NOAA Technical Report NWS 36

Water Available for Runoff for 1 to 15 Days Duration and Return Periods of 2 to 100 Years for Selected Agricultural Regions in the Northwest United States

Silver Spring, Md.
April 1983

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

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(Continued on inside back cover)

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Water Available for Runoff for 1 to 15 Days Duration and Return Periods of 2 to 100 Years for Selected Agricultural Regions in the Northwest United States

F. Richards, J.F. Miller, E.A. Zurndorfer, and N.S. Foat

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John V. Byrne, Administrator

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Richard E. Hallgren, Acting Assistant Administrator

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ACRONYMNS

A_i, A_j — weights used in calculation of duration interpolation formulas

H — elevation (ft)

L_f — latent heat of fusion (7.5 in. melt/in. condensate)

M — amount of melt (in.)

MAP — mean annual precipitation (in.)

MFMAX — maximum melt factor (in./(12 hr °F))

MFMIN — minimum melt factor (in./(12 hr °F))

NMFMAX — maximum negative melt factor (in./(12 hr °F))

NOAA — National Oceanic and Atmospheric Administration

NWS — National Weather Service

NWSRFS — National Weather Service River Forecast System

P — pressure (in. of H_g)

Q_e — latent heat transfer due to condensation (in./12 hr)

Q_h — sensible heat transfer (in./12 hr)

Q_n — net heat transfer due to radiative processes (in./12 hr)

Q_r — heat transfer by rainwater (in./12 hr)

RMS — root mean square

SCS — Soil Conservation Service (U.S. Department of Agriculture)

T_A — air temperature (°F)

$T_{A_{max}}$ — daily maximum air temperature (°F)

$T_{A_{min}}$ — daily minimum air temperature (°F)

T_d — "daytime" air temperature (°F)

T_I — antecedent temperature index (°F)

T_n — "nightime" air temperature (°F)

T_s — snow surface temperature (°F)

W_i, W_j, W_n — WAR amounts for i-, j-, and n-day durations (in.)

$W_{i,j}$ — WAR amounts for i-yr return period and j-day duration (in.)

WAR — water available for runoff (in.)

WE — water equivalent (in.)

X_i — independent variables (i = 1,2....12) in regression equations used to aid analysis in data sparse areas (see Appendix D, table D-1).

σ — Stefan-Boltzman constant (5.51×10^{-11} in./day °F)

WATER AVAILABLE FOR RUNOFF FOR 1 TO 15 DAYS DURATION AND RETURN PERIODS OF 2 TO 100 YEARS FOR SELECTED AGRICULTURAL REGIONS IN THE NORTHWEST UNITED STATES

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ABSTRACT--Through adaptation of the National Weather Service River Forecast System (NWSRFS) snow accumulation and ablation model, this study estimates the frequency of water available for runoff (WAR) from snowmelt and precipitation over selected agricultural areas in the northwest United States. The report outlines the adaptation, testing, and use of the NWSRFS model and presents maps of 1-, 5-, and 15-day WAR values for 2- and 100-yr return periods. Comparison of WAR-frequency estimates with previous precipitation-frequency values shows regions of substantial difference. As a byproduct of the analysis, model-derived water equivalent frequency estimates are also presented.

1. INTRODUCTION

Precipitation-frequency studies are available which depict the amount of precipitation likely to occur for various durations and return periods (Yarnell 1935; U.S. Weather Bureau 1953, revised 1955, U.S. Weather Bureau 1954; Hershfield 1961; Miller 1964; Miller et al. 1973). Such information is used for planning and design of hydrologic structures and for flood evaluation reports. This use of precipitation-frequency values assumes that the precipitation is immediately available for runoff or infiltration. There are, however, areas where a significant amount of the annual precipitation falls as snow and is accumulated in a snowpack. At some later time this stored water is released for runoff. The release will occur during warmer weather and may or may not be accompanied by precipitation. Depending upon the local climatology, this melt might come as one or more thaws during the winter, or the snowpack could continue to increase until spring. In either case, over a period of a few days, the melting snow could release greater amounts of water than any single precipitation event during the year. Since hydrologic structures must be designed to handle runoff no matter what the source, frequency of precipitation alone may be inadequate for design purposes.

U.S. Department of Agriculture, Soil Conservation Service (SCS) engineers have found that, in certain parts of the Northwest United States (fig. 1), comparison of runoff and streamflow with precipitation-frequency values indicated the latter did not appear to adequately account for the volume of observed runoff. This study is an attempt to quantify the water release from a snowpack for agricultural lands in the northwest United States. The following sections describe how available climatic records of precipitation and temperature data (at the stations listed in appendix A) were used as input to an adaptation of the National Weather Service River Forecast System (NWSRFS) snow accumulation and ablation model. The model output combined rainfall with snowmelt to enable determination of 1- to 15-day annual series of water available for runoff (WAR). These data were then fit to a Fisher-Tippett Type I distribution. The resulting frequency estimates are the basis for 2- and 100-yr, 1-, 5- and 15-day WAR maps included in appendix E. Although varying infiltration rates due to soil types and conditions, such as soil frost, are an important part of the total problem, they are excluded from this meteorological study. As a byproduct of the study, frequency estimates of model derived 1-day water equivalent values are presented in appendix C.

The present study is a sequel to a similar study for the Snake River Basin in Idaho (Frederick and Tracey, 1976). While the two studies differ in some details, they use the same basic snowmelt model and the same general approach. The present study areas are contiguous with the Snake River Basin. As a matter of convenience, WAR maps presented in appendix E also include the results from Frederick and Tracey (1976) for 2- and 100-yr, 5- and 15-day amounts. Durational and return period interpolation can be performed by applying the figures or formulas in section 7 to values read from the maps in appendix E. Section 7.3 provides examples illustrating the use of both duration and return period interpolation.

2. DATA

Since there are few available long records of daily water-release data*, WAR estimates were generated using a snow accumulation and ablation model that is presently used by National Weather Service River Forecast Centers. The operational use of this model requires

*The Soil Conservation Service, U.S. Department of Agriculture, maintains snow courses within the study area, primarily in the higher elevations. While these data do not provide daily estimates of water equivalent amounts, they can be quite useful for other applications and may be helpful in assessing the reliability of WAR estimates at snow course locations. Recently, snow pillows have been placed at numerous higher elevation locations throughout portions of the study area. Data are telemetered to collection locations on a regular basis. When a sufficiently long record has been collected, these data could provide excellent water equivalent observations and the possibility of estimating WAR frequency amounts at the observation locations. More information on these data can be obtained by contacting the Soil Conservation Service, West National Technical Center, 511 NW Broadway, Portland, OR 97209.

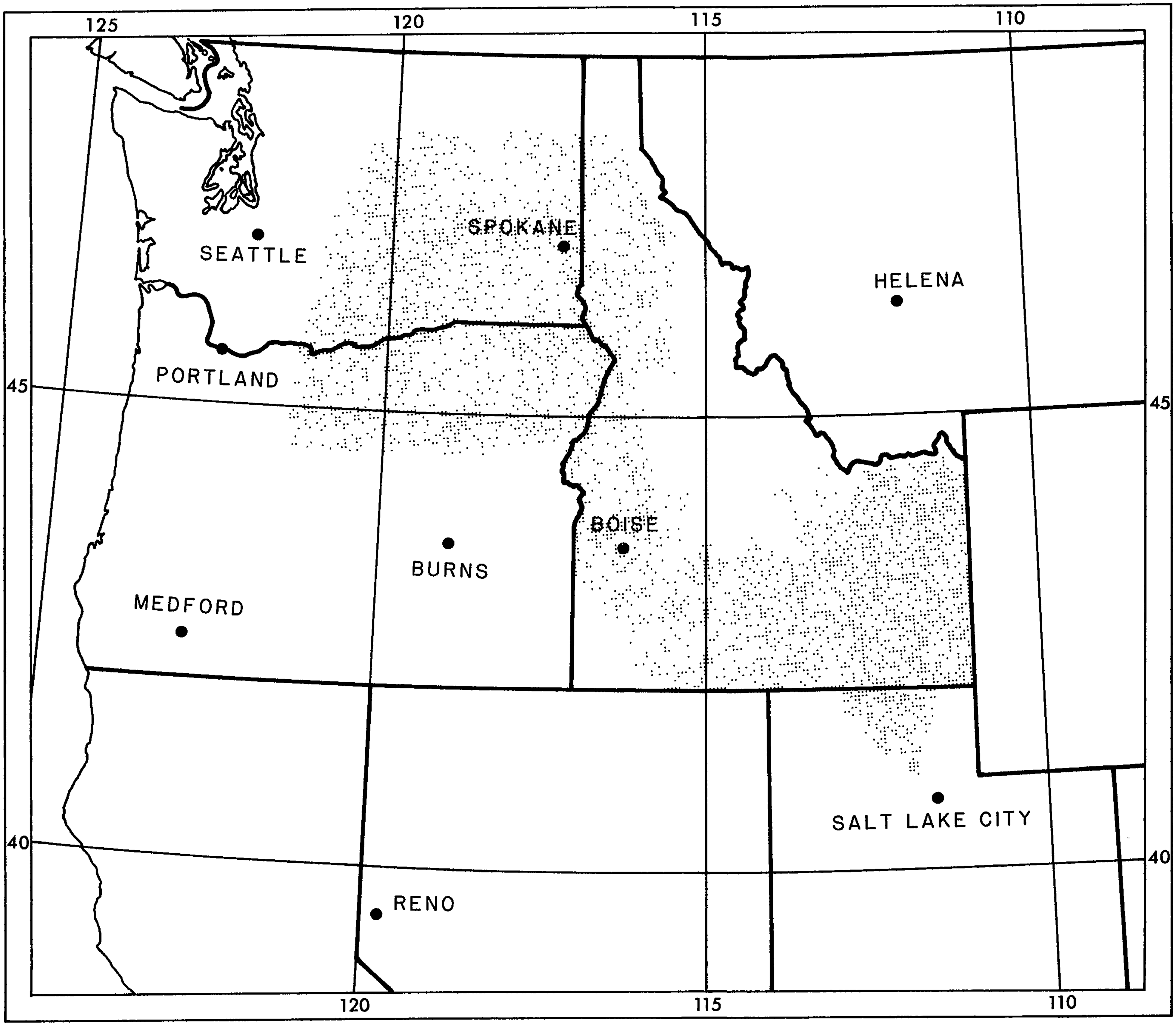


Figure 1.—Map of the northwest United States showing areas covered by WAR-frequency estimates contained in this study.

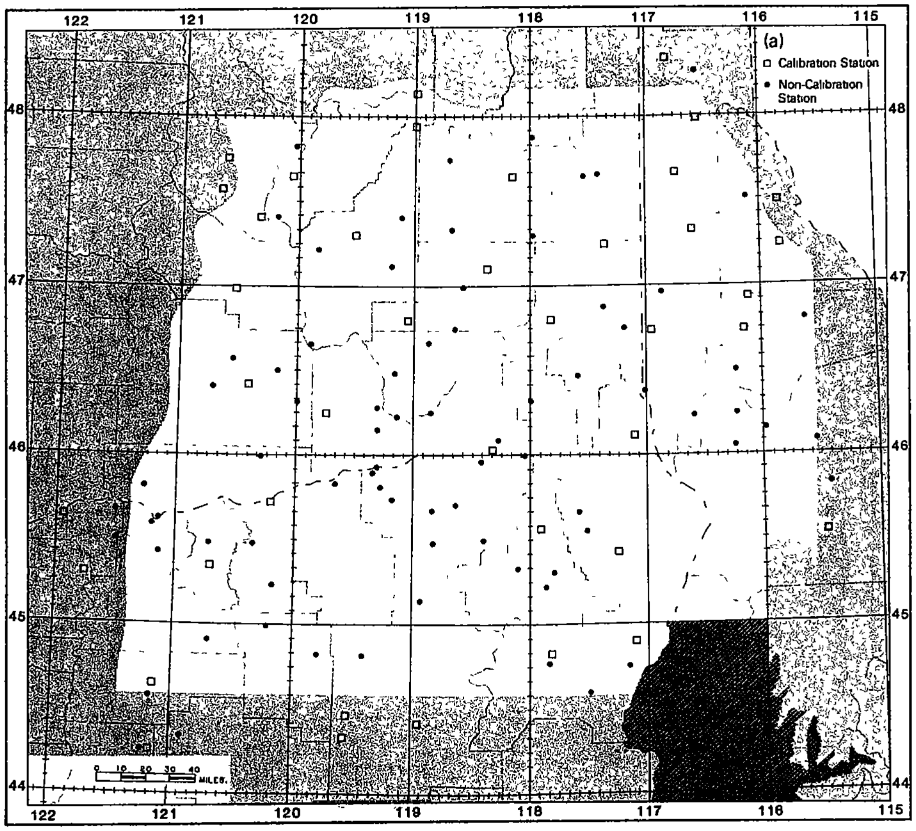
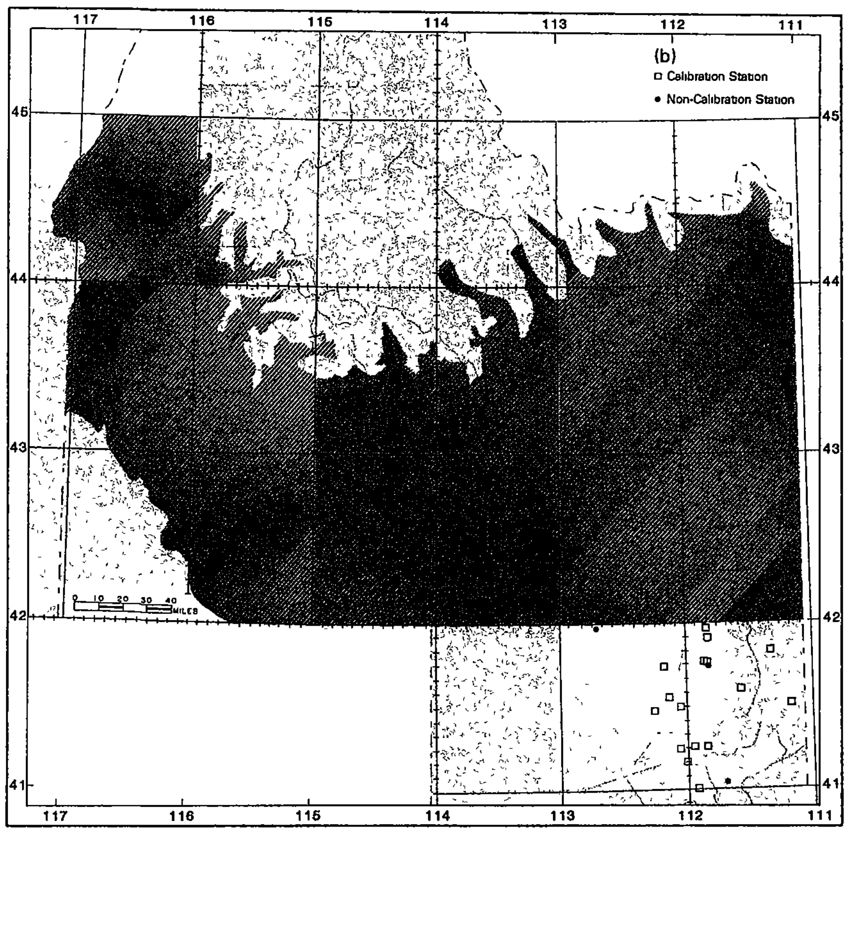


Figure 2.—Map of portions of Washington, Oregon, Idaho and Utah showing the region of interest for this study, (unshaded portion) (a) northwest portion of study area (Tri-State region) and (b) southeast portion of study area. The hatched area shows the area considered by Frederick and Tracey (1976).



6-hour estimates or observations of precipitation and temperature as primary input. For the purposes of this study, the present observation network reporting on a 6-hour interval is not sufficient to adequately define small-scale spatial variations. For this reason, it was necessary to use daily data collected from a nationwide network made up primarily of cooperative observers. These data are assembled and published monthly by NOAA's National Climatic Data Center (Environmental Data Service, 1948-76). These data include daily maximum and minimum temperatures and daily precipitation totals. Also, snowfall amounts and snow on the ground may be observed, but not necessarily on a daily basis. Published data on daily water equivalent of snow on the ground are only available at a small number of stations and are estimated on a regular basis only at some NWS synoptic observing stations. These data have also been stored on computer-compatible magnetic tape (Peck et al. 1977).

Use of daily observations for added spatial resolution came at the cost of temporal resolution. To bring the time increment closer to the 6 hours used in the operational model, it was decided to use a 12-hour time step in the present adaptation of the model. Important in this selection was the fact that the maximum and minimum temperatures provide information on how to estimate representative "daytime" and "nighttime" (i.e., 12-hr) temperatures. Also considered was the fact that most winter storms tend to produce more nearly uniform precipitation over 24-hr periods compared to the more sporadic convective precipitation common in the summer.

Some cooperative observers do not routinely make measurements of snowfall and snow on the ground. In addition, because of factors such as wind, sheltering, slope, and orientation, representative snow measurements are quite difficult to obtain. The NWSRFS snow accumulation and ablation model is ideally suited to deal with these problems. It is designed to model both the buildup and subsequent meltoff of a snow pack. If adequately calibrated, the model enables the estimation of snowmelt for those stations with no snow observations and provides consistent (and presumably representative) estimates for those stations with some snow data. In order for the model to "build" a realistic snowpack, continuous temperature and precipitation data must be available for input. Unfortunately, a number of stations had gaps in their data. Missing data were estimated using observations from surrounding stations. The interpolation was dependent on the correlation between the available data at the stations involved. The length of the gap that was filled was limited by both the degree of correlation with surrounding stations and other meteorological constraints. A detailed discussion of the data processing, including the scheme used to fill missing data, is presented in Appendix B.

Figure 1 shows the location of the study area. The areas of primary interest in this study are agricultural lands (a) in and around the Columbia River basin of eastern Washington and northern Oregon east of the Cascades, extending into western Idaho (fig. 2a), and (b) a portion of northern Utah (fig. 2b). For convenience, the portion of the study area shown in figure 2a will be referred to as the "Tri-State region." While the study focused on the relatively low lying portions of these regions, the area was extended into the surrounding higher elevations to aid analysis along the periphery of the areas of main interest. As discussed later, WAR estimates in the higher elevations are likely to be less reliable than those for the lower lying agricultural portions of main interest. A smoothed topographic map encompassing the study areas is shown in figure 3. These extensions also made the area contiguous with that of a similar study of the Snake River Basin (Frederick and Tracey, 1976). As a convenience, results from the previous study

Figure 3.—Generalized topography for areas included in this study. Elevations shown are in ft. The shaded area highlights elevations greater than 3,000 ft and the darker shading indicates areas above 7,000 ft.

are also included in this report. The only computations in this study that were made for the Snake River Basin (hatched area on figure 2) were for six stations in two overlap regions. This was done to ensure consistency between the two studies.

The Tri-State region of the study area shown in figure 2a includes the Palouse region and other agricultural areas of eastern Washington, Oregon, western Idaho and the surrounding higher elevations. It extends along 44° 35'N, from the Snake River study area on the east to a point 15 miles east of the crest of the Cascade Mountains on the west. The boundary then runs northward, remaining 15 miles east of a generalized crest line through the Cascade Mountains. At 48° 00'N the boundary proceeds eastward to 119° 53'W. From here, it continues northward and then eastward along a line 10 miles north of the Columbia River. At 118° 15'W, the boundary turns north, being defined by the Columbia River itself. At 48° 10'N it extends eastward to a point 15 miles west of the crest of the Bitteroot Mountains and then turns southeastward, remaining 15 miles west of the crest, to 47° 19'N, 115° 35'W. The boundary then proceeds south along 115° 35'W to the Salmon River. It follows the Salmon River west to 116° 00'W and then turns southward to the area included in the Snake River study.

Table 1.—Number of stations used and average period of record, by state

	Number of stations	Average period of record
Idaho	25	24.8
Oregon	46	23.3
Washington	52	23.4
Total (Tri-State region)	123	23.6
Utah*	22	24.2

*Includes three stations in southeast Idaho

The portion of northern Utah covered by this study extends from the Idaho state line southward along the crest of the Wasatch Mountains to 41° 00'N, and then westward to the shore of the Great Salt Lake. It follows the shoreline northwestward to 41° 38'N, 113° 00'W and proceeds due north to the Idaho state line.

The locations of the stations that were used are indicated in figure 2. All stations had at least 15 years of data. Since the magnetic tapes had data available from 1948 to 1976, the maximum period of record was 28 water years, extending from October to September. Table 1 is a summary of the number of available stations and the average period of record in each state. Also included are separate figures for the entire Tri-State region.

3. NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM SNOW ACCUMULATION AND ABLATION MODEL

The National Weather Service (NWS) has developed an energy balance model for snow accumulation and meltoff (Anderson 1973) for use in its River Forecast Service. This model uses basin averages of 6-hr temperature and precipitation values as its primary input to estimate the accumulation and melt of snow. Also needed for the model, but of less importance, are wind movement and atmospheric pressure. The relevant physical processes involved in snowmelt are parameterized on the basis of air temperature. The model is calibrated to a given area primarily through determination of "melt factors" which relate the heat exchange at the air-snow interface to air temperature. One factor, simply called the melt factor, is used when air temperature exceeds 32°F; it determines how much melting occurs. The negative melt factor accounts for heat storage (positive or negative) within the snowpack when air temperature is below 32°F. Both factors vary sinusoidally with a minimum on December 21 and a maximum on June 21 (fig. 4). The melt factors implicitly contain the effects of long- and short-wave radiation and attempt to model the annual variation of the radiation budget at the surface. Units of melt factor are inches of water per °F per unit time.*

* In general, it is NOAA policy to use metric units in all scientific work. An exception was made in the case of this report for the following reasons: (1) many engineers - the primary users of this report - still use British units, (2) comparison with a previous report on WAR for the Snake River Basin in Idaho is facilitated, and (3) the model and a number of the calibration constants were developed in British units and there is no simple way to convert them.

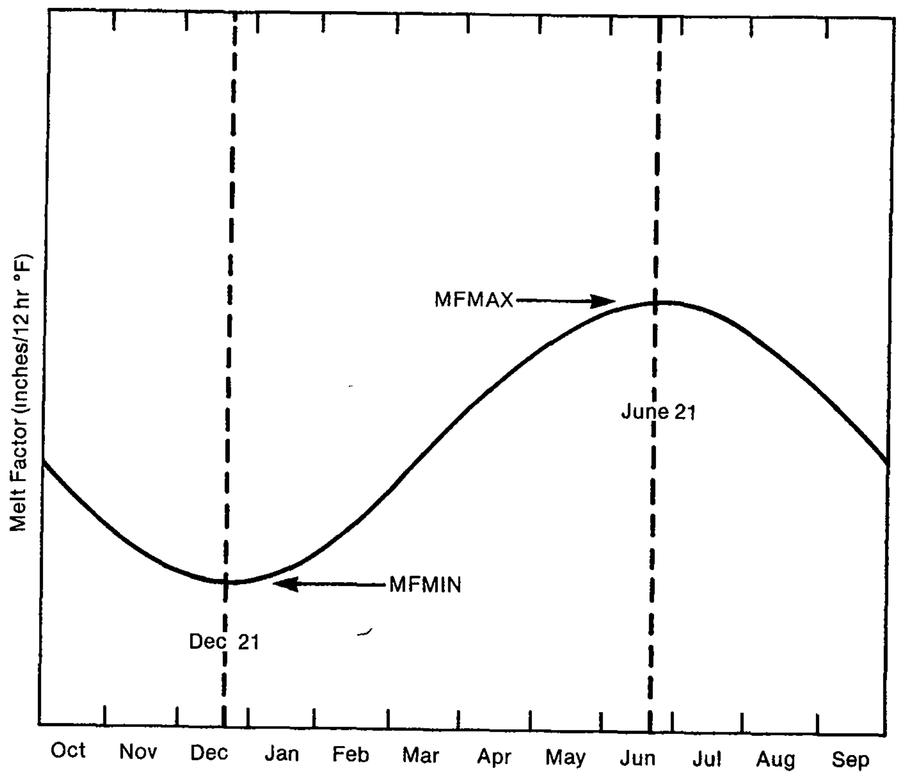


Figure 4.—Schematic showing annual variation of the melt factors.

3.1 Basic Model

The NWSRFS model operates on successive time periods to keep running energy budgets for five accounts. These accounts are combined to keep track of the buildup and meltoff of the snowpack. All accounts are maintained in units of water equivalent. The first account keeps track of the water equivalent of new snow added to the existing snowpack. The second account is for rain added to the liquid retained in the snowpack. Heat exchange across the air/snow interface is monitored in the third account. Above freezing temperatures result in melt. During rainfall, this heat exchange is estimated by parameterizing radiation, conduction, condensation of water vapor, and/or heat received from the rain falling on a snowpack. The net gain or loss of heat within the snowpack is recorded in the fourth account. When this heat gain raises the temperature of the snowpack to 32°F, additional gain is used to produce melt. This melt, together with liquid water received from accounts 2, 3, or 4, is passed to the fifth account, liquid water suspended in the snowpack. When the suspended liquid water exceeds the limit that can be held by the snowpack, it is released as runoff. The accounting process is shown schematically in figure 5. Heat exchange at the ground/snow interface is usually small compared to the heat exchange at the air/snow interface and varies more slowly. While the operational implementation of the model assumes a small constant rate of melt taking place at the soil/snow interface, it is neglected in this study. Whatever its value, it is much smaller than the total snowmelt associated with the annual events. Also omitted are the effects of sublimation and interception of the snow by vegetation.

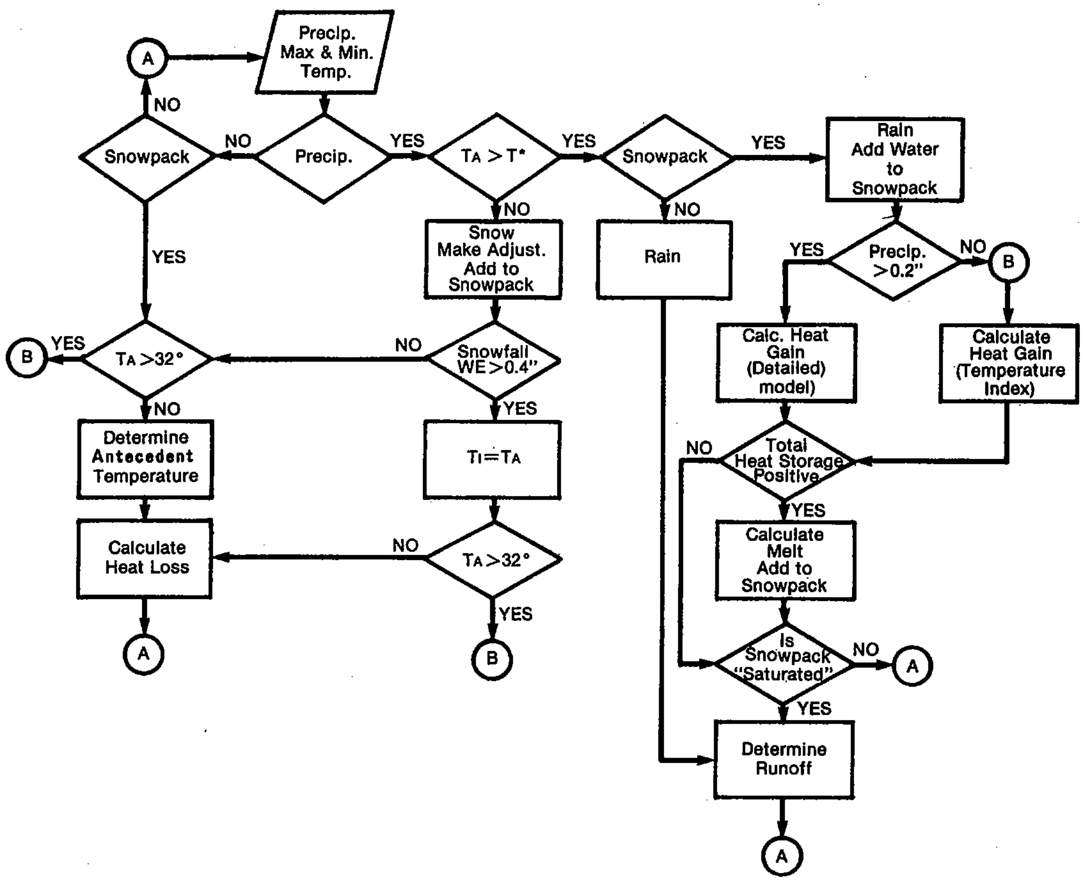


Figure 5.--Flow diagram showing principal features of the present adaptation of the NWSRFS snow accumulation and ablation model.

3.2 Accounting Procedures

Features of the NWSRFS snow accumulation and ablation model pertinent to this study are summarized below. Further details are found in NOAA Technical Memorandum NWS HYDRO-17 (Anderson 1973).

