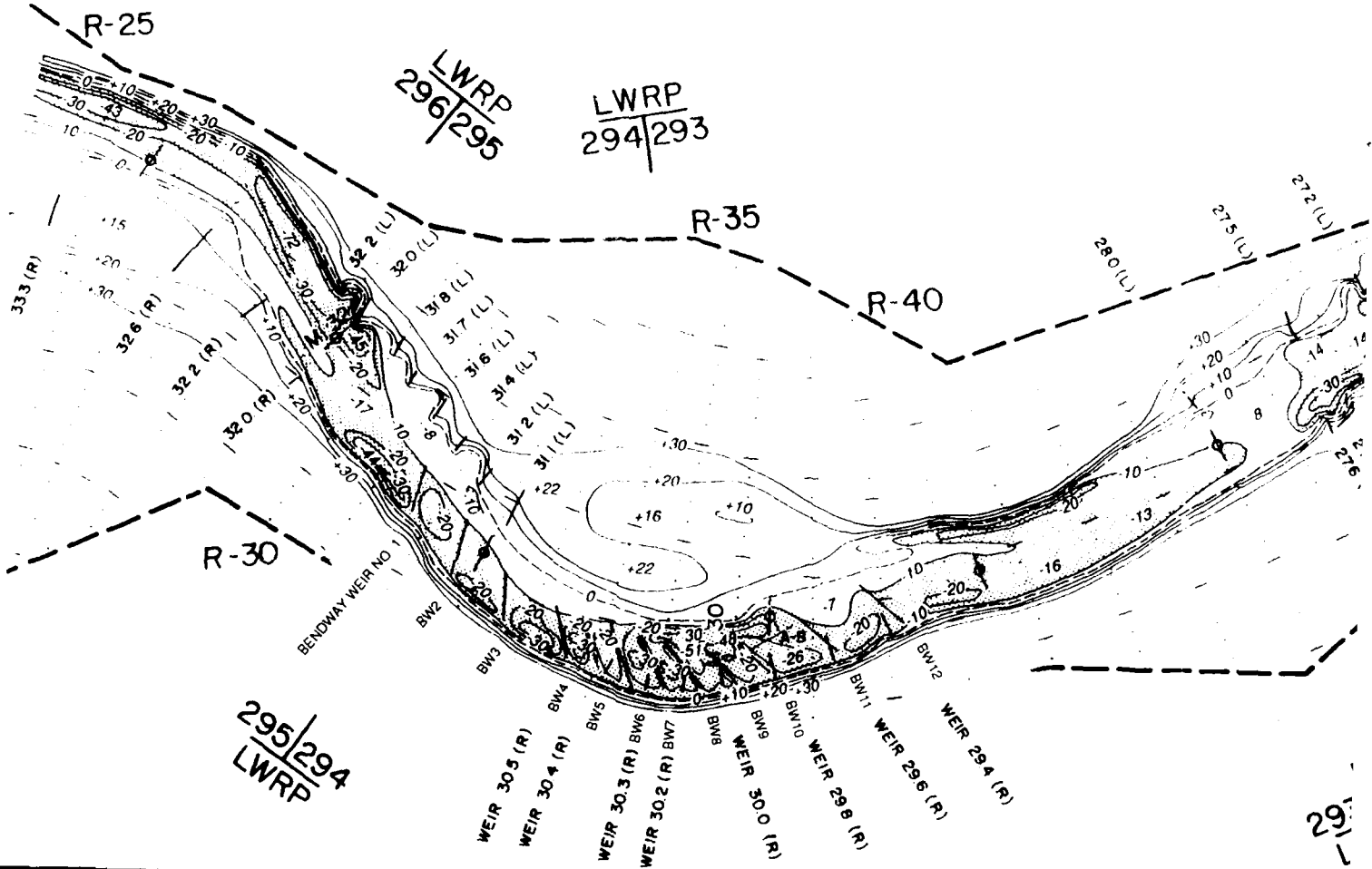
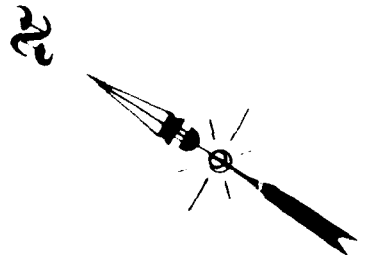
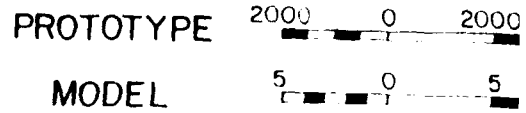
32  
19

