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Surface Hydrologic Investigations Of The Columbia Plateau Region, Washington

L. S. Leonhart

July 1979

Prepared for the United States
Department of Energy
Under Contract DE-AC06-77RL01030

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SURFACE HYDROLOGIC INVESTIGATIONS OF THE COLUMBIA PLATEAU REGION, WASHINGTON

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for
Basalt Waste Isolation Program

July 23, 1979

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ABSTRACT

The Washington State portion of the Columbia Plateau is divided into six hydrologic sub-basins on the basis of the principal surface drainage systems present, structural and topographic relationships, and political and other considerations. Baseline descriptions of the surface water systems and resources are presented for the Columbia Plateau with emphasis on the Pasco Sub-basin. A preliminary evaluation of the hydrologic budget for each sub-basin is derived. For each sub-basin, recharge/discharge relationships arising from precipitation/evapotranspiration/runoff, stream losses and gains, and artificial mechanisms are determined on the basis of available data. The net exchange between surface and ground-water systems is evaluated and relative estimates of the net ground-water flow into or out of the sub-basin are obtained.

An evaluation is made of hydrologic risk factors arising from: (1) tributary flooding in eastern Washington; and, (2) major flooding of the Columbia River within the Pasco Sub-basin. Scenarios are presented for credible natural and man-generated catastrophic events.

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SURFACE HYDROLOGIC INVESTIGATIONS OF THE COLUMBIA PLATEAU REGION, WASHINGTON

INTRODUCTION

PURPOSE and SCOPE

This report presents a conceptual description of the regional surface hydrologic system of the Columbia Plateau within Washington State. It is prepared within the context of preliminary site characterization for the U.S. Department of Energy's Basalt Waste Isolation Program (operated by Rockwell Hanford Operations). The study represents a contribution to the overall regional hydrologic studies which also encompass ground-water system reconnaissance and modeling.

The area referred to as the Columbia Plateau corresponds in a general sense with the outcrop of the Columbia River Basalt Group and occupies approximately 50,000 square miles including parts of Washington, Oregon, and Idaho (Plate 1). In this study, special emphasis has been placed on the Washington State portion of the plateau and, specifically, the Pasco Basin.

The underlying objectives of this study include:

1. Development of a baseline description of the surface water systems and resources within the Columbia Plateau;
2. Identification of interactive mechanisms between the surface and ground-water systems; and
3. Evaluation of corresponding hydrologic risk phenomena.

This report will demonstrate the relevance of individual studies to the Basalt Waste Isolation Program's purpose of investigating the feasibility of deep geologic storage of radioactive wastes within the Columbia River basalts. It should be noted that this study is intended to complement concurrent and parallel investigations of the Columbia Plateau regional ground-water system(s). Careful integration of these efforts will be required before a truly comprehensive description of the Columbia Plateau regional hydrology can be advanced.

APPROACH

In recognition of the concurrent and parallel investigations of the Columbia Plateau regional ground-water system, this study focuses primarily on hydrometeorology and surface water budgets and regards ground-water recharge and discharge as outputs and inputs, respectively, to the surface water system. Thus, a great deal of data relating to precipitation, evapotranspiration, storage, streamflow, consumptive use, and inter-basin transfer have been assembled and analyzed. All data were obtained from existing reports and the analyses are based entirely on existing data.

The Columbia Plateau study area was divided into six surface hydrologic sub-basins based on the principal flow systems observed and on other considerations. They are as follows:

1. Horse Heaven Plateau Sub-basin;
2. Yakima River Sub-basin;
3. Pasco Sub-basin;
4. Walla Walla River Sub-basin;
5. Palouse/Snake Sub-basin;
6. Big Bend Sub-basin.

Further descriptions of these areas are provided below in sections entitled "Surface Water Hydrology" and "Sub-basin Descriptions." In a strict hydrologic sense, these designations do not constitute "true" hydrologic sub-basins, but are, rather, portions of other basins or groups of several smaller basins. The necessity for such a hydrologically non-traditional arrangement stems from the need to account for other criteria such as geology and political boundaries. Additionally, for certain parameters such as water use, it was necessary to rely on state, county, or other boundaries because of the organization of the data record. Thus, for the Washington State portion of the Columbia Plateau, the following counties nearly encompass the study area boundaries; Adams, Asotin, Benton, Columbia, Douglas, Franklin, Garfield, Grant, Kittitas, Klickitat, Lincoln, Spokane, Walla Walla, Whitman, and Yakima.

A consequence of this discrete arrangement of data is the inclusion of data extraneous to the study area. This is particularly true of data for Kittitas, Klickitat, Spokane, Whitman, and Yakima Counties. Additionally, small portions of the study area are situated in Chelan, Ferry, Okanogan, Skamania, and Stevens Counties. The same situation was encountered in working with standard Water Resource Inventory Areas (WRIA) of Washington and with established irrigation districts. Nevertheless, these discrepancies are of comparatively minor significance in providing a regional view of the hydrologic system. Locations of Washington State counties and WRIAs, as well as descriptions of their water resources, are provided in the sub-section entitled "Water Use." Their relationships to the hydrologic sub-basins are established in the sub-section entitled "Sub-basin Descriptions."

Mapped data for the State of Washington, such as precipitation, evaporation, and runoff, were capable of being digitized and, therefore, more precise statistics for those parameters could be generated for each sub-basin. Manipulation in this fashion also permitted differencing of the contoured surfaces for various purposes such as delineating areas of potential recharge. Hydrologic budget evaluations by sub-basin were prepared on the basis of such data.

Extensive evaluation of flood risk has been performed for the Columbia River system by various water management agencies. Hence, further analysis of flood probability is not necessary.

Information presented on flood hazards in this study is, therefore, limited to existing reports. Emphasis is placed on flood risk evaluations for the Pasco Basin.

REGIONAL SETTING

Superlative and contrasting natural phenomena have characterized the Columbia Plateau throughout its geologic history. McKee (1972), for example, described the region's geologic history as being marked by some of the largest floods of all times, referring first to regional flooding by basaltic lavas which inundated the plateau with, in places, a thickness in excess of 5,000 feet, and then McKee reviews the catastrophic floods of meltwater from glacial Lake Missoula which resulted in one of the world's most intricately channeled landscapes.

Since the close of the last ice age, the magnitude of the natural phenomena has diminished; however, extreme contrasts remain. For example, the arid, central portion of the Columbia Plateau (in the vicinity of the Pasco Basin) is criss-crossed by one of the largest river systems in North America, the Columbia, and its tributaries, the Snake and Yakima Rivers. A cultural contrast can also be drawn between the traditional agrarian societies and the technologically complex nuclear industries which the region supports. In a sense, the contrasting natural environment has been responsible for interfacing these two societies--the region supports agriculture because of the rich, glacial and volcanic soils, warm and sunny climate, and available irrigation waters. The area was initially selected as a site for atomic energy development, at least partly, because of its abundant surface water supply, low population, and relative isolation.

Physiography

The Columbia Plateau region, for the purposes of the regional hydrology studies, can be described as the intermontane region which essentially coincides with the outcrop area of the Columbia River Basalt Group (Plate 1). Most of the region is located in Washington, but large areas also lie in western Idaho and northeastern Oregon. It is bounded by the Cascade Range on the west, the Okanogan Highlands to the north, the Rocky Mountains to the east, and the Blue Mountains to the south and southeast.

Freeman, Forrester, and Lupher (1945) subdivided the Washington State portion of the Columbia Plateau (Columbia Basin Sub-province) into six distinct geomorphic sections as follows:

1. Central Plains section;
2. Yakima Folds section;
3. Waterville Plateau section;
4. Channeled Scablands section;
5. Palouse Hills section; and,
6. North-Central Oregon Plateau section.

The locations of these sections, as well as other units within the remaining portion of the Columbia Plateau, are given in Figure 1.

To describe these sub-provinces in brief, the Waterville Plateau has a metamorphic and plutonic bedrock complex and its overlying basaltic formations are relatively undisturbed tectonically. The region also bears many geomorphic features which are characteristic of the Channeled Scablands, such as extensive exposure of bare Columbia River Basalt, deep coulees, and paleochannels. In contrast, Palouse Hills topography is characterized by a rolling and well-dissected thick veneer of silt (Palouse Soil) of eolian origin which overlies the Columbia River Basalt. The North-Central Oregon Plateau section is a moderately dissected basalt plateau which rises steeply from north to south and abuts against the Blue Mountains.

Of primary interest to the Basalt Waste Isolation Program are the Central Plains and Yakima Folds geomorphic units which are the sections of the Columbia Plateau within which the Hanford Site is situated. The Central Plains, as described by Thornbury (1965), represent a major downwarping within the Columbia Plateau. Two major structural basins, the Quincy Basin and Pasco Basin, lie within the section and are separated by two east-west-trending anticlinal ridges (the Frenchman Hills and the Saddle Mountains as shown in Figure 2) which are part of the Yakima Folds. In Pleistocene times, these basins functioned as sinks for glacial outwash which was flushed through the Channeled Scablands section from the northeast. As a result, a veneer of glaciofluvial and lacustrine silts and gravels has accumulated.

The Yakima Folds section lies to the west of the Central Plains and is characterized by a series of east-west-trending anticlinal ridges and intervening synclinal valleys (Figure 2). Of primary interest are the Saddle Mountains which provide the northern boundary of the Pasco Basin, the Umtanum, Yakima, and Rattlesnake Ridges which "finger" into the Pasco Basin from the west, and the Horse Heaven Hills forming the southern boundary of the Pasco Basin.

The folds and certain other structures are important to the surface water and shallow ground-water systems in that they determine the flow patterns and form boundaries. The Yakima River, for example, cuts across several anticlinal ridges above the town of Yakima, Washington, and is,

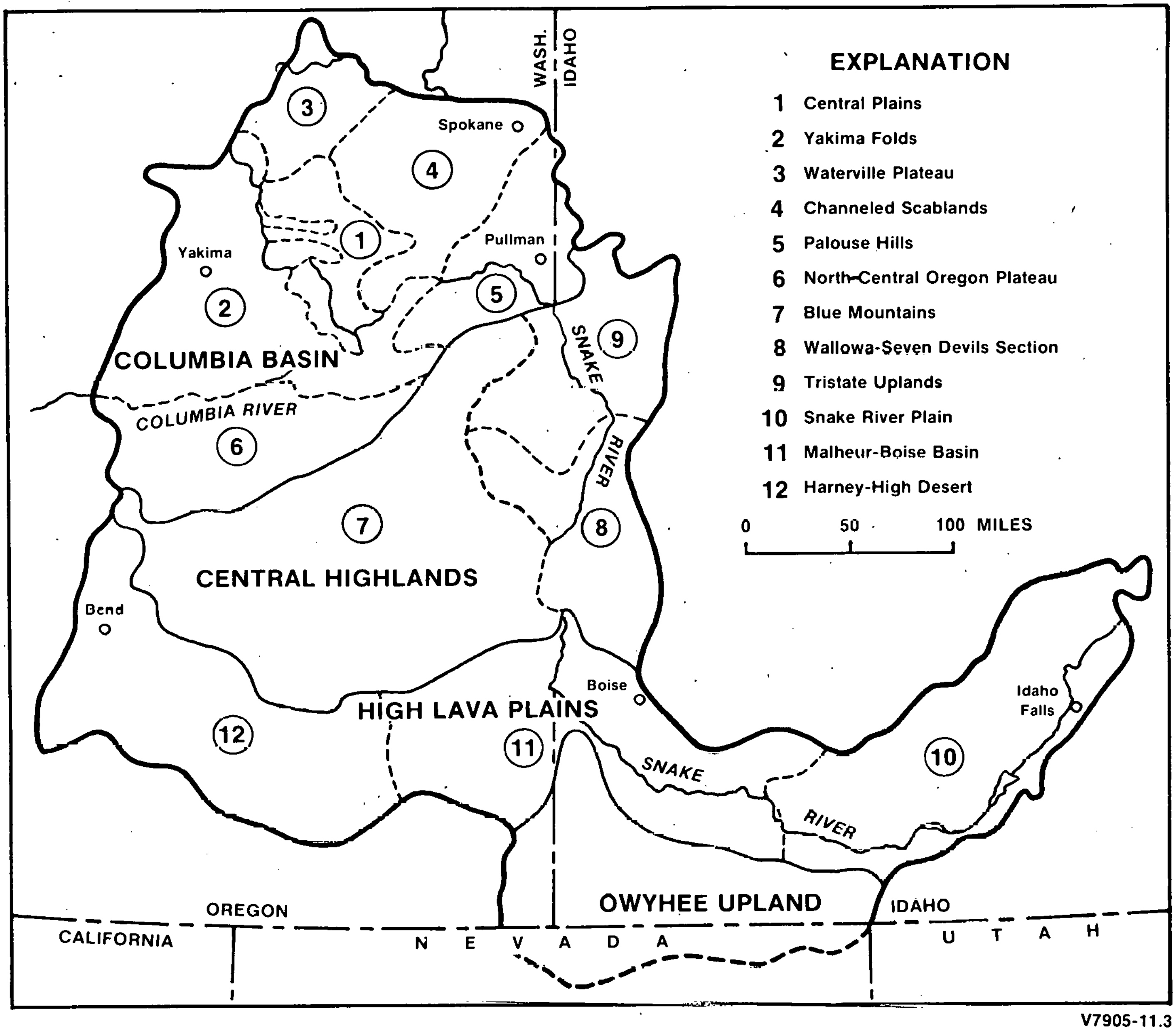

FIGURE 1. Geomorphic Units within the Columbia Plateau (after Freeman, Forrester, and Lupher, 1945).

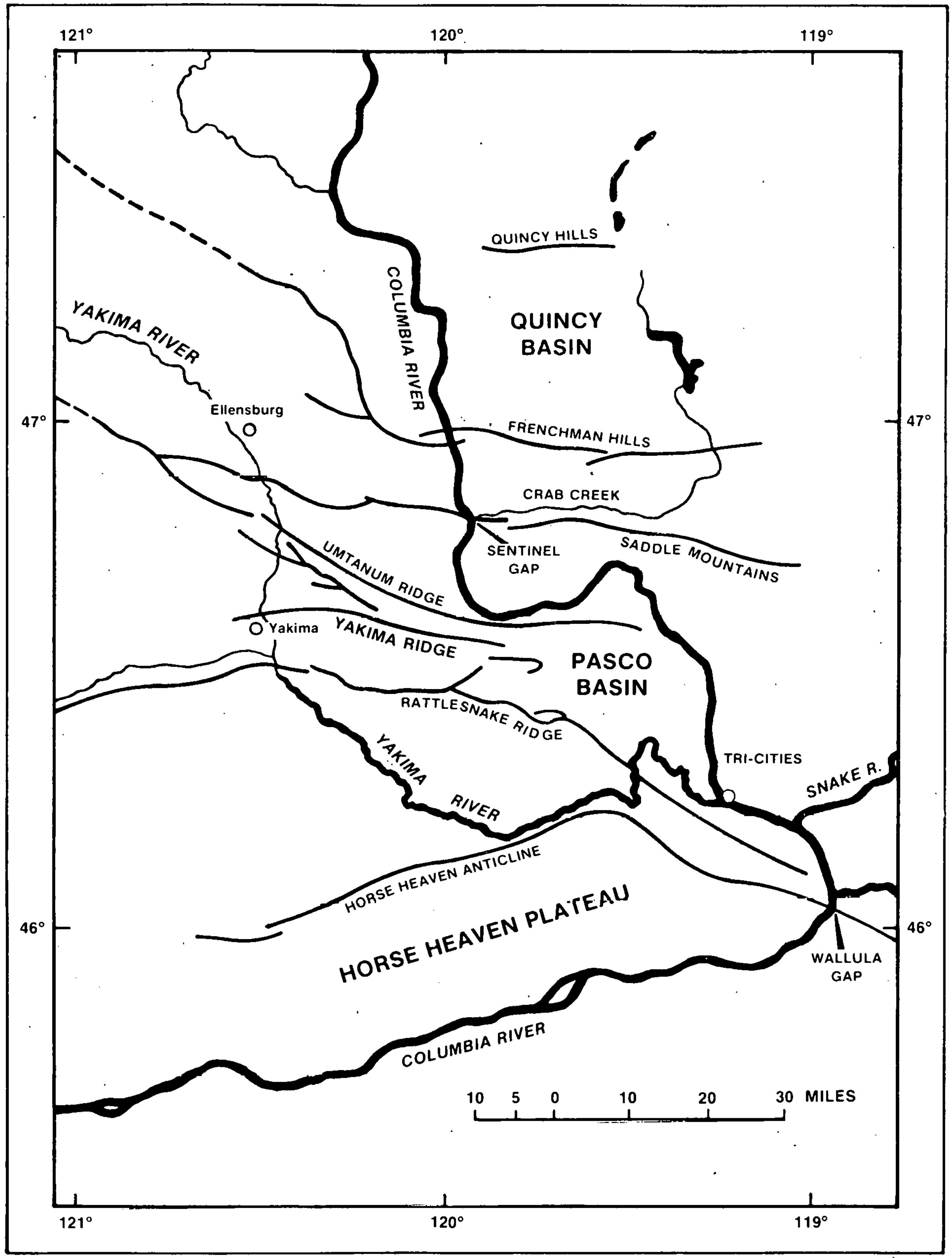

FIGURE 2. Axes of Major Anticlinal Ridges within the Central Columbia Plateau (after Waters, 1955).

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therefore, considered to be antecedent along that stretch. Along most of its lower stretch, however, the stream flows primarily along synclinal valleys. The Columbia River is also an antecedent stream and, apparently, the only stream sufficiently energetic to have maintained its westward course throughout the uplift of the Cascade Range.

Other Columbia Plateau structures of importance to the hydrologic system are the erosional and depositional features of the Channeled Scablands, such as coulees, pendant bars, grooves, potholes, rock basins, inner channels, cataracts, and other bedrock macro- and meso-forms. Such structures can influence stream course, velocity, misfitting, etc. For example, Baker (1978) sites a portion of Crab Creek as an example of an overfit stream (i.e., the flow is too great for the valley in which it flows).

Stratigraphy

Because of the great thickness of the basalts and associated rocks within the Columbia Plateau, knowledge of the pre-basalt stratigraphy is limited to inferred evidence from the study of outcrops, deep geophysical surveys, and a few drill holes near the plateau margins. On the basis of such studies, geologists have identified clastic sediments (approximately 200 feet thick) underlain by latite at a location approximately 115 miles northeast of the Pasco Basin; Precambrian Belt Series metasediments in the vicinity of Spokane; Permian and Triassic greenstones in the middle Snake River Canyon; and Mesozoic plutonic, metasedimentary, and metavolcanic rocks as well as early Cenozoic continental sediments and lavas along the Cascades underlying the basalt rock (WPPSS, 1974).

As indicated earlier, the Columbia River Basalt Group comprises the dominant stratigraphic feature within the Columbia Plateau. The group consists of tholeiitic flood basalts interbedded with sedimentary strata of the Ellensburg Formation and extends areally over approximately 100,000 square miles. The estimated volume of the basalt is about 50,000 cubic miles (Waters, 1962). Stratigraphic units as observed within the Columbia River Basalt Group within the Pasco Basin are presented in Figure 3.

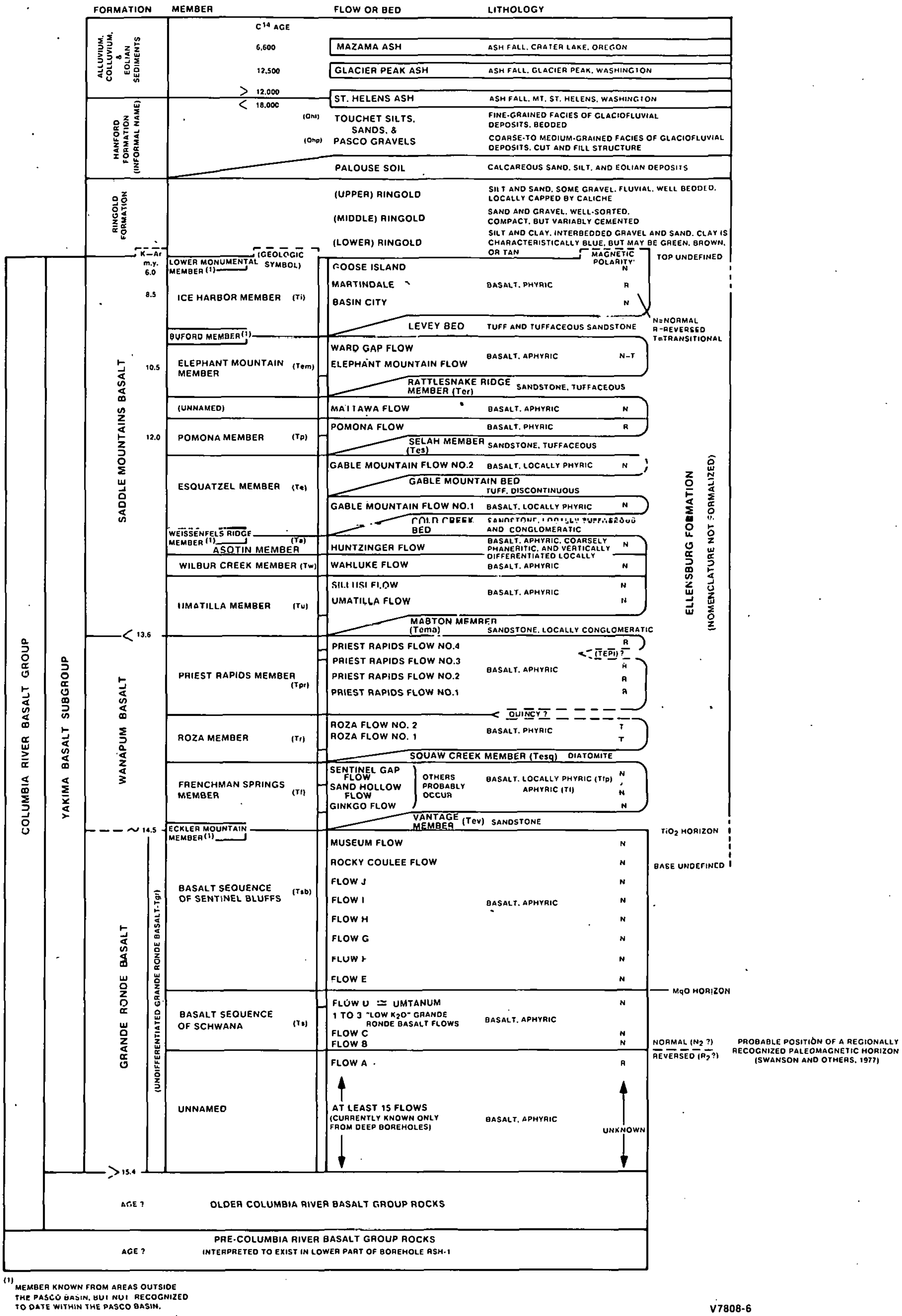

FIGURE 3. Columbia River Basalt Stratigraphy as Observed within the Pasco Basin (after Ledgerwood, Myers, and Cross, 1978).

Flows within the Columbia River Basalt range from a few feet to more than 300 feet thick, but most are between 35 and 100 feet thick. The areal extents of individual flows exhibit similar variability. Thicker flows have been interpreted to represent ponding within pre-basalt valleys along the plateau margins, structurally controlled basins that developed during the volcanism, or in narrow canyons eroded into older flows. The formation of columns is characteristic of static cooling that occurred within ponded lava (Swanson and Wright, 1978). Vesicular or brecciated zones are characteristic of flow tops.

Deformation during the later stages of Columbia River Basalt volcanism resulted in the emergence of the Yakima Folds system along the western plateau margins and fingering into the plateau interior. Growth of these folds created a system of structural ridges and basins, which include areas in the vicinity of Ellensburg, Ephrata, Yakima, and Pasco, Washington and Umatilla, Oregon. Thick sequences of sediments consisting of glacial outwash, lacustrine sediments, alluvial gravels, colluvial materials, and ash and eolian deposits transported from the surrounding highlands accumulated in these basins forming a post-basalt overburden.

Clastic sediments of the Pliocene Ringold Formation accumulated in the Quincy, Pasco, and Walla Walla Basins in the central portion of the plateau (Merriam and Buwalda, 1916; Newcomb, 1958; and Gustafson, 1978). Catastrophic floods at the close of the Pleistocene Epoch resulted in the deposition of thick sequences of glaciofluvial sediments of the Hanford formation (informal name) in these central plateau basins (Bretz, 1959). The Hanford formation overlies the Ringold Formation and the Columbia River Basalt Group.

On the western margin of the plateau in the Yakima and Ellensburg Basins, Ellensburg sediments continued to aggrade after cessation of the Columbia River Basalt volcanism. The Pliocene Thorp gravels (Porter, 1976; Taber and Others, 1977) overlie the Ellensburg Formation in the Ellensburg Basin. The Ringold Formation and glaciofluvial sediments are present in the lower Yakima Basin. In the Umatilla Basin, The Dalles Formation (Condon, 1902) was deposited on the Columbia River Basalt. Impoundment of flood waters in Glacial Lake Lewis during the late Pleistocene resulted in the deposition of glaciofluvial sediments of the Hanford formation in the Umatilla Basin.

These overburden formations are important to the local, shallow ground-water systems and also, in some areas, can control the amount of fluid exchange between such shallow ground-water systems and the basalt aquifers. The storage, rate, and direction of ground-water movement through these sediments are primarily controlled through lithofacies.

Climatography

Climate within the Columbia Plateau region is influenced by several factors including topography, distance and direction from the ocean, the prevailing westerly winds, and the position and intensity of the high- and low-pressure centers over the Pacific (Phillips, 1965, 1970; Donaldson and Ruscha, 1975).

Elevation is highly variable over the Columbia Plateau region ranging from sea level at the mouth of the Columbia River to well over 6,000 feet above mean sea level (MSL) in the mountainous areas rimming the plateau. The highest elevations at which Columbia River Basalt is found probably occur in the Wallowa Mountains in Oregon. Within the Washington State portion of the plateau, the Columbia River Basalt is found up to a maximum of about 4,000 feet in parts of Yakima County. The lowest elevations within the Pasco Basin, near the central portion of the plateau, are just under 400 feet.

The Rocky Mountains in western Canada shield the central plateau from cold arctic air masses moving southward. The Cascade Range forms a barrier to the easterly movement of moist and comparatively mild air in winter and cool air in summer. Most weather systems crossing the plateau travel with the prevailing westerly winds. In summer, air from the continent results in low relative humidity and high temperature; while in winter, it produces clear, cold, dry weather. Extremes in both winter and summer generally occur when the plateau is under the influence of air from over the continent. Maritime air moving in from the Pacific Ocean has a moderating influence throughout the year (Phillips, 1970).

Air masses with origins over the continent and others from over the ocean reach the Columbia Plateau and exert their influence on the climate. Summers are generally sunny, warm, and dry with a few very hot days when temperatures exceed 100 degrees Fahrenheit (°F). In the winter, frequent changes in the weather are caused by Pacific Ocean storm systems carried eastward by prevailing winds and cold arctic air masses moving southward across Canada. Daily temperature range is about 10 to 15°F in the winter and 30 to 35°F in the summer (Phillips, 1965, 1970; Donaldson and Ruscha, 1975).

Annual average precipitation ranges from less than 10 inches in the central, low-lying desert areas to over 25 inches on the higher mountain slopes. About two-thirds of the annual precipitation falls from October through March. Most precipitation falling between mid-December and mid-February is in the form of snow. Snowfall accumulation generally increases with elevation, but generally does not exceed 15 to 20 inches or remain on the ground longer than 6 weeks in the lower elevations. Annual loss of water by evaporation from lakes and reservoirs is estimated to range between 32 and 42+ inches.

Surface Water Hydrology

The Columbia River, along its 1,214-mile course, drains portions of 7 states and Canada (Figure 4), an area of approximately 259,000 square miles.

From its origin in the Rocky Mountain Trench southwest of Calgary, Alberta, the Columbia flows northwest for 150 miles before turning south on its course into the United States. The river enters the Columbia Plateau from the Okanogan Highlands, where it joins with the Spokane River, and immediately begins a westerly course along the Okanogan Highlands/Columbia Plateau margin. It turns south again at the foot of the north Cascades near Pateros, Washington, and maintains a southerly course for approximately 150 miles. The area enclosed to the south and east of the river is referred to as the Big Bend Sub-basin of the Columbia Plateau. Along the southerly course, the river cuts through several anticlinal ridge structures including the Saddle Mountains (at Sentinel Gap) before being diverted from its course at Umtanum Ridge close to the approximate location where it enters the Hanford Site. Upon clearing the easternmost expression of this structure (Gable Mountain), the Columbia resumes its southerly course joining with the Yakima River from the west and its principal tributary, the Snake River, from the east below the Hanford Site in the vicinity of the Tri-Cities (Richland, Kennewick, Pasco, Washington). Beyond this point, the Columbia joins

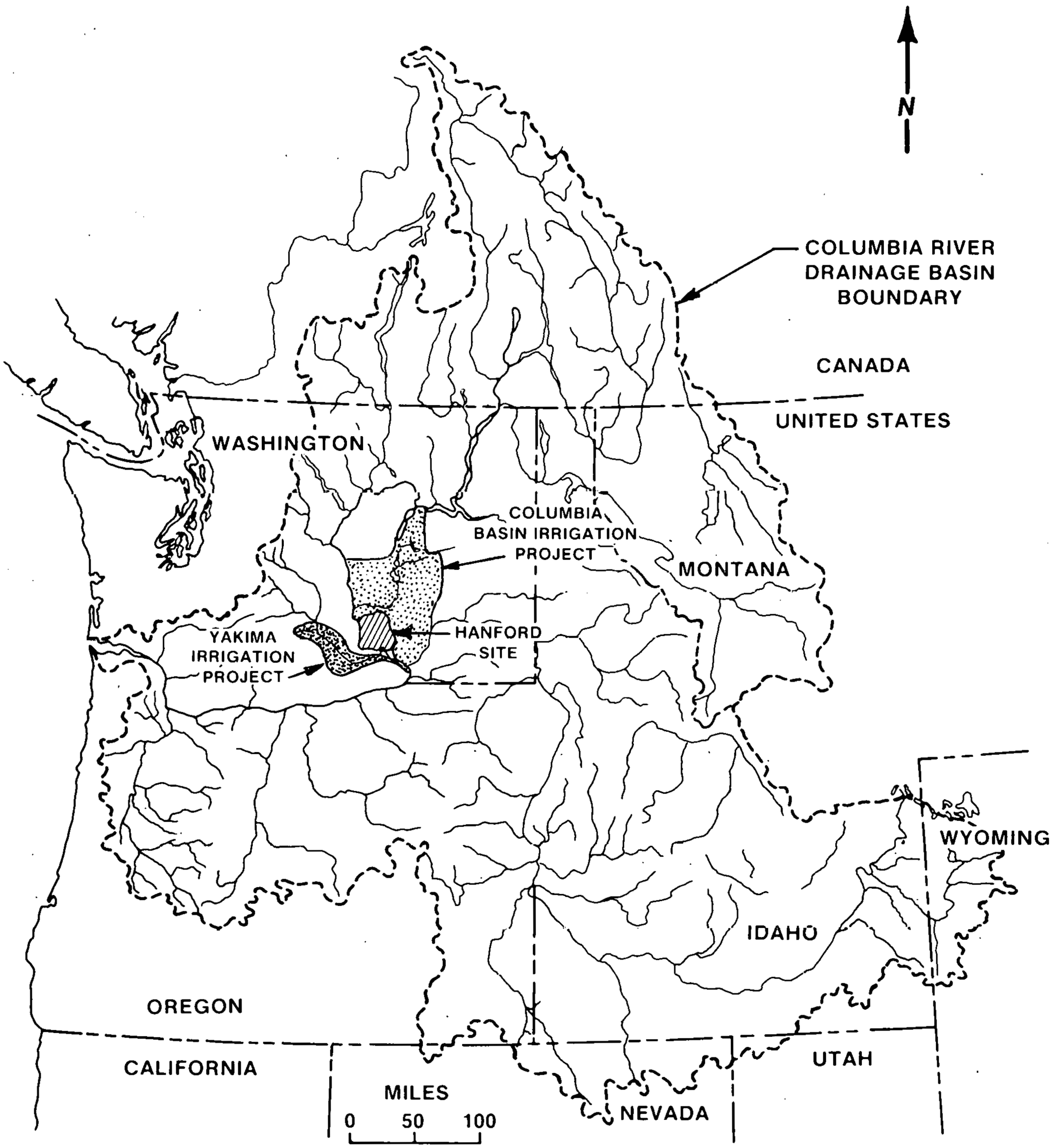

FIGURE 4. Regional Map of the Columbia River Drainage System.

with the Walla Walla River before gapping the Horse Heaven Hills anticline at Wallula Gap. The Columbia then begins a 300-mile westerly course to its mouth at the Pacific Ocean.

Hydrologically, the Columbia Plateau can be segregated into sub-basins according to the major surface drainage systems present. Figure 5 shows such a segregation with respect to the Washington State portion of the plateau. The Pasco Sub-basin, although shown among the other sub-basins, is not hydrologically discrete from the adjacent sub-basins of the Columbia Plateau. It is treated separately, however, because it incorporates the Hanford Site and because of its relative significance to the Basalt Waste Isolation Program. All of the other sub-basins interface in some fashion with the Pasco Sub-basin. It should also be noted that the validity of making such hydrologic segregations for the Columbia Plateau is limited to shallow ground-water and surface-water systems. The geometries and areal extents of the deep, regional ground-water systems are currently being identified in other Basalt Waste Isolation Program hydrology activities.

Of further hydrologic significance is the extensive network of multi-purpose water resources projects which have been developed in the region. Most notably, the Grand Coulee Dam forms the 80,000-acre Franklin D. Roosevelt Lake which has a 9.4 million acre-feet capacity. Combined with the 15.5 million acre-feet of storage upstream in Canadian reservoirs, a total of 30 million acre-feet of usable storage is available in the basin above Grand Coulee Dam to regulate the flow of the Columbia River for power and flood control. Additionally, the system has been designed to deliver a full supply of water to 1,095,000 acres of irrigable land within the Columbia Basin Irrigation Project (Figure 4). The Yakima Irrigation Project (Figure 4) maintains a storage capacity of about 1 million acre-feet and is designed to deliver irrigation to 461,500 acres. Although no comparably significant irrigation development has occurred along the Snake River, several dams and reservoir projects have been constructed for other multipurpose uses. In certain areas excluded from the delivery of imported irrigation waters, considerable ground-water resource development is supporting local agriculture.

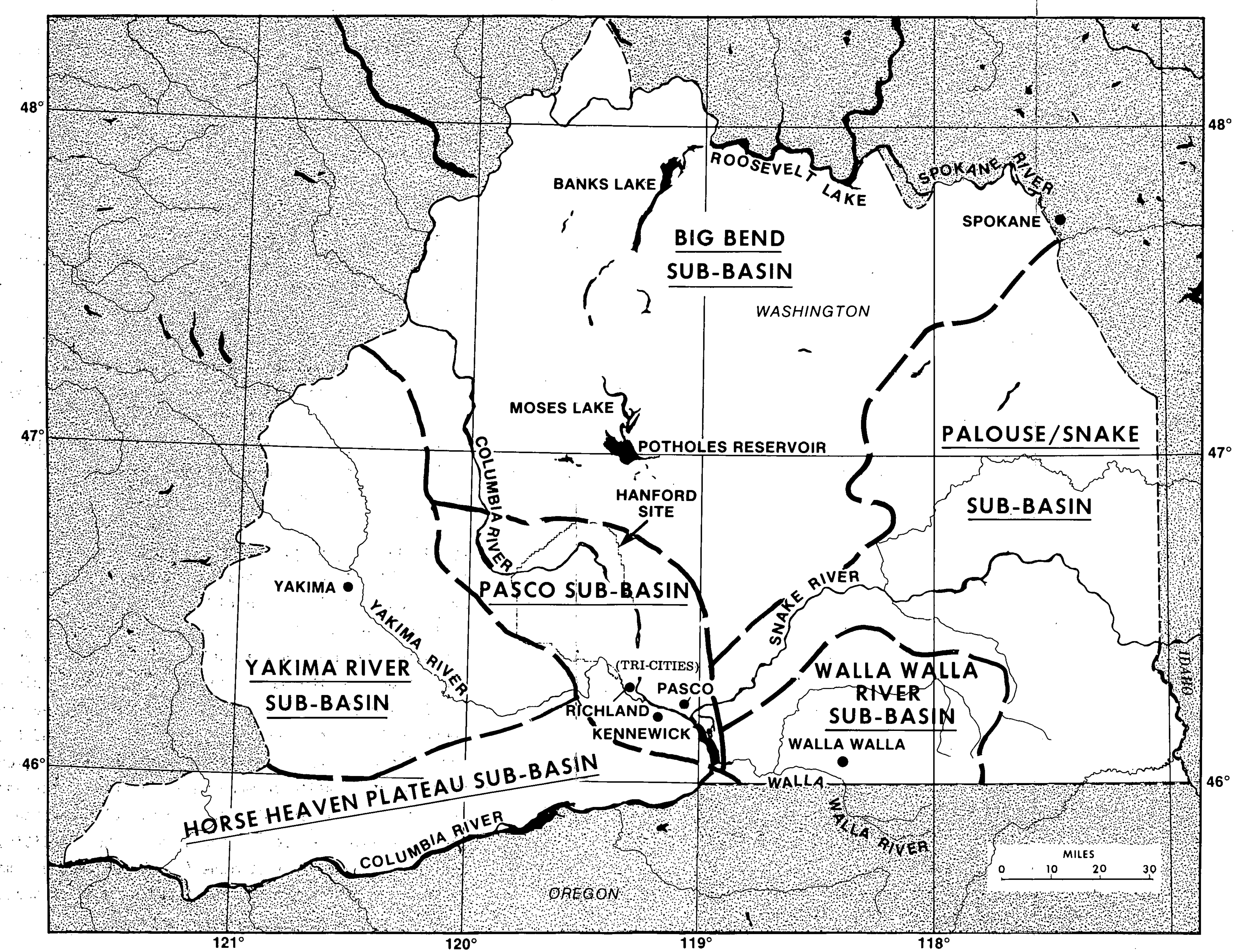

FIGURE 5. Designated Hydrologic Sub-basins within the Washington State Portion of the Columbia Plateau.

