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**HYD-87**

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HYDRAULIC LABORATORY  
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HYD 87



## PREFACE

The investigations on the backwater effects of the Grand Coulee Dam were made by the Bureau of Reclamation at Grand Coulee, Washington, and at Denver, Colorado. At the Grand Coulee office, the backwater calculations and studies were made under the direction of F. A. Banks, Supervising Engineer, by J. C. Sharp, Assistant Engineer. The backwater studies at the Denver office were made under the direction of D. C. McConaughy, Senior Engineer, by W. M. Borland, Associate Engineer, and C. A. Wentz, Assistant Engineer. The hydraulic model of the Little Dalles was constructed and tested under the supervision of R. A. Goodpasture, Assistant Engineer, by direction of J. E. Warnock, Engineer.

These investigations were made under the general supervision of J. L. Savage, Chief Designing Engineer. All engineering work of the Bureau of Reclamation is under the direction of S. O. Harper, Chief Engineer, and all activities of the Bureau are under the direction of J. C. Page, Commissioner.

Denver, Colorado, November 28, 1940.

MEMORANDUM TO THE CHIEF DESIGNING ENGINEER  
(W. M. Borland and R. A. Goodpasture)

Subject: Investigations of backwater of the Columbia River Reservoir.

1. Introduction. The Grand Coulee Dam located on the Columbia River about 150 miles downstream from the Canadian boundary will, when completed, form a vast lake which may rise as high as elevation 1290.0. At some discharges and reservoir elevations, there will be a small amount of backwater at the International Boundary. The investigations presented in this report were made to determine the backwater conditions along the upper reaches of the reservoir and to develop some plan of channel improvement to prevent excessive backwater along the Nelson branch of the Great Northern Railroad, and to reduce such backwater as there may be at the International Boundary.

2. Field data. Major observation stations were established at critical points where water surface elevations have been observed, especially at flood stages, since March 1930. Those observations were made by the Geological Survey and Corps of Engineers. In 1932 the Dominion Water and Power Bureau cooperated with the Geological Survey in making observations, and this program has been continued to the present time. In 1935 several additional observation stations were established by the Bureau of Reclamation, making a total of 17 stations between Kettle Falls and the Boundary (figure 1). Soundings of various river cross sections were made by the Washington Water Power Company in connection with a proposed power development at Kettle Falls. Later, the Bureau of Reclamation took additional soundings at the Little Dalles and at the International Boundary. Altogether, 41 river cross sections are available along the upper end of the reservoir where they are most needed in the backwater computations. In 1937 the Bureau of Reclamation ran a line of precise levels between Grand Coulee Dam and the International Boundary and discovered an error of 1.7 feet in the difference of elevation which had previously been used between these two points. All field data have been corrected to conform to this new line of precise levels.

The water surface elevations were observed at the major observation stations indicated on figure 1 for discharges ranging from 17,800 to 420,000 second-feet. The magnitude of the discharge on the observation days was secured by deducting the discharge of the Kettle River as determined at the gaging station near Laurier, Washington, from the discharge at the Kettle Falls gaging station on

the Columbia River. The tributaries of the Columbia River between the mouth of the Kettle River and the mouth of the Clark Fork are all very small and do not materially affect the flow, so that the discharge obtained in the above manner is applicable throughout the reach being studied. A number of discharges arrived at by the above method were checked, with a difference of less than five percent, by adding the flow of the Columbia River as determined at Trail, British Columbia, to the flow of the Clark Fork below Z Canyon.

3. Analysis of field data. The rating curves at the major observation stations were accurately defined up to 420,000 second-feet. These curves were extrapolated by various methods with the aid of meager field data to include the 1894 flood, estimated as 650,000 second-feet. With the discharge, the water surface elevations, and the river cross sections given, the roughness coefficient,  $n$ , in the Kutter-Chezy formula was computed between observation stations for natural flow conditions. The roughness coefficient was then plotted against average water surface elevation for each reach. The roughness coefficient was found to vary with the discharge and stage; for discharges greater than 420,000 second-feet the roughness coefficient versus stage curves was extrapolated and so adjusted that it was in agreement with the extrapolated rating curves. The value of  $n$  was usually found to decrease with an increase in the stage of the river. As the stage of the river rises, the rough perimeter characterizing the low-water flow, evidenced by numerous falls and rapids, becomes an increasingly smaller part of the total, the submerged banks are smoother than the low-water bed, and, as a result, the value of  $n$  decreases with increasing stages. Under natural flow conditions increases in stage correspond to increases in discharge; under backwater conditions this is not true, but the same wetted section should give the same value of  $n$ . This reasoning was confirmed by the model tests. Accordingly, with any backwater stage, a value of  $n$  for any reach is determined from the  $n$  versus average water surface elevation curve. This coefficient is designated "backwater  $n$ ."

4. Backwater calculations. The Kutter-Chezy and the Manning formulas are the two most frequently used for computing flow in open channels. Of these, the Kutter-Chezy formula has enjoyed wider use than Manning's and was adopted for the backwater computations, except below the Little Dalles where, due to the marked decrease in the slope of the backwater energy gradient, the Manning formula was used, since it gave a somewhat greater energy loss. Accordingly, all computations upstream were conservatively based on the backwater rating curve at the foot of the Little Dalles as given by the Manning formula. Upstream from this point, the slope of the energy gradient was steeper and the Kutter formula was used, as above stated. Figure 3 shows the computed backwater surface profiles.

5. The Little Dalles. The Great Northern Railroad parallels the Columbia River for about 37 miles below the Canadian border (figure 1). Between the head of the Little Dalles and the International Boundary the backwater at high flood stages would cover the tracks in some places. Under natural flow conditions, a flood of 450,000 second-feet has done some damage to the track and embankments. A location was sought where channel improvement would reduce the amount of backwater at high discharges. Such a location is found at the Little Dalles, 15-1/2 miles below the International Boundary, where the river is restricted to a very narrow, deep channel for a distance of 2,500 feet. For a discharge of 400,000 second-feet, with the reservoir water surface at elevation 1290.0, there would be a head loss of 15.5 feet through these rapids (figure 3); but channel improvement at this location, according to plan 5 herein-after discussed, would reduce this loss to only 8.5 feet, which is about 15.5 feet less than would exist under natural flow conditions with an unimproved channel. This indicated clearly the advantageous effect of channel improvement. A topographic sketch of the Little Dalles is shown in figure 4.

6. Model studies of the Little Dalles. Because of doubt as to the applicability of energy loss formulae to such an extremely rough river channel, an hydraulic model was built and tested to determine the losses through the Little Dalles with backwater conditions and to develop a plan for channel improvement. A 1 to 120 hydraulic model was built to represent the river between the major observation stations at the Little Dalles (figure 5). The model was constructed from the field topography and a careful study of prototype pictures. The model was roughened by adding lumps of concrete to the bed and the walls of the channel so that when natural flow conditions were reproduced at the foot of the Little Dalles the upstream rating curves obtained from the model agreed reasonably well with those obtained from the prototype (figure 6).

After the model had been calibrated to simulate natural flow conditions, backwater conditions corresponding to a reservoir water surface at elevation 1290.0 at the dam were produced. To accomplish this, the rating curve as computed for backwater conditions at the lower end of the Little Dalles was reproduced in the model and the resulting water surface elevations at the head of the Little Dalles were observed (figure 7). The computed backwater was found to give slightly lower water surface elevations for a discharge of 200,000 second-feet than were indicated by the model. For all other discharges the model gave lower elevations than those computed. The discrepancy was always less than or equal to 1.10 feet and never greater than five percent of the total energy loss in the Little Dalles when there was any appreciable change in the water surface elevation.

