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FLOOD RISK ANALYSIS OF COLD CREEK NEAR THE HANFORD SITE

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SUMMARY

As required by the proposed rule of 10 CFR 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories," the Pacific Northwest Laboratory has analyzed the flood potential at the 18-mi^2 reference repository location located on the Hanford Site near Richland, Washington. This work was requested and funded by Rockwell Hanford Operations in conjunction with the Basalt Waste Isolation Project (U.S. Department of Energy Prime Contract No. DE-AC06-77RL01030). It is emphasized that this work is not intended as a basis for engineering design, but rather as an initial, regional appraisal of whether detailed engineering design analysis will be required. In order to achieve the detail required for engineering design specifications, the study results should be refined using more detailed channel geometry data, and the topography of the western portion of the reference repository location should be mapped using a contour interval of not less than 2 ft.

Potential flooding at the reference repository location, located along the western boundary of the Pasco Basin, was analyzed both on a local and regional basis. Review of historical and theoretical flooding of the Columbia and Yakima Rivers indicates that there is no direct danger to the reference repository location due to flooding from these water courses. A detailed evaluation of local flooding in Cold Creek, an ephemeral channel adjacent to the reference repository location, was performed using empirically derived methodologies. The evaluation included development of maximum annual flood frequency curves, probable maximum flood peak discharges, and computation of water surface profiles. These results indicate a potential for limited flooding within the western portion of the reference repository location. These results indicate that about 3.5 mi^2 of the reference repository location would be inundated by the probable maximum flood. The maximum depth of inundation along the widest point of the floodplain within the reference repository location is about 7.7 ft (based on minimal topographic resolution). Results also show that, under probable maximum flood conditions, access to the reference repository location from the east and north would, most likely, be unimpaired, although Route 240 would be flooded and unusable.

These results are considered to be conservative based on several conservative factors assumed in computing the flood magnitudes. Also, based on the evaluation of study results, it is recommended that a more detailed study be performed if design of flood protection measures is necessary in the future.

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INTRODUCTION

Paragraph 60.11(a) of the proposed rule 10 CFR Part 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories," requires the U.S. Department of Energy (DOE) to submit a site characterization report for candidate repository sites to the U.S. Nuclear Regulatory Commission (NRC). As discussed in the draft NRC guidelines entitled "Standard Format and Content of Site Characterization Report for High-Level Waste Geologic Repositories," one of the functions of a site characterization report is to demonstrate that candidate sites meet the technical requirements of 10 CFR Part 60.[a] One such requirement is that candidate repository sites should meet flood design standards that ensure virtually no risk of exceedance caused by precipitation and any resulting dam failures.

One location being investigated as a deep geologic waste repository is within the Columbia River basalt beneath the Hanford Site in the state of Washington. The Basalt Waste Isolation Project (BWIP), operated by Rockwell Hanford Operations (Rockwell) under contract to DOE, is chartered with evaluating the feasibility of utilizing the Columbia River basalt as a repository medium. The location selected within the Hanford Site as a possible repository is the reference repository location as identified in Figure 1. The reference repository location is situated directly west of the 200 East Area and encompasses the 200 West Area.

At the request of Rockwell, the Pacific Northwest Laboratory has analyzed the potential for flooding at the reference repository location. The objectives of the study were to: 1) identify possible effects of flooding at the site, and 2) provide a preliminary basis for designing protection measures for surface facilities and access roads against flooding. Meeting these objectives would fulfill Rockwell's reporting requirements as identified under Chapter 5 of the draft NRC guidelines.[a] This report presents the results of the study and includes discussions of regional flood potential, flood potential at the site, and effects of stream sedimentation.

(a) Draft guidelines informally issued pursuant to the proposed rule 10 CFR Part 60.

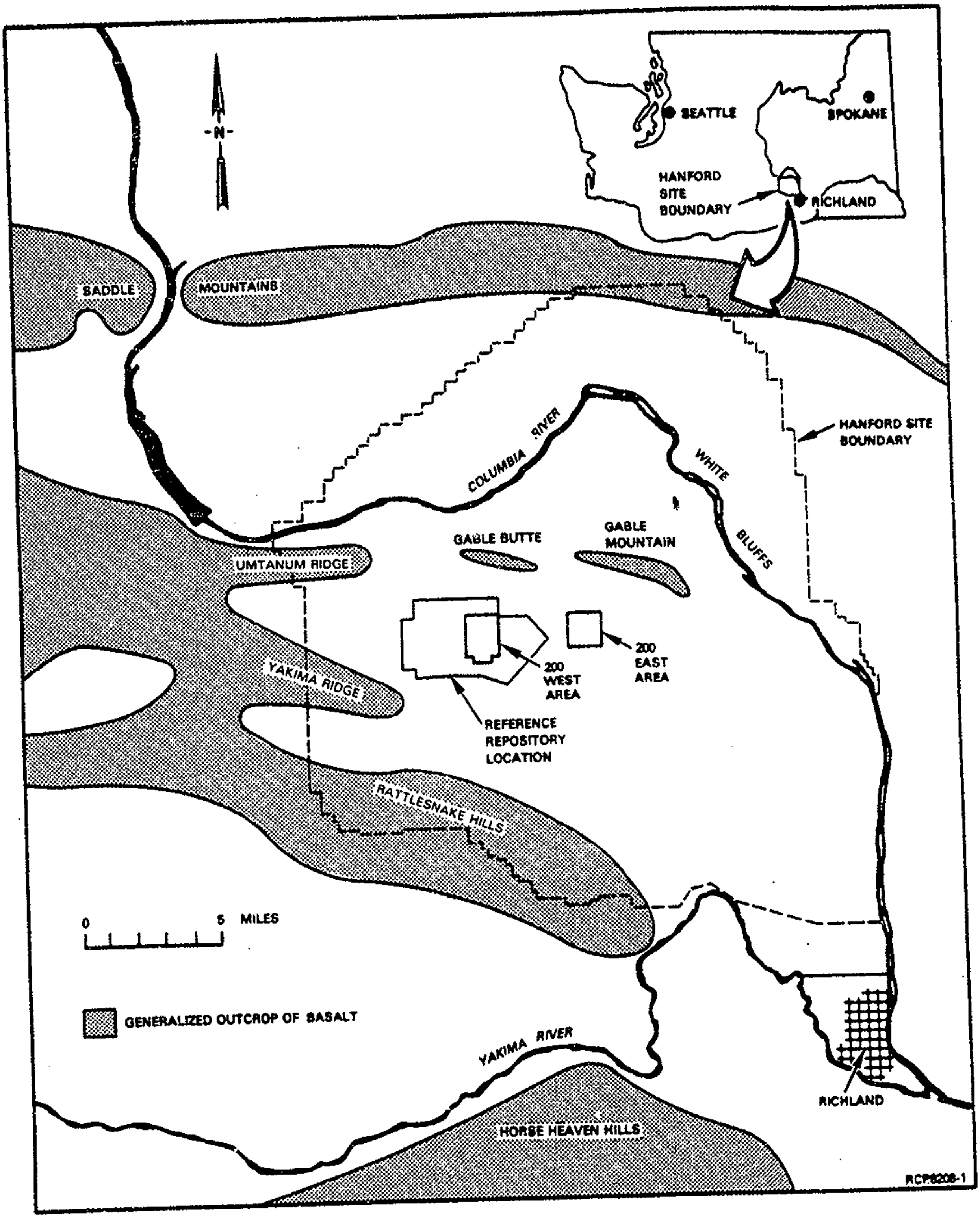

FIGURE 1. Location Map - Hanford Site and the Reference Repository Location

BACKGROUND

Of the natural phenomena that could adversely affect a deep geologic radioactive waste repository constructed within the Pasco Basin, flooding is the most probable, although not necessarily the most damaging (Gephart et al. 1979). Flooding would have its greatest impact on the surface facilities of a repository during the period following construction and prior to permanent closure and sealing. This period, known as the "operating phase," would only last about 50 yr. After the repository is sealed in the basalt, the possibility of flooding having significant impact would be minimal. Therefore, for the short term, once design flood levels have been determined, flood protection measures can be designed to reasonably eliminate flood risk. In the long term, surface streams adjacent to repositories can be expected to undergo radical change: perhaps significantly changing course and producing deep surface erosion. However, since geologic repositories would be constructed deep underground, attention here will be focused on flooding and erosional effects to surface facilities in the short term.

SITE DESCRIPTION

PASCO BASIN

The reference repository location, shown in Figure 2, is located partially within the Cold Creek watershed, which is located within the Pasco Basin. The general geologic, topographic, and climatic features of the Pasco Basin significantly influence the flood-generating mechanisms and potential of Cold Creek. This section briefly describes these features and presents some of the important details regarding Cold Creek and the reference repository location.

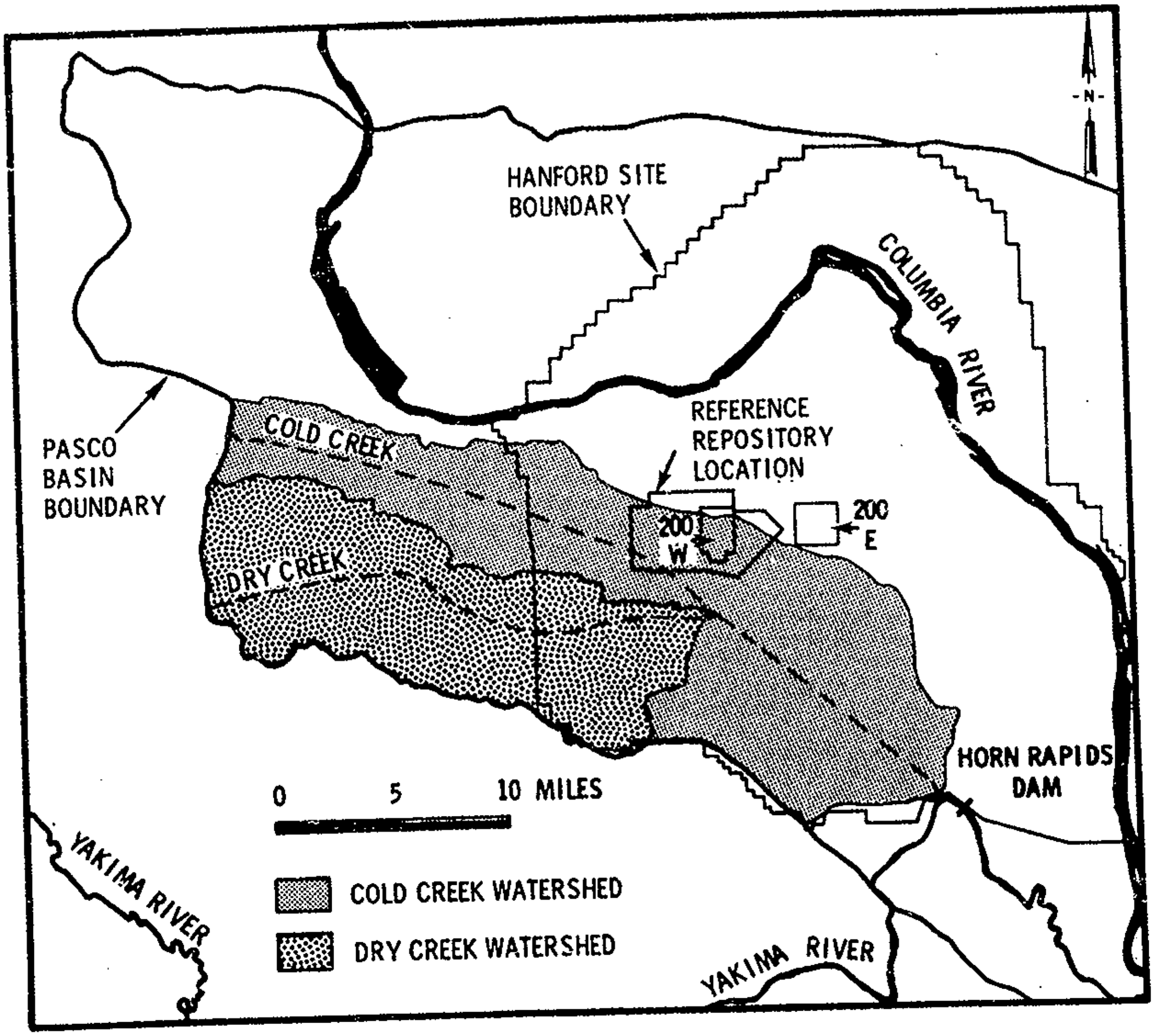

FIGURE 2. Reference Repository Location and the Cold Creek Watershed

As described by Gephart et al. (1979), the Pasco Basin, an area of about 2,000 mi^2 in south-central Washington, lies completely within the Columbia Plateau. The basin is a structural and topographic low into which the Columbia, Snake, and Yakima Rivers drain. The basin boundaries include the Saddle Mountains to the north, Umtanum and Yakima Ridges to the west, and the Rattlesnake and Horse Heaven Hills to the south and southwest. A broad regional monocline is the buried structural border to the east. The highest of these basalt rock outcrops is the Yakima Ridge with elevations of greater than 4,000 ft above mean sea level (MSL).

The topography of the basin is varied and includes basalt ridges, fluvial plains, and scabland tracts and coulees. The central portion of the basin is partially filled with continental clastic sediments transported into the area by river and periglacial systems from the surrounding highlands. The general surface topography of these sediments forms a broad plain ranging in elevation from 400 to 900 ft MSL.

The Pasco Basin climate is dominated by the high Cascade Range to the west and the prevailing eastward direction of storm fronts from the Pacific Ocean eastward over these high mountains. The orographic effect on weather is dramatic in that the region is dry and has very mild temperatures with occasional periods of high winds. Summers are generally hot and dry; most of the moisture comes during the relatively mild winters.

Average annual precipitation is 6.25 in., ranging from 6 in. within the Hanford Site to over 15 in. atop Rattlesnake Mountain. Stone, Jenne, and Thorpe (1972) note that 37% of the annual precipitation occurs during November, December, and January, whereas, only 10% occurs in July, August, and September. A slight secondary maximum in precipitation occurs in late spring. About 45% of all precipitation falling during the months of December through February is in the form of snow.

Runoff within the basin is very low, averaging less than 0.5 in./yr for most of the basin. However, a few ephemeral streams do exist within the basin, but they have relatively short reaches and small discharges. Two such streams are Cold Creek and its main tributary, Dry Creek.

COLD CREEK WATERSHED

The Cold Creek watershed is located along the western boundary of the Pasco Basin, having a northwest/southeast orientation. As shown in Figure 3, the basin is bordered on the west by the Rattlesnake Hills and the Yakima Ridge, on the north by the Umtanum Ridge, and on the east by the central portion of the Hanford Site. The rectangular shaped 336 mi^2 watershed drains into the Yakima River at about 1 mi upstream of Horn Rapids Dam. Elevations in the watershed range from about 420 ft MSL at its outlet to over 4,000 ft MSL in its headwaters along the Yakima Ridge.

Lying in the rainshadow of the Rattlesnake Hills and Yakima Ridge, the Cold Creek basin has an arid to semiarid climate. Due to the effects of these ridges and the Cascade Range which lies to the west, average annual precipitation is quite low, averaging from 6 in. in the lower Cold Creek Valley to 10 in. in the higher elevations. Consistent with the general pattern in the Pasco Basin, most of the precipitation, about 60% of the annual amount, generally occurs as low intensity rainfall and snow during the months of November through February. The greatest amount falls on the upper slopes of Rattlesnake Mountain at elevations over 2,700 ft. June through September is the driest period of the year accounting for only about 15% of the total annual rainfall. However, the potential does exist during these months for significant amounts of rain to fall during local, short duration, high intensity thunderstorms (Thorp and Hinds 1977; Gutknecht et al. 1981).