Ground-Water Hydrology

Although much development of ground-water resources within the Columbia Plateau has taken place within recent years, no effort has been made to develop a conceptual model of the regional ground-water flow system in a comprehensive fashion. This is one of the current goals of the Basalt Waste Isolation Program, and ongoing efforts are working toward the objective of preparing such a model.

In general terms, in the context of this report, it is convenient to refer to shallow ground-water systems which are generally unconfined or semi-confined, situated within the basalt overburden materials or uppermost basalt horizons, and generally limited in areal extent to a single sub-basin or a part of a sub-basin. The distance of travel from their area of recharge to the location of discharge is comparatively small. Deep ground-water systems generally occur within the basalt formations and are of comparatively greater areal extent, have longer flow paths, and may result in inter-basin flow. An arbitrary cutoff of 200 feet below land surface has been designated by the State of Washington for the purpose of regulation and management of ground water resource development.

Demography, Industry, and Agriculture

In 1978, population statistics (Washington State Office of Financial Management, 1978) for the 15 Washington State counties of the Columbia Plateau show that the total population for the region is 827,500. Table 1 provides population statistics for each county and Table 2 lists the populations for the major population centers within the region.

Industrial activity within the region has been spurred by the construction of dams on the principal streams and the generation of hydroelectric power. The energy has been used regionally to foster development of major primary metals installations and other small manufacturing operations. Other activities carried out throughout the region include the nuclear industry in the Tri-Cities, distribution activities centered in Spokane (which has become a major railhead for interstate commerce), and food processing and storage facilities associated with the agricultural areas.

TABLE 1. 1978 Populations of the 15 Washington State Counties Encompassing the Columbia Plateau Region.

(After Washington State Office of Financial Management, 1978.)

County	Population
Adams	14,200
Asotin	15,600
Benton	90,600
Columbia	4,600
Douglas	20,600
Franklin	30,400
Garfield	2,700
Grant	46,100
Kittitas	25,600
Klickitat	14,400
Spokane	320,300
Walla Walla	43,800
Whitman	41,900
Yakima	156,700
Total	827,500

TABLE 2. 1978 Populations of Metropolitan Areas within the Washington State Portion of the Columbia Plateau having Populations in Excess of 10,000.

(After Washington State Office of Financial Management, 1978.)

County	City	Population
Benton	Kennewick	26,564
Benton	Richland	32,350
Franklin	Pasco	16,000
Grant	Moses Lake	10,900
Kittitas	Ellensburg	12,800
Spokane	Spokane	176,700
Walla Walla	Walla Walla	24,570
Whitman	Pullman	23,300
Yakima	Yakima	52,250

Agriculture is widespread particularly in the Yakima Valley, Columbia Basin, and Palouse Hills areas. Development of the Yakima and Columbia Basin Irrigation Projects is largely responsible for the recent and continuing agricultural growth. Principal agricultural products in the Yakima Valley have been apples and soft fruits, hops, mint, grapes, and vegetables. In the Columbia Basin and Palouse Hills areas, wheat, potatoes, sugar beets, hay, and peas have dominated agricultural production. Livestock production, including cattle and hogs, is also common.

WATER RESOURCES

The following sections describe water resources data utilized within this report for the preparation of surface water budgets for the six Columbia Plateau sub-basins.

PRECIPITATION

Precipitation processes operating within the Columbia Plateau region are of three principal types:

1. Orographic--precipitation resulting from the ascent of moist air masses over a topographic barrier;
2. Convective--precipitation resulting from the buoyancy of air due to differential heating of underlying land masses; and,
3. Frontal--precipitation resulting from the movement and interfacing of large air masses having significantly different physical properties.

Because each of these processes display grossly different precipitation characteristics, they also result in different characteristics with regard to potential ground water recharge as follows.

1. Orographic precipitation is related to elevation, slope characteristics, slope aspect, and the distance from the moisture source. The relative, spatial distribution tends to be similar from storm to storm, and, where orographic effects are dominant, individual storm patterns are similar to the annual precipitation pattern. Although the amount of available moisture decreases with elevation during a storm event, for long periods of record, precipitation can generally be shown to be in direct correlation with elevation. Precipitation is also greater on the windward side of the topographic feature to a significant degree. Another consideration is that for high mountain ranges, while rain is falling at the lower elevations, snow may be falling at higher elevations and, thus, may not immediately contribute to runoff. Because of the relative consistency of orographic precipitation over the long term, orographic precipitation mechanisms are extremely important in the evaluation of regional recharge.
2. Convective precipitation usually results from storms of comparatively small dimensions, and is composed of a series of coalescing and moving storm cells. Precipitation consists of large raindrops falling to the earth with high energy and intensity. Time duration

is generally short and, thereby, convective precipitation mechanisms for the most part favor runoff as opposed to infiltration generation. Additionally, convective precipitation processes are more common in the warm seasons than in the winter.

3. Frontal precipitation events by comparison with convective precipitation are generally more areally extensive and of longer duration and lesser intensity. Frontal systems may result in moderate- to long-duration storms depending upon their rate of movement. In some instances, the system may stagnate over an area resulting in sustained, heavy rains. Frontal systems may be important both in terms of recharge and runoff depending on several factors. Virtually all precipitation that occurs during the winter season in the interior plateau is the result of frontal mechanisms.

Precipitation in the form of snowfall can be extremely important to the surface hydrology, particularly of upland areas. It has already been noted that the amount and distribution of snowpack and the rate of melting can be primary factors in determining regional runoff and recharge. Although the depth of snowfall over an area tends to be more uniform than rainfall, it may undergo considerable redistribution and differential melting before appearing as recharge or runoff. Perhaps the primary factor preventing proper integration of snowpack contributions within the hydrologic budget is a general lack of spatial data. The rate of melting is also important with regard to flooding, particularly in the springtime.

The distribution of mean annual precipitation for the Washington State portion of the Columbia Plateau is shown on Plate 2. The plate reveals that the lowest quantities of precipitation occur at the lower elevations within the west-central part of the region (specifically, within the Pasco Sub-basin). Annual precipitation in this area is generally less than 10 inches, with exceptions noted at higher elevations (above about 2,000 feet) where mean annual precipitation can exceed 15 inches. There are 2 principal reasons for the aridity of this region: first, elevation; and second, rain shadow effects of the Cascade Range. The greatest amount of precipitation occurs in the western part of the region along the Cascades, which receive extremely high quantities of precipitation via orographic effects acting upon moist air masses moving from the Pacific. Other regions of high precipitation occur within the northern, eastern, and southeastern highland areas. In a general way, the isohyets conform to topograhic contours. The maximum precipitation for the Columbia Plateau is probably in excess of 50 inches annually in parts of the upper Yakima River Sub-basin and possibly the Blue Mountains in the Palouse/Snake Sub-basin. A summary of mean annual precipitation statistics for various stations within and adjacent to the Columbia Plateau is presented in Appendix A.

EVAPORATION/TRANSPIRATION

Evaporation is defined as the process by which water changes from a liquid state to a gaseous state. Transpiration accomplishes the same transformation, but is performed by plants. The combined loss of water to the atmosphere by evaporative and transpirative processes is referred to, in the context of a hydrologic budget, as evapotranspiration. A distinction is also drawn between actual and potential evapotranspiration. Actual evapotranspiration (AET) is the observed losses to the atmosphere and potential evapotranspiration (PET) is the losses that would be observed if the quantity of moisture were not limiting.

Evaporation measurements are obtained at various stations across the Columbia Plateau using Class A-type evaporation pans. The stations are generally associated with agricultural research stations and are situated in low-lying agricultural areas. Figure 6 shows a generalized distribution for Class A pan evaporation across the Columbia Plateau region. Several facts should be noted in interpretation and use of such data. In particular, the data are highly generalized. The map was prepared on the basis of sparsely distributed stations and does not attempt to detail differences due to elevation and microclimatological effects. Secondly, pan evaporation measurements are characterized by inherent errors which tend to provide readings higher than those observed in corresponding natural conditions. In most applications, an empirical pan coefficient is applied as a means of more closely approximating the natural evaporation. Figure 7 is, therefore, a corresponding map of pan coefficients to be applied to Figure 6 in estimating actual evaporation.

Figure 6 reveals a roughly elliptical pattern with the highest evaporation values occurring in the central portion of the Columbia

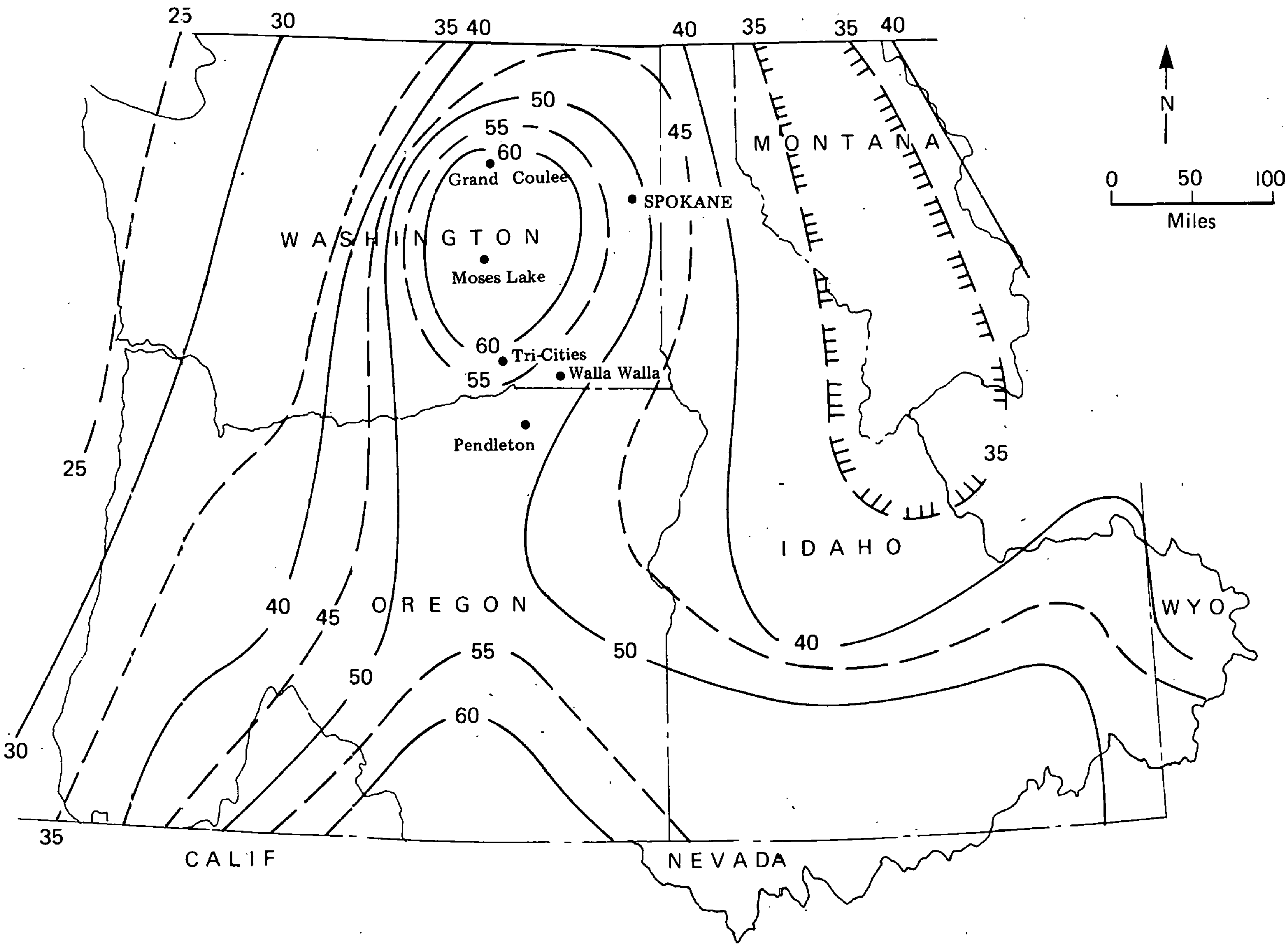

FIGURE 6. Average Annual Class A Pan Evaporation in Inches for the Period 1946-1955 (after Pacific Northwest River Basins Commission, 1969).

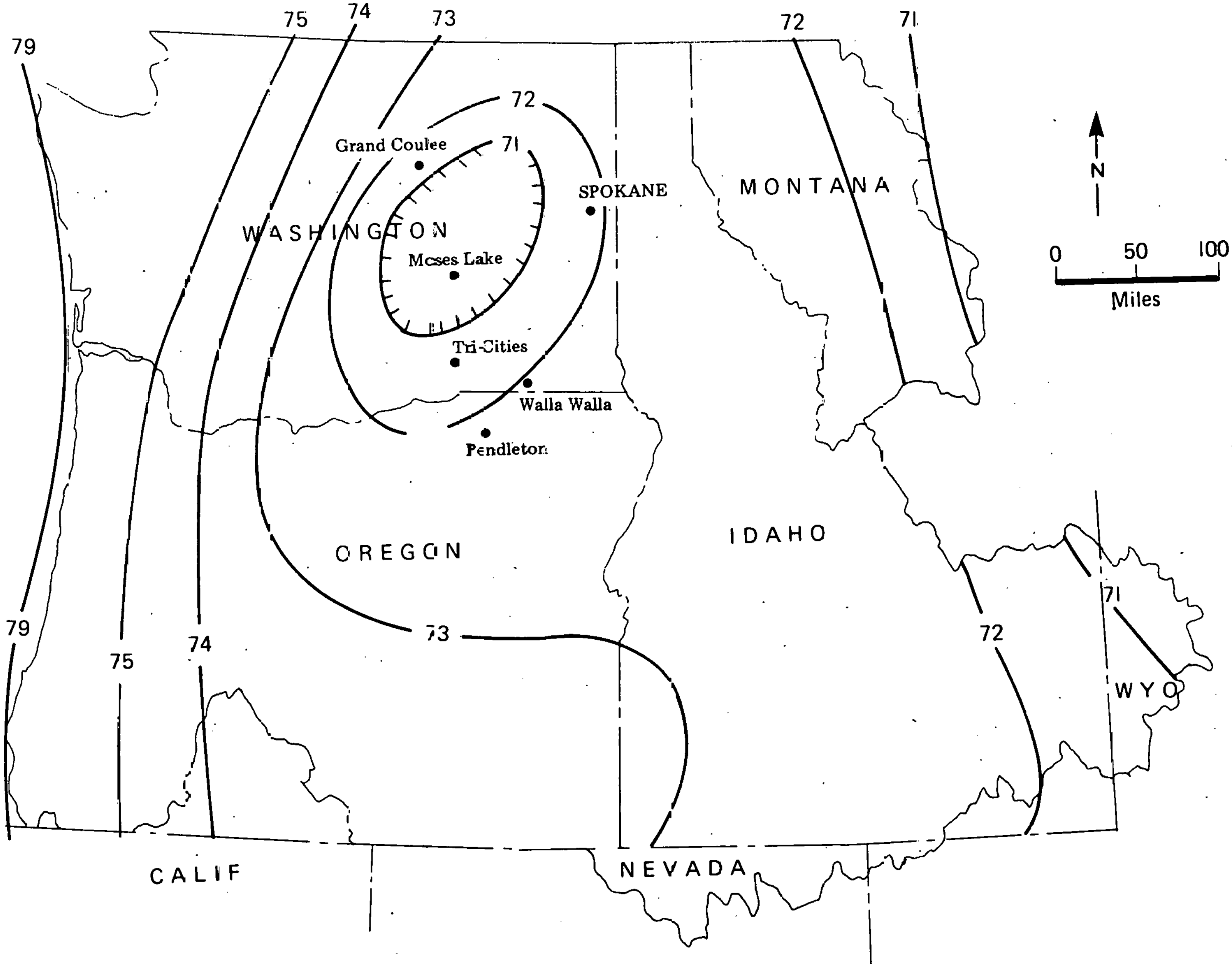

FIGURE 7. Average Annual Class A Pan Coefficient in Percent (after Pacific Northwest River Basins Commission, 1969).

Plateau centered approximately over Moses Lake, Washington and decreasing almost concentrically outward. The pattern is no doubt due to the higher temperatures and insolation and flatter topography of the central basin area.

Figure 8, which shows the distribution of mean annual lake evaporation, reveals a similar, although proportionately lower, pattern and is, therefore, presented with the same notations and explanations as the pan evaporation distribution map. This figure may also be construed as an approximation of the regional distribution of PET.

The AET and PET estimates have been computed using the Thornthwaite-Mather technique (1957) for soils having an assumed six-inch water-holding capacity in the root zone for various stations within and adjacent to the Columbia Plateau. The results are tabulated within Appendix A. A sampling of these data for several stations distributed across the Columbia Plateau has been plotted graphically in an effort to ascertain the amount of excess soil moisture available for deep percolation on an annual basis. The plots are shown in Appendix B. According to the theory of the Thornthwaite-Mather technique, it is necessary to exceed the field capacity of the soil before recharge to the ground-water table (i.e., deep percolation) can occur. For the above plots, it was assumed that a six-inch water-holding capacity existed. Thusly, none of the plots showed ground-water recharge potential during any month. Under actual conditions, however, the spatial variability of recharge is important because:

1. Spatial variability of precipitation exists; and,
2. Field capacity of soils can be highly variable.

For many areas within the plateau, microclimatological and soil conditions probably favor a certain amount of ground-water recharge in spite of these balances.

Plate 3 illustrates the generalized distribution of mean annual AET for the Columbia Plateau plotted on the basis of the data in Appendix A. The pattern obtained is grossly similar to that shown for mean annual pan and lake evaporation, but with the lower values appearing in the center and increasing outward. It is also noted that the pattern is centered

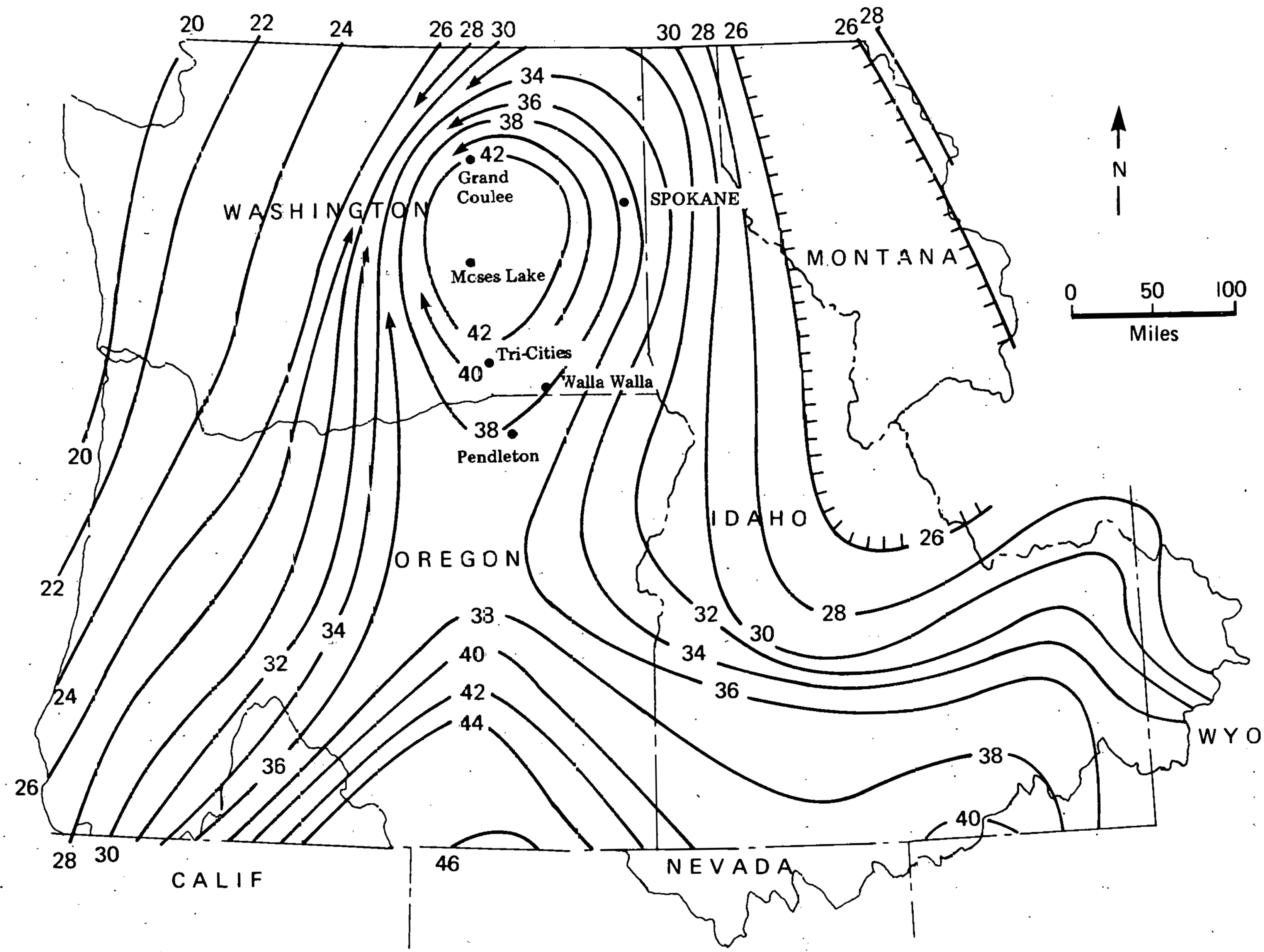

FIGURE 8. Average Annual Lake Evaporation in Inches for the Period 1946-1955 (after Pacific Northwest River Basins Commission, 1969).

over the Pasco Basin in contrast to the aforementioned figures which have their centers approximately over Moses Lake. The explanation is strongly dependent upon the temporal and spatial distribution of precipitation. As has already been noted, there is a depression in the isohyetal map which is centered at about the same location as that for the AET map. Thus, as precipitation increases outward from this center, the value of the AET approaches that for PET.

Using available data from the Hanford Meteorological Station (within the Pasco Sub-basin), Wallace (1977) compared methods for computation of PET. His results are compared in Table 3, and show that all methods yield an annual value of 5 to 9 times the mean annual precipitation. Wallace notes that the values obtained from the Thornthwaite-Mather and Penman methods are similar, but that the Morton method yields a significantly higher value. Because the Morton method was calibrated using data from arid stations, the value obtained may be more truly representative of the amount of evapotranspiration at Hanford.

TABLE 3. Comparison of Methods for Computing Potential Evapotranspiration Using Hanford Meteorological Station Data.

(After Wallace, 1977.)

Method	Annual Evapotranspiration (inches)
Thornthwaite-Mather	29.4
Penman	31.3
Morton	54.8

STREAMS

In general, streamflow is supported by two mechanisms:

1. Direct surface runoff (DSRO); and,
2. Baseflow from discharging ground waters and interflow.

The DSRO includes channelized and overland flow which arrives at the principal stream solely by surface courses. Unless the stream is gauged, DSRO must be evaluated empirically on the basis of precipitation-event parameters. Baseflow characteristics for a given stream are generally evaluated on the basis of hydrograph separation, the contribution of the baseflow being the remaining portion of the hydrograph in the absence of contribution from a storm event.

In the Columbia Plateau region, most perennial streams have their headwaters in highlands outside of the region and are maintained by snowmelt runoff and precipitation which occur at these higher elevations. The streams are, therefore, "exotic" to the arid interior of the plateau. With regard to the degree of runoff contribution to surface water courses from within the plateau, Figure 9 is a map of the distribution of mean annual runoff in Washington State. Variability is primarily due to spatial variability of precipitation; however, basin characteristics such as infiltration capacity, slope, and vegetation and event characteristics such as intensity, duration, antecedent moisture, and form of precipitation can be important secondary factors. On the basis of the percentage of runoff resulting from a given volume of precipitation, a basin-wide runoff coefficient can be derived for use in simulating rainfall/runoff events. While Figure 9 reflects considerable smoothing and generalization of the runoff contours, it can be seen that runoff contributions to surface flow are extremely low throughout most of the plateau. The lowest values occur in the center of the area and are practically negligible. Runoff increases greatly as the terrain becomes steeper to the west, north, east, and southeast along the mountain ranges.

Baseflow is an extremely difficult parameter to assess due to the exotic character of the streams present as earlier discussed. It is, however, possible to draw inferences with regard to whether streams are

FIGURE 9. Distribution of Mean Annual Runoff in Inches within the Washington State Portion of the Columbia Plateau (map prepared by U.S. Department of Agriculture, 1972).

gaining or losing over a given reach, but generally such quantities are several orders of magnitude less than the total flow.

LAKES

As a part of its mandate to inventory water resources within the State of Washington, the Washington State Department of Ecology (WSDOE) maintains a tabulation and evaluation (Wolcott, 1973) of all lakes within the state. For the purpose of the inventory, WSDOE applies the following criteria.

1. The body of water must fit Webster's definition of a lake as follows:

   "A considerable inland body of standing water; also an expanded part of a river. When a body of water is so shallow that aquatic plants grow in most of it, it is usually called a pond; when the pond is mostly filled with vegetation, it becomes a marsh."

2. The body of water must have a surface area of at least one acre.

3. If the body of water is a named lake, it was so classified regardless of surface area.

4. If the body of water is a marsh, but contains some open water the year around, it was classified as a lake.

5. If a number of lakes exist within a limited area, all or most of which are under one acre in size, they were classified as a single unit.

Table 4 lists the numbers and acreages of lakes within the 15 Washington State counties within the Columbia Plateau. The principal lakes and reservoirs within the Columbia Plateau are those associated with the various multipurpose water resource projects. A listing of these is provided in Table 5.

WATER USE

Water use in the State of Washington correlates with the increase in municipal, industrial, and agricultural development. Periodic summaries of these water-use categories are prepared by the U.S. Geological Survey (USGS) (Dion and Lum, 1977) and listed by counties and by WRIAs as

TABLE 4. Natural and Artificial Lake Acreages in the 15 Washington State Counties of the Columbia Plateau.

(After Wolcott, 1973.)

County	Number of Lakes	Surface Area (acres)
Adams	133	4,392.6
Asotin	15	5,861.5*
Benton	31	33,984.7*
Columbia	16	41.3
Douglas	237	19,694.4
Franklin	49	17,282.2
Garfield	7	32.1
Grant	227	172,530.9
Kittitas	221	14,301.0
Klickitat	48	31,948.1
Lincoln	248	4,599.3
Spokane	496	16,015.7
Walla Walla	19	962.4
Whitman	142	20,490.2*
Yakima	320	6,578.2
Total	2,209	348,714.6

*Washington State portion of waters lying on state line.

TABLE 5. Principal Lakes and Reservoirs within and adjacent to the Columbia Plateau, Washington.

(After Wolcott, 1973.)

Lake or Reservoir	Washington County	Stream	Mean Elevation (feet MSL)	Surface Area (acres)	Storage Capacity (acre-feet)	Year of Initial Operation	Uses
Banks Lake	Grant, Douglas	Canal fed	1,560	24,900	1,014,200	1951	Recreation, irrigation storage
Bumping Lake	Yakima	Bumping River	3,426	1,310	33,700	1910	Recreation, irrigation storage
Cle Elum Lake	Kittitas	Cle Elum River	2,223	4,810	435,900	1932	Recreation, irrigation storage
Franklin D. Roosevelt Lake	Grant, Stevens, Ferry, Lincoln, Okanogan	Columbia River	1,288	79,000	9,562,000	1939	Recreation, irrigation, power, flood control, fishery, navigation
Kachess Lake	Kittitas	Kachess River	2,254	4,540	239,000	1905	Recreation, power, irrigation
Keechelus Lake	Kittitas	Yakima River	2,517	2,560	157,800	1914	Recreation, power, irrigation
Lower Monumental Dam Reservoir	Franklin, Walla Walla, Whitman, Columbia	Snake River	540	6,590	375,000	1967	Power, navigation, recreation
Moses Lake	Grant	*	*	6,800	131,000	*	*
Potholes Reservoir	Grant	Crab Creek Valley	1,046	28,200	523,000	1949	Recreation, irrigation
Priest Rapids Dam Reservoir	Grant, Yakima, Kittitas	Columbia River	488	7,700	44,800	1960	Power, recreation
Rimrock Lake	Yakima	Tieton River	2,918	2,530	193,000	1925	Recreation, irrigation
Lake Sacajawea	Franklin, Walla Walla	Snake River	440	8,370	405,000	1961	Navigation, power, recreation
Lake Wallula	Benton, Franklin	Columbia River	340	38,800	1,350,000	1953	Navigation, power, recreation
Wanapum Dam Reservoir	Kittitas, Douglas, Chelan, Grant, Yakima	Columbia River	571	14,680	163,000	1963	Power

*Not reported.

designated by the state. Figures 10 and 11, respectively, depict the locations of the Washington State counties and eastern Washington WRIAs. Table 6 lists the names of the WRIAs appearing on Figure 11. As discussed earlier, there is not a precise coincidence of county and WRIA boundaries with those of the Columbia Plateau hydrologic sub-basins designated for the purpose of this report (Figure 5); however, careful selection of areas has allowed a sufficiently reasonable approximation of water-use statistics for the purpose of preparing water budgets.

Municipal water use as inventoried by USGS includes the sum of all water delivered by water-supply systems serving more than 100 people in each county or WRIA. The category includes water supplied by municipal systems for domestic, commercial, industrial, fire protection, street washing, system flushing, and variable amounts of minor uses for irrigation, stock watering, and leakage. Self-supplied industrial water and all individual rural water uses are excluded. The inventory reveals that, on a regional basis, surface water was the source of 91 percent of the total municipal supply in western Washington, but only 9 percent of the total municipal supply in eastern Washington (Dion and Lum, 1977).

The USGS subdivides the industrial water-use category into municipally and self-supplied classes. Another listing provides water-use statistics for 19 Standard Industrial Classes (SIC); however, the categories apply primarily to manufactured products and do not account for water use for energy generation. Further, no separation is made between consumptive and non-consumptive uses. The county using the most water for industrial purposes is, by far, Benton County.

Irrigation use includes water diverted from streams, imported by canals and/or withdrawn from lakes and reservoirs, or pumped from the ground for application upon lands for the purpose of plant watering. Small quantities of stock water uses, rural domestic uses, and evaporation and conveyance losses are also included. Among the Washington counties, Franklin, Grant, and Yakima Counties are the largest users of irrigation water. Irrigation constitutes the largest of the three water-use categories discussed.

Statistics for the 15-county area comprising the Columbia Plateau for each water-use category are presented in Tables 7, 8, and 9.

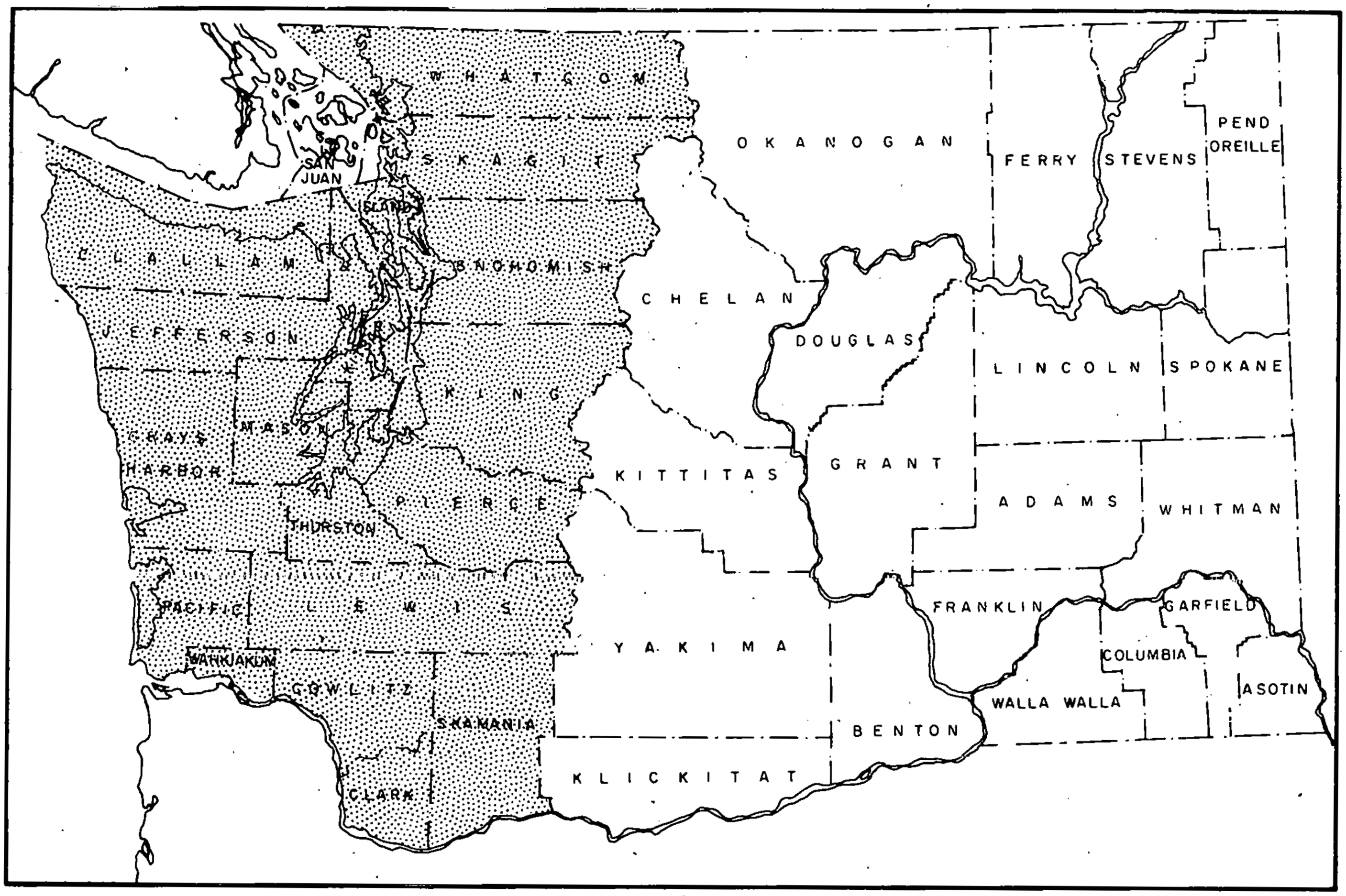

FIGURE 10. Counties of Eastern Washington.