Account 1 - New Snow (Water Equivalent)

This model determines whether precipitation is rain or snow on the basis of a temperature threshold (T^*). The temperature chosen as a threshold value is not necessarily 32°F because (1) snow can occur when surface air temperatures are warmer than freezing and (2) the temperature value represents a 12-hr period, during which warmer or colder temperatures may have occurred. The selection of a threshold value will be considered in section 4.1. Precipitation that occurs at temperatures below the threshold is assumed to be snow. Turbulence at the gage orifice can cause significant underestimation of precipitation amounts during snowfall. Because of this, the observed precipitation amount is increased by an adjustment factor that attempts to account for precipitation gage deficiency in catching snowfall. The new precipitation, if snow, is added to the water equivalent of the snowpack.

Account 2 - Rainfall

Rainfall on a snowpack is added to the liquid water suspended in the snowpack and the new total passed to account 5, while rainfall on bare ground is considered immediately available for runoff.

Account 3 - Heat Exchange at the Air/Snow Interface

The model assumes that melt can occur at the snow surface when the air temperature of the 12-hr base period is above 32°F. During periods with no rain, this heat exchange is parameterized as the product of a melt factor and the air temperature (°F) minus 32. The resulting amount is passed to account 5.

Melt during rainfall can be modeled in greater detail by making the following assumptions: 1) solar radiation is zero, 2) incoming long wave radiation equals black body radiation at the ambient air temperature, 3) snow surface temperature is 32°F, and 4) the dew point and the temperature of the rainwater equals the ambient air temperature. Under these assumptions, the energy balance at the snow surface can be expressed as:

$$M = Q_n + Q_e + Q_h + Q_r, \tag{1}$$

where M is the amount of melt.

Q_n is the net heat transfer by radiation. It is specified as,

$$Q_n = \sigma (T_A^4 - T_s^4) / L_f, \tag{2}$$

where σ is the Stefan-Boltzmann constant, T_A is the air temperature, T_s is the snow surface temperature (32°F), and L_f is the latent heat of fusion (used to convert to water equivalent units). Q_e is the latent heat transfer due to condensation and is the product of three factors. The first factor is the latent heat of melt plus the condensational heating that would result when the air was cooled by the extraction of this heat to cause melting. The second term is a wind factor. The third factor is the difference between the vapor pressure of the ambient air and that of the snow surface (at 32°F).

The model assumes that the eddy transfer coefficients for heat and vapor are equal. The sensible heat transfer, Q_h, is obtained from Q_e using the Bowen ratio concept. The Bowen ratio, Q_h/Q_e, is assumed to equal a psychrometric constant times the difference between air and snow surface temperatures divided by the difference between vapor pressure of the air and vapor pressure at the saturation temperature of the snow surface. (The snow surface temperature is held at 32° during rain.) The psychrometric constant contains conversion units and also depends upon atmospheric pressure.

Q_r is the heat transferred by rainwater. It is the product of (1) the precipitation amount, (2) the difference between the rain temperature (assumed to equal ambient air temperature) and 32°F (snow surface temperature), and (3) the specific heat of water expressed as equivalent inches of melt. Melt computed through application of these relations is added to the water content of the snowpack (account 5).

Account 4 – Heat Storage Within the Snowpack

The snowpack gains or loses heat depending on whether the air is warmer or colder than the snowpack. This accounting is done through use of an antecedent temperature index (T_I). This index models the lag of the temperature in the surface layer of the snow behind that of the air temperature. T_I is calculated by adding to the T_I of the preceding 12-hour base period the difference between the present air temperature and the preceding T_I times a factor between 0.0 and 1.0. The time required for the snow-surface temperature to reach an approximate equilibrium with the air temperature becomes longer as this factor decreases. Because T_I represents the temperature of the upper layers of the snowpack, it is not allowed to exceed 32°F. If a significant amount of new snowfall occurs during the computation period, T_I is set to the temperature of the new snow. T_I is then used to keep account of the heat storage within the snowpack. The appropriate melt factor times the difference between air temperature and T_I determines the change in heat storage. When the total heat storage becomes positive, the excess heat is converted to melt, the water content of this melt is passed to account 5, and account 4 reverts to zero.

Account 5 – Liquid Water Held in the Snowpack

A snowpack holds water until it becomes saturated. Beyond this limit, the excess water is released and is available for runoff. Account 5 keeps track of the liquid water passed to it from the previous accounts and releases any water in excess of the snowpack holding capacity. The maximum holding capacity is defined as a percentage of the total water content of the snowpack.

3.3 Adaptation of the Model

As adapted to the present study, the NWSRFS model uses station observations of daily maximum and minimum temperature and precipitation as principal inputs. The computation period is 12 hr. The temperature for the 12-hr "daytime" period (T_d) is estimated as

$$T_d = 0.75\, T_{A_{max}} + 0.25\, T_{A_{min}}, \tag{3}$$

where $T_{A_{max}}$ is the daily maximum air temperature, and $T_{A_{min}}$ is the daily minimum air temperature. The "nighttime" temperature (T_n) is

$$T_n = 0.25\, T_{A_{max}} + 0.75\, T_{A_{min}}. \tag{4}$$

These formulas give full weight to each observation.

Frederick and Tracey (1976) examined the diurnal precipitation variation for the Snake River Valley and found no strong tendency for either "daytime" or "nighttime" precipitation. Because meteorological conditions in both the Tri-State region and in northern Utah are similar, the daily precipitation amounts were generally divided equally between both 12-hr periods in the present study. One exception was made for stations that had snowfall data available. When snowfall was reported during a 24-hr period, enough precipitation was assigned to the 12-hr "nighttime" interval (colder temperature) to equal the observed snowfall. A ratio of 6 in. of snow to 1 in. of water equivalent was used for this adjustment. While snowfall in many storms throughout the study area may have differed from this 6-to-1 ratio, this value was adopted because examination of model simulations during the calibration process indicated it improved the results of the model simulations. Because other factors were also set during the calibration process, the 6-to-1 ratio is not necessarily a typical density of new snow; it should be considered an empirical calibration factor.

The present adaption defines the snow season as the period from October through May, and simulation runs began on October 1. Although this is a relatively long winter season, a number of higher elevation stations occasionally reported snow in October, and the snowpack at a number of stations lasted well into May.

4. CALIBRATION AND APPLICATION OF THE MODEL

Before the NWSRFS snow accumulation and ablation model could be applied, several parameters had to be specified. Some of these parameters were estimated directly from observations, but most had to be estimated. The process of specifying appropriate values for these parameters was done using trial values and determining how well the model results matched known quantities. The calibration process was only as good as the data that were available for

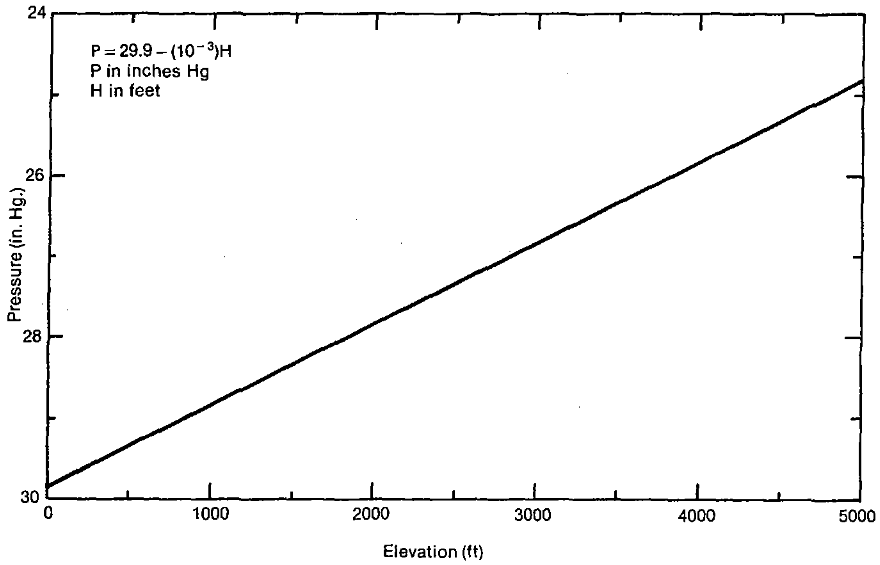


Figure 6.—Variation of pressure with elevation as used in the model.

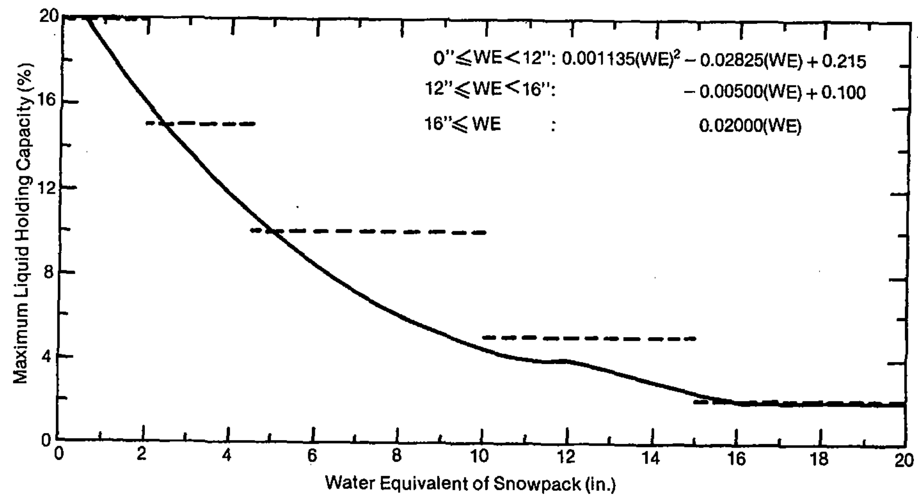


Figure 7.—Variation of liquid water holding capacity as a function of snow depth as adopted in the present study (solid line) and that adopted by Frederick and Tracey (dashed lines).

verification. Furthermore, appropriate calibration constants determined for a particular station for a particular snow season did not always produce good simulations for other stations or even other years at the same station because of variations between two locations or year-to-year differences in the meteorological conditions. Resources did not allow calibration of all stations that had snow observations. Therefore, all available years of data for 43 (out of 123) stations were selected to calibrate the model in the Tri-State region. We felt this was adequate to depict the large-scale variation of the calibration factors. Because the Utah area was considerably smaller, all stations with snowfall data were used in the calibration process (18 out of 22 stations).

Two meteorological quantities that had to be specified were wind speed and atmospheric pressure. Very few cooperative stations measure either of these quantities. We used the monthly mean wind speed from the nearest NWS synoptic station. These data were smoothed over overlapping intervals to minimize jumps from one month to the next. The variation of atmospheric pressure with elevation was estimated using the linear relationship shown in figure 6. While the actual wind and pressure at a given station could differ from the values specified, Frederick and Tracey (1976) performed a sensitivity analysis for the Snake River Basin and showed that simulation results were not changed significantly as long as the values used for these quantities fell within the range normally observed.

The factor used in the determination of the antecedent temperature index (T_I) was set to 0.25 for all stations. The value of this factor has no effect on the total amount of melt -- it only affects the timing of the melt. The value was determined subjectively by detailed comparison of model results with observed data. Any errors introduced by selection of an inappropriate value for this factor will be most important for 1-day WAR amounts. (See sec. 5.2 for a for a discussion of the reliability of the short-duration WAR estimates.) Another factor that had to be specified was the maximum amount of liquid water that can remain suspended in the snowpack. Because very few measurements of this quantity have been made, there was little guidance in its selection. In regions of significant snowcover, the fraction of the total water content of a snowpack that is in liquid form is likely to decrease as the depth of snowpack increases. Deep snowpacks tend to be relatively "dry." As the snow starts to settle and/or melt, the relative amount of liquid in the snowpack tends to increase. The extreme case is a shallow slush layer with a very large fraction of liquid water. The variation of the maximum liquid water holding capacity selected for use in this study is shown as the solid line in figure 7. The analytic specification of the curve was adopted to yield values that were comparable to those used by Frederick and Tracey (1976), shown as dashed lines, but that varied continuously rather than as a series of step functions.

4.1 Model Calibration

The method of calibrating our adaptation of the NWSRFS snow accumulation and ablation model began with the selection of initial values for the parameters discussed above. Using these values, the calibration process involved a trial-and-error variation of the rain-snow temperature threshold, the gage correction factor (to account for undercatch of snow), and the two melt factors until the simulated results approached observed values. The preferred calibration quantity would be daily observations of water equivalent. Since such series of data were hardly ever available for stations within the study area, the calibration was made using observed snow depth.

For this study, stations indicated with open boxes on figure 2 had published daily maximum and minimum temperatures, precipitation, and snow-on-the ground observations and were selected as calibration stations. These stations are representative of all geographical sections of the study area and have a wide variety of elevations and terrain. The aim of the calibration process was to simulate a time series of water equivalent of snow on the ground that was

(1) similar to the observed time series of depth of snow on the ground, and (2) to have both curves reach zero within a few days of each other. In judging the similarity of the profiles, subjective consideration was given to the ripening of the snowpack as the season progressed. Also used for verification of the model output were a very limited number of observations of water equivalent of snow on the ground.

The sinusoidal variation of the melt factors (figure 4) required the specification of two numbers: either the mean value and the amplitude of the variation or the maximum and minimum values. The latter approach was used. Furthermore, the model was provided with only three values: 1) the maximum melt factor (MFMAX, applies to June 21), 2) the minimum melt factor (MFMIN, applies to December 21) and 3) the maximum negative melt factor (NMFMAX, applies to June 21). The minimum negative melt factor (NMFMIN) was computed from these three values as follows:

$$\text{NMFMIN} = \frac{\text{MFMIN}}{\text{MFMAX}} \times \text{NMFMAX} \qquad (5)$$

At the completion of the calibration process, it was determined that there was little <u>systematic</u> variation in the rain-snow temperature threshold, the gage adjustment factor, and the negative melt factor throughout a given region. The fact that there was no systematic variation does <u>not</u> imply that there was no variation at all. The most stable factor was the negative melt factor. Most calibration stations in the Tri-State region showed good results using a value of 0.015 in./°F/12 hr. This value was selected for use at all non-calibration stations. The gage adjustment factor, which accounts for underestimation of precipitation amounts during snowfall due to turbulence at the gage, is strongly affected by gage exposure and wind. If the gage site is not changed, the only significant variable is wind speed and direction. Examination of the calibration stations indicated that an "optimum" gage adjustment for the same station appeared to vary from year-to-year, and possibly from one event to another. Typically, the year-to-year variation at a given station was as large as the variation between different stations. For this reason, a weighted average gage adjustment factor for each station was calculated (see below for the method of weighting each year). All calibration stations in the two regions were then averaged to determine a single value of 1.14 for the Tri-State region and 1.15 for the northern Utah area. These values were used in all subsequent simulations of their respective regions.

The rain-snow temperature threshold (T^*) also showed considerable year-to-year and station-to-station variation. It was treated similar to the gage adjustment factor: weighted averages were determined for each calibration station and the average of these values was used for further work. In the Tri-State region the value used was 34.2°F, and in northern Utah it was 33.5°F.

Only the maximum and minimum melt factors appeared to show systematic spatial variation. Like the other three calibration factors, they also exhibited considerable year-to-year variation at some stations. While some portion of the temporal variability seemed to be associated with certain meteorological conditions (e.g., larger difference between maximum and minimum melt factors for heavy snowpacks, larger minimum melt factors for those years with predominantly early season snowfall, and larger maximum melt factors for those years where most snow occurs late in the snow season), it was not evident how the year-to-year variability could be readily modeled. In addition, there appeared to be a

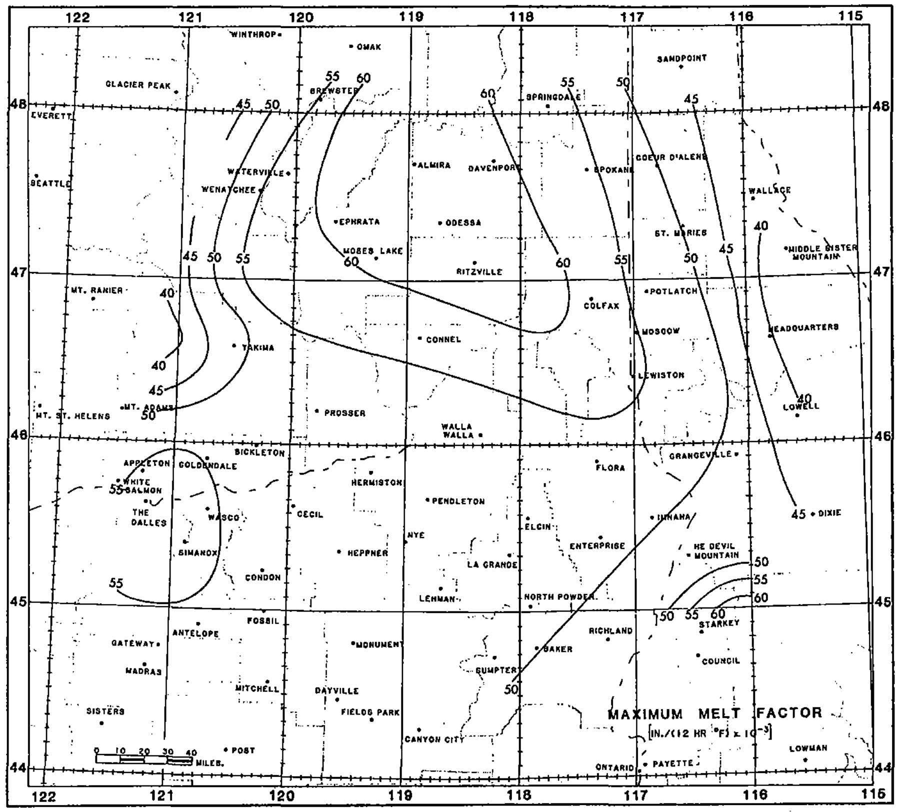


Figure 8.--Map depicting adopted variation of the maximum melt factor (units are [in./(12 hr.°F)] x 10^{-3}).

considerable "random" component to the variability. For each station, a weighted average of the available years was calculated. The weights were assigned subjectively. A weight of 5 was used for those years that simultaneously met all the following criteria: 1) the station had observations of snow on the ground for a substantial portion of the snow season, 2) at least one day had an observation of at least 12 in. of snow on the ground, and 3) the model results appeared to agree well with the available observed data. If all three conditions were not met, the weight assigned to the year was one. The weighted average maximum and minimum melt factors were plotted and analyzed (figures 8 and 9). The analyst (subjectively) smoothed small scale variations and considered broad topographic features in an attempt to capture the large-scale pattern.

4.2 An Example of the Calibration Procedure

A typical example of the final calibration for the 1954-1955 snow season at Elk River, Idaho, is shown in figure 10. This calibration meets all criteria for assigning a weight of 5 for averaging purposes: more than 12 in. of snow occurred, verification data are available, the observed variations generally match the model output, and both the observed values and model values reached zero on April 19, 1955. For plotting purposes, the model-derived water equivalent values are scaled by a factor of four. This implies a constant snowpack density throughout the snow season. The fact that snow

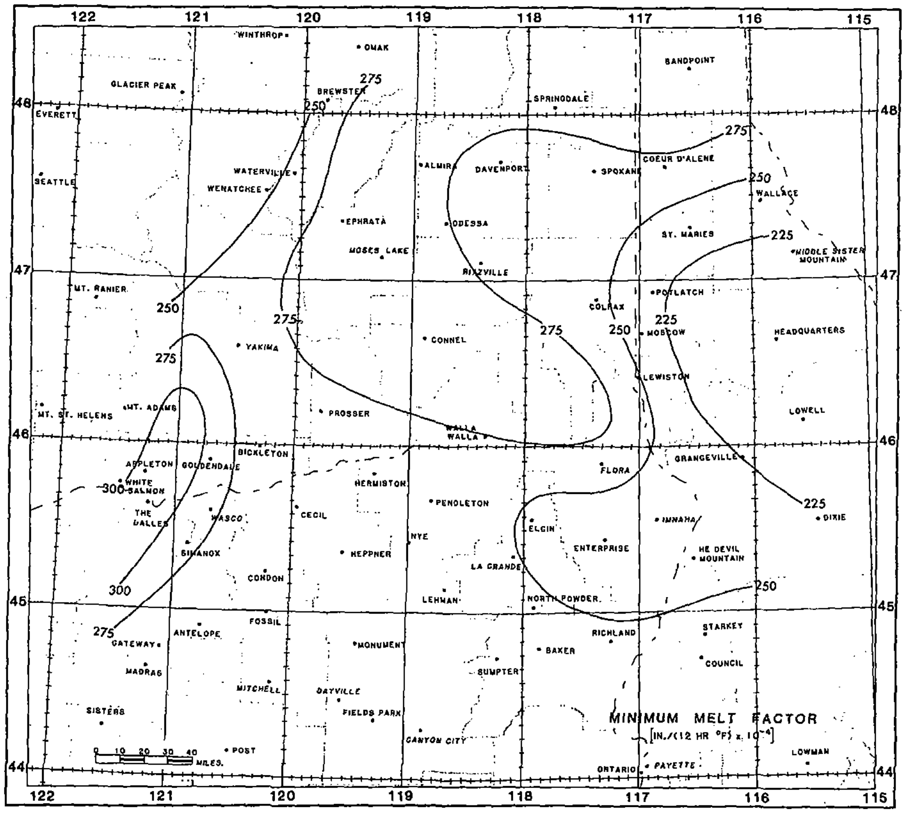


Figure 9.—Map depicting adopted variation of the minimum melt factor (units are [in./(12 hr.°F)] x 10^{-4}).

tends to be "fluffy" shortly after falling and then settles accounts for some portion of the discrepancy between the two curves. At shorter time scales associated with snowfall events, the increases shown by the observed snow on the ground tend to be larger than those for the model-generated water equivalent values. As the freshly fallen snow settles, the observed snow-on-the-ground values decrease even when no melt or loss of water content is predicted by the model. This leads to instances when the observed depths of snow on the ground decrease more rapidly than the model water equivalent estimates. The variation of density with time also occurs on a seasonal time scale. Figure 10 shows that the scaled water equivalent values are generally less than the observed snow-on-the-ground values through early March. By late March, during the spring melt, the observed snow-on-the ground values are consistently lower than the model water equivalent estimates and probably reflect a "ripe" snowpack with a snow-depth to water-equivalent ratio considerably different than 4 to 1.

In general, the calibration process was most successful in matching model results to observed snow-on-the-ground observations for those years when substantial snowfall occurred. At all stations, however, there were instances of the model simulating rain when snow fell and vice versa. An example of the former occurs at the start of the buildup of the snowpack shown in figure 10. The opposite situation occurred around January 18, 1955, where there is a water equivalent increase accompanied by a decrease in the observed snow on the ground. In both cases, these differences were small compared to the total snowpack accumulation. Similar errors at stations with considerably smaller annual snowfall amounts could lead to considerably larger relative errors, although the magnitudes of the errors were generally modest.

A common situation at stations with little snowfall that led to poorer quality calibrations was the occurrence of two or more distinct snowpack buildups separated by a complete or nearly complete meltoff. In a number of instances the fixed annual cycle imposed on the melt factors (fig. 4) precluded the simultaneous matching of both events with observed values. Typically, good fit of one event was at the expense of poorer fit of the other(s). In such cases, effort was made to optimize the calibration for the event that produced the largest WAR values.

4.3 Application of the Model

Values of the maximum and minimum melt factor were read from the maps shown in figures 8 and 9 for all stations not indicated by open boxes in figure 2. These melt factor values, together with the calibration constants that were not allowed to vary over a region (Tri-State region or northern Utah), were used to simulate the buildup and meltoff of snow at these stations. The "daytime" and a "nighttime" WAR estimates were added to produce daily values. The model was run for the entire snow season (October through May). For several higher elevation stations with extreme snowfall amounts, the simulation was extended into June to model late season snowmelt. While no attempt was made to calibrate the model in detail at these stations, all simulations were monitored to ensure that the results were reasonable and consistent with whatever data were available for verification. For several years, the model simulations of significant melt events seemed questionable and did not appear to agree with observations. For those years only, the calibration constants were adjusted to produce "better" simulations.

5. STATISTICAL ANALYSIS

5.1 All-Season WAR Frequency Estimates

In those areas where annual snowfall is either infrequent or light, most annual events are a result of rain only. If the threshold temperature is appropriate, the snowmelt model used in this study treats this situation properly - the rainfall amount is immediately made available for runoff. Because the model was only run for an 8-month snow season it is possible that some annual maximum WAR values occurred as rain events during the summer (especially for the shorter durations). For this reason, 1-to 15-day precipitation totals were determined for the June through September period. For the purposes of this study, a water year was specified as extending from the beginning of October through the end of the following September. The snow-season WAR values were compared to the summer values for each water year, and the larger of the two was selected to form an all-season (annual) WAR series.

At each station, the 15 different all-season maximum WAR series, one for each duration, were fit to a Fisher-Tippett Type I frequency distribution using the Gumbel fitting technique (Gumbel 1958). This distribution has been used in previous precipitation-frequency studies (Hershfield 1961, Miller 1964, Miller et al. 1973) and its adequacy discussed by Hershfield and Kohler (1960). Its use in this study facilitates comparison of results with both previous precipitation-frequency studies as well as with Frederick and Tracey (1976) who also used the same distribution. No attempt was

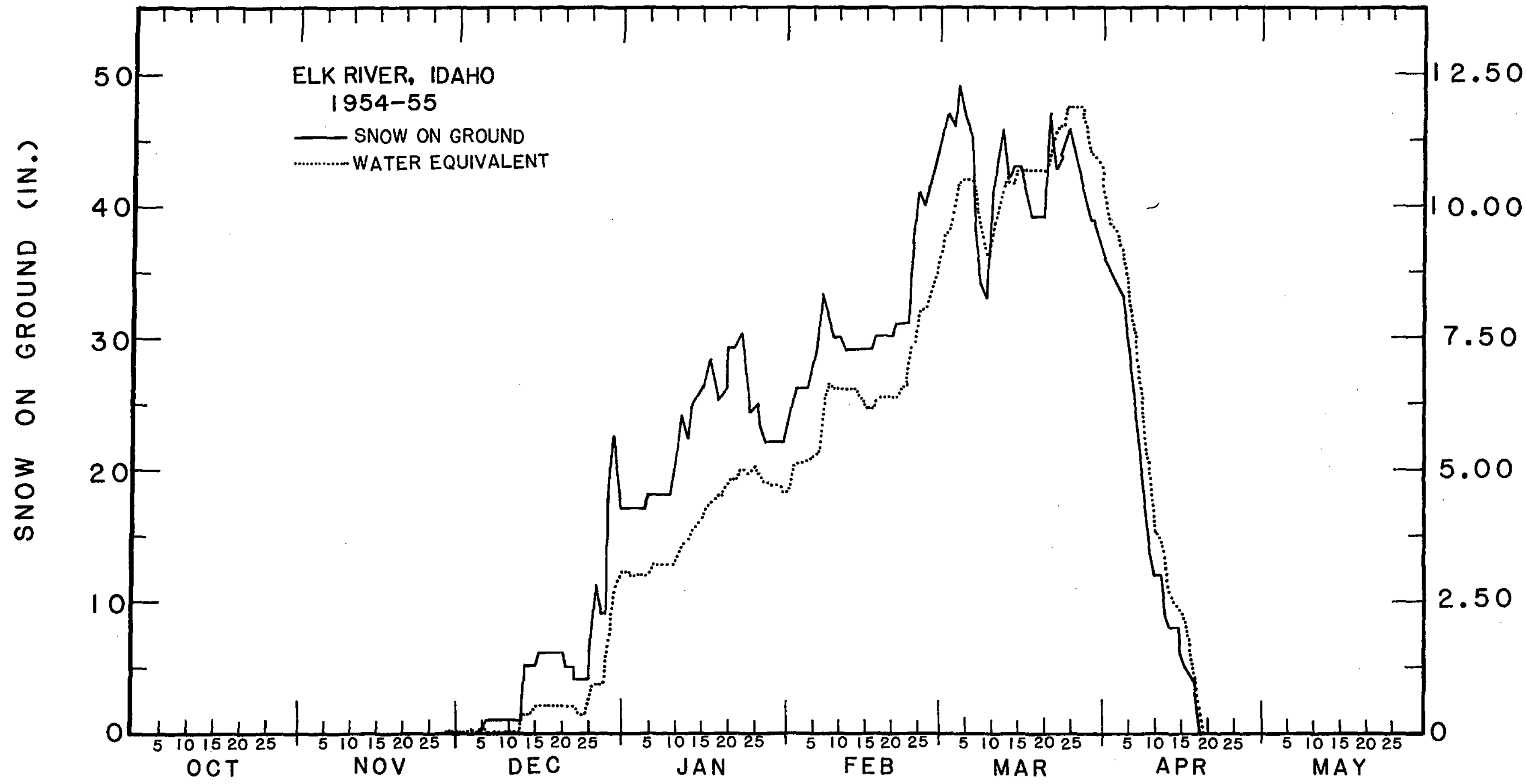


Figure 10.—Comparison of model water equivalent estimates and observed snow on the ground for the 1954-55 snow season at Elk River, Idaho.

made to determine whether the fitting technique or the distribution were optimally suited to WAR data.