Generally, the Cold Creek basin has a well-developed drainage system as illustrated in Figure 3. This is most likely due to the loose surface materials, sparse vegetation consisting primarily of cheatgrass and sagebrush, high surface relief, and a more humid paleoclimate. In contrast, the southeastern portion of the basin including the reference repository location is characterized by surficial glaciofluvial deposits that have been reworked by the wind and do not have well-defined drainage patterns.

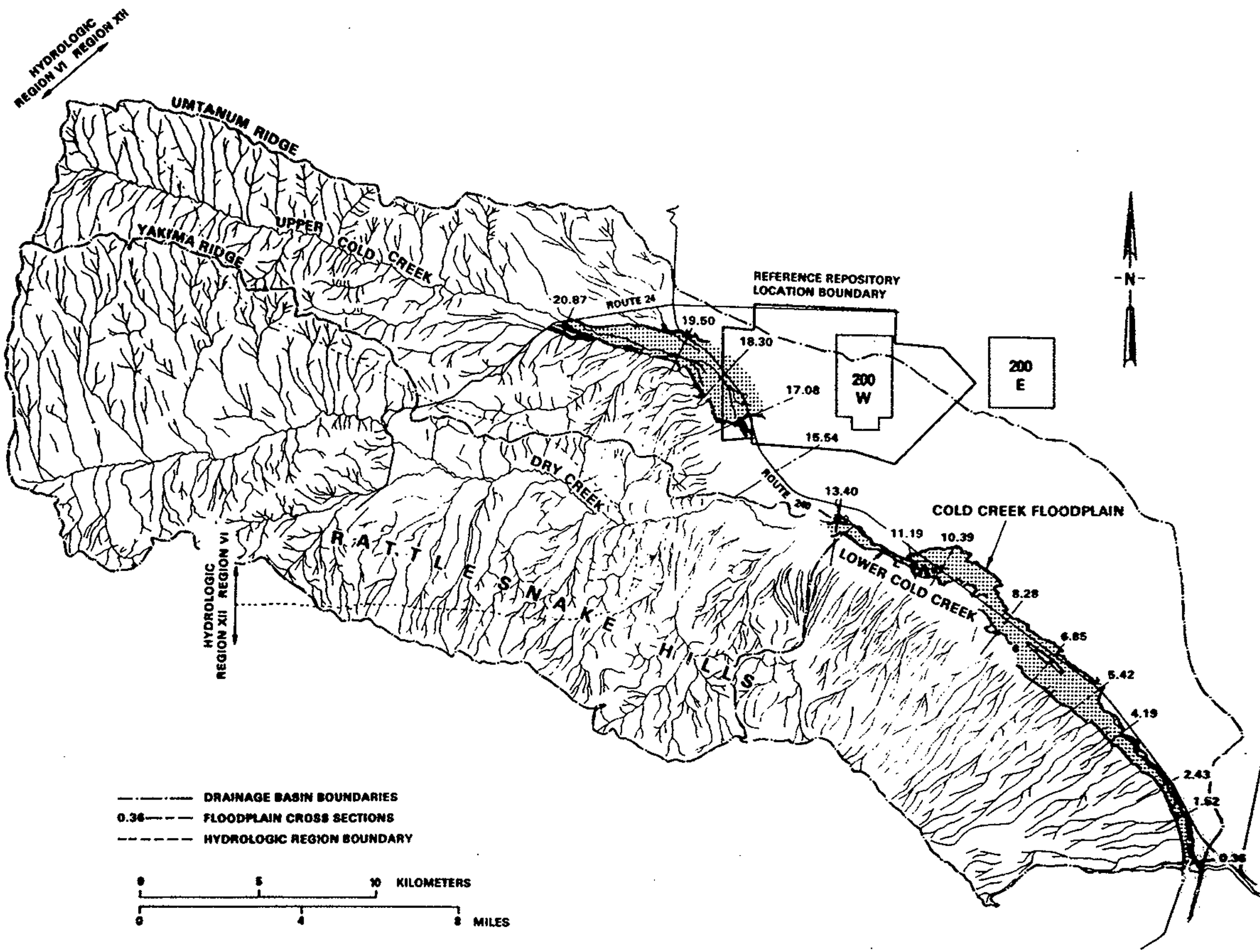

FIGURE 3. Drainage Area Map of Cold Creek Basin

Again referring to Figure 3, most of the reference repository location lies within the Cold Creek watershed along the eastern divide. The reference repository location, with an area of approximately 12.8 mi^2, extends westward from the western edge of the 200 East Area and encompasses the 200 West Area. The westernmost portion of the reference repository location crosses the Cold Creek channel. As determined from the U.S. Geological Survey topographic map (20-ft contour intervals), the ground surface elevations of the site range from 620 to 760 ft MSL, generally sloping toward the Cold Creek channel.

In discussing the occurrence of runoff in the Cold Creek watershed, a distinction is made between the upper and lower portions of Cold Creek watershed as indicated in Figure 3. Upper Cold Creek rises between Umtanum Ridge on the north and Yakima Ridge on the south and terminates along the base of the ridges. Runoff from the upper Cold Creek watershed passes over the southwestern corner of the reference repository location site through Cold Creek distributary channels that, under normal flow conditions, terminate within the reference repository location. As evidenced by the lack of significant drainage rills or gullies, it is unlikely the site area contributes appreciable runoff under normal conditions. Lower Cold Creek derives most of its flow from Dry Creek, which is the major tributary of Cold Creek. The remaining runoff within lower Cold Creek is derived from the Rattlesnake Hills drainage system.

COLD CREEK FLOODPLAIN

The floodplain of Cold Creek begins approximately where Route 24 crosses the upper Cold Creek channel (see Figure 3). Flow passes under Route 24 through a concrete culvert. The culvert is located about 21 valley miles upstream from the Yakima River. In order to determine the approximate location of the valley floor boundary, aerial photography was flown at a scale of 1:12,000 along the axis of Cold Creek Valley from Route 24 to the Yakima River. Based on stereographic interpretation of aerial photography, the low-lying bluffs and rock outcrops were mapped and shown in Figure 3 as the boundary of the Cold Creek floodplain. These boundaries indicate the probable limits of any significant lateral reworking of surface material during high flows.

Beginning at the Route 24 culvert, the Cold Creek floodplain is about 2,500 ft wide. The distance between valley walls gradually increases until they are about 1 mi apart at valley mile 19.0. Below this point the left-side valley wall (viewed in the downstream direction) diverges sharply to the left. At approximately valley mile 17.0, a low-lying outcrop appears to partially extend in a transverse direction across the valley floor axis. Beyond this point there seems to be no well-defined floodplain limits until about mile 13.5. Valley mile 13.0 marks the approximate location of the Dry Creek-Cold Creek confluence. Below the confluence the valley's walls are about 2,000 ft apart and narrow to about 750 ft at valley mile 11.0. In the down-valley direction from mile 11.0, the floodplain widens to about 1 mi. The floodplain maintains a width of about 1/2 to 1 mi until about 5 mi above the Yakima River. Below this point the valley narrows to about 2,000 ft or less to the mouth of Cold Creek at the Yakima River.

When viewed over its entire length, Cold Creek Valley resembles a scabland-type channel partially disguised by overlying sediment deposits. Due to the limited width of the aerial photography coverage, the mapping was extended over the reference repository location. There may be other branches of eroded channel covered by the surficial sediments of the reference repository location. The values of valley slope from Route 24 to the Yakima River are shown in Table 1. Valley slopes along Cold Creek vary from 147.7 ft/mi just below Route 24 to 4.1 ft/mi at valley mile 2.43.

TABLE 1. Cold Creek Valley Slopes

Valley Miles Above Yakima River	Slope (ft/mi)	Slope (ft/ft)
20.87 - 19.5	147.7	0.028
19.54 - 17.08	24.4	0.0046
17.08 - 13.40	10.9	0.0021
13.40 - 11.19	21.9	0.0041
11.19 - 16.28	10.9	0.0021
8.28 - 5.42	13.8	0.0026
5.42 - 2.43	4.1	0.0008
2.43 - 0.00	24.7	0.0047

COLD CREEK CHANNEL

Beginning at the upstream culvert at Route 24, the upper Cold Creek channel has a well-developed braided pattern with multiple channels. Aerial photography reveals many other similar channel traces along the valley floor. The extremely braided condition is due primarily to the very steep valley slope above mile 19.54 that provides high flow velocities and sediment transport capacity that lead to an overall channel instability. The observed characteristics of a braided stream system are that it changes its alignment rapidly, transports large quantities of sediment, is very wide and shallow even at flood flow, and is, in general, unpredictable (Simons and Senturk 1976).

Below mile 19.54 the valley slope flattens to 24.4 ft/mi, which extends downstream to mile 17.35. Because of the greatly decreased valley slope, much of the sediment load from the steeper upstream segment would tend to be deposited along this channel segment and possibly form an alluvial fan. The present-day Cold Creek channel system more closely resembles a drainage pattern of distributary channels over an alluvial fan in that the channels tend to spread out in a fan-shaped network, eventually becoming discontinuous. These channels extend over the southwest corner of the reference repository location. There appears to be a tendency for flows from some of these channels to be directed generally westward and over the reference repository location. The area topography including the valley wall orientation at the southwest repository corner would indicate this to be the case. Route 240, which extends along the Cold Creek Valley axis, would possibly restrict some of the lesser flows from spreading out over the reference repository location unless overtopped or breached.

There is no apparent Cold Creek stream channel on either side of Route 240 for about the next 3 mi indicating that under present climatic conditions the upper and lower Cold Creek watersheds are essentially separate drainage systems. The source of the upper Cold Creek discharge is the drainage basin area bounded by the Umtanum and Yakima Ridges. Very little runoff is contributed by the eastern portion of the upper basin area where the reference repository location is located.

The lower Cold Creek drainage system originates at about valley mile 14.0 and joins the Dry Creek channel about 1 mi downstream. The Cold Creek channel below Dry Creek flows through a narrow floodplain segment for about 2 mi. The floodplain is bounded by low-lying bluffs and is about 800 ft at its narrowest point. The channel is positioned along the base of the left valley boundary. The local valley slope steepens to 44.4 ft/mi through this narrow section; however, evidence of channel braiding is not apparent due to the very narrow floodplain limits.

Below valley mile 11.0, the floodplain widens abruptly to about 5,500 ft while decreasing the valley slope to about 5.2 ft/mi. At approximately mile 10.5, the channel passes under the Route 240 roadway. During field reconnaissance, no culvert was found that allowed passage of flow under the highway, and since the channel disappears a short distance on the other side, present flow conditions are probably of no concern. Most of the runoff for this channel segment originates from the Dry Creek watershed, while a very small percentage is contributed from short lateral drainage gullies along the Rattlesnake Hills. Down valley from the point where the channel becomes discontinuous there is no easily defined channel for approximately the next 5 mi, although some short discontinuous channel segments are visible in the aerial photography.

About 5 mi above the Yakima River the floodplain narrows to about 3,000 ft with a valley slope of 4.1 ft/mi. From that point downstream the floodplain gradually narrows to about 1,500 ft near the Yakima River. The Cold Creek channel also reappears at about 5 mi upstream of the Yakima River and is very well defined from that point to the Yakima River. The runoff contributing to this channel originates from the lateral drainage gullies along the Rattlesnake Hills.

REGIONAL FLOODING

To comprehensively analyze the flood risk at the reference repository location, consideration must be given to both local canyon flooding and regional basin flooding. This section contains a brief summary of past flooding on the Columbia and Yakima Rivers, their areal extent, and what effects, if any, such floods would have on the reference repository location. This section is followed by a detailed analysis of canyon flooding.

COLUMBIA RIVER

Major floods on the Columbia River result from rapid spring melting of the winter snowpack over a wide area, generally augmented by rain, or by above-normal precipitation in May, accompanied by a major chinook wind, which causes rapid area temperature rise. The maximum historical flood on record is that of June 7, 1894, which was generated by a combination of hydrometerologic conditions, including heavy snowpack and rapid melt plus rainfall. The peak discharge during the flood at the Columbia River's Hanford Reach was 740,000 ft^3/s as estimated from the high-water mark at Wenatchee, Washington. The largest recent flood occurred in 1948 with an observed peak discharge of 690,000 ft^3/s at Hanford. Flood flows of the magnitude of the 1948 and 1894 floods are now highly unlikely due to upstream regulation at Priest Rapids Dam. Actual river flows currently range between 36,000 and 160,000 ft^3/s, whereas, unregulated flows (prior to Priest Rapids Dam construction) ranged between 70,000 and 380,000 ft^3/s (WPPSS, 1980).

The 1894 flood, the highest flood on record, inundated areas less than 400 ft MSL. The approximate floodplain associated with this flood is shown in Figure 4. A flood of this magnitude inundates the 100 F Area and sections of the Richland community but would have no consequence on the reference repository location. The major four-lane highway on the Hanford Site would be flooded near the old Hanford Townsite cutting off a direct route from the repository to Richland. However, access from the west via Route 240 would still be possible. Today's regulated maximum flow, 160,000 ft^3/s, has no effect on any facilities on the Hanford Site.

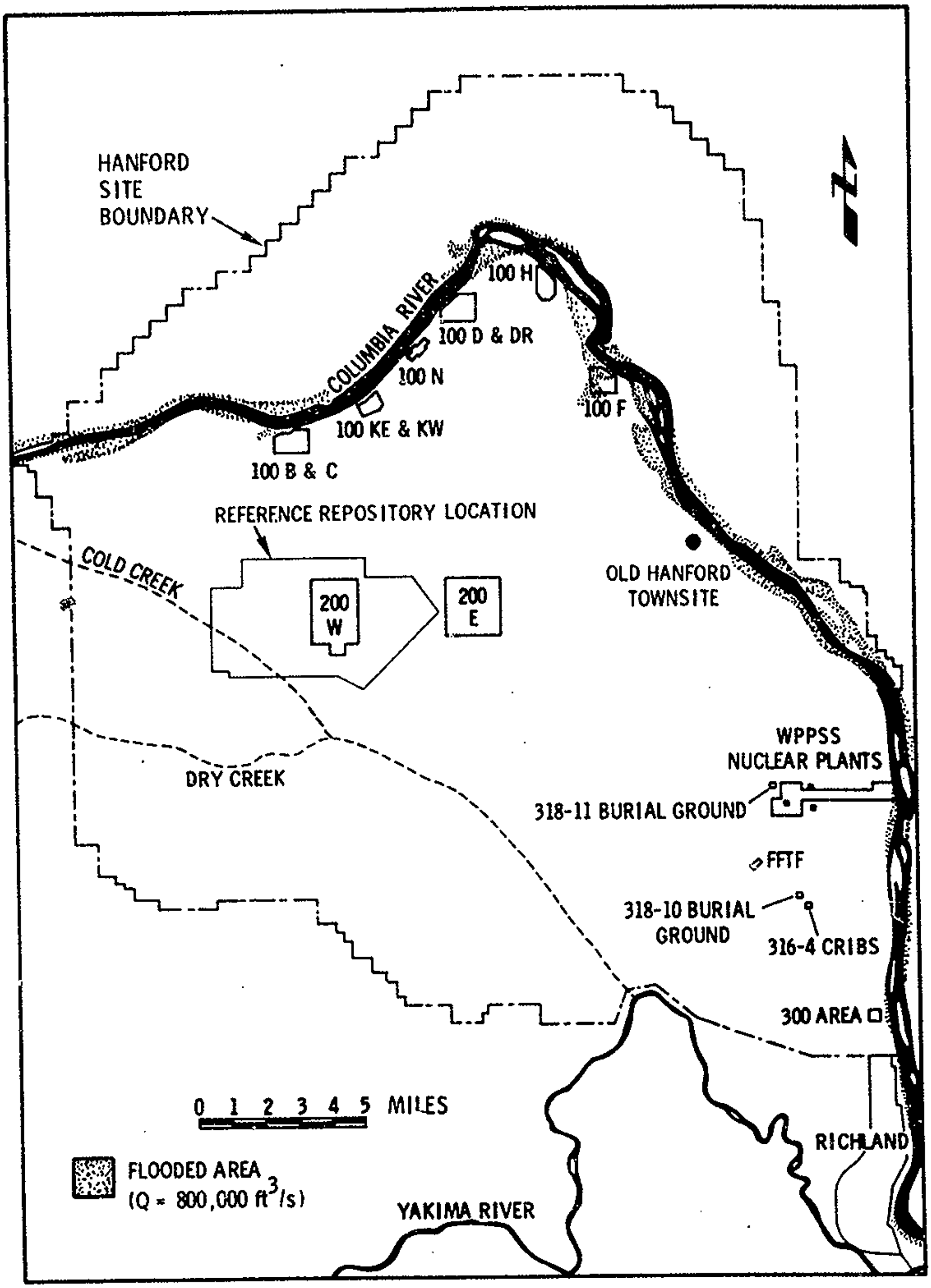

FIGURE 4. 1948 Flood - Flood Area in the Vicinity of the Reference Repository Location (After ERDA, 1976)

Associated with evaluating maximum flooding is the concept of the probable maximum flood (PMF), which is determined from the upper limit of precipitation falling on a drainage area and other hydrologic factors (such as antecedent moisture conditions, snowmelt and tributary conditions) that will result in maximum runoff. The PMF for the Columbia River below Priest Rapids Dam is calculated as 1,400,000 ft^3/s (Leonhart, 1979). The floodplain associated with the PMF is shown in Figure 5. This magnitude flood would inundate the 100 Areas and large areas within the city of Richland. The 200 and 300 Areas, as well as the central portion of the Hanford Site remain unaffected.