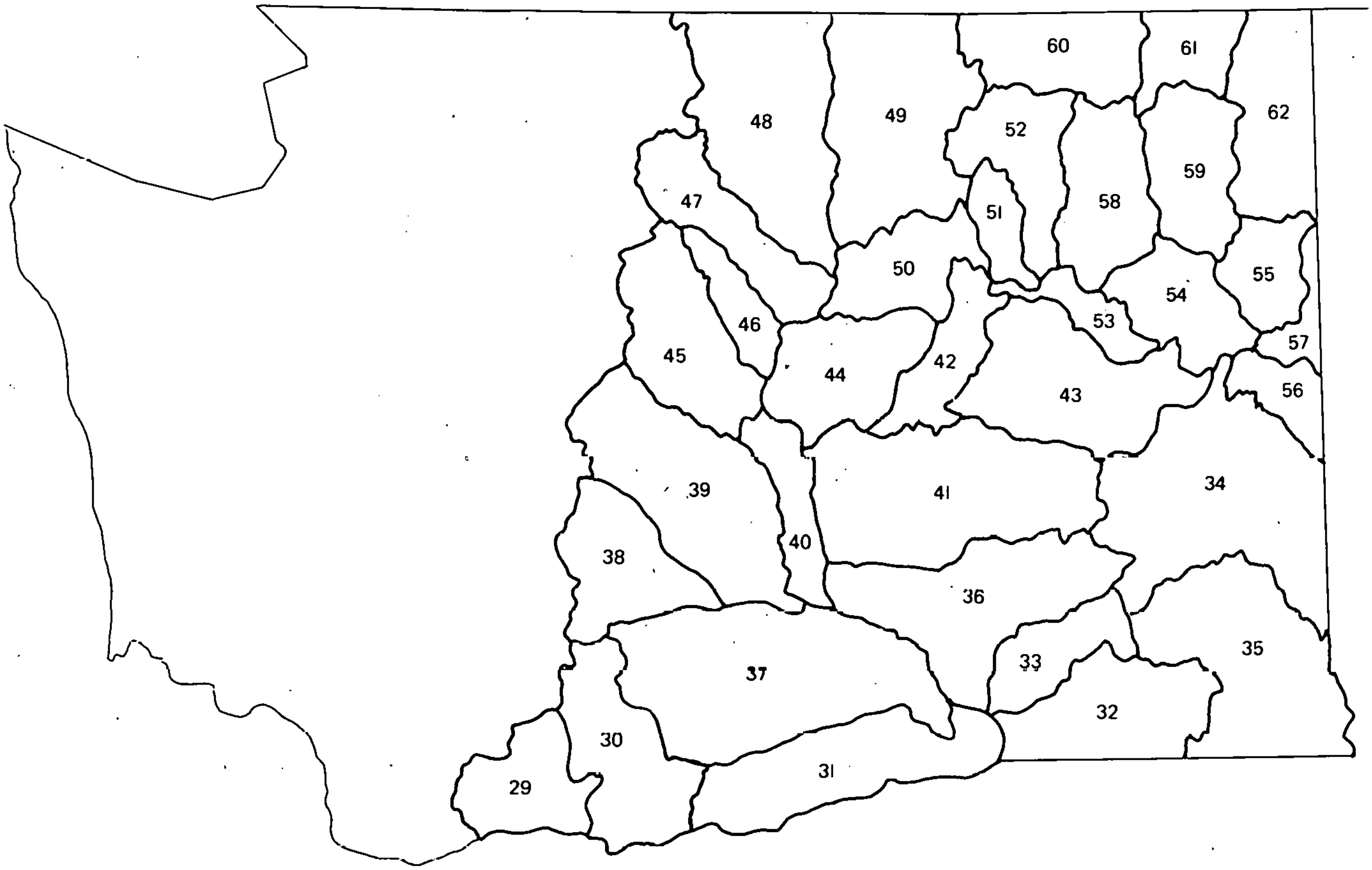

FIGURE 11. Washington State Water Resource Inventory Areas of Eastern Washington. (Note: Names for numbered WRIAs appear on Table 6.)

TABLE 6. Water Resource Inventory Areas of Eastern Washington.

Number	Name	Number	Name
32	Walla Walla	48	Methow
33	Lower Snake	49	Okanogan
34	Palouse	50	Foster
35	Middle Snake	51	Nespelem
36	Esquatzel Coulee	52	Sanpoil
37	Lower Yakima	53	Lower Lake Roosevelt
38	Naches	54	Lower Spokane
39	Upper Yakima	55	Little Spokane
40	Alkali-Squilchuck	56	Hangman
41	Lower Crab	57	Middle Spokane
42	Grand Coulee	58	Middle Lake Roosevelt
43	Upper Crab-Wilson	59	Colville
44	Moses Coulee	60	Kettle
45	Wenatchee	61	Upper Lake Roosevelt
46	Entiat	62	Pend Oreille
47	Chelan		

TABLE 7. 1975 Annual Municipal Ground and Surface Water-Use Statistics by County Within the Washington State Portion of the Columbia Plateau.

(After Dion and Lum, 1977.)

County	Annual Municipal Water Use (acre-feet per year) GW	SW	Population Served
Adams	2,808	0	7,380
Asotin	6,310	0	13,400
Benton	9,495	16,428	67,200
Columbia	1,363	0	2,950
Douglas	2,323	0	15,000
Franklin	2,434	6,000	22,700
Garfield	509	0	1,800
Grant	10,990	442	29,300
Kittitas	4,195	466	18,000
Klickitat	230	2,207	10,000
Lincoln	2,541	0	6,170
Spokane	87,362	0	286,000
Walla Walla	7,344	4,585	34,500
Whitman	6,417	0	33,100
Yakima	10,910	10,247	82,900
Total	155,231	40,375	630,400

Total (all sources) 195,609

SW = surface water.
GW = ground water.

TABLE 8. 1975 Annual Industrial Ground and Surface Water-Use Statistics for Municipally and Self-Supplied Sources by County in the Washington State Portion of the Columbia Plateau.

(After Dion and Lum, 1977.)

	Annual Industrial Water Use (acre-feet per year)			
	Self-Supplied		Municipally Supplied	
County	GW	SW	GW	SW
Adams	2,210	0	927	0
Asotin	0	0	43	0
Benton	11,196	401,619	1,467	2,007
Columbia	89	0	160	0
Douglas	3,416	0	0	0
Franklin	1,197	0	1,501	49
Garfield	0	0	0	0
Grant	5,997	0	1,132	0
Kittitas	221	0	608	0
Klickitat	0	5,978	0	0
Lincoln	0	0	0	0
Spokane	8,710	31,107	1,538	0
Walla Walla	743	15,317	1,516	1,037
Whitman	0	0	28	0
Yakima	12,862	0	1,556	249
Total	46,641	454,021	10,476	3,342

Total (all sources) 514,478

TABLE 9. 1975 Annual Irrigation Ground and Surface Water-Use Statistics by County Served in the Washington State Portion of the Columbia Plateau.

(After Dion and Lum, 1977.)

County	Annual Irrigation Water Use (acre-feet per year) GW	SW	Acres Irrigated	Average Application Rate (feet per year)
Adams	31,500	215,775	79,900	3.1
Asotin	2,070	2,532	2,000	2.3
Benton	0	563,206	124,680	4.5
Columbia	0	13,500	4,500	3.0
Douglas	0	38,530	11,120	3.5
Franklin	26,460	831,805	203,940	4.2
Garfield	340	2,475	1,500	1.9
Grant	20,800	1,210,755	303,499	4.1
Kittitas	0	525,000	105,000	5.0
Klickitat	32,555	30,636	26,915	2.3
Lincoln	2,625	48,735	35,000	1.5
Spokane	45,807	520	29,130	1.6
Walla Walla	7,881	188,140	106,021	3.0
Whitman	2,515	5,283	7,800	1.0
Yakima	5,250	1,402,135	318,401	4.4
Total	177,803	5,079,027	1,449,406	3.6 (average*)

Total (all sources) 5,256,830

*Found by dividing the total actual irrigation water use (all sources) by the total acres irrigated.

Specific water-use activities within the Columbia Plateau region which occupy significant percentages of the total regional water use include the Columbia and Yakima Irrigation Projects and the U.S. Department of Energy operations at the Hanford Site. The following sections discuss details relating to each of these activities.

COLUMBIA BASIN PROJECT

The Columbia Basin Project is a multipurpose water resource project begun in 1939 with the construction of the Grand Coulee Dam on the Columbia River and the creation of the 9.6-million-acre-foot capacity Franklin D. Roosevelt Lake. The project provides irrigation water, hydroelectric power generation, flood control, recreation, and fish and wildlife enhancement to several counties in eastern Washington. In addition to the Grand Coulee Dam, there are 4 other storage dams on the project, as well as 3 power plants, 5 substations, 17 miles of transmission lines, 19 major pumping plants, 333 miles of canals, pipelines, and tunnels, 1,933 miles of distribution laterals, and 3,163 miles of drains. Irrigation service is currently available to over 543,000 acres of project land and, ultimately, is expected to be available to nearly 1.1 million acres. In 1977, a full supply of irrigation water was delivered to 511,000 acres resulting in a gross crop value of over $200 million. Hydroelectric power generated at Grand Coulee Dam in 1976 was about 22.8 billion kilowatt hours, producing a revenue of nearly $7.8 million (statistics after U.S. Department of the Interior, 1978b).

The irrigation system originates at the Grand Coulee Dam, where withdrawals are taken from Franklin D. Roosevelt Lake at about the 1,208-foot level (MSL). Diversions generally average in excess of 2 million acre-feet per year. Hydroelectric power is used to lift the water onto the adjacent plateau where it is stored in Banks Lake (Figure 12), which has a maximum surface elevation of about 1,570 feet (MSL). Storage capacity in Banks Lake is approximately 150,000 acre-feet. Water enters the distribution system via the Bacon Siphon and Tunnel and flows into Billy Clapp Lake. Upon leaving Billy Clapp Lake, the Main Canal system is bifurcated into the West Canal serving the Quincy Irrigation District and the East Low Canal serving the East Irrigation District.

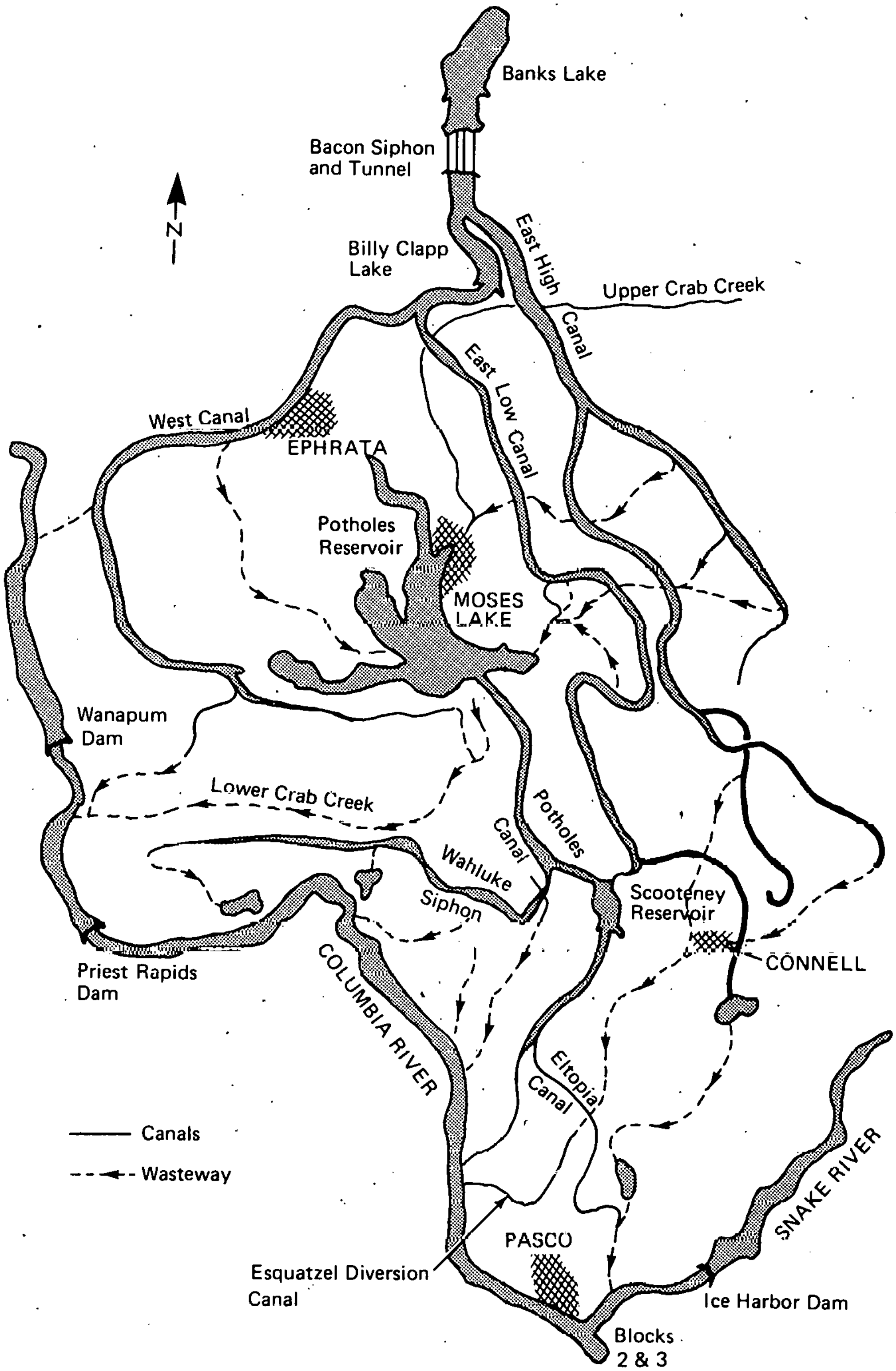

FIGURE 12. Generalized Schematic of the Columbia Basin Irrigation Project Distribution System (after U.S. Department of the Interior, 1977).

A second Bacon Siphon and Tunnel has recently been completed which will provide irrigation water for a proposed East High Canal.

Waste water, runoff, and interflow are collected in the central Potholes area, the source area for the Potholes Canal which serves the southern portion of the eastern and southern portions of the project. Just above Scooteney Reservoir, the Wahluke Siphon withdraws water for the Wahluke Branch Canal, which provides water to the area south of the Saddle Mountains and north of the Columbia River on the Wahluke Slope. The remainder of the water in the Potholes Canal flows into Scooteney Reservoir and onward into Franklin County. Blocks 2 and 3, which lie south of the Snake River, are supplied by separate withdrawals near the mouth of the Snake River. Appendix C presents recent data related to water distribution within the project.

A certain amount of private irrigation by wells is also developing in adjacent areas not served by project water. In particular, the area east of the Potholes Reservoir, known as the "Black Sands Area," has received authorization from the State of Washington for withdrawals of up to 117,000 acre-feet per year. For the Quincy Basin as a whole, the state has authorized withdrawals of 54,560 acre-feet per year from the shallow (less than 200 feet below land surface) aquifers, but, accounting for artificial recharge, a total of 177,000 acre-feet per year will be allowed. To a large extent, development of irrigation by ground water has been encouraged to relieve the situation of rising ground-water levels in the area. Allocation for the deep zone is limited to 97,901 acre-feet per year. Development of ground-water irrigation systems is also proceeding in Franklin County to the north and west of Pasco.

YAKIMA PROJECT

The Yakima Project consists of 6 storage dams and reservoirs, 5 diversion dams, 436 miles of canals, 1,510 miles of laterals, 30 pumping plants, 70 miles of drains, 2 power plants, and 74 miles of transmission lines serving Kittitas, Yakima, and Benton Counties in south-central Washington. At present, the project provides full or supplemental irrigation for about 462,000 acres in addition to about 45,000 acres irrigated by private interests. In 1975, the gross crop value for the project was over $233 million on 398,165 irrigated acres. Five irrigation districts share reimbursement for irrigation and, as of 1976, had repaid about 46 percent of the total. The 2 hydroelectric power plants produced nearly 160 million kilowatt hours and marketed power to the Bonneville Power Administration for $500,000. Revenues from power have repaid an additional $15.1 million toward the $51.7 million total cost (U.S. Department of the Interior, 1978b). Table 10 provides a general description of the Yakima Irrigation Project and its irrigation areas and Figure 13 depicts the system schematically.

HANFORD OPERATIONS

Water use associated with the U.S. Department of Energy at the Hanford Site stems primarily from two activities:

1. Nuclear fuel and waste processing operations at the 200 Areas; and,
2. Operation of N-Reactor (currently the only reactor in operation, although two additional reactors are under construction).

The combination of these two activities occupies a major percentage of the industrial water use in Benton County and the State of Washington.

Water from the Columbia River is transported to the fuel and waste processing (200) areas via a pipeline network known as the "export water system." Within each area, there is a "distribution system" that delivers both sanitary water and raw water. Discharge of these waters may occur in several ways, including:

1. Evaporation from reservoirs and settling tanks;
2. Steam released during blowdown of the boilers and as steam condensates to French drains along steam lines;
3. Septic tank discharge to sanitary tile fields;
4. Discharge to cribs and special-purpose tile fields;
5. Discharge to open trenches, pits, or marshes;
6. Discharge of waste waters to perennial ponds via unlined conveyance ditches; and,
7. Unplanned leakage from pipelines (Summers, 1975).

TABLE 10. Yakima Irrigation Project Districts and Associated Areas.

(After U.S. Department of the Interior, 1976.)

Division or Area	General Location	Irrigable Area (acres)	Major Irrigation Facilities	Source of Water[a]	Operating Organization
Kittitas	Kittitas Valley near Ellensburg	57,000	Easton Diversion Dam, Main Canal, North and South Branch Canals	Keechelus and Kachess Reservoirs	Kittitas Reclamation District
Tieton	Upper Yakima Valley	27,000	Tieton Diversion Dam Tieton Canal	Tieton Reservoir	Yakima-Tieton Irrigation District
Sunnyside	Lower Yakima Valley	104,000	Sunnyside Diversion Dam, Sunnyside Canal, pumping plants	All project reservoirs	Sunnyside Valley Irrigation District and others
Roza	Lower valley north of Sunnyside Division	72,500	Roza Diversion Dam, Ridge Canal, and pumping plants	Keechelus, Cle Elum, Kachess Reservoirs	Roza Irrigation District
Kennewick	Extreme Lower Yakima Valley, Benton County	19,200	Prosser Diversion Dam, Chandler Canal, pumping plants, Kennewick Main Canal	(Some storage, but largely return flow)	Kennewick Irrigation District
Storage			Reservoirs: Keechelus; Kachess; Cle Elum; Tieton; Bumping; Clear Creek	Regulates storage and distributes natural flow	Bureau of Reclamation
Wapato Project[b] (Indian)	Lower Yakima Valley south of river	136,000[c]	Main and pump canals, and drainage works	All Yakima Project reservoirs	Bureau of Indian Affairs
Miscellaneous Areas[c]	Scattered	45,800	Numerous diversions, canals	Natural flow and storage water from reservoirs	Various irrigation districts, companies, and individuals

[a]Water supply for all areas comes from natural flow, storage, and return flow.
[b]Special and Warren Act contractors.
[c]Acreage in the Ahtanum and Toppenish-Simcoe units of the Wapato Project not dependent upon Yakima Irrigation Project for water.

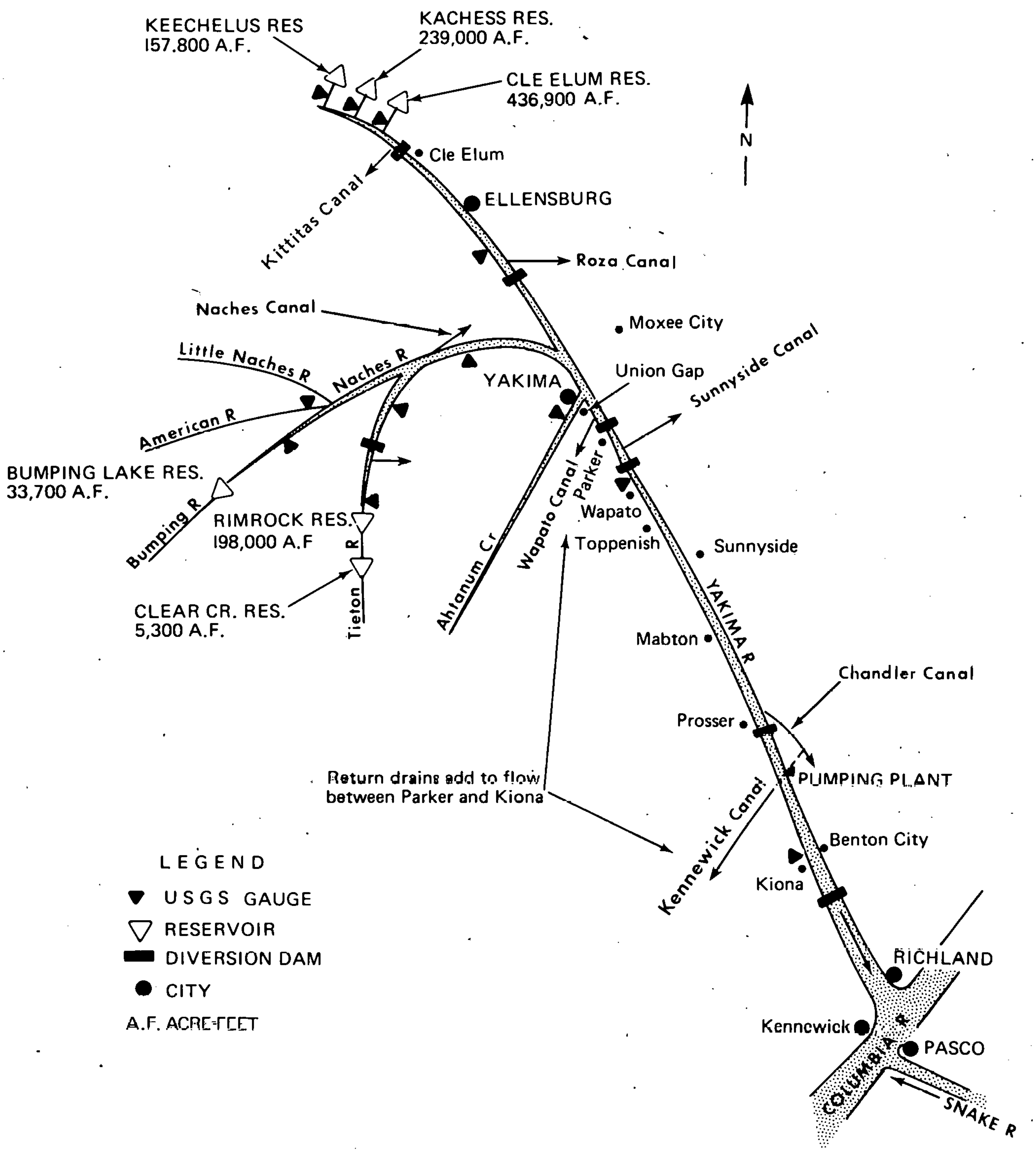

FIGURE 13. Generalized Schematic of the Yakima Project.

In summary, withdrawn surface waters are not returned directly to the system, but rather are discharged to the atmosphere or ground water system. According to Summers (1975), the quantity withdrawn from the Columbia River is on the order of 15,000 acre-feet per year, of which 26-36 percent remains unaccounted for. Figure 14 shows the location of various surface water bodies within the Hanford Site.

Water use in nuclear power generation can be variable depending upon the power output design of the reactor, type of cooling system utilized, plant efficiency, and other factors related to the plant design. Because N-Reactor is a "dual-purpose reactor," its water requirements may be slightly greater than those of a typical commercial reactor. For typical systems, it has been estimated (Giusti and Meyer, 1977) that 63 percent of the thermal energy generated by a reactor is transferred to the water-cooling system.

Typical water consumption requirements for once-through cooling systems are estimated at 18 cubic feet per second (about 13,000 acre-feet annually). Estimated water consumption by the proposed Washington Public Power Supply System, Inc. (WPPSS) Units 1 and 4 (currently under construction on the Hanford Site) is 101 cubic feet per second (about 73,000 acre-feet annually) (Giusti and Meyer, 1977). It should be noted, however, that the projection of water-use rates to annual volumes assumes continuous operation and thereby an upper limit for consumption.

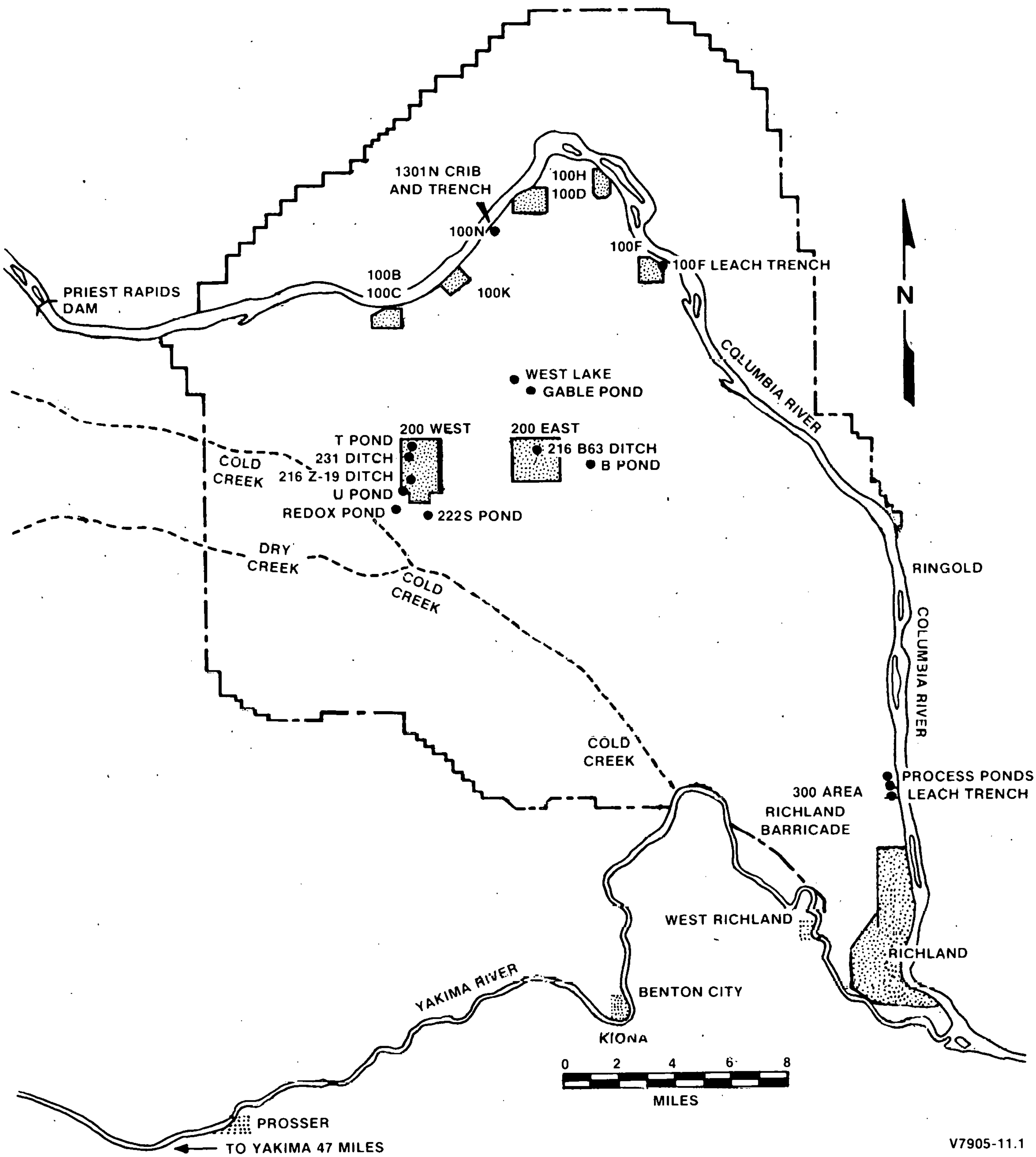

FIGURE 14. Surface Water Areas on the Hanford Site.

WATER BUDGET STUDIES

In an effort to ascertain the probable mechanisms for recharging and discharging the ground-water system(s) within the Columbia Plateau, preliminary quantitative evaluations of the various components of the hydrologic cycle have been performed. The numbers generated as a result of this exercise can be combined into a hydrologic budget for the system, however, it is emphasized that such budgets are only preliminary. Many of the budget components were approximated on the basis of assumptions which may or may not be supported in light of more detailed examination. In any case, the effort assists in conceptualizing the overall hydrologic system operating within the Columbia Plateau region.

For the purpose of this analysis, the six sub-basins within the Washington State portion of the Columbia Plateau as shown in Figure 5 were used. It is important to reiterate that these sub-basins (and the Columbia Plateau itself) are not necessarily discrete hydrologically. The designations reflect various geologic and political considerations as well.

The general hydrology of each of the six sub-basins is discussed in the section entitled "Sub-basin Descriptions" and a preliminary synthesis of their hydrologic budgets is contained in the section entitled "Budget Evaluation."

SUB-BASIN DESCRIPTIONS

For each of the six hydrologic sub-basins within the Washington State portion of the Columbia Plateau, a description of the hydrometeorologic system and surface water budget is provided. Maps showing the drainage network and schematics of the principal streams and USGS gauging system are also presented by sub-basin.

Horse Heaven Plateau Sub-basin

The Horse Heaven Plateau Sub-basin is the southwesternmost area of the Washington State portion of the Columbia Plateau (Figure 15). It occupies approximately 1.6 million acres including most of Klickitat, about the southern third of Benton, and a very small portion of Yakima

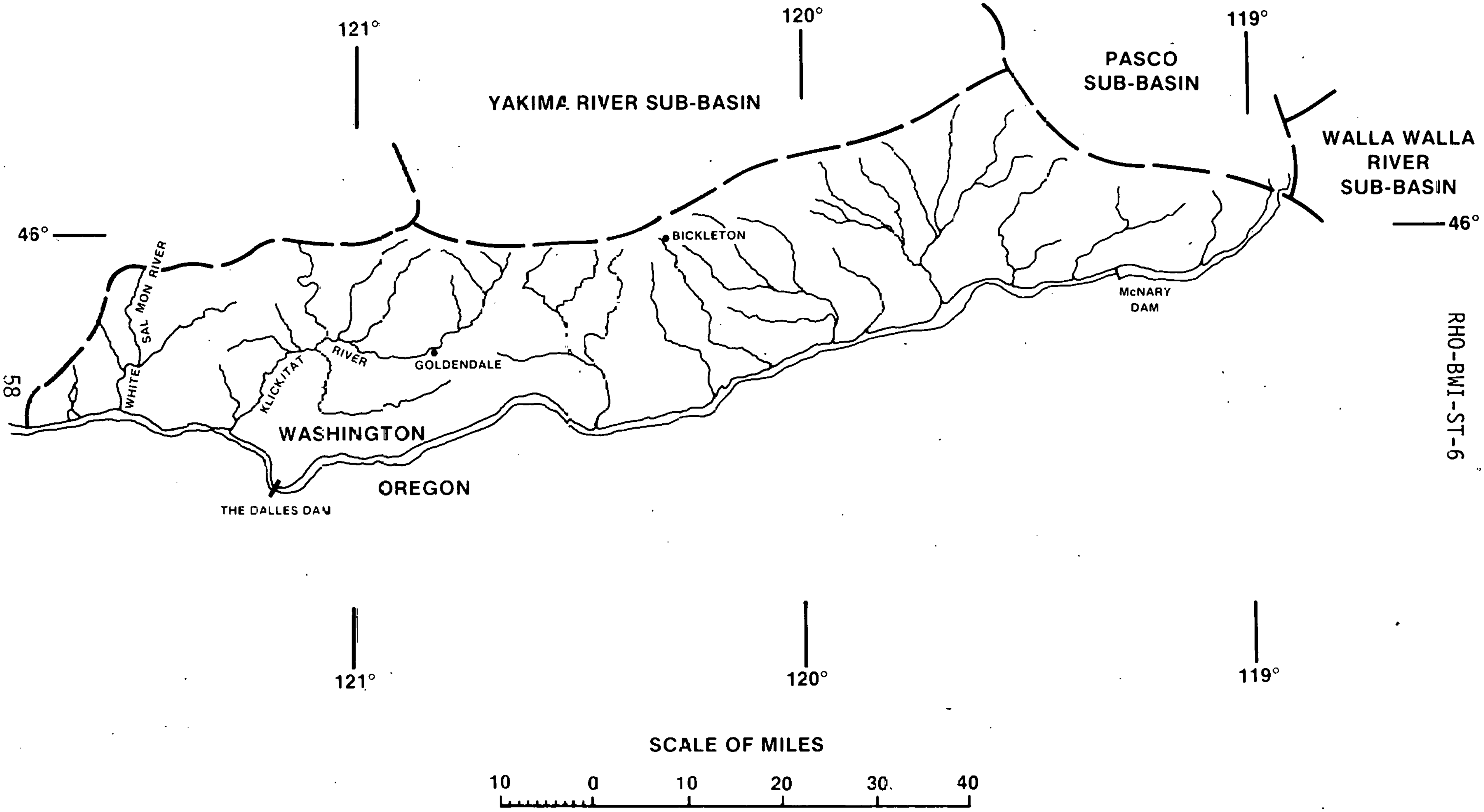

FIGURE 15. Surface Drainage within the Horse Heaven Plateau Sub-basin.

Counties. The Columbia River forms the southern boundary of the sub-basin, the western boundary roughly coincides with the White Salmon River, and the northern boundary is the approximate crest of the Horse Heaven anticline which extends across the Columbia River at Wallula Gap. The sub-basin is not discrete hydrologically, in the sense that the main stream, the Columbia River, receives runoff from areas outside the sub-basin to the south (in Oregon). In fact, the principal tributaries along the reach between McNary Dam and The Dalles Dam all enter from the Oregon side.

Mean annual precipitation within the Horse Heaven Plateau Sub-basin ranges from less than 8 inches in the eastern portions to greater than 50 inches in the extreme west. Total precipitation over the entire basin is estimated at 2.4 million acre-feet; annually averaging about 18 inches.

The areal distribution of mean annual runoff is also wide, ranging from less than 0.5 inch in the east to more than 30 inches in the west; averaging over 5 inches and totaling about 0.7 million acre-feet. The basin-wide runoff coefficient is, therefore, about 29 percent.

Evaporation data are scant, but, in general terms, average annual pan evaporation ranges from about 40 to 60 inches, average annual lake evaporation ranges from about 26 to 40 inches, and AET for a 6-inch water-holding capacity soil ranges from less than 8 inches in the eastern area to probably more than 15 inches in the westernmost portion. Total AET for the sub-basin is estimated at 1.5 million acre-feet, averaging 11.6 inches. The corresponding estimates for lake evaporation are 4.6 million acre-feet per year and 35 inches per year.

Water use in Klickitat County is summarized in Table 11. It is assumed that water use in the portion of Benton County lying within and in the portion of Klickitat County lying outside the Horse Heaven Plateau Sub-basin is negligible based on the distribution of population, industrial, and agricultural centers. Thus, water use in the sub-basin is essentially equivalent to that for Klickitat County.

Streamflow within the sub-basin is recorded as inflow at the McNary Dam site and outflow below The Dalles Dam. Average annual flow at these stations is 134,200,000 and 140,600,000 acre-feet, respectively. A total gauged flow of 1,788,000 acre-feet enters the Columbia River along this

TABLE 11. Annual Ground and Surface Water Use in Municipal, Industrial, and Irrigation Categories in Klickitat County, Washington Based on 1975 Statistics.

(After Dion and Lum, 1977; all values are listed in acre-feet per year.)

Annual Municipal Water Use		Annual Industrial Water Use: Self-Supplied		Annual Industrial Water Use: Municipally Supplied		Annual Irrigation Water Use	
GW	SW	GW	SW	GW	SW	GW	SW
250	2,207	0	5,978	0	0	32,555	30,636

reach from the tributaries on the Oregon side. The intermittent and ephemeral streams entering from the Horse Heaven Plateau are not gauged. The Klickitat and White Salmon Rivers join the Columbia River from the north side below The Dalles Dam. Figure 16 provides a schematic of the USGS gauging network within the sub-basin.

<u>Yakima River Sub-basin</u>

The Yakima River Sub-basin is situated in the western portion of the Columbia Plateau to the north of the Horse Heaven Plateau Sub-basin (Figure 17). Headwaters of the Yakima River lie outside the Columbia Plateau margins along the east-west drainage divide formed by the Cascade Range. The sub-basin drains into the Pasco Sub-basin via the Yakima River. Areally, the Yakima River Sub-basin occupies approximately 2.6 million acres including about the eastern two-thirds of Yakima, a portion of western Benton, about half of Kittitas, and a small part of Klickitat and Chelan Counties. Topographic and structural divides form the eastern and southern boundaries of the sub-basin, whereas the Columbia Plateau margin has been designated as the western edge. Principal tributaries joining the Yakima River within the sub-basin include the Kachess River, Cle Elum River, Teanaway River, Naneum Creek, Naches River, Ahtanum Creek, Toppenish Creek, and Satus Creek. Extensive multipurpose water resource development occurs within the sub-basin related principally to the Yakima Project which is operated by the U.S. Department of the Interior, Bureau of Reclamation.