Because of difficulties that accompany underwater excavation, especially if the material must be broken up and removed, it is desirable that the channel improvement should not extend below low-water level. This requires that the excavation be done in the winter months with the reservoir at or below elevation 1240.0.

The channel improvement studies on the hydraulic model were made in steps by removing various portions of the simulated rock that noticeably disturbed flow conditions (figure 8). A rating curve for gage 11 at the head of the Little Dalles was obtained for each excavation plan (figure 7). The first improvement study was made with the large rock island at the entrance to the Little Dalles removed to elevation 1255.0. Subsequent tests showed that no additional improvement was gained by further excavation to elevation 1250.0. A portion of the upstream left bank was next removed to improve entrance conditions (excavation plan 1, figure 8). Since this did not produce the desired improvement, a portion of the left bank was removed as far downstream as the cove. After several minor changes, a total of 270,000 cubic yards was removed above elevation 1255.0 (excavation plan 5, figure 8). This plan restored natural flow conditions above the Little Dalles at a discharge of 400,000 second-feet for reservoir elevation 1290.0.

7. Backwater with improved channel. Figure 7 shows that the recommended channel improvement will not only restore natural flow conditions at the head of the Little Dalles for a discharge of 400,000 second-feet, as stated above, but also that some additional improvement is obtained for all larger floods. This improvement is greatest at the head of the Little Dalles but is still noticeable at the International Boundary (figure 10). Profiles of the backwater for natural and improved channel are shown on figure 8. The amount of backwater at the International Boundary with channel improvement is shown as curve No. 5, figure 11. The following table gives the water surface elevations at the International Boundary for natural flow and backwater conditions for both natural and improved channels, with reservoir water surface at elevation 1290.0.

TABLE I  
WATER SURFACE ELEVATIONS AT INTERNATIONAL BOUNDARY

| Discharge | Natural Flow Conditions | Backwater Conditions*      |                                          |
|-----------|-------------------------|----------------------------|------------------------------------------|
|           |                         | Natural Channel Conditions | Improved Channel Excavation Plan No. 5** |
| 0         | 1284.20***              | 1290.00 (+5.80)            | 1290.00 (+5.80)                          |
| 20,000    | 1289.80                 | 1291.88 (+2.08)            | 1291.88 (+2.08)                          |
| 50,000    | 1296.05                 |                            |                                          |
| 100,000   | 1303.50                 | 1303.50 (0)                | 1303.42 (0)                              |
| 200,000   | 1313.65                 | 1313.98 (+0.33)            | 1313.79 (+0.14)                          |
| 300,000   | 1321.70                 | 1322.57 (+0.87)            | 1321.70 (+0.49)                          |
| 400,000   | 1329.10                 | 1330.32 (+1.22)            | 1329.10 (0)                              |
| 500,000   | 1336.00                 | 1337.56 (+1.56)            | 1334.97 (-1.03)                          |
| 650,000   | 1346.00                 | 1346.95 (+0.95)            | 1342.90 (-3.10)                          |

Figure in parentheses indicates backwater if plus and improvement if minus.

\*Reservoir water surface elevation 1290 at the dam.

\*\*Based on model results for zone 3.

\*\*\*Water surface elevation for zero discharge obtained by extending rating curve at International Boundary until it intersects the line of zero discharge. Lowest point in the river bed at this section is at elevation 1272.

Note: For the period April 1913 to September 30, 1939, incl., the following discharge data of the Columbia River are recorded at Grand Coulee Dam:

|                                     |                     |
|-------------------------------------|---------------------|
| Minimum discharge                   | 15,300 second-feet  |
| Maximum discharge                   | 492,000 second-feet |
| Maximum discharge (mean for 27 yr.) | 358,148 second-feet |
| Average discharge (26-year record)  | 107,700 second-feet |

An inspection of the table shows that for floods greater than 400,000 second-feet the water surface elevations above the Little Dalles will not be as high with full reservoir and channel improvement as they are at the present time. Accordingly, conditions along the railroad would be better than at present. The table and figures 3 and 11 show that with the improved channel the greatest amount of backwater at the International Boundary will be at small discharges, with an actual reduction in stage for floods above 400,000 second-feet. According to records for the past 27 years, a flood with a

magnitude of 400,000 second-feet or larger is likely to occur on an average of once in about 5 years, or, on the basis of the 82-year record available at the Dalles, Oregon, a flood of this magnitude or larger is likely to occur on an average of once in about 3 years. If the reservoir surface is lowered approximately 12 feet with channel improvement, plan 5, there will be no backwater at the International Boundary for any discharge, but, with the reservoir at elevation 1290 at the dam, backwater with any discharge less than 335,000 second-feet will not exceed the water surface elevation of ordinary high water for the past 27 years, the term "ordinary high water" being defined as the stage most likely to be reached or exceeded each year by the peak of the annual flood. At the International Boundary the ordinary high water elevation is 1325.0. For discharges between 335,000 second-feet and 400,000 second-feet the backwater surface will be a maximum of about 0.4 foot above the present water surface.

8. Analysis of excavation studies. Past experience has shown that the railroad, under present conditions, is safe against damage for discharges up to 400,000 second-feet. As shown above, channel improvement according to plan 5 will insure that the water surface above the Little Dalles, after the reservoir is in operation, will be lower than the natural water surface elevation for greater discharges. A further study was made to determine whether it would be economically feasible to effect a greater improvement by reducing still further the stage above which the water surface, with reservoir in operation, would lie below the natural water surface. Accordingly, the amount of excavation for each excavation plan was plotted against the corresponding discharge at which natural conditions were restored upstream and an approximate extension obtained by logarithmic plotting (figure 9). The intersection of the natural rating curve at gage 11 with the backwater rating curve at gage 13 (figure 7) shows that no amount of excavation would restore natural conditions below a discharge of 297,000 second-feet. The channel improvement curve, therefore, must be asymptotic to this discharge as shown on figure 9. This curve indicates that plan 5 represents about the limit of economic excavation and that approximately 270,000 cubic yards of additional excavation would be required to reproduce natural conditions at a discharge of 350,000 second-feet. Plan 5 is accordingly recommended.

9. Conclusions. It is concluded:

(a) That, without channel improvement and with a full reservoir there would exist at the International Boundary from 0 to 2.75 feet of backwater for discharges below 100,000 second-feet but no threat of damage is involved thereby, because the water surface elevation for these discharges will be from 0 to 12 feet below the natural-flow

stage for mean annual discharge. There will be about 1.5 to 1.0 feet of backwater at extreme high flows, with about 1.0 foot at ordinary flood stages, there being no backwater for a discharge of 100,000 second-feet.

(b) That, without channel improvement and with a full reservoir, backwater along the railroad above the Little Dalles would be from 2 to 10 feet higher than at present for discharges ranging between 650,000 and 300,000 second-feet and that, for discharges in the neighborhood of 450,000 second-feet, which have previously caused some damage, the backwater surface would be about at the same elevation as the natural surface for discharges 75,000 second-feet greater.

(c) That, for discharges less than 50,000 second-feet, it is impossible to lower backwater at the International Boundary except by lowering the water surface of Columbia River Reservoir.