Potential dam failures on the Columbia River have been extensively evaluated in conjunction with siting a nuclear repository on the Hanford Site. Upstream dam failures may arise from a number of causes; however, the magnitude of the resulting flood depends upon the degree of the breach. The U.S. Army Corps of Engineers (1951) conducted a number of scenarios for the effects of dam failures at Grand Coulee Dam assuming flow conditions on the order of 400,000 ft^3/s. The resulting discharge at the outfall of Grand Coulee was determined to be 21,000,000 ft^3/s. Near Richland, this flow would diminish to 8,000,000 ft^3/s accounting for flow augmentation due to failure of earth portions of downstream dams and release of their respective storages. The resulting inundations from the 50% breach scenario is depicted in Figure 6. In addition to the areas inundated by the PMF are the remainder of the 100 Areas, nearly all of the city of Richland, the 300 Areas and the Washington Public Power Supply System, Inc. reactor sites. Although the central portion of the Hanford Site largely remains unaffected, a small arm of floodwater inundating the lowlands between Gable Butte and Gable Mountain would affect the highway to the southside of these mountains and possibly the reference repository location.

No determinations have been made to this point with respect to breaches greater than 50% at Grand Coulee Dam or of failures of dams upstream of Grand Coulee and associated resonant failures of dams downstream (Leonhart, 1980).

A third catastrophic event that could result in flooding portions of the Hanford Site is river blockage and flooding due to landslides along the Columbia River. One slide area extends along a 250-ft bluff from river mile 376 downstream to river mile 355. This area, commonly referred to as White Bluffs,

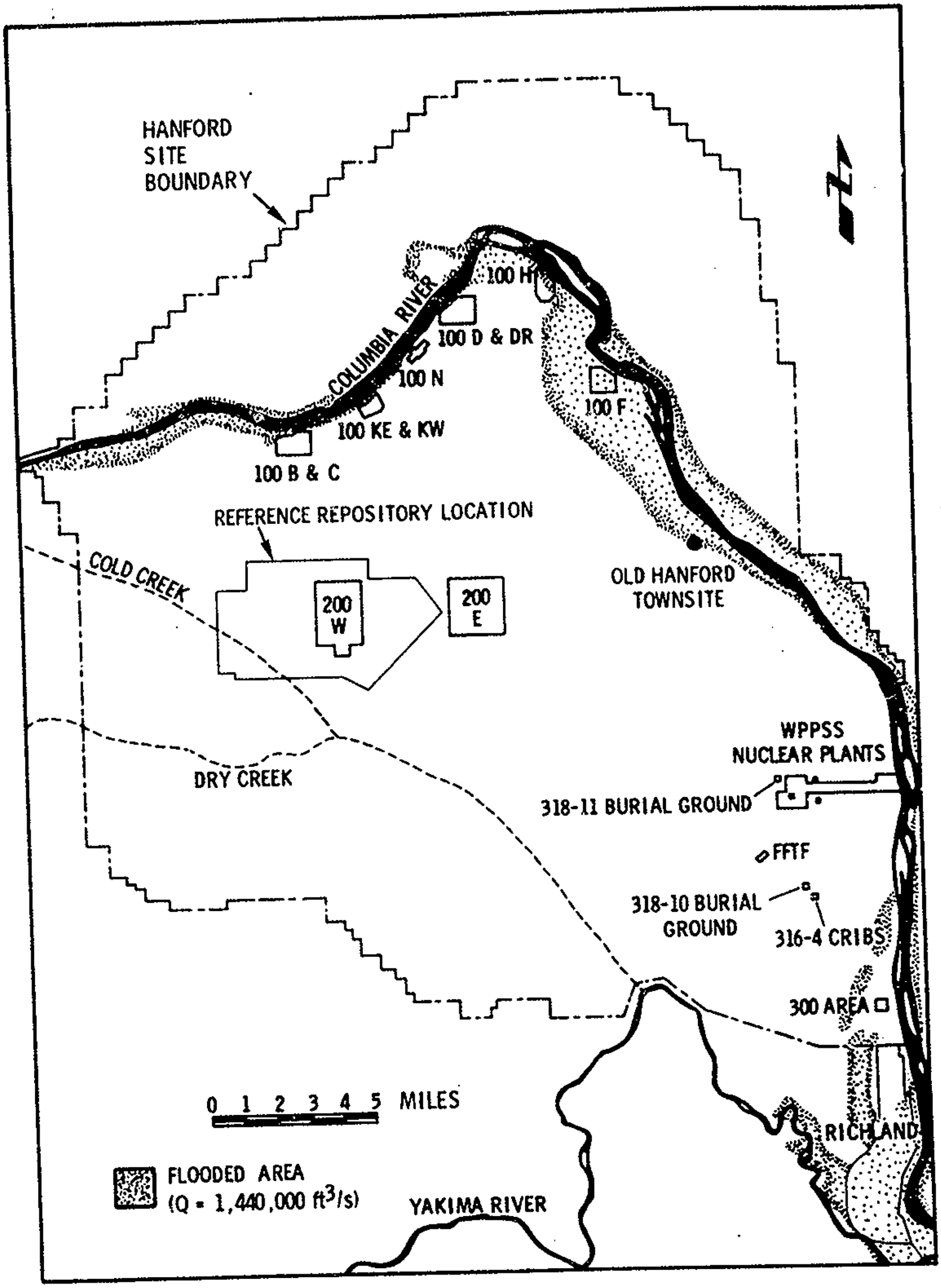

FIGURE 5. Probable Maximum Flood - Flooded Area in the Vicinity of the Reference Repository Location (After ERDA, 1976)

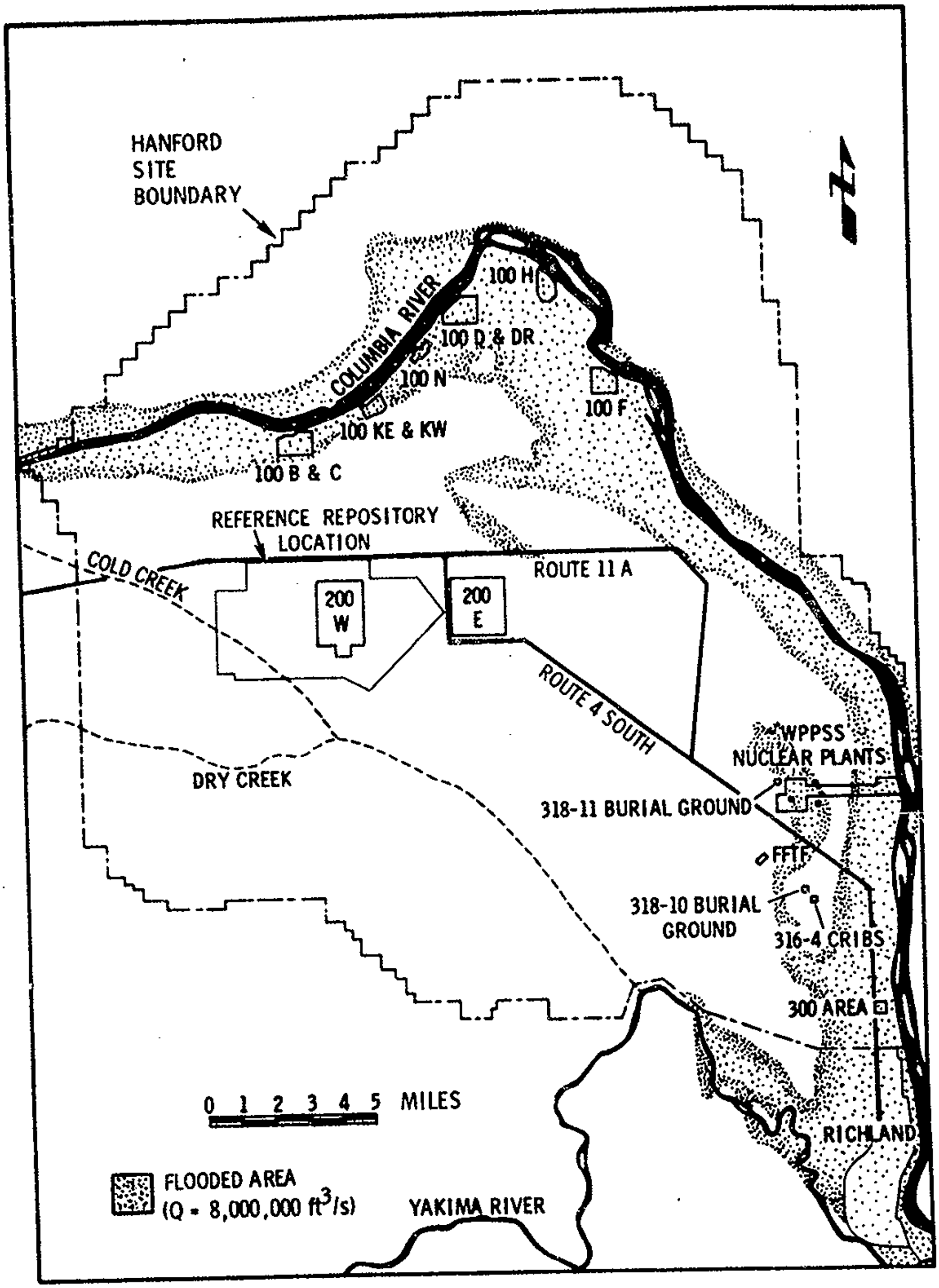

FIGURE 6. Flooded Area in the Vicinity of the Reference Repository Location Resulting from a 50% Breach of Grand Coulee Dam (After ERDA, 1976)

has been recently undermined by irrigation water and waste ponds near its face. Instability problems caused by loss of shear strength in the bluffs due to the addition of water have resulted. Calculations indicate that a 1 million-yd^3 landslide concurrent with a flood flow of 600,000 ft^3/s (200-yr flood) would result in a flood wave crest elevation of 400 ft MSL. A PMF, 1,400,000 ft^3/s, would result in a flood wave crest of 410 ft MSL (Harty, 1979). In both cases, the reference repository location would be unaffected, although the main roadway from Richland would be inundated in the vicinity of the old Hanford Townsite. Areas inundated from such a landslide event would be simlar to those shown in Figure 5.

YAKIMA RIVER

Yakima River floods occur as a result of the same hydrometerological events that induce Columbia River flood flows. In addition to spring snowmelt and warm rains, ice and debris jams contribute to flooding on the Yakima River (WPPSS, 1980). Since 1862 there have been 16 major floods on the Yakima River. The most severe occurred in November 1906, December 1933, and May 1948. The peak discharge magnitude of these floods measured at Kiona, Washington were 66,000, 67,000, and 37,000 ft^3/s, respectively (Bodhaine and Thomas, 1964). The recurrence interval for the 1933 and 1948 floods are estimated at 170 and 33 yr, respectively. The most recent flood occurred in December 1977 with a peak discharge of 29,000 ft^3/s and recurrence interval of 14 yr (FEMA, 1980).

A comparison of flood magnitude cannot be made on discharge volume alone because the progressive development of six irrigation storage projects has changed the natural flow regime of the Yakima River. The 1906 flood discharge represents natural flow conditions, whereas, the 1933 and subsequent discharges were modified by the present system of reservoirs. Irrigation reservoir development has reduced the flood potential of the Yakima River considerably. For example, the December 1933 flood was reduced from 83,000 to 54,000 ft^3/s at Yakima, Washington by management of upstream reservoir storage facilities. A December 1959 flood which uncontrolled could have been 55,000 ft^3/s (at Yakima) was reduced to 27,400 ft^3/s.

Flood-susceptible areas due to the 100-yr flood on the Yakima River are shown in Figure 7. Flooded areas in the vicinity of Horn Rapids Dam could potentially influence the southern section of the Hanford Site; however, they would not affect the reference repository location. The Yakima River north of Benton City is physically separated from the Hanford Site by the Rattlesnake Hills and Umtanum Ridge. These topographic barriers prevent any potential flooding on the Yakima River from affecting the reference repository location.