293/292  
LWRP

# LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

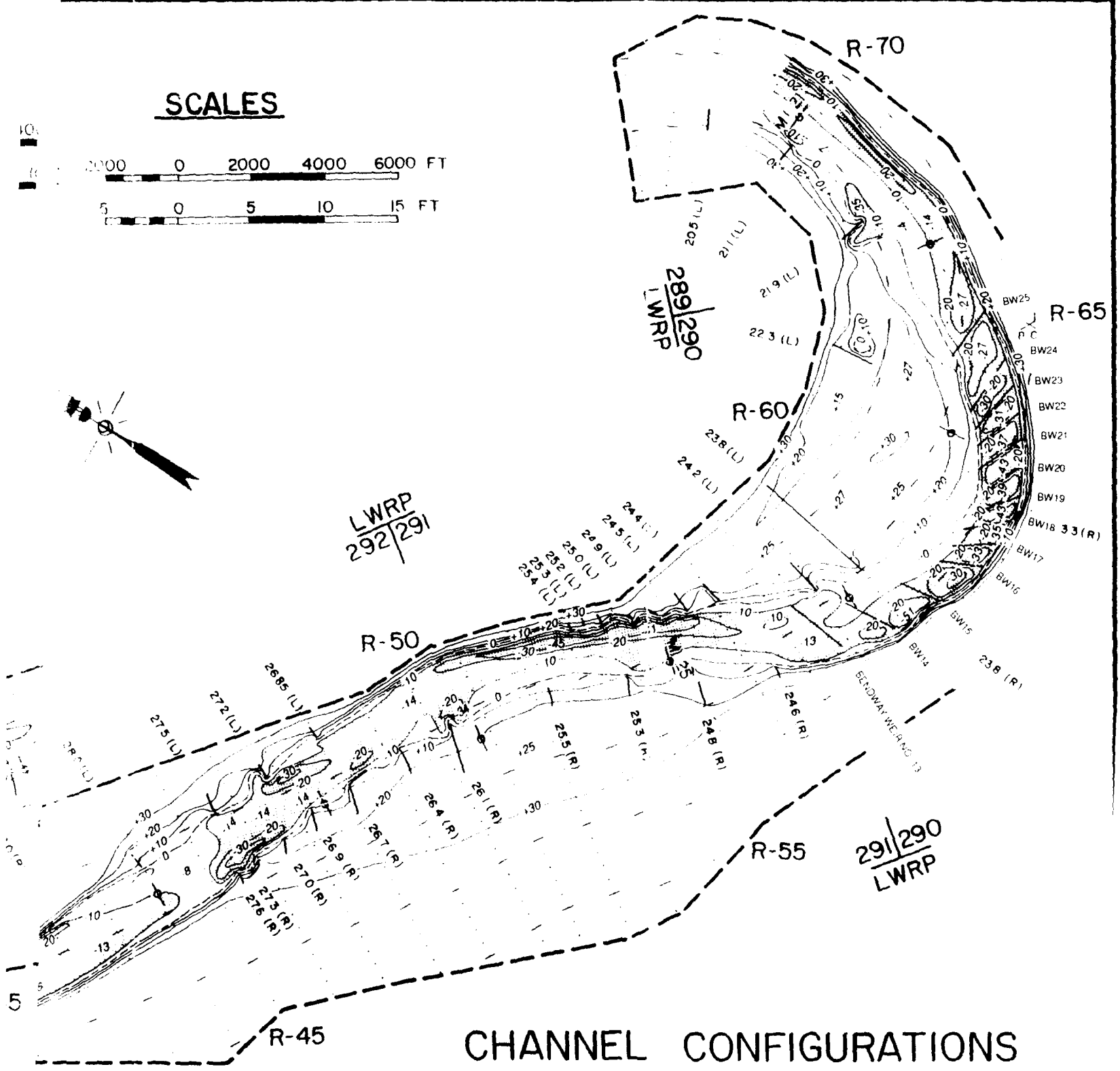
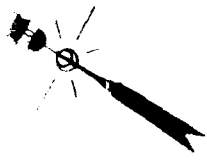
# SCALES



**SCALES**

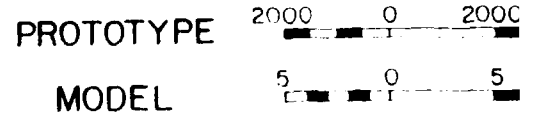
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5 0 5 10 15 FT