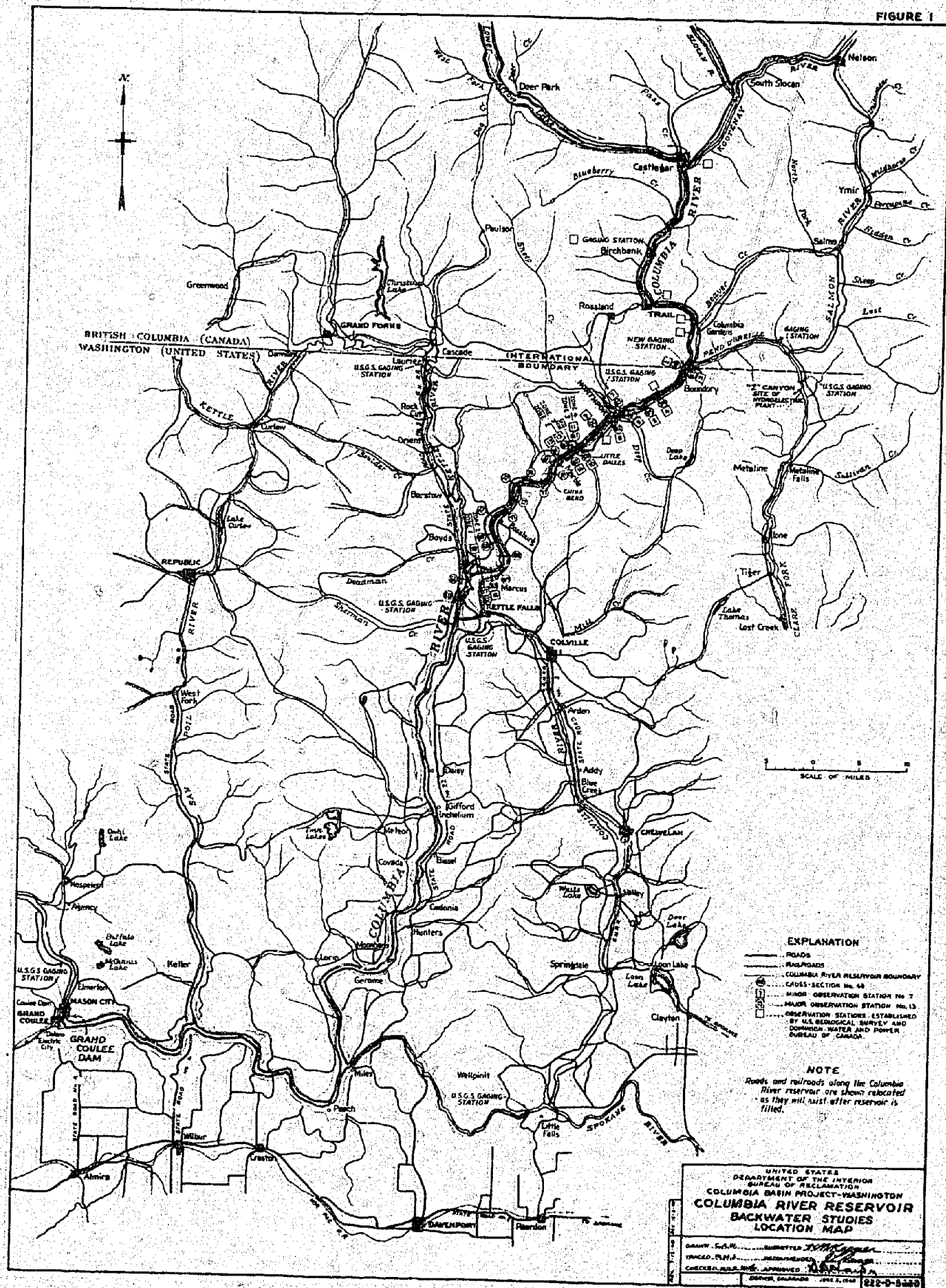
(d) That, by channel improvement plan 5 at the Little Dalles, the backwater for reservoir water surface at elevation 1290 can be so reduced that it lies below the ordinary high-water elevation of natural flow at the International Boundary for floods of less than 335,000 second-feet, lies below the present water surface for floods greater than 400,000 second-feet, and will not be more than 0.4 foot above the present water surface for floods between 335,000 second-feet and 400,000 second-feet.

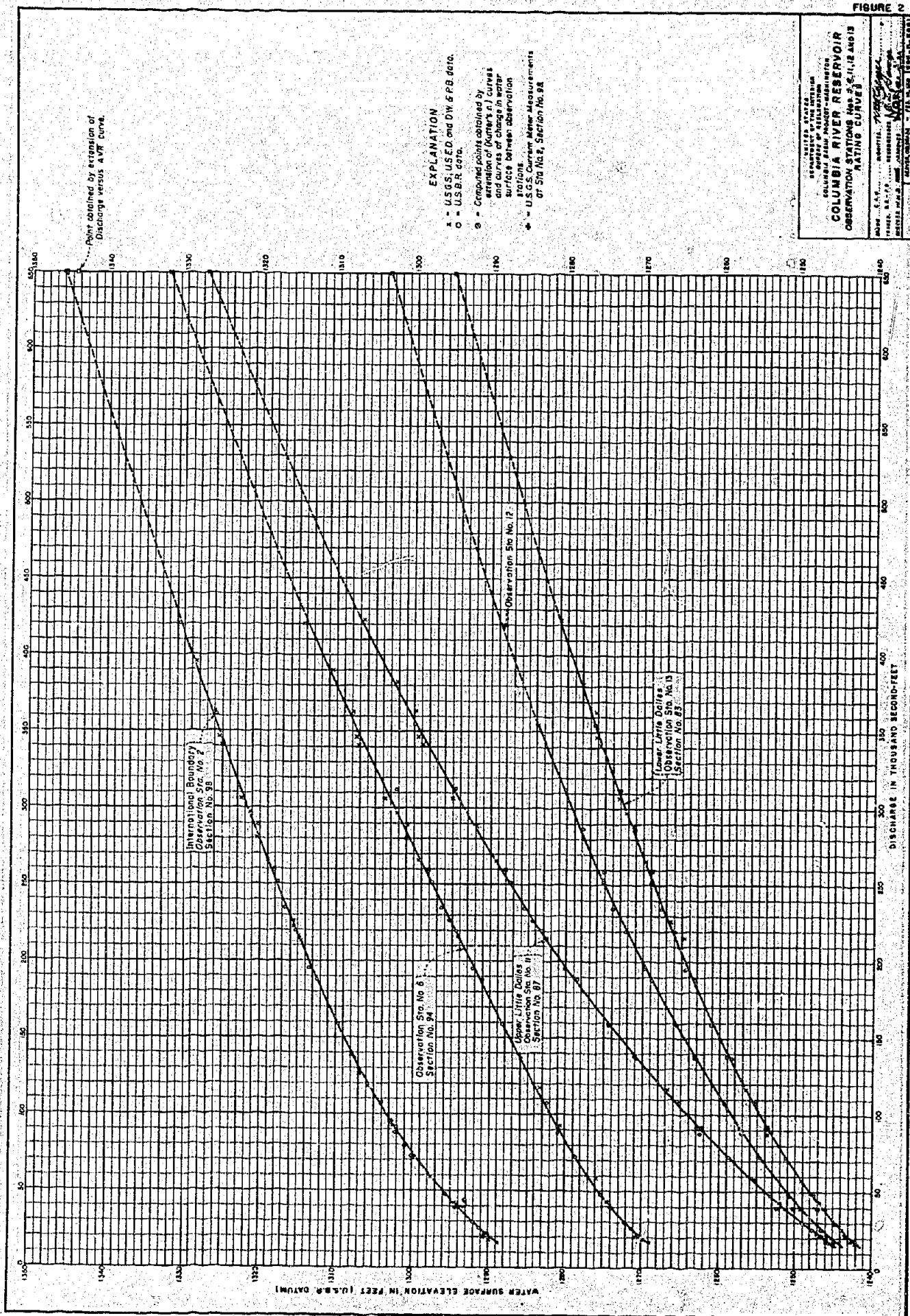
(e) That, by this improvement and with a full reservoir, the water surface along the railroad above the Little Dalles will be no higher than under present conditions for a discharge of 400,000 second feet and will be lower than under present conditions for greater discharges by amounts up to about 10 feet for a discharge of 650,000 second-feet.