It is generally accepted that with extreme rainfall events, the annual series (made up of the largest event in each year) and the corresponding partial duration series (made up of the largest "n" events from an "n-year" period of record) may differ because two or more large precipitation events can occur in the same year. However, this situation is less likely for stations that have substantial snowpacks. At these stations, extreme snowmelt events, with or without additional precipitation, are likely to occur only once during the melt season. It is unlikely that an extreme event will be followed by either more snow buildup or cessation of melting with a second or third significant event occurring in the same season, especially at the longer durations. In the areas that have smaller annual snowfall, it is more likely that a snowpack can melt during a winter and then build up and melt again. It is also likely in these areas that annual maximum WAR events could come from rain. It was concluded that the annual series WAR frequency estimates for the study area would lend themselves to partial-duration adjustments in the lower elevations, but not in the mountains. The available data are insufficient to define the limits of these two areas or how the adjustment factor varies in the intervening transition zone. Therefore, maps presented in this report represent annual series values. For users needing partial-duration values, the factors listed in table 2 should be applied to convert from annual series to partial-duration series for the regions where appropriate.

In addition to partial duration adjustments, many precipitation-frequency atlases also include an adjustment that accounts for the possibility that a single annual precipitation event may be divided between two adjoining observation days. It is possible that the largest annual 1440-minute (1-day) precipitation

Table 2.—Empirical factors for converting annual series to partial duration series (after Langbein 1949)

Return period	Conversion factor
2-yr	1.13
5-yr	1.04
10-yr	1.01
25-yr	1.00
50-yr	1.00
100-yr	1.00

amount could be split because of fixed observation times. Empirical "n-minute adjustment factors" have been calculated for daily precipitation observations (Hershfield 1961). No corresponding values for WAR amounts have been determined. Therefore, all results in this publication are in terms of observation day amounts, and this fact should be noted when comparing the maps in appendix E to precipitation-frequency maps.

WAR frequency maps for 1-, 5-, and 15-day durations and for return periods of 2 and 100 years for both the Tri-State region and northern Utah are presented in appendix E. The detail in the analyses is not justified on the basis of the station data alone. Guidance to interpolation between stations was provided by developing relations between the frequency estimates and meteorological and topographic features at the stations. The results were used to produce frequency estimates on a 5-minute latitude-longitude grid. The approach is essentially the same as that used by Miller et al. (1973) in NOAA Atlas 2. Appendix D presents details on the development of the regression equations used to provide frequency estimates at the grid points. The gridded estimates together with the station data were then subjectively analyzed. As part of the analysis, the fields were smoothed somewhat and greatest weight was placed on the station data.

5.2 Shorter Duration Estimates

The NWSRFS snow accumulation and ablation model was developed primarily for operational purposes. Generally, it is applied to a basin rather than at a point. For this study, the model was adapted to use climatic station data rather than real time observations. This adaptation used maximum and minimum temperature observations to compute an approximation of the average temperature over a 12-hr period. Daily 24-hr precipitation was usually divided equally between two 12-hr periods. Approximations in lieu of observed wind movement and atmospheric pressure were also introduced into the adaptation. Each of the approximations introduced was considered reasonable and made the best possible use of the climatic data available.

In any use of approximations, an implicit assumption is made that the errors introduced by their use are randomly distributed about their true value. If the data are averaged over times longer than the time scale of fluctuations or spatially averaged over considerable areas, the resulting estimates are likely to be reasonably representative of the underlying true value. Examination of the time series while calibrating the model at single points indicated that many 1- to 3- or 4-day changes of model water equivalent estimates were sometimes significantly different from changes in observed snow on the ground. While some of the differences can be attributed to problems with snowfall observations and density variations, there were enough remaining discrepancies to indicate the approximations and assumptions used in the model parameterizations, in the adaptation of the model, and in the treatment of the data may lead to short-duration estimates of inferior quality. Integration over four or more days appeared sufficient to allow a substantial portion of the "random" error to cancel out and produce reasonable estimates. Because there was no truly adequate ground truth available at the station locations, it is impossible to assess how much error or bias remains in the final results; but, as the duration decreases, the degree of confidence in the WAR estimates is also reduced. Short duration estimates, especially 1-day values, should be used with some caution.

6. MERGER WITH SNAKE RIVER BASIN ESTIMATES

The present study is a sequel to a similar study for the Snake River Basin in Idaho (Frederick and Tracey 1976). The same basic model was used in both studies and the adaptations were quite similar. Since the two areas considered in the present study are contiguous with the Snake River Basin, annual WAR maps for both studies have been combined for ease of use (appendix E). While no attempt was made to recompute snowmelt in the Snake River Basin, calculations were made for six stations in regions where both studies overlapped. The results are shown in table 3.

Differences between the two studies arise from 1) the use of additional years of data in the present study, 2) variations in the way the NWSRFS model was adapted for WAR computations, 3) different approaches to calibration, 4) slightly different methods used to combine snow season and summer events to form annual series, and 5) the use of different gridding equations to provide guidance in drawing detailed features in orographic areas.

The only difference between the data used in the present study and that of Frederick and Tracey (1976) was the length of record available. Both studies used the same source of data (Peck et al. 1977). The present study had three more years of data available. As with Frederick and Tracey (1976), no stations with less than 15 years of data were used in the final frequency analyses. Our computations at the intercomparison stations using only the years available to Frederick and Tracey showed no significant differences introduced by the slightly longer record used in the present study.

Another area of difference between the present study and that for the Snake River region concerned the specification of certain model parameters. In the computation of the antecedent temperature index, Frederick and Tracey used a factor of 0.5, whereas this study used 0.25. Frederick and Tracey fixed the rain-snow temperature threshold at 33°F and the gage adjustment factor (during snowfall) at 1.20. In the present study these values were determined as part of an initial calibration process for each area (34.2°F and 1.14 for the Tri-State region, and 33.5°F and 1.15 for the area in Utah). The final difference was in the specification of the maximum liquid water holding capacity of the snowpack. For each station, Frederick and Tracey used a single constant value that depended on the long-term average snowfall at that station. The values they used depended on snow on the ground and are shown by the dashed lines in figure 7 (sec. 4). Since there was no reliable way to determine the snowpack density, we chose to scale their snow on the ground by a factor of 0.25. This was done for display purposes only, and we do not intend to imply that this fixed density is based on either observation or theory. Clearly, the discussion in section 4.2 demonstrates density variations throughout the winter. The relationship used in the present study differs in that the variation with amount of snow is smoother and the factor can vary with the depth of the snowpack throughout the snow season. It is believed that these differences did not generally have a significant effect on the WAR frequency estimates determined by the two studies.

Model calibration was potentially a significant source of dissimilarity between the results of the present study and those of Frederick and Tracey (1976). This is primarily due to the fact that the calibration process was largely subjective. There is no unique combination of adjustable parameters that leads to a good calibration. Ideally, the observed snow on the ground and the

Table 3.--Intercomparison between the present study and results from Frederick and Tracey (1976) for common stations in Idaho

Station	ID	Elevation (ft.)	Correlation between annual series 5-day	Correlation between annual series 15-day	WAR frequency estimates 2-yr 5-day P-S*	2-yr 5-day F-T°	2-yr 15-day P-S*	2-yr 15-day F-T°	100-yr 5-day P-S*	100-yr 5-day F-T°	100-yr 15-day P-S*	100-yr 15-day F-T°
West												
McCall	5708	5025	0.77	0.71	4.65	4.52	8.95	9.13	8.54	9.06	17.76	19.56
Payette	6891	2150	0.97	0.95	1.57	1.50	2.26	2.29	3.60	3.59	4.77	4.82
New Meadows Ranger Station	6388	3870	0.84	0.83	4.08	4.06	7.12	7.34	8.75	8.72	14.84	14.50
Southeast												
Malad City	5559	4467	0.95	0.94	1.82	1.83	2.92	2.94	4.06	4.33	7.40	7.65
Oakley	6542	4600	0.98	0.98	1.44	1.55	2.10	2.25	3.43	3.56	5.12	5.42
Strevell	8786	5290	0.89	0.95	1.56	1.56	2.22	2.24	3.42	3.75	5.16	5.76

*P-S: Results from present study
°F-T: Data from study by Frederick and Tracey (1976)

model's water-equivalent time series would be quite similar with coincident local maxima and minima, and with both starting and ending at the same time. In a number of cases, this ideal correspondence was not attainable for the reasons discussed in section 4. This led to frequent occurrences where tradeoffs between "goodness of fit" using one criteria, e.g., date when both snow on the ground and water equivalent went to zero, had to be weighed against another criteria, e.g., the simultaneous occurrence of significant melt events. While general guidelines were used, model limitations, data inaccuracies, and other factors ultimately meant that the considerable degree of subjective judgement used in the calibration process had the greatest potential for creating differences between the present study and that of Frederick and Tracey (1976).

The method of constructing the annual series in this study also differed from that used in the Snake River study. Frederick and Tracey (1976) selected the larger of 1) the maximum WAR value of the snow season (October to May) or 2) the maximum precipitation event of the water year (starting October 1) regardless of form of precipitation. In the present study, we considered it possible that the annual maximum event could fall as snow and be released over a duration longer than the actual precipitation event. In some cases, this could lead to a situation in which the water that actually became available for runoff for a specific duration could be less than the maximum precipitation in some event for the same duration. We therefore formed our annual series by selecting the larger of 1) the maximum WAR value for the snow season or 2) the largest summer (June to September) precipitation event.

To evaluate the total effect of all the above differences on the final results, three stations in western Idaho (McCall, New Meadows Ranger Station, and Payette) and three stations in southeastern Idaho (Malad City, Oakley, and Strevell) that were used in the Snake River Study, were also used in this study.

Table 3 summarizes the results at these intercomparison stations. In general, the WAR frequency estimates agree quite well. Except for McCall, and possibly New Meadows Ranger Station, the correlation coefficients for the series of each year's maxima were quite high. In the right-hand portion of table 3, containing WAR frequency estimates, the first column of each pair are results from the present study and the second column contains Frederick and Tracey's estimates. The larger discrepancies occur for the 100-yr, 15-day amounts, but the two values seldom differ by more than 10 percent. We consider this to be within the overall accuracy of our ability to estimate WAR. While there is a tendency for the WAR estimates of Frederick and Tracey to be larger, the number of comparison stations is small, and there are enough cases in the present study where the estimates are larger, that we conclude that there are no clearly discernible differences between the two studies arising from the first four possible sources given at the beginning of this section.

The last reason for possible differences between the two studies, namely the use of different equations to provide guidance in the analysis between stations, did lead to some notable differences. The interpolation equations in appendix D were derived using station data which probably did not adequately depict the spatial variation along the periphery of either study area. For this reason, the greatest uncertainty in the analysis of both studies includes the regions where the merger took place. Since the station data in the merger regions were generally consistent, an attempt was made to subjectively reconcile any discrepancies in the analysis.

The changes made in the merger area in the vicinity of 45°N 117°W were more extensive than those necessary in the area around the Utah-Idaho state line. Frederick and Tracey (1976) did not show the strong gradient associated with the deep valley formed by the Snake River in the Hells Canyon area along the Oregon-Idaho state line. Almost certainly, this was because they had no WAR information on in the Tri-State region were somewhat larger than those in northern Utah. The coefficient of variation (ratio of mean to standard deviation) showed no discernible systematic variation with region, return period, or elevation. Using the average values for each category, the following pair of equations was solved for A_i and A_j at each intermediate duration:

$$W_n = A_i W_i + A_j W_j \quad (6)$$

and

$$A_i + A_j = 1 \quad (7)$$

where

W_n is the n-day WAR estimate,

A_i is the weight applied to the (known) shorter duration WAR estimate,

A_j is the weight applied to the (known) longer duration WAR estimate,

W_i is the (known) shorter duration WAR estimate, and

W_j is the (known) longer duration WAR estimate.

The subscripts i and j were specified as

$i = 1, j = 5$ if $1 < n < 5$

and

$i = 5, j = 15$ if $5 < n < 15$.

Based on an examination of the weight factors, it was determined that one set of factors was appropriate for all elevations, return periods, and regions, including the Snake River Region of Frederick and Tracey. These values are presented in table 4. While these factors may lead to slight overestimates in Utah, the station-to-station variation within each region was considerable, and it was felt that any possible regional variation was not significant. A nomogram for quick interpolation is provided in figure 12. Figure 12a is for durations between 1 and 5 days and figure 12b is for durations between 5 and 15 days.

In addition to previously discussed sources of error associated with the model simulation, the use of the interpolation factors can result in further error. These errors are largely due to inadequate spatial sampling, given the limited number of available stations. Assuming the station values are "correct," an estimate of one component of the interpolation error can be quantified: the degree to which the interpolation factors provide accurate estimates at the stations themselves. At each station, the 1-, 5-, and 15-day values were combined with the factors given in table 4 to produce estimates for intermediate durations. The difference between the interpolated value and the model result at each station was used to determine root mean square (RMS) errors for the intermediate durations. These values, expressed as a percentage of the mean value for each duration, are presented in the right hand column of table 4. In practice, there are additional interpolation errors due to inaccuracies in locating and reading point values from the fields of WAR estimates.

Table 4.—Duration interpolation factors and resulting RMS errors at the stations

Duration	1-day factor	5-day factor	15-day factor	RMS error
1	1.000	0.0	-	-
2	0.605	0.395	-	8.6%
3	0.345	0.655	-	7.3%
4	0.159	0.841	-	5.6%
5	0.0	1.000	0.0	-
6	-	0.856	0.144	3.4%
7	-	0.756	0.244	4.2%
8	-	0.651	0.349	5.2%
9	-	0.549	0.451	5.0%
10	-	0.451	0.549	4.5%
11	-	0.353	0.647	3.9%
12	-	0.254	0.746	3.2%
13	-	0.162	0.838	2.5%
14	-	0.080	0.920	1.6%
15	-	0.0	1.000	-

7.2 Return Period Interpolation

Table 5 presents a numerical solution for the return period diagram (fig. 13). Figure 13 is based on the Gumbel method of fitting the Fisher-Tippett Type I distribution. Both the equations and the diagram for return period computations use annual series data (which is depicted on the maps).

7.3 Examples of Duration and Return Period Interpolation

The equations and nomograms in this section can be used to determine WAR estimates for durations and return periods intermediate to those provided by the maps in appendix E. Examples of two applications are given: (1) the estimation of a 7-day 10-yr WAR amount at 47°N, 119°W, and (2) the estimation of a 3-day 50-yr WAR amount at 41°30'N, 112°10'W. The first location is in the central portion of the Tri-state region in Washington and the second is in Utah. The WAR amounts in table 6 form the basis for the

Table 5.—Return period interpolation factors

Return period	100-yr. multiplier	2-yr. multiplier
5	0.268	0.732
10	0.445	0.555
25	0.669	0.331
50	0.835	0.165

following interpolations and were read from figures E-3 through E-10.

Estimation of the 7-day 10-yr WAR amount at 47°N, 119°W, requires estimates of the 10-yr 5- and 15-day WAR amounts. To use the nomogram shown in figure 12, the first step is to select WAR amounts to apply to the ordinate. Both figures 14a and 14b use a scale ranging from 0 to 6. Once the scale is fixed, the 2- and 100-yr 5-day WAR amounts are plotted and a straight line is drawn connecting them. The point where this straight line intersects the vertical line above the 10-yr point on the abscissa gives the 5-day 10-yr estimate. In this case, the amount is 2.17 in. (fig. 14a). Figure 14b shows how this same procedure is used to determine that the 15-day 10-yr WAR amount at 47°N, 119°W, is 2.85 in.

Table 5 provides an alternate method of obtaining the same WAR estimates. The estimates are sums of two numbers. The first number is found by multiplying the 100-yr WAR amounts by the factor shown on the line for the 10-yr return period (i.e., 0.445). The second number is the product of the corresponding factor for the 2-yr return period (i.e., 0.555) and the 2-yr WAR values. The computations are as follows:

5-day 10-yr = 0.445(3.16) + 0.555(1.38) = 2.17

15-day 10-yr = 0.445(4.18) + 0.555(1.79) = 2.85

These values are the same as the estimates found using the nomogram method (fig. 14). The advantage of using the numerical computation is that it eliminates (1) the possibility of incorrectly plotting either the 2-yr or 100-yr value and (2) the inaccuracies in reading exactly where the straight line intersects the desired return period.

To obtain the 7-day 10-yr WAR estimate, duration interpolation must be performed on the 5- and 15-day 10-yr WAR amounts just found. Application of the nomogram method (fig. 11b) again requires assigning WAR amounts to the ordinate. For this example, we chose to let the scale range from 2.0 to 3.0, as shown in figure 15. The 5- and 15-day amounts are plotted and a straight line is drawn connecting them, as shown. The resulting 7-day 10-yr WAR estimate is 2.34 in. Numerical calculation can be accomplished using table 4. The factors applied to the 5- and 15-day WAR amounts to determine the 7-day value are 0.756 and 0.244, respectively. Hence,

7-day 10-yr = 0.756(2.17) + 0.244(2.85) = 2.34

Again, use of the numerical computation is subject to less uncertainty than estimation using the nomogram.

Determination of the 3-day 50-yr WAR amount at 41°30'N, 112°10'W, is shown in figures 16 and 17. Figures 16a and 16b provide 1- and 5-day 50-yr estimates of 2.47 and 4.25 in., respectively. Using these values and the nomogram shown in figure 11a yields a 3-day 50-yr WAR amount of 3.64 in., as shown

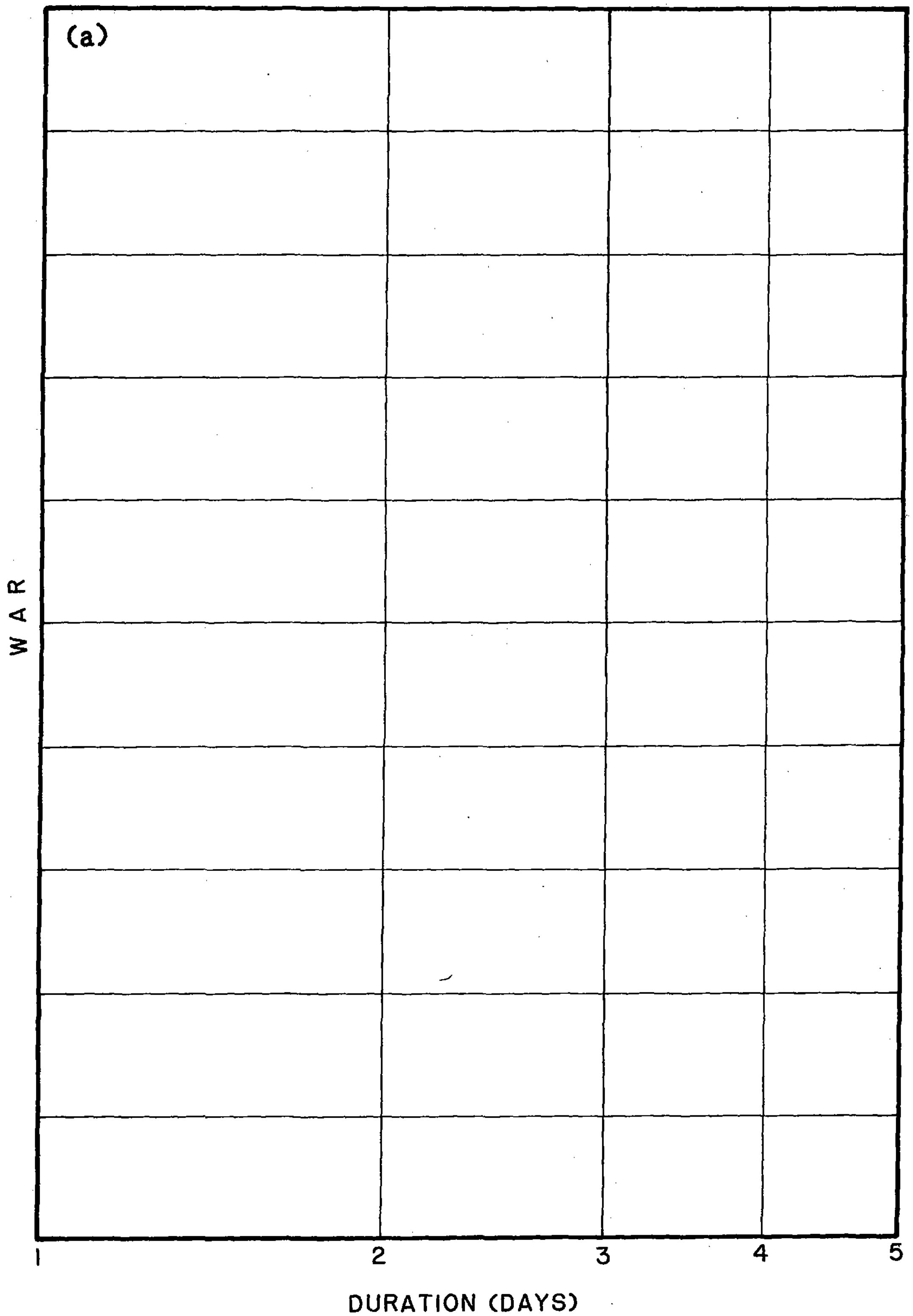


Figure 12a.--Nomogram for duration interpolation for durations less than 5 days.

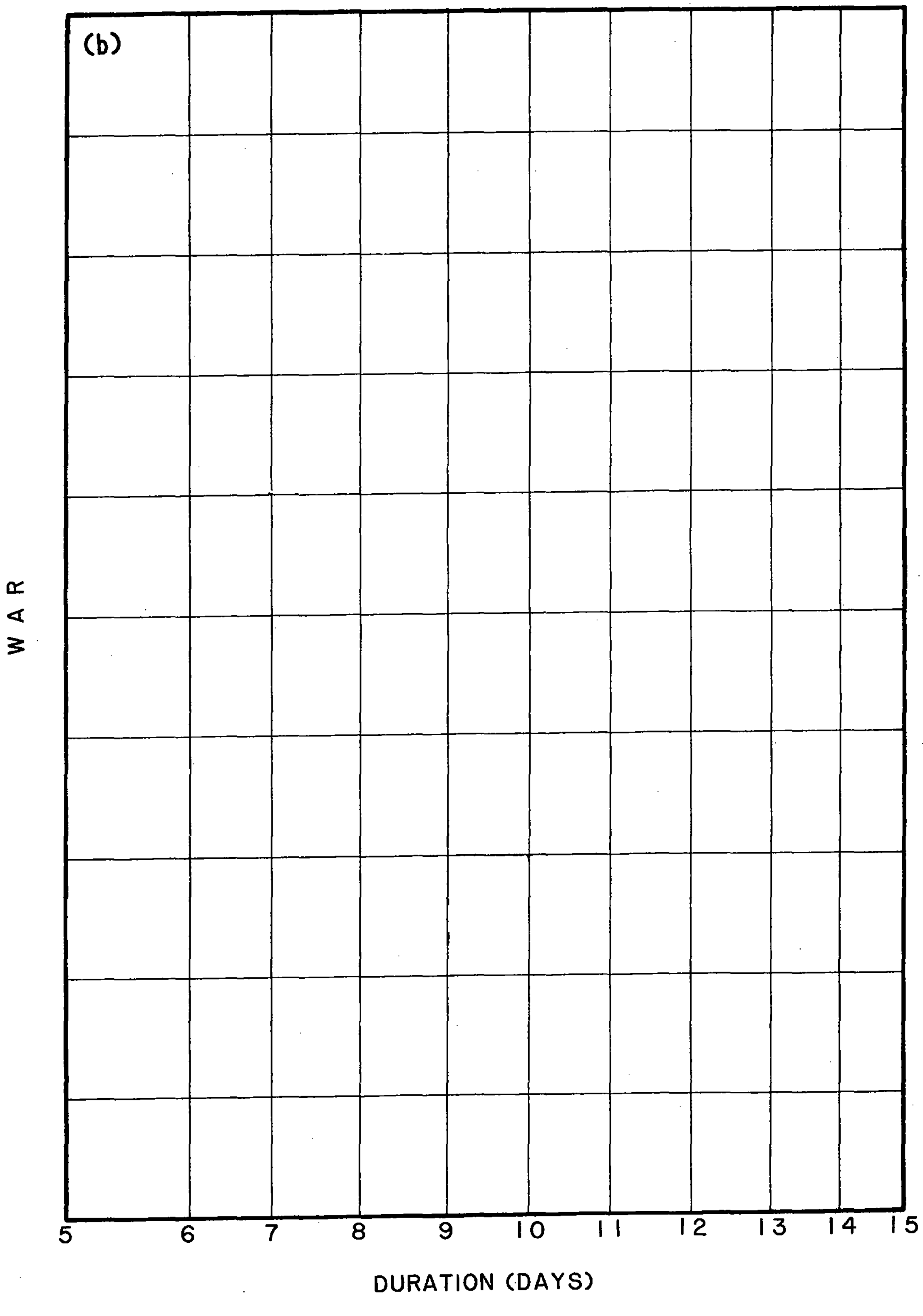


Figure 12b.--Nomogram for duration interpolation for durations between 5 and 15 days.

in figure 17. Using tables 5 and 4, the numerical computations would be:

1-day 50-yr = 0.835(2.74) + 0.165(1.10) = 2.47

5-day 50-yr = 0.835(4.70) + 0.165(1.98) = 4.25

3-day 50-yr = 0.345(2.47) + 0.655(4.25) = 3.64

8. DISCUSSION

Careful comparison of the maps in this report (appendix E) with those of Frederick and Tracey (1976) will reveal differences in the analysis philosophy used by the two sets of authors in drawing isolines. It is generally accepted that there is much more detail in the spatial patterns of precipitation fields than can be determined on the basis of station data alone. Variations in a given storm can occur on scales much smaller than the station separation. While maps involving long term statistics such as mean annual precipitation or precipitation-frequency depict fields that are smoother because storm-to-storm variability is minimized by long averaging periods, such fields can still contain variability associated with "permanent" factors such as topography, distance from moisture supply, prevailing atmospheric flow patterns, seasonal variation of precipitation, etc. These features, and in particular topography, occur on scales smaller than the station separation. All factors, at all scales, can interact in an unknown way to produce the "real" patterns the analyst attempts to depict. Different analysts make different assumptions about how these factors affect the precipitation fields, and these judgements are reflected in their analysis of a particular field.

Because of their limited numbers, the same station data can be interpreted in a wide variety of ways. The use of regression equations to aid interpolation between the stations (described in appendix D) is an attempt to impose a certain level of objectivity and to ensure consistent analysis. Even when this approach is followed there can still be considerable variation from analyst to analyst. The regression equations also depend on the sample of observations used to develop them, and there is no way to know whether they adequately depict all factors important to the intrastation variability. All of these factors contributed to differences in analysis between the present study and that of Frederick and Tracey (1976). They chose to conform the isohyets more closely to the topographic features than was done in the present study. We chose a higher degree of smoothing, not because we were sure the WAR fields were as smooth as shown, but because we could not be confident in our ability to accurately depict the smaller scale variations. Except in the merger regions (described in the previous section) we made every attempt to faithfully reproduce the level of detail intended by Frederick and Tracey (1976) for the Snake River region. Any modifications made to their analysis were inadvertent and should not be considered "improvements."