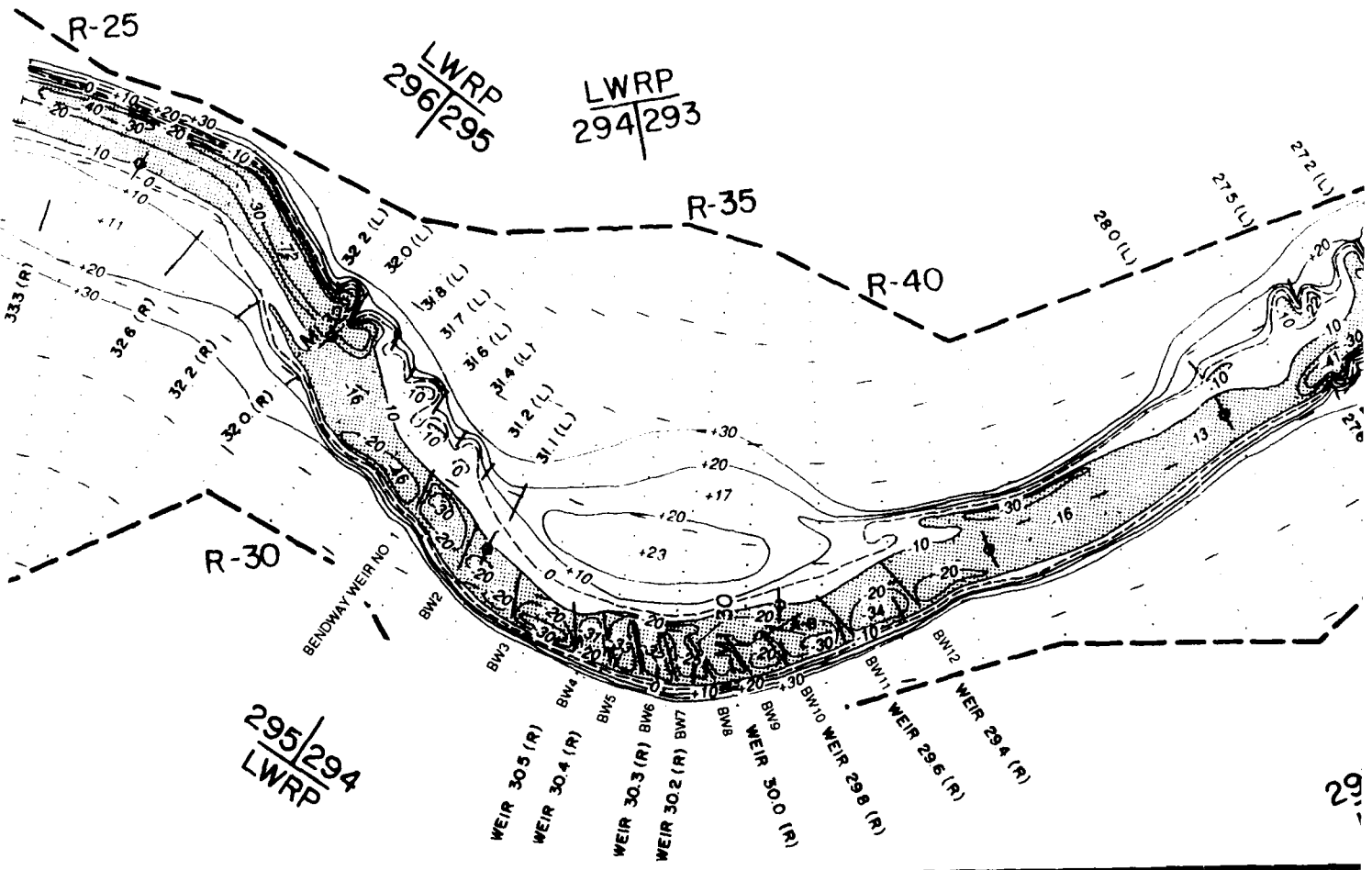
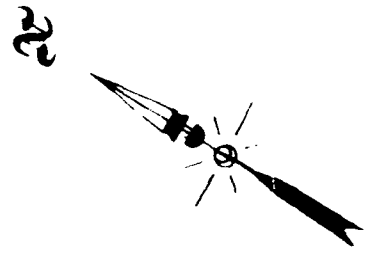
**CHANNEL CONFIGURATIONS  
PLAN O RUN 6**