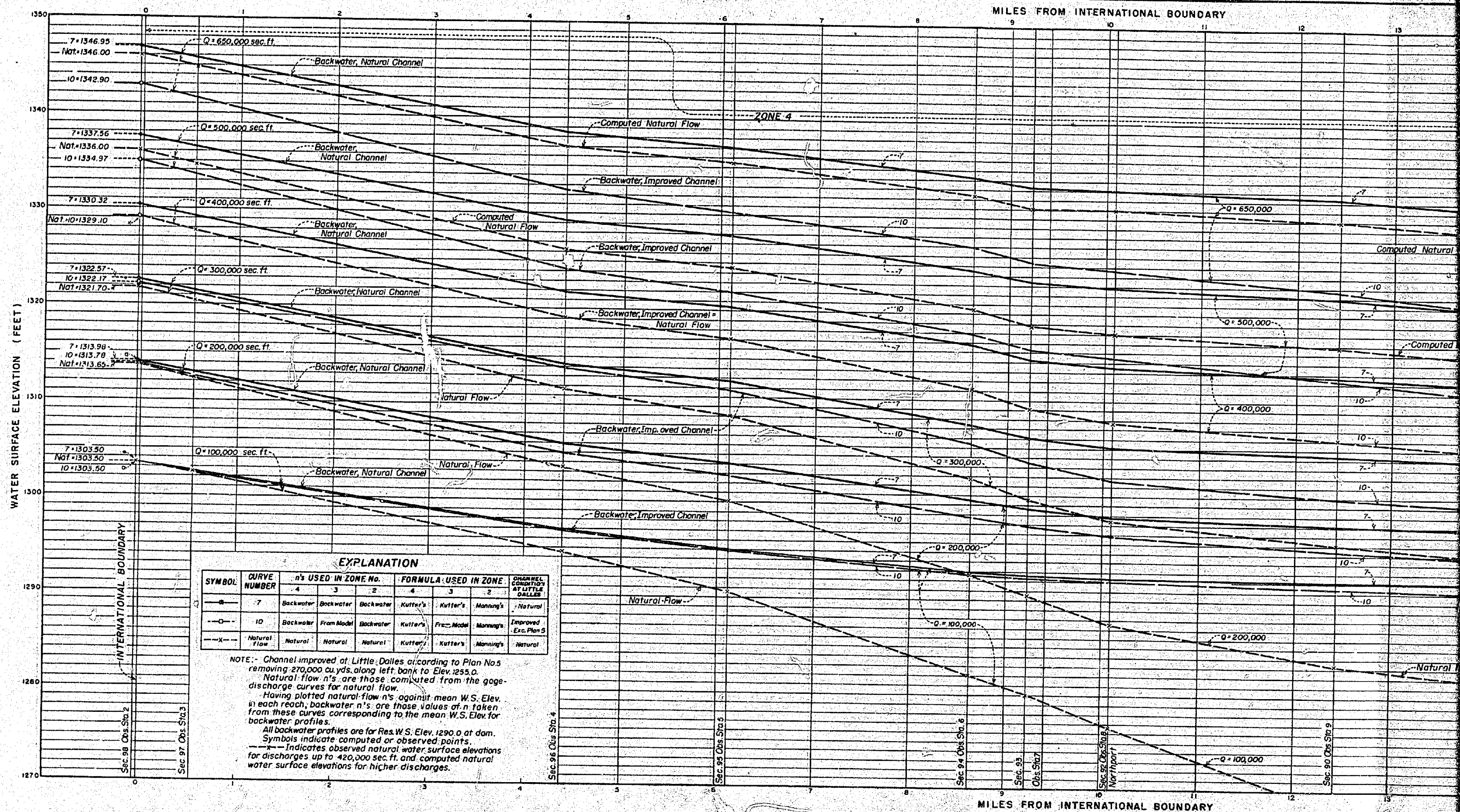
(f) That, channel improvement at the Little Dalles, according to excavation plan 5, affords a satisfactory solution of the backwater problem and additional excavation is not economically justified.