Mean annual precipitation within the Yakima River Sub-basin ranges from less than 8 inches in portions of Benton County to more than 50 inches on the higher slopes. Total precipitation over the entire basin is estimated at 3.3 million acre-feet annually, averaging more than 15 inches.

The areal distribution of mean annual runoff ranges from less than 0.5 inch in Benton County to more than 40 inches along the western margin, averaging over 4 inches, and totaling about 1 million acre-feet. The basin-wide runoff coefficient is, therefore, about 28 percent.

Evaporation data have been recorded primarily in the low-lying, agricultural areas and are only estimated for the higher elevations. Average annual pan evaporation ranges from about 45 to 60 inches, average

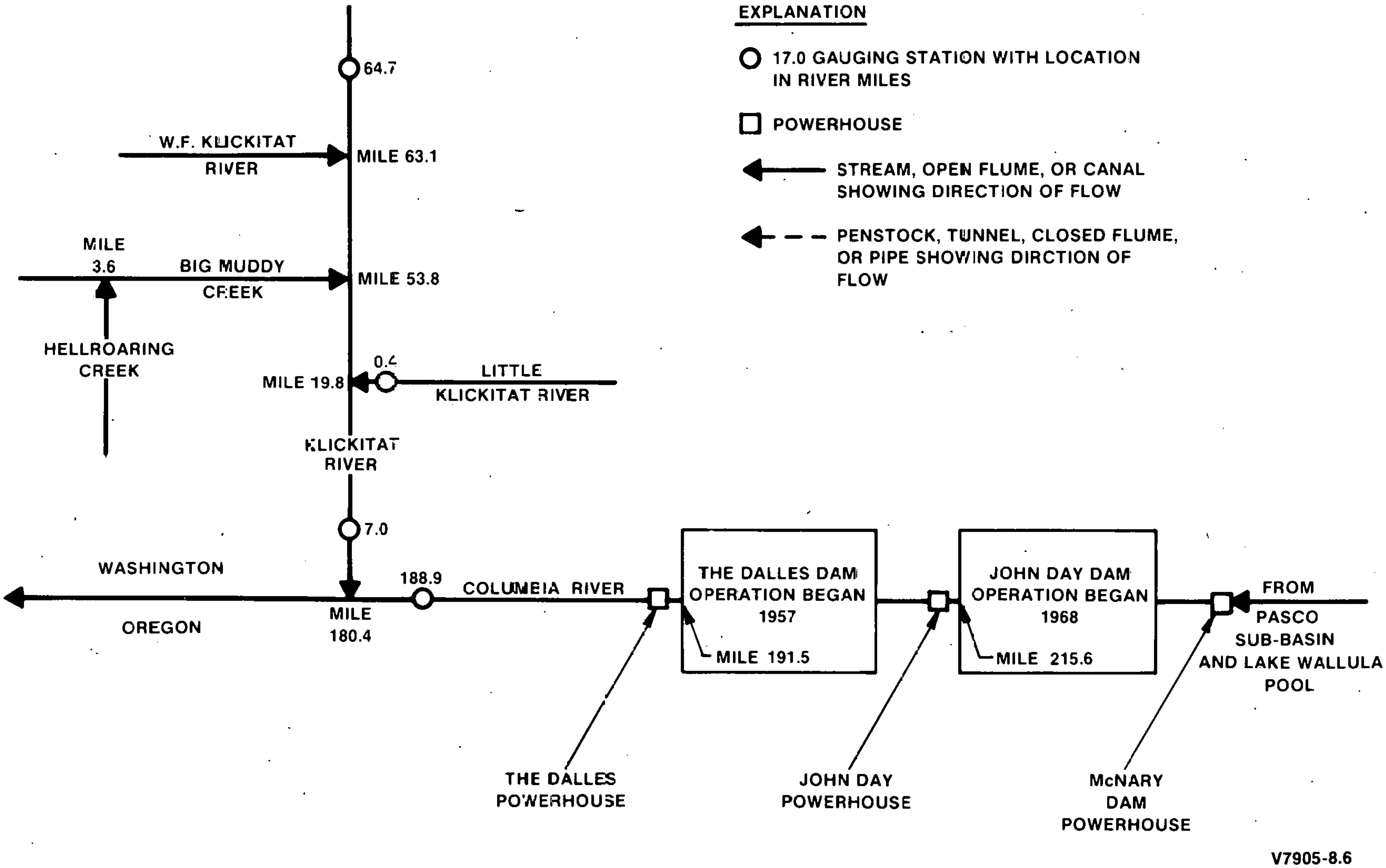

FIGURE 16. Schematic of the U.S. Geological Survey Gauging Network for the Horse Heaven Plateau Sub-basin.

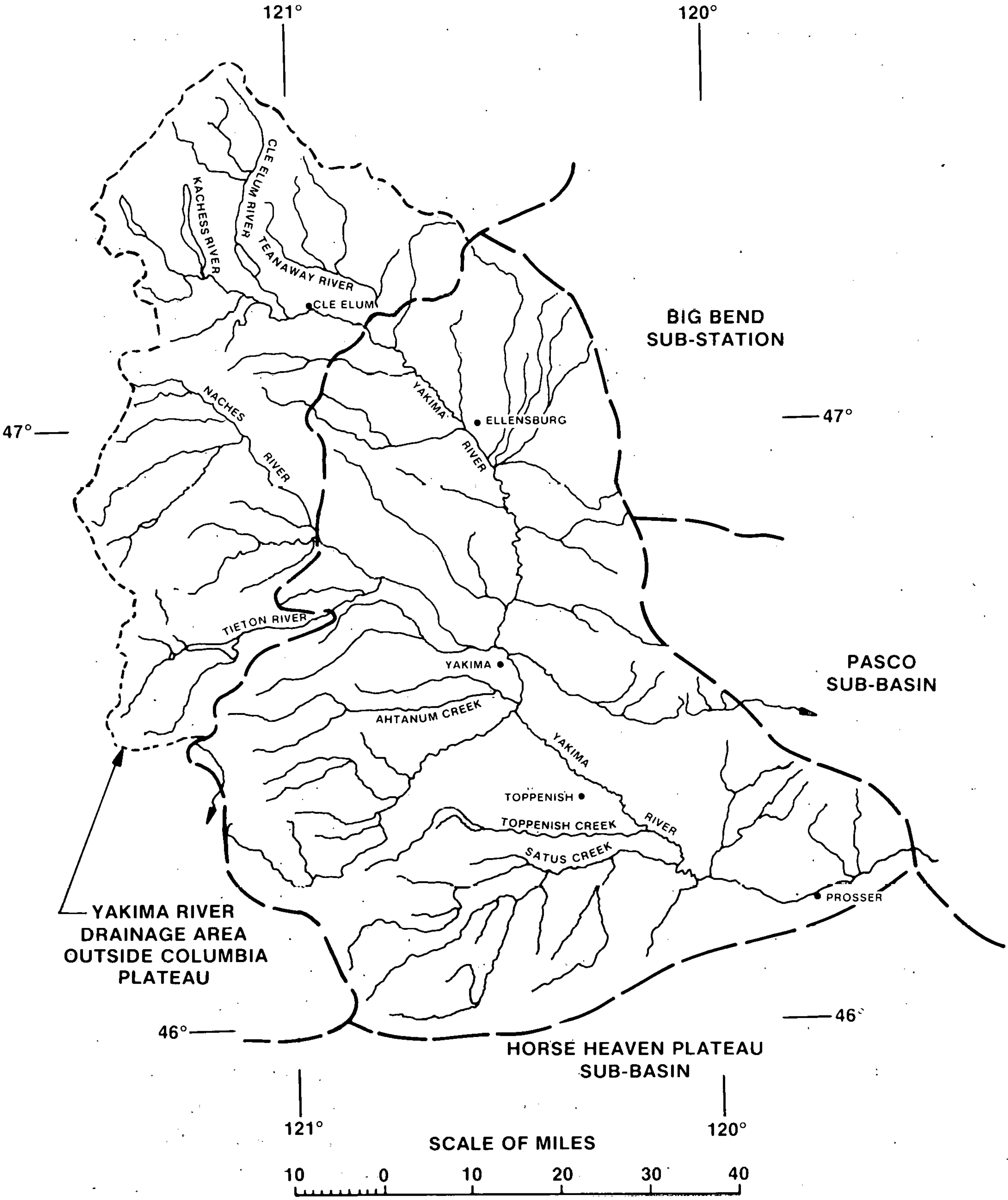

FIGURE 17. Surface Drainage within the Yakima River Sub-basin.

annual lake evaporation ranges from about 32 to 41 inches, and AET for a 6-inch water-holding capacity soil ranges from about 7.5 inches in Benton County to more than 12 inches at the higher elevations. Total AET for the sub-basin is estimated at 2.3 million acre-feet annually, averaging about 10.6 inches. The corresponding estimates for potential lake evaporation are 7.4 million acre-feet per year and 34 inches per year.

Water-use statistics for Yakima and Kittitas Counties are essentially the same as those for the Yakima River Sub-basin. Noteworthy exceptions of undetermined significance are the Prosser area in Benton County and the Wenatchee area in southeast Chelan County. The western portions of Yakima and Kittitas Counties lie outside the area of consideration, but very few developments occur in these areas. Table 12, therefore, summarizes water use in Yakima and Kittitas Counties. Average annual diversions within the entire Yakima River Basin are estimated at 2.4 million acre-feet for irrigation of approximately 500,000 acres (U.S. Army Corps of Engineers, 1978). Diversions for municipal and industrial uses are comparatively small. Power diversions are non-consumptive. Relatively small quantities of ground water are being withdrawn for irrigation purposes within the sub-basin. Generally, such development occurs at certain locations not served by the irrigation project such as the Moxee Valley. Statistics related to this parameter are generally not well documented.

Streamflow within the Yakima River Sub basin is recorded as inflow at the USGS gauge near Cle Elum, Washington and outflow below Kiona, Washington (Figure 18). Average annual flow at these stations is estimated at 1,478,000 acre-feet and 2,636,000 acre-feet, respectively. For the purpose of water balance computation, the U.S. Bureau of Reclamation has used annual flow estimates of 1,280,000 and 2,785,000 acre-feet, respectively, for the Cle Elum and Kiona stations based on average flow during recent years. Because of the degree of flow regulation and hydrographic modification by the U.S. Bureau of Reclamation and other agencies, the USGS has not presented statistical analyses for many of the gauging stations in the flow records. A total gauged flow of 1,305,000 acre-feet enters the Yakima River from tributaries along this reach. Diversions along the reach (exclusive of power diversions which do not provide a net change in flow volume along

TABLE 12. Annual Ground and Surface Water Use in Municipal, Industrial, and Irrigation Categories in Kittitas and Yakima Counties, Washington Based on 1975 Statistics.

(After Dion, and Lum, 1977; all values are listed in acre-feet per year.)

	Annual Municipal Water Use		Annual Industrial Water Use				Annual Irrigation Water Use	
			Self-Supplied		Municipally Supplied			
County	GW	SW	GW	SW	GW	SW	GW	SW
Kittitas	4,195	466	221	0	608	0	0	525,000
Yakima	10,910	10,247	12,862	0	1,556	249	5,250	1,402,135
Total	15,105	10,713	13,083	0	2,164	249	5,250	1,927,135

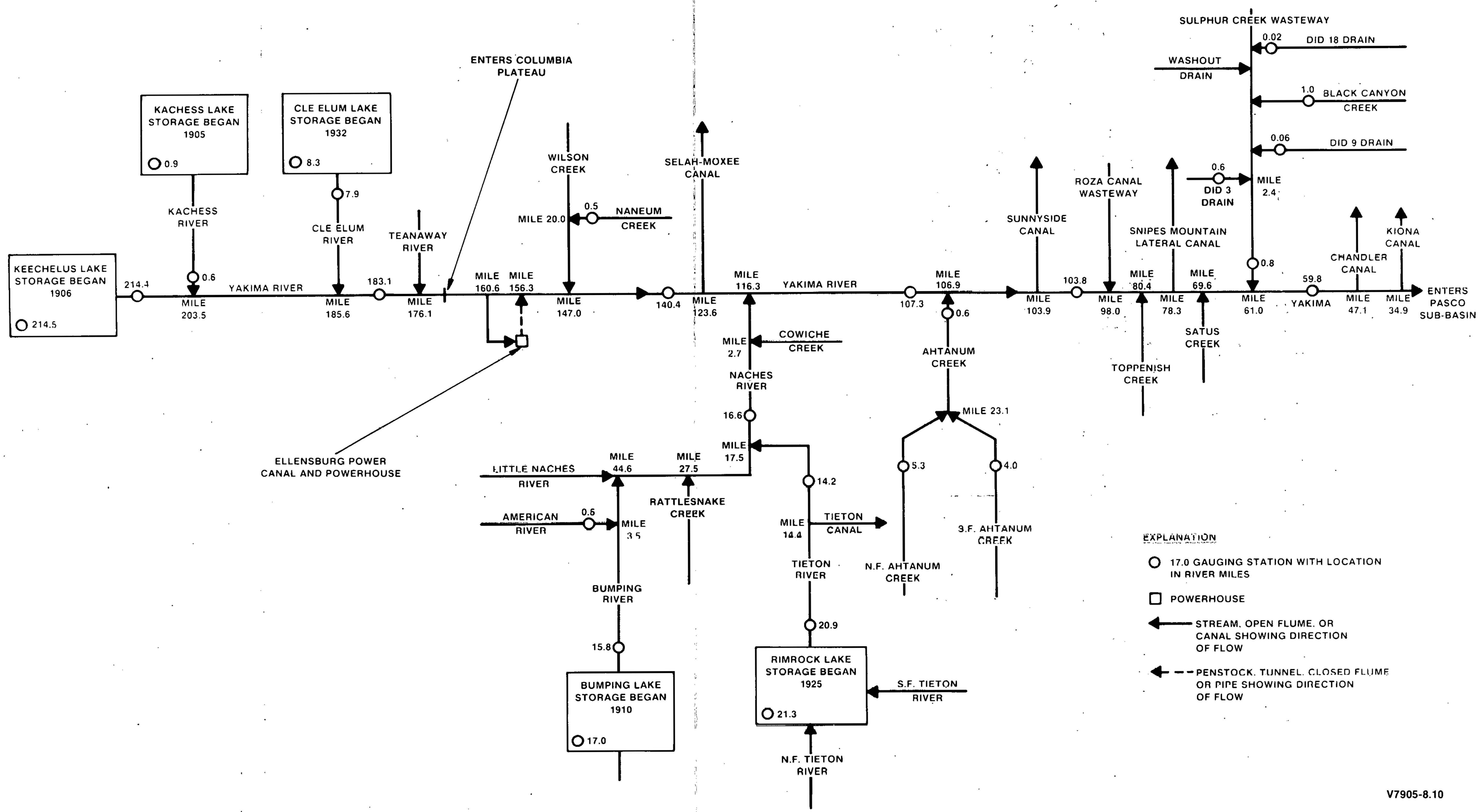

FIGURE 18. Schematic of the U.S. Geological Survey Gauging Network for the Yakima River Sub-basin.

the reach) total 1,519,000 acre-feet annually and return flows are estimated at 135,000 acre-feet annually. Thus, there is an apparent consumption of 1,170,000 acre-feet per year, which probably includes return flow to the Yakima River via the ground-water system. Figure 18 provides a schematic of the USGS gauging network within the sub-basin.

Pasco Sub-basin

The Pasco Sub-basin is the centralmost sub-basin within the Columbia Plateau (Figure 19). In a general sense, it is topographically the lowest among the Columbia Plateau sub-basins with the possible exception of the southern portion of the Horse Heaven Plateau Sub-basin. As a result, surface drainage from all the other sub-basins enters the Pasco Sub-basin (again with the exception of the Horse Heaven Plateau Sub-basin which receives the outflow of the Pasco Sub-basin via the Columbia River through Wallula Gap). The Pasco Sub-basin is also the only sub-basin that is contiguous with all of the other sub-basins. In area, the Pasco Sub-basin occupies approximately 1.2 million acres including about the northeast third of Benton, the western third of Franklin, a small portion of southernmost Grant, and small corners of Yakima, Kittitas, and Walla Walla Counties. Topographic and structural divides form the western and northern boundaries; whereas the eastern boundary was somewhat arbitrarily chosen on the basis of combined structural, topographic, hydrologic, demographic, and other considerations. The main stream, the Columbia River, is joined within the sub-basin by major tributaries including the Yakima, Snake, and Walla Walla Rivers. Virtually no streams are supported by hydrologic systems operating solely within the Pasco Sub-basin.

Mean annual precipitation within the Pasco Sub-basin ranges from less than 7 inches within the Hanford Site to just over 15 inches atop Rattlesnake Mountain. Total precipitation over the entire basin is estimated at 0.8 million acre-feet annually, averaging less than 8 inches.

Mean annual runoff is very low, generally less than 0.5 inch for most of the sub-basin. Total annual runoff is less than .025 million acre-feet per year, and the basin-wide runoff coefficient for all practical purposes is zero.

Average annual pan evaporation is between 55 and 60+ inches, average annual lake evaporation ranges from about 39 to 42+ inches, and actual

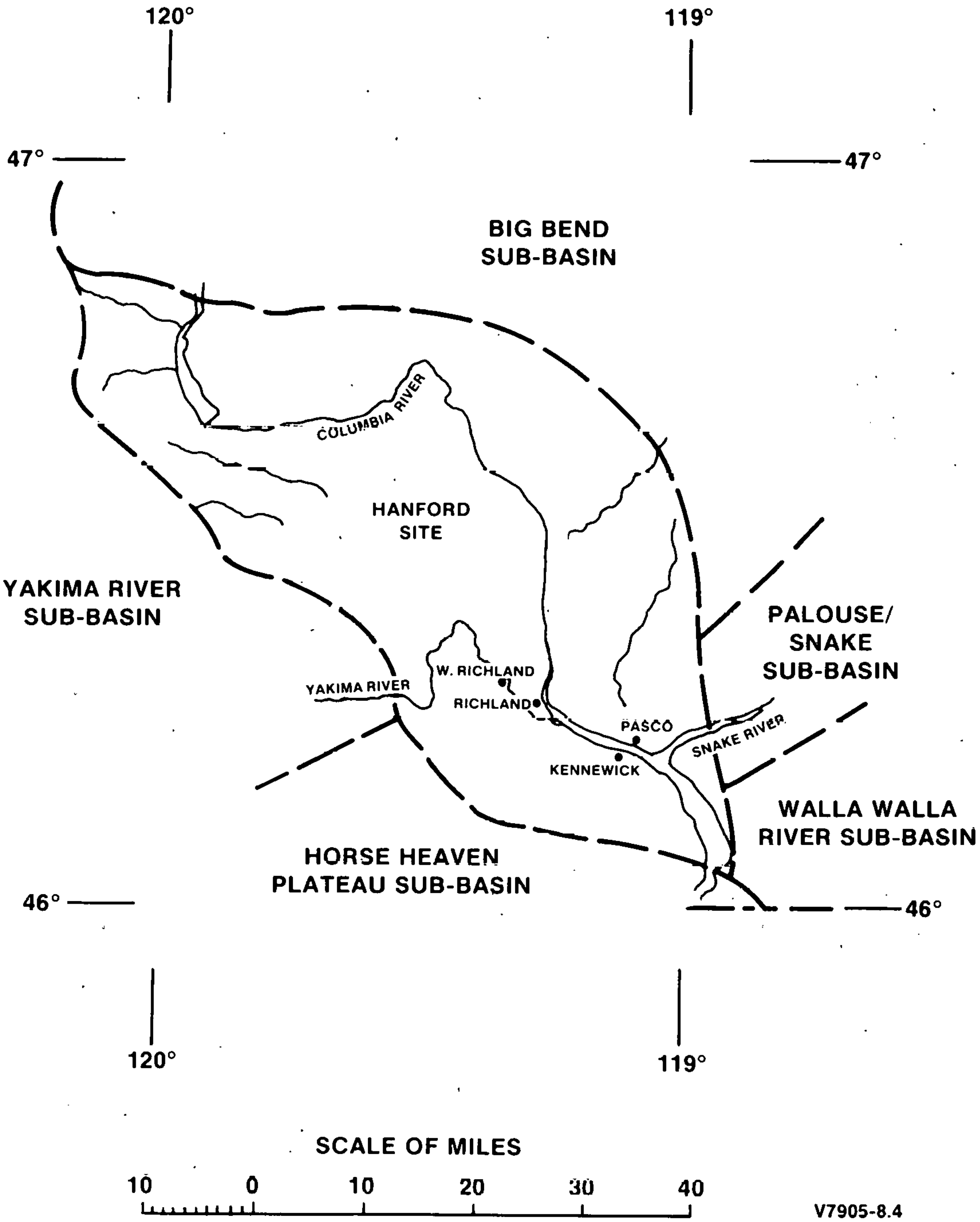

FIGURE 19. Surface Drainage within the Pasco Sub-basin.

AET for a 6-inch water-holding capacity soil is about 7.5 to 8.5 inches. Total AET for the sub-basin is estimated at 0.8 million acre-feet annually, averaging 7.5 inches. The corresponding estimates for potential lake evapotranspiration are 4.2 million acre-feet per year and 42 inches per year.

Municipal and industrial water-use statistics for Benton and Franklin Counties appear to provide reasonable estimates of water use in the Pasco Sub-basin for these categories. The distribution of agricultural water use, however, does not coincide as well with the sub-basin designation. The major percentage of land irrigated by surface water sources receives water imported from the Big Bend Sub-basin via the Columbia Basin Irrigation Project. The small volume of this imported water that is returned to the Columbia River is accounted for within the preliminary budget for the Pasco Sub-basin. Other areas receive water diverted from the Yakima River Sub-basin via the Kennewick Canal (Figure 13). Estimates of direct irrigation use within the Pasco Sub-basin were made on the basis of applying estimated application rates for each county to the known area of land under irrigation. To some extent, it was possible to segregate between irrigation from ground- and surface-water sources. Table 13 summarizes statistics for municipal and industrial water use in Benton and Franklin Counties; whereas Table 14 summarizes irrigation water use within the Pasco Sub-basin by the portion of the county represented. As earlier noted, Benton County is, by far, the largest industrial user of water among Washington's 39 counties. To a large extent, this water use results from the nuclear industry activities concentrated within the Hanford Site along the Columbia River. A large portion of this volume is utilized for reactor cooling purposes and is non-consumptive. Another large portion is utilized in Hanford nuclear fuel and waste processing activities, most of which (estimated at 15,000 acre-feet per year) is discharged to the ground and which enters the ground-water system or is evaporated. The principal, municipal withdrawals occur in the Tri-Cities area, and the principal areas irrigated from ground-water sources are in the areas just to the north and west of Pasco in Franklin County and in the Horse Heaven Hills in Benton County.

TABLE 13. Annual Ground and Surface Water Use in Municipal and Industrial Categories in Benton and Franklin Counties, Washington Based on 1975 Statistics.

(After Dion and Lum, 1977; all values are listed in acre-feet per year.)

	Annual Municipal Water Use		Annual Industrial Water Use			
			Self-Supplied		Municipally Supplied	
County	GW	SW	GW	SW	GW	SW
Benton	9,495	16,428	11,196	401,619	1,467	2,007
Franklin	2,434	6,000	1,197	0	1,501	49
Total	11,929	22,428	12,393	401,619	2,968	2,056

TABLE 14. Estimates of Annual Irrigation Water Use in the Pasco Sub-basin by County.

	Annual Irrigation Water Use (acre-feet per year)	
County	GW	SW
Benton	21,300[a]	205,000[b]
Franklin	26,460[c]	559,000[d]
Grant	N.A.	143,600[e]
Total	47,760	907,600

[a]Based on County Extension Agent's report (Gerlitz, 1978). A total of 4,735 acres of land irrigated by wells in the Horse Heaven Hills of Benton County was multiplied by a factor of 4.5 acre-feet application per acre per year.

[b]Estimate based on the U.S. Department of the Interior water balance for the Yakima Irrigation Project. A total of 115,000 acre-feet per year below Kiona plus about 90,000 acre-feet per year imported via the Kennewick Canal.

[c]Based on 1975 figures by Dion and Lum (1977) for entire Franklin County.

[d]Based on irrigated acreages within the Franklin County portion of the Pasco Sub-basin as ascertained from the January 1978 Columbia Basin Irrigation Project map (U.S. Department of the Interior, 1978a). Acreages were multiplied by a factor of 4.2 acre-feet application per acre per year. All waters are imported from the Big Bend Sub-basin, with the exception of about 19,400 acre-feet per year which are diverted for irrigation of the 4,622 acres within Blocks 2 and 3.

[e]Based on irrigated acreages with the Grant County portion of the Pasco Sub-basin as ascertained from the January 1978 Columbia Basin Irrigation Project map (U.S. Department of the Interior, 1978a). Acreages were multiplied by a factor of 4.1 acre-feet application per acre per year. All waters are assumed to be imported from the Big Bend Sub-basin.

Streamflow within the Pasco Sub-basin is recorded as inflow at the USGS gauge below Priest Rapids Dam and outflow below McNary Dam. Average annual flow at these stations is 87,230,000 acre-feet and 134,200,000 acre-feet, respectively. A total gauged flow of about 44,830,000 acre-feet per year enters as tributaries, plus an additional 225,000 acre-feet as irrigation returns enter the Columbia River main stem along the reach. Figure 20 provides a schematic of the USGS gauging network within the sub-basin.

Walla Walla River Sub-basin

The Walla Walla River Sub-basin is situated in the south-central portion of the Columbia Plateau adjacent to the Pasco and Palouse/Snake Sub-basins (Figure 21). It is the smallest of the sub-basins within the Columbia Plateau, occupying about 900,000 acres. Its northern and eastern boundaries are formed by the drainage divide with the Palouse/Snake Sub-basin, the western boundary is drawn along the eastern bank of the Columbia River, and the southern boundary is the political border between Washington and Oregon. The sub-basin occupies over half of Walla Walla County and the southwestern portion of Columbia County. Principal tributaries of the Walla Walla River include its north and south forks, Mill Creek, and the Touchet River. The confluence of the north and south forks of the Walla Walla River is situated to the south in Oregon.

Mean annual precipitation within the Walla Walla River Sub-basin ranges from less than 8 inches in the western part of the sub-basin to over 40 inches in the southeast along the Blue Mountains. Total precipitation over the entire basin is more than 1.6 million acre-feet annually, averaging nearly 22 inches.

The areal distribution of runoff ranges from less than 0.5 inch in the western portion to over 30 inches in the southeast, averaging about 3 inches, and totalling about 0.2 million acre-feet. The basin-wide runoff coefficient is, therefore, about 15 percent.

Evaporation data have been recorded at two stations situated in the low-lying, agricultural areas. Average annual pan evaporation ranges from about 50 to 57 inches, average annual lake evaporation ranges from about 36 to 40 inches, and actual AET for a 6-inch water-holding

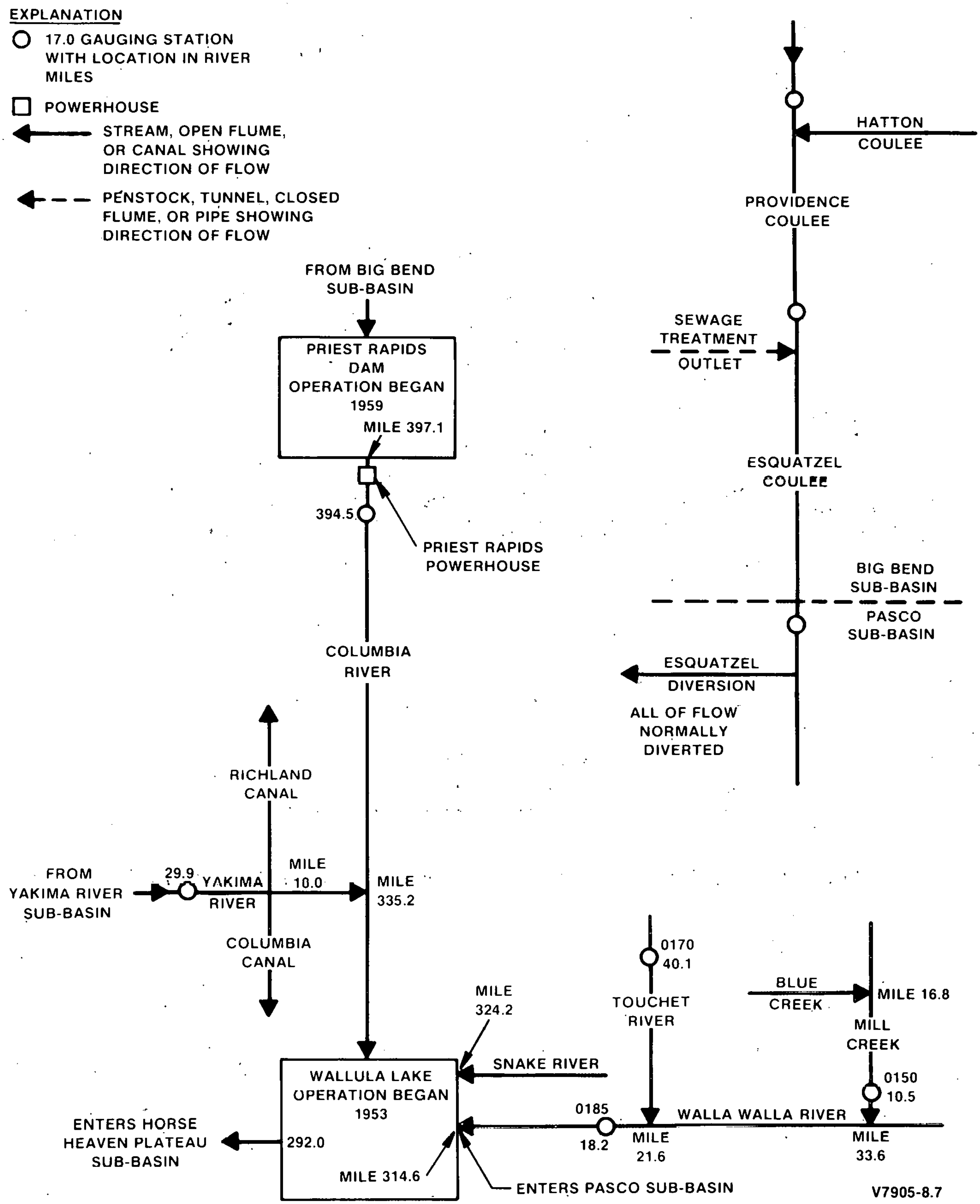

FIGURE 20. Schematic of the U.S. Geological Survey Gauging Network for the Pasco Sub-basin.

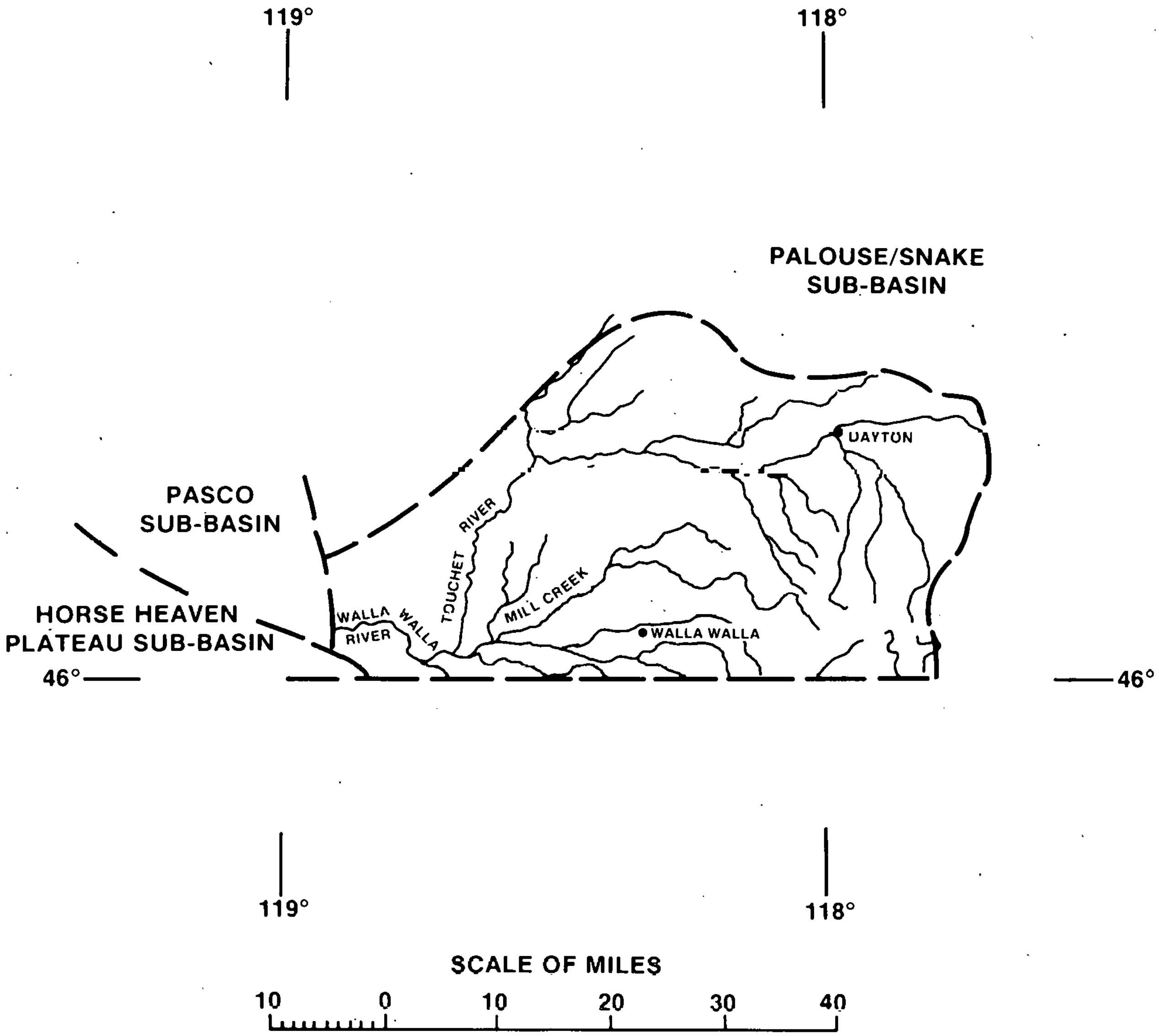

FIGURE 21. Surface Drainage within the Walla Walla River Sub-basin.

capacity soil ranges from less than 10 inches in the westernmost area to about 19.5 inches near Dayton. Total AET for the sub-basin is estimated at about 1.0 million acre-feet annually, averaging about 13 inches. The corresponding estimates for potential lake evaporation are 2.8 million acre-feet per year and 37 inches per year.

Water-use statistics for Walla Walla County are essentially the same as for the Walla Walla River Sub-basin, considering the distribution of population, industry, and agriculture within the sub-basin. Table 15, therefore, summarizes water use in Walla Walla County.

Streamflow within the Walla Walla River Sub-basin is difficult to evaluate because the only gauge downstream from the confluence of its north and south forks is at Touchet, which is only 18.2 miles from its point of discharge to the Columbia River. For the purpose of performing a reach inventory, it was, however, assumed that the inflow was approximately equivalent to the sum of the flows of the north and south forks and the flow at the USGS gauge near Touchet was equivalent to the outflow. In this case, average inflow is approximately 169,000 acre-feet per year and outflow averages 431,800 acre-feet per year. An approximate total gauged flow of 245,000 acre-feet per year enters the Walla Walla River from the Touchet River and Mill Creek along this reach. A slight amount of ground-water recharge from the stream probably occurs along the reach; however, the distance between gauges and other factors prevent precise estimation. A partial schematic of the USGS gauging network for the sub-basin is included within Figure 20.

Palouse/Snake Sub-basin

The Palouse/Snake Sub-basin is situated in the eastern portion of the Columbia Plateau to the north of the Walla Walla River Sub-basin and south of the Big Bend Sub-basin (Figure 22). It includes all of Asotin and Garfield, major portions of Whitman and Columbia, about half of Franklin, and portions of Adams, Lincoln, and Spokane Counties and occupies approximately 4.4 million acres. The western boundary of the Palouse/Snake Sub-basin abuts against the Pasco Sub-basin and is arbitrarily drawn across the approximate location of Ice Harbor Dam on the Snake River. Its northwestern boundary is the divide between the Palouse/Snake drainage and the Big Bend drainage, the northeastern

TABLE 15. Annual Ground and Surface Water Use in Municipal, Industrial, and Irrigation Categories in Walla Walla County, Washington Based on 1975 Statistics.

(After Dion and Lum, 1977; all values are listed in acre-feet per year.)