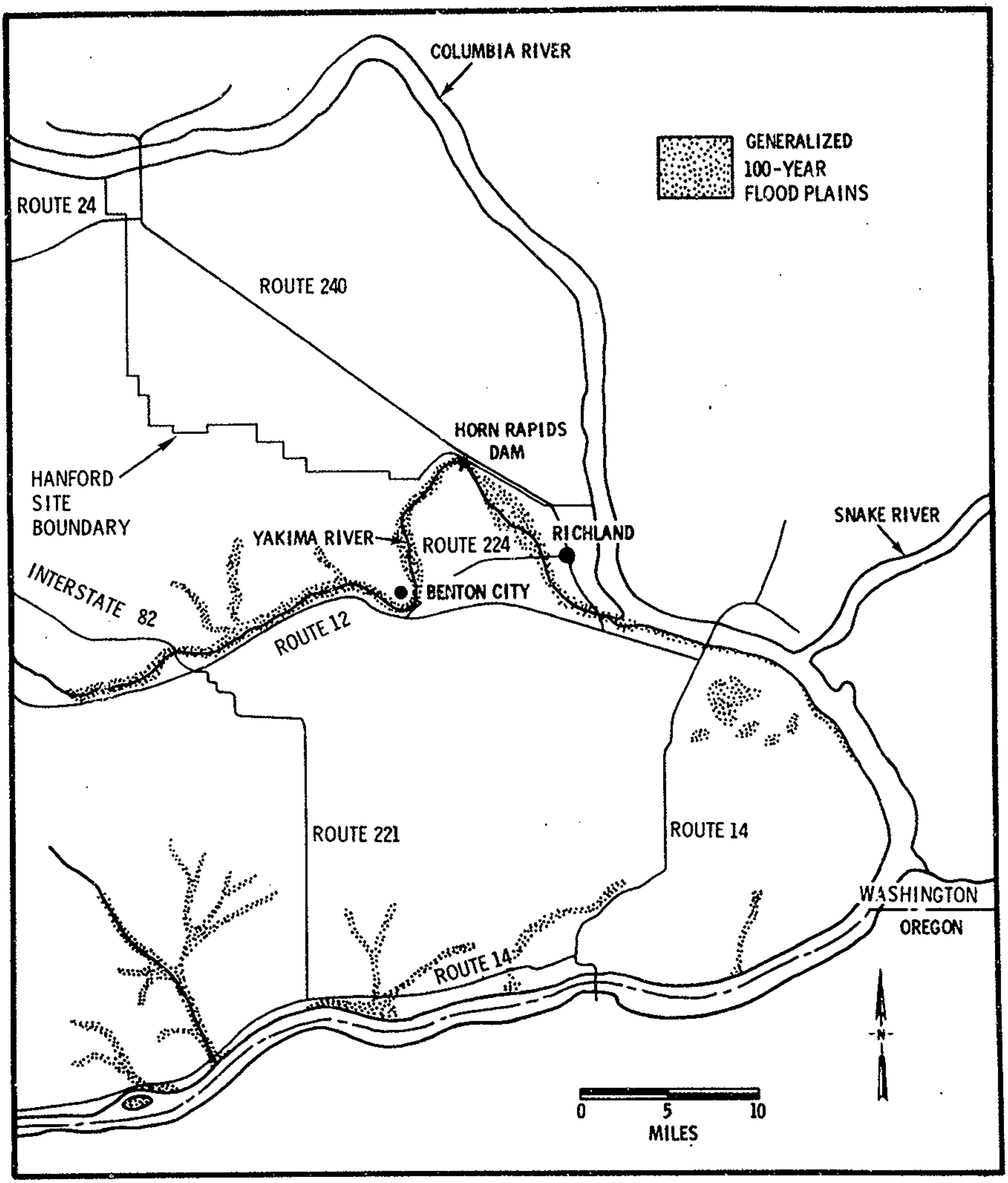

FIGURE 7. 100-Year Flooded Area for the Yakima River in the Vicinity of the Hanford Site (FEMA, 1980)

LOCAL FLOODING

The only major source of local flooding in the vicinity of the reference repository location is the Cold Creek watershed. In analyzing the effects of possible Cold Creek flooding, the objectives were twofold: 1) estimate the probability with which flooding of the site will occur, and 2) estimate the effects of the worst possible flooding conditions (i.e., the PMF). Steps necessary to accomplish these objectives were as follows:

- Estimate Cold Creek discharge magnitude and frequency
- Estimate probable maximum precipitation (PMP) and the resultant PMF discharge
- Determine flood stages and flood stage frequency associated with the above discharges at the reference repository location and access roads.

A detailed discussion of these steps is presented below.

DISCHARGE MAGNITUDE AND FREQUENCY

For an ungaged stream such as Cold Creek, regression equations defined by basin and climatic characteristics must be used to estimate flood-peak discharge magnitudes for selected return periods. In a study by Cummans et al. (1975), annual peak-flow data from stream gaging stations on unregulated streams in Washington having 10 or more years of record were used to determine a Log-Pearson Type III frequency curve for each station. Flood magnitudes having recurrence intervals of 2, 5, 10, 25, 50, and 100 yr were then related to physical and climatic indices of the drainage basins by multiple-regression analysis.

The set of estimating equations finally selected as most practical were defined from two areal groupings, one based on data for all sites in western Washington (west of the Cascade Range crest) and the other for all sites in eastern Washington. Equations for western Washington used drainage area and mean annual precipitation as the independent variables, while equations for eastern Washington also include forest cover as an estimating variable. The state was further divided into 12 hydrologic regions using differences in surficial soils to define regional boundaries. The Cold Creek basin lies partially in two subregions, VI and XII. The boundary between the two regions where it disects the Cold Creek basin is shown in Figure 3. Table 2 summarizes the equations for the two regions which are in the general form:

$$Q_T = \underline{a}A^{b_1} P^{b_2} F^{b_3}$$

where

Q_T = the flood magnitude for recurrence interval T (ft^3/s)
$\underline{a}$ = regression constant that varies for each region and recurrence interval
A = the drainage area size (mi^2)
P = mean annual precipitation (in.)
F = forest cover (percent of drainage area)
b_1, b_2, b_3 = regression coefficients that vary for each region and recurrence interval.

TABLE 2. Summary of Regression Equations

Recurrence Interval (T)	Regression Constant ($\underline{a}$)	Regression Coefficient: Drainage Area (A)	Regression Coefficient: Annual Precipitation (P)	Regression Coefficient: Forest Cover (F)
		Region VI		
5	0.260	0.90	1.35	-0.21
10	0.741	0.88	1.16	-0.23
25	1.77	0.87	1.03	-0.25
50	2.97	0.86	0.95	-0.27
100	4.70	0.85	0.89	-0.29
		Region XII		
5	0.157	0.90	1.35	-0.20
10	0.629	0.88	1.16	-0.23
25	1.76	0.87	1.03	-0.25
50	3.05	0.86	0.95	-0.27
100	4.83	0.85	0.89	-0.29

The above equations were applied to Cold Creek to estimate discharges at two locations, Cold Creek upstream of its confluence with Dry Creek (Location 1) and Cold Creek at the Yakima River (Location 2). At both locations, the upstream drainage areas overlap into two hydrologic regions; therefore, the discharges were computed for the subareas in each region and the final values determined as an areal weighted average. The results of the computations are presented in Table 3, while log-probability plots are shown in Figure 8. The figure also includes the observed discharge frequency curve for Esquatzel Coulee at Connell, a 234 mi^2 drainage area approximately 30 mi to the northeast of Cold Creek in hydrologic subregion XII. Comparing the estimated Cold Creek frequency curves to the observed Esquatzel Coulee curve, it can be seen that their magnitudes and slopes are similar.

TABLE 3. Results of Peak Discharge Magnitude and Frequency Computations

Location	A (mi^2)	P (in.)	$F^{(a)}$	Discharge (ft^3/s) Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}
(1) Upper Cold Creek (upstream of Dry Creek)	86	10	0.01	560	1,400	2,900	4,300	6,300
(2) Lower Cold Creek (at the Yakima River)	336	10	0.01	2,100	4,400	9,400	13,900	19,900

(a) Percent of drainage area

PROBABLE MAXIMUM FLOOD ANALYSIS

Chapter 5 of the NRC guidelines, entitled "Standard Format and Content of Site Characterization Reports for High-Level Waste Geologic Repositories,"[a] states that if potential for flooding exists at a site, a detailed PMF analysis must be performed. The procedures recommended by the guidelines are those presented in American National Standards Institute (ANSI) Standard N170-1976," "Standards for Determining Design Basis Flooding at Power Reactor Sites" (ANS, 1976). When implemented, these procedures provide a design basis flood for which there is virtually no risk of exceedence (PMF).

(a) Draft guidelines informally issued pursuant to the proposed rule 10 CFR Part 60.

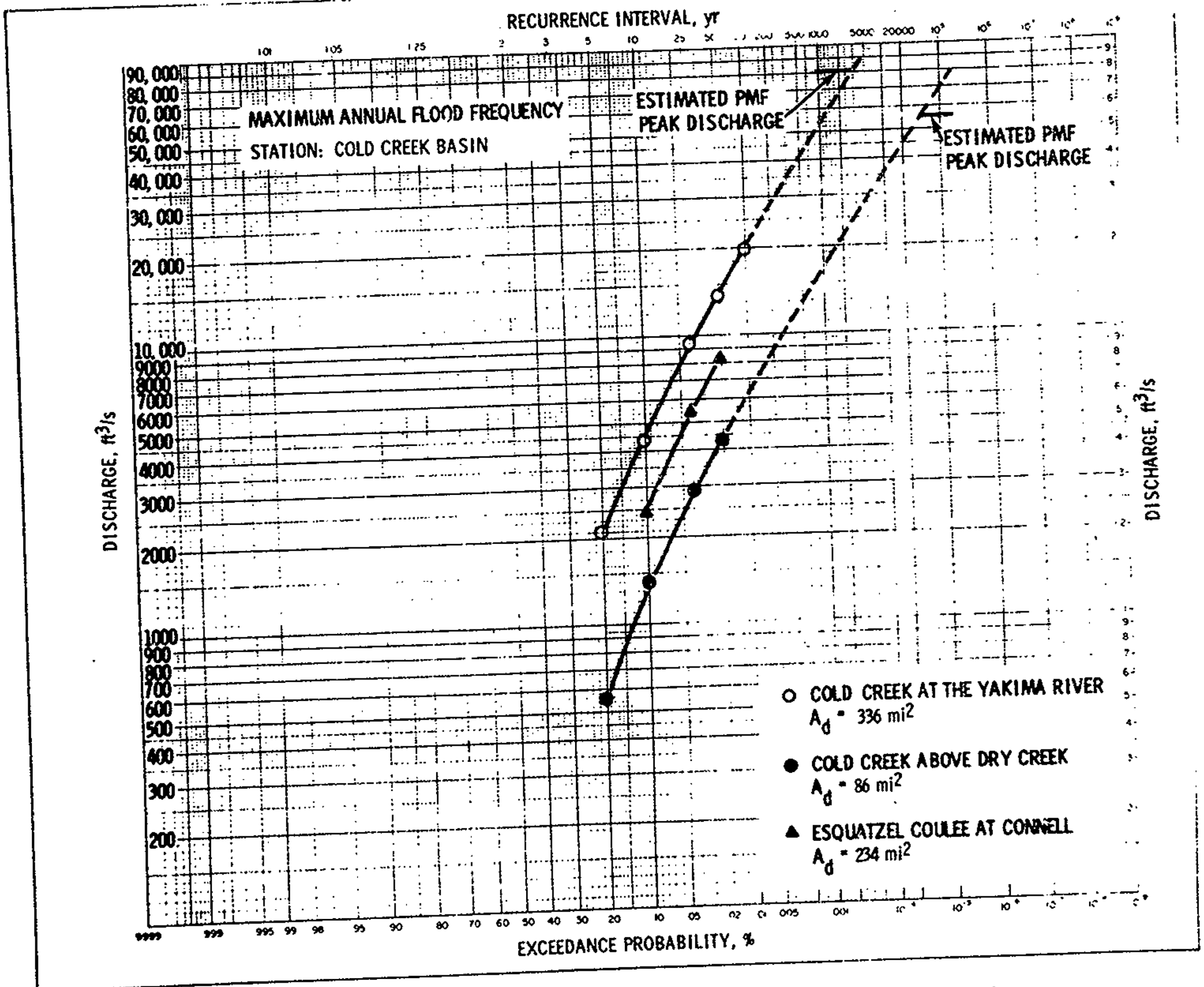

FIGURE 8. Maximum Annual Flood Frequency: Cold Creek Basin

In developing the PMF for Cold Creek, the Cold Creek watershed was hypothetically subjected to the PMP, the estimated depth and duration of precipitation occurring over the Cold Creek watershed at a given time of year for which there is virtually no risk of exceedance. Given this precipitation event, which approximates the maximum physically possible, the initial abstractions and infiltration losses were subtracted to determine the amount of direct runoff, and the discharge hydrograph was generated. Descriptions of the procedures for doing this follow.

PMP Determination

The PMP for the Cold Creek Basin was developed at Locations 1 and 2 using procedures developed by the U.S. Weather Bureau (1966). As discussed in the U.S. Weather Bureau report, PMPs east of the Cascade Range can occur as general storms of durations up to 72 hr throughout the months of October through June or for smaller basins as thunderstorms of shorter durations.

The storm that would produce the general PMP is characterized as having precipitation centers largely dependent on both orography and convergence processes in the atmosphere. The general storms are typically a source of broad-scale vertical motions and precipitation that move inland from the Pacific Ocean. Within the storms, general areas of precipitation correspond to frontal storms. On a smaller scale, instability of thunderstorms is an important aspect of many such storms. In addition to the above, referred to as convergence precipitation, precipitation also occurs due to orographic lifting on mountain slopes. Slopes lift the inflowing moist air causing adiabatic cooling. This reduces the air's capacity to hold moisture, and precipitation results. The first slopes encountered by moist air currents are the most effective in producing precipitation. However, secondary ridges become more important as the distance between ridges increases. In addition, some areas east of the Cascades can utilize moisture inflow from several directions, including the southeast and northwest, depending on the direction of slope faces.

Using the procedures presented by the U.S. Weather Bureau (1966), the general storm PMP for the Cold Creek Basin at Location 1 was computed for each of the months of October through June. The maximum precipitation was computed to occur in a storm during the month of June, producing a 3-day total of 12.43 in. and having a maximum 6-hr rainfall of 4.52 in.

The U.S. Weather Bureau report also discusses intense local summer thunderstorms for small basins east of the Cascades that exceed the potential from general storms (e.g., the 4 in. of precipitation in 30 min reported at Girds Creek, Oregon, July 13, 1956).

Generally, even though the highest monthly rain east of the Cascades can occur during the winter, summer months contain the highest daily values characterized by short duration intense local rainfall. This climatic trend is explained in part by the influence in summer of Gulf of Mexico moisture.

The U.S. Weather Bureau procedures developed for computing the general storm PMP did not include thunderstorms in their development, thus separate procedures were provided. Based on these procedures, the 6-hr PMP thunderstorm for Location 1 was computed to be 7.30 in. During the general storm PMP, the maximum 6-hr as previously discussed, was only 4.52 in. Almost 18 hr would be required for an amount of rain comparable to the thunderstorm PMP to fall during the general storm PMP. Hence, it is clear the thunderstorm rainfall, having a much greater intensity, would produce a higher peak discharge.

In applying summer thunderstorms to a specific basin, an important consideration is the manner in which PMP amounts decrease with increasing drainage area. The procedures presented by the U.S. Weather Bureau report are consistent with this concept as seen in the results of the thunderstorm PMP computations for Location 2. There is a marked reduction in precipitation depths for the larger drainage area. The storm rainfall time distributions for the two locations are presented in Table 4.

TABLE 4. PMP Thunderstorm Time Distributions

Location	Drainage Area (mi^2)	Incremental Rainfall Amounts (in.) Duration (hr) 1	2	3	4	5	6	Summation
(1) Upper Cold Creek (above Dry Creek)	86	0.4	1.4	3.9	0.7	0.5	0.4	7.30
(2) Lower Cold Creek (at the Yakima River)	363	0.2	1.1	2.3	0.5	0.3	0.2	4.60

Rainfall/Runoff

Direct runoff for the PMP thunderstorms at the two locations was estimated using the Soil Conservation Service curve number approach presented by the U.S. Bureau of Reclamation (1977). In this method the complex processes of interception, depression storage, and infiltration are lumped into a single initial abstraction. The method correlates rainfall and direct runoff as a function of soil type, land use, and hydrologic condition. Relations derived from test plot and watershed runoff data are referred to as curve numbers. The curve numbers vary in value from 0 to 100 where 0 indicates for a given amount of rainfall no runoff will occur, while for a curve number of 100 all of the rainfall will runoff. For a thunderstorm PMP in the geographic region in which Cold Creek is located having a sage or grass ground cover, the recommended curve number is 85. This value is conservative and accounts for the effects of high rainfall intensity that tend to decrease the amount of infiltration. Assuming less extreme rainfall intensity, the recommended curve number value for the Cold Creek soils and cover would be 64. For the 7.3-in. rainfall computed for Location 1, the lower curve number would change the runoff from 5.55 to 3.24 in., a reduction of over 40%. The accumulative runoff amounts computed for the two locations are presented in Table 5.