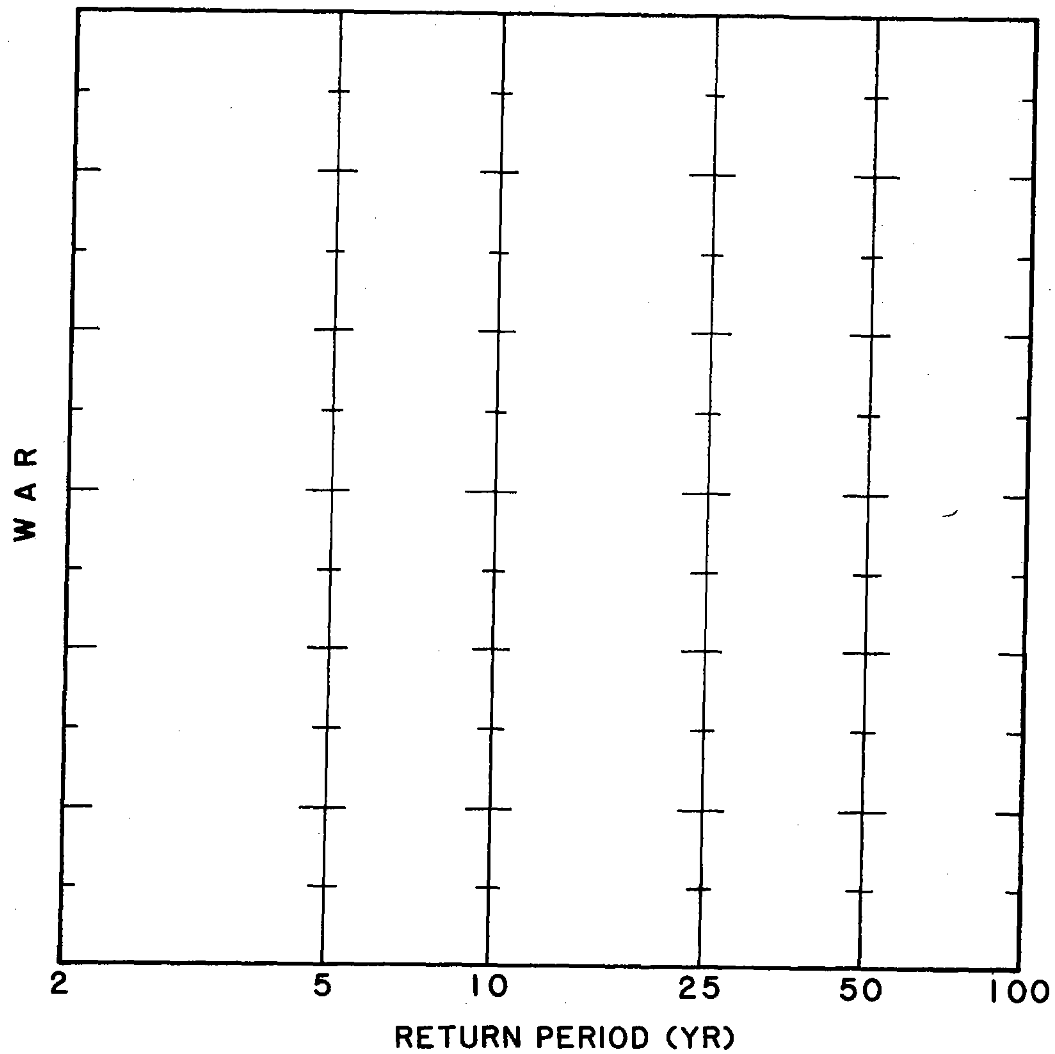


Figure 13.--Nomogram for estimating WAR values for return periods between 2 and 100 years.

In general, the spatial variation shown by both studies is quite similar, especially in its broadscale features (see appendix E). There appeared to be an underlying decrease from northwest to southeast which was probably related to distance from the major moisture supply (Pacific Ocean). The smaller-scale variations in the WAR fields are generally related to the topography with larger values associated with the higher elevations. (See fig. 3 for elevation contours.) Both studies show broad minima in major basins (Columbia River drainage in Washington and northern Oregon, and the Snake River valley in Idaho). In a few areas, minima occurred in the lee of major topographic barriers. A prominent example is the broad minimum just to the west of the point where the Washington, Oregon, and Idaho state lines meet. The WAR maximum to the west along the crest of the Blue Mountains suggests that the moisture supply is depleted when westerly flow, forced up the Blue Mountains, condenses and results in considerable precipitation and higher WAR amounts. Lower WAR amounts associated with the larger valleys, such

Table 6.--WAR amounts at 47°N, 119°W and 41°30'N, 112°10'W

		47°N, 119°W	41°30'N, 112°10'W
2-yr	1-day	-	1.10
100-yr	1-day	-	2.74
2-yr	5-day	1.38	1.98
100-yr	5-day	3.16	4.70
2-yr	15-day	1.79	-
100-yr	15-day	4.18	-

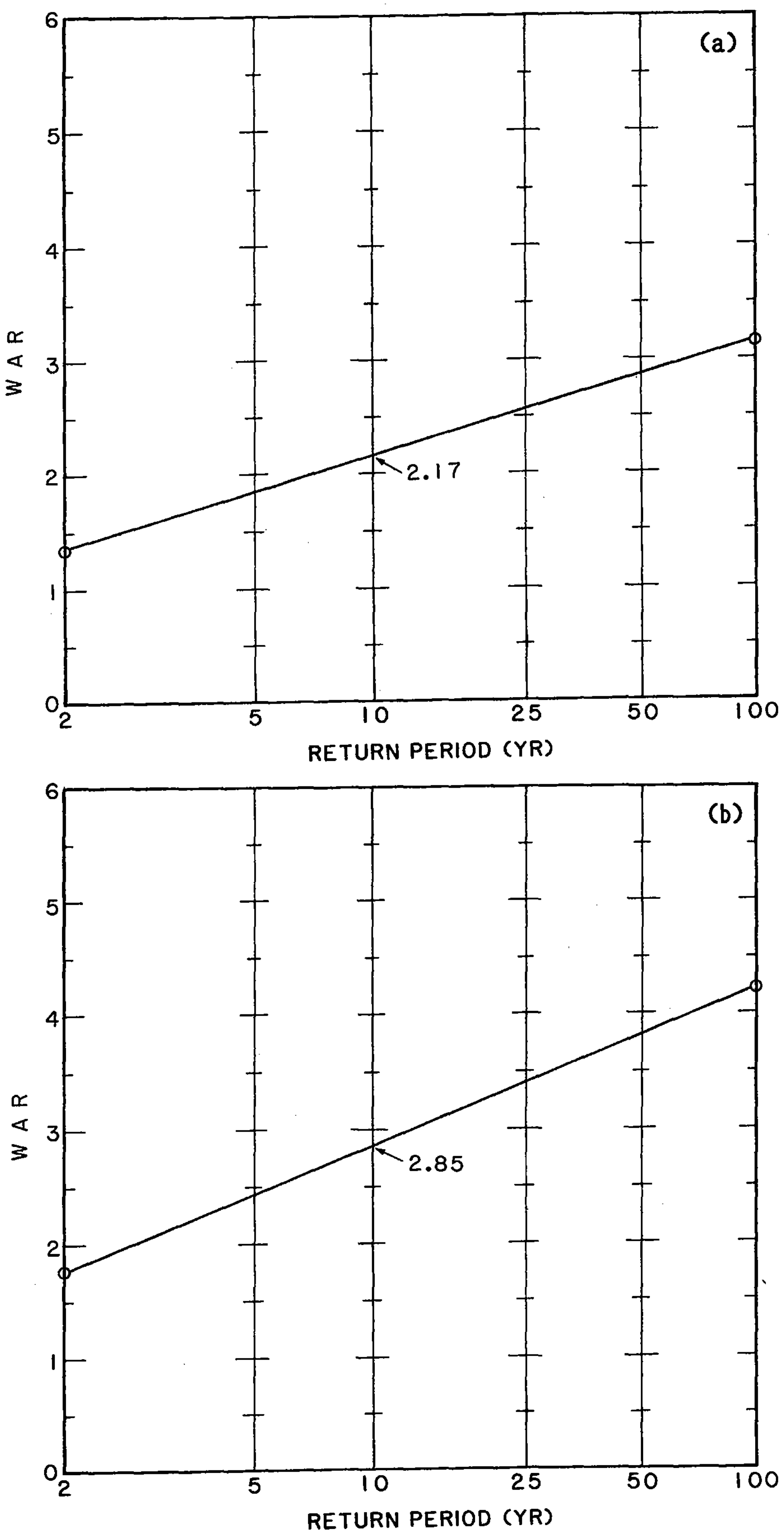


Figure 14.--Examples of WAR return period interpolation for 47°N, 119°W, (a) 5-day amounts, and (b) 15-day amounts.

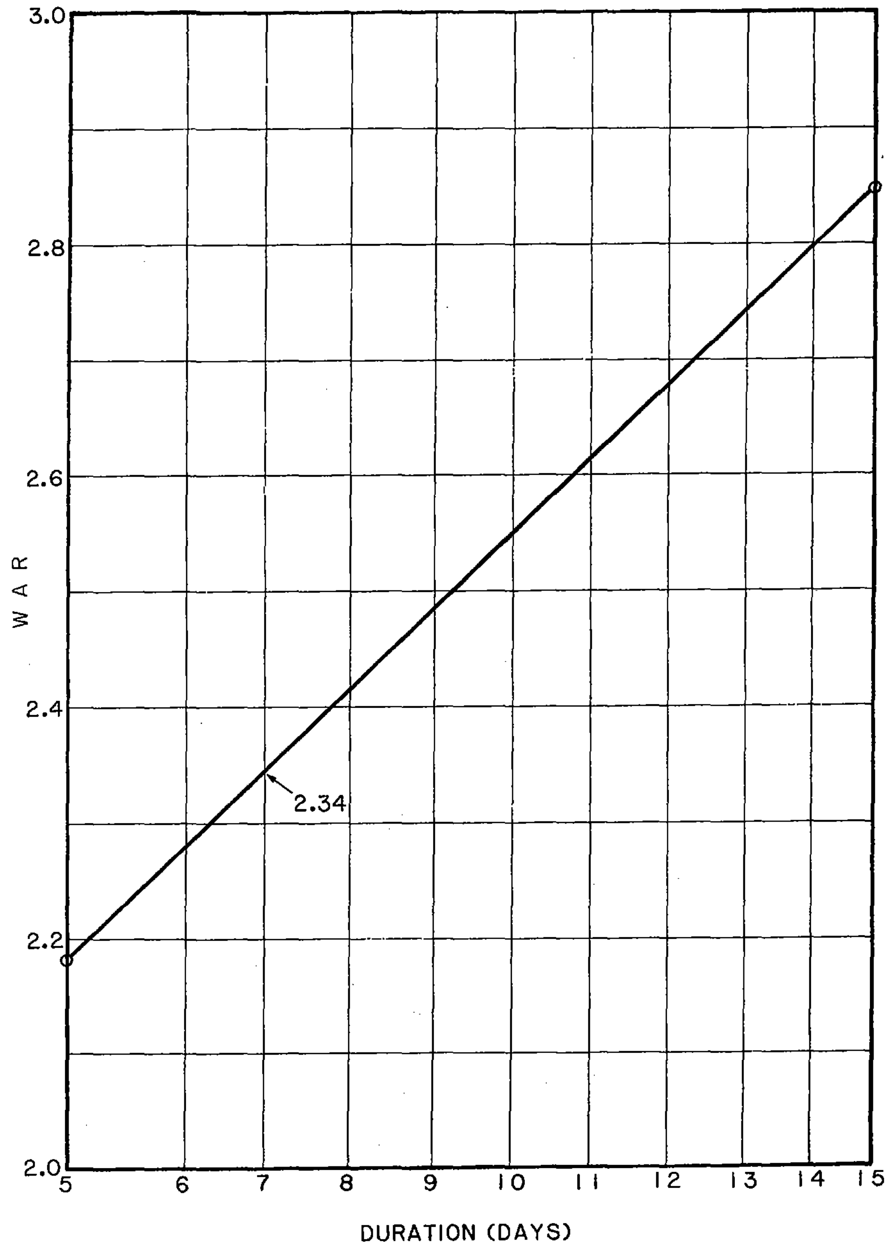
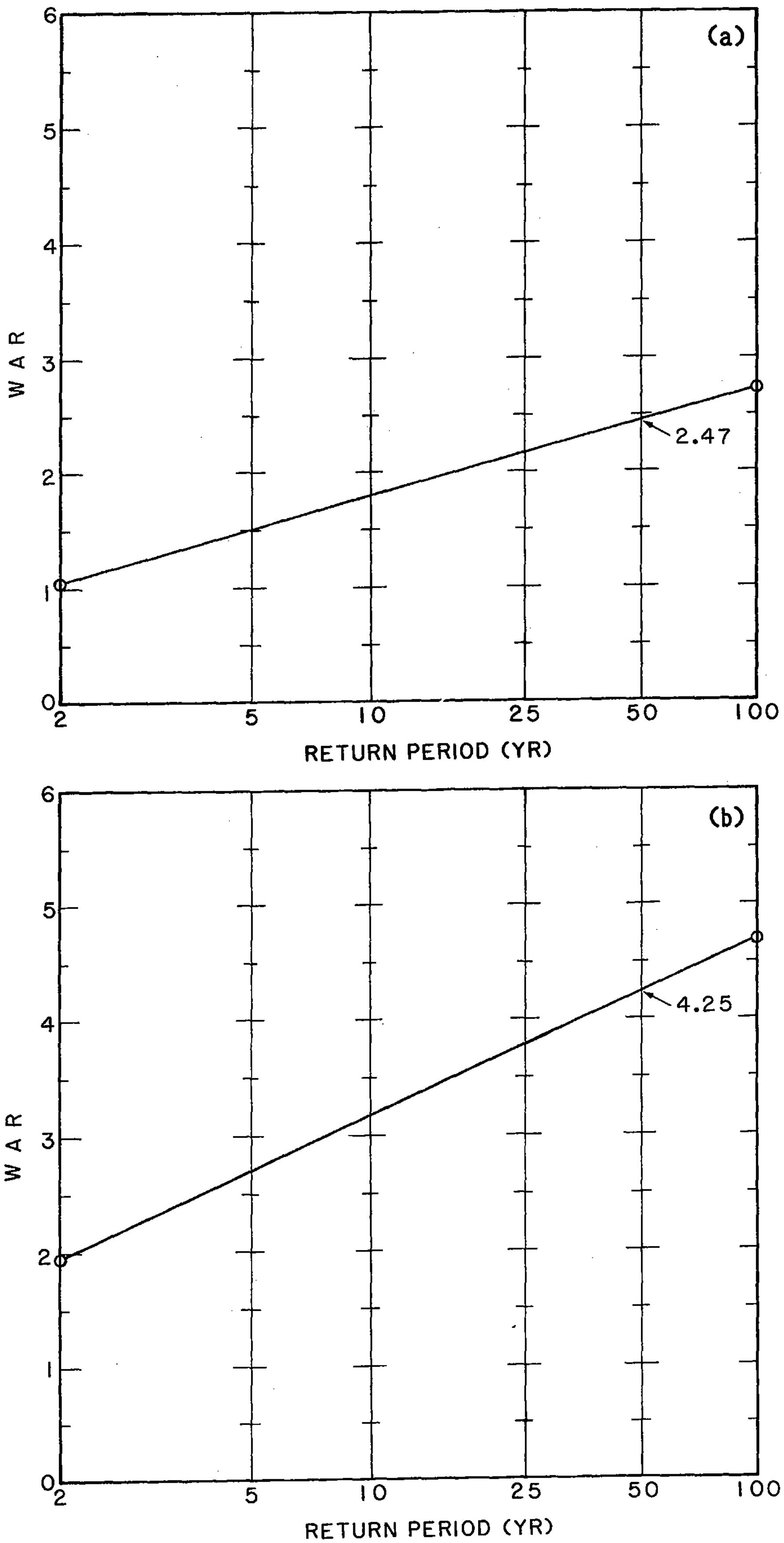


Figure 15.--Example of WAR duration interpolation for the 10-yr amounts at 47°N, 119°W.



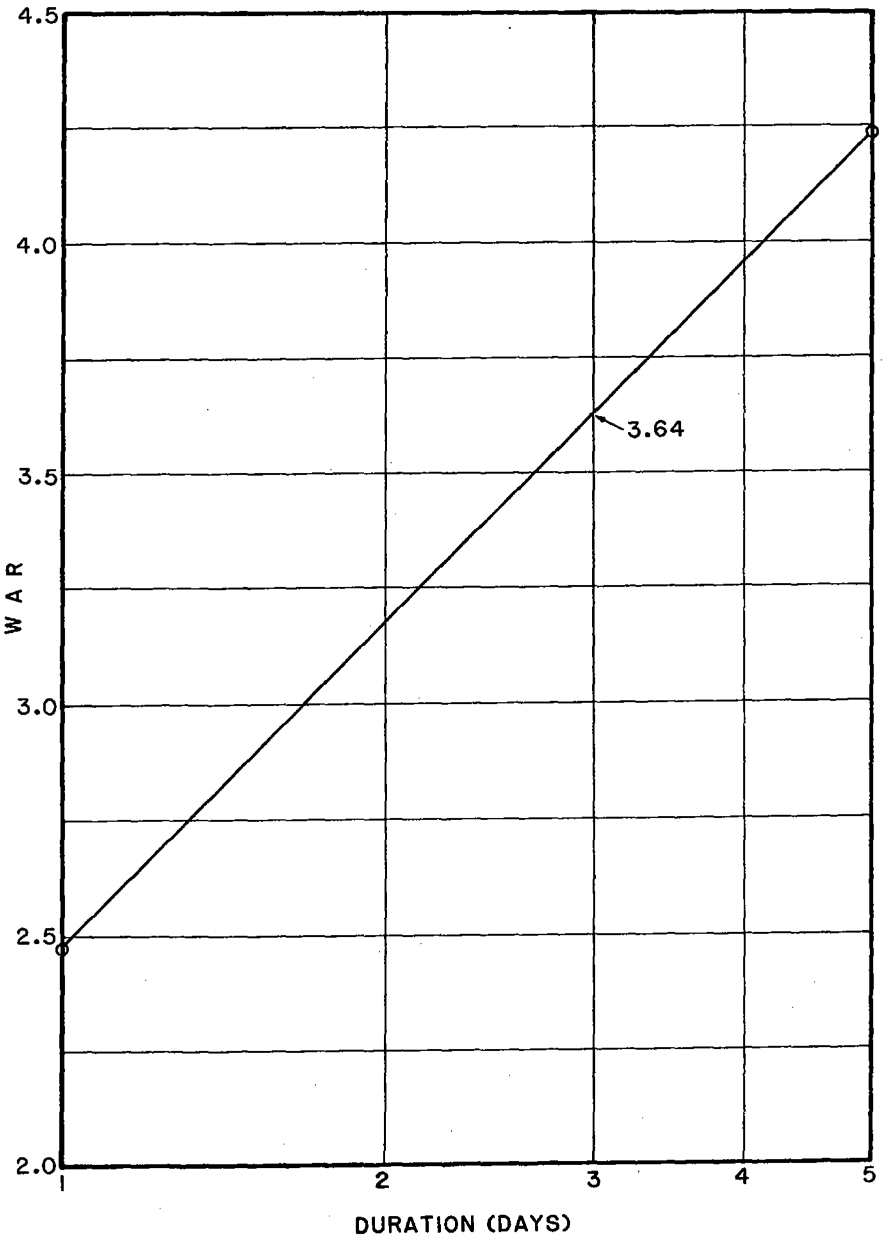


Figure 17.—Example of WAR duration interpolation for the 50-yr amounts at 41°30'N, 112°10'W.

← **Figure 16.**—Examples of WAR return period interpolation for 41°30'N, 112°10'W, (a) 1-day amounts, and (b) 5-day amounts.

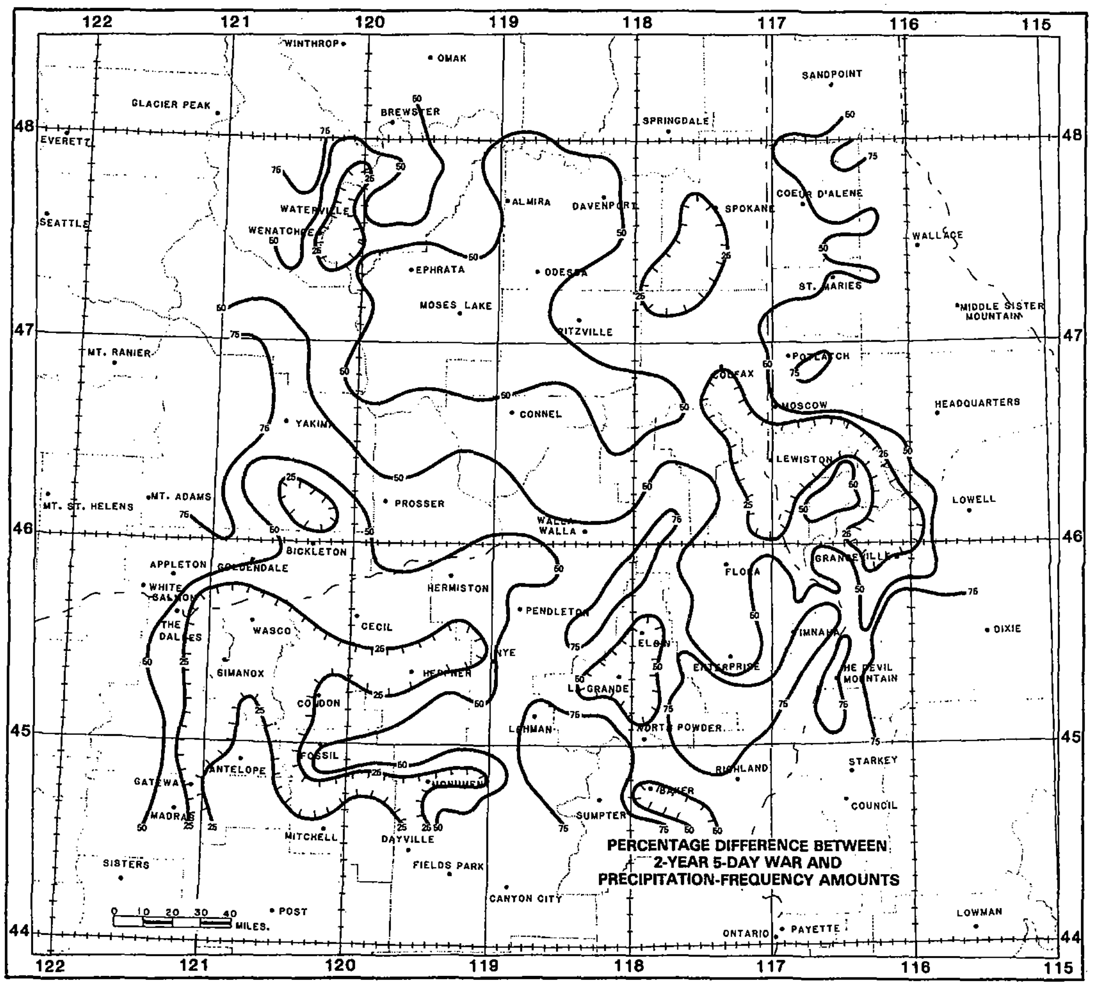


Figure 18.—Comparison of 2-yr 5-day WAR estimates found in the present study with 2-yr 5-day precipitation-frequency estimates found by application of the techniques described by Miller (1964).

as the Yakima Valley and the John Day River Valley, are prominent in the analysis. Although there were indications of lower WAR amounts in some of the smaller valleys, the resolution of the data was not sufficient to determine whether all such valleys were consistently associated with localized minima. Valleys, especially those in higher elevations, may have been too limited in size to significantly affect the larger-scale meteorological flow that produced high WAR values over broad mountainous areas. An enhanced snowpack, due to accumulation of snow blowing into smaller valleys, may also have increased the snowpack above that due to local precipitation alone. Because of these considerations, we chose not to include such small-scale detail in the analysis.

WAR values from this study were compared to precipitation-frequency estimates from NOAA Atlas 2 (Miller et al. 1973). This comparison indicated that the WAR values were generally about 10 percent larger than the 2-yr 24-hr (annual series) precipitation amounts, with some differences as large as 25 percent associated with higher elevations. The annual series for both the precipitation and WAR amounts were generally similar. The modest differences resulted, in part, from the fact that short-duration snowmelt processes generally cannot make water available as rapidly as extreme short duration rainfall rates. Hence, short duration rain events are more likely to produce the maximum annual WAR event than snowmelt, although these rain events may be enhanced by snowmelt.

Differences between precipitation and WAR frequency estimates at longer durations could be expected to be larger because the time scale associated with extreme snowmelt events is probably longer than 24 hr. To evaluate these differences we determined 2-yr 5- and 10-day precipitation amounts using an approach similar to that used by Miller (1964). Miller outlines a method of using 2-yr 24-hr and 2-yr 1-hr precipitation-frequency and latitude to estimate 2-yr 10-day precipitation-frequency amounts. The method involves the use of figure 6 in that publication. This figure was digitized for computer processing and 2-yr 10-day precipitation-frequency values were estimated using the 2-yr 24-hr and 2-yr 1-hr values from NOAA Atlas 2 (Miller et al. 1973). Five-day estimates were obtained by using the interpolation nomogram in Miller (1964). The next step involved estimation of the 100-yr values. In Miller (1964), the 100-yr 10-day map was obtained through application of a geographically varying ratio to the 2-yr 10-day map. The same ratio was used in this study to convert 2-yr 10-day to 100-yr 10-day values. The 100-yr 5-day precipitation-frequency maps were generated using the duration interpolation diagram in Miller. The 2- and 100-yr 10-day WAR amounts were computed by the procedure of this study, namely using the 5- and 15-day maps and the factors in table 4.

An example of the differences between 2-yr 5-day WAR-frequency estimates for the present study and precipitation-frequency estimates for a portion of the study area is shown in figure 18. While the general pattern is similar to the differences between the 2-yr 24-hr NOAA Atlas 2 and WAR frequency values (not shown), the magnitude of the differences is considerably larger. This figure highlights the relationship of the differences to elevation. Smaller differences are generally associated with major valleys and the broad basin between the Cascades and the Bitterroots. The largest differences are associated with the 7,000-ft elevation contours where WAR values were as much as twice as large as the precipitation estimates. Other local maxima, as well as localized minima associated with small valleys also occur, but are not shown in the analysis. The main purpose of this figure is to focus on the broadscale differences between the precipitation and WAR estimates. These differences are generally similar but are possibly somewhat smaller than the corresponding comparison described by Frederick and Tracey (1976). This appears to be consistent with adjustments necessary in the merger regions. In general, the WAR amounts of Frederick and Tracey were reduced slightly to ensure continuous isolines across the interface. In other words, the results of Frederick and Tracey, while generally consistent with those of the present study, may have regions of relatively higher amounts with respect to 5- and 10-day estimates of precipitation-frequency amounts determined by the methods outlined by Miller (1964).

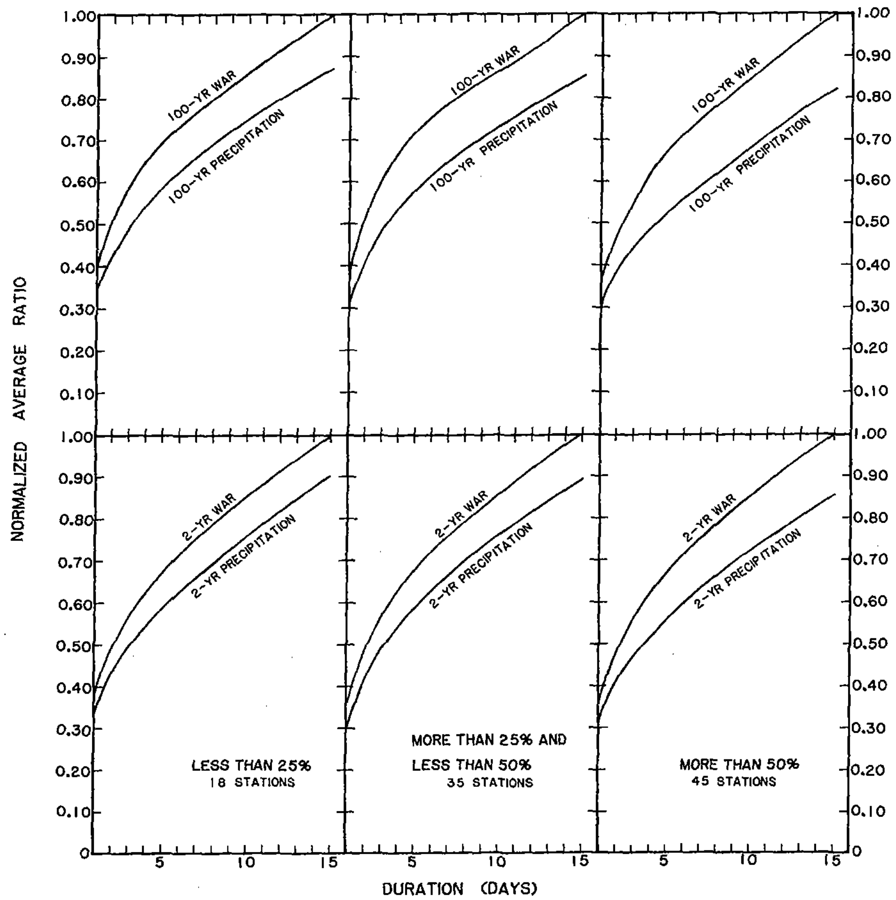


Figure 19.--Effect of NWSRFS snow accumulation and ablation model on the input data. For each duration, the WAR and precipitation frequency estimates are normalized with either the 2-yr or 100-yr WAR amount and the average of all stations is plotted.

Another comparison was made in an attempt to isolate effects due to the physical processes embodied in the snowmelt model. At 98 stations within the area shown in figure 18, 1- to 15-day annual maximum precipitation series were determined and frequency values estimated. The stations were stratified into three groups located in those regions of figure 18 where the differences between precipitation and WAR estimates were (1) less than 25 percent (2) between 25 and 50 percent, and (3) greater than 50 percent. At all stations within each group, the 2-yr 1- to 15-day precipitation and WAR values were normalized by the 2-yr 15-day WAR value. Similarly, all 100-yr values (both precipitation and WAR) were normalized with the 100-yr 15-day WAR value. The normalized values for all stations within each group were averaged and the results plotted as a function of duration (fig. 19). At both the 2- and 100-yr return periods the WAR values exceed the precipitation values at all durations in all three groups. The differences increase with duration, and the differences for the 100-yr values are consistently larger than those for the 2-yr values for all three groups.