Annual Municipal Water Use		Annual Industrial Water Use				Annual Irrigation Water Use	
		Self-Supplied		Municipally Supplied			
GW	SW	GW	SW	GW	SW	GW	SW
7,344	4,585	743	15,317	1,516	1,037	7,881	18,840

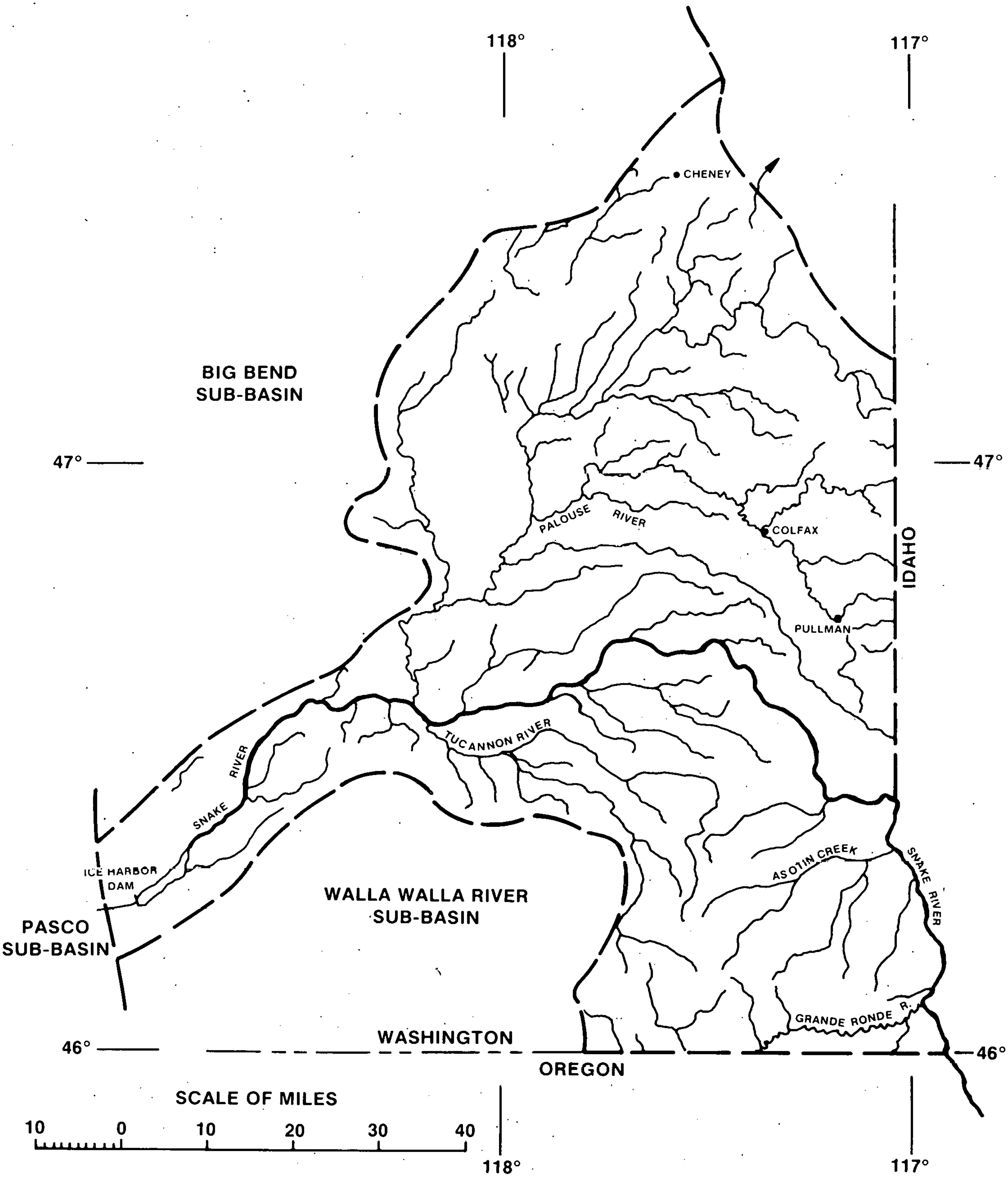

FIGURE 22. Surface Drainage within the Palouse/Snake Sub-basin.

boundary is the approximate separation between the Spokane River and Palouse River drainages, and the southwestern boundary is the divide between the Snake and Walla Walla Rivers. The other boundaries are essentially the political boundaries between Washington and Idaho and Washington and Oregon.

Mean annual precipitation within the Palouse/Snake Sub-basin ranges from less than 10 inches at nearby Ice Harbor Dam to more than 45 inches in parts of Columbia County. Total precipitation over the entire sub-basin is estimated at 6.5 million acre-feet, annually averaging about 18 inches.

The areal distribution of mean annual runoff ranges from less than 0.5 inch to more than 30 inches at locations corresponding approximately with the precipitation extremes noted above, averaging about 3 inches and totaling about 1.1 million acre-feet. The basin-wide runoff coefficient is, therefore, about 18 percent.

Average annual pan evaporation ranges from about 45 to 57 inches, average annual lake evaporation ranges from about 30 to 41 inches, and AET for a 6-inch water-holding capacity soil ranges from less than 8 inches near the Pasco Sub-basin to more than 15 inches in the eastern areas. Total AET for the sub-basin is estimated at 5.0 million acre-feet per year, averaging about 13.8 inches. The corresponding estimates for potential annual lake evaporation are 13.8 million acre-feet per year and 38 inches per year.

Water-use statistics for Asotin, Columbia, Garfield, and Whitman Counties plus the Lower Snake WRIA essentially approximate water use for the Palouse/Snake Sub-basin. Statistics for these areas are presented in Table 16.

Streamflow within the Palouse/Snake Sub-basin is recorded as inflow below the Hells Canyon Dam site along the Idaho-Oregon border and outflow below Ice Harbor Dam. Average annual flow at these stations is 15,870,000 and 40,900,000 acre-feet per year, respectively. A total gauged flow of about 22,680,000 acre-feet per year enters as tributaries along this reach via the Salmon, Grande Ronde, Imnaha, Clearwater, Tucannon, and Palouse Rivers and Asotin Creek. Figure 23 provides a schematic of the USGS gauging network for the sub-basin.

TABLE 16. Annual Ground and Surface Water Use in Municipal, Industrial, and Irrigation Categories in Various Areas of the Palouse/Snake Sub-basin Based on 1975 Statistics.

(After Dion and Lum, 1977; all values are listed in acre-feet per year.)

Area	Annual Municipal Water Use GW	Annual Municipal Water Use SW	Annual Industrial Water Use: Self-Supplied GW	Annual Industrial Water Use: Self-Supplied SW	Annual Industrial Water Use: Municipally Supplied GW	Annual Industrial Water Use: Municipally Supplied SW	Annual Irrigation Water Use GW	Annual Irrigation Water Use SW
Asotin County	6,310	0	0	0	43	0	2,070	2,532
Columbia County	1,363	0	89	0	160	0	0	13,500
Garfield County	509	0	0	0	0	0	340	2,475
Whitman County	6,417	0	0	0	28	0	2,515	5,283
Lower Snake WRIA	74	0	0	0	0	0	2,640	173,373
Total	14,673	0	89	0	231	0	7,565	197,163

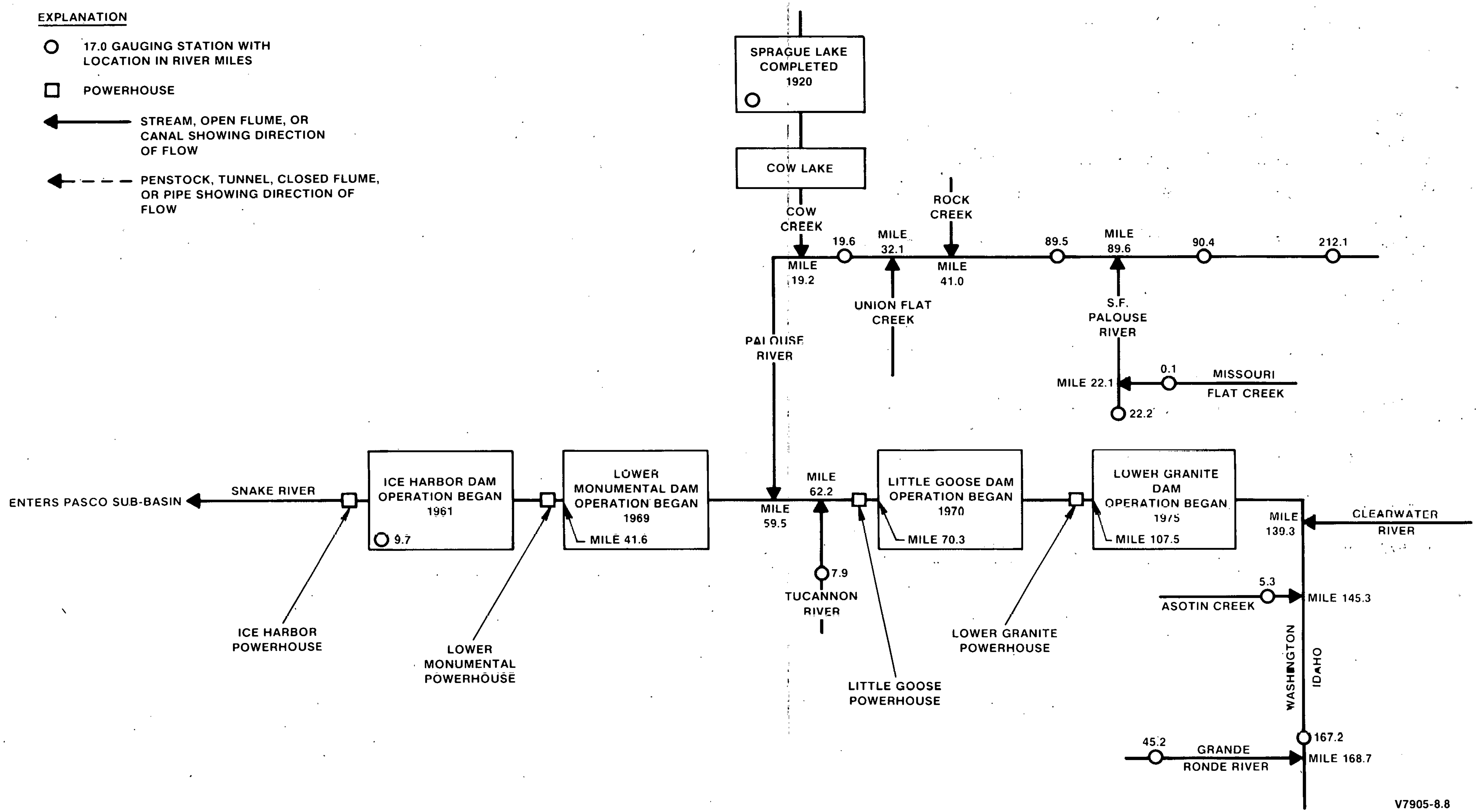

FIGURE 23. Schematic of the U.S. Geological Survey Gauging Network for the Palouse/Snake Sub-basin.

Big Bend Sub-basin

The Big Bend Sub-basin is the largest of the Columbia Plateau hydrologic sub-basins and is situated in the north-central part of the region (Figure 24). It includes most of Adams, Douglas, Grant, and Lincoln Counties and parts of Chelan, Ferry, Franklin, Kittitas, Okanogan, Spokane, and Stevens Counties, and occupies about 6.8 million acres. Its northern border is the approximate boundary between the Columbia Plateau and the Okanogan Highlands and roughly parallels the Columbia River. On the southeast, it is bounded by its drainage divide with the Palouse/Snake Sub-basin. Its boundary with the upper Yakima River Sub-basin and the northern Pasco Sub-basin is both topographic and structural. The principal drainage within the Big Bend Sub-basin is the Columbia River; however, the principal tributaries to the Columbia River enter from outside the sub-basin from the north and northwest. Very little contribution to the flow of the Columbia is received from within the Big Bend Sub-basin. The Columbia River, however, contributes considerable quantities of water via diversions to the central part of the sub-basin.

Mean annual precipitation within the Big Bend Sub-basin ranges from less than 9 inches to slightly more than 15 inches. Total precipitation over the entire sub-basin is estimated at 5.7 million acre feet, annually averaging about 10 inches.

The distribution of mean annual runoff ranges from less than 0.5 inch to nearly 5 inches, but is generally low throughout most of the sub-basin. Average runoff for the sub-basin is about 0.8 inch and total annual runoff is about .47 million acre-feet per year. The basin-wide runoff coefficient, is, therefore, about 8 percent.

Average annual pan evaporation ranges from about 50 to more than 60 inches. Average annual lake evaporation ranges from about 36 to more than 42 inches and is probably greater than 42 inches over a large part of the sub-basin. The AET for the sub-basin is estimated at 5.8 million acre-feet per year, averaging 10 inches. The corresponding estimates for potential lake evaporation are 23.5 million acre-feet per year and 41 inches per year.

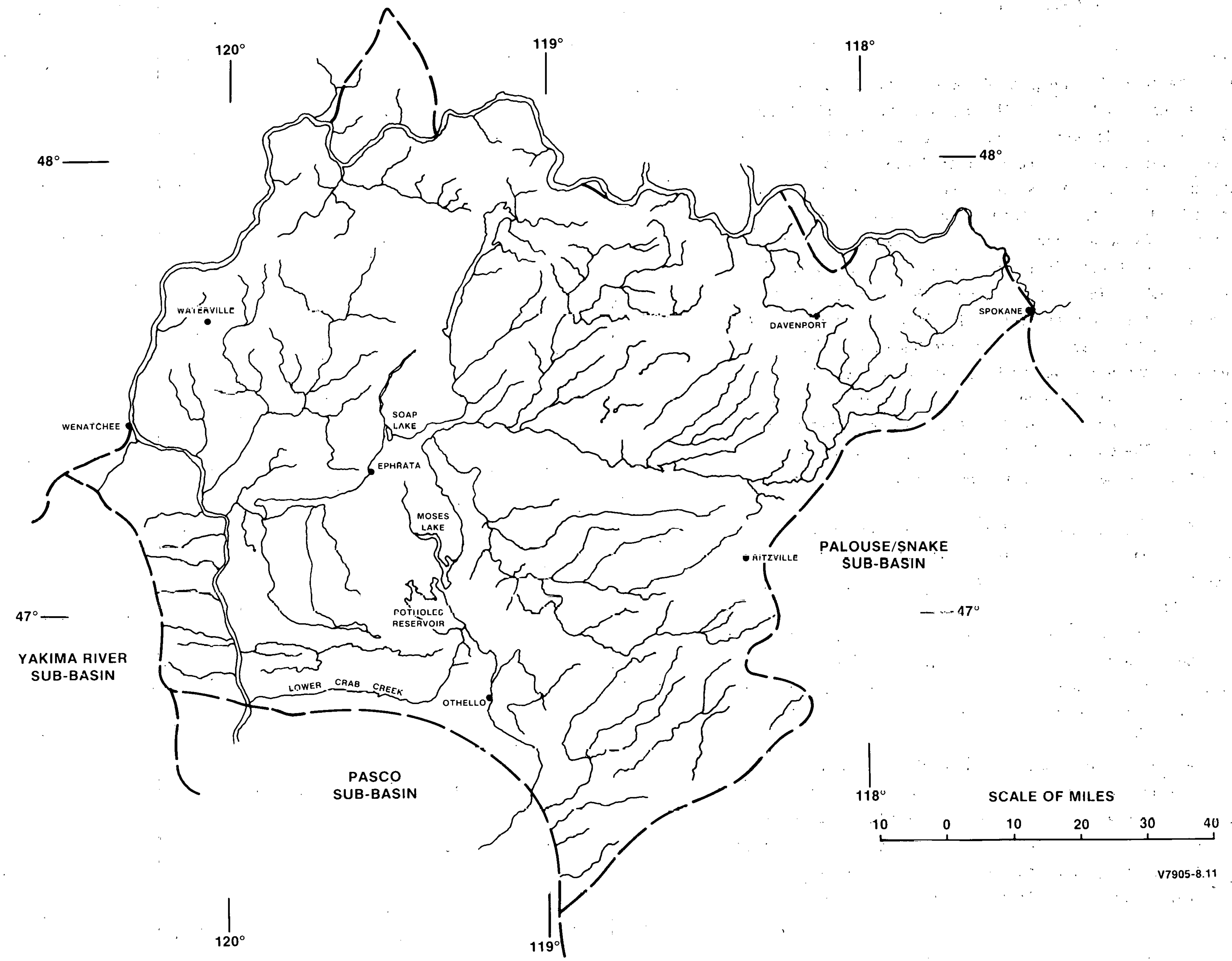

FIGURE 24. Surface Drainage within the Big Bend Sub-basin.

Water-use statistics for the Big Bend Sub-basin can be best approximated by using WRIAs as designated by the State of Washington. Thusly, a close estimate can be obtained with statistics for the Alkali-Squilchuck, Lower Crab, Grand Coulee, Upper Crab-Wilson, Moses Coulee, Foster, Lower Lake Roosevelt, and Lower Spokane WRIAs. One notable exception is the Esquatzel Coulee WRIA, the upper half of which is situated within the Big Bend Sub-basin and the lower half of which is within the Pasco Sub-basin. Because no known major municipal or industrial areas are situated within this WRIA, it has been assumed that statistics for the above-named WRIAs provide a reasonable approximation for the sub-basin. For irrigation use, however, it becomes necessary to review the distribution more closely. Thus, statistics for irrigation in the upper Esquatzel Coulee area have been prepared on the basis of estimates for water delivery within the Columbia Basin Irrigation Project blocks. Statistics for ground-water withdrawals for irrigation in this area are even more obscure, but volumes are assumed to be small. The principal ground-water withdrawals for irrigation occur within the Quincy Basin north of the Potholes Reservoir and west of Moses Lake, where the state has announced that it would grant ground-water permits for withdrawal of about 177,000 acre-feet of water annually. Table 17 lists water-use statistics for municipal and industrial categories and Table 18 provides corresponding statistics for agricultural uses.

Streamflow within the Big Bend Sub-basin is recorded as inflow at Grand Coulee Dam and as outflow below Priest Rapids Dam. Average annual flow at these stations is 80,060,000 and 87,230,000 acre-feet per year, respectively. A total gauged flow of about 8 million acre-feet enters the Columbia River along this reach chiefly from tributaries ouside the Columbia Plateau margin on the north and northwest sides of the Columbia River. The principal tributaries include the Okanogan, Methow, Chelan, Entiat, and Wenatchee Rivers. Approximately 2.1 million acre-feet per year are withdrawn above the gauge for maintenance of the Columbia Basin Irrigation Project. Figure 25 provides a schematic of the USGS gauging network for the sub-basin.

TABLE 17. Annual Ground and Surface Water Use in Municipal and Industrial Categories in Various Water Resource Inventory Areas within the Approximate Big Bend Sub-basin Area Based on 1975 Statistics.

(After Dion and Lum, 1977; all values are listed in acre-feet per year.)

	Annual Municipal Water Use		Annual Industrial Water Use			
			Self-Supplied		Municipally Supplied	
WRIA Name (Number)	GW	SW	GW	SW	GW	SW
Alkali-Squilchuck (40)	0	9,296	74	346,895	0	1,679
Lower Crab (41)	12,663	0	8,207	0	2,056	0
Grand Coulee (42)	1,096	442	0	0	0	0
Upper Crab-Wilson (43)	2,946	0	0	0	0	0
Moses Coulee (44)	1,749	0	3,416	0	0	0
Foster (50)	583	0	0	0	0	0
Lower Lake Roosevelt (53)	605	810	0	0	0	0
Lower Spokane (54)	11,886	0	448	0	568	0
Total	31,528	10,548	12,145	346,895	2,624	1,679

TABLE 18. Annual Ground and Surface Water Use for Irrigation in Various Water Resource Inventory Areas within the Approximate Big Bend Sub-basin Area Based on 1975 Statistics.

(After by Dion and Lum, 1977; all values are listed in acre-feet per year.)

WRIA Name (Number)	Annual Irrigation Water Use GW	SW
Alkali-Squilchuck (40)	0	15,079
Lower Crab (41)	26,500	1,159,448
Grand Coulee (42)	4,800	56,155
Upper Crab-Wilson (43)	2,772	39,970
Moses Coulee (44)	0	35,539
Foster (50)	1,750	2,991
Lower Lake Roosevelt (53)	919	6,840
Lower Spokane (54)	2,578	1,562
Upper Esquatzel Coulee[a]	N.A.	202,800
Total	39,319	1,520,384

[a]Based on irrigated acreages within the Esquatzel Coulee WRIA portion of the Big Bend Sub-basin as ascertained from the January 1978 Columbia Basin Irrigation Project map (U.S. Department of the Interior, 1978a). Acreages were multiplied by a factor of 3.9 acre-feet application per acre per year.

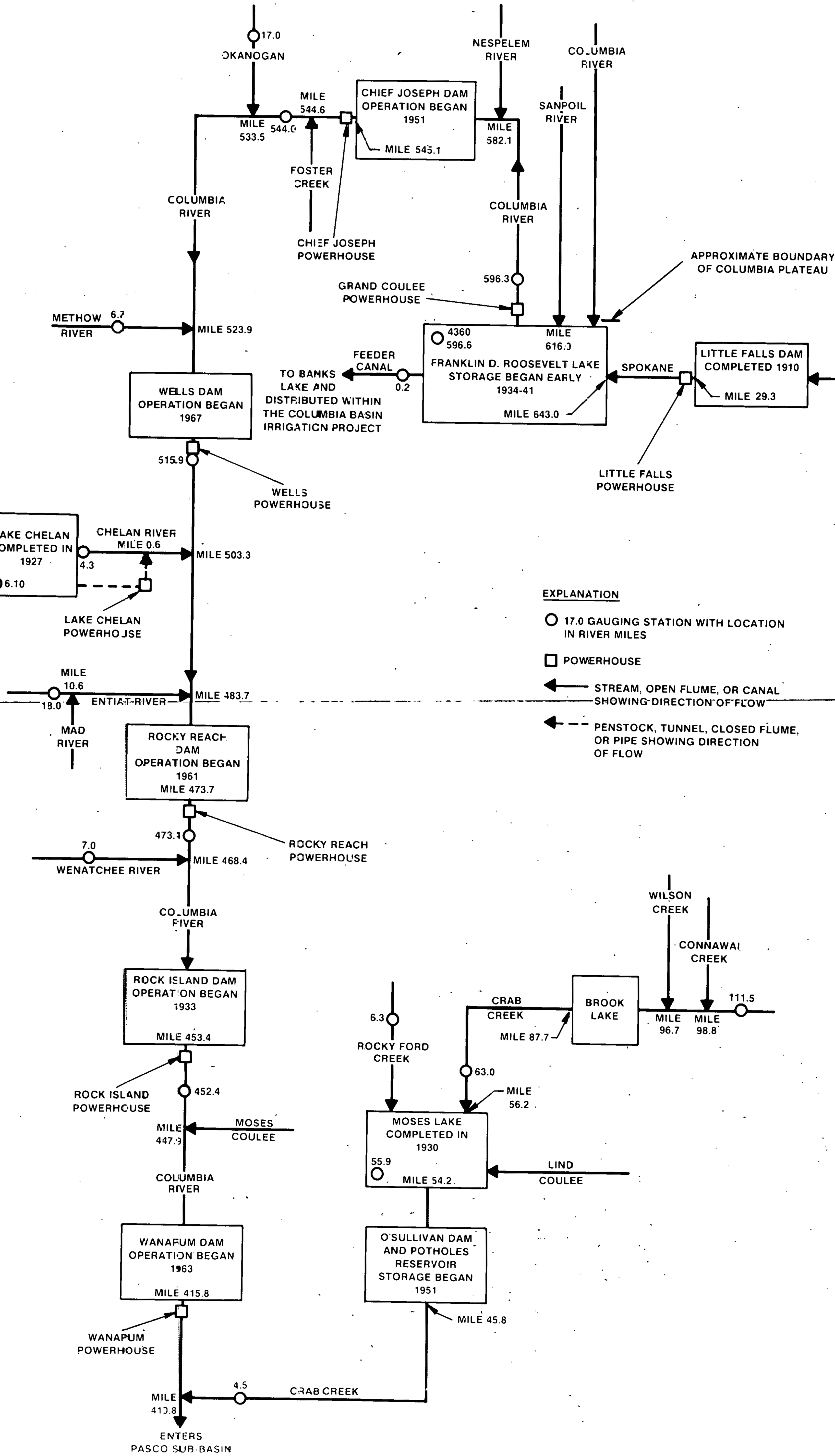

FIGURE 25. Schematic of the U.S. Geological Survey Gauging Network for the Big Bend Sub-basin.

BUDGET EVALUATION

In preparing hydrologic budgets, the following balance is generally applied:

$$Q_{in} - Q_{out} = \Delta S \quad (1)$$

where

Q_{in} = the annual volume of water entering the system or basin;

Q_{out} = the annual volume of water leaving the system or basin; and,

ΔS = the net change in storage within the system or basin each year.

It is also generally assumed that there is no net change in annual storage, or, in other words, the system is in steady-state equilibrium. Thusly,

$$Q_{in} = Q_{out} \quad (2)$$

The existence of steady-state conditions within the Columbia Plateau's hydrologic system has not been determined. Under natural conditions, steady-state is often observed, or the rate of change is barely observable. However, when a system is perturbed by human activities, it may take several years to achieve equilibrium at a new level. Within the Columbia Plateau, several human activities have had the potential for imposing such stresses on the hydrologic system. The most notable include the several hydrographic modifications which have been made upon the major streams, the inter-basin transfer of large quantities of water for irrigation purposes, and the withdrawal of ground waters for various municipal, industrial, and agricultural purposes.

In order to assess properly the impacts of these activities, it is necessary to evaluate both surface-water and ground-water parameters. However, because this study deals primarily with surface water, a departure from traditional budgeting studies has been made in an effort to assess, to the extent possible, the interaction between the surface-water and ground-water systems.

Input Parameters (Q_{in})

In terms of surface water systems, the following equation summarizes the principal inputs to the system:

$$Q_{in} = P + S + D + W \qquad (3)$$

where

P = precipitation;

S = streamflow inputs;

D = water imported from other basins; and,

W = ground-water withdrawals or discharge to the surface water system.

Data for mean annual precipitation (P) over the 1930-1957 period has been mapped by the U.S. Weather Bureau and is shown on Plate 2. Additionally, records for about 80 meteorological stations across and adjacent to the Columbia Plateau have been summarized in various reports by the Washington State University Cooperative Extension Service (Phillips, 1965, 1970; Donaldson and Ruscha, 1975). These data are listed in Appendix A.

Long-term records and statistics for streamflow inputs (S) are maintained by the USGS. Approximately 100 gauging stations have at least partial records in eastern Washington. Corresponding statistics are available for stations in the adjacent areas of Oregon and Idaho. The record is supplemented by data from other water resource agencies such as the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and Bonneville Power Administration.

Statistics and records of surface water diversions (D) are generally maintained by the U.S. Bureau of Reclamation. Supplementary data in certain locations are available through agricultural agencies at various levels of government and irrigation districts. The two most significant projects which involve such inter-basin transfer of surface water are the Yakima and Columbia Basin Irrigation Projects described earlier. Waters applied for irrigation are mostly consumed by the evapotranspiration process. A smaller portion of these waters is returned to the surface-water system via wasteways and interflow. The quantities involved in interflow discharge are particularly difficult to assess and generally are implicit within streamflow records.

Ground-water withdrawals (W) are made for various municipal, industrial, agricultural, and ground-water management purposes. Of particular interest to surface water budgeting are non-consumptive uses of ground water, wherein the waters are discharged to the surface-water system following their use. For example, municipal supplies which are discharged as treated effluents to a stream would be classified as non-consumptive. Statistics on the use of ground water for municipal, industrial, and irrigation purposes in Washington State are summarized periodically by the USGS (Dion and Lum, 1977). Unfortunately, the summaries do not distinguish between consumptive and non-consumptive uses. A further problem, as previously noted, arises from the segregation of data by counties and by WRIAs which do not coincide well with sub-basin designations within the Columbia Plateau.

<u>Output Parameters</u> (Q_{out})

In terms of surface-water systems, the following equation summarizes the principal inputs to the system:

$$Q_{out} = ET + CU + R + O \qquad (4)$$

where

ET = losses due to evaporation and transpiration factors;

CU = consumptive use losses of surface water;

R = artificial recharge to the ground-water system; and,

O = is stream outflow.

Actual losses due to evapotranspiration (ET) have been estimated empirically on the basis of meteorological data at about 35 stations within and adjacent to the Columbia Plateau. A preliminary map of the distribution of the actual AET parameter across the Columbia Plateau has been generated from these data and is shown in Plate 3. An average value for actual evapotranspiration was obtained by means of planimetering and weighting techniques.

Consumptive use (CU) as applied in this context refers to surface water withdrawals for municipal, industrial, agricultural, and other purposes and which are evaporated or otherwise removed from the system upon their use. As was the case for ground-water withdrawals (W), data relating to consumptive use are not well documented.

Stream outflow (O) includes water exiting the sub-basin via discrete water courses including streams and canals. Records and statistics are generally found in the same sources as the stream inflow (S) parameter.

Artificial recharge to the ground-water system (R) results from several sources including excessive application of irrigation waters, ground-water management practices, and waste-disposal practices. With regard to recharge from irrigation, the volume involved is dependent upon the physical characteristics of the soil and irrigation-management practices. It is estimated that, for agricultural lands within the Columbia Plateau, 20 to 40 percent of the water applied "deep percolates" into the ground-water table.

Evaluation of Recharge and Discharge

Ground-water recharge within a particular sub-basin generally occurs by one of four mechanisms:

1. Direct precipitation/infiltration/deep percolation systems;
2. Ground-water inflow from other sub-basins;
3. Infiltration from losing (influent) streams; and,
4. Artificial mechanisms such as irrigation or waste disposal.

Ground-water discharge within a particular sub-basin also can be accomplished via four mechanisms:

1. Natural springs and seeps;
2. Ground-water outflow to other sub-basins;
3. Ground-water outflow to gaining (effluent) streams; and,
4. Ground-water withdrawals by wells.

Because the scope of this study was limited to surface water, no effort was made directly to evaluate ground-water underflow between sub-basins. Further, data on the discharge characteristics of springs and seeps were not available, so analysis of such parameters was also omitted.

Using the available precipitation, evapotranspiration, and runoff records and maps, it was possible to estimate the amount and areal distribution of potential recharge across the Columbia Plateau and along its margins resulting from direct precipitation/infiltration/deep percolation mechanisms. These relationships are presented in Plate 4. Errors associated with the methodology include those related to:

1. The spatial distribution of data points;
2. The temporal variance of hydrometeorological parameters;
3. Computer differencing routines;
4. The accuracy of evapotranspiration estimates; and,
5. Failure to account for elevation effects on the evapotranspiration map.

Other sources of error may be mitigated internally. For example, infiltration variablility is implicit within the runoff parameter. For analysis within a single sub-basin, the following relationship was applied:

$$PR = P - ET - RO \quad (5)$$

where

PR = annual recharge potential from precipitation;

P = mean annual precipitation volume for the sub-basin;

ET = mean annual AET losses from the sub-basin; and,

RO = mean annual runoff from the sub-basin.

Perhaps the biggest error associated with this methodology stems from the failure to account for temporal and spatial variance of the evapotranspiration (ET) parameter. In any case, the data generated provide at least a qualitative indication of this part of the hydrologic balance within the sub-basin.

The exchange between stream and ground-water systems was evaluated by means of stream reach inventories between successive gauges. The inventories for the principal stream within the Columbia Plateau are contained in Appendix D. The principal problems associated with this methodology are:

1. Due to the number and spacing of gauging stations, length and completeness of records, etc., it was not possible to provide meaningful analysis of recharge/discharge relationships on the small streams within the sub-basin, thereby providing only a partial evaluation within the sub-basin; and,

2. On the principal streams, the losses and gains noted were usually within the error margin of the gauging instruments; Figure 26 demonstrates graphically the magnitude of errors for various flow volumes and degrees of precision.

Other errors stem from incomplete data on surface water withdrawals and return flows and failure to account for variances due to averages based on varying periods of record. The balance applied in the analysis was as follows:

$$PSL = IF + TR + RF - DW - OF \qquad (6)$$

where

PSL = potential annual loss from the stream to the ground-water system;

IF = annual inflow to the sub-basin from the principal stream;

TR = annual tributary inflow to the principal stream;

RF = average annual volume of irrigation return flow to the principal stream;

DW = average annual volume of water diverted into the sub-basin via canals, etc.; and,

OF = annual outflow from the sub-basin via the principal stream.

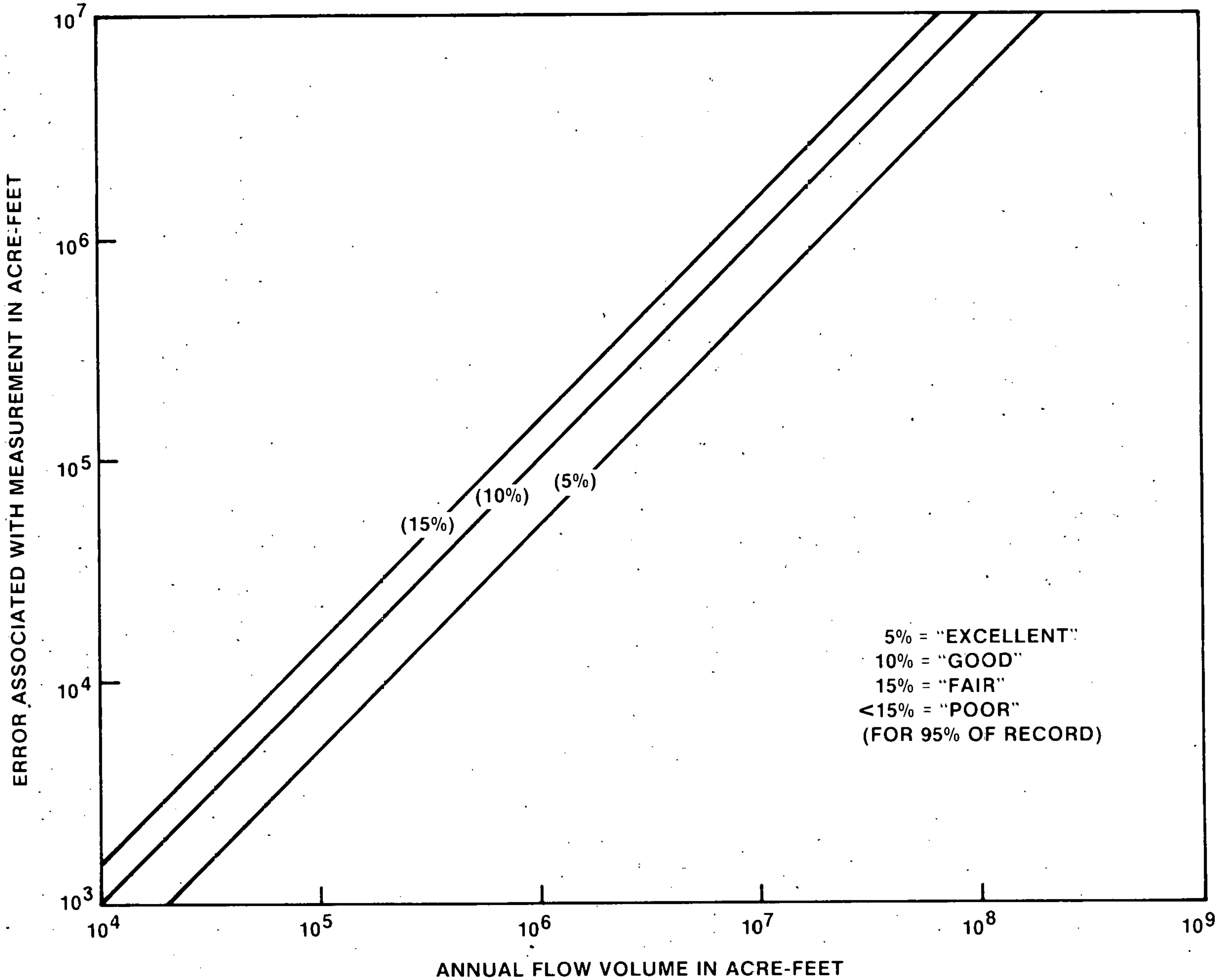

FIGURE 26. Error Magnitudes Associated with Various Stream Discharges and Degrees of Precision in Measurement.

If the computed value of PSL is positive, indicating ground-water recharge, the stream may be classified as a losing (influent) stream along a particular reach. Conversely, if the value of PSL is negative, indicating ground-water discharge, the stream may be classified as a gaining (effluent) stream along a particular reach. The following budget analyses, however, present the gross characteristics of the principal stream averaged over the entire sub-basin. Appendix D provides a finer resolution of this parameter within individual sub-basins. As was the case for recharge from precipitation, the basin-wide recharge and discharge values generated as a result of the stream reach inventory should be regarded as qualitative due to the possible sources of error described above.