TABLE 5. PMP Thunderstorm Direct Runoff

Location	Time (hr)	Accumulative Rain (in.)	Accumulative Runoff (in.)
(1) Upper Cold Creek (above Dry Creek)	0	0.0	0.0
	1	0.4	0.001
	2	1.8	0.66
	3	5.7	4.03
	4	6.4	4.69
	5	6.9	5.17
	6	7.3	5.55
(2) Lower Cold Creek (at the Yakima River)	0	0.0	0.0
	1	0.2	0.0
	2	1.3	0.33
	3	3.6	2.11
	4	4.1	2.56
	5	4.4	2.83
	6	4.6	3.01

PMF Hydrograph Development

The approach used to compute hydrographs resulting from the PMP thunderstorm hourly direct-runoff amounts shown in Table 5 was the unit graph method. Since the Cold Creek watershed is ungaged, a procedure for developing unit graphs without benefit of observed hydrographs was required. Hence, a triangular unit graph procedure developed by the Soil Conservation Service and presented by the U.S. Bureau of Reclamation (1977) was employed. The procedure relates the time-to-peak of the unit graph to the time of concentration of the watershed, where the time of concentration of the hydrograph is a function of watershed characteristics. The resulting unit graphs for Locations 1 and 2, shown in Figure 9, have peaks of 30,000 and 13,000 ft^3/s, respectively. Applying these unit graphs to the runoff values in Table 5, discharge hydrographs were computed (Figures 10 and 11). The peak discharges for Locations 1 and 2 were 55,000 and 80,000 ft^3/s, respectively. Time-to-peaks for the two hydrographs are 5-1/2 hr and 8 hr, respectively. By extrapolating the frequency curves in Figure 8, a conservative estimate of the return period for the PMF peak discharges is greater than 4,000 yr. It should be noted this value is for qualitative evaluation only since, by the strictest interpretation of the PMF definition, its probability of occurring approaches zero.

Hydraulics

For purposes of analyzing flood risk, it is necessary to determine the stage-discharge relationships at critical locations along Cold Creek such as at the reference repository location or along Route 240. Given the stage-discharge relationships, they can be combined with discharge-frequency information to estimate elevation-frequency relationships at the selected locations. To determine these relationships for Cold Creek, the U.S. Army Corps of Engineers' HEC-2 Water Surface Profiles computer programs were used (U.S. Army Corps of Engineers, 1975).

HEC-2 computes water surface profiles for steady gradually varied flow by solving the one-dimensional energy equation with energy loss due to friction evaluated with Manning's equation. The computational procedure employed is generally known as the "Standard Step Method."

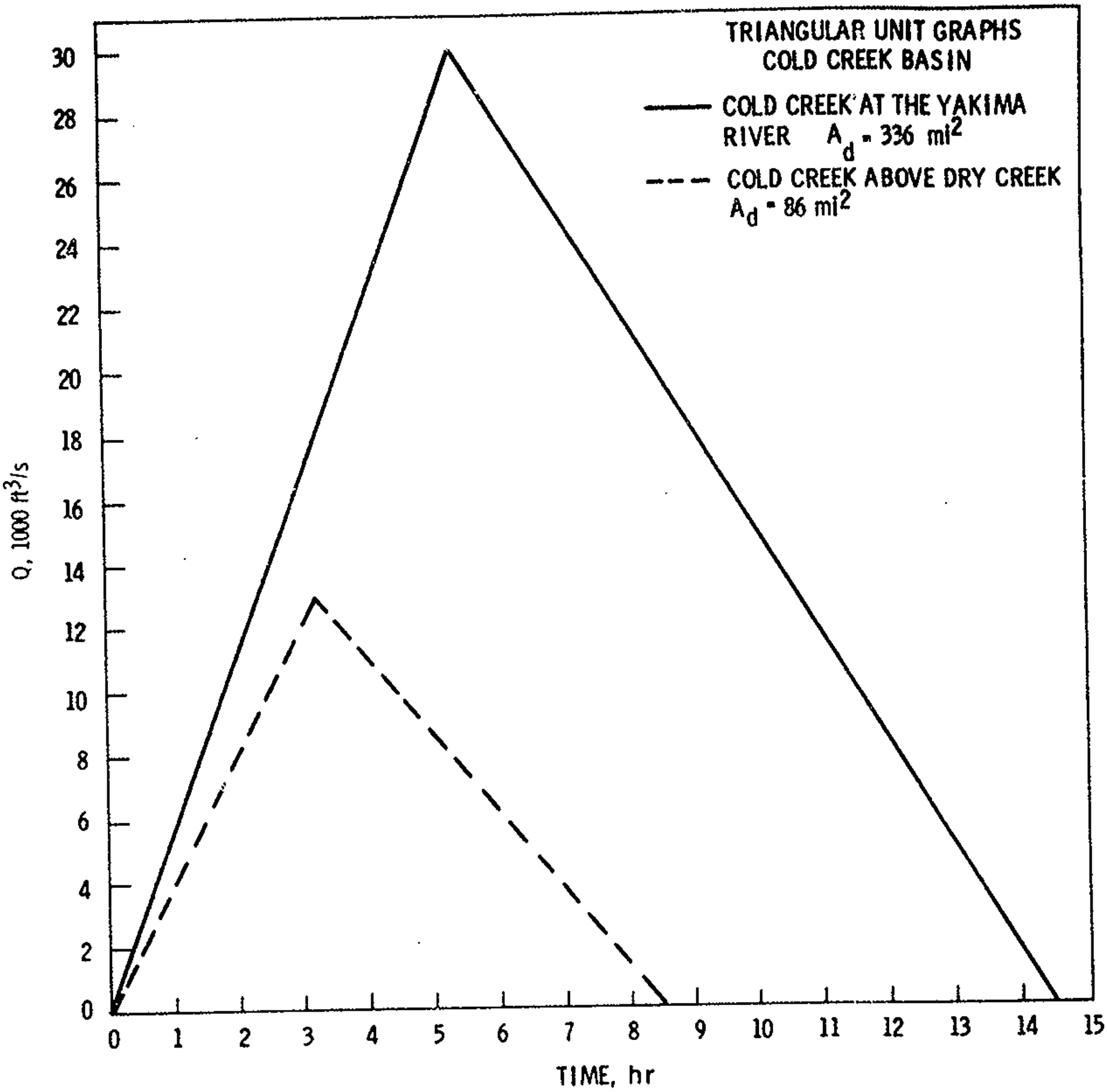

FIGURE 9. Cold Creek Triangular Unit Graphs

In computing the flow profile for a given discharge, several kinds of information are required by HEC-2, including channel cross sections and a continuous stream bed profile. Generally these data are obtained by a hydrographic survey or from a contour map of the channel bottom. However, for this study, due to the nature of the Cold Creek channel, a combination of these two approaches was employed. Using areal photography and U.S. Geological Survey topographic maps, transects of hydraulic control were identified and located. Based on field observations, it was then determined whether to obtain the cross sections from the topographic maps, from field surveys, or both.

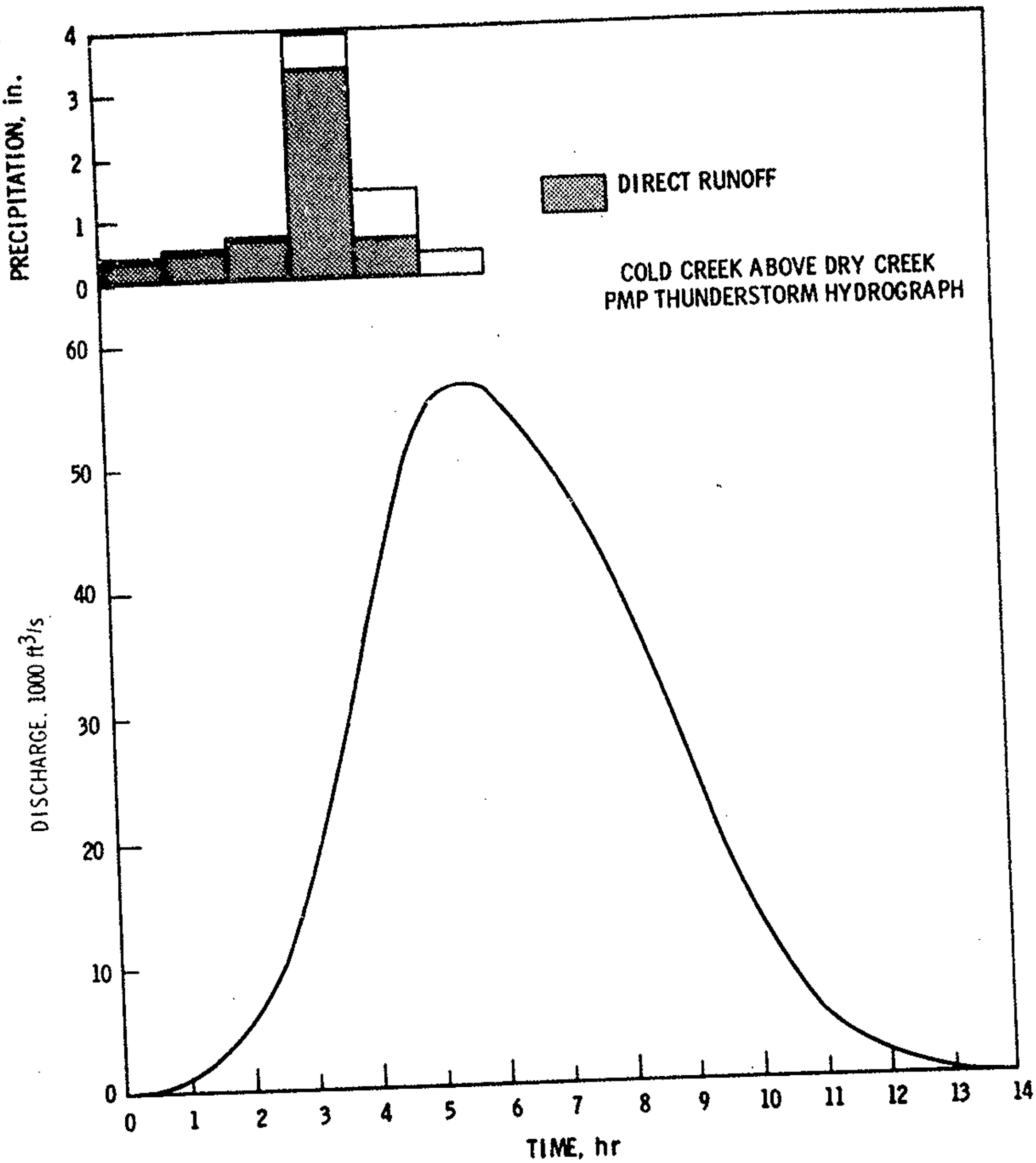

FIGURE 10. PMP Thunderstorm Hydrograph: Location 1, Upper Cold Creek

In general, the Cold Creek cross sections consist of small, intermittent, low flow channels 30 to 50 ft wide superimposed on the wide, rectangular-shape floodplain that varies from 750 to 12,000 ft wide. Due to these characteristics, in most instances information obtained from the topographic maps was ade quate. However, in a few instances locations were identified in the field wh there was sufficient variation that all or part of the section required a

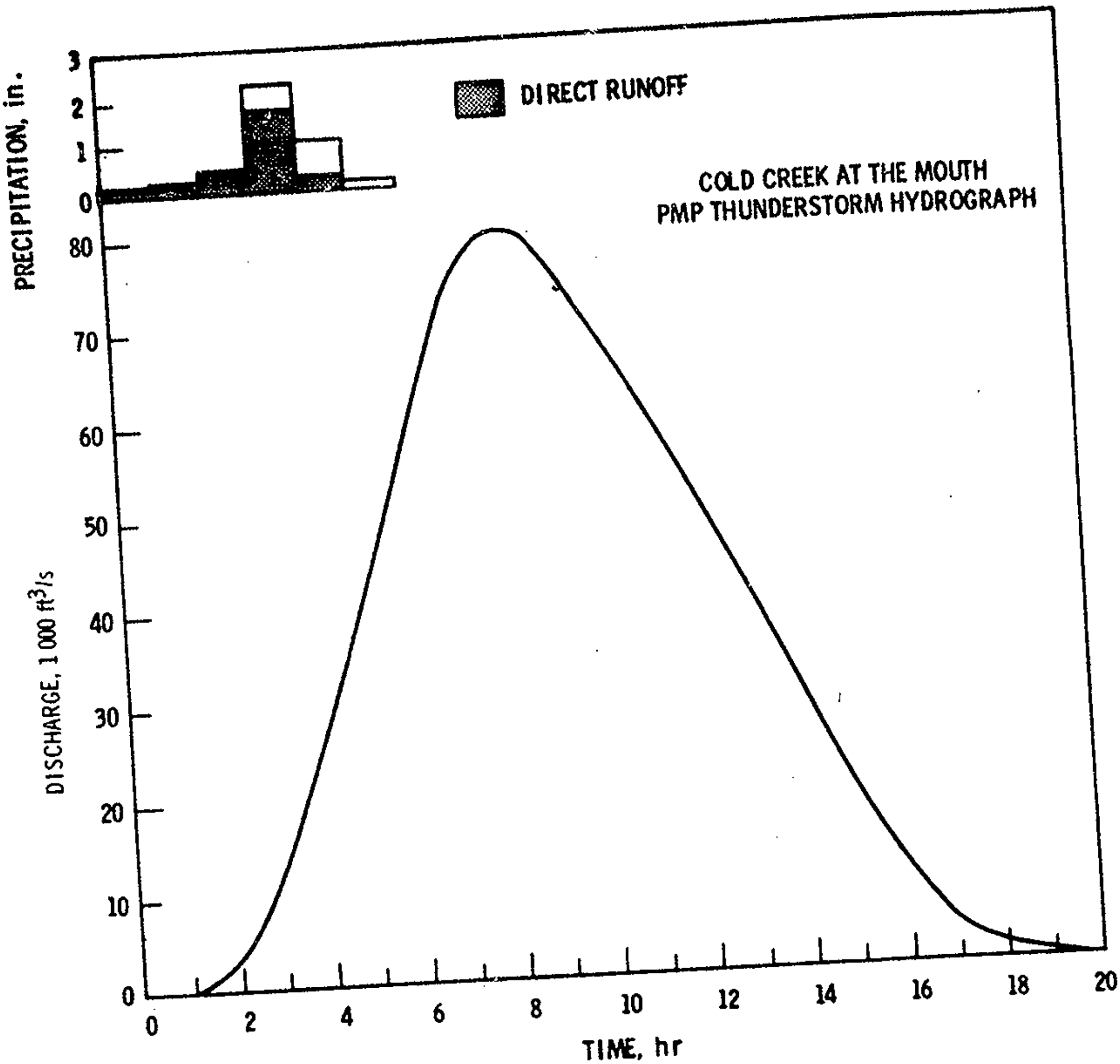

FIGURE 11. PMP Thunderstorm Hydrograph: Location 2, Lower Cold Creek

field survey. Plots of the cross sections used in the study are included in the Appendix. The subsections surveyed in the field are identified on the individual cross section plots.