SCALES



LEGEND

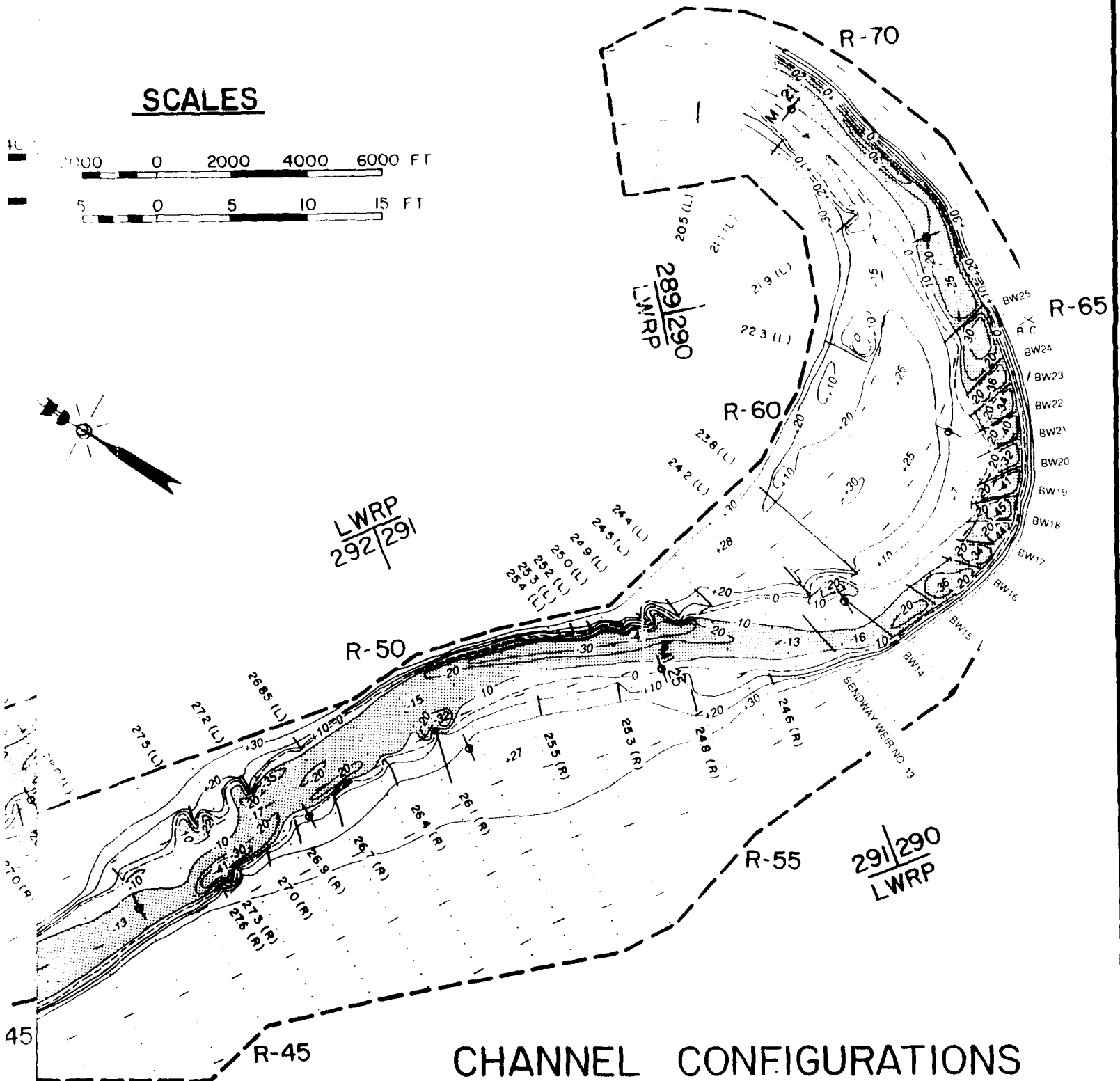
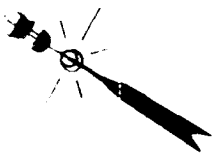
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- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



**SCALES**


0 2000 4000 6000 FT

5 0 5 10 15 FT

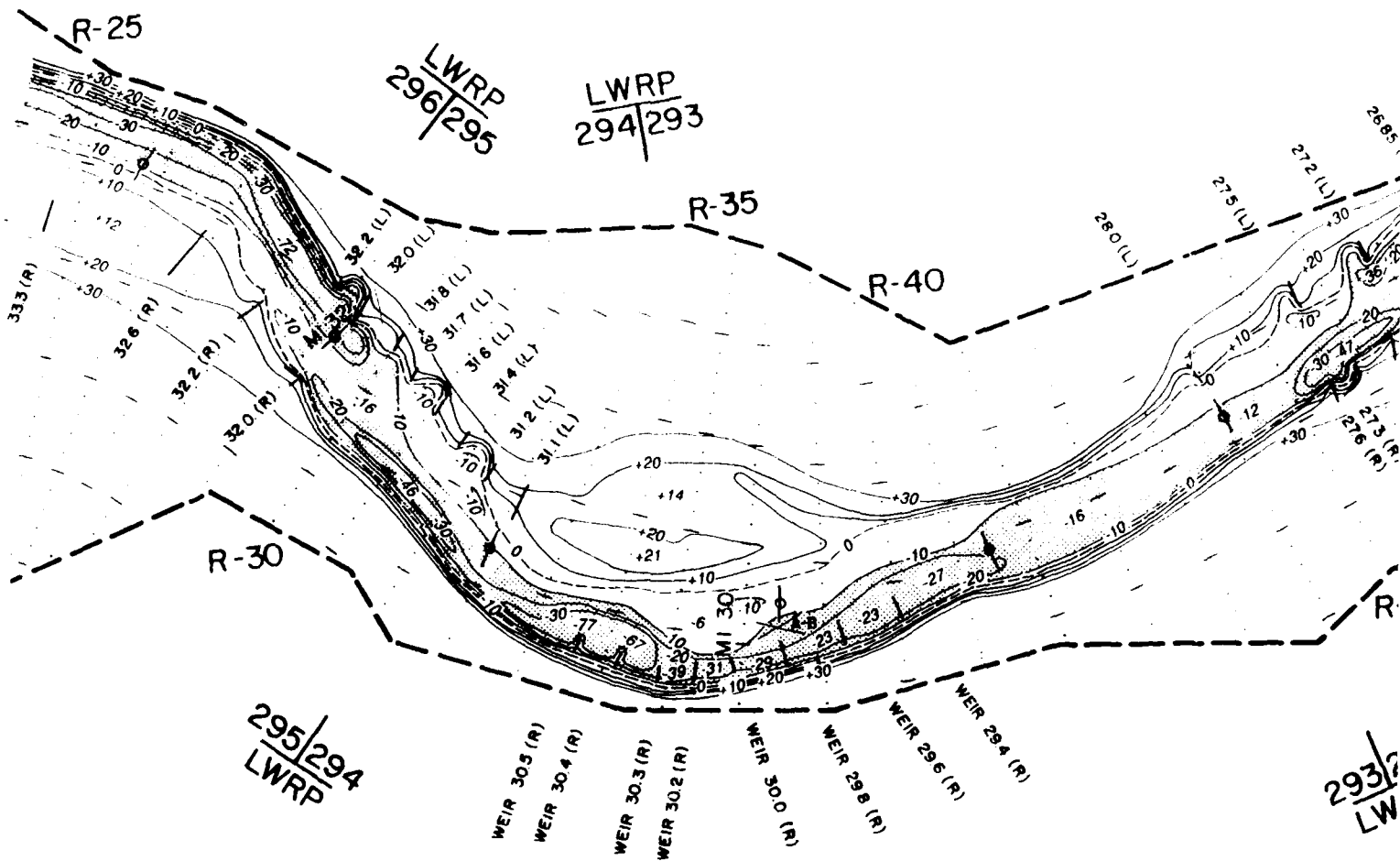
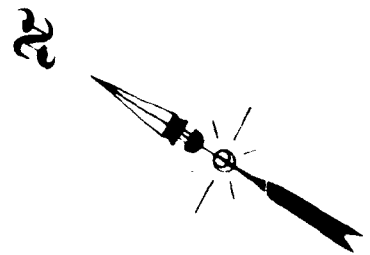
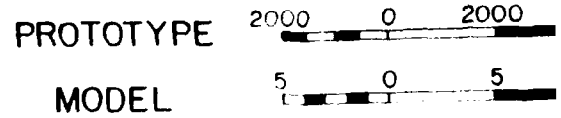