Finally, with regard to human manipulation of the ground-water and surface-water systems, recharge and discharge relationships are highly variable depending upon such factors as the type of water withdrawal (i.e., ground or surface), the type of use (consumptive versus non-consumptive), management practices, etc. Thus, in order to provide estimates of the quantities of recharge and discharge, it was necessary to make assumptions regarding the percentage of exchange versus the volume used.

The relationship applied for determining recharge from artificial mechanisms was:

$$AR = 0.1\ IN_{sw} + 0.3\ IR_{sw} \tag{7}$$

where

AR = an estimate of potential recharge due to artificial mechanisms;

IN_{SW} = the volume of surface water used annually for industrial purposes (supplied both independently and from municipal sources); and,

IR_{SW} = the volume of surface water used annually for irrigation purposes.

The coefficients are only preliminary and are not based on any rigorous empirical analysis. The coefficient for industrial use is a pure estimate based on the fact that a large portion of industrial water use is within the power industry and is non-consumptive. The coefficient for irrigation water use is based on the observed range in the percentage of applied irrigation water that deep percolates (20 to 40 percent).

For potential discharge within a given sub-basin due to artificial mechanisms it was assumed that:

$$WG = 0.35M_{gw} + 0.8IN_{gw} + IR_{gw} \tag{8}$$

where

WG = an estimate of probable discharge due to ground-water withdrawals;

M_{gw} = the volume of ground water used annually for municipal purposes (excluding municipally supplied industrial waters);

IN_{gw} = the volume of ground water used annually for industrial purposes (supplied both independently and from municipal sources); and,

IR_{gw} = the volume of ground water used annually for irrigation purposes.

The coefficients in Equation 8 should also be regarded as preliminary. The coefficient for municipal water use is based on consumptive-use statistics for the City of Richland, Washington. The coefficient for industrial water use is based on the assumption that most uses are largely non-consumptive, but a portion of the water withdrawn may undergo subsurface disposal as waste water by injection or infiltration. Ground-water withdrawals for irrigation purposes are assumed to be entirely consumptive.

In combining the above recharge and discharge equations (Equations 7 and 8), we can express the net recharge from artificial mechanisms (RAM) as:

$$RAM = AR - WG \tag{9}$$

A positive value for RAM would, therefore, indicate artificial recharge potential, and a negative value would indicate net ground-water discharge due to artificial mechanisms.

To determine the overall balance between recharge and discharge for a sub-basin, the following relationship was applied:

$$NR = PR + PSL + RAM \qquad (10)$$

where

NR = net annual recharge from all sources within the sub-basin.

If a positive value of NR was obtained, it was taken as an indication that the sub-basin as a whole was an area of potential ground-water recharge within the region; if a negative value was obtained, the sub-basin was suspected to be an area of potential ground-water discharge. Further, sub-basins which, thusly, can be classified as ground-water recharge areas suggest transfer of water out of the sub-basin via ground-water paths; sub-basins, thusly, suggesting a potential for discharge indicate the probable movement of ground water into the sub-basin from adjacent areas.

Sub-basin Budgets

The following pages represent the application of the preceding equations for balancing surface hydrologic systems for the Columbia Plateau sub-basins.

1. Horse Heaven Plateau Sub-basin

A. Precipitation/Infiltration/Deep Percolation

Parameter	AF/yr
Precipitation (P)	2,406,000
Evapotranspiration (ET)	1,550,000
Runoff (RO)	730,000

PR = P - ET - RO

= 153,000 AF/yr (probable ground-water recharge from precipitation)

B. Stream Reach Inventory

Parameter	AF/yr
Inflow (IF), McNary Dam	134,200,000
Tributaries (TR)	1,788,000
Outflow (OF), The Dalles Dam	140,600,000

PSL = IF + TR + RF - DW - OF

= -4,612,000 AF/yr (probable ground-water discharge to the Columbia River)

C. Water Use Inventory

Parameter	AF/yr GW	AF/yr SW
Municipal (M)	230	2,207
Industrial (IN)	0	5,978
Irrigation (IR)	32,555	30,636

AR $= 0.1\ IN_{SW} + 0.3\ IR_{SW} = 10{,}000$ AF/yr

WG $= 0.35\ M_{gw} + 0.8\ IN_{gw} + IR_{gw} = 33{,}000$ AF/yr

RAM = AR - WG

= -23,000 AF/yr (probable ground-water discharge from artificial mechanisms)

D. Net Exchange

Recharge Parameter	AF/yr
Precipitation (PR)	153,000
Stream loss (PSL)	-4,612,000
Artificial mechanisms (RAM)	-23,000

NR = PR + PSL + RAM

= -4,482,000 AF/yr (probable ground-water discharge from sub-basin)

The balance shows a net discharge from the sub-basin of about 4,482,000 acre-feet per year. This suggests probable ground-water inflow from adjacent sub-basins.

2. Yakima River Sub-basin

A. Precipitation/Infiltration/Deep Percolation

Parameter	AF/yr
Precipitation (P)	3,328,000
Evapotranspiration (ET)	2,280,000
Runoff (RO)	950,000

PR = P - ET - RO

= 98,000 AF/yr (probable ground-water recharge from precipitation)

B. Stream Reach Inventory

Parameter	AF/yr
Inflow (IF), Cle Elum	1,280,000
Tributaries (TR)	2,980,000
Return Flows (RF)	2,915,000
Diversions (DW)	4,238,000
Outflow (OF), Kiona	2,636,000

PSL = IF + TR + RF - DW - OF

= 301,000 AF/yr (probable ground-water discharge to the Yakima River)

C. Water Use Inventory

Parameter	AF/yr GW	AF/yr SW
Municipal (M)	12,941	2,207
Industrial (IN)	15,247	249
Irrigation (IR)	5,250	1,927,135

$AR = 0.1\ IN_{sw} + 0.3\ IR_{sw} = 578,000$ AF/yr

$WG = 0.35\ M_{gw} + 0.8\ IN_{gw} + IR_{gw} = 22,000$ AF/yr

RAM = AR - WG

= 556,000 AF/yr (probable ground-water discharge from artificial mechanisms)

D. Net Exchange

Recharge Parameter	AF/yr
Precipitation (PR)	98,000
Stream loss (PSL)	301,000
Artificial mechanisms (RAM)	556,000

NR = PR + PSL + RAM

= 955,000 AF/yr (probable ground-water recharge within sub-basin)

The balance shows a net recharge within the sub-basin of about 955,000 acre-feet per year. This suggests probable ground-water outflow to adjacent sub-basins.

3. Pasco Sub-basin

A. Precipitation/Infiltration/Deep Percolation

Parameter	AF/yr
Precipitation (P)	756,000
Evapotranspiration (ET)	750,000
Runoff (RO)	0

PR = P - ET - RO

= 6,000 AF/yr (probable ground-water recharge from precipitation)

B. Stream Reach Inventory

Parameter	AF/yr
Inflow (IF), Priest Rapids Dam	87,230,000
Tributaries (TR)	43,832,000
Return Flows (RF)	225,000
Outflow (OF), McNary Dam	134,200,000

PSL = IF + TR + RF - DW - OF

= -2,913,000 AF/yr (probable ground-water discharge to the Columbia River)

C. Water Use Inventory

Parameter	AF/yr GW	AF/yr SW
Municipal (M)	8,961	20,372
Industrial (IN)	15,361	403,675
Irrigation (IR)	47,760	907,600

AR = $0.1\ IN_{SW} + 0.3\ IR_{SW}$ = 313,000 AF/yr

WG = $0.35\ M_{gw} + 0.8\ IN_{gw} + IR_{gw}$ = 63,000 AF/yr

RAM = AR - WG

= 250,000 AF/yr (probable ground-water recharge from artificial mechanisms)

D. Net Exchange

Recharge Parameter	AF/yr
Precipitation (PR)	6,000
Stream loss (PSL)	-2,913,000
Artificial mechanisms (RAM)	250,000

NR = PR + PSL + RAM

= -2,657,000 AF/yr (probable ground-water discharge from sub-basins)

The balance shows a net discharge from the sub-basin of about 2,657,000 acre-feet per year. This suggests probable ground-water inflow from adjacent sub-basins.

4. Walla Walla Sub-basin

A. Precipitation/Infiltration/Deep Percolation

Parameter	AF/yr
Precipitation (P)	1,624,000
Evapotranspiration (ET)	981,000
Runoff (RO)	236,000

PR = P - ET - RO

= 407,000 AF/yr (probable ground-water recharge from precipitation)

B. Stream Reach Inventory

Parameter	AF/yr
Inflow (IF) estimated	169,000
Tributaries (TR)	244,500
Outflow (OF), Touchet	431,800

PSL = IF + TR + RF - DW - OF

= -18,000 AF/yr (probable ground-water discharge to the Walla Walla River)

C. Water Use Inventory

Parameter	AF/yr GW	AF/yr SW
Municipal (M)	6,828	3,648
Industrial (IN)	2,259	16,354
Irrigation (IR)	7,881	18,840

AR $= 0.1\ IN_{SW} + 0.3\ IR_{SW}$ = 7,000 AF/yr

WG $= 0.35\ M_{gw} + 0.8\ IN_{gw} + IR_{gw}$ = 12,000 AF/yr

RAM = AR - WG

= -5,000 AF/yr (potential ground-water discharge from artificial mechanisms)

D. Net Exchange

Recharge Parameter	AF/yr
Precipitation (PR)	407,000
Stream loss (PSL)	-18,000
Artificial mechanisms (RAM)	-5,000

NR = PR + PSL + RAM

= 384,000 AF/yr (probable ground-water recharge within sub-basin)

The balance shows a net recharge within the sub-basin of about 384,000 acre-feet per year. This suggests probable ground-water outflow to adjacent sub-basins.

5. Palouse/Snake Sub-basin

A. Precipitation/Infiltration/Deep Percolation

Parameter	AF/yr
Precipitation (P)	6,522,000
Evapotranspiration (ET)	5,060,000
Runoff (RO)	1,143,000

$PR = P - ET - RO$

$= 319{,}000$ AF/yr (probable ground-water recharge from precipitation)

B. Stream Reach Inventory

Parameter	AF/yr
Inflow (IF), Anatone	26,300,000
Tributaries (TR)	11,893,430
Outflow (OF), Ice Harbor Dam	40,900,000

$PSL = IF + TR + RF - DW - OF$

$= 2{,}707{,}000$ AF/yr (probable ground-water discharge to the Snake River)

C. Water Use Inventory

Parameter	AF/yr GW	AF/yr SW
Municipal (M)	14,442	0
Industrial (IN)	320	0
Irrigation (IR)	7,565	197,163

$AR = 0.1\ IN_{sw} + 0.3\ IR_{sw} = 59{,}000$ AF/yr

$WG = 0.35\ M_{gw} + 0.8\ IN_{gw} + IR_{gw} = 13{,}000$ AF/yr

$RAM = AR - WG$

$= 46{,}000$ AF/yr (probable ground-water recharge from artificial mechanisms)

D. Net Exchange

Recharge Parameter	AF/yr
Precipitation (PR)	319,000
Stream loss (PSL)	2,707,000
Artificial mechanisms (RAM)	46,000

$NR = PR + PSL + RAM$

$= -2{,}342{,}000$ AF/yr (probable ground-water discharge from sub-basin)

The balance shows a net discharge from the sub basin of about 2,342,000 acre-feet per year. This suggests probable ground-water inflow from adjacent sub-basins.

6. Big Bend Sub-basin

A. Precipitation/Infiltration/Deep Percolation

Parameter	AF/yr
Precipitation (P)	5,668,000
Evapotranspiration (ET)	5,203,000
Runoff (RO)	465,000

PR = P - ET - RO

= 0 (ground-water recharge from precipitation negligible)

B. Stream Reach Inventory

Parameter	AF/yr
Inflow (IF), Grand Coulee Dam	80,060,000
Tributaries (TR)	7,518,000
Return flows (RF)	56,000 est.
Diversion (DW), all above Grand Coulee Dam	N.A.
Outflow (OF),	87,230,000

PSL = IF + TR + RF - DW - OF

= 404,000 AF/yr (probable ground-water recharge from Columbia River)

C. Water Use Inventory

Parameter	AF/yr GW	AF/yr SW
Municipal (M)	18,204	8,869
Industrial (IN)	14,769	348,544
Irrigation (IR)	39,319	1,520,384

$AR = 0.1\ IN_{sw} + 0.3\ IR_{sw} = 491{,}000$ AF/yr

$WG = 0.35\ M_{gw} + 0.8\ IN_{gw} + IR_{gw} = 58{,}000$ AF/yr

RAM = AR - WG

= 433,000 AF/yr (probable ground-water recharge from artificial mechanisms)

D. Net Exchange

Recharge Parameter	AF/yr
Precipitation (PR)	0
Stream loss (PSL)	404,000
Artificial mechanisms (RAM)	433,000

NR = PR + PSL + RAM

= 837,000 AF/yr (probable ground-water recharge within sub-basin)

The balance shows a net discharge from the sub-basin of about 837,000 acre-feet per year. This suggests probable ground-water outflow to adjacent sub-basins.

Explanation of Results

Table 19 presents a summary of the sub-basin balances derived in the previous section and further provides total and net figures for the Columbia Plateau area as a whole.

In a comparative sense, it appears that for most sub-basins, and the Columbia Plateau area as a whole, recharge by stream loss mechanisms (PSL) is at least an order of magnitude greater than recharge by precipitation (PR). In part, this fact may be the result of failure to account for local systems that may be operating within the sub-basins, and also the selection of sub-basin boundaries may have, for some sub-basins such as the Palouse/Snake, excluded likely recharge areas from the analysis.

The one exception to this relationship is the Walla Walla River Sub-basin which receives a proportionately high amount of precipitation relative to evapotranspiration and runoff losses. This effect may be attributable to higher infiltration capacities and/or vertical permeabilities of the soils and strata or to several other factors. The lowest values of recharge from precipitation were observed within the Pasco and Big Bend Sub-basins owing to extremely high evapotranspiration losses. Actual evaporation and transpiration losses within the Big Bend Sub-basin, in fact, may well exceed the evapotranspiration losses computed due to the cumulative losses from the numerous small lakes and other surface water bodies present (which are not accounted for within Equation 5).

The stream reach inventories performed suggest that ground-water discharge is entering the Columbia River along the Horse Heaven Plateau Sub-basin and within the Pasco Sub-basin and the Snake River within the Palouse/Snake Sub-basin. A smaller amount of discharge occurs within the Walla Walla River Sub-basin. In the Yakima River and Big Bend Sub-basins, the trend suggests recharge of the ground water by the Yakima and Columbia Rivers, respectively. One potential problem with the stream reach analyses is that recent development (in the past 30 years) of the Columbia Basin and Yakima Irrigation Projects has probably resulted in considerable non-equilibrium in the respective sub-basins. However, the record on which the annual averages for streamflow is based is often

TABLE 19. Summary of Recharge/Discharge Relationships within the Washington State Portion of the Columbia Plateau and its Sub-basins.

(All values are given in acre-feet per year; positive numbers indicate probable ground-water recharge; negative numbers indicate probable ground-water discharge.)

	Recharge Mechanisms			
Sub-basin	Precipitation/Infiltration/Deep Percolation (PR)	Stream Loss (PSL)	Artificial Mechanisms (RAM)	Net Recharge (NR)
Horse Heaven Plateau	153,000	-4,612,000	-23,000	-4,482,000
Yakima River	98,000	301,000	556,000	955,000
Pasco	6,000	-2,913,000	250,000	-2,657,000
Walla Walla River	407,000	-18,000	-5,000	384,000
Palouse/Snake	319,000	-2,707,000	46,000	-2,342,000
Big Bend	0	404,000	433,000	837,000
Total	983,000	-9,545,000	1,257,000	-7,305,000

considerably longer, thereby possibly incorporating a period of near-equilibrium. For the Snake River, separation between stream gauges is unusually long and the stream reach inventory is, therefore, highly generalized. Some of the more local gains and losses probably do not appear.

For artificial mechanisms (RAM), all sub-basins showed a net recharge effect with the exception of the Horse Heaven Plateau and the Walla Walla River Sub-basins which suggested slight quantities of discharge.

Although the numbers are somewhat tentative, it is reasonable to expect a considerable amount of recharge due to agricultural practice in the region. The discharge values computed for the Horse Heaven Plateau and Walla Walla River Sub-basins are apparently due primarily to the higher percentage of ground-water withdrawals for irrigation relative to importations and/or surface-water withdrawals. The highest recharge values occurred within the Yakima River, Big Bend, and Pasco Sub-basins, in decreasing order. These areas correspond to the areas served by U.S. Department of the Interior irrigation projects.

The net budgets (NR) show that the Horse Heaven Plateau, Pasco, and Palouse/Snake Sub-basins are probably receiving ground-water inflow from adjacent sub-basins; whereas budgets for the Yakima River, Walla Walla River, and Big Bend Sub-basins suggest inter-basin transfer of ground waters recharged within the sub-basin, assuming that steady-state or near steady-state conditions exist for the hydrologic system. Overall, the Washington State portion of the Columbia Plateau appears to have a net influx of ground water from adjacent areas, which is seemingly consistent with the topography and geology. However, uncertainties in the analytical methodology, as noted above, remain. Moreover, the selection of sub-basin boundaries may have a significant effect upon the net recharge value. This is probably the case for the Palouse/Snake Sub-basin which is apparently truncated hydrologically from likely recharge areas to the east and south by the state boundaries. Similar conditions are probable for the Horse Heaven Plateau and Walla Walla Sub-basins. In the Yakima River and Big Bend Sub-basins, the ground-water inflow from adjacent mountainous areas may be a component of the hydrologic balance that remains unquantified in this method of analysis. Thus, the validity of the values obtained and conclusions drawn with regard to relative movement of ground water are probably limited to the shallowest ground-water systems. Regional underflow from other sub-basins between deep regional ground-water systems and shallow ground-water systems remain unquantifiable variables within this context.

Table 19 provides a summary of the results discussed above. In general, the analytical results are consistent with previous interpretations which were performed on the basis of regional ground-water flow (such as LaSala, Doty, and Pearson, 1973; Tanaka, Hansen, and Skrivan, 1974; Summers, Weber, and Schwab, 1978, and the U.S. Army Corps of Engineers, 1978).

HYDROLOGIC RISK EVALUATION

Of all natural catastrophic events that could adversely affect a radioactive waste facility constructed within the Pasco Basin, flooding is the most probable, although not necessarily the most damaging. Flooding presents the greatest risk to a subsurface repository during the so-called operating phase, which is the period following construction and prior to permanent closure and sealing.

Evaluation of flood risk involves quantification of two event-related parameters (frequency and magnitude). Frequency can be evaluated in terms of "return period" or "recurrence interval" which represents the average period (generally given in years) between the occurrence of a flood of a given magnitude and an equal or larger flood. The term is related to probability as follows:

$$t_r = 1/p \qquad (11)$$

where

t_r = return period; and,

p = probability of occurrence.

Thus, the concept of a 100-year flood event means that, over a long period of record (e.g., 1,000 years), there will be 1,000/100, or 10 floods equal to or greater than the 100-year flood. Theoretically, although not likely, all such events could occur within the time period of a few years, or conversely, they could occur 100 years apart. Obviously, the length of the period of record available is important to the prediction, and there is a level of confidence associated with the probability assigned to a given event.

Flood magnitudes can be assigned probabilities as discussed above, but the primary consideration with regard to siting risk is the definition of the flood plain for a given magnitude. The extent of the flood plain can be mapped geologically, or, for single events of a given magnitude, topography can serve as the basis for delineation.

Generally, two scenarios are relevent in terms of flooding within eastern Washington:

(1) Canyon flooding on smaller, unregulated, intermittent, and ephemeral streams adjacent to the higher land areas; and,

(2) Basin flooding along the major streams, particularly the Columbia River.

CANYON FLOODING

Definition of flood hazards on the smaller streams has been provided for various purposes including zoning, flood insurance, and highway and other engineering designs. The USGS (Cummans, Collings, and Nassar, 1975) has prepared a publication which describes computation of flood magnitude and frequency according to the log-Pearson Type III method, which is purportedly valid for unregulated streams having a minimum of 10 years of record. Regression equations of the form:

$$Q_T = \underline{a}\, A^{b_1} P^{b_2} F^{b_3} \qquad (12)$$

are used, where

Q_T	=	the flood magnitude for recurrence interval T in cubic feet per second;
A	=	the drainage area in square miles;
P	=	the mean annual precipitation in inches;
F	=	the forest cover in percent of the total basin area;
$\underline{a}$	=	a dimensionless regression constant for the specific region and recurrence interval being considered; and,
b_1, b_2, b_3	=	dimensionless regression constants for the corresponding parameter and the specific recurrence interval being considered.

Plate 5 shows the segregation of the State of Washington into various physiographic zones having similar flood characteristics as determined by Cummans, Collings, and Nassar (1975). Zones V, VI, X, XI, and XII are within the Columbia Plateau area, with the Pasco Basin situated almost entirely within Zone XII. Tables 20 and 21 provide ranges of coefficients and parameter values characteristic within these zones. Table 22 provides a means of estimating the statistical validity of the methodology according to the number of years of record available. Evaluations for the various flood events would not be statistically valid unless, at least, the corresponding number of years of record were available, as a minimum.

BASIN FLOODING

Flooding on the lower Columbia River has been extensively evaluated by the U.S. Army Corps of Engineers in conjunction with its water resources engineering activities. Associated with these activities are certain probability concepts related to design and management. The more commonly applied concepts are those of probable maximum floods (PMF), standard project floods (SPF), and design floods. The following paragraphs provide a cursory discussion of these concepts for the purpose of providing the reader with a basis for comparing the significance of various flow magnitudes.

The PMF is determined on the basis of the rationale that an upper limit of precipitation (i.e., probable maximum precipitation) is capable of falling upon a given drainage area. The analysis also accounts for the combination of other hydrologic factors (such as antecedent moisture conditions, snowmelt, tributary contributions, etc.) which will result in the maximum runoff event physically possible. The magnitude of the PMF is quite large when compared with even the SPF; however, flows in excess of 80 percent of the PMF have been noted in some parts of the world (Linsley and Franzini, 1972). Generally projects are not designed to account for the PMF unless project failure would result in substantial loss of life.

TABLE 20. Summary of Regression Coefficients for Estimating Magnitudes and Frequencies of Floods in Eastern Washington by "Flood Zones."

(After Cummans, Collings, and Nassar, 1975.)

Recurrence Interval T	Regression Coefficient: Regression Constant a	Regression Coefficient: Drainage Area A	Regression Coefficient: Annual Precipitation P	Regression Coefficient: Forest Cover F	Standard Error of Estimate (percent)
		Region V			
5	0.982	0.90	1.35	-0.21	65.1
10	2.87	0.88	1.16	-0.23	73.9
25	7.51	0.87	1.03	-0.25	91.1
50	13.6	0.86	0.95	-0.27	105
100	23.4	0.85	0.89	-0.29	121
		Region VI			
5	0.260	0.90	1.35	-0.21	50.2
10	0.741	0.88	1.16	-0.23	45.2
25	1.77	0.87	1.03	-0.25	48.3
50	2.87	0.86	0.95	-0.27	55.7
100	4.70	0.85	0.89	-0.29	66.2
		Region X			
5	0.449	0.90	1.35	-0.21	90.1
10	1.16	0.88	1.16	-0.23	93.1
25	2.54	0.87	1.03	-0.25	104.0
50	4.03	0.86	0.95	-0.27	115
100	6.05	0.85	0.89	-0.29	129
		Region XI			
5	0.450	0.90	1.35	-0.21	66.6
10	1.36	0.88	1.16	-0.23	62.2
25	3.59	0.87	1.03	-0.25	63.3
50	6.61	0.86	0.95	-0.27	72.1
100	11.5	0.85	0.89	-0.29	88.0
		Region XII			
5	0.157	0.90	1.35	-0.21	93.6
10	0.629	0.88	1.16	-0.23	54.0
25	1.76	0.87	1.03	-0.25	56.6
50	3.05	0.86	0.95	-0.27	67.0
100	4.83	0.85	0.89	-0.29	81.8

TABLE 21. Parameter Ranges for Estimating Magnitudes and Frequencies of Floods in Eastern Washington by "Flood Zones."

(After Cummans, Collings, and Nassar, 1975.)

	Drainage Area	Annual Precipitation P	Forest Cover F
Region V			
Maximum	1,297	36	95
Minimum	0.38	10	0.01
Region VI			
Maximum	434	106	99
Minimum	0.65	10	0.01
Region X			
Maximum	1,042	22	78
Minimum	0.21	10	0.01
Region XI			
Maximum	2,500	40	87
Minimum	0.54	10	0.01
Region XII			
Maximum	234	10	0.01
Minimum	1.80	10	0.01

TABLE 22. Minimum Periods of Record Required to Achieve Statistical Validity for Various Flooding Events.

(After Cummans, Collings, and Nassar, 1975.)

Recurrence Interval (years)	10	25	50	100
Years of Record	10	15	20	25

The SPF, on the other hand, generally excludes synergistic or compounding hydrologic phenomena and is based solely on the rainfall/runoff relationship for the largest precipitation event observed for the basin in question. Although the probability of the resulting theoretical flow is unknown and, therefore, the SPF for projects in different regions cannot be compared directly, it is usually about 50 percent of the PMF computed for the area. Although the SPF has a higher probability of occurrence than the PMF, the SPF is never exceeded by more than a few percent of the floods within the general region (Linsley and Franzini, 1972).

The design flood for a given project may be either greater or less than the SPF. This parameter generally represents a management decision on the basis of tangible and intangible benefits resulting from alternative project designs and a corresponding implicit decision with regard to "acceptable risk."

Magnitudes of SPFs and PMFs have been estimated for the Columbia River at McNary Dam as shown in Table 23. Table 24 compares the discharge rate of the dam-regulated PMF and other floods with the calculated, natural PMF discharge of the Columbia River at The Dalles, Oregon. The comparison is made with The Dalles station because of the relative length of the gauging record available for that station. For the dam-regulated PMF, the discharge rate remains greater than 80 percent of the peak rate for nearly a month. Consequently, inundated regions would be subjected to erosion for an extended period. Flow rates along the Hanford Site are considerably less than those indicated in Table 24 because the Snake, Yakima, and other smaller rivers empty into Lake Wallula downstream from Hanford. For comparison, some related statistics for the Columbia River below Priest Rapids Dam are provided in Table 25.

Another consideration with regard to basin flooding is that of catastrophic events which result in the failure due to breaching of the principal dams upstream from the Hanford Site on the Columbia River.

Such scenarios were evaluated by the U.S. Energy Research and Development Administration (1976). The scenarios presented postulated that Grand Coulee Dam was breached due to detonation of a nuclear device. The resultant flooding discharges due to 25 and 50 percent

TABLE 23. "Standard Project Flood" and "Probable Maximum Flood" Magnitudes for the Columbia River at McNary Dam.

(After U.S. Army Corps of Engineers, 1969.)

	Standard Project Flood		Probable Maximum Flood	
Discharge Units	Natural	Regulated	Natural	Regulated
(Cubic feet per second) x 10^3	1,490	810	2,610	2,100
Cubic feet per second per square mile	6.94	3.79	12.20	9.80

TABLE 24. Predicted and Measured Peak Discharges of the Columbia River at The Dalles, Oregon.

(After U.S. Army Corps of Engineers, 1969.)

Event	Peak Discharge (x 10^3 cubic feet per second)	Ratio of Each Peak to Natural PMF
Natural Probable Maximum Flood (PMF)	2,660	1.0
Regulated PMF	2,060	0.77
Natural Standard Project Flood (SPF)	1,550	0.58
Regulated SPF	840	0.32
Greatest Peak of Record (1894)	1,240	0.47
2nd Greatest Peak of Record (1948)	1,010	0.38
3rd Greatest Peak of Record (1876)	958	0.36
100-Year Frequency Natural Peak	1,200	0.45
100-Year Frequency Regulated Peak as of 1975	690	0.26
Mean of Observed Annual Peaks	583	0.22
Greatest Median Daily Discharge	495	0.19

TABLE 25. Selected Flood Statistics for the Columbia River below Priest Rapids Dam.

Event	Peak Discharge (x 10^3 cubic feet per second
Regulated PMF	1,440
Greatest Peak (1894)	740 (est.)
2nd Greatest Peak (1948)	693

breaches of the dam were estimated to be 5,280,000 and 8,000,000 cubic feet per second, respectively. Figures 27 through 30 show the Hanford areas which would be inundated under various scenarios. No scenarios have yet assessed the effects of resonant failures starting with dams upstream from Grand Coulee in Canada.

The National Academy of Science (1978) has also reviewed scenarios involving climatic changed to conditions equivalent to those of the late-Pleistocene Epoch of geologic time, wherein the Pasco Basin endured episodes of severe flooding, scouring, and backfilling. As a result, the ancestral Columbia River at Hanford cut down to and scoured the Ringold Formation and the basaltic bedrock near Gable Butte and Gable Mountain. Erosion also occurred on the flanks of the Rattlesnake Hills. The study concluded, however, that such erosive action from such flooding events would not affect a potential geologic repository within the Pasco Basin, unless perhaps through moderate alteration of the ground-water regime resulting in increased rate of leaching of contaminants from the repository.

For a deep geologic repository, flooding probably poses the greatest risk during the "operating phase," which is about a 50-year period following construction and prior to permanent sealing or closure. Thus, the question of the probability of a given event occurring during the operating phase becomes relevant. The probability distribution function applied to this situation is the binomial distribution:

$$P_y(y) = \binom{n}{y} p^y (1-p)^{n-y} \qquad (13)$$

where

$P_y(y)$ = the probability of the event (Y) being considered;

n = the number of discrete trials (years);

y = the number of occurrences; and,

p = the probability of the event.

It can be seen that the probability of a given event occurring within a specified number of trials (years) would be the complement of the probability of the event not occurring within the same period. In other

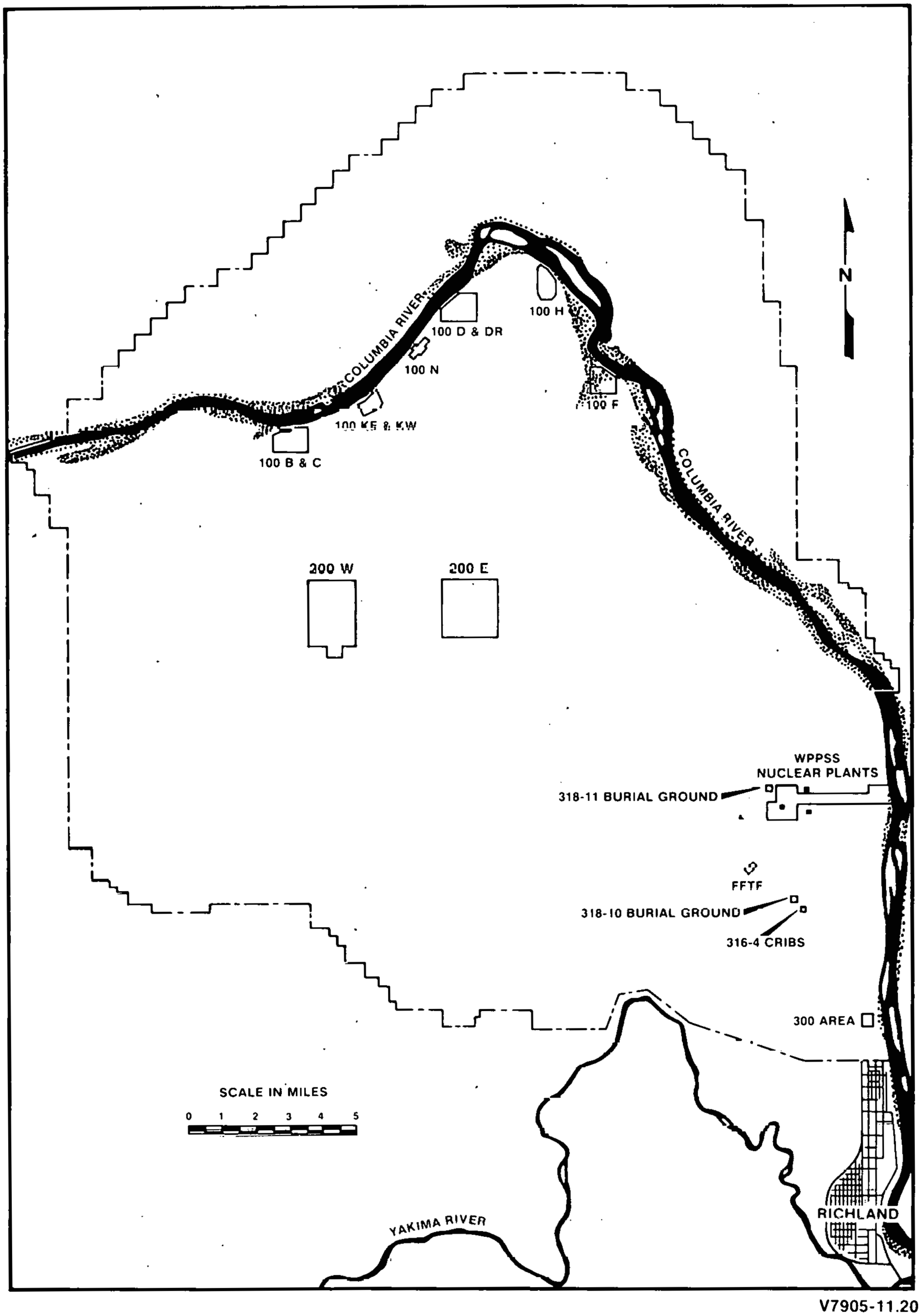

FIGURE 27. Highest Flood on Record (800,000 cubic feet per second) (after U.S. Energy Research and Development Administration, 1976; inundated areas shown in dots).

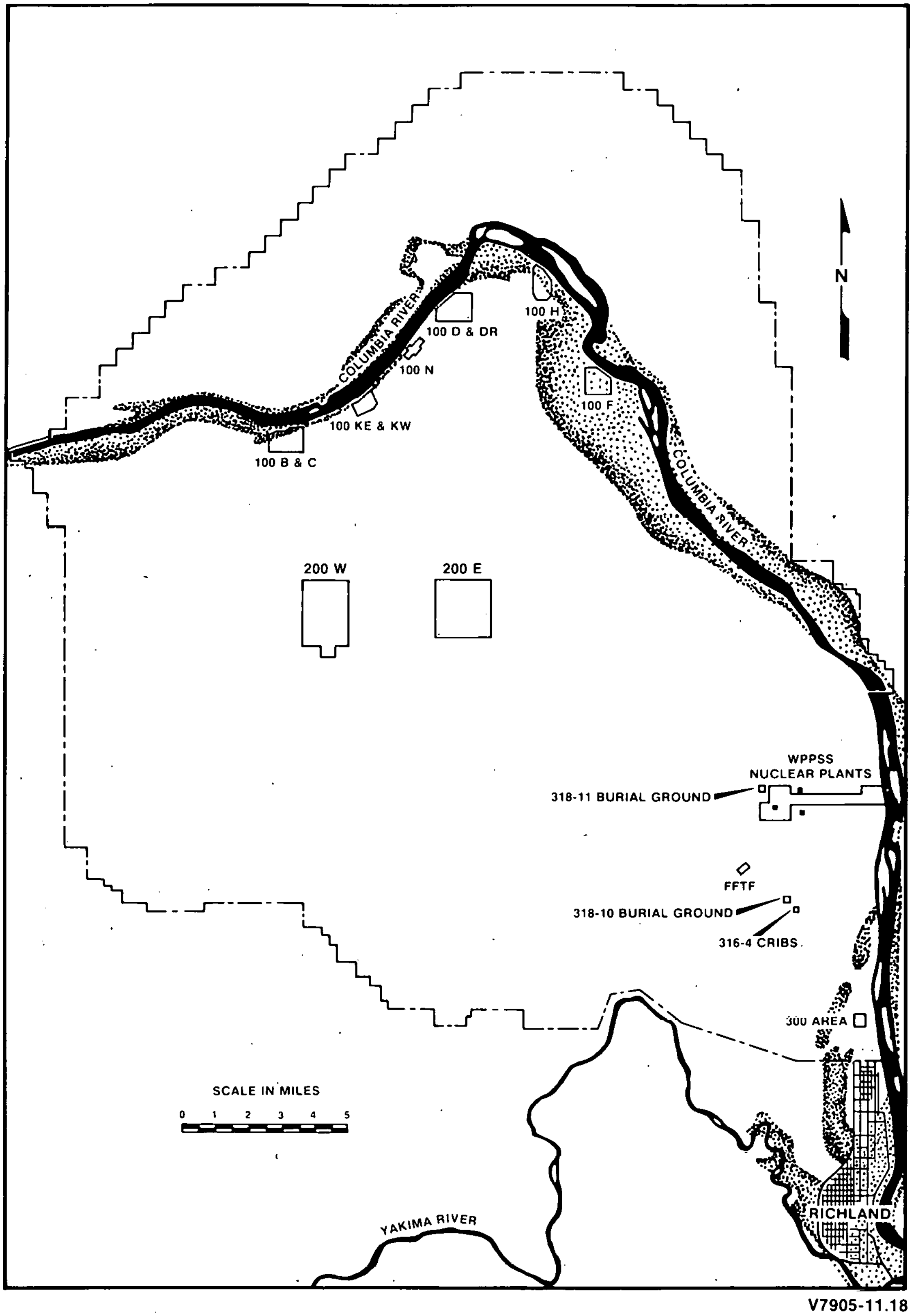

FIGURE 28. Probable Maximum Flood (1,440,000 cubic feet per second) (after U.S. Energy Research and Development Administration, 1976; inundated areas shown in dots).