A total of 15 cross sections were used in the hydraulic analysis. Locations are shown in Figure 12. On the average the sections are about 1.5 mi apart. The roughness coefficient used for the hydraulic analysis was a Manning's "n" value of 0.07, the upper limit of recommended values for floodplain areas covered by scattered brush and heavy weeds (Simons and Senturk, 1976). The downstream control used was the overflow section of the Hanford Road assuming the box culvert underneath the road was completely clogged with debris.

For each water surface profile computed, the flow distribution used assumed constant flow from the downstream control section up to the confluence of Dry Creek. The discharge for this reach was that computed at the mouth of Cold Creek. Upstream of the confluence, a constant flow equivalent to the Cold Creek discharge above Dry Creek was assumed.

RESULTS: INTERPRETATION AND EVALUATION

INTERPRETATION

The results of the hydraulic analysis are shown in Figures 12 and 13. The flooded area of the PMF peak discharge is illustrated in Figure 12. Generally the flooded area is contained within the valley floodplain previously described. The flooded area extends over about 3.5 mi^2 of the western end of the reference repository location. The water surface profile of the PMF peak discharge presented in Figure 13 indicates the maximum depth of inundation at the cross section taken at mile 17.08, which traverses the southwestern corner of the reference repository location, is about 7.7 ft. Along the cross section at mile 15.54, just south of the reference repository location, the maximum inundation would be about 22 ft. This increase in depth is probably attributable to the abrupt narrowing and deepening of the valley at this point.

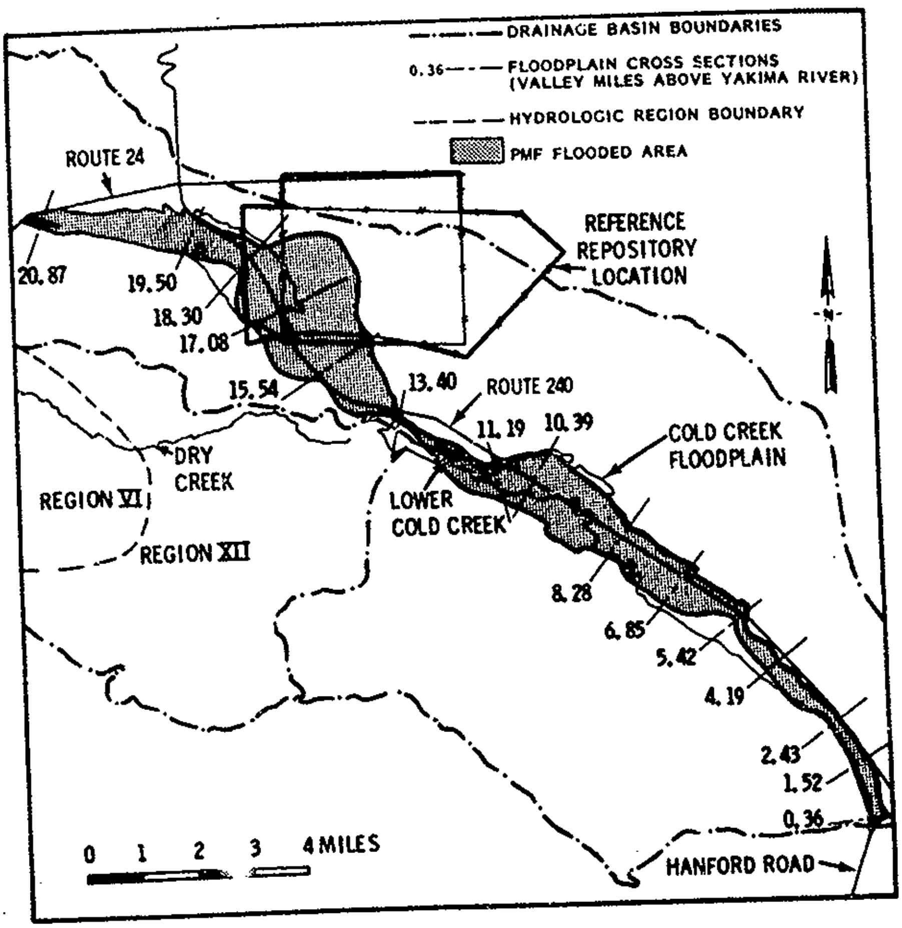

FIGURE 12. Cold Creek PMF Flooded Area

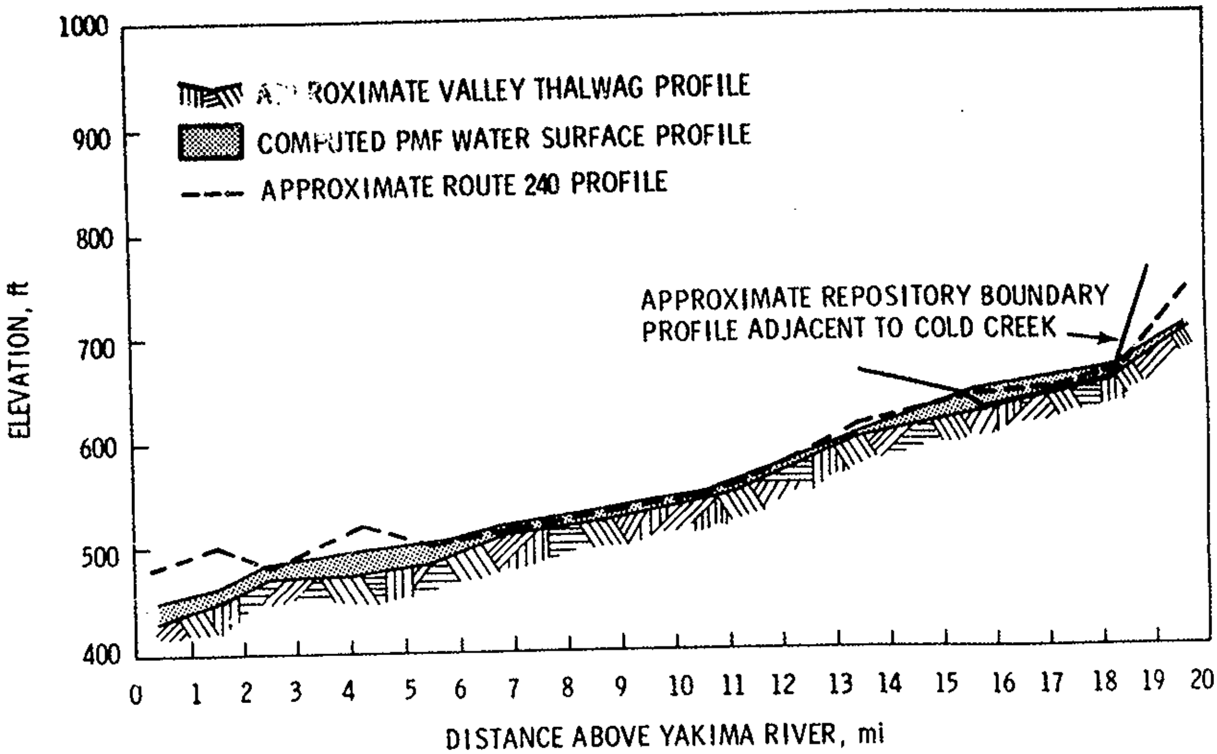

FIGURE 13. Cold Creek Computed PMF Water Surface Profile

An approximate stage-frequency curve for Cold Creek at mile 15.54 is shown in Figure 14. This curve was constructed by extrapolating from the computed 100-yr stage to the computed PMF stage which was plotted at the return period estimated from Figure 8. This rough approximation shows that at the lowest point of the reference repository location surface relative to flow depth, flooding to depths of 5 ft will occur on the average once in every 200 yr.

Relating to another aspect of reference repository location safety against flooding, a significant portion of Route 240 will be under water during the Cold Creek PMF (as shown in Figure 13). This will prevent access to the site along this route. Though surrounding areas would experience greater than normal rainfall during the Cold Creek PMF, it seems extremely unlikely that Route 240 north of the Yakima Barricade would be affected. There is also access from the east on a number of routes that probably would not be flooded simultaneously with Route 240. Therefore, the loss of Route 240 may be significant but not critical.

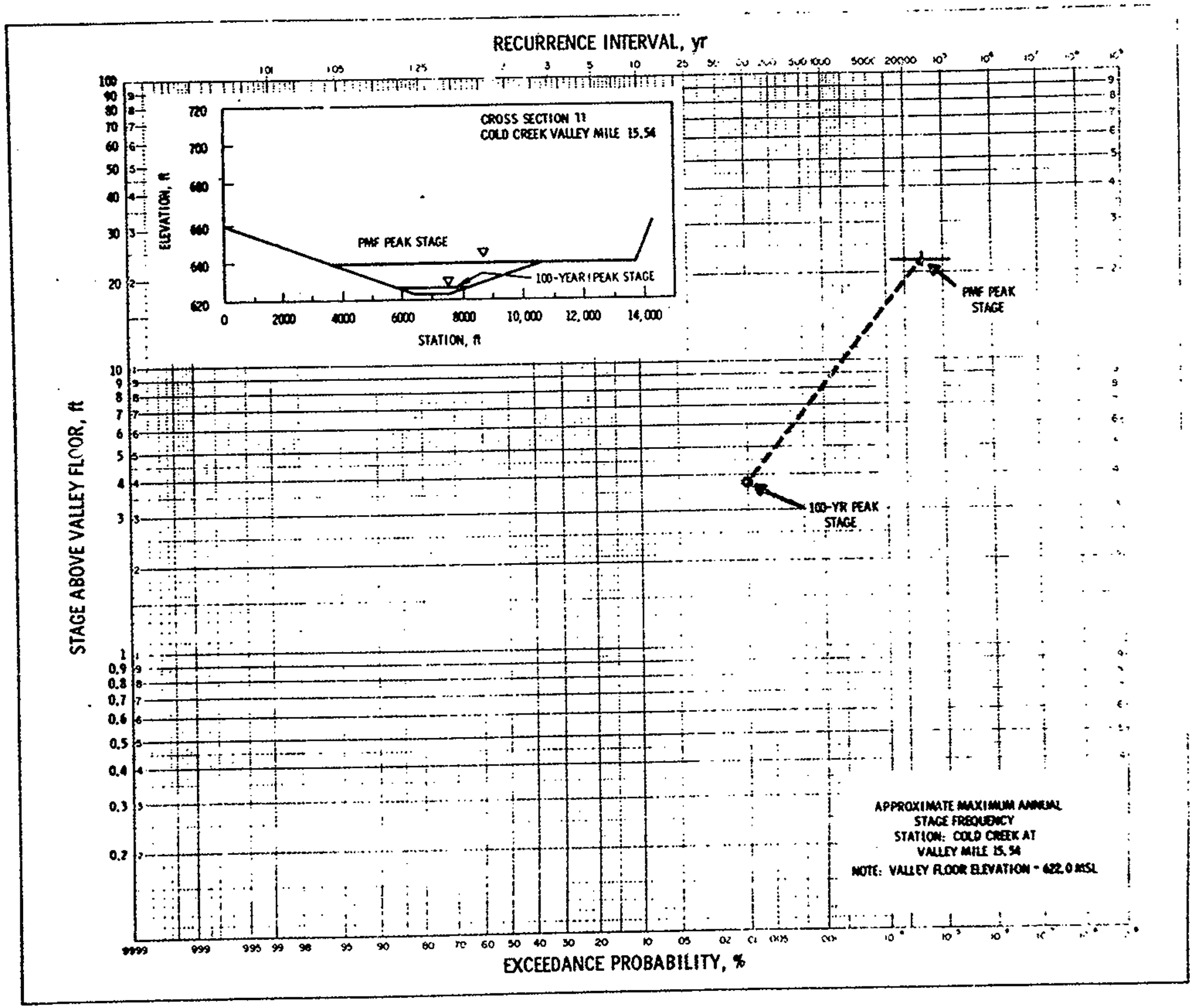

FIGURE 14. Estimated Maximum Annual Stage Frequency: Cold Creek Mile 15.54

Finally, flood flows of the magnitude of the PMF will cause significant floodplain erosion along its pathway and completely change the present channel size and shape. A flood flow with a peak 55,000 or 80,000 ft^3/s will require a much larger channel size than presently available. An estimate of the required approximate channel width can be estimated by the use of Lacey's regime equations as described by Neill (1973). Graphs of the Lacey equations are shown in Figure 15. These equations were developed from a large number of measured data points and are used by hydraulic engineers as a guide to estimating a suitable width of a waterway opening under a bridge. The equations are based on measurements of the top bank width of self-adjusting alluvial channels for both river and canal. The upper curve of Figure 15 is more applicable to shifting channels in sandy material, while the lower curve is applicable to relatively stable channels in more scour-resistant materials. The upper curve would be more appropriate for the Cold Creek system downstream of Route 24. Based on the curves of Figure 15 the channel width required for a discharge of 55,000 ft^3/s is 700 ft and 800 ft for a discharge of 80,000 ft^3/s. These widths should be considered as upper limits since the channel-forming discharge would be slightly less than the peak values due to their relatively short duration. However, they do provide reasonable estimates of channel scour limits.

EVALUATION

One idea kept in mind throughout the performance of this study was that the results obtained would be used as the basis for preliminary design of flood protection measures and estimating potential flood risks at the reference repository location; therefore, these results should be "conservative" from the standpoint that if bias is introduced, the bias would result in higher-than-actual computed stages for a given discharge. Therefore, a number of assumptions were made. Perhaps the most conservative of these was the manner in which the flow distributions were developed for the hydraulic analysis For example, in computing the PMF water surface profile, the flow used above Dry Creek was the Cold Creek PMF discharge of 55,000 ft^3/s that was computed for the 86 mi^2 above the confluence. The flow in the reach downstream of the confluence was the Cold Creek PMF discharge of 80,000 ft^3/s computed for

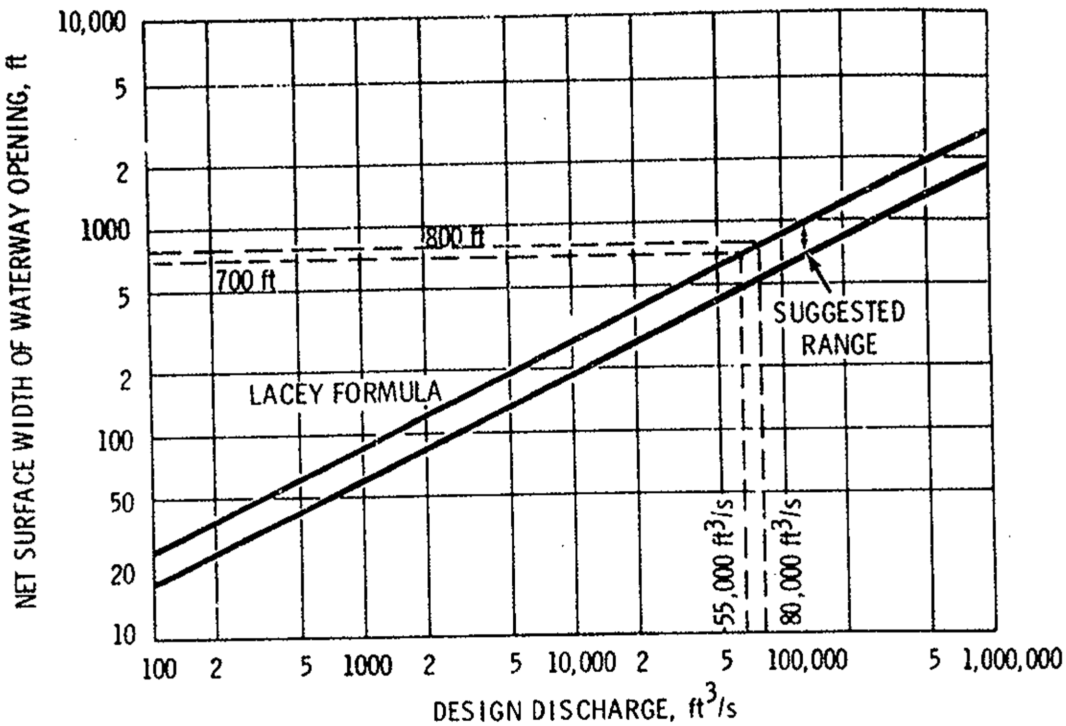

FIGURE 15. Estimate of Cold Creek Flood Channel Width Using Lacey's Regime Equations (Neill 1973)

the 335 mi^2 above the Yakima River. Inherent in using this flow distribution is the assumption that the PMF on the 86 mi^2 drainage area occurs simultaneously with the PMF on the entire watershed. During a PMP over the 86 mi^2, undoubtedly heavy rainfall would occur over the Dry Creek drainage and the area downstream. However, it is not likely the rainfall would be of PMP proportions. Therefore, higher flows were assumed in the channel downstream of the site than would probably occur, resulting in greater computed backwater effect. This in turn produced higher computed stages at the reference repository location.