W. M. Borland,  
R. A. Goodpasture.

FIGURE 1







**FIGURE 3**

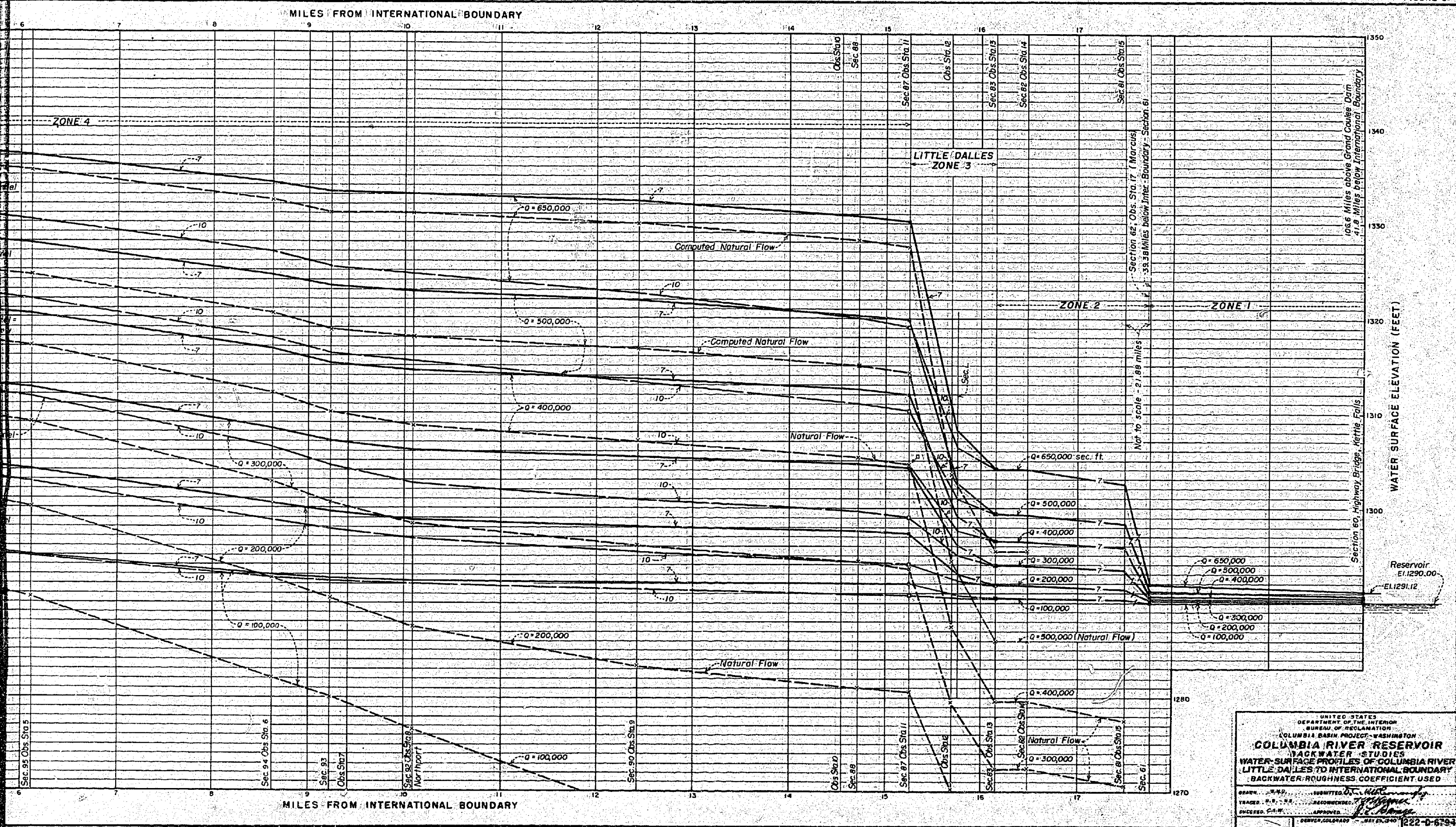
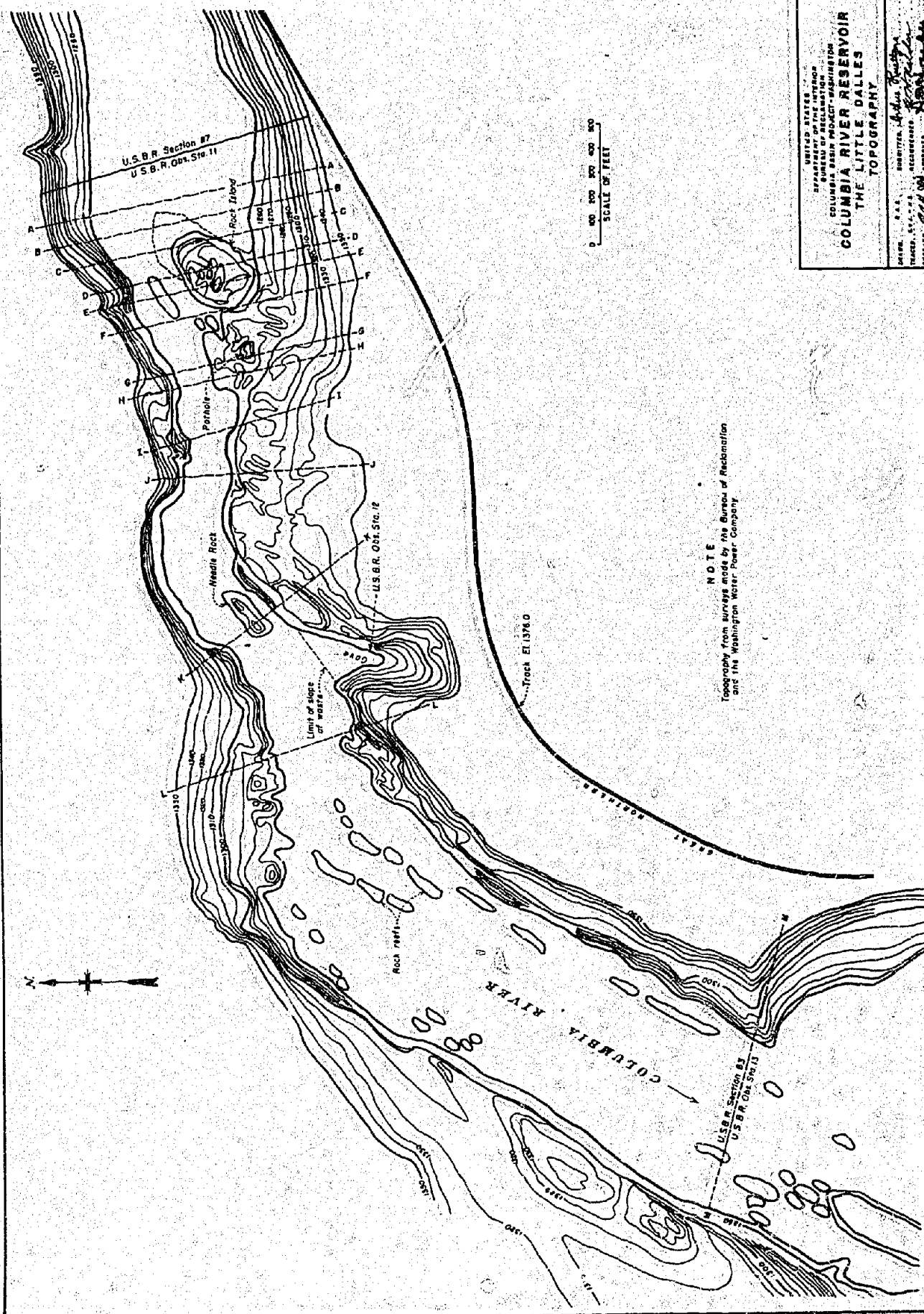