**CHANNEL CONFIGURATIONS  
PLAN R RUN 6**

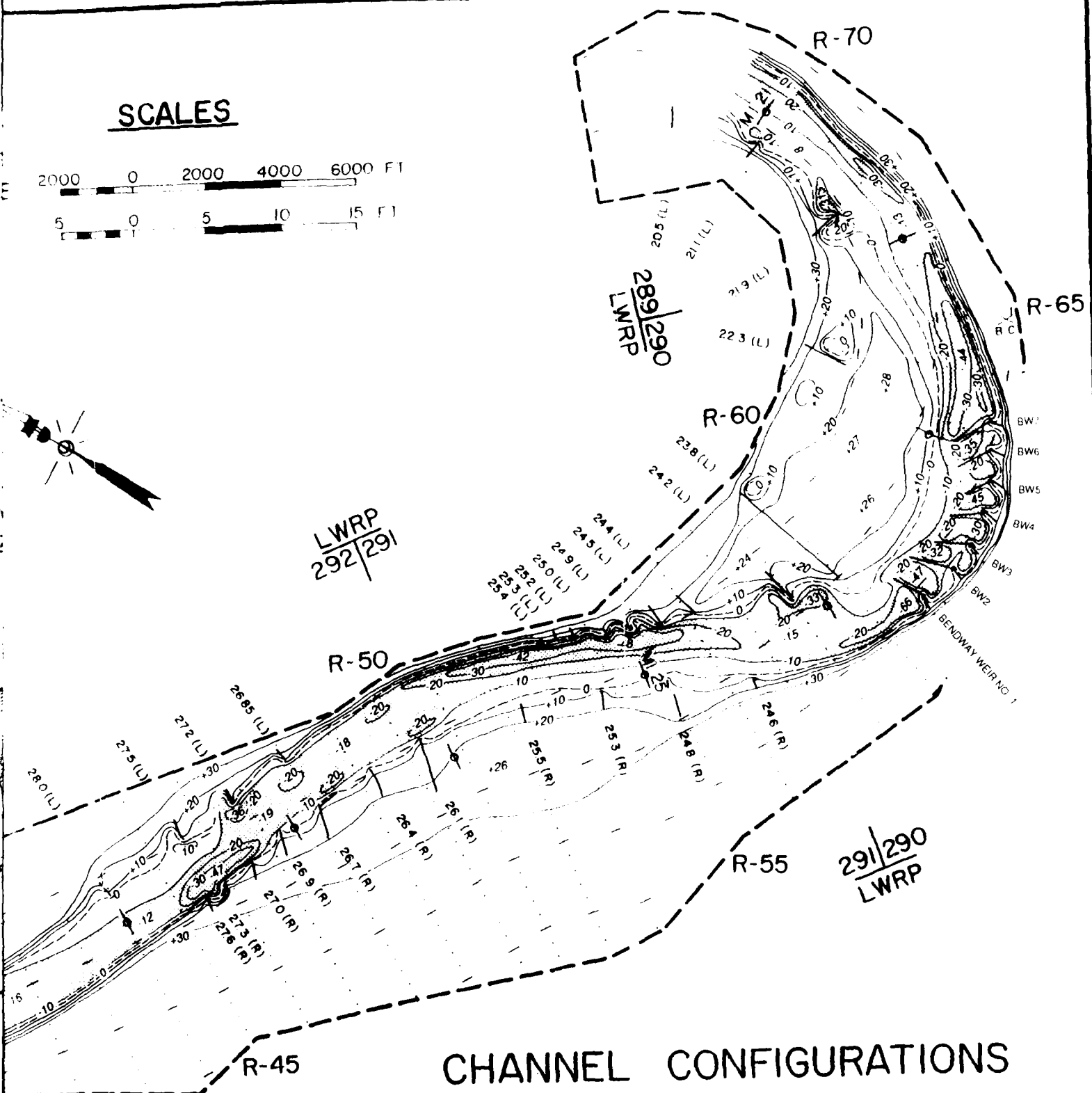
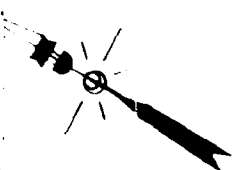
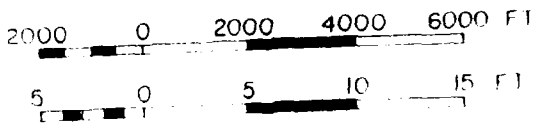
# LEGEND