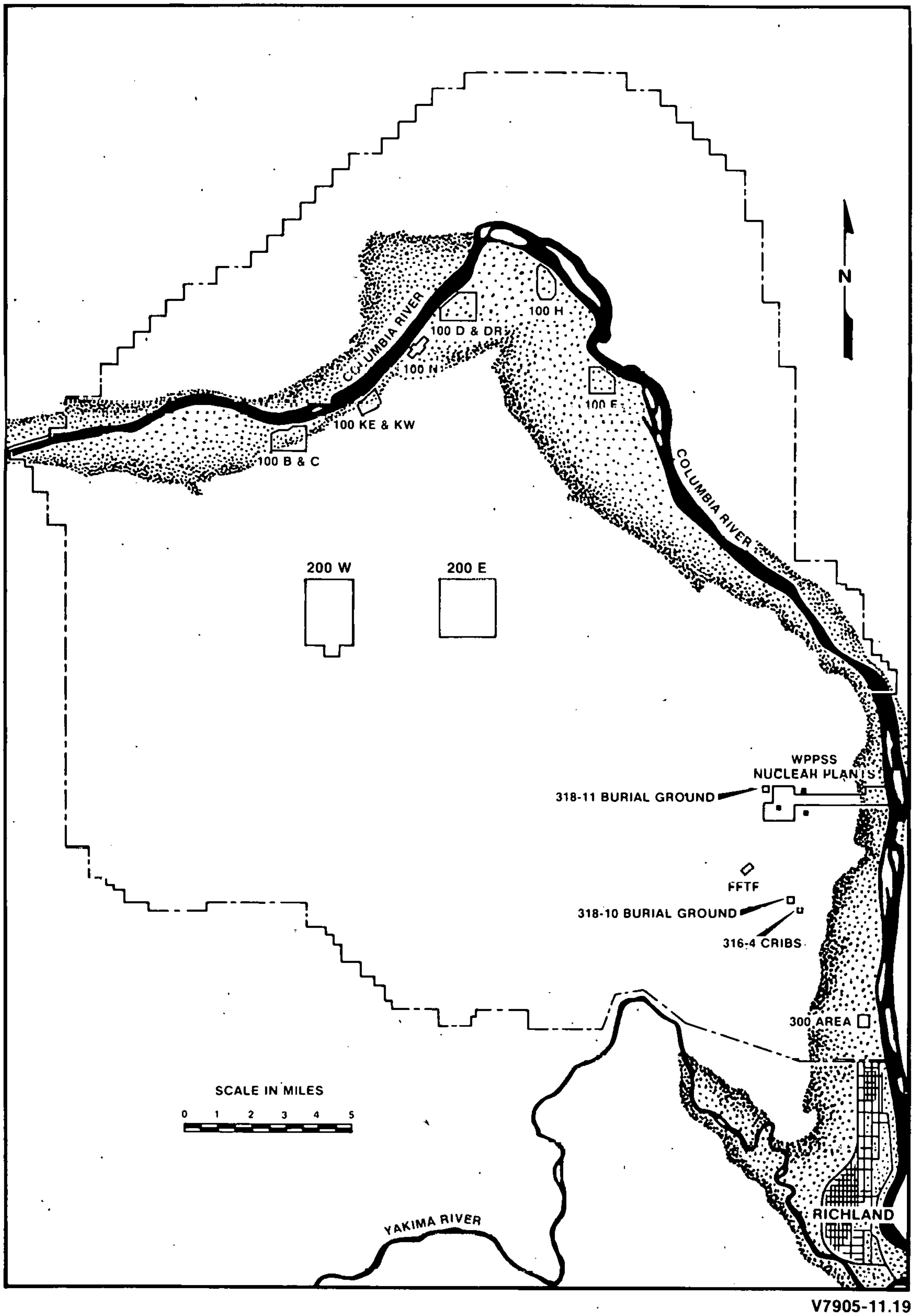

FIGURE 29. Flood Resulting from a 25 Percent Breach of Grand Coulee Dam (5,280,000 cubic feet per second) (after U.S. Energy Research and Development Administration, 1976; inundated areas shown in dots).

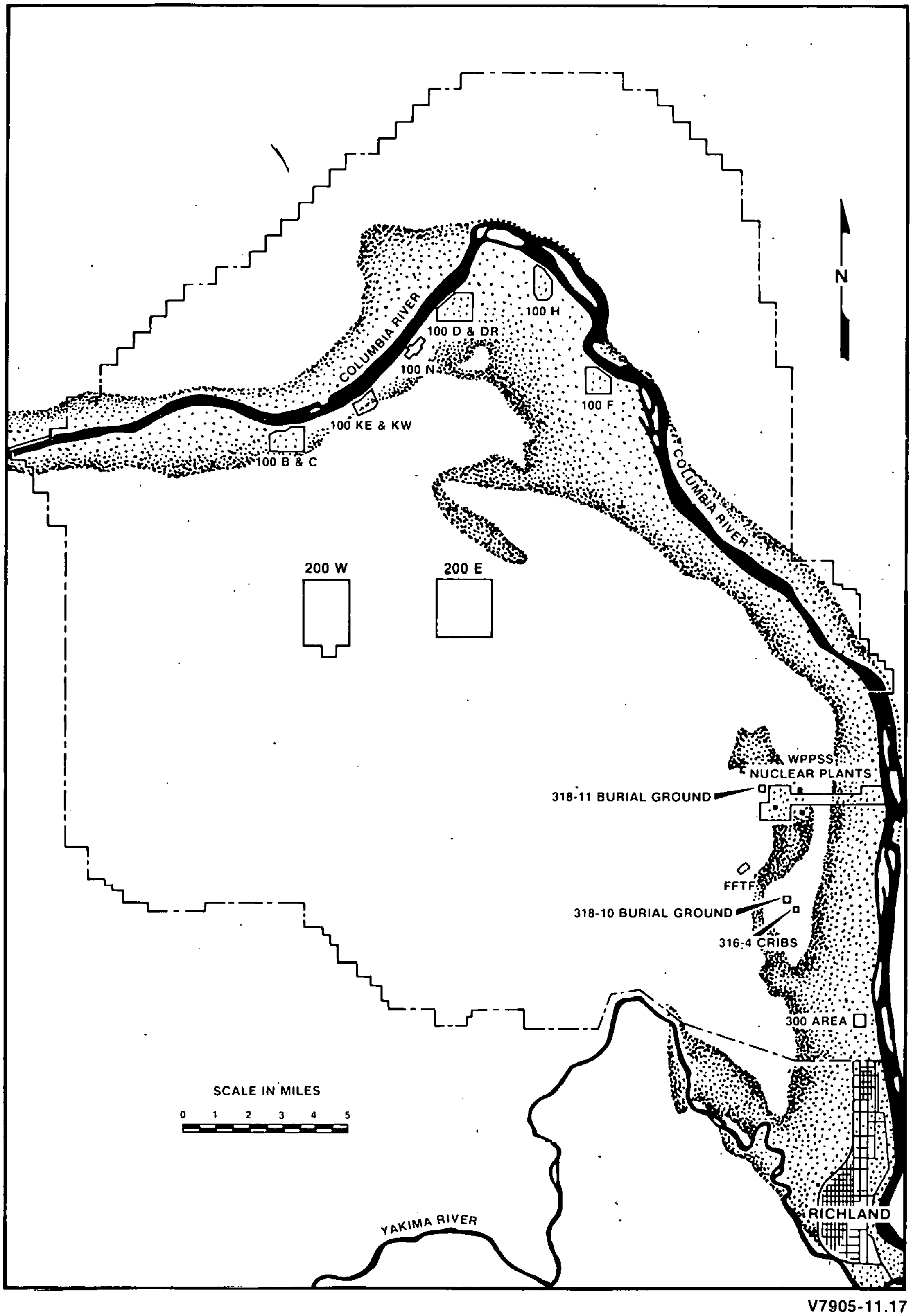

FIGURE 30. Flood Resulting from a 50 Percent Breach of Grand Coulee Dam (8,000,000 cubic feet per second) (after U.S. Energy Research and Development Administration, 1976; inundated area shown in dots).

words, it would not be realistic to evaluate the risk of the event occurring exactly once within the time period because the probability of the event occurring more than once is also a concern. For example, the probability of a 100-year flood event occurring at least once within a 25-year period is computed as follows:

$$P_y(y) = \binom{25}{0} (.01)^0 (.99)^{25} \tag{14}$$

$$= 0.78$$

which is the probability of non-occurrence. The occurrence probability would, therefore, be:

$$1 - P_y(y) = 0.22. \tag{15}$$

Similarly, the probability for a 100-year flood event occurring within a 50-year period is 39 percent. Such studies, if properly designed, might be used to corroborate or to refute the above findings.

Finally, several flooding scenarios have been presented. It is apparent on the basis of these that a single flooding event need not pose a threat to a permanent, properly sited repository.

In summary, with regard to the evaluation of flood risk to a deep geologic repository, it can be concluded that:

1. The highest risk occurs during the 25- to 50-year operating phase of the repository;

2. The hazardous areas with respect to both basin flooding and canyon flooding occupy an extremely small percentage of the available land area, and, therefore, the possibility of eliminating flood risk factors is good; and

3. The impact of flooding upon a potential repository is extremely low following permanent closure.

CONCLUSIONS

Overall, this study leads to the conclusion that very little recharge to the regional ground-water system occurs within the plateau itself. Recharge resulting from stream losses probably represents a more significant contribution to basin-wide recharge than the other mechanisms, but overall, the regional hydrologic system apparently relies on the surplus from basins adjacent to the Columbia Plateau which arrives via surface runoff, marginal recharge, and underflow. While the sub-basin designations for the study of the surface-water systems would seem to be valid from shallow ground-water and surface-water systems, they probably do not adequately reflect hydrologic segregation with regard to the deep, regional ground-water flow system(s). Nevertheless, they have been shown to be somewhat useful in evaluating probable inter-basin effects.

In addition to providing an overview of the surface-water resources present and related topics for the Columbia Plateau, an effort has been made to utilize, to the extent possible, surface-water information for the interpretation of regional ground-water flow. In general, this effort has achieved success toward that goal, in the sense that a preliminary, qualitative (if not a semi-quantitative) evaluation of ground-water recharge and discharge within the Columbia Plateau sub-basins and of inter-basin ground-water transfer was obtained. At the same time, the limitations of surface-water analyses have been realized. It would not be productive to attempt further refinement of this analysis without the benefit of ground-water head relationships and related information, assuming that the definition of ground-water/surface-water interactions is the primary objective.

More specifically, the assessment of recharge/discharge relationships has been based on examinations of three primary mechanisms:

1. Precipitation/infiltration/deep percolation;
2. Stream losses and gains; and,
3. Artificial mechanisms.

The acquisition of more detailed and/or corroborative data on the above mechanisms would provide a more meaningful and more quantitative analysis.

For recharge from direct precipitation, the primary uncertainties are associated with the water loss components of the balance, evapotranspiration, and runoff, respectively in order of uncertainty. In recharge areas, AET is said to be considerably less than potential (Freeze and Cherry, 1979). Thus, it would seem that there may be a correlation between the difference between AET and PET and the quantity of recharge. Examination of the hydrometeorological data in Appendix A, however, does not support such a relationship. This fact may very well indicate systematic errors in estimating evapotranspiration parameters and water balance assumptions. For example, the Thornthwaite-Mather technique is predicated on certain assumptions such as the water-holding capacity of the soils present. Generalization of a 6-inch water-holding capacity across the Columbia Plateau may not be valid. For this reason, spatial generalizations, such as those contained in Plates 3 and 4, based on these data should be regarded as preliminary. Another problem with the use of these data stems from the failure to account properly for spatial variances such as those associated with elevation.

The stream reach inventories are believed to provide a reasonable indication of recharge and discharge boundaries for the purpose of regional numerical modeling, depending upon the resolution required. Plate 6 presents a mapping of the recharge and discharge reaches along the principal streams within the Columbia Plateau as identified through the stream reach inventories. Interpretations provided within the U.S. Army Corps of Engineers' Yakima Valley study (1978) are also included where losses and gains were not determinable by reach inventory methods. It should be recognized, however, that the figure constitutes a generalization owing to the fact that, along some reaches, the distance between gauges was a hundred stream miles or more. Further, where hydrographic modifications were extreme, assumptions regarding flow were required. Recharge/discharge relationships, as well as their magnitudes, are no doubt more intricate than the results presented. Another problem may arise from variances inherent in the use of long-term averages. Because these averages represent periods prior to the installation of several major hydrographic modifications as well as periods hence, the use of long-term averages may be somewhat erroneous. If further analyses of this type are required, it may be preferable to rely on flow averages for more recent periods. Alternatively, it may be profitable to employ hydrograph separation or to attempt balances for low-flow conditions as means of quantifying baseflow. Finally, the limitations of the gauging instruments relative to the magnitude of the recharge and discharge parameters have already been discussed and may also be mitigated by means of the above techniques.

In assessing recharge and discharge relationships due to artificial mechanisms, it may be necessary to gain a more comprehensive understanding of consumptive versus non-consumptive uses. In doing so, a better spatial resolution of water-use intensity would also be useful. The primary impact upon the hydrologic cycle from water use appears to be due to irrigation. Efforts are currently under way to provide a sufficiently detailed resolution of the effects of this use upon the regional ground-water system. However, even when these studies are complete, considerable uncertainty will remain with respect to the ultimate fate of recharging irrigation waters. It is recognized that appreciable quantities of excessively applied irrigation waters may become tied up in interflow and eventually discharged to surface streams. The size of this contribution to baseflow remains unquantified or, at best, only partially quantified. Another relevant consideration is the dynamics of water use. It is evident that considerable adjustment of the regional hydrologic system is occurring as a result of irrigation development and other major water resource developments (Walters and Grolier 1960; Garrett, 1968; Tanaka, Hansen, and Skrivan, 1974; Luzier and Skrivan, 1975; U.S. Army Corps of Engineers, 1979) as evidenced by rising ground-water levels in areas of water importation and declining levels in areas of intense pumpage.

Two further areas of investigation which may be of potential utility in possible future evaluations of the hydrologic budgets for certain areas within the Columbia Plateau are:

1. Evaluation of hydrologic budgets for lakes (such as Lake Wallula); and,

2. Water quality analyses.

Such studies, if properly designed, might be used to corroborate or to refute the above findings.

Finally, several flooding scenarios have been presented. It is apparent on the basis of these that a single flooding event need not pose a threat to a permanent, properly sited repository. Flooding poses the greatest risk potential during the "operating phase" of the repository.

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APPENDIX A

HYDROMETEOROLOGICAL DATA

Hydrometerological data summary for stations within and adjacent to the Columbia Plateau

County	Station	Latitude (degrees)	Longitude (degrees)	Elevation (feet MSL)	Average Annual Precipitation (inches)	Average Annual Actual Evap. 6-inch soil	Average Annual Potential Evapo-transpiration	Years of Record
Adams	Hatton 8E	46.77	118.67	1428.	9.94	9.9	25.8	30
Adams	Lind Exp. Stn.	47.00	118.58	1625.	10.11	10.0	27.2	30
Adams	Othello	46.83	119.17	1110.	8.16	8.2	26.7	19
Adams	Ritzville	47.12	118.37	1825.	11.67	11.7	25.6	30
Asotin	Alpowa Ranch	46.42	117.20	730.	10.82			10
Asotin	Anatone	46.13	117.13	3590.	22.10	15.6	22.3	30
Asotin	Clarkston Hts.	46.38	117.08	1185.	13.15	13.1	26.9	22
Benton	Hanford	46.58	119.38	385	6.39			12
Benton	Kennewick	46.22	119.13	392	7.49	7.5	29.1	30
Benton	Kennewick 10SW	46.13	119.30	1500	9.93			11
Benton	McNary Dam	45.95	119.30	348	7.64			13
Benton	Mottinger	45.93	119.15	307	8.34			26
Benton	Prosser	46.20	119.77	675	8.53			30
Benton	Prosser 4NE	46.25	119.75	840	7.77	7.8	26.8	30
Benton	Richland 25NNW	46.57	119.58	733	6.73			30
Chelan	Chelan Lakeside	47.83	120.03	1120	11.2	11.2	26.8	30
Chelan	Leavenworth 3S	47.57	120.67	1128	23.2	12.5	25.3	30
Chelan	Stehekin 3NW	48.33	120.70	1150	33.8	12.9	23.9	30
Chelan	Wenatchee	47.40	120.20	1229	8.8	8.9	27.2	30
Columbia	Dayton	46.32	117.98	1620	19.53	19.5	26.0	30
Columbia	Dayton 5NW	46.37	118.07	1710	17.32			10
Columbia	Dayton 9SE	46.13	117.85	2335	26.82			10
Columbia	Huntsville	46.30	118.12	1400	17.57			13
Columbia	Touchet Ridge	46.12	117.98	3600	36.63			13
Douglas	Chief Jos. Dm	48.00	119.50	810	9.72			12
Douglas	Mansfield	47.82	119.63	2265	11.26			30
Douglas	Waterville	47.65	120.07	2620	11.57	11.4	23.4	30
Franklin	Connell 12SE	46.73	118.93	1078	9.44			16
Franklin	Eltopia	46.48	119.17	895	8.47			11
Franklin	Kahlotus 4SW	46.60	118.60	1340	10.37			30
Franklin	Mesa 4W	46.60	119.08	875	7.72			11
Franklin	Pasco	46.22	119.10	360	7.40			20
Garfield	Peola	46.32	117.48	4000	20.09			28
Garfield	Pomeroy	46.47	117.62	1810	16.58	14.5	25.5	30
Garfield	Wawawai	46.65	117.40	695	18.74			30

Hydrometerological data summary for stations within and adjacent to the Columbia Plateau

County	Station	Latitude (degrees)	Longitude (degrees)	Elevation (feet MSL)	Average Annual Precipitation (inches)	Average Annual Actual Evap. 6-inch soil	Average Annual Potential Evapo-transpiration	Years of Record
Grant	Coulee Dm 1SW	47.95	119.00	1702	10.66			19
Grant	Hartline	47.68	119.10	1905	10.91	11.0	26.3	30
Grant	Moses Lake 3E	47.12	119.20	1208	8.10			13
Grant	Ruff 3SW	48.12	119.05	1440	9.62	9.6	26.4	38
Grant	Wahluke	46.65	119.72	416	6.36			14
Grant	Wilson Cr	47.42	119.12	1276	9.17	9.2	26.2	21
Klickitat	Bickleton	46.00	120.30	3000	12.63	11.3	24.3	30
Kootenai	Coeur d'Alene	47.68	116.75	2160	26.13			30
Latah	Moscow	46.73	117.00	2628	22.21			30
Latah	Potlach	46.92	116.88	2550	24.49			30
Lewis	Winchester	46.23	116.60	3950	24.16			15
Lincoln	Davenport	47.65	118.15	2450	16.72	13.9	23.6	30
Lincoln	Harrington 5S	47.42	118.25	2167	12.94			30
Lincoln	Odessa	47.33	118.67	1540	10.81	10.8	25.5	30
Lincoln	Sprague	47.30	117.98	1925	14.70	13.3	25.2	30
Lincoln	Wilbur	47.75	118.70	2163	12.93	12.5	23.9	30
NezPerce	Lewiston	46.38	117.02	733	13.85			27
NezPerce	Lewiston WBAS	46.38	117.02	1431	13.24			30
Okanogan	Conconully	48.57	119.75	2275	14.9	13.6	23.3	30
Okanogan	Nespelem 2S	48.13	118.98	1890	13.3	13.2	24.9	30
Okanogan	Omak 2NW	48.43	119.53	1228	11.3	11.3	25.7	15
Okanogan	Stockdill Ranch	48.37	120.35	2200	19.0	12.2	21.1	30
Okanogan	Winthrop 1WSW	48.47	120.18	1755	14.5	11.9	23.7	30
Pend Or.	Newport	48.18	117.05	2135	27.16	15.6	22.6	30
Spokane	Cheney	47.48	117.58	2400	19.32			18
Spokane	Deer Park 2E	47.95	117.43	2144	22.03	14.2	23.0	30
Spokane	Mt. Spokane	47.92	117.12	5890	47.57			08
Stevens	Wellpinit	47.88	117.98	2450	20.17			30
Umatilla	Mil Freewtr 4NW	45.97	118.43	962	14.14			30
Umatilla	Walla Wa 13ESE	46.00	118.05	2400	42.91			21
Walla Wa	Attalia	46.10	118.95	360	6.87			10
Walla Wa	Dixie 4SE	46.10	118.10	2350	26.93			26
Walla Wa	Mill Cr.	46.02	118.12	2000	39.56			30
Walla Wa	Mill Cr. Dam	46.07	118.16	1275	17.61			13
Walla Wa	Pleasant View	46.52	118.33	1650	12.39			25
Walla Wa	Touchet	46.03	118.67	443	9.83			10

Hydrometerological data summary for stations within and adjacent to the Columbia Plateau

County	Station	Latitude (degrees)	Longitude (degrees)	Elevation (feet MSL)	Average Annual Precipitation (inches)	Average Annual Actual Evap. 6-inch soil	Average Annual Potential Evapo-transpiration	Years of Record
Walla Wa	Walla Walla FAA	46.10	118.28	1185	18.43			12
Walla Wa	Walla Walla 3W	46.05	118.40	800	15.33	13.9	28.4	18
Walla Wa	Walla Walla WBO	46.03	118.20	949	15.50			30
Whitman	Colfax 1NW	46.88	117.38	1955	20.97	15.4	24.9	30
Whitman	Ewan	47.12	117.73	1720	16.32			21
Whitman	LaCrosse 3ESE	46.80	117.82	1546	14.05	13.1	25.5	30
Whitman	Pullman 2NW	46.77	117.20	2545	20.49	14.8	24.6	30
Whitman	Rosalia	46.23	117.37	2400	18.31	14.7	24.5	30
Whitman	Tekoa	47.22	117.08	2610	22.32			22
Yakima	Rattlesnake Mt.	46.38	119.72	2800	13.27			6

APPENDIX B

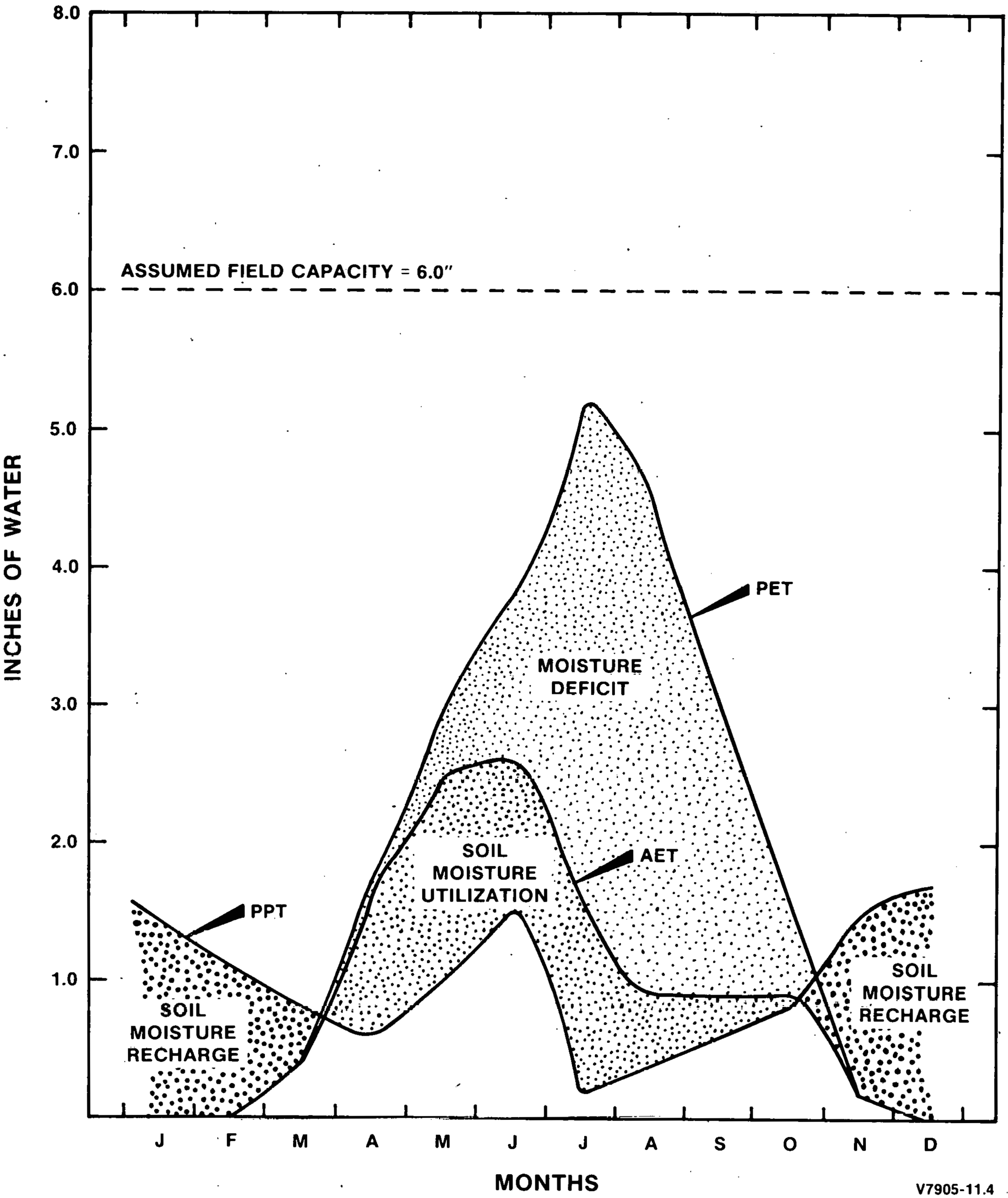
WATER BALANCE PLOTS

EXPLANATIONS

PPT = Precipitation

AET = Actual evapotranspiration

PET = Potential Evapotranspiration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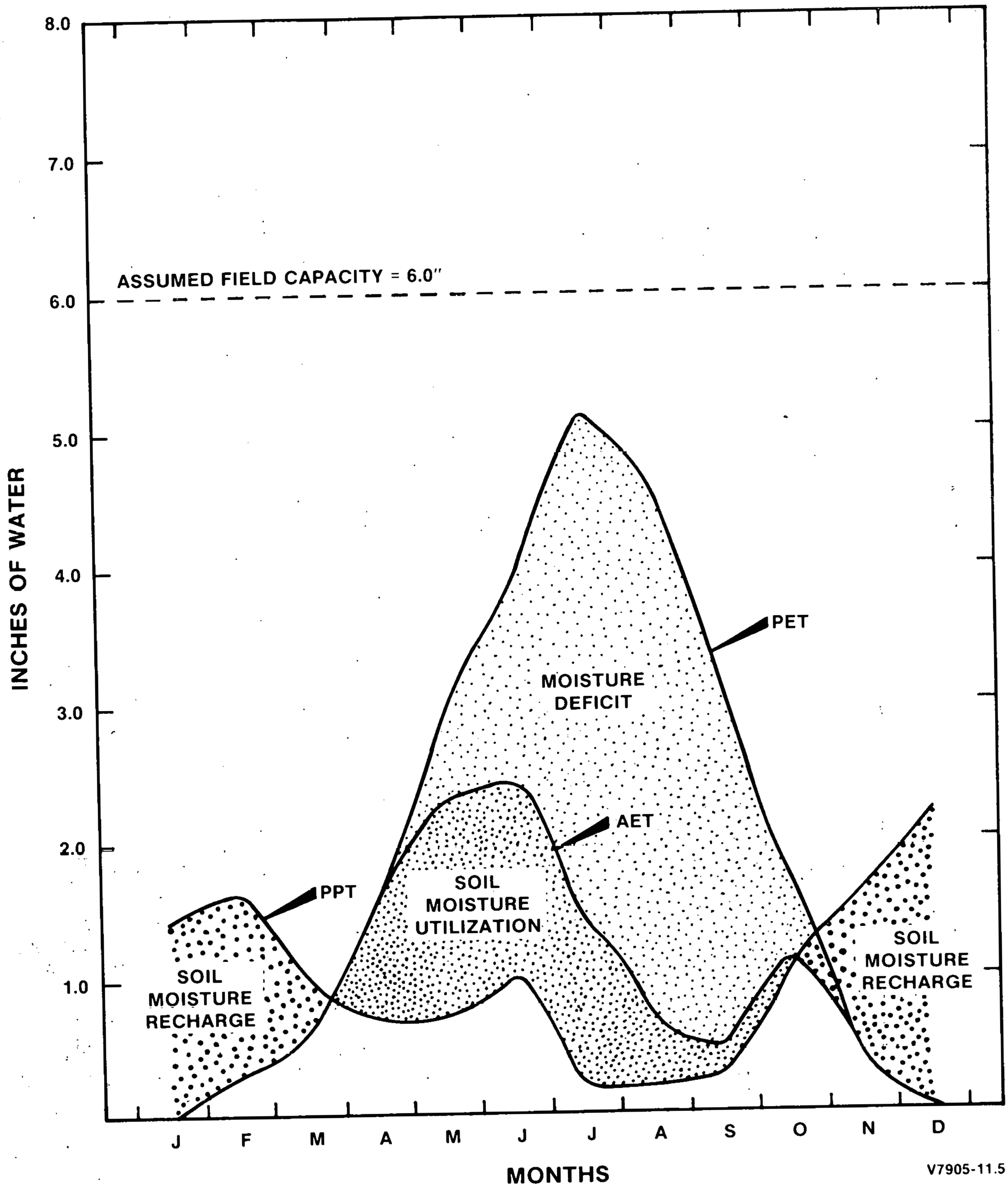
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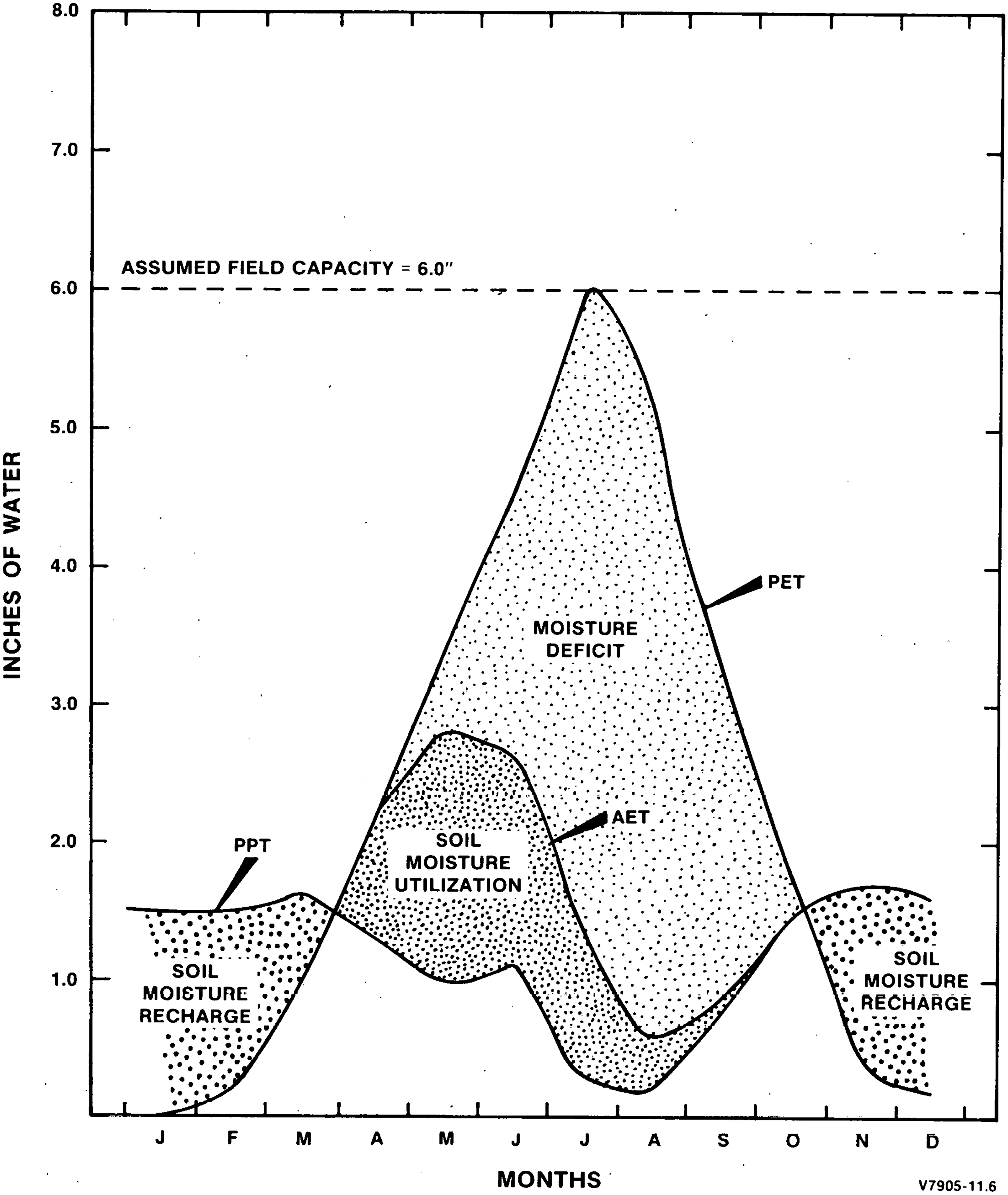
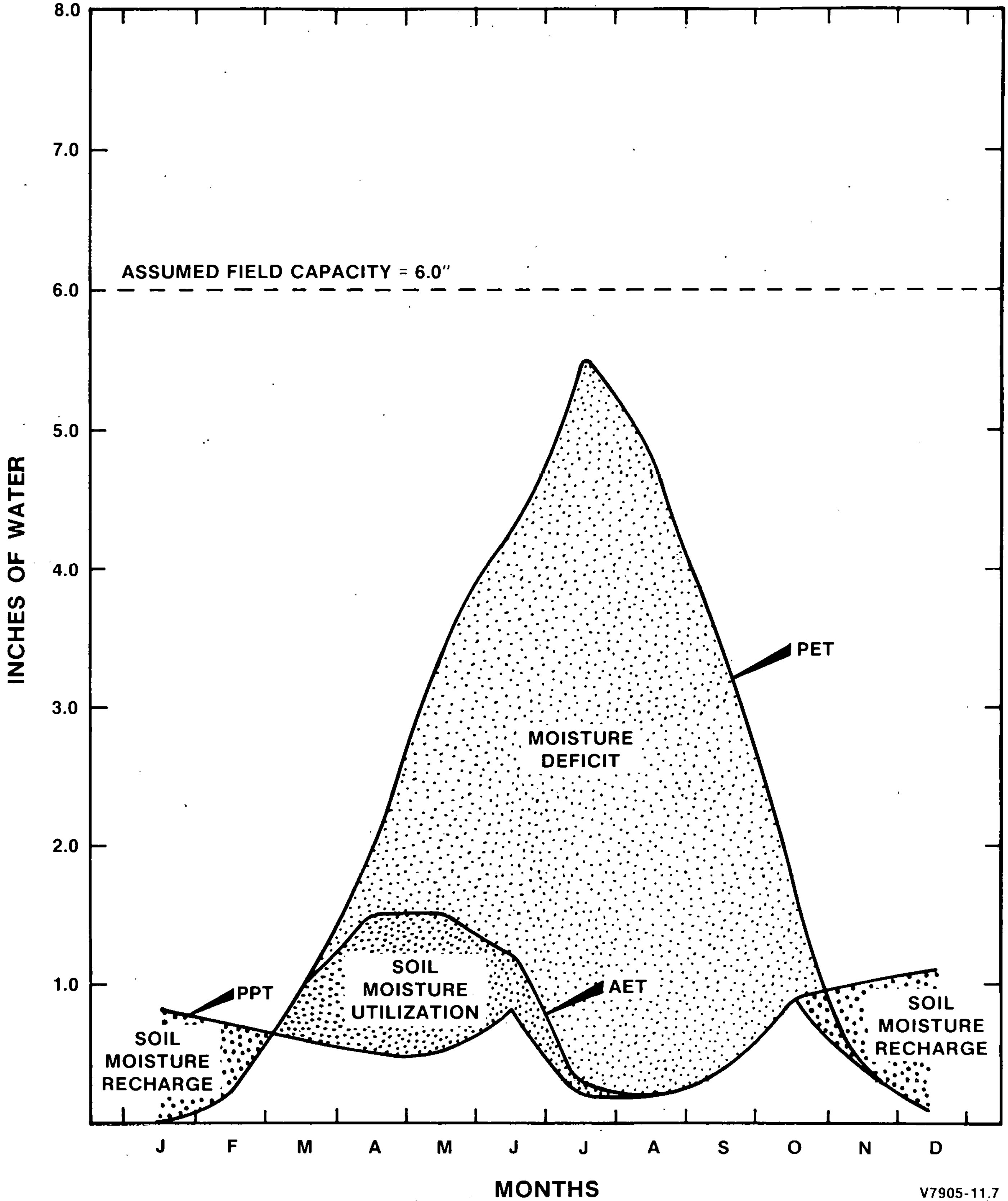
Bickleton