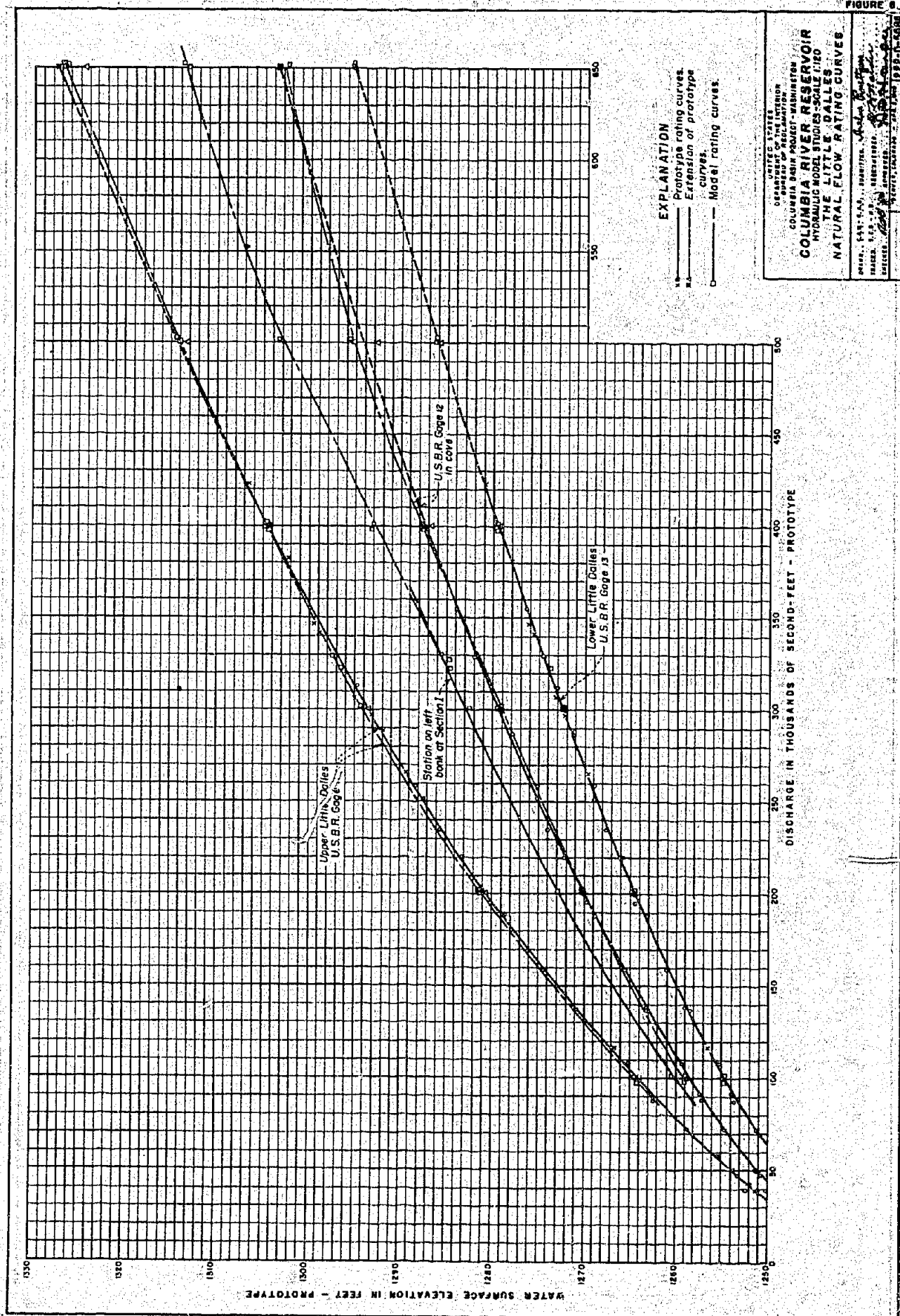
FIGURE 4

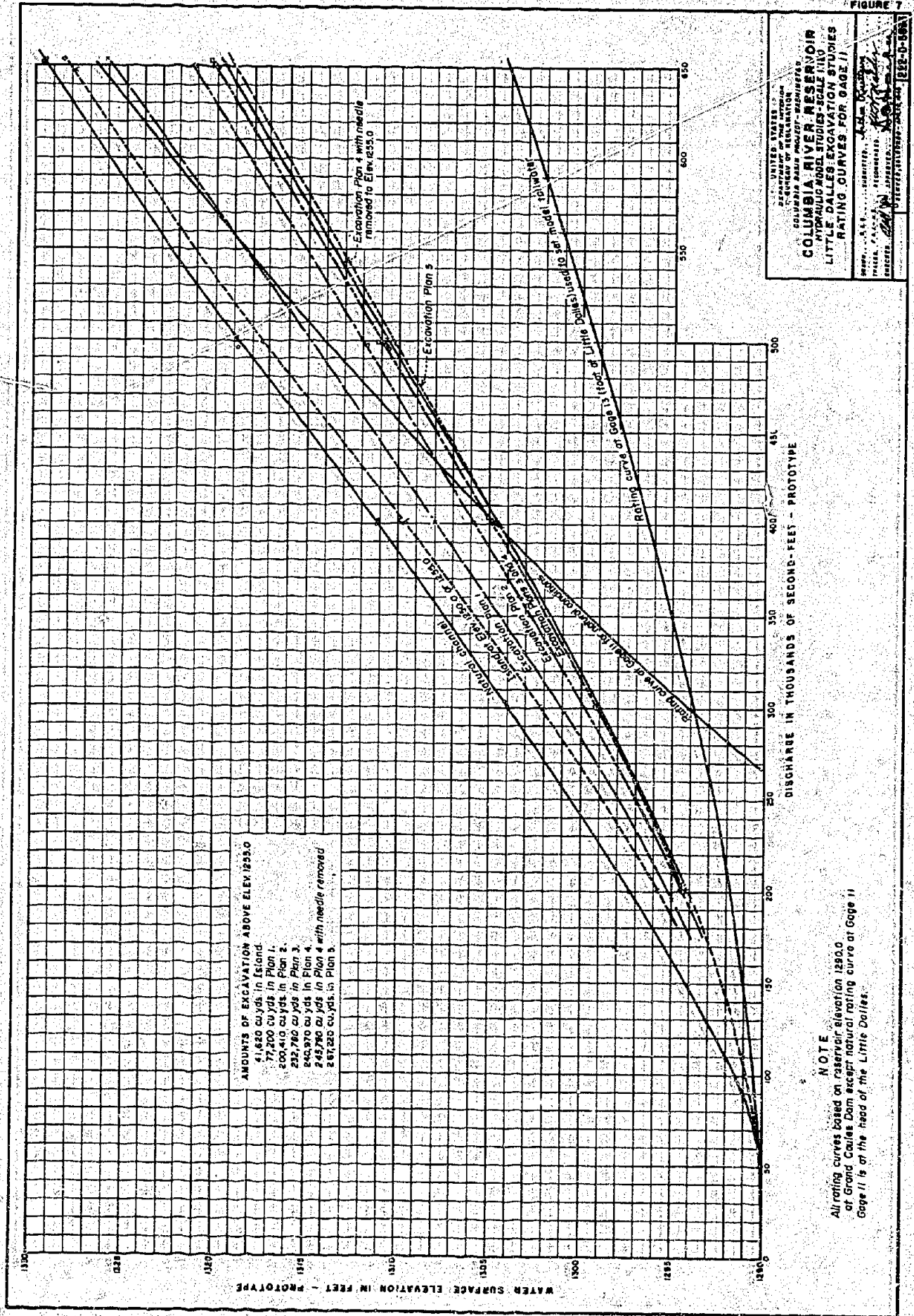


NOTE  
Topography from surveys made by the Bureau of Reclamation  
and the Washington Water Power Company

|                                                                      |                             |
|----------------------------------------------------------------------|-----------------------------|
| UNITED STATES<br>DEPARTMENT OF THE INTERIOR<br>BUREAU OF RECLAMATION |                             |
| COLUMBIA RIVER PROJECT - WASHINGTON                                  |                             |
| THE LITTLE DALLES<br>TOPOGRAPHY                                      |                             |
| DESIGNED BY<br>H. A. HARRIS                                          | DRAWN BY<br>J. H. HARRIS    |
| CHECKED BY<br>J. H. HARRIS                                           | APPROVED BY<br>J. H. HARRIS |
| REVISION NO. 1 - JAN. 17, 1913                                       |                             |