9. SUMMARY AND CONCLUSIONS

Climatic precipitation and temperature data were used as input to a snow accumulation and ablation model that yielded annual maximum WAR series. These data were fit to a Fisher-Tippett Type I frequency distribution and the resulting values were used to produce maps of WAR-frequency estimates (appendix E). The broad features of the spatial variation of the WAR field were qualitatively similar to previously published precipitation-frequency maps at the shorter durations, with the WAR values at least 10 percent larger for the 24-hr duration. As both the duration and return period increased, the geographic pattern of the WAR values did not vary significantly, but the magnitudes became progressively larger than corresponding precipitation values. The increase was greatest in higher elevations where snowpack accumulation and spring snowmelt were considerable. At durations in excess of five days, there were broad higher elevation regions where the WAR-frequency values were more than 50 percent greater than corresponding precipitation-frequency values. At some of the highest elevations, the 10-day, 100-yr WAR amounts were as much as three times as large as previous precipitation-frequency estimates. This study's main purpose was to provide WAR estimates in the lower-lying agricultural areas. It's use in higher elevations should be used with some caution because there were a limited number of stations in the mountainous portions of the study area. Additionally, the effect of the orography probably produces patterns far more complex than we were able to depict on the maps in appendix E. Any application involving use of these estimates in the higher elevation regions should fully take into account these uncertainties. Examination of any available snow course or snow pillow data could reduce the degree of uncertainty somewhat.

ACKNOWLEDGMENTS

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APPENDIX A: LIST OF STATIONS

This appendix contains a list of stations used in the analysis of the WAR maps contained in this report. The stations are listed by state and, for each state, they are listed in alphabetical order. A station "ID" code associated with each station is provided for use with appendix C. In addition, each station's location and elevation are listed. Finally, the mean annual precipitation (MAP) and the average annual snowfall at each station are given. MAP values for stations without asterisks came from "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days, 1941-1970" (Environmental Data Service 1973). MAP values were not directly available at those stations marked with asterisks. In Utah, the values with asterisks were estimated from "Normal Annual Seasonal May-September and October-April Precipitation Maps" prepared by the NWS River Forecast Center in Salt Lake City, Utah, and are based on the 1931-60 period. (These maps may be obtained from the Utah State Engineer Office, State Capitol Building, Salt Lake City, Utah 84114). The remaining MAP values marked with asterisks are estimates read from "Normal Annual Precipitation Map" prepared by the NWS River Forecast Center in Portland, Oregon, and are based on a period from 1930-57. (This map is available from the National Technical Service Center, U.S. Department of Agriculture, Soil Conservation Service, Room 209, 511 NW Broadway, Portland, Oregon 97209). Mean snowfall data came from the "Climatic Summary of the United States - Supplement for 1951 through 1960" (Environmental Data Service, 1964-65) and its predecessor publications. The averages in the table included available data for the years 1931-60. The actual number of years used in the calculation of the average is also indicated.

I D A H O

ID	LOCATION	LAT. (DEG/MIN)	LONG. (DEG/MIN)	ELEV. (FT)	MAP (IN)	SNOWFALL (IN)	NO. YRS
525	AVERY RANGER STA	47 15	115 48	2492	33.86		
667	BAYVIEW MODEL BASIN	47 59	116 33	2075	23.00*		
1956	COEUR D'ALENE 1 E	47 41	116 45	2158	26.03	49.8	29
2154	COTTONWOOD	46 03	116 21	3411	20.00*	43.3	26
2575	DIXIE	45 33	115 28	5610	29.00*		
2875	ELK CITY	45 49	115 26	4058	21.00*		
2892	ELK RIVER 1 S	46 46	116 11	2918	40.00*		
3143	FENN RANGER STA	46 06	115 33	1585	36.87		
3771	GRANGEVILLE	45 55	116 08	3355	23.49		
4150	HEADQUARTERS	46 38	115 48	3138	44.60*		
4831	KELLOGG	47 32	116 08	2305	30.56	57.2	21
5011	KOOSKIA	46 09	115 59	1260	25.72		
5241	LEWISTON WSO AP	46 23	117 01	1413	13.21		
5559	MALAD CITY	42 10	112 19	4467	14.50*		
5708	MC CALL	44 54	116 07	5025	28.18	136.0	25
6152	MOSCOW UNIV OF IDA	46 44	116 58	2660	22.62	52.5	20
6388	NEW MEADOWS RGR ST	44 58	116 17	3870	26.20	94.2	20
6424	NEZPERCE	46 15	116 15	3145	22.20	51.6	28
6542	OAKLEY	42 14	113 53	4600	11.54	28.7	29
6681	OROFINO	46 29	116 15	1027	26.06	23.6	15
6891	PAYETTE	44 05	116 56	2150	11.15	20.8	30
7301	POTLATCH 3NNE	46 58	116 53	2600	24.49	48.5	24
7386	PRIEST RIVER EXP S	48 21	116 50	2380	33.30	93.3	30
8062	SAINT MARIES	47 19	116 34	2220	29.98		
8137	SANDPOINT EXP STA	48 17	116 34	2100	33.21	78.3	30
8786	STREVELL	42 01	113 17	5290	11.15		
9498	WALLACE WOODLAND PK	47 30	115 53	2935	36.92	105.7	20
9840	WINCHESTER 1SE	46 14	116 37	3950	22.50*		

U T A H

ID	LOCATION	LAT. (DEG/MIN)	LONG. (DEG/MIN)	ELEV. (FT)	MAP (IN)	SNOWFALL (IN)	NO. YRS
506	BEAR RIVER REFUGE	41 28	112 16	4208	11.97		
924	BRIGHAM CITY	41 29	112 02	4335	19.31		
1731	CORINNE	41 33	112 07	4230	15.62		
2721	FARMINGTON	40 59	111 54	4267	19.00*		
3122	GARLAND	41 44	112 10	4340	15.20*		
3671	HARDWARE RANCH	41 36	111 34	5550	16.00*		
4856	LAKETOWN	41 49	111 19	5980	11.58	47.1	21
5082	LEWISTON	41 58	111 50	4481	17.64	61.3	21
5132	LOGAN RADIO KVNU	41 46	111 50	4504	17.40*		
5186	LOGAN UTAH ST UNIV	41 45	111 49	4785	17.59	65.4	30
5190	LOGAN USU EXP STA	41 46	111 49	4608	18.00*		
5826	MORGAN	41 02	111 41	5070	17.08		
6404	OGDEN PIONEER PH	41 15	111 57	4350	20.11		
6414	OGDEN SUGAR FACTORY	41 14	112 02	4280	16.19		
6869	PINEVIEW DAM	41 15	111 50	4940	28.59	122.1	25
7271	RICHMOND	41 54	111 49	4680	18.52	71.8	21
7318	RIVERDALE PH	41 09	112 00	4390	17.50	41.7	20
7931	SNOWVILLE	41 58	112 43	4560	11.50*		
9595	WOODRUFF	41 32	111 09	6315	9.26	41.1	30

O R E G O N

ID	LOCATION	LAT. (DEG/MIN)	LONG. (DEG/MIN)	ELEV. (FT)	MAP (IN)	SNOWFALL (IN)	NO. YRS
197	ANTELOPE 1 N	44 55	120 43	2835	13.24	23.3	30
265	ARLINGTON	45 43	120 12	315	9.30		
412	BAKER FAA AP	44 50	117 49	3368	8.20*		
417	BAKER KBKR	44 47	117 50	3444	11.25		
897	BONNEVILLE DAM	45 38	121 57	60	75.95	22.3	20
1765	CONDON	45 14	120 11	2830	13.23	31.1	30
1926	COVE 1 ENE	45 18	117 48	3115	23.44	45.3	20
2168	DAYVILLE	44 28	119 32	2364	12.10		
2440	DUFUR	45 27	121 08	1330	12.53	24.7	20
2482	DURKEE 3NNW	44 37	117 29	2780	8.50*		
2564	ECHO	45 45	119 11	660	10.16	10.9	20
2597	ELGIN	45 34	117 55	2655	23.78		
2672	ENTERPRISE	45 26	117 16	3790	13.59	45.5	20
3038	FOSSIL	45 00	120 13	2650	14.30*		
3121	FRIEND	45 21	121 15	2440	17.67		
3402	GOVERNMENT CAMP	45 18	121 45	3980	84.00*		
3604	HALFWAY	44 53	117 07	2670	20.78		
3827	HEPPNER	45 21	119 33	1950	13.91	16.3	30
3847	HERMISTON 2 S	45 49	119 17	624	8.93	11.0	28
4003	HOOD RIVER EXP STA	45 41	121 31	500	30.65	34.1	20
4291	JOHN DAY	44 26	118 57	3063	13.60*		
4411	KENT	45 12	120 42	2720	11.42	23.5	21
4615	LA GRANDE	45 20	118 07	2805	20.14	36.5	21
5139	MADRAS	44 38	121 08	2230	10.19	15.3	30
5396	MEACHAMN WSO AP	45 30	118 24	4050	32.68		
5515	METOLIUS 1 W	44 35	121 11	2500	8.70*		
5545	MIKKALO 6 W	45 28	120 21	1550	10.88		
5593	MILTON FREEWATER 4	45 58	118 25	839	14.25	12.2	24
5610	MINAM 7 NE	45 41	117 35	3584	24.52		
5711	MONUMENT 2	44 49	119 25	1995	11.10*		
5734	MORO	45 29	120 43	1868	11.77	22.4	21
6464	PARKDALE	45 31	121 31	1740	55.00*	95.4	30
6540	PENDLETON BR EX ST	45 43	118 38	1487	12.30*		
6546	PENDLETON WSO AP	45 41	118 51	1482	12.31	18.5	26
6634	PILOT ROCK 1 SE	45 29	118 49	1720	14.48		
6883	PRINEVILLE 4 NW	44 21	120 54	2840	10.49	14.7	30
7052	REDMOND 2 W	44 16	121 13	3010	8.49	17.0	20
7062	REDMOND FAA AP	44 16	121 09	3075	9.03		
7160	RICHLAND	44 46	117 10	2215	13.40*		
8009	SPRAY	44 50	119 47	1770	9.40*		
8407	THE DALLES	45 36	121 12	102	13.80*	24.0	21
8726	UKIAH	45 08	118 55	3355	18.22		
8734	UMATILLA	45 55	119 21	270	9.10*	9.0	20
8746	UNION EXP STA	45 13	117 53	2765	14.32	23.9	21
8985	WALLA WALLA 13ESE	46 00	118 03	2400	42.11		
8997	WALLOWA	45 34	117 32	2923	18.52	49.9	23

W A S H I N G T O N

ID	LOCATION	LAT. (DEG/MIN)	LONG. (DEG/MIN)	ELEV. (FT)	MAP (IN)	SNOWFALL (IN)	NO. YRS
184	ANATONE	46 08	117 09	3570	21.50*		
217	APPLETON	45 49	121 15	2336	35.00*		
668	BICKLETON	46 00	120 18	3000	13.55	29.3	20
1350	CHELAN	47 50	120 02	1120	10.91	44.9	30
1400	CHIEF JOSEPH DAM	48 00	119 39	810	9.60*		
1586	COLFAX 1 NW	46 53	117 23	1955	20.37	26.8	28
1690	CONNELL 1 W	46 40	118 53	1020	8.70*		
1767	COULEE DAM 1 SW	47 57	119 00	1700	11.60*		
1968	DALLESPORT FAA AP	45 37	121 09	222	13.23		
2007	DAVENPORT	47 39	118 09	2460	16.28	49.7	22
2030	DAYTON 1 WSW	46 19	118 00	1557	19.32	19.8	30
2505	ELLENSBURG	46 59	120 32	1520	9.90*		
2540	ELTOPIA 7 WNW	46 29	119 10	895	8.00*		
2614	EPHRATA FAA AP	47 18	119 32	1259	8.26	17.6	28
3546	HATTON 9 ESE	46 45	118 39	1430	10.05	14.4	29
3883	ICE HARBOR DAM	46 15	118 52	368	86.00*		
4154	KENNEWICK	46 13	119 08	392	7.59	12.4	30
4159	KENNEWICK 10 SW	46 08	119 18	1500	9.90*		
4338	LACROSSE 3 ESE	46 48	117 49	1546	13.53	17.2	30
4572	LEAVENWORTH 3 S	47 34	120 40	1128	24.22	94.3	24
4679	LIND 3 NE	47 00	118 35	1625	9.91	16.2	24
5231	MCNARY DAM	45 57	119 18	361	7.80*		
5613	MOSES LAKE 3 E	47 07	119 12	1208	8.00*		
5638	MOXEE CITY 10 E	46 31	120 10	1550	9.20*		
5832	NESPELEM 2 S	48 08	118 59	1890	13.33	31.8	25
6039	ODESSA	47 20	118 41	1540	10.42	18.9	20
6215	OTHELLO 6 ESE	46 48	119 03	1190	8.08		
6534	PLAIN	47 47	120 39	1940	25.96		
6610	POMEROY	46 28	117 37	1810	16.13		
6747	PRIEST RAPIDS DAM	46 39	119 54	460	9.60*		
6768	PROSSER 4 NE	46 15	119 45	903	7.88		
6789	PULLMAN 2 NW	46 46	117 12	2545	20.91		
6830	QUINCY 1 S	47 13	119 51	1274	8.15		
7015	RICHLAND	46 17	119 18	357	9.30*		
7059	RITZVILLE 1SSE	47 07	118 22	1830	11.84	15.5	30
7180	ROSALIA	47 14	117 22	2400	18.03	29.2	27
7727	SMYRNA	46 50	119 40	560	8.30*		
7933	SPOKANE	47 40	117 25	1875	19.00*		
7938	SPOKANE WSO AP	47 38	117 32	2349	17.42		
7956	SPRAGUE	47 18	117 59	1930	14.97	22.4	28
8207	SUNNYSIDE	46 19	120 00	747	6.81	11.6	30
8928	WALLA WALLA FAA AP	46 06	118 17	1170	17.00*		
8931	WALLA WALLA WSO	46 02	118 20	949	16.01		
8959	WAPATO	46 26	120 25	850	7.28		
9012	WATERVILLE	47 39	120 04	2620	11.56		
9058	WELLPINIT	47 53	117 59	2450	19.75	58.8	29
9074	WENATCHEE	47 25	120 19	634	8.95	31.5	30
9082	WENATCHEE FAA AP	47 24	120 12	1229	9.40*		
9191	WHITE SWAN R S	46 23	120 43	970	12.00*		
9238	WILBUR	47 45	118 42	2160	12.66		
9327	WILSON CREEK	47 25	119 07	1276	9.20	19.6	29
9465	YAKIMA WSO	46 34	120 32	1064	8.00		

APPENDIX B: DATA PROCESSING

As indicated in section 2, the daily data used for this study were obtained from magnetic tapes, prepared by the National Climatic Data Center in Asheville, North Carolina, for the National Weather Service's (NWS) Office of Hydrology (Peck et al., 1977). Depending on the particular station, these tapes contain observations of some or all of the following: precipitation, maximum and minimum air temperature, snowfall, snow on the ground, and water equivalent of snow cover. Almost all stations record precipitation amounts as well as maximum and minimum temperatures. In the areas of the western United States where the water supply is heavily dependent on snowfall, a large number of the stations also report snowfall and snow on the ground. Few stations report water equivalent. The original set of data tapes covered the period 1948-73. These tapes were supplemented by a set of data tapes covering the years 1974-76. Subject to funding availability, updates are planned for subsequent periods, but, at the time of this study, no further data were available to the Office of Hydrology. Not all stations had observations for all years. (See table 1 in text.)

While only those stations with 15 or more years of data were ultimately used, all available precipitation, maximum and minimum temperature, snowfall, snow on the ground, and water equivalent data for all stations within the study area were extracted from the magnetic tapes and transferred to direct access disk files. An indexing system allowed random access to any quantity for any station and for any year. This greatly facilitated quality control and further processing of the data. Because the primary inputs to the snowmelt model were precipitation and maximum and minimum temperature, these quantities were automatically screened for potential problems. A computer program flagged large gaps in the data, printed all values outside predetermined upper and lower bounds, and produced frequency distributions of the data for each year. Using the frequency distributions, the program also indicated the dates of observations that were "outliers." Another possible problem, limited to precipitation, was the occurrence of accumulations. Accumulated precipitation is a total over some number of days, and is recorded on the last day of the accumulation period. Accumulations extending over long periods were also automatically flagged. The program flagged large day-to-day temperature variations. Large changes usually indicated either erroneous data or the passage of a frontal system.

The output from the screening program was used as the basis of a manual review and edit of the data. No data were actually discarded or edited automatically. In some cases, data available in published form (Environmental Data Service, 1948-76), had not been included on the magnetic tapes. The manual edit also added these values to the data base.

On completion of the manual editing, the data base was "clean" but still had gaps due to missing data, and, in the case of precipitation, due to accumulations. Because the snowmelt model required continuous observations, these gaps had to be filled if the model were to be run on a given year. For missing values, linear interpolation between the last observation before the gap and the first observation after the gap was rejected. This would not have been appropriate for precipitation because of its sporadic day-to-day variability. While the time variation of temperature is considerably smoother than that of precipitation, winter precipitation is frequently associated with the passage of frontal systems. Because accurate temperatures are vital to the model's ability to discriminate between rain and snow and, hence, are crucial to the successful modeling of snowpack buildup, temporal interpolation may not have provided adequate estimates.

As an alternate to time interpolation, the possibility of spatial interpolation was examined. Scatter diagrams showing the relationship between daily observations of precipitation and maximum and minimum temperature between pairs of stations were generated. Although the scatter was considerable in some cases, there was no indication that the relationship was anything but linear. The scatter increased as the separation between the two stations became larger, and there was much more scatter for precipitation than for either maximum or minimum temperatures.

Based on an examination of the scatter diagrams (not shown), linear correlation coefficients between precipitation or temperature at a number of "base" stations and all other stations within the study area were calculated and plotted as a function of separation distance. (To avoid the amount of computing time that would have been required, the correlation as a function of separation distance was computed for only a representative sample of stations.) This was used as a guide to determine separation distances over which spatial interpolation would be reasonable. Figure B-1 shows an example of how the correlation between precipitation, and maximum and minimum temperatures at Anatone, Washington, and other stations within the study area varied as a function of separation distance. These curves are based on averages of all stations falling within 3-mile radius intervals. They show a general decrease with separation distance. The low precipitation correlation around 25 miles appeared to be specific to Anatone because it did not occur at other stations that were examined. Similar anomalously low (and high) correlations occurred randomly at separation distances that varied from station to station.

The curves for maximum and minimum temperature at Anatone show much higher correlation than for precipitation, and the decrease with increasing separation distance is much smaller. This reflects the fact that spatial temperature variation is much smoother than that for precipitation which, at times, tends to be stochastic in nature. Based on the data sample that was examined, the factor limiting the separation distance over which spatial filling was attempted was the spatial decay of the precipitation correlation coefficient. A preliminary range cutoff of 50 miles was selected. At this range, a typical precipitation correlation coefficient was about 0.5 and the maximum and minimum temperature correlations were about 0.9 and 0.8, respectively.

All stations were automatically examined on a year-by-year basis for missing data. For those stations that had missing values, a search was made for all other stations that fell within 50 miles of that station. A further check was made to eliminate all stations that were more than 100 feet above or below the station with missing data. Correlation coefficients were computed between the station with missing data and all stations within this cylinder (radius 50 mi, height 200 ft) centered on the station.

If there were more than four stations within the cylinder, the four stations with the highest correlations were selected. This selection was made separately for each year and for each quantity. This meant that the stations used to fill one variable, say maximum temperature, could be different from those used to fill another, such as minimum temperature. Also, the stations used could vary from year to year. If there were less than four stations available, those that were available were used. In any case, 1) no station was used if the correlation was less than 0.37, 2) at least one station had to have a correlation of 0.5 before filling was attempted, 3) stations with correlations less than 0.5 were flagged to indicate that the interpolations should be checked, and 4) the length of the gap to be filled was no greater than a preselected duration. Because of the highly variable nature of precipitation, gaps longer

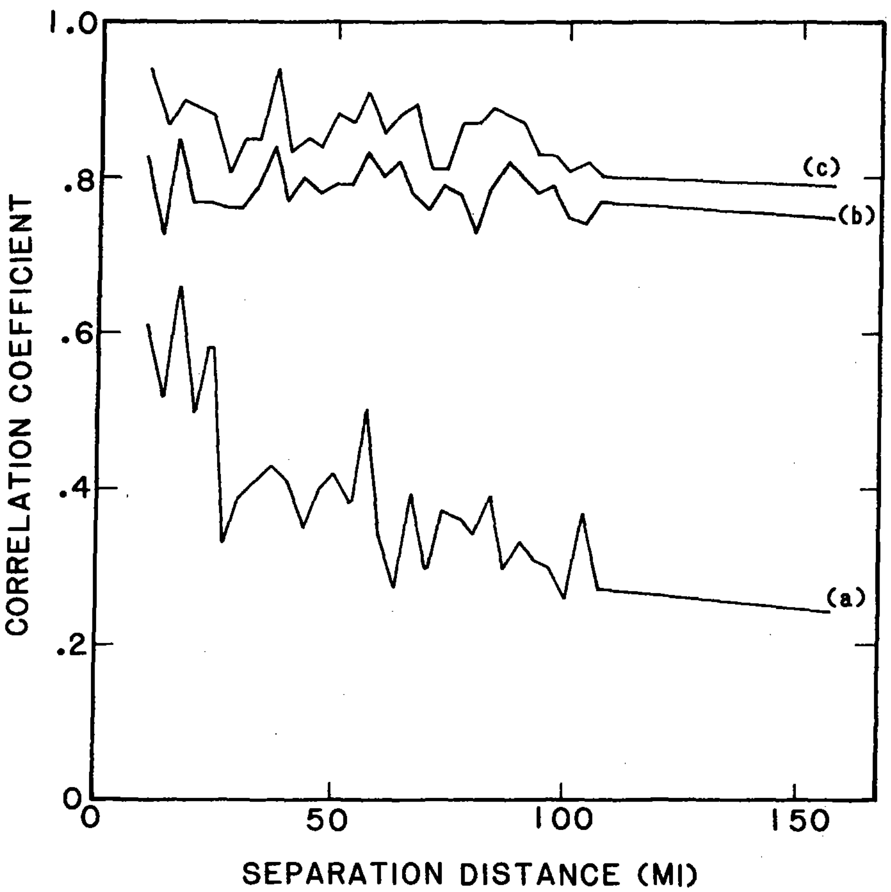


Figure B-1.--Correlation between (a) daily precipitation amounts (b) minimum temperature, and (c) maximum temperature at Anatone, Washington, and all other stations as a function of separation distance. All correlation coefficients within 3-mi radial intervals were averaged.

than one week were generally not filled on the first pass. The very high correlation between the temperatures at various stations permitted sufficient confidence to allow filling of temperature gaps of almost any length.

Using those stations available within the cylinder that met the above conditions, a missing value was filled with the weighted average of the simultaneous values of the surrounding stations. The weighting factors were determined by normalizing the square(s) of the correlation coefficient(s) between the station with gaps and the surrounding station(s) by the sum of squares of all correlation coefficients. (The square of the correlation coefficient is a measure of the amount of variability that a linear relationship between the two stations would explain.) In the case of large gaps in the temperature data, there had to be at least 100 days where both the station with missing values and the one used for filling

Table B-1.--Example of scheme used to distribute precipitation accumulations

Day	Station A: Precipitation amount (in.) before	Station A: after	Station B: Precip. amt. (in.)	Station B: Fraction of total amount	Station C: Precip. amt. (in.)	Station C: Fraction of total amount	Factor
1	*	0.11	0.20	0.19	0	0	0.095
2	*	0.25	0.25	0.24	0.20	0.17	0.205
3	*	0	0	0	0	0	0
4	*	0.82	0.60	0.57	0.95	0.79	0.680
5	1.20	0.02	0	0	0.05	0.04	0.020
Total	1.20		1.05		1.20		

had simultaneous observations. This was done as a practical matter to ensure representative correlation coefficients and, hence, representative weights. A bias adjustment was also made to the temperature data, primarily to account for the vertical lapse rate of temperature. This was done by simply adding or subtracting the mean difference between the two stations' temperatures before the weighted average was computed.

In some cases, all missing data for a particular station, year and quantity were not filled on the first pass. Generally, at least one more pass was attempted in order to fill the remaining missing values. The approach was to examine the correlation at more stations by increasing either the radius and/or the elevation used to define the cylinder containing these stations. The amount of radial and elevation increase depended on whether the quantity was precipitation or temperature. In the case of precipitation, the limits were more stringent because of the rapid decrease in correlation as a function of separation distance (fig. B-1). On occasion, a second pass was made in an attempt to fill gaps in the precipitation data that were longer than a week when the surrounding stations showed high correlation with the station containing the missing data. In all cases of precipitation filling, large interpolated values (more than 1 in./day) were manually verifed against supporting data from surrounding stations.

The method of filling gaps in the precipitation data that resulted from accumulations was also based on those stations falling within the cylinder described above; the stations used were identified and selected in the same manner. Since the total amount of precipitation that fell during the gap was known, the limit on the interval that could be filled was increased to two weeks. The remaining problem was to determine how to distribute the precipitation over the accumulation interval. For each surrounding station used, the total precipitation that fell during the accumulation interval was determined. Then the fraction of this total that fell on each day was determined. The weighted average of all fractions was then applied to the accumulation total for the station to be filled.

To illustrate this, consider the example presented in table B-1. Data from three hypothetical stations are presented. Over this period a total of 1.20 in. of precipitation fell at station A.

During this same period 1.05 in. fell at station B and 1.20 in. fell at station C. For station B, 0.19 of the 5-day total fell on day one, 0.24 fell on day two, no precipitation fell on day three, 0.57 of the total fell on day four, and none fell on day five. The corresponding values for station C are: 0, 0.17, 0, 0.79, and 0.04 percent. Assuming both stations are within the cylinder, and that both have the same correlation (equal weights), the factors applied to the accumulation for station A are given in the last column. That is, the day one value is found by multiplying 1.20 by 0.095, etc. The resulting interpolated amounts for station A are given in the "after" column. When all accumulation gaps were not filled during the first pass, subsequent passes with increased limits (on the search cylinder size) were generally attempted.

In some cases small gaps, either due to missing values or accumulations, could not be filled using the above approach because there were no stations within the cylinder with a high enough correlation. In a few isolated cases, if it was unlikely that erroneous values would be introduced, subjective interpolations were made. The most common case occurred when a missing precipitation value was filled with zero because few if any of the surrounding stations recorded any appreciable precipitation.

APPENDIX C

Model-Derived, 1-Day Water Equivalent Frequency Estimates

As a by-product of this study, annual series of 1-day water equivalent values were determined from the model simulations. While the frequency estimates in this appendix are given to two decimal places, this is not meant to imply confidence at this level. In general, the same problems associated with short duration WAR estimates are likely to affect the water equivalent estimates. (See section 5.2.) In addition to these model-associated uncertainties that are nearly impossible to quantify, there are uncertainties associated with the fitting of the data (using the Gumbel technique) to the Fisher-Tippett Type I frequency distribution. While it seems reasonable to fit the data to a Fisher-Tippett distribution, we are unaware of any work examining the appropriateness of the use of this distribution with water equivalent measurements. No attempt was made to explore this question as part of this study. The only component of uncertainty that was readily quantifiable is that associated with the (small) sample size. For each station in the table that follows, two values are given for each return period. The numbers on the first line are the water equivalent frequency estimates. The numbers on the second line provide a factor that can be added to or subtracted from the corresponding frequency estimate to yield the 95 percent confidence interval and were determined using the technique of Kaczmarek (1957). As a practical matter, the values provided in this section should probably be rounded to the nearest whole number. We feel that no greater confidence is warranted.

Water equivalent frequency estimates in this appendix are only provided at station locations. Maps portraying these fields would have been subject to considerable uncertainty in data sparse regions. Additionally, the work required to depict these fields was beyond the scope of this study. The listing that follows is divided into two sections: the first section contains the stations in the Tri-State region and the second contains estimates for stations in the northern Utah area. The stations are identified by their code numbers. The first two-digit number is the state code (10 = ID, 35 = OR, 42 = UT, 45 = WA) and the second 3- or 4-digit number is the station code. Appendix A contains a table providing a list of station code numbers, station names, and their locations that can be used as a cross reference.