A factor ignored in the analysis is the effect of channel seepage in reducing flows. There is considerable evidence that under normal flow conditions, runoff originating in the headwaters of Cold Creek infiltrate into the channel alluvium before reaching the confluence of Dry Creek. Similarly, the flows originating in Dry Creek are greatly reduced before reaching the Yakima River. Under conditions where channel seepage is not appreciable, there is a distinct increase in channel size with increasing contributing drainage area as you move along the channel in the downstream direction. In Cold Creek, however, the normal flow channel is intermittent, disappearing at about mile 10.0, reappearing again at mile 5.0, and gradually decreasing in size near the mouth.

Another area in which conservatism was introduced into the study results was in selecting the roughness coefficient for the hydraulic analysis. As discussed in an earlier section, a Mannings "n" value of 0.070 was used. The range of values recommended by Simons and Senturk (1976) for conditions similar to the Cold Creek floodplain varied from 0.035 to 0.070. To provide a measure of the sensitivity of study results to the roughness coefficient, the assumed value was increased 20% to a value of 0.084. This resulted in an increase in the computed stage at the reference repository location site of about 1 ft. Under flood flow conditions in Cold Creek, the brush and cheatgrass along the floodplain will most likely be washed out or, at the very least, flatten to the point of reducing floodplain roughness. Therefore, it is highly unlikely the actual roughness coefficient could be greater than 0.070 ft and even if it were 20% higher, stages would not be significantly increased.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study show the present day Cold Creek system consists of two discontinuous segments: 1) upper Cold Creek that directly impacts on the reference repository location, and 2) the lower Cold Creek channel that includes flow from Dry Creek. A PMF flow would connect the channel segments creating a wide and shallow braided stream channel. The flood would inundate an area of the southwestern corner of the repository site of approximately 3.5 mi^2. A preliminary estimate of maximum elevations for which flood protection would be required is approximately 645 ft MSL from Cold Creek Valley miles 15.0 to 18.0 (disregarding wind waves or runup). The duration of the PMF or other floods of sufficient magnitude to inundate a major portion of the reference repository location surface would be of short duration and would present no danger to below ground facilities. However, the sediment transport rate would be very high and where valley slope decreases abruptly, such as it does just above the southwest corner of the reference repository location, extensive quantities of sediment would deposit. The flow would be expected to overtop and/or breach the Route 240 roadbed as well as produce localized areas of both scour and deposition within the repository boundaries. Loss of Route 240, however, does not present a critical problem since it is unlikely that access from the north and east would be simultaneously impaired. These results may be considered to represent a highly conservative case.

The major limitation of the study results is the heavy reliance placed on the use of U.S. Geological Survey topographic maps in developing the channel geometry information that was used in the hydraulic analysis. The best available map was a 1951 edition with a 1:62,500 scale and 20-ft contour intervals. While a field survey was performed, due to the areal extent of the PMF (approximately 20 mi by 1 to 2 mi), a detailed survey over the entire area was not feasible. It is felt that the results of the study are sufficiently accurate to provide the preliminary information required in the site characterization report; but, if actual design of flood protection measures is necessary at some point in the future, the study results should be refined using more detailed channel geometry data. The most practical means of obtaining this data would be to use low-level aerial photographs in developing a 2-ft contour interval topographic map of the floodplain.

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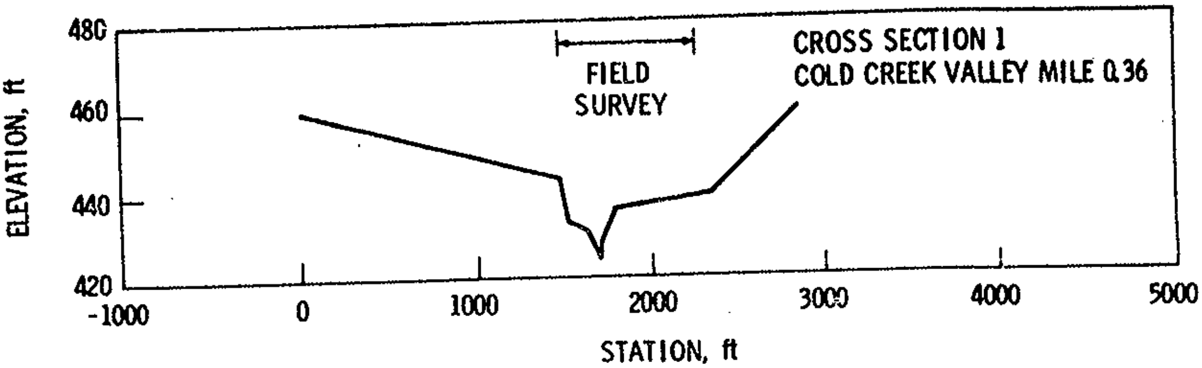
APPENDIX