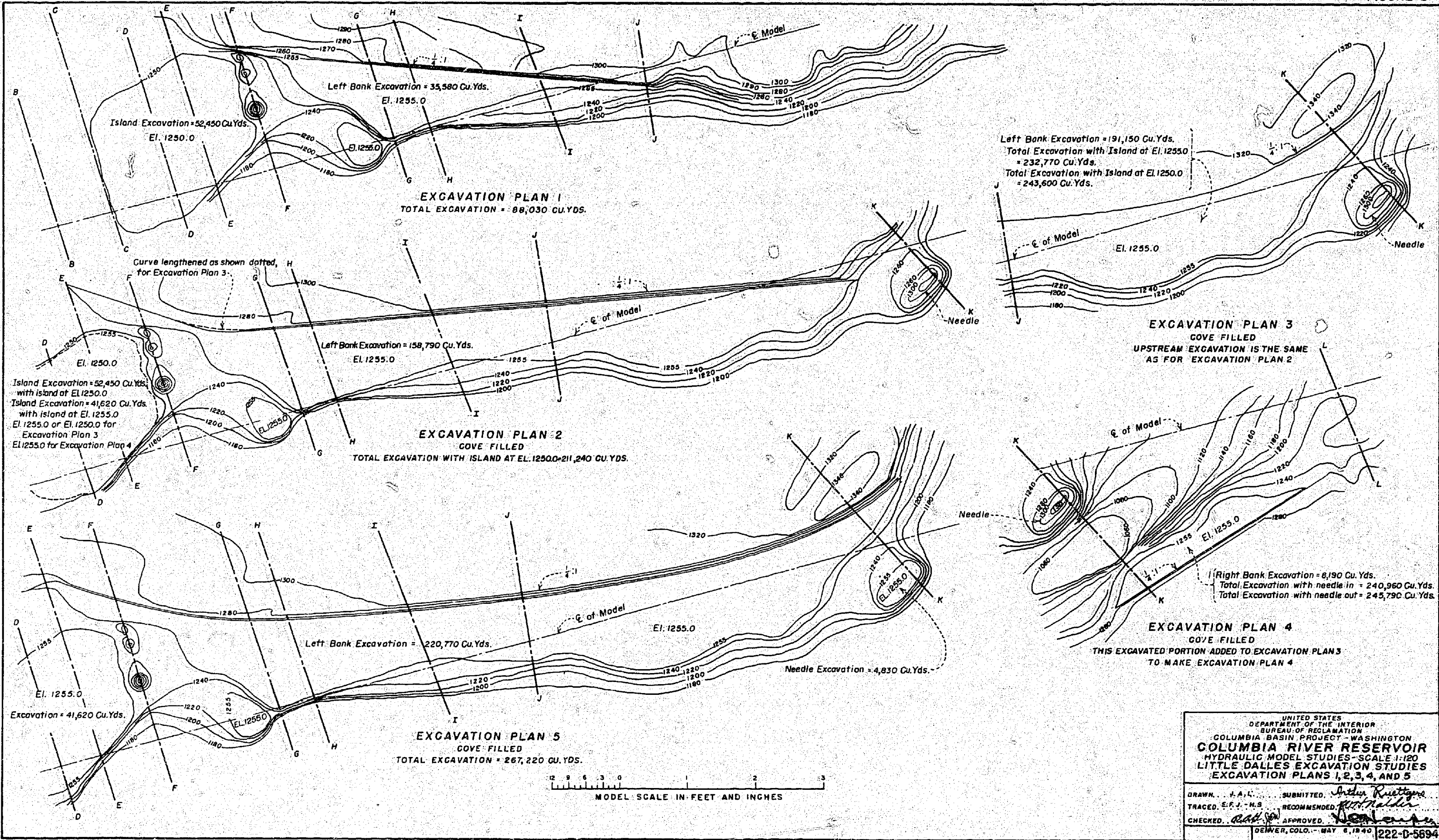
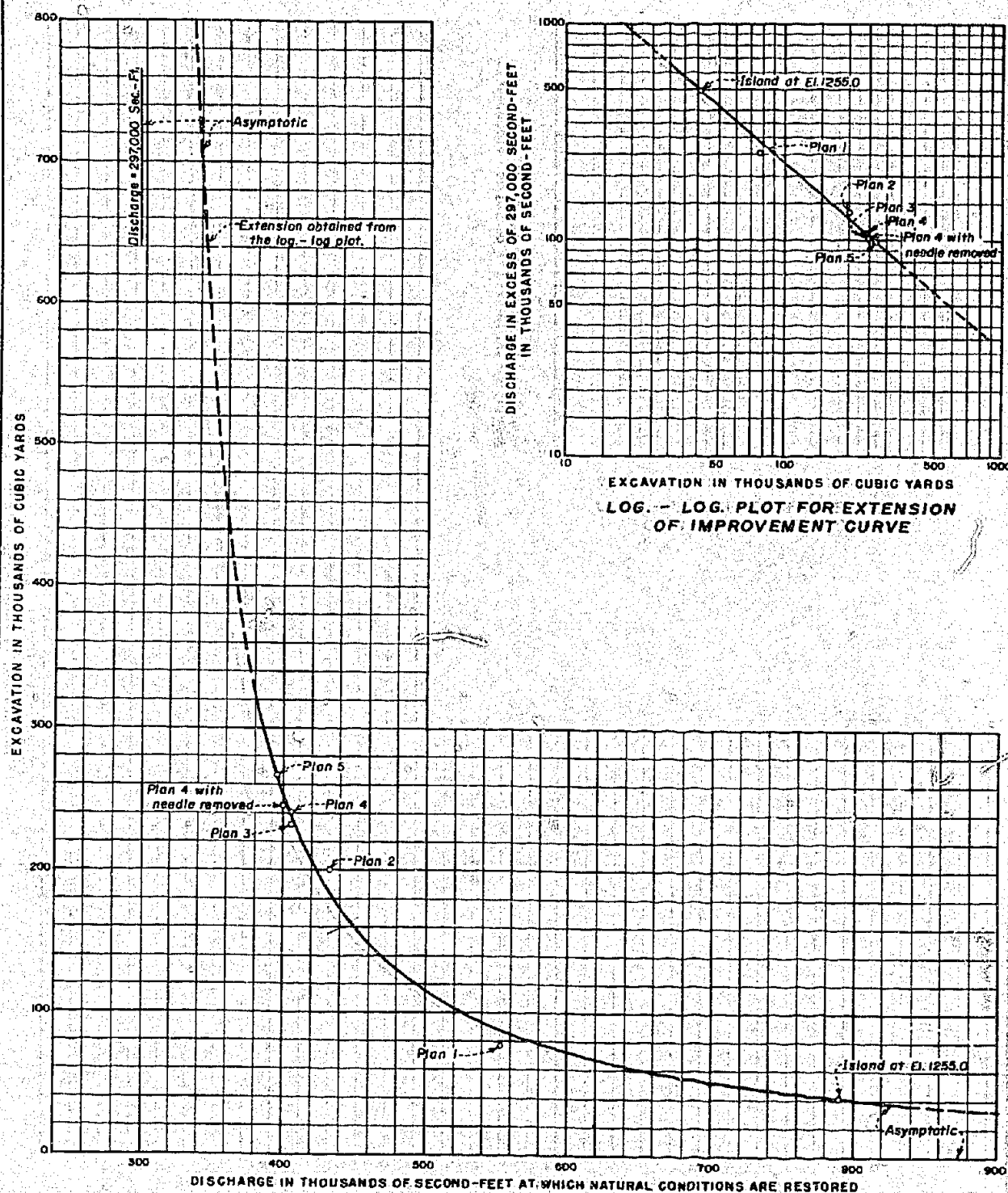


FIGURE 9



NOTE  
Reservoir elevation 1290.0  
at Grand Coulee Dam.

BUREAU OF RECLAMATION  
**COLUMBIA RIVER RESERVOIR**  
HYDRAULIC MODEL STUDIES - SCALE 1:120  
**COMPARISON OF IMPROVEMENT AND EXCAVATION AT THE LITTLE DALLES  
BACKWATER CONDITIONS**