TRI-STATE REGION

STATE/ STATION	NO. YRS.	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
10/ 525	20	5.52	9.22	11.67	14.77	17.07	19.35
		1.18	2.20	3.06	4.20	5.06	5.93
10/ 667	28	2.58	4.42	5.64	7.18	8.32	9.46
		0.52	0.94	1.30	1.78	2.14	2.50
10/1956	28	2.97	5.64	7.41	9.65	11.30	12.95
		0.75	1.36	1.88	2.58	3.10	3.63
10/2154	19	1.96	3.93	5.23	6.88	8.10	9.31
		0.64	1.20	1.67	2.29	2.76	3.23
10/2575	24	15.11	20.09	23.39	27.55	30.64	33.71
		1.48	2.73	3.78	5.18	6.23	7.29

TRI-STATE REGION

STATE/ STATION	NO. YRS.	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
10/2875	16	8.27 1.64	12.99 3.11	16.12 4.34	20.07 5.97	23.00 7.20	25.91 8.43
10/2892	24	10.36 1.59	15.69 2.92	19.23 4.05	23.69 5.55	27.01 6.69	30.30 7.62
10/3143	28	4.58 0.95	7.99 1.74	10.24 2.40	13.08 3.28	15.19 3.95	17.29 4.62
10/3771	23	1.49 0.32	2.56 0.60	3.26 0.83	4.16 1.14	4.82 1.37	5.48 1.60
10/4150	17	9.18 1.78	14.43 3.36	17.91 4.69	22.29 6.44	25.55 7.77	28.78 9.10
10/4831	26	3.15 0.76	5.80 1.40	7.55 1.94	9.77 2.65	11.42 3.19	13.05 3.74
10/5011	27	1.18 0.21	1.91 0.38	2.40 0.53	3.01 0.72	3.47 0.87	3.92 1.02
10/5241	28	0.65 0.17	1.25 0.30	1.64 0.42	2.14 0.57	2.51 0.69	2.87 0.81
10/5708	27	10.74 0.90	13.89 1.64	15.98 2.27	18.62 3.10	20.58 3.73	22.52 4.36
10/6152	28	2.33 0.62	4.56 1.14	6.03 1.57	7.90 2.15	9.28 2.59	10.65 3.03
10/6388	26	7.10 0.77	9.77 1.41	11.54 1.95	13.77 2.67	15.43 3.22	17.08 3.76
10/6424	24	1.68 0.30	2.67 0.54	3.33 0.76	4.16 1.03	4.78 1.25	5.39 1.46
10/6681	28	1.33 0.35	2.60 0.65	3.44 0.89	4.50 1.22	5.29 1.47	6.07 1.72
10/6891	27	0.94 0.18	1.58 0.33	2.01 0.46	2.55 0.63	2.95 0.76	3.35 0.89
10/7301	24	2.08 0.53	3.87 0.98	5.05 1.36	6.55 1.86	7.66 2.24	8.76 2.62
10/7386	28	8.08 0.95	11.49 1.74	13.74 2.40	16.59 3.29	18.71 3.96	20.80 4.63
10/8062	26	3.42 0.73	5.96 1.34	7.65 1.86	9.77 2.54	11.35 3.06	12.92 3.58
10/8137	28	5.32 0.84	8.31 1.52	10.29 2.11	12.79 2.88	14.64 3.47	16.48 4.06
10/9498	28	5.74 0.97	9.21 1.77	11.51 2.45	14.42 3.35	16.58 4.03	18.71 4.72
10/9840	17	3.01 0.71	5.09 1.33	6.47 1.86	8.21 2.56	9.51 3.08	10.79 3.61
35/ 197	28	0.78 0.16	1.37 0.30	1.75 0.41	2.24 0.56	2.61 0.68	2.97 0.79
35/ 265	27	0.62 0.17	1.21 0.31	1.60 0.42	2.09 0.58	2.46 0.70	2.82 0.81
35/ 412	28	0.93 0.17	1.53 0.31	1.94 0.43	2.44 0.59	2.82 0.71	3.20 0.82
35/ 417	25	1.05 0.20	1.75 0.37	2.21 0.52	2.79 0.71	3.22 0.86	3.65 1.00
35/ 897	28	2.28 0.62	4.48 1.12	5.94 1.55	7.78 2.13	9.15 2.56	10.50 2.99
35/1765	25	0.81 0.15	1.34 0.28	1.69 0.39	2.13 0.54	2.46 0.65	2.78 0.76
35/1926	24	1.15 0.27	2.07 0.50	2.68 0.70	3.45 0.96	4.02 1.15	4.59 1.35

TRI-STATE REGION

STATE/ STATION	NO. YRS.	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
35/2168	24	0.51 0.10	0.84 0.18	1.06 0.25	1.34 0.34	1.54 0.42	1.75 0.49
35/2440	25	1.19 0.32	2.29 0.59	3.02 0.82	3.95 1.13	4.63 1.35	5.31 1.58
35/2482	26	0.88 0.25	1.74 0.45	2.30 0.63	3.02 0.86	3.55 1.03	4.08 1.21
35/2564	17	0.58 0.15	1.04 0.29	1.34 0.41	1.72 0.56	2.01 0.68	2.29 0.79
35/2597	23	1.66 0.41	3.01 0.75	3.90 1.04	5.02 1.43	5.86 1.72	6.68 2.01
35/2672	27	1.10 0.21	1.83 0.38	2.31 0.52	2.92 0.72	3.38 0.86	3.82 1.01
35/3038	24	0.65 0.16	1.21 0.30	1.57 0.42	2.03 0.57	2.38 0.69	2.72 0.81
35/3121	26	2.22 0.52	4.03 0.95	5.23 1.32	6.74 1.81	7.86 2.18	8.97 2.54
35/3402	15	17.15 4.20	28.99 8.01	36.86 11.21	46.73 15.43	54.07 18.62	61.36 21.81
35/3604	23	4.56 0.76	7.07 1.40	8.74 1.95	10.84 2.67	12.41 3.22	13.96 3.76
35/3827	26	0.74 0.15	1.27 0.28	1.63 0.39	2.07 0.53	2.41 0.64	2.73 0.75
35/3847	28	0.66 0.12	1.10 0.22	1.39 0.31	1.75 0.42	2.02 0.51	2.29 0.59
35/4003	27	2.31 0.62	4.48 1.13	5.91 1.56	7.73 2.13	9.08 2.57	10.41 3.00
35/4291	20	0.66 0.12	1.03 0.22	1.28 0.31	1.59 0.42	1.82 0.51	2.04 0.59
35/4411	28	0.90 0.18	1.56 0.34	1.99 0.47	2.55 0.64	2.96 0.77	3.36 0.90
35/4615	17	1.16 0.41	2.36 0.77	3.15 1.07	4.15 1.47	4.89 1.77	5.63 2.08
35/5139	26	0.65 0.14	1.16 0.27	1.49 0.37	1.91 0.50	2.22 0.61	2.53 0.71
35/5396	22	7.34 1.45	12.04 2.68	15.15 3.72	19.08 5.10	22.00 6.14	24.90 7.19
35/5515	21	0.58 0.15	1.05 0.27	1.36 0.38	1.75 0.52	2.04 0.62	2.32 0.73
35/5545	19	0.57 0.12	0.95 0.23	1.20 0.33	1.53 0.45	1.76 0.54	2.00 0.63
35/5593	25	0.72 0.15	1.23 0.28	1.58 0.39	2.01 0.53	2.33 0.64	2.65 0.74
35/5610	15	4.96 0.91	7.52 1.74	9.22 2.43	11.37 3.34	12.96 4.03	14.54 4.72
35/5711	15	0.60 0.13	0.96 0.25	1.20 0.34	1.51 0.47	1.73 0.57	1.96 0.67
35/5734	28	0.95 0.20	1.65 0.36	2.11 0.50	2.70 0.68	3.14 0.82	3.57 0.95
35/6464	19	4.49 1.32	8.54 2.46	11.22 3.43	14.60 4.71	17.12 5.68	19.61 6.65
35/6540	18	0.86 0.24	1.59 0.46	2.08 0.64	2.69 0.87	3.14 1.05	3.59 1.23
35/6546	28	0.67 0.17	1.26 0.30	1.66 0.42	2.16 0.58	2.53 0.69	2.90 0.81

TRI-STATE REGION

STATE/ STATION	NO. YRS.	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
35/6634	20	0.69 0.14	1.14 0.26	1.43 0.37	1.80 0.51	2.08 0.61	2.35 0.71
35/6883	27	0.61 0.11	0.99 0.19	1.23 0.27	1.55 0.37	1.78 0.44	2.01 0.52
35/7052	28	0.70 0.13	1.16 0.24	1.47 0.33	1.87 0.45	2.16 0.54	2.44 0.64
35/7062	27	0.86 0.16	1.42 0.29	1.79 0.40	2.26 0.55	2.60 0.66	2.95 0.77
35/7160	16	0.87 0.22	1.49 0.41	1.91 0.57	2.43 0.79	2.81 0.95	3.20 1.11
35/8009	18	0.39 0.10	0.69 0.18	0.88 0.26	1.13 0.35	1.31 0.43	1.50 0.50
35/8407	20	1.16 0.45	2.55 0.85	3.47 1.18	4.64 1.62	5.51 1.96	6.36 2.29
35/8726	24	1.73 0.29	2.69 0.53	3.33 0.73	4.14 1.00	4.74 1.21	5.33 1.41
35/8734	17	0.53 0.19	1.07 0.35	1.44 0.49	1.89 0.67	2.23 0.81	2.57 0.95
35/8746	28	0.65 0.10	1.02 0.19	1.26 0.26	1.57 0.35	1.79 0.42	2.02 0.50
35/8985	27	3.84 1.18	8.00 2.16	10.76 2.99	14.24 4.09	16.82 4.92	19.38 5.75
35/8997	22	1.58 0.36	2.74 0.66	3.50 0.91	4.47 1.25	5.18 1.51	5.90 1.77
45/ 184	25	2.59 0.48	4.24 0.88	5.33 1.23	6.71 1.68	7.73 2.02	8.74 2.36
45/ 217	17	5.37 1.56	9.98 2.95	13.03 4.12	16.88 5.66	19.74 6.82	22.58 7.99
45/ 668	21	1.86 0.49	3.42 0.91	4.45 1.26	5.76 1.73	6.73 2.08	7.69 2.44
45/1350	18	1.57 0.47	2.98 0.88	3.91 1.22	5.09 1.68	5.96 2.03	6.83 2.37
45/1400	24	1.56 0.38	2.84 0.70	3.69 0.98	4.77 1.34	5.57 1.61	6.36 1.88
45/1586	28	1.39 0.42	2.89 0.76	3.88 1.06	5.13 1.44	6.06 1.74	6.98 2.03
45/1690	15	0.71 0.25	1.40 0.47	1.86 0.66	2.44 0.91	2.88 1.09	3.30 1.28
45/1767	28	1.46 0.24	2.34 0.45	2.91 0.62	3.65 0.84	4.19 1.01	4.72 1.19
45/1968	28	1.28 0.35	2.54 0.64	3.37 0.89	4.42 1.21	5.20 1.46	5.97 1.70
45/2007	24	2.56 0.59	4.54 1.09	5.86 1.51	7.52 2.06	8.75 2.49	9.97 2.91
45/2030	26	0.97 0.26	1.86 0.47	2.44 0.65	3.19 0.89	3.74 1.07	4.28 1.25
45/2505	20	1.56 0.42	2.89 0.79	3.77 1.10	4.88 1.51	5.71 1.82	6.52 2.13
45/2540	17	0.70 0.19	1.27 0.36	1.65 0.51	2.12 0.70	2.48 0.84	2.83 0.99

TRI-STATE REGION

STATE/ STATION	NO. YRS.	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
45/2614	27	1.37 0.27	2.34 0.50	2.98 0.69	3.79 0.95	4.39 1.14	4.99 1.34
45/3546	28	0.95 0.24	1.80 0.43	2.36 0.60	3.07 0.82	3.60 0.99	4.13 1.16
45/3883	19	0.58 0.19	1.17 0.36	1.56 0.50	2.05 0.68	2.41 0.83	2.78 0.97
45/4154	28	0.53 0.14	1.01 0.25	1.34 0.34	1.74 0.47	2.05 0.57	2.35 0.66
45/4159	24	0.80 0.16	1.35 0.30	1.72 0.42	2.18 0.57	2.52 0.69	2.86 0.81
45/4338	28	0.94 0.21	1.70 0.39	2.20 0.54	2.84 0.74	3.31 0.88	3.78 1.03
45/4572	24	9.29 1.69	14.99 3.12	18.76 4.33	23.53 5.92	27.06 7.13	30.57 8.34
45/4679	28	0.86 0.17	1.45 0.30	1.85 0.42	2.34 0.57	2.71 0.69	3.07 0.80
45/5231	15	0.39 0.13	0.74 0.24	0.96 0.34	1.25 0.47	1.47 0.56	1.68 0.66
45/5613	24	0.95 0.22	1.70 0.41	2.20 0.57	2.82 0.78	3.29 0.94	3.75 1.10
45/5688	28	0.77 0.21	1.51 0.38	2.01 0.52	2.63 0.72	3.09 0.86	3.54 1.01
45/5832	28	1.76 0.29	2.78 0.52	3.46 0.72	4.31 0.99	4.95 1.19	5.58 1.39
45/6039	28	1.18 0.25	2.07 0.45	2.65 0.63	3.40 0.86	3.95 1.03	4.50 1.21
45/6215	23	0.78 0.23	1.52 0.42	2.02 0.58	2.64 0.79	3.10 0.95	3.56 1.12
45/6534	15	11.17 2.10	17.10 4.01	21.03 5.61	25.99 7.73	29.66 9.32	33.32 10.92
45/6610	27	0.77 0.17	1.36 0.31	1.76 0.43	2.26 0.59	2.63 0.70	2.99 0.82
45/6747	19	0.61 0.18	1.18 0.35	1.55 0.48	2.03 0.66	2.38 0.80	2.73 0.93
45/6768	27	0.61 0.13	1.06 0.23	1.36 0.32	1.73 0.44	2.01 0.53	2.29 0.62
45/6789	27	2.32 0.52	4.16 0.95	5.38 1.32	6.92 1.81	8.06 2.17	9.19 2.54
45/6880	27	1.23 0.29	2.24 0.53	2.92 0.73	3.77 1.00	4.40 1.20	5.02 1.40
45/7015	27	0.48 0.10	0.85 0.19	1.09 0.27	1.39 0.36	1.62 0.44	1.84 0.51
45/7059	28	1.25 0.25	2.13 0.45	2.71 0.62	3.45 0.85	4.00 1.02	4.54 1.20
45/7180	25	1.27 0.46	2.83 0.84	3.86 1.16	5.16 1.59	6.13 1.91	7.09 2.24
45/7727	18	1.01 0.23	1.69 0.43	2.14 0.59	2.71 0.81	3.13 0.98	3.55 1.15
45/7933	17	1.16 0.56	2.81 1.06	3.90 1.48	5.29 2.03	6.31 2.45	7.33 2.87

TRI-STATE REGION

STATE/ STATION	NO. YRS.	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
45/7938	26	2.61 0.63	4.81 1.16	6.26 1.61	8.10 2.20	9.47 2.65	10.82 3.10
45/7956	21	1.69 0.44	3.08 0.81	4.01 1.13	5.18 1.55	6.04 1.87	6.90 2.18
45/8207	28	0.63 0.15	1.17 0.28	1.53 0.38	1.98 0.52	2.32 0.63	2.65 0.73
45/8928	26	0.82 0.20	1.50 0.36	1.95 0.50	2.52 0.68	2.94 0.82	3.36 0.95
45/8931	28	0.91 0.17	1.52 0.32	1.93 0.44	2.45 0.60	2.83 0.72	3.21 0.84
45/8959	28	0.91 0.28	1.90 0.51	2.57 0.71	3.40 0.96	4.02 1.16	4.64 1.36
45/9012	15	2.98 0.68	4.90 1.30	6.17 1.82	7.78 2.50	8.97 3.02	10.15 3.54
45/9058	15	3.33 1.05	6.30 2.01	8.27 2.81	10.75 3.87	12.60 4.67	14.43 5.47
45/9074	26	1.44 0.32	2.54 0.58	3.26 0.80	4.18 1.10	4.87 1.32	5.54 1.55
45/9082	16	1.72 0.50	3.17 0.95	4.12 1.33	5.33 1.82	6.22 2.20	7.11 2.58
45/9191	17	1.43 0.45	2.74 0.84	3.61 1.17	4.71 1.61	5.53 1.95	6.34 2.28
45/9238	26	1.67 0.39	3.04 0.72	3.94 1.00	5.09 1.37	5.94 1.65	6.78 1.93
45/9327	28	1.09 0.23	1.91 0.42	2.45 0.58	3.13 0.79	3.63 0.95	4.14 1.11
45/9465	28	1.30 0.35	2.55 0.64	3.38 0.88	4.42 1.21	5.20 1.45	5.97 1.70

UTAH REGION

STATE/ STATION	NO. YRS.	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
10/5559	27	2.05 0.43	3.55 0.78	4.54 1.08	5.80 1.47	6.73 1.77	7.65 2.07
10/6542	27	0.74 0.11	1.13 0.21	1.39 0.28	1.73 0.39	1.97 0.47	2.22 0.55
10/8786	24	0.96 0.25	1.79 0.46	2.34 0.63	3.04 0.86	3.56 1.04	4.07 1.22
42/ 506	28	1.09 0.23	1.91 0.42	2.46 0.58	3.14 0.79	3.65 0.96	4.16 1.12
42/ 924	25	1.82 0.39	3.16 0.72	4.05 1.00	5.17 1.37	6.01 1.65	6.84 1.93
42/1731	16	2.11 0.46	3.44 0.87	4.32 1.22	5.43 1.68	6.26 2.03	7.08 2.37
42/2721	16	1.66 0.58	3.34 1.10	4.46 1.54	5.86 2.12	6.90 2.56	7.94 3.00
42/3122	17	1.57 0.53	3.13 1.00	4.17 1.40	5.48 1.92	6.45 2.32	7.41 2.71
42/3671	16	3.10 0.62	4.88 1.17	6.06 1.64	7.55 2.25	8.66 2.72	9.76 3.18
42/4856	24	2.20 0.39	3.50 0.71	4.36 0.99	5.45 1.35	6.26 1.63	7.06 1.90
42/5082	28	2.44 0.53	4.34 0.97	5.60 1.34	7.20 1.84	8.38 2.21	9.55 2.59
42/5182	18	1.22 0.28	2.05 0.52	2.61 0.73	3.31 1.00	3.83 1.20	4.34 1.41
42/5186	28	2.12 0.39	3.52 0.71	4.44 0.99	5.61 1.35	6.48 1.62	7.34 1.90
42/5190	26	1.67 0.36	2.92 0.66	3.74 0.91	4.79 1.25	5.57 1.51	6.34 1.76
42/5826	28	2.46 0.54	4.39 0.99	5.67 1.37	7.29 1.87	8.50 2.25	9.69 2.63
42/6404	28	1.84 0.35	3.10 0.64	3.93 0.89	4.98 1.21	5.76 1.46	6.53 1.70
42/6414	27	1.01 0.26	1.93 0.48	2.54 0.36	3.32 0.91	3.89 1.09	4.46 1.28
42/6869	26	6.93 1.06	10.61 1.94	13.05 2.69	16.13 3.68	18.41 4.43	20.68 5.19
42/7271	27	2.30 0.47	3.94 0.85	5.03 1.18	6.40 1.61	7.42 1.94	8.43 2.27
42/7318	28	1.17 0.31	2.29 0.57	3.03 0.79	3.96 1.08	4.66 1.30	5.35 1.52
42/7931	20	1.54 0.37	2.69 0.68	3.45 0.95	4.41 1.30	5.12 1.57	5.82 1.84
42/9595	28	1.54 0.33	2.70 0.59	3.47 0.82	4.45 1.12	5.17 1.35	5.88 1.58

APPENDIX D: DETAILS OF WAR MAP ANALYSIS

The separation between locations where observations were available was so large that, for a significant portion of the study area, the station data alone were inadequate to define small-scale variations in the water available for runoff (WAR) field. This was particularly true in the orographic areas. An assumption was made that a significant part of the station-to-station variability could be related to topographic and meteorological factors. At all stations in each region, a number of factors such as station elevation, slope of the terrain around the station, latitude, longitude, and mean annual precipitation (MAP) were determined. Using these data as candidate predictors of the WAR estimates at the stations, screening regression was performed on the data to attempt to determine equations that could describe a relation of WAR to quantities that could be estimated at points where no observations were available. The resulting equations were applied on a 5-minute latitude-longitude grid of points. The analysis of the WAR fields presented in this publication was performed on maps that included both the 5-minute grid data and the WAR amounts at the stations. This approach is the same as that used by Miller et al. (1973) in the NOAA Atlas 2 series for precipitation-frequency and by Frederick and Tracey (1976) in their study of WAR in the Snake River Valley.

The Tri-State region of the study was too complex to be considered meteorologically homogeneous. The region was divided into smaller subregions over which it was assumed that a single interpolation equation would be adequate. In an approach such as this, there is almost always a tradeoff between the need for a relatively small region that has similar meteorological conditions everywhere within the region and an area large enough to assure an adequate number of stations to allow confidence in the equations developed. The most obvious division was between the orographic areas and a second region that included the floor of the Columbia River basin. For the latter, the topographic variability was modest; we assumed that the stations were not strongly influenced by local topograhic effects and, therefore, were representative of broader areas than the mountainous locations. For the station density available, it was not deemed necessary to develop equations to aid in interpolation between stations in this region (basin floor).

We initially divided the orographic areas into four separate regions. The first, along the western portion of the study area was influenced by the broad scale flow over the Cascades and was primarily made up of lee-side stations. The second area was a mountainous region mainly in Idaho, but it included parts of both Washington and Oregon. These mountains run primarily north-south and roughly parallel to those in the first region. A third region was made up of mountains in the southern portion of the basin. This area is subject to relatively unimpeded moisture flow into the basin through the Columbia River Valley. The last region included the mountainous areas in the northern portion of the study area. Initially, equations were developed for each orographic region. In doing so, no region had enough stations to provide sufficient confidence in the reliability of the resulting equations. Examination of the results indicated that the predictors selected by the screening regression for both the northern and western areas were similar. Both the eastern and southern regions also yielded prediction equations that had a number of common factors (predictors). Because of these similarities, the four orographic regions were combined to create two regions for which final interpolation relations were determined. These regions are shown in figure D-1. The boundary of the region including the basin floor, corresponds roughly to the 2,500 ft elevation contour. The northwest region includes mountainous portions above 2,500 ft that

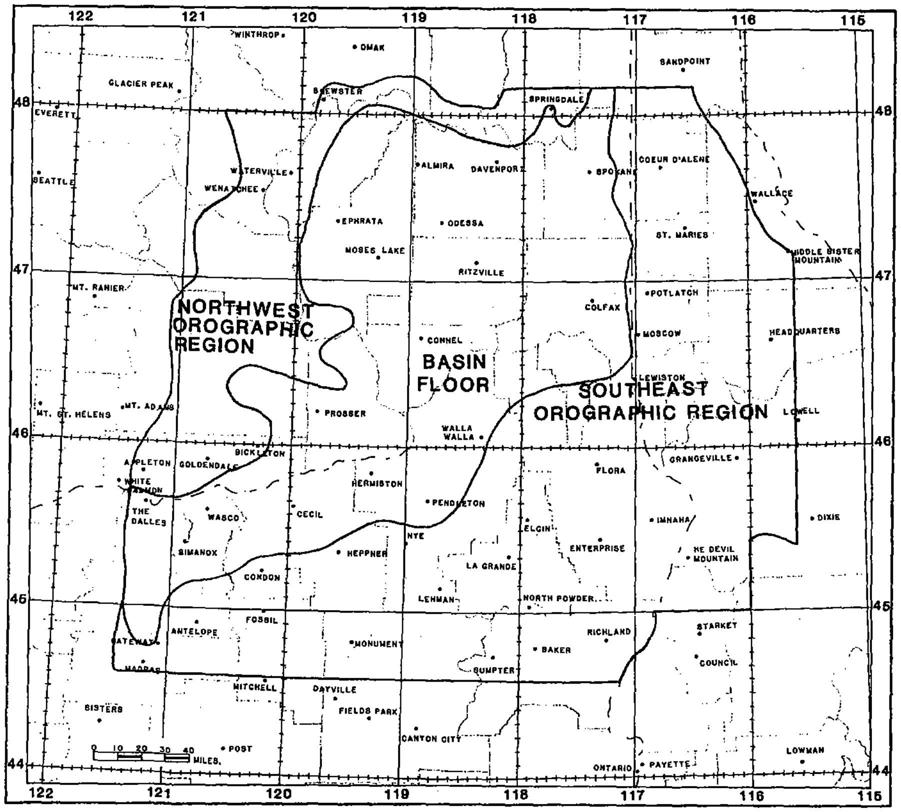


Figure D-1.—Map defining the regions over which a single interpolation equation was used to produce grid-point WAR-frequency estimates that were used to guide the analysis in data sparse regions.

are north and west of the Columbia River. The southeastern region is made up of the orographic areas above 2,500 ft south and east of the Columbia River. Even after this consolidation, neither orographic region had a large number of higher elevation stations. Application of the resulting equations in the highest elevations must be considered an extrapolation rather than a interpolation with a resulting lower degree of confidence in the grid-point estimates.

While the Utah portion of the study included a relatively flat portion in the west and a mountainous area in the east, there were so few stations available that no attempt was made to divide the region. Because there were practically no stations representing conditions in the mountains, special care was taken in the use of the interpolation equations in the higher elevations.

Equations used to provide guidance in analyzing between stations should, ideally, involve only quantities that can be observationally determined at each grid point. Unfortunately, it was not possible to obtain interpolation equations using such factors that simultaneously explained a considerable portion of the variance and had only a few terms. If there are a large number of terms in the equation, there can be little confidence that the equation depicts underlying phenomena that account for variability within the region. (It becomes an exercise in curve fitting.) Therefore,

Table D-1.—Regression equations used to interpolate between station locations

	Northwest Tri-State	Southeast Tri-State	Utah
2-yr 1-day	$W_{2,1} = 0.23 + 0.39(W_{2,5})$	$W_{2,1} = 0.06 + 0.28(W_{2,5}) + 0.07(X_6) - 0.02(X_5)$	$W_{2,1} = 0.52 + 0.30(W_{2,5}) + 0.13(X_{10})$
100-yr 1-day	$W_{100,1} = 0.64 + 0.40(W_{100,5}) - 0.92(X_3)$	$W_{100,1} = 0.05 + 2.05(W_{2,1}) + 0.31(X_7) + 0.08(X_6)$	$W_{100,1} = 1.33 + 1.16(W_{2,1}) + 0.23(X_{12}) - 0.12(X_{11})$
2-yr 5-day	$W_{2,5} = 0.76 + 0.10(X_1)$	$W_{2,5} = -0.02 + 0.09(X_1) + 0.39(X_4) + 0.02(X_5)$	$W_{2,5} = 0.84 + 0.08(X_1) - 0.45(X_8) + 0.53(X_9)$
100-yr 5-day	$W_{100,5} = 1.21 + 2.23(W_{2,5}) + 0.22(X_2)$	$W_{100,5} = 0.32 + 1.95(W_{2,5}) + 0.67(X_7) + 0.17(X_6)$	$W_{100,5} = 0.48 + 2.02(W_{2,5}) - 0.58(X_4)$
2-yr 15-day	$W_{2,15} = -0.54 + 1.79(W_{2,5})$	$W_{2,15} = -0.86 + 1.96(W_{2,5})$	$W_{2,15} = -0.57 + 2.30(W_{2,5})$
100-yr 15-day	$W_{100,15} = 1.33 + 2.09(W_{2,15})$	$W_{100,15} = 0.85 + 2.04(W_{2,15})$	$W_{100,15} = -0.51 + 2.30(W_{2,15}) - 0.82(X_{13})$

Explanations for Table D1

X_1 = mean annual precipitation

X_2 = difference between station elevation and average elevation at 2.5 mi (8 points)

X_3 = north-south slope across the station (grid-point) location: difference between 3-point average elevation 20 mi north and 20 mi south of the location, divided by 40

X_4 = north-south slope across the station (grid-point) location: difference between 3-point average elevation 10 mi north and 10 mi south of the location, divided by 20

X_5 = north-south slope based on the difference between the station (grid-point) elevation and the highest feature north of the station (between 315-45°) within 20 mi of the station (grid-point) divided by the separation distance between the high point and the station

X_6 = longitude minus 120

X_7 = east-west slope based on the difference between the average elevation within 2.5 mi of the station (grid-point) and the 3-point average elevation 20 mi east of the station (grid-point), divided by 20

X_8 = east-west slope based on the difference between the average elevation within 2.5 mi of the station (grid-point) and the 3-point average elevation 5 mi west of the station (grid-point), divided by 5

X_9 = east-west slope based on the difference between the average elevation within 5 mi of the station (grid-point) and the 3-point average elevation 10 mi west of the station (grid-point), divided by 10

X_{10} = east-west slope based on the difference between the average elevation within 2.5 mi of the station (grid-point) and the 3-point average elevation 10 mi west of the station (grid-point), divided by 10

X_{11} = north-south slope based on the difference between the station (grid-point) elevation and the 3-point average elevation 2.5 mi north of the station (grid-point), divided by 2.5

X_{12} = north-south slope based on the difference between the average elevation within 5 mi of the station (grid-point) and the 3-point average elevation 10 mi north of the station (grid-point), divided by 10

X_{13} = east-west slope based on the difference between the station (grid-point) elevation and the 3-point average elevation 10 mi west of the station (grid-point), divided by 10 we decided to use MAP as a predictor. While MAP may be an excellent predictor whose value is known at the stations, maps depicting it are subject to similar station density problems that led to the development of interpolation equations in this study. Away from the stations, there may be error in the MAP field. Equations using this quantity as a predictor include this unknown error in the grid-point estimates. Thus, even though the regression equations explain most of the variability at the station locations they may provide poorer estimates at the grid-points. However, the station density problem is somewhat less severe since there are usually a greater number of stations available for use in developing MAP fields.