-  -10 FT LWRP AND BELOW
- 31.6 (L) PROTOTYPE DIKE
- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE

# SCALES



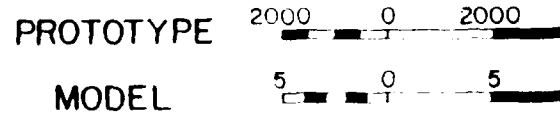
# SCALES




## CHANNEL CONFIGURATIONS PLAN P RUN 2

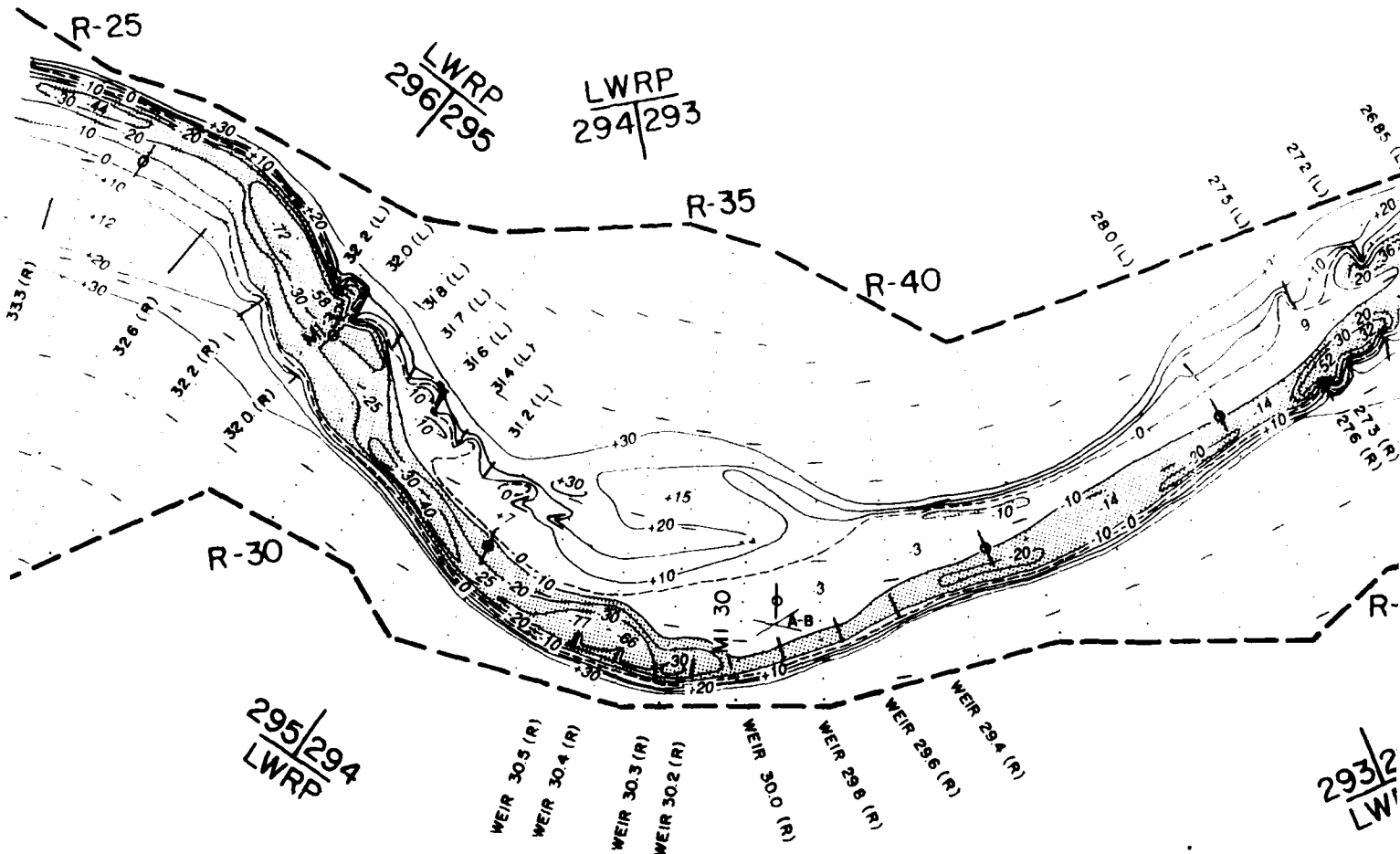
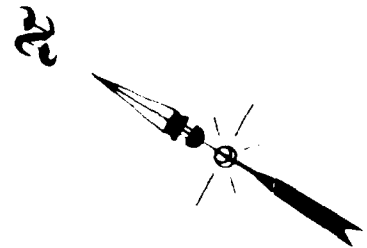