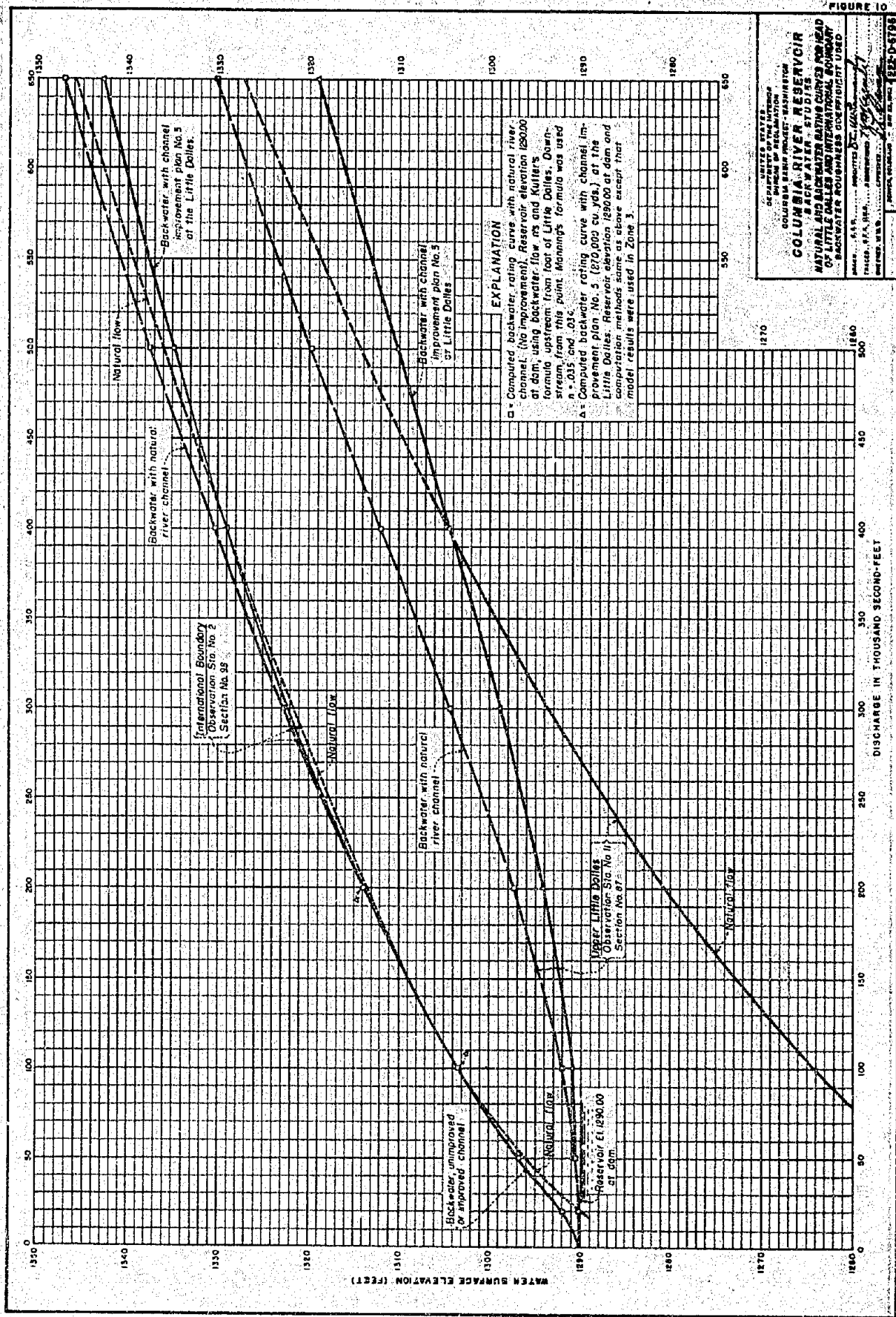
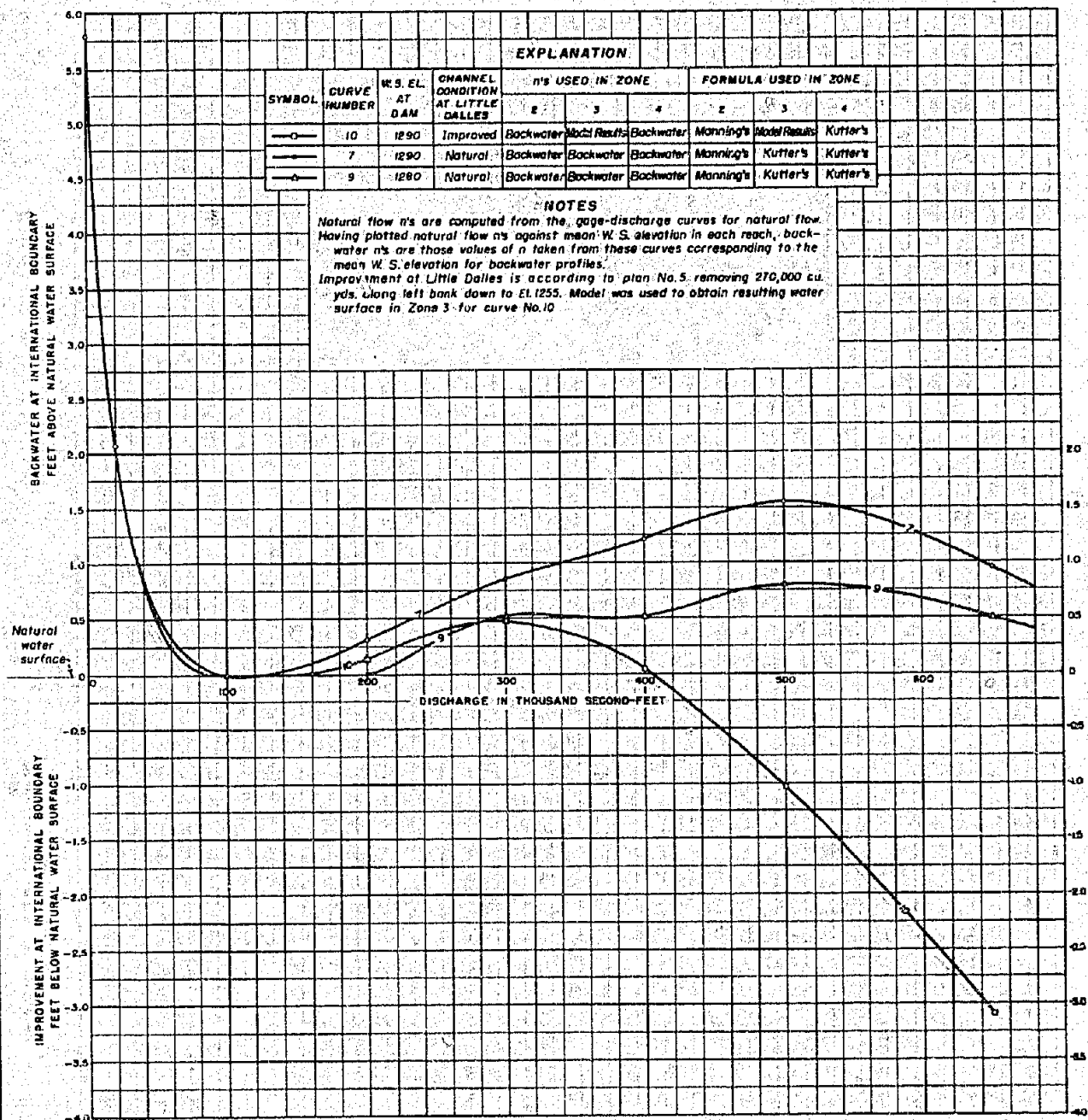


FIGURE 10

UNITED STATES  
DEPARTMENT OF AGRICULTURE  
COLUMBIA RIVER PROJECT - WASHINGTON  
NATURAL AND BACKWATER RATING CURVES FOR HEAD  
OF LITTLE DALLES AND INTERNATIONAL BOUNDARY  
- BACKWATER ROUGHNESS COEFFICIENT USED

PAKER, F.A. JR., ASSISTANT DISTRICT ENGINEER  
JANUARY 1934

222-D-5798



## LOCATION OF ZONES

Zone No. 1 - Grand Coulee Dam to Marcus.  
Zone No. 2 - Marcus to Foot of Little Dalles.  
Zone No. 3 - Little Dalles.  
Zone No. 4 - Head of Little Dalles to International Boundary.

UNITED STATES  
DEPARTMENT OF THE INTERIOR  
BUREAU OF RECLAMATION  
COLUMBIA BASIN PROJECT, WASHINGTON  
**COLUMBIA RIVER RESERVOIR**  
BACKWATER STUDIES  
BACKWATER AND IMPROVEMENT AT  
INTERNATIONAL BOUNDARY  
BACKWATER ROUGHNESS COEFFICIENT USED

PROJECT, S.W. - LOCATION *See Map*  
TRANS. S.E. - S.W. - ALLEGEDLY *See Map*  
COLUMBIA CAN - APPROVED *See Map*  
COLUMBIA CAN - APPROVED *See Map*

RECORD, HOLDING - CIVIL DIV. **224 D-2753**