The interpolation equations used in the three subregions for which they were required are presented in table D-1. The predictors used in these equations are dependent on the sequence in which the maps were analyzed. The first map analyzed was the 2-yr 5-day map. This field was chosen because we felt the results at this duration and return period were more reliable than the 1-day amounts and the 100-yr return period. As discussed in the text, the implementation of the model in this study at point locations probably lead to poorer day-to-day simulations (sec. 5.2). There appeared to be a considerable amount of compensation for summations over several days. Hence, the assumption was made that a 5-day total would be more reliable. While we could have started our analysis with the 2-yr 15-day map, the 5-day map was preferred because it could be used directly to provide guidance for analysis of both the 1-day and the 15-day maps.

The first attempt to develop an equation to use as an aid to interpolation between the stations for the 2-yr 5-day WAR field withheld MAP as a candidate predictor. The number of terms required to explain a significant portion of the variance was determined to be too large. When MAP was allowed into the screening regression, it was the first predictor selected. In the northwest portion of the Tri-State region, no additional quantity was found that could provide a meaningful reduction in the remaining unexplained variance. In the other two regions, additional terms were included that acted as "second order corrections" to the basic MAP field. In both cases these terms involved slopes: north-south slopes in the southeast Tri-State region and east-west slopes in Utah.

The order of analysis of the remaining maps was: 2-yr 1-day, 100-yr 5-day, 100-yr 1-day, 2-yr 15-day, and 100-yr 15-day. In all cases the screening regression selected one of the previously analyzed WAR fields as the primary predictor. (See table D-1.) All three regions used the 2-yr 5-day WAR field to predict the 2-yr 1-day WAR field. In the southeast Tri-State region and in Utah, additional terms provided second order corrections. In both regions slopes were involved; in the southeast Tri-State region, longitude was also a factor. For all three regions, the 2-yr 5-day WAR field was the only quantity used to help interpolate between stations for the 2-yr 15-day field. Similarly, grid-point estimates of the 100-yr 5-day field in all three regions depended on the 2-yr 5-day field. But in this case, there were second-order terms that varied from region to region. Of interest is the additional term in the equation for the northwest Tri-State region. It was essentially a measure of the local exposure of the station (grid point) location. The equations for the 100-yr 1-day field are the only case in which the same "primary" predictor was not selected for all three regions. The 100-yr 5-day field was selected for the northwest Tri-State region, while the 2-yr 1-day WAR field was used in the other two regions. The 2-yr 15-day WAR field was selected by the screening regression to provide guidance in analyzing the 100-yr 15-day field. Only in Utah did an additional term provide any meaningful enhancement.

The most striking feature of the interpolation equations is their interdependence. Since all are somehow related to the 2-yr 5-day WAR field, they are also related to the MAP field. We consider it reasonable that these relationships occurred in the statistical analysis because we believe that such mutual dependencies exist in nature. The most common "correction" terms involved either east-west or north-south slopes. Both may have plausible physical bases. Moisture bearing flow in these areas usually has a westerly component. Air with high humidity is forced to rise when it encounters significant orographic features. This ascent is accompanied by adiabatic cooling, leading to condensation and precipitation. That this, in fact, may have been the underlying physical factor is strengthened by the absence of an east-west slope term in any of the equations for the northwest portion of the Tri-State region. In this area, much of the available moisture in the air would probably be depleted by flow over the Cascades. A north-south slope could be related to either enhanced snowpack buildup on north facing slopes, to enhanced melt on south facing slopes, or to both factors. The appearance of longitude occurs only in the southeast Tri-State region and could be related to the distance from the Pacific which is the major source of moisture.

Table D-2 summarizes the statistics relating to the regression analysis. In all cases the correlation was high. But as mentioned above, all equations depend either directly or indirectly on MAP. While this quantity is known accurately at station locations, there may be considerable uncertainty in MAP analysis between the stations. Therefore, the ability to accurately predict WAR at the grid points is limited by the accuracy of the MAP field at these locations. Therefore, the impression of accuracy given by the correlation coefficient or the standard error of estimate probably overstates the quality of the grid-point estimates. The standard error of estimate, as a percentage of the mean of the station values, is largest in the Tri-State region (10-15 percent). In Utah it is considerably smaller (5-8 percent), but this may be due in part to fewer stations and to the generally larger number of terms in the equations. Further, most of the stations available were in relatively flat terrain, leading to a rather simple and meteorologically homogenous set of stations. Because of this, less reliance was placed on the grid-point estimates in the mountainous portions of this region.

Once the interpolation equation for a particular region, duration, and return period was set, the quantities necessary to generate the predictors involved were read from a 5-minute latitude-longitude grid of points. This was done by placing a transparency containing markings at the eight major points on the compass at ranges of 2.5, 5, 10, and 20 miles away from the central location. For instance, predictor X_2 (table D-1) was made up of the elevation at the central point and the eight points (N, NE, E, SE, S, SW, W, and NW) at a range 2.5 miles from the central point. X_2 was calculated by subtracting the elevation at the central point from the average elevation at the eight points 2.5 miles away from the central point. Another example is X_{10}: it was found by reading the nine points mentioned above and the elevation 10 miles away from the central point to the southwest, west, and northwest. The average of the central nine points and the average elevation of the three western points were then determined. The slope was found by forming the difference of the two averages and dividing by 10 miles. All elevations were expressed in hundreds of feet. Most predictors were made up of average elevations to provide more stable predictors. By using a fixed grid, the point elevations read from topographic maps may not have been truly representative of the topography on a scale likely to interact with the prevailing precipitation processes.

Table D-2.—Statistics relating to the regression equations in table D1

		Northwest Tri-State			Southeast Tri-State			Utah		
Number of Stations		28			59			21		
		Correlation coefficient	Station mean (in.)	Standard error of estimate (in.-%)	Correlation coefficient	Station mean (in.)	Standard error of estimate (in.-%)	Correlation coefficient	Station mean (in.)	Standard error of estimate (in.-%)
2-yr	1-day	0.99	1.32	0.10- 7.5	0.96	1.23	0.11- 8.9	0.91	1.13	0.09-8.0
100-yr	1-day	0.97	3.42	0.48-14.0	0.94	2.88	0.29-10.1	0.93	2.62	0.16-6.1
2-yr	5-day	0.98	2.76	0.41-14.9	0.92	2.52	0.44-17.5	0.93	2.19	0.14-6.4
100-yr	5-day	0.98	6.98	0.94-13.5	0.96	5.91	0.58- 9.8	0.89	4.67	0.36-7.7
2-yr	15-day	0.99	4.41	0.42- 9.5	0.98	4.09	0.43-10.5	0.96	3.09	0.16-5.2
100-yr	15-day	0.99	10.53	1.12-10.6	0.98	9.20	0.86- 9.3	0.93	6.90	0.55-8.0

X_5 is the only example of a subgroup of slopes used as candidate predictors that attempted to determine representative slopes not dependent on specific grid-point elevations. This group of predictors used the elevation of the highest significant feature within a pie-shaped sector defined by a 90-degree azimuth interval and within some fixed range. A difference was formed between the typical elevation of this prominent feature and the station elevation, and this difference was divided by the separation distance between the two to yield a slope.

The actual map analysis involved plotting the grid-point estimates together with the station values on a base map. In addition to the station values, the length of record and the deviation from the regression estimate were also plotted. In general, the analysis was done using a map containing generalized topography as an underlay. This allowed additional subjective consideration of the influence of topography on the WAR fields. For maps using another WAR field as the primary predictor, the predictor field was also often used as an underlay to aid the analysis process. Ultimately the analysis was a subjective attempt to fit the station data, the grid-point estimates, the topography and any other meteorological information available to the analyst into a consistent result. In a number of cases the available information was not internally consistent. The analyst was forced to exercise considerable judgement in the most extreme cases.

When each map was completed, the resulting fields were read at the grid-point locations and ratios of the completed fields were computed. This was done to ensure consistency among the entire set of maps. This last step involved an examination of ratio fields to ensure that the variation was regular and that gradients in the ratio fields could be explained on the basis of reasonable meteorological principles. As part of the consistency checking using ratio fields, we also compared the 1-day WAR fields to results from NOAA Atlas 2. (See sec. B for discussion of these comparisons.) In this comparison, we assumed that the WAR amounts should be at least as large as the values from NOAA Atlas 2 since the former should include all large rain-only events as well as rain-on-snow events that could be larger than rain-only events. We examined the station data for examples of annual events occurring as snow only. In these cases, the precipitation recorded for the 24-hr period could be released over a period of melt, producing a WAR amount less than the annual precipitation amount. While there were some instances of this, they were infrequent and tended to fall in the central portion of the ranked WAR series. They had no appreciable influence on the statistics for any station in this study. A further rationale for ensuring that the WAR estimates be larger than the precipitation amounts in NOAA Atlas 2 is the longer record length available at a number of stations used in the latter. This made sampling problems less likely. Consistency checks associated with NOAA Atlas 2 produced no modifications in the orographic areas and only limited modifications in the lower-lying portions.

APPENDIX E

WAR FREQUENCY MAPS

Tri-State Region

1-Day

E-1. 2-yr
E-2. 100-yr

5-Day

E-3. 2-yr
E-4. 100-yr

15-Day

E-5. 2-yr
E-6. 100-yr

Northeastern Utah

1-Day

E-7. 2-yr
E-8. 100-yr

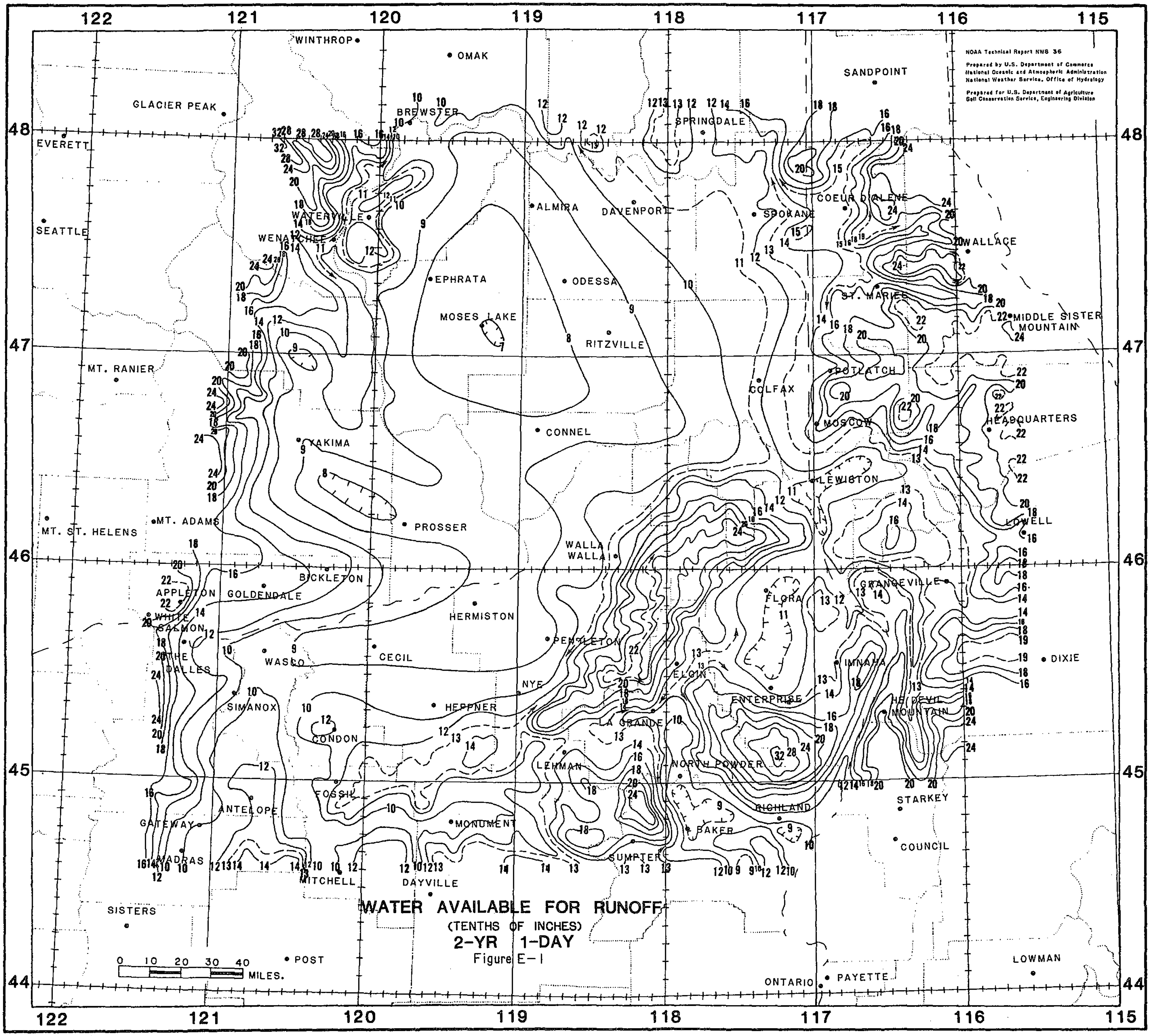
Snake River (after Frederick and Tracey 1976) and Northwestern Utah

5-Day

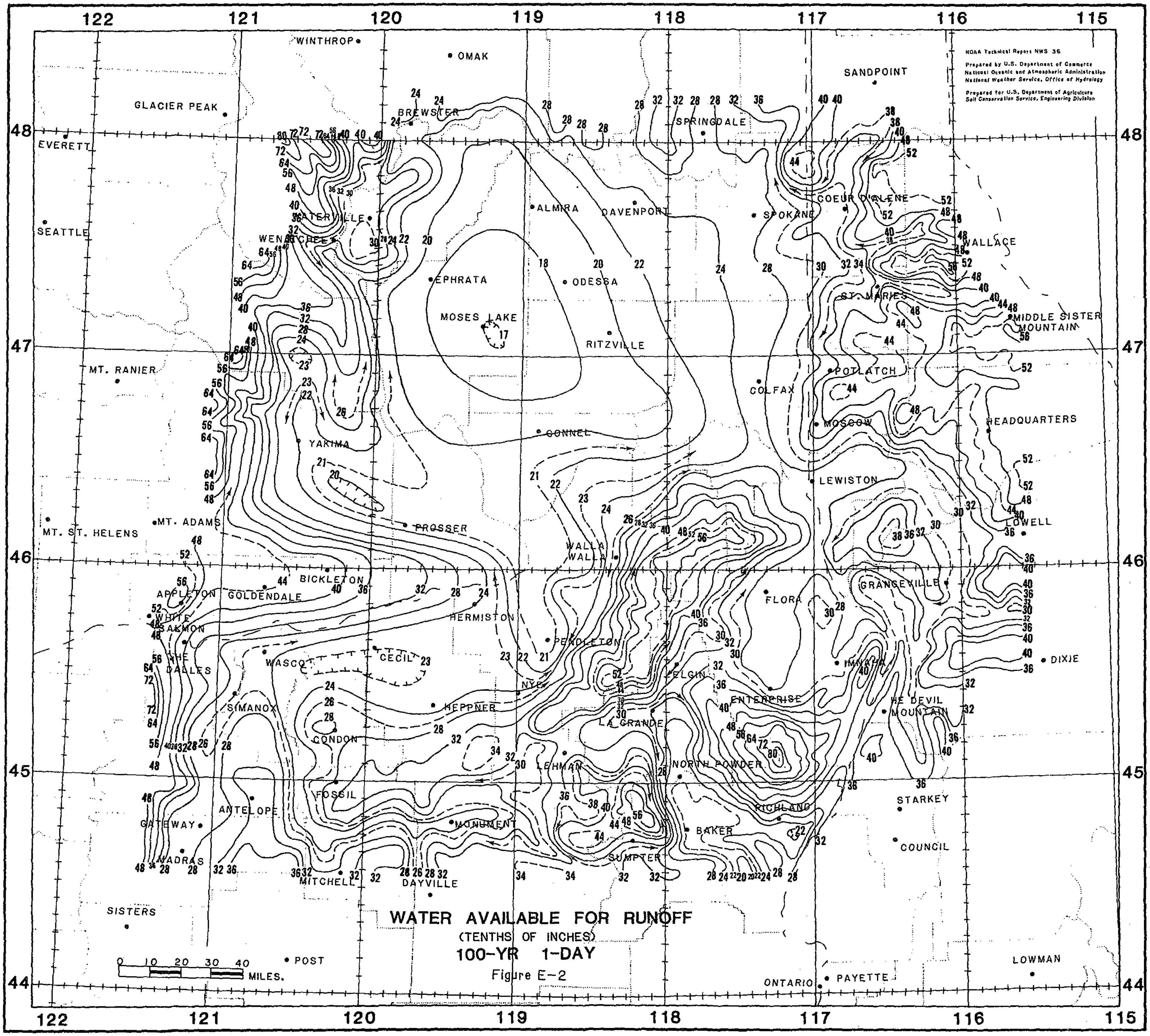
E-9. 2-yr
E-10. 100-yr

15-Day

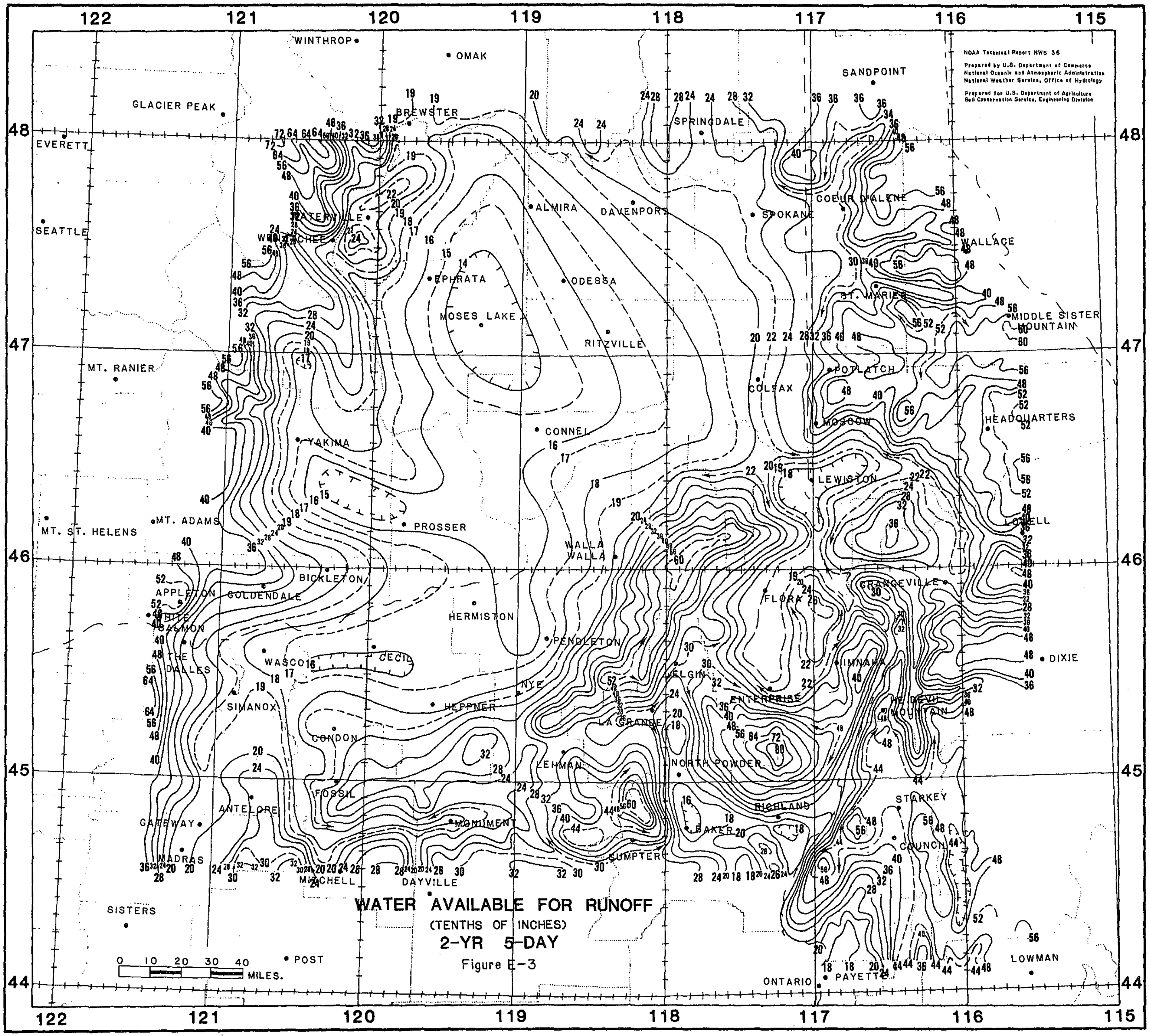
E-11. 2-yr
E-12. 100-yr



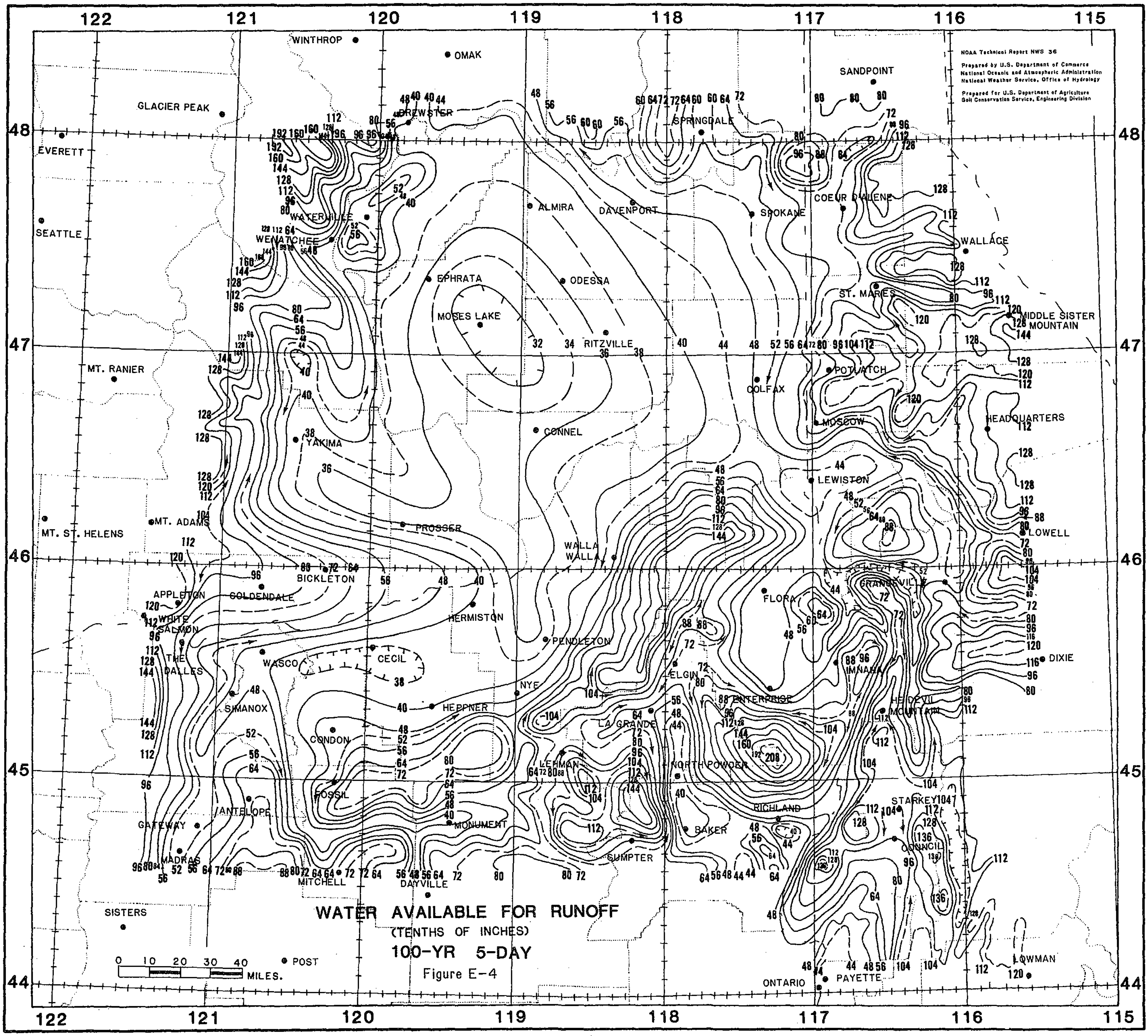
WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
2-YR 1-DAY
Figure E-1



WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
100-YR 1-DAY
Figure E-2



WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
2-YR 5-DAY
Figure E-3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SANDPOINT
GLACIER PEAK
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EVERETT
SEATTLE
WATERVILLE
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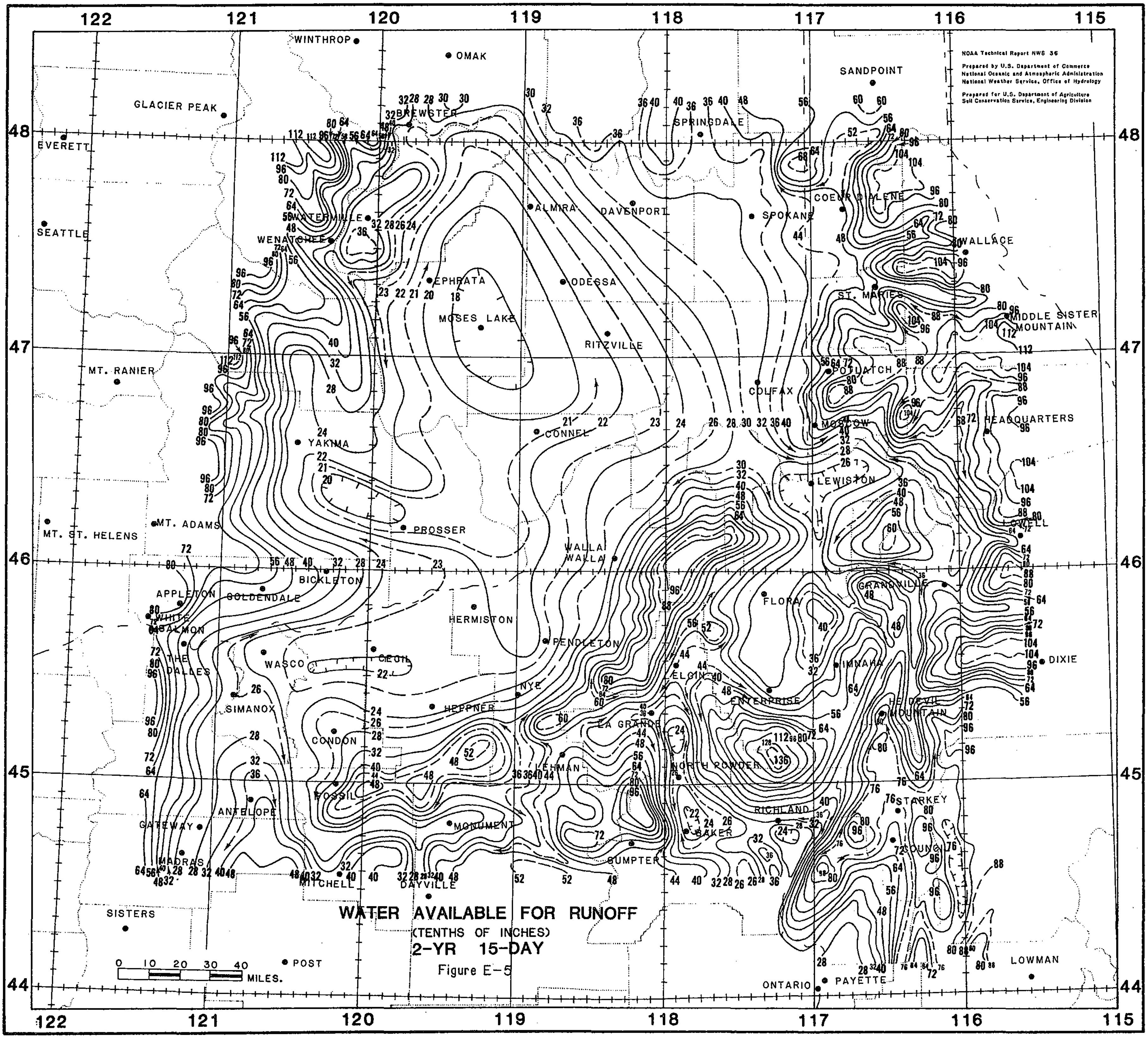
ALMIRA
DAVENPORT
SPOKANE
COEUR D'ALENE
WALLACE
EPHRATA
ODESSA
ST. MARIES
MOSES LAKE
RITZVILLE
MIDDLE SISTER MOUNTAIN
MT. RANIER
POTLATCH
COLFAX
MOSCOW
HEADQUARTERS
CONNEL
YAKIMA
LEWISTON
MT. ADAMS
MT. ST. HELENS
PROSSER
LOWELL
WALLA WALLA
BICKLETON
APPLETON
GOLDENDALE
GRANGEVILLE
FLORA
HERMISTON
WHITE SALMON
PENDLETON
THE DALLES
WASCO
CECIL
IMNAHA
DIXIE
ELGIN
NYE
SIMANOX
HEPPNER
ENTERPRISE
HE DEVIL MOUNTAIN
LA GRANDE
CONDON
LEHMAN
NORTH POWDER
FOSSIL
RICHLAND
STARKEY
ANTELOPE
GATEWAY
MONUMENT
BAKER
COUNCIL
MADRAS
SUMPTER
MITCHELL
DAYVILLE
SISTERS
POST
MILES.
ONTARIO
PAYETTE
LOWMAN
WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
100-YR 5-DAY
Figure E-4