# SCALES



# LEGEND

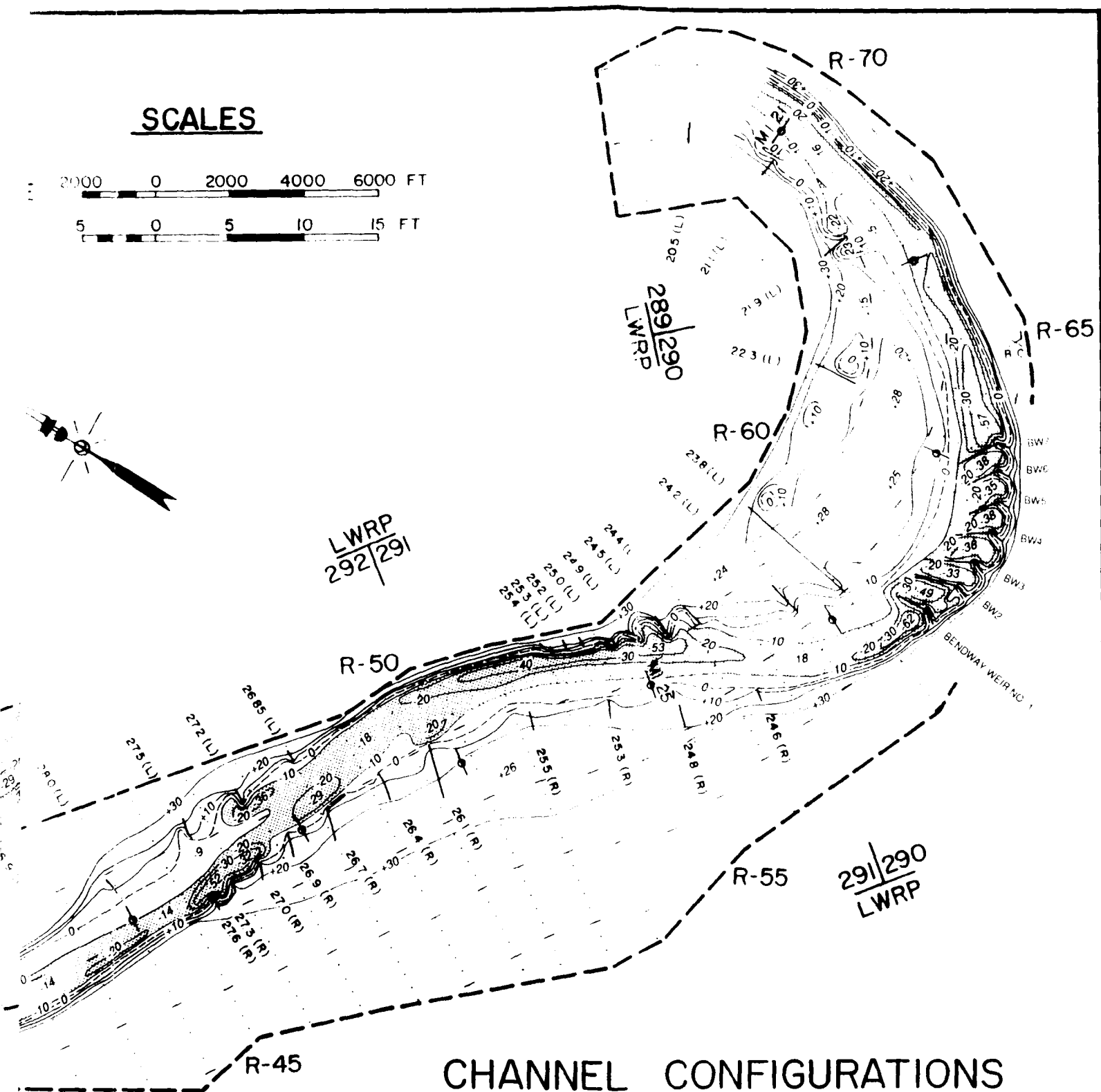
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- WEIR 30.5 (R) PROTOTYPE WEIR
- BW4 MODEL BENDWAY WEIR
- D1 MODEL DIKE
- LD1 MODEL LONGITUDINAL DIKE