COLD CREEK CHANNEL CROSS SECTIONS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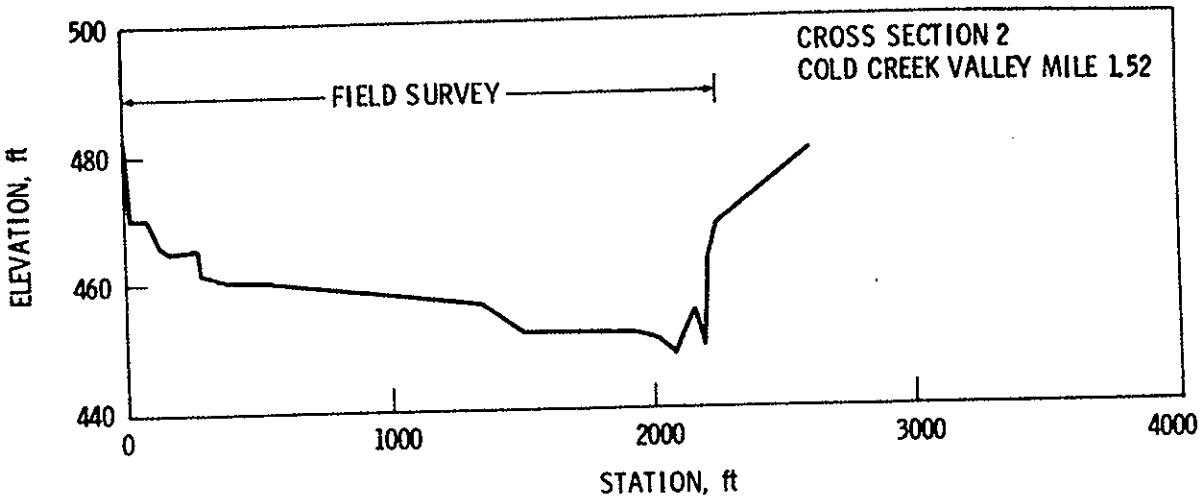
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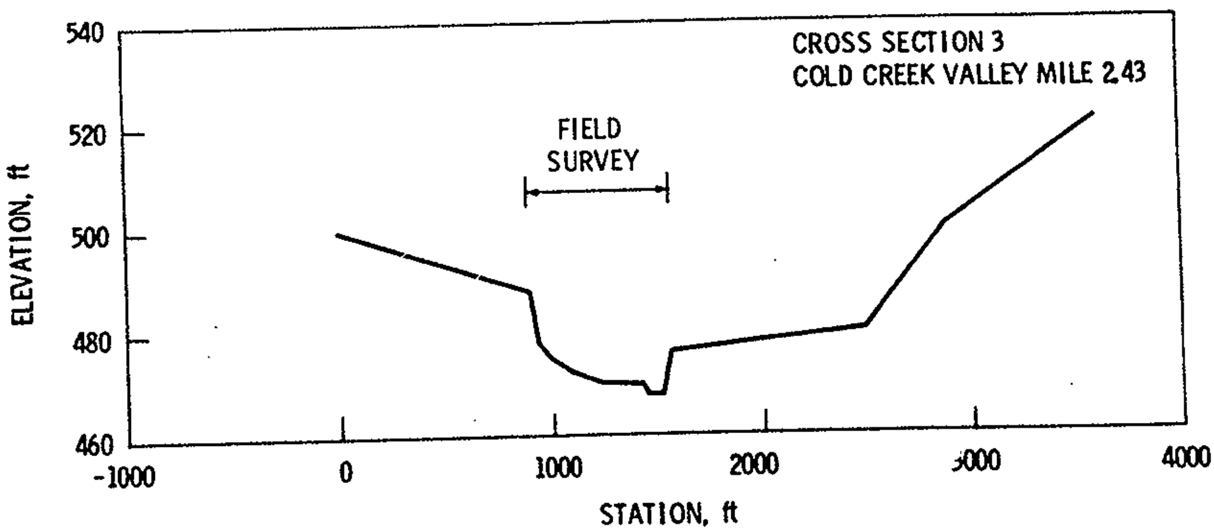
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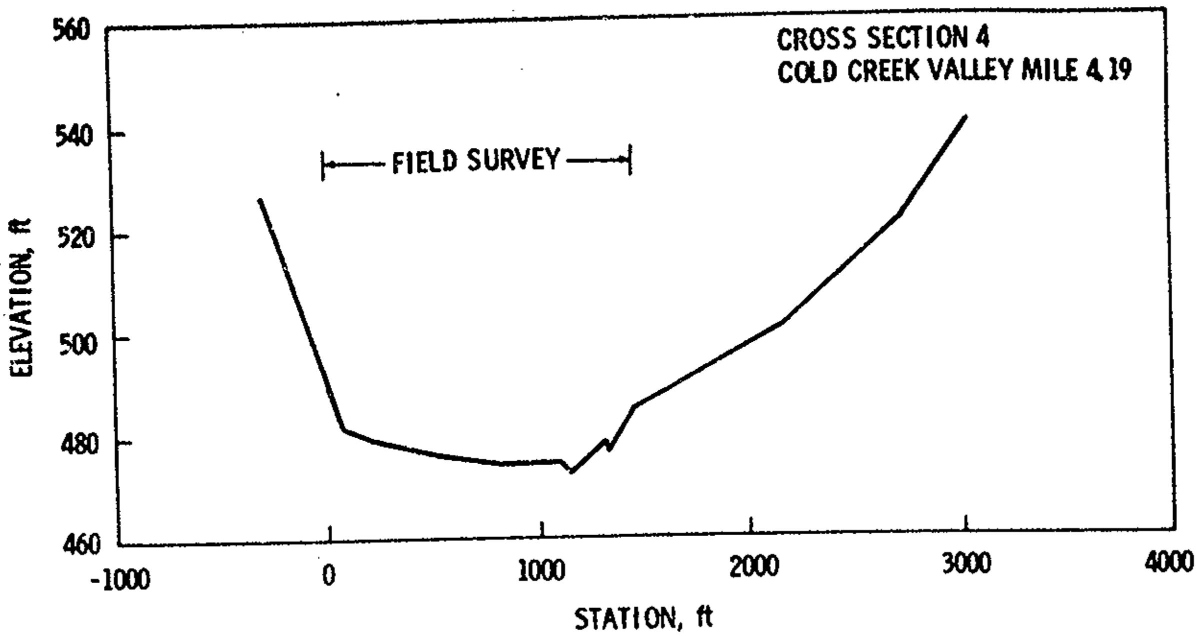
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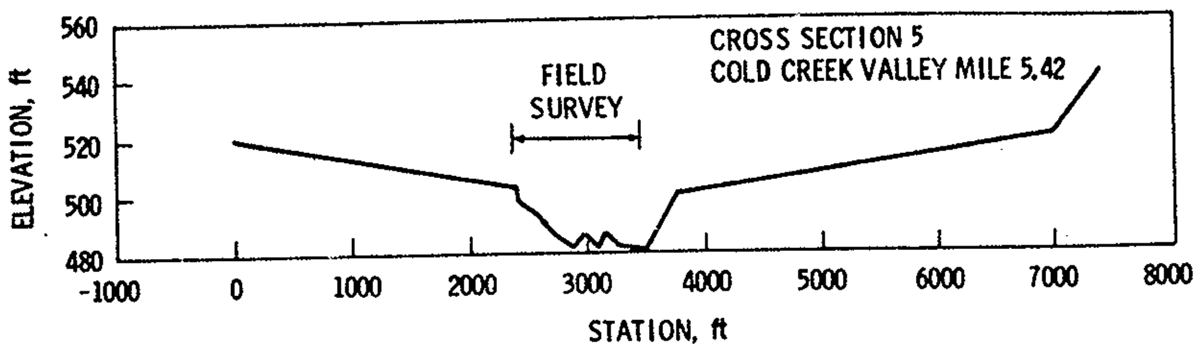
STATION, ft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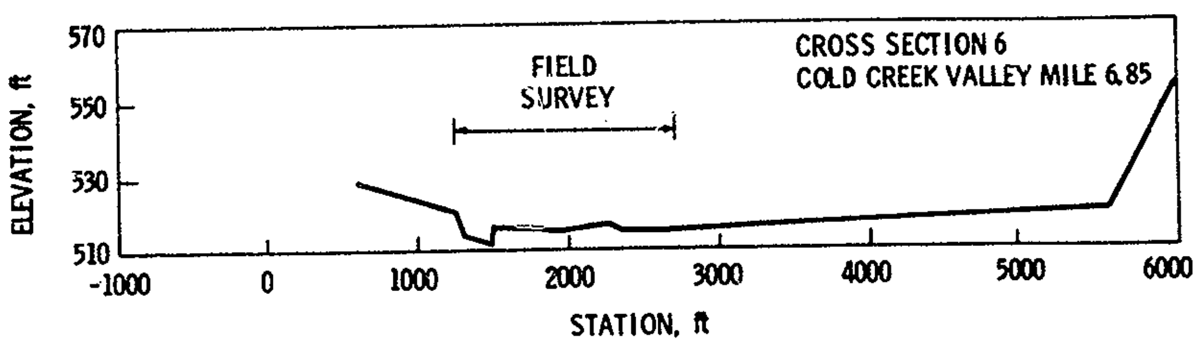
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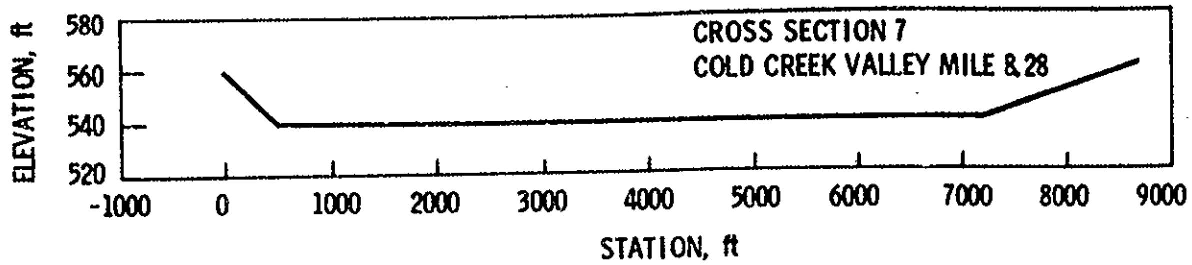
STATION, ft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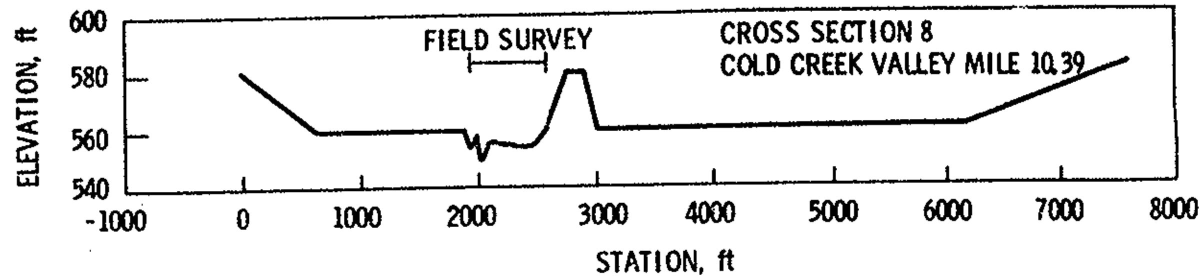
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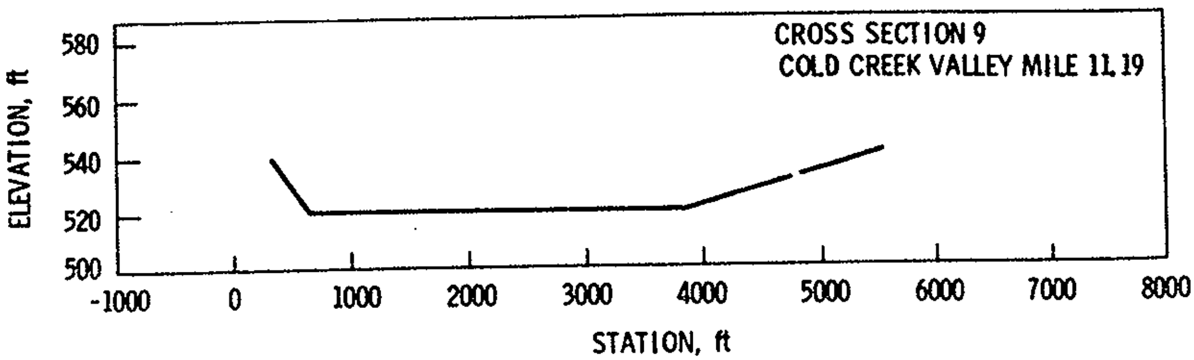
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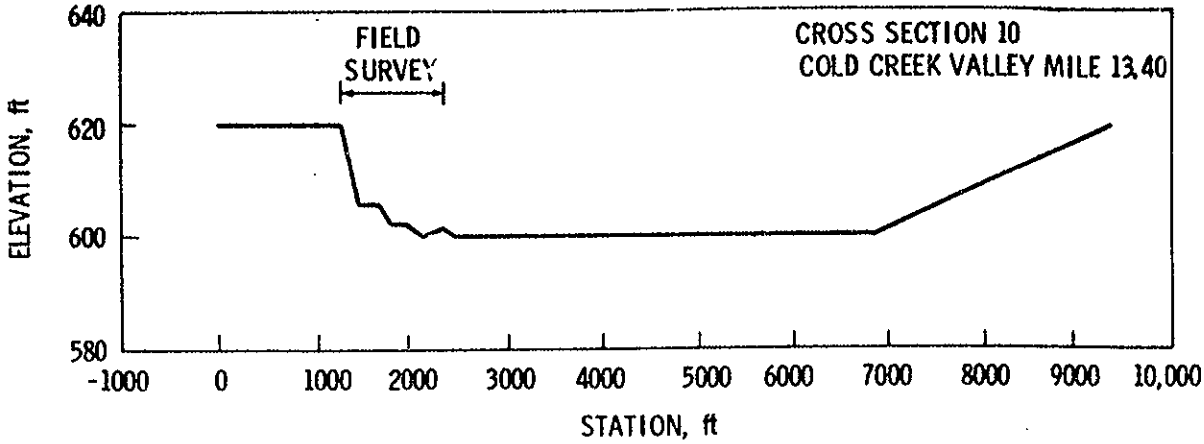
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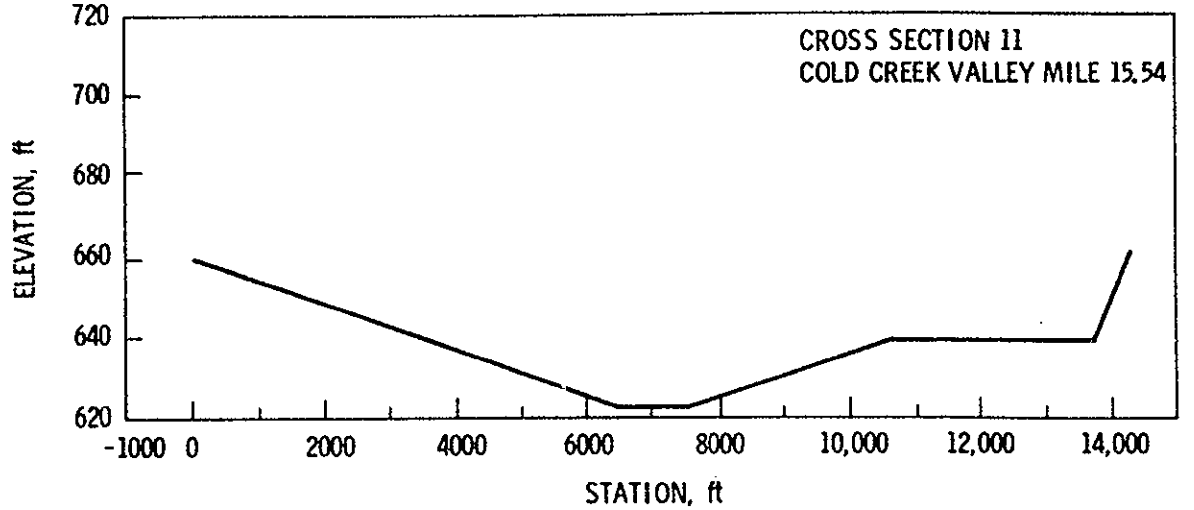
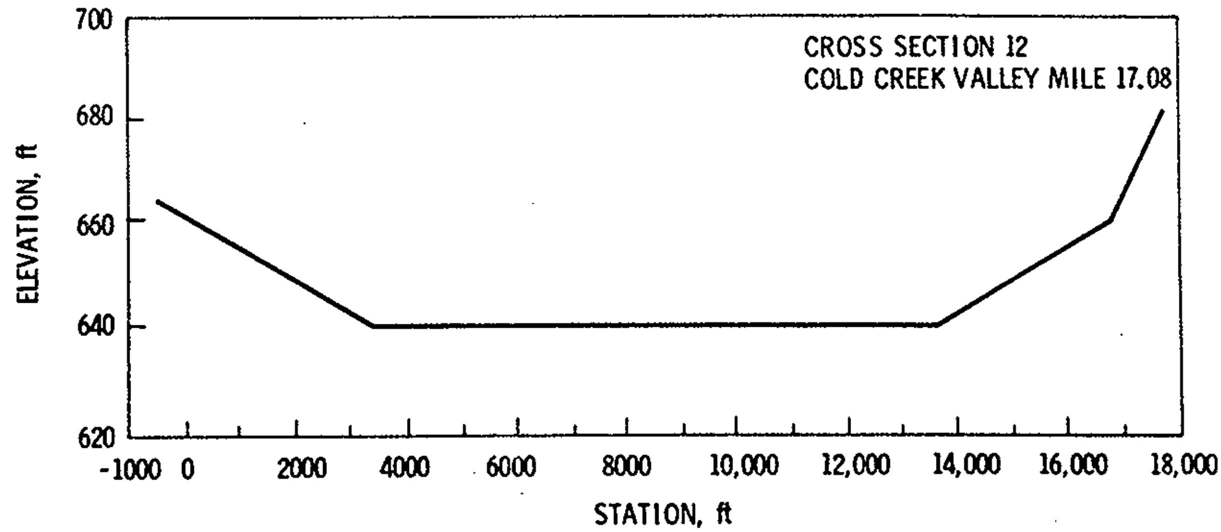
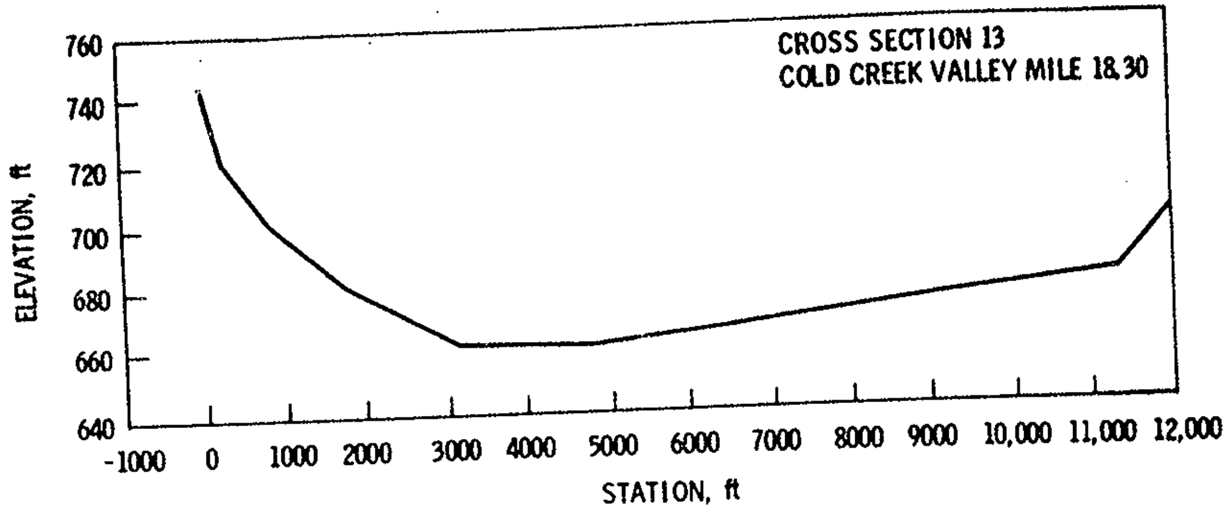
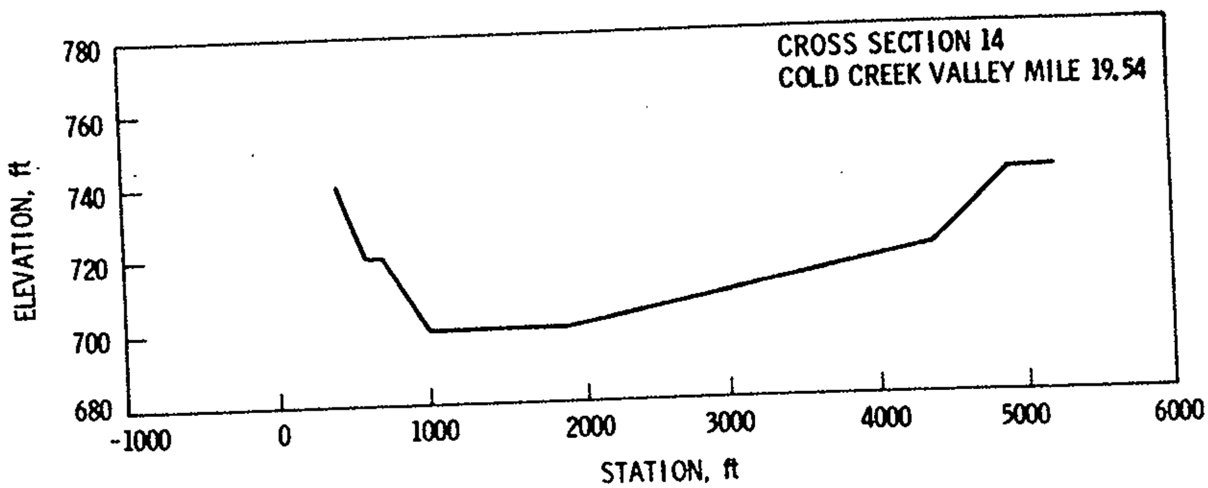
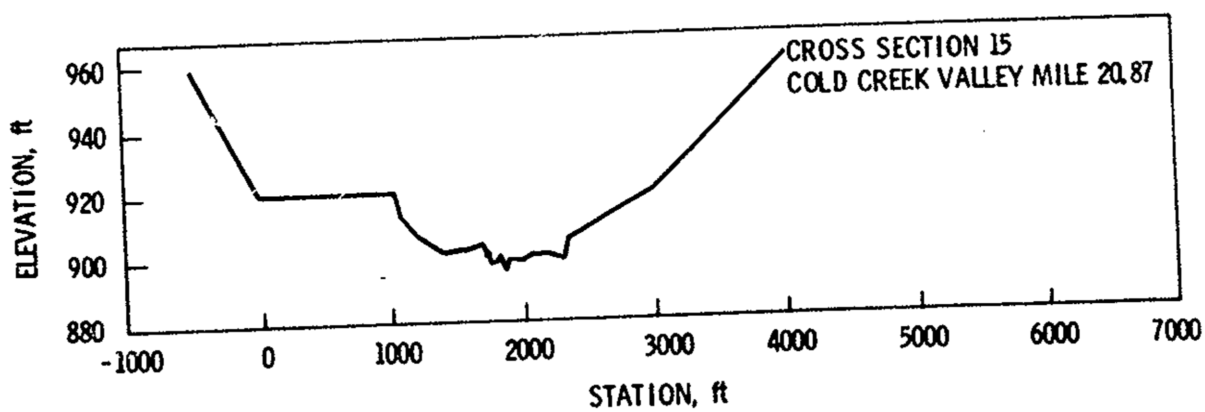
10,000
STATION, ft


CROSS SECTION 11
COLD CREEK VALLEY MILE 15.54
ELEVATION, ft
720
700
680
660
640
620
-1000
0
2000
4000
6000
8000
10,000
12,000
14,000
STATION, ft


CROSS SECTION 12
COLD CREEK VALLEY MILE 17.08
ELEVATION, ft
700
680
660
640
620
-1000
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000
18,000
STATION, ft


CROSS SECTION 13
COLD CREEK VALLEY MILE 18.30
ELEVATION, ft
760
740
720
700
680
660
640
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
11,000
12,000
STATION, ft


CROSS SECTION 14
COLD CREEK VALLEY MILE 19.54
ELEVATION, ft
780
760
740
720
700
680
-1000
0
1000
2000
3000
4000
5000
6000
STATION, ft


CROSS SECTION 15
COLD CREEK VALLEY MILE 20.87
ELEVATION, ft
960
940
920
900
880
-1000
0
1000
2000
3000
4000
5000
6000
7000
STATION, ft

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