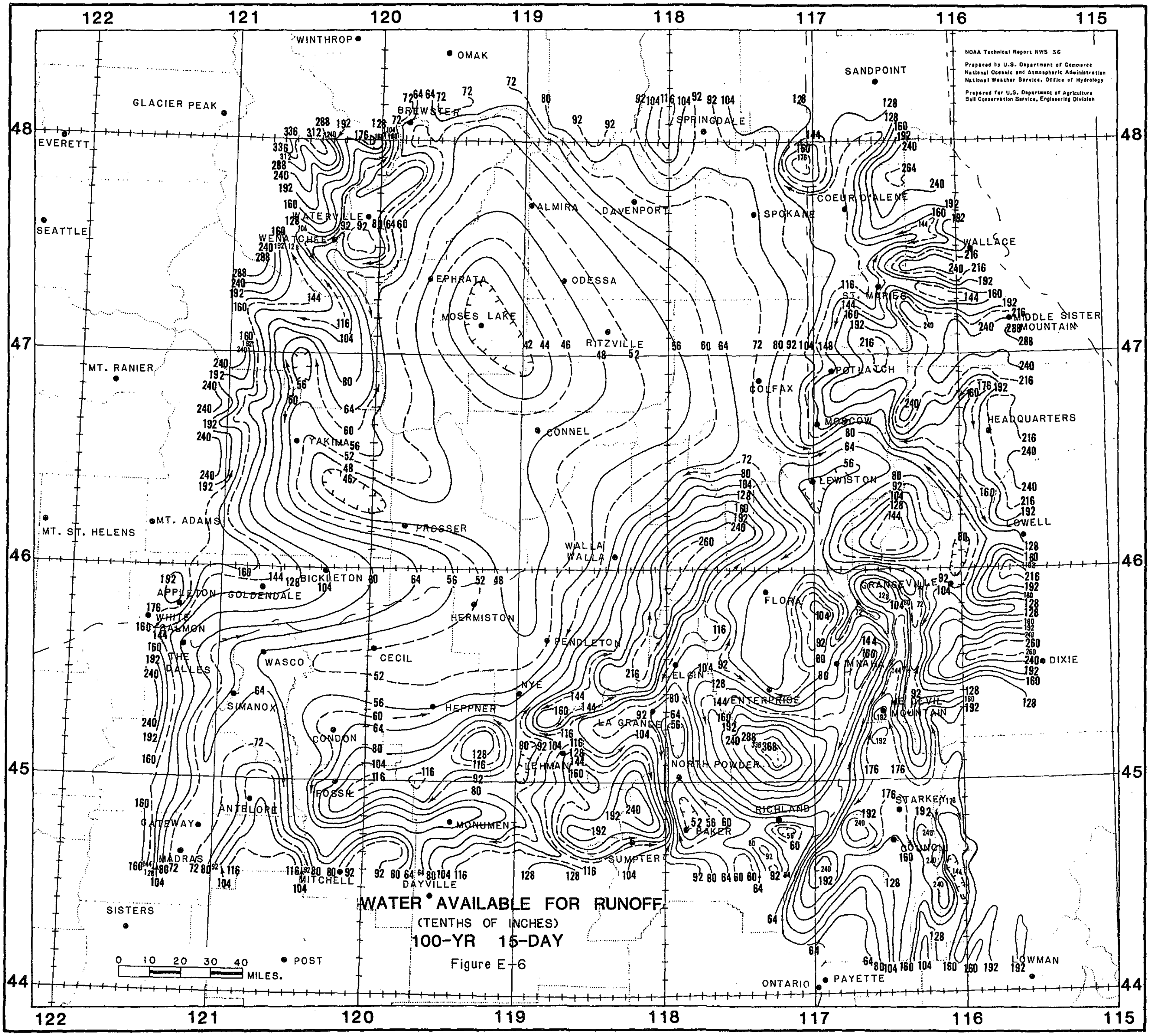


WATER AVAILABLE FOR RUNOFF

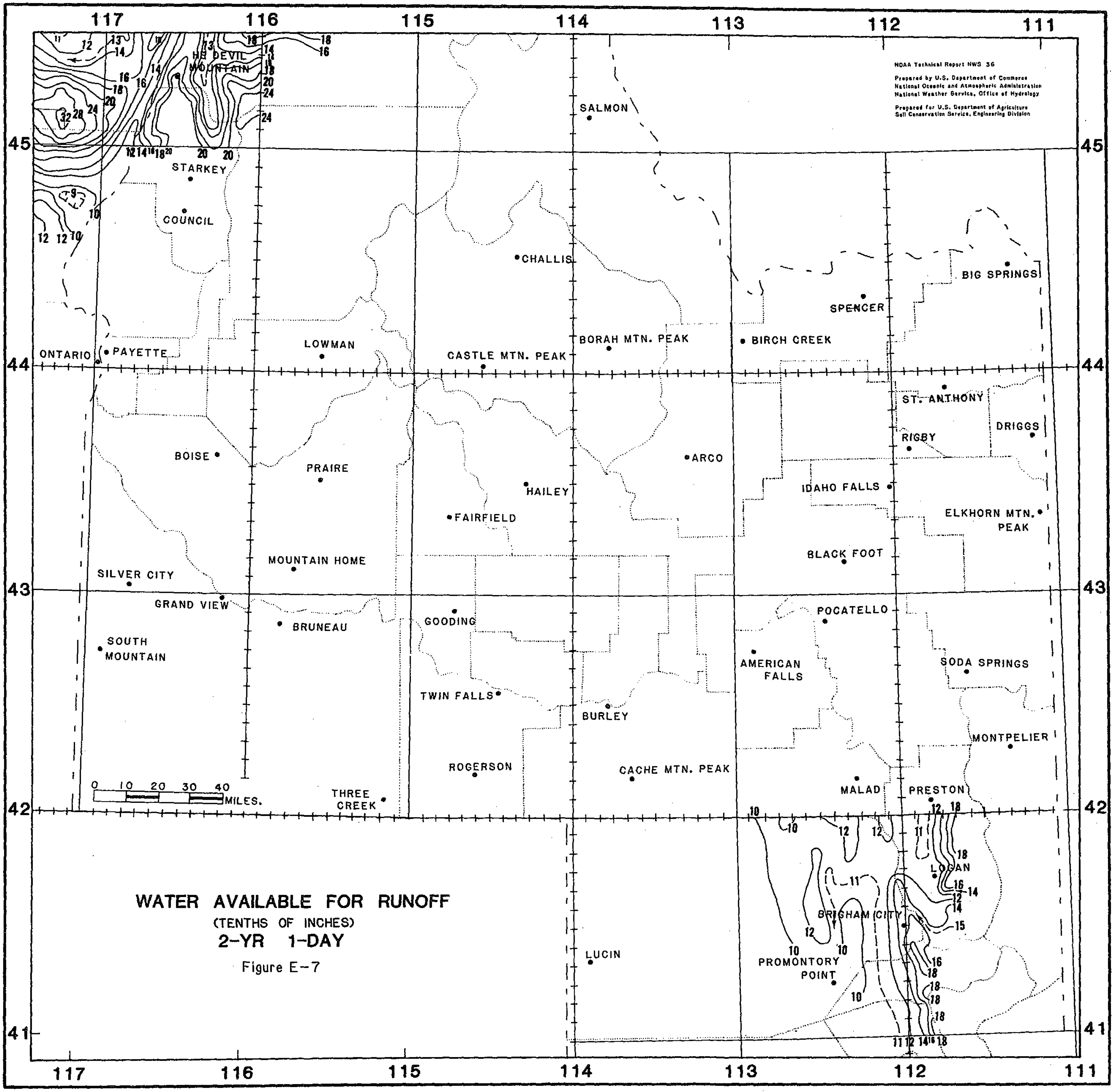
(TENTHS OF INCHES)

2-YR 15-DAY

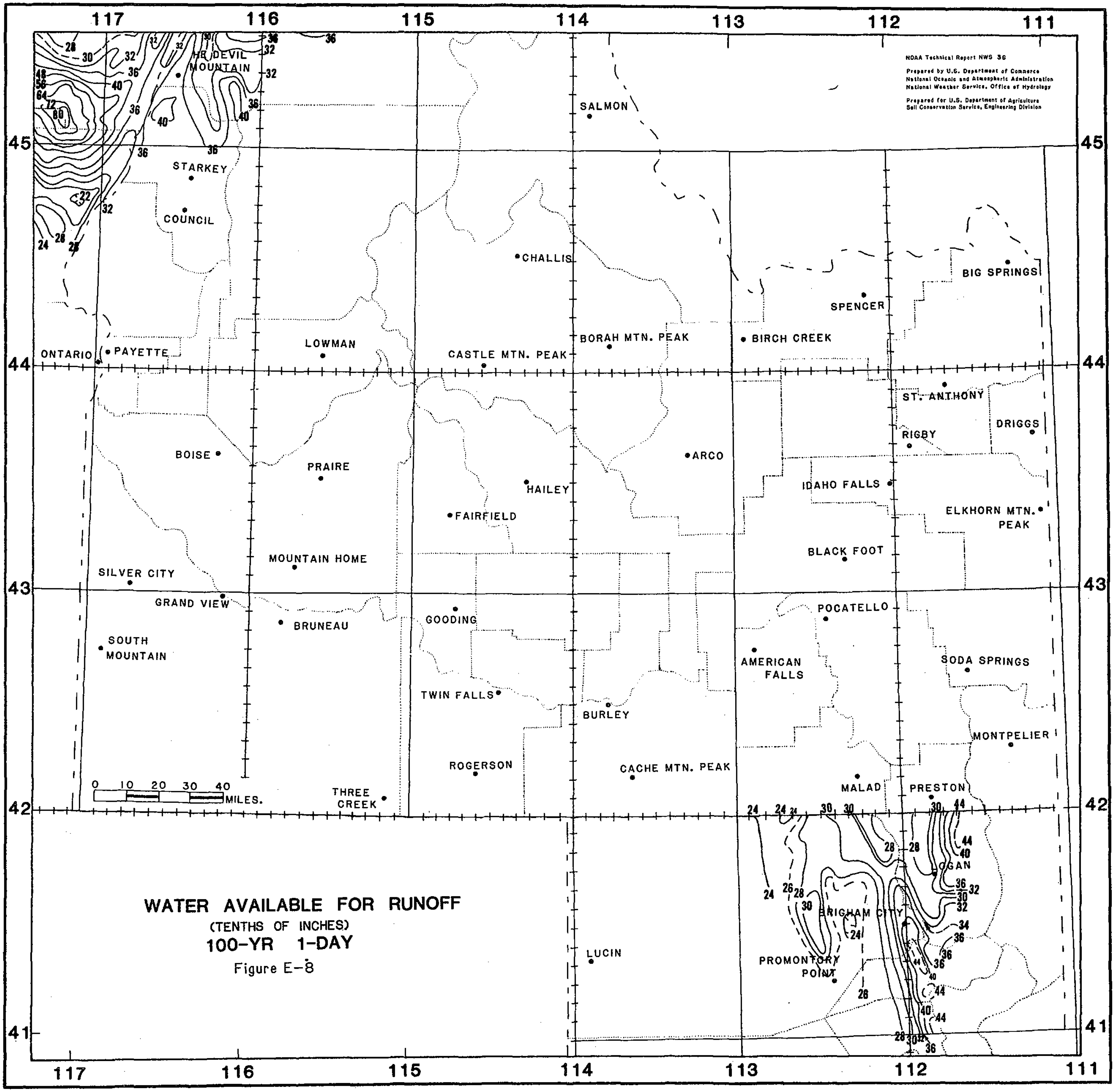
Figure E-5



WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
100-YR 15-DAY
Figure E-6



WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
2-YR 1-DAY
Figure E-7

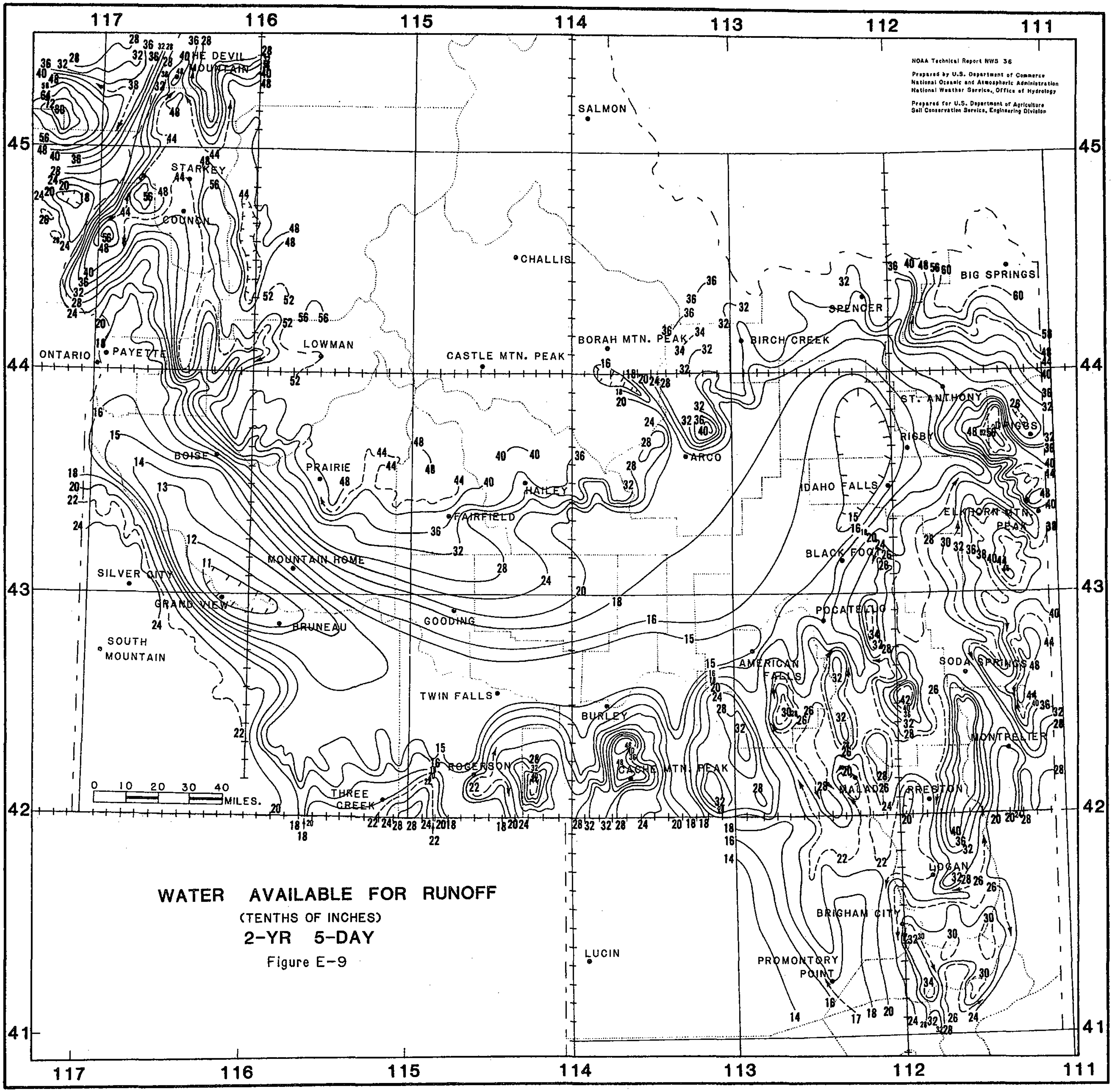


WATER AVAILABLE FOR RUNOFF

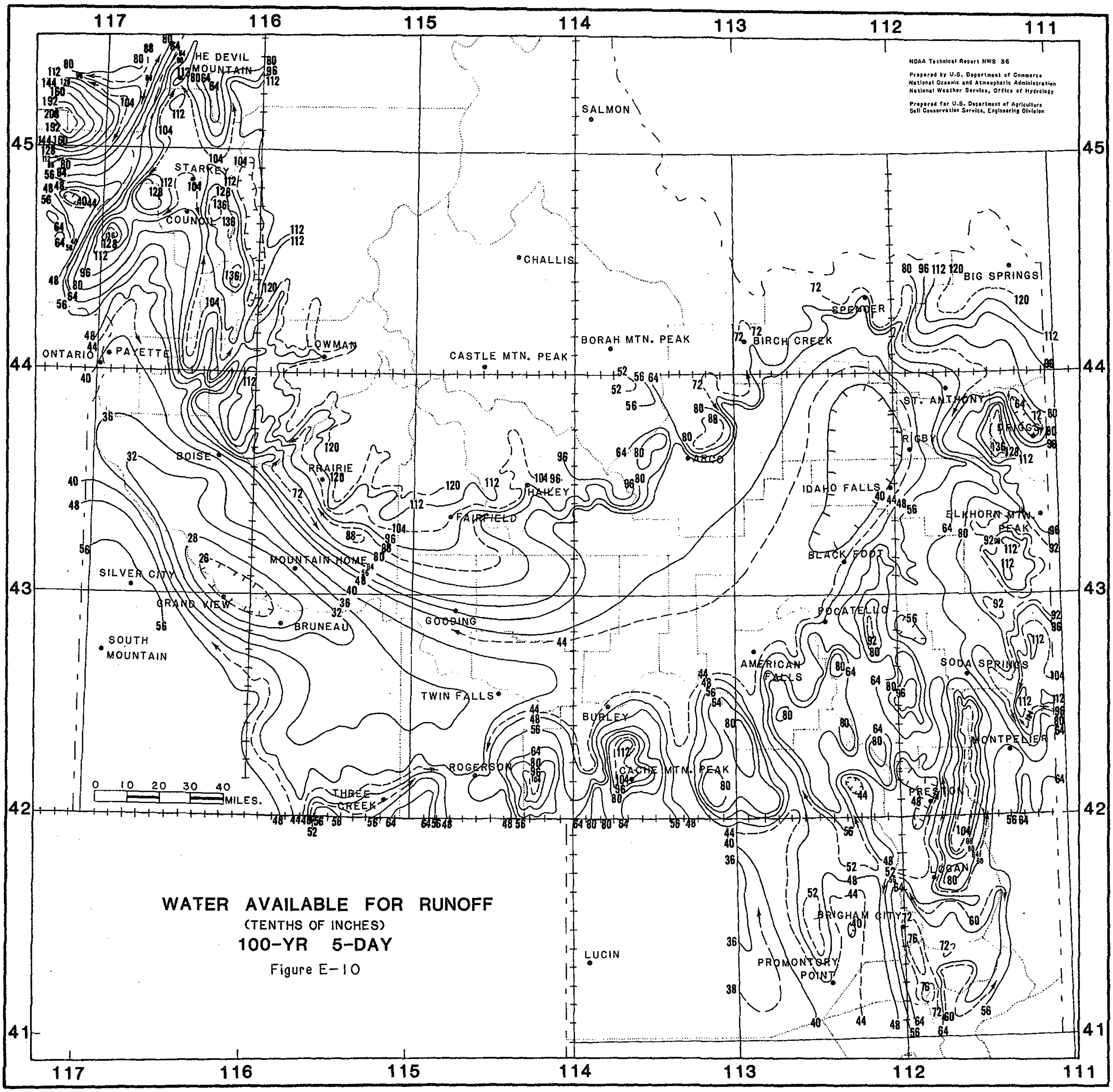
(TENTHS OF INCHES)

100-YR 1-DAY

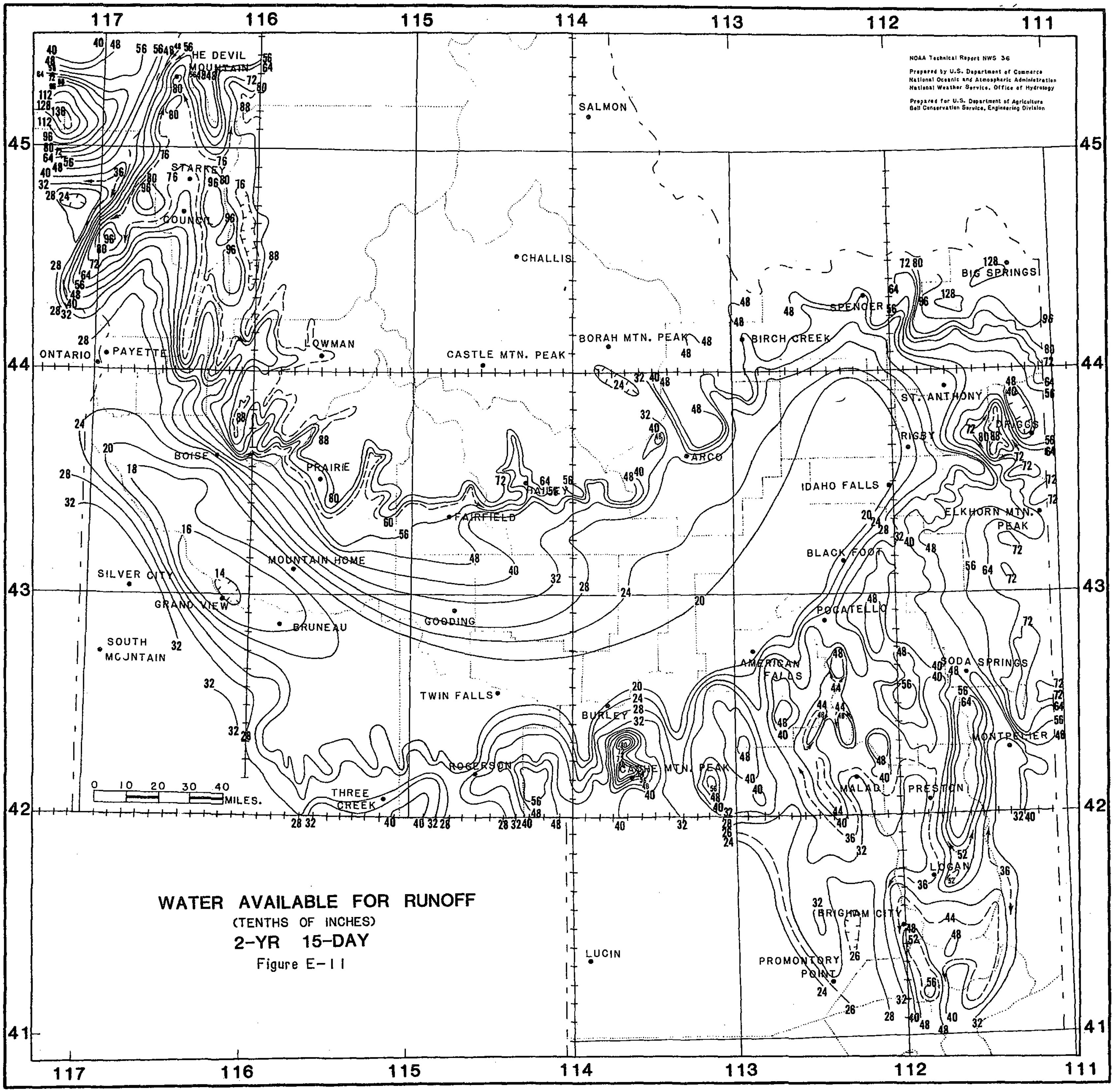
Figure E-8



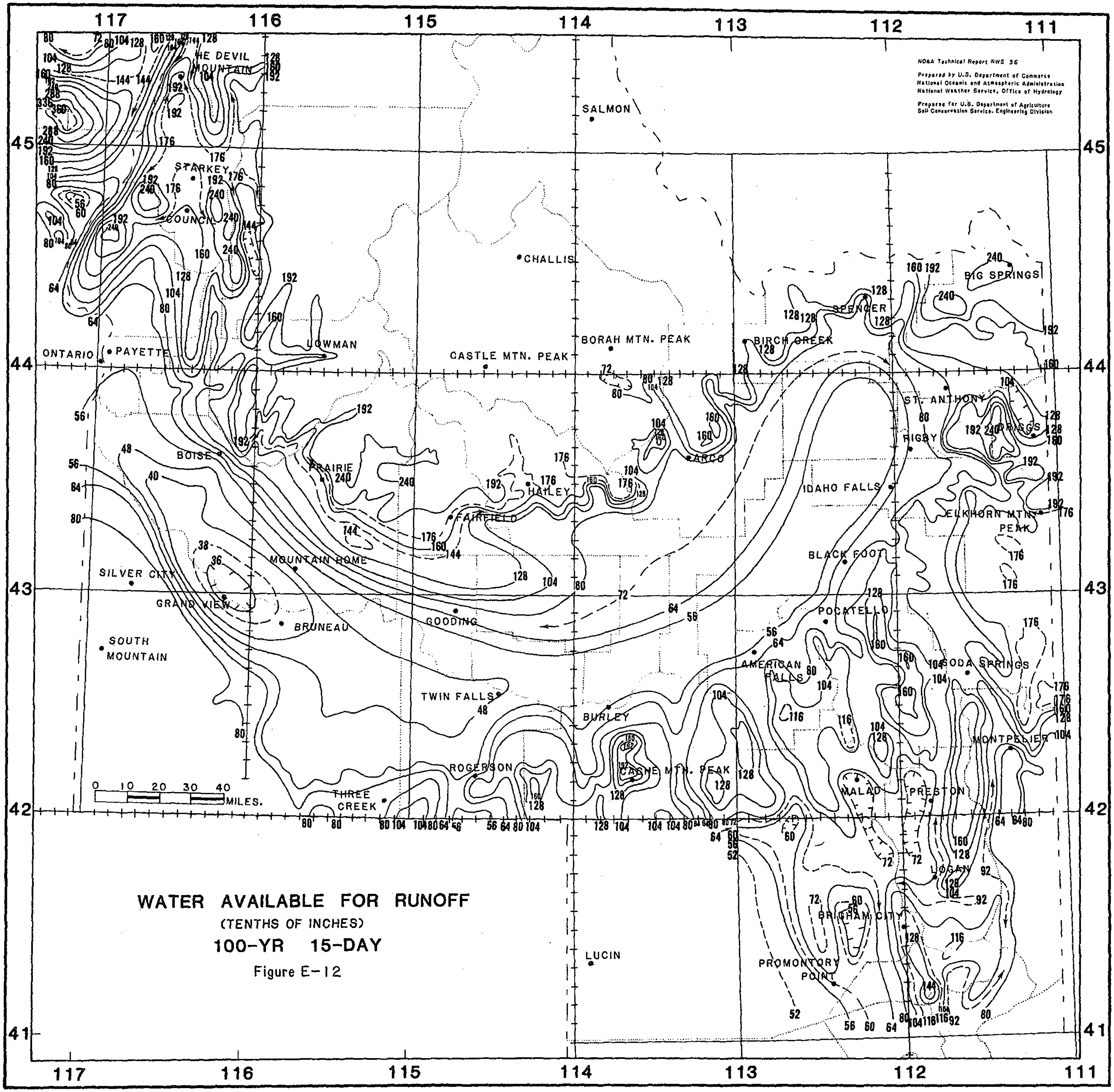
WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
2-YR 5-DAY
Figure E-9



WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
100-YR 5-DAY
Figure E-10



WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
2-YR 15-DAY
Figure E-11



WATER AVAILABLE FOR RUNOFF
(TENTHS OF INCHES)
100-YR 15-DAY
Figure E-12

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