**SCALES**

0 2000 4000 6000 FT

5 0 5 10 15 FT



**CHANNEL CONFIGURATIONS**

**PLAN Q RUN 1  
1983 FLOOD HYDROGRAPH**

293/292  
LWRP

# REPORT DOCUMENTATION PAGE

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<b>6. AUTHOR(S)</b> David L. Derrick                      James P. Crutchfield Thomas J. Pokrefke, Jr.              Raymond R. Henderson Marden B. Boyd	
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<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  U.S. Army Engineer Waterways Experiment Station 3909 Halls Ferry Road, Vicksburg, MS 39180-6199	<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  Technical Report HL-94-10
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**11. SUPPLEMENTARY NOTES**  
  
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**13. ABSTRACT (Maximum 200 words)**

This investigation is one of a series of model studies used to determine the effectiveness of various dike and bendway weir systems proposed for the improvement of several troublesome reaches on the Mississippi River. This report describes and gives results of test concerned with the development of plans for the improvement of the Dogtooth Bend reach of the middle Mississippi River, located 20 miles above the confluence of the Ohio and Mississippi Rivers. A movable-bed model reproducing approximately 19.4 miles of the Mississippi River (horizontal scale 1:400, vertical scale 1:100) and using granulated coal as the bed material was employed to develop plans that would improve and stabilize the navigation channel through the reach and eliminate or reduce the need for maintenance dredging. The goals of this study were to improve current flow patterns and widen the navigation channel in Dogtooth and Price's Landing Bends and in the crossings immediately downstream of both bends.

Currents concentrating on the outside bank of a number of bends have caused serious problems for barge traffic and major damage to bank stabilization and protection structures. During a high-water event in 1983 the bank line at Dry Bayou (mile 23.3) failed, allowing the river to flow overland for approximately

(Continued)

<b>14. SUBJECT TERMS</b> Bendway weirs                      Sills (training structures) Channel improvement              Weirs (training structures) Dikes (training structures)        Navigation                              (Continued)	<b>15. NUMBER OF PAGES</b> 104
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<b>17. SECURITY CLASSIFICATION OF REPORT</b>  UNCLASSIFIED	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b>  UNCLASSIFIED	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b>	<b>20. LIMITATION OF ABSTRACT</b>
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13. (Concluded).

5 miles. Damage to bank protection structures and farmland was significant. Typically a narrow navigation channel through a bend forces tows to flank (a series of start and stop maneuvers) during low and medium stages, slowing the maneuvering tow and delaying any upstream or downstream traffic waiting for the flanking tow to clear the bend. The economic impact of such delays on the Mississippi River between St. Louis, MO, and Cairo, IL, has been estimated at between 13 and 26 million dollars annually, depending on river conditions. Also, winter ice jams at the bends have caused traffic bottlenecks, the costs of which have not been ascertained. Dredging in the bends and crossings to improve navigation has also been a major expense for the Corps. Annual dredging costs on the open river section of the middle Mississippi River (miles 198.7 to 0.0) alone average between 4 and 6 million dollars in the bends, with another 5 to 6 million dollars spent on the crossings.

Model test results indicate that construction of a series of upstream-angled underwater sills (bendway weirs) within the navigation channel of a bendway results in the following improvements: the navigation channel through the bendway is widened, deposition occurs at the toe of the revetment on the outside of the bend stabilizing the bank, surface water velocities are more uniform across any cross section, flow patterns in the bends are generally parallel with the banks and do not concentrate on the outside bank of the bend, the navigation channel in the crossing downstream of the bend is both deeper and wider, and the navigation channel through the bend and downstream crossing is better aligned.

The use of bendway weirs could also result in several environmental benefits. The habitat of the least tern (a federally protected endangered sea bird species whose territory includes the bendway point bars) should not be affected or disturbed. The navigation channel is reshaped from an inverted triangle into a wider, shallower trapezoid. This new channel shape results in an improved and expanded usable aquatic habitat area, which, with time, should translate into increased densities of aquatic life. The diversity of aquatic life might also be increased. Finally, the improved navigation channel should result in a marked decrease in the amount of channel maintenance dredging performed, resulting in less dredged material to be disposed of.

14. (Concluded).

Mississippi River  
Movable-bed model  
Hydraulic models  
River training structures