Walla Walla 3W



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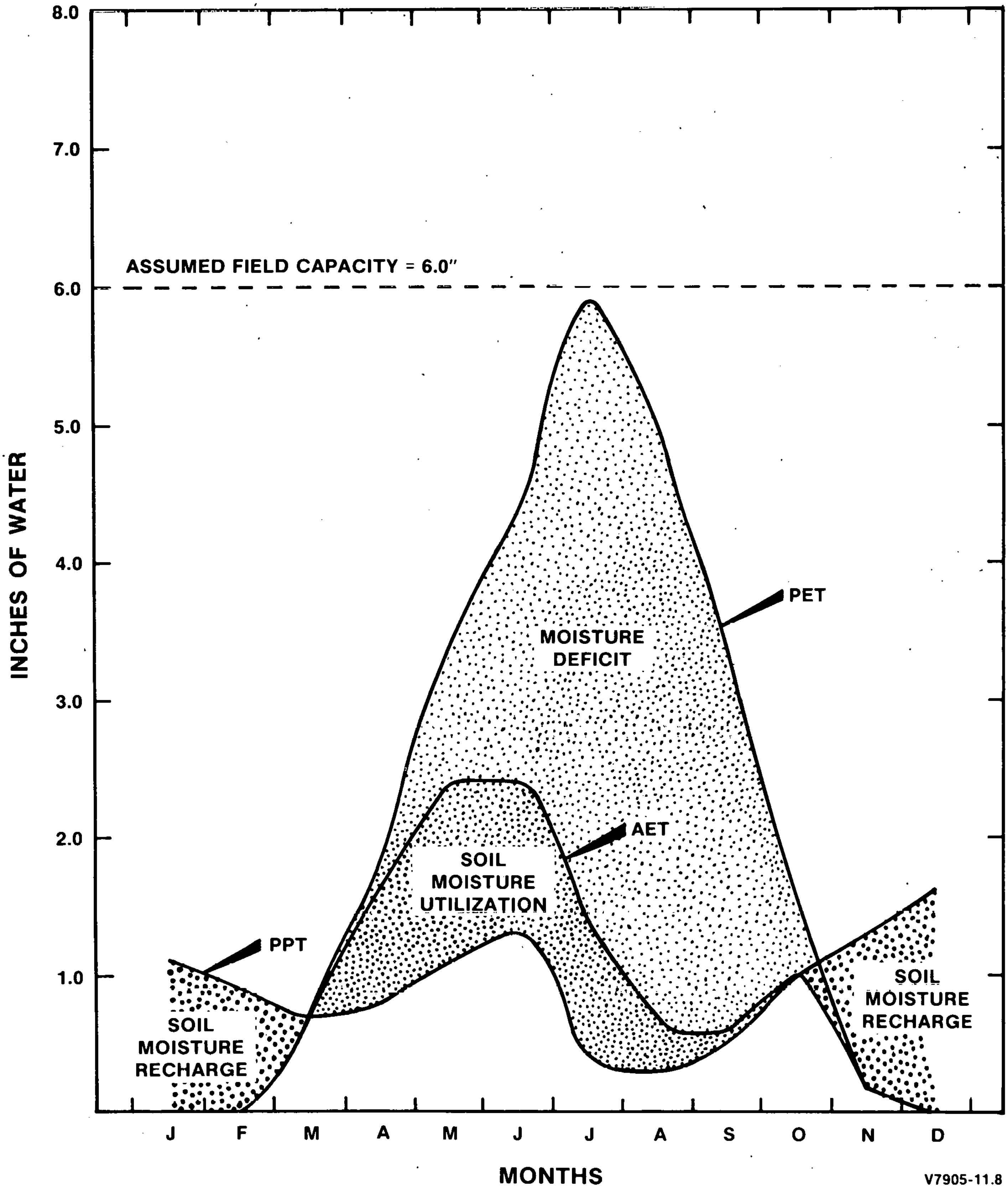
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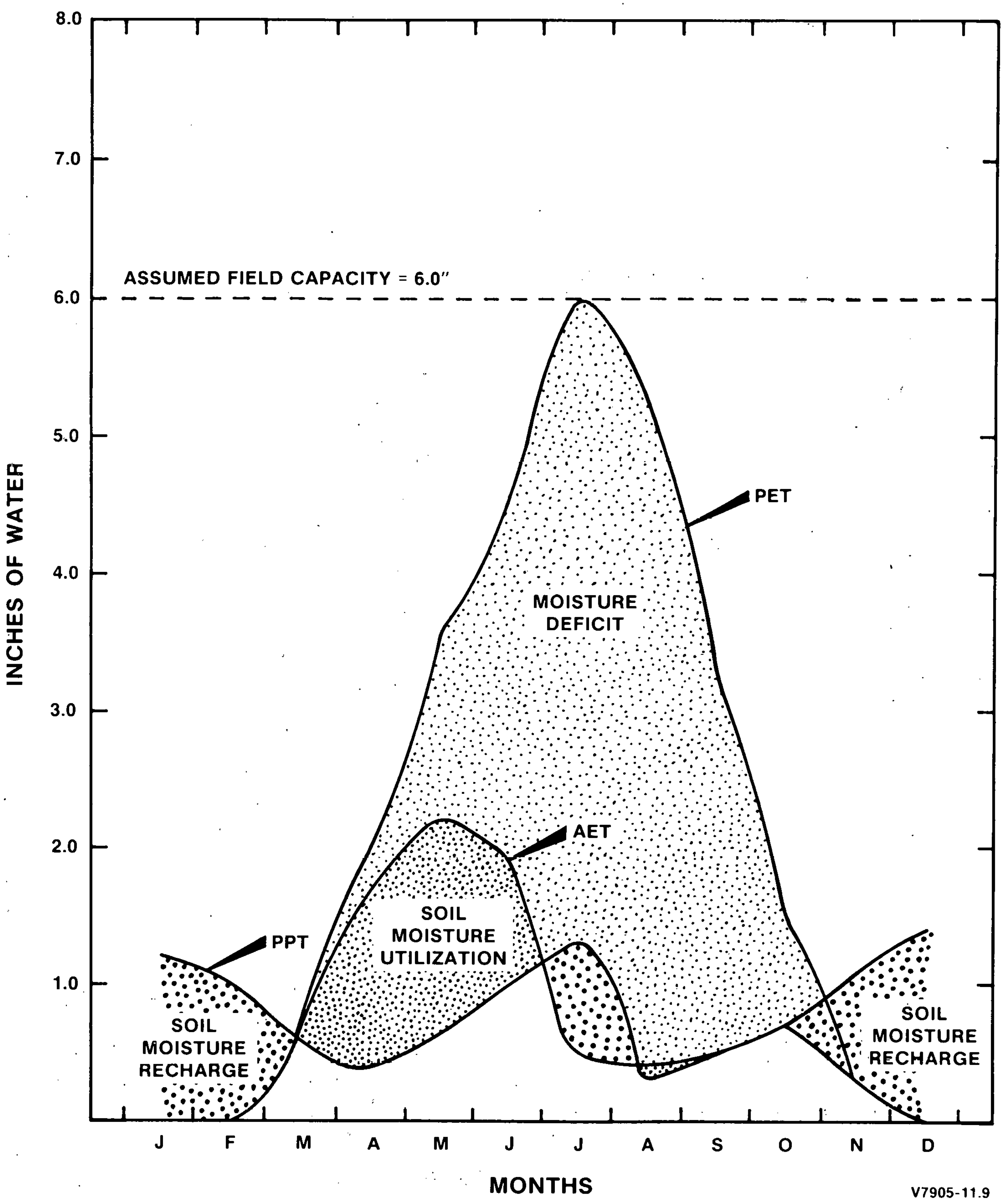
Hartline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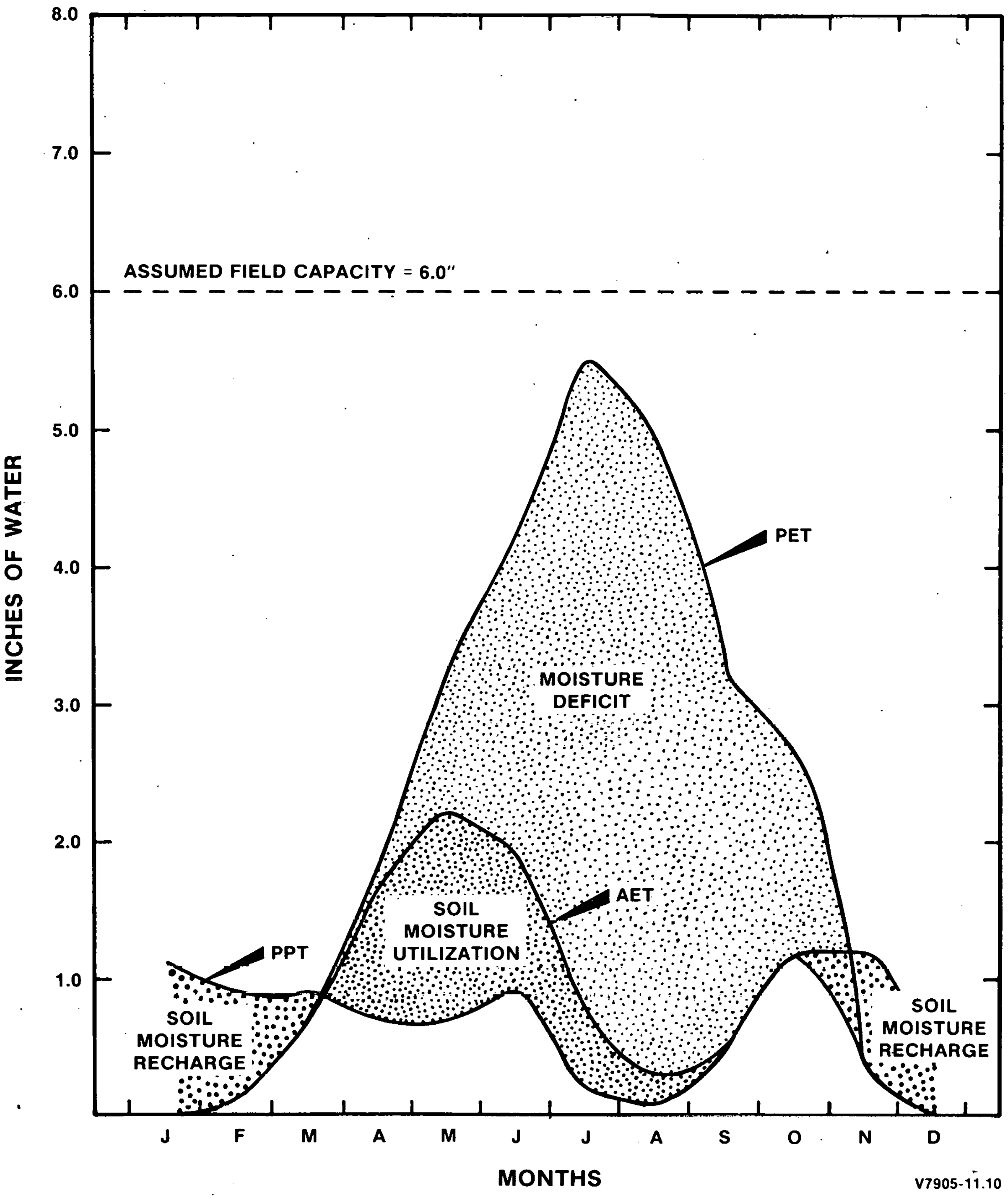
Wenatchee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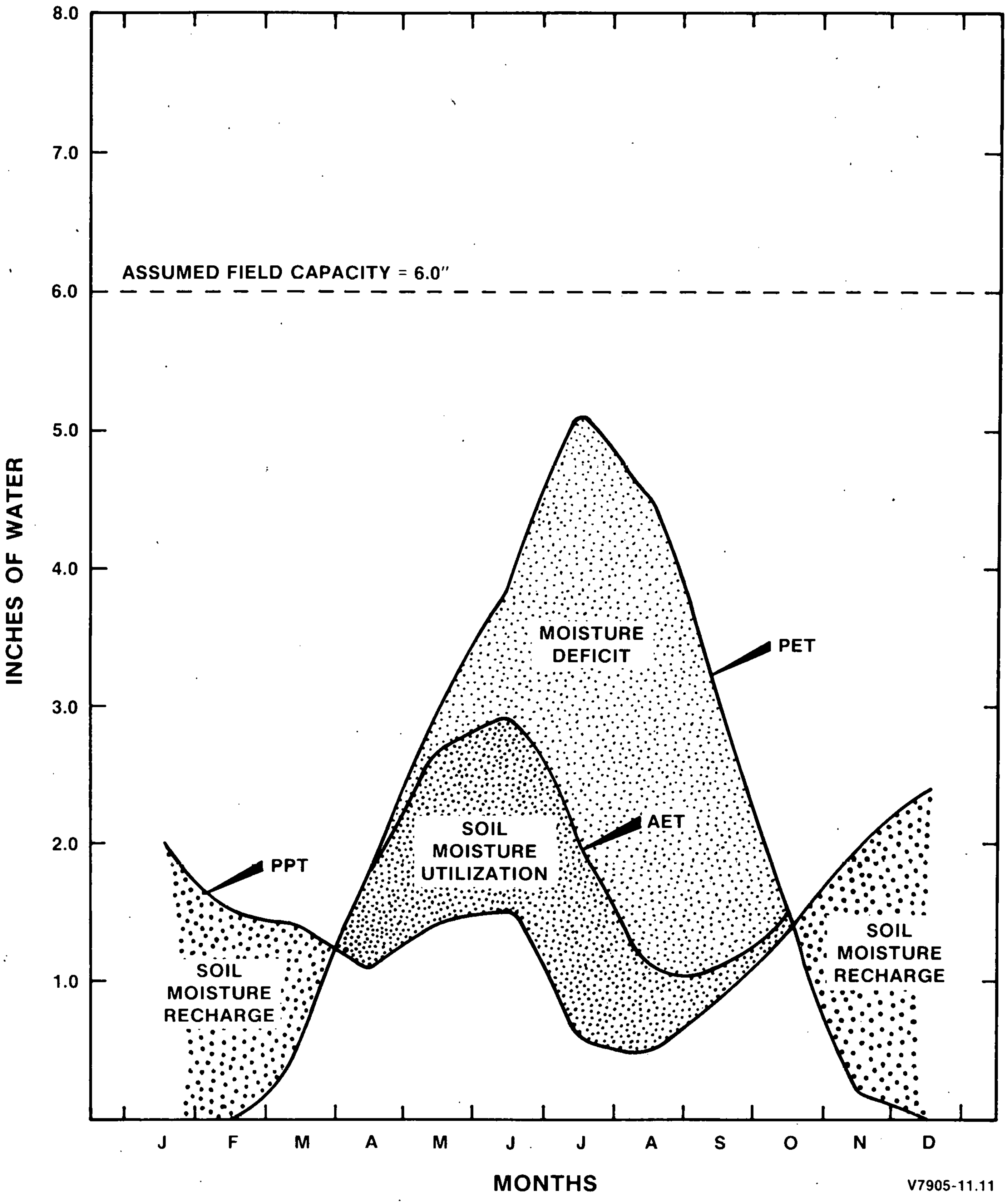
Hatton 8E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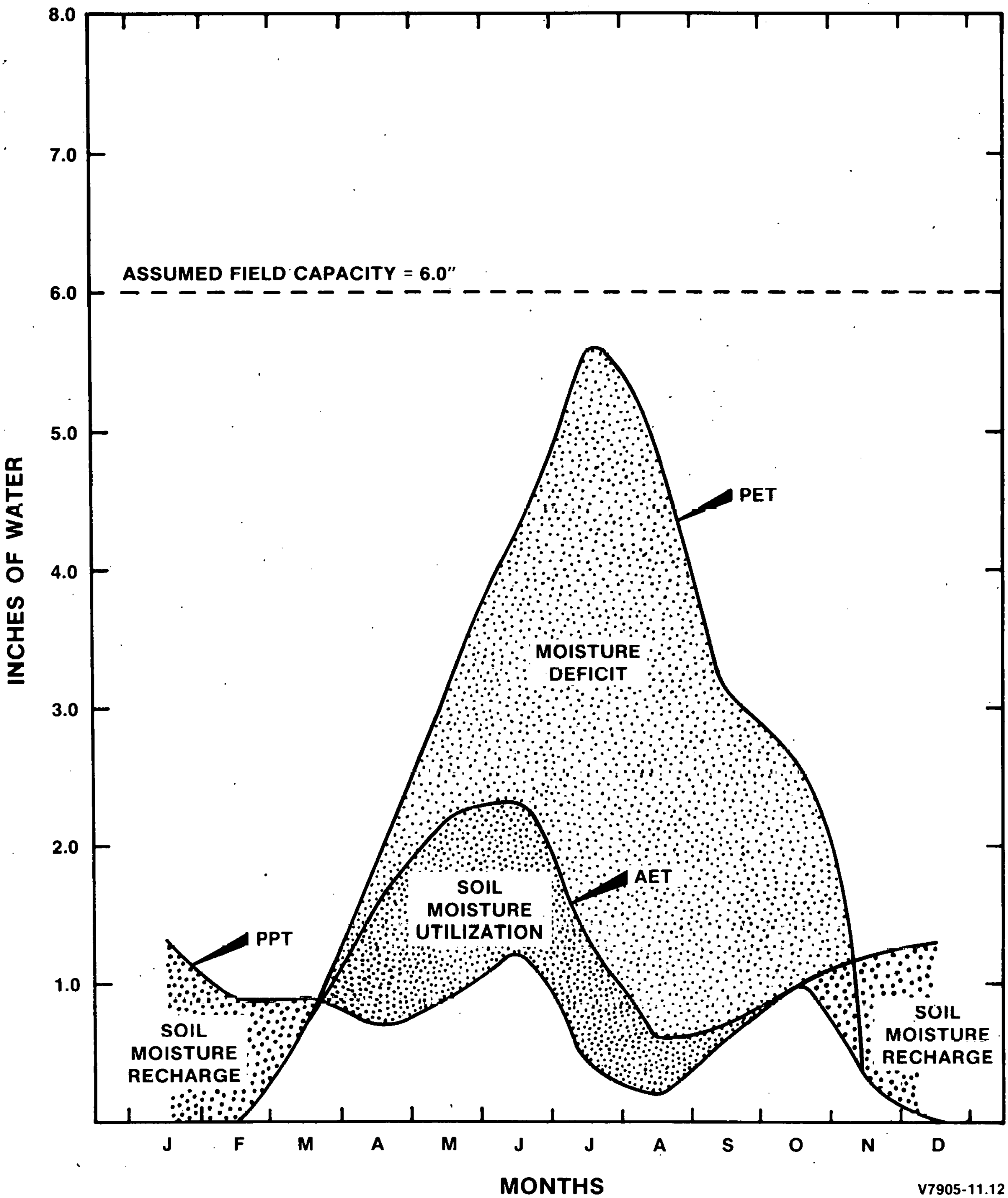
Davenport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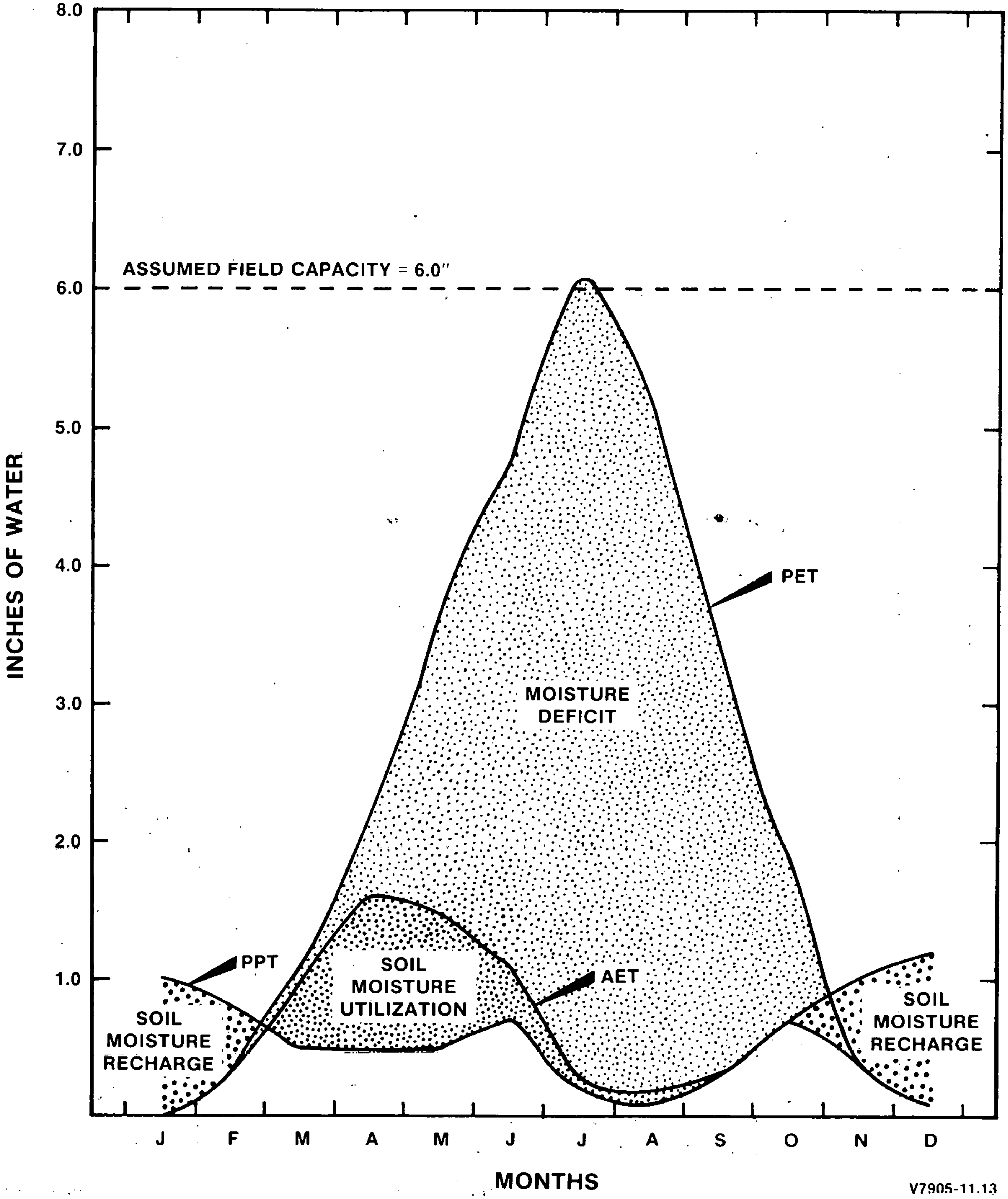
Odessa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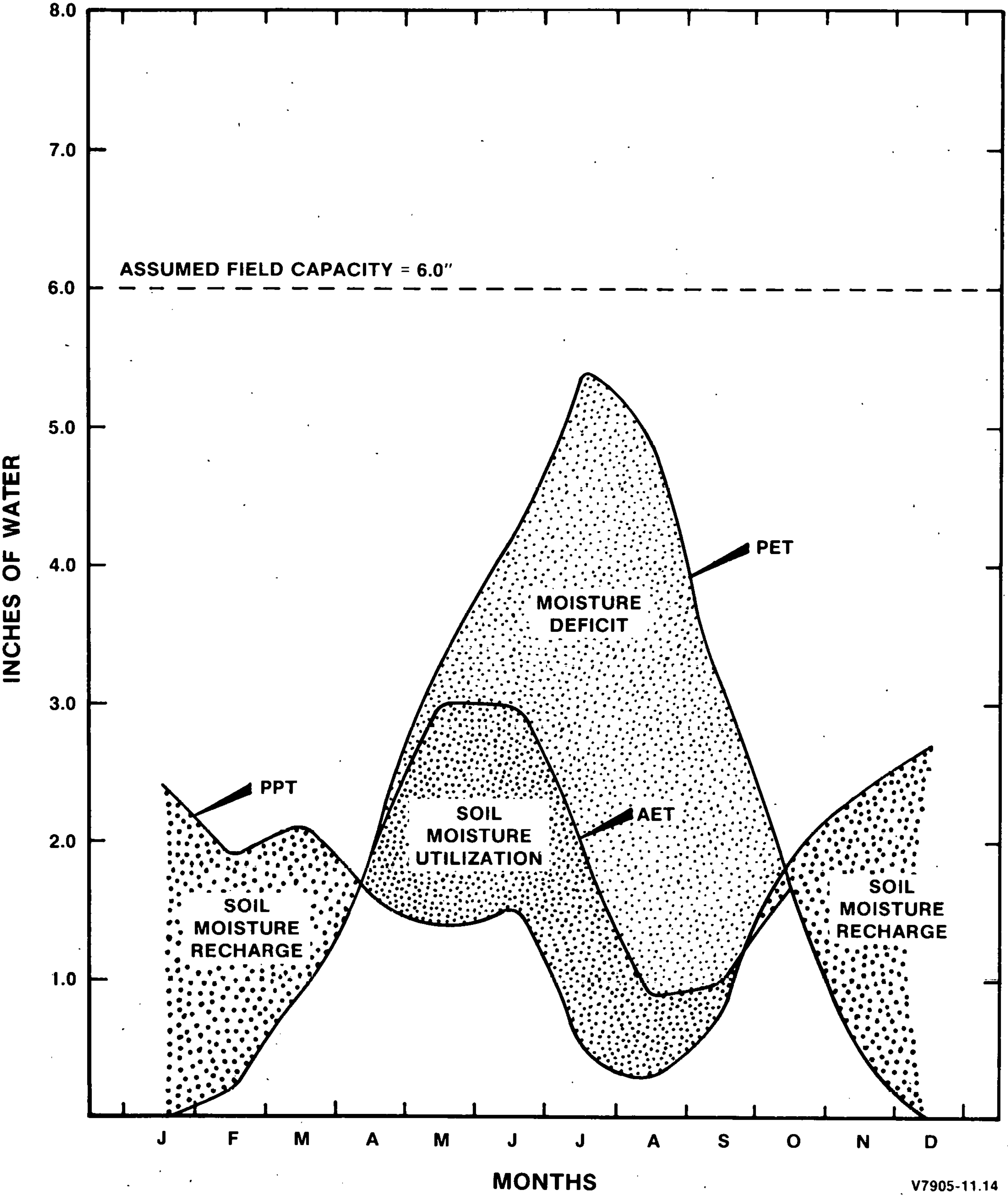
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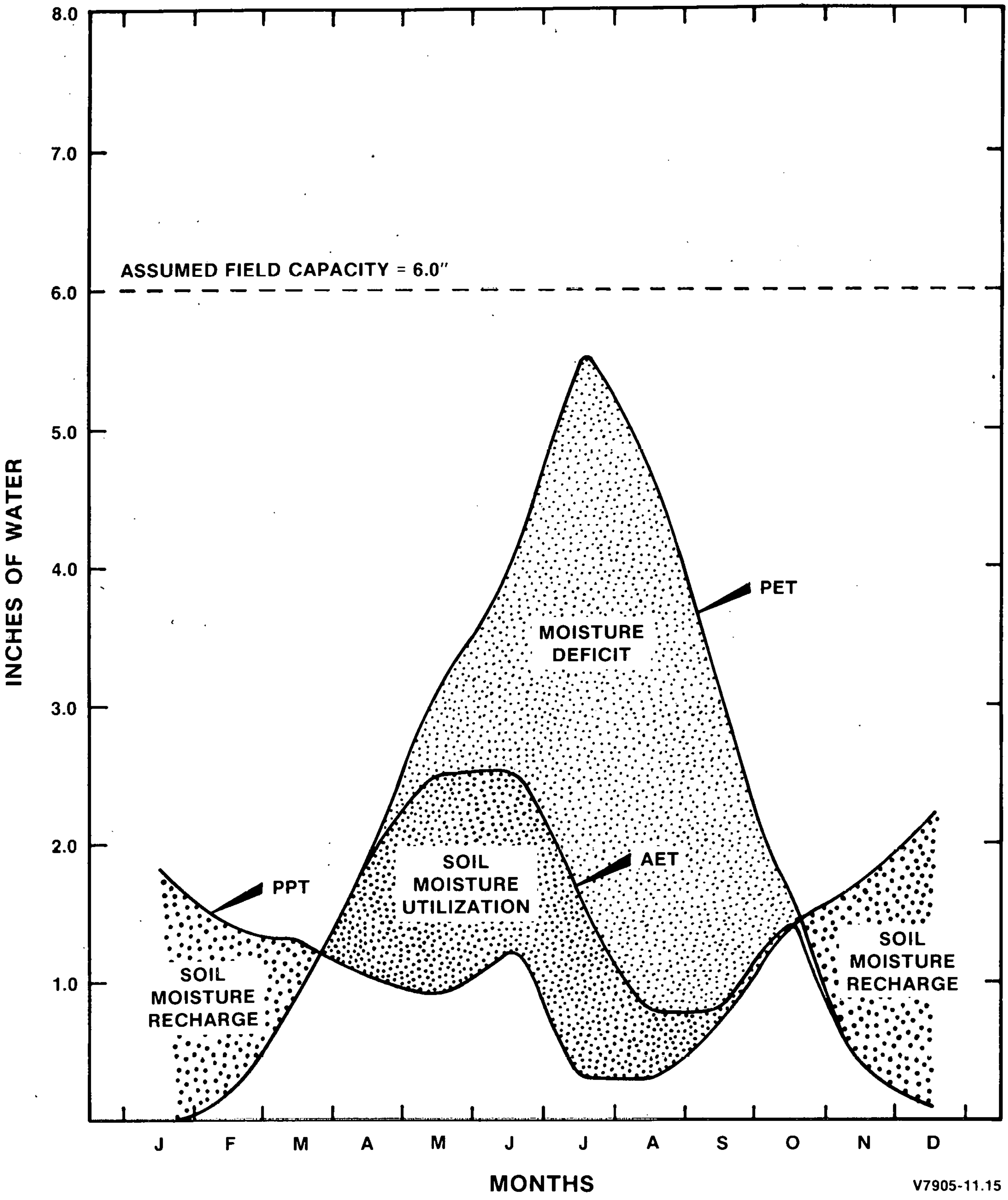
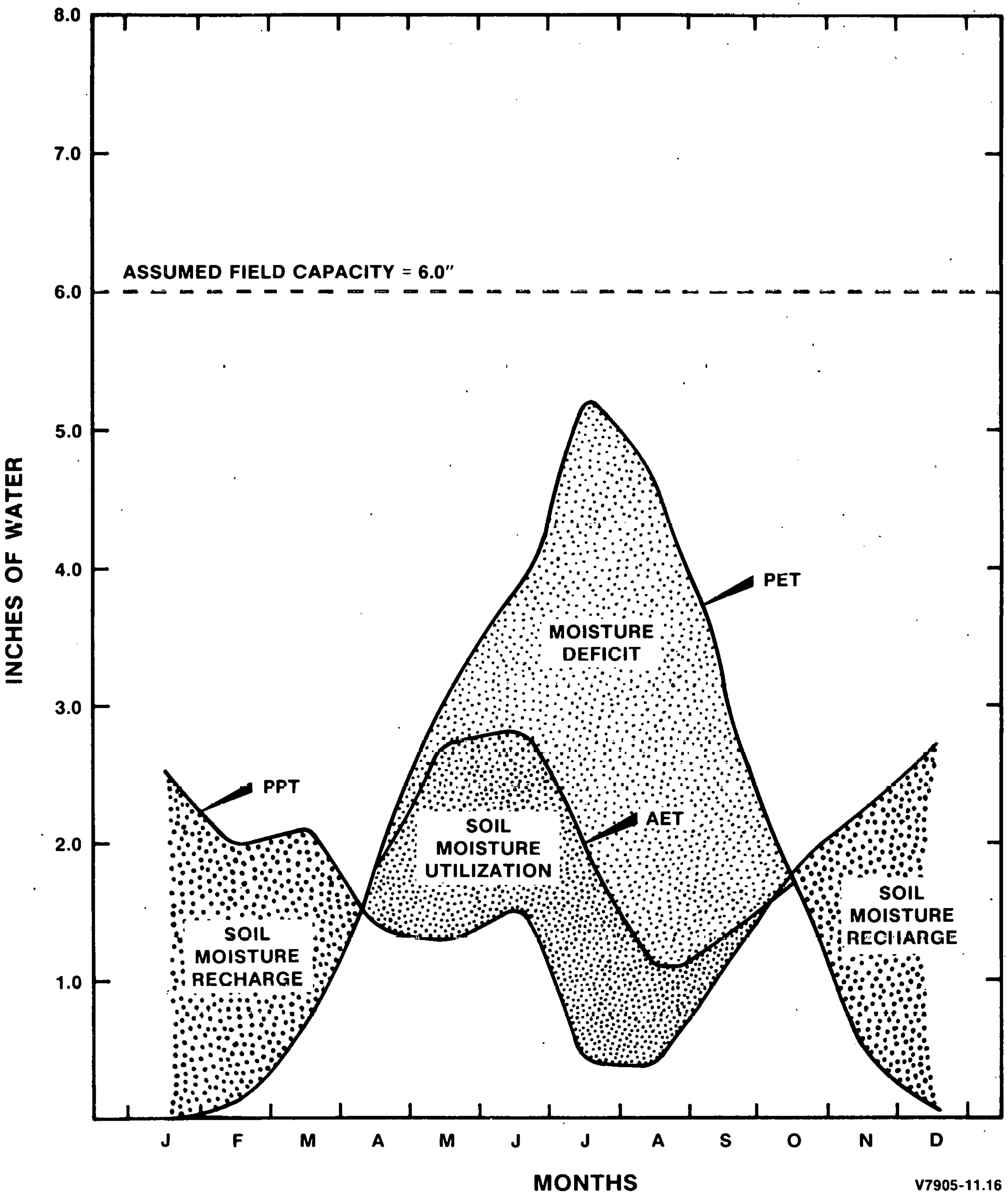
Dayton



LaCrosse 3ESE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Pullman 2NW

APPENDIX C

COLUMBIA BASIN IRRIGATION PROJECT
1977 WATER DISTRIBUTION

Form 7-322 (July 1960)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MONTHLY WATER DISTRIBUTION

Project Columbia Basin (Excluding Blocks 2 & 3) Area Irrigated 529,858 Acres (d) Year 1977

QUANTITIES IN ACRE-FEET

MONTH	Diverted from Stream 1	Inflow from Reservoirs and other sources	Delivered to Reservoirs 2	Net Supply 3	Main Canal Waste *	Main Canal Losses	Delivered to Laterals a	Lateral Waste	Lateral Losses	Non-Irrigation Deliveries b	DELIVERED TO FARMS c Total	Per Acre
January,	0	2,280	1,590	690	0	690	0	0	0	0	0	0
February,	4,480	3,510	1,990	6,000	0	6,000[4]	0	0	-60	0	60	0
March,	215,290	6,570	92,710	129,150	8,540	54,210[4]	66,390	11,450	16,740	30	38,170	0.07
April,	581,500	17,950	133,390	466,060	9,960	74,370	381,720	29,410	53,690	210	298,420	0.56
May,	471,920	22,220	31,460	462,680	11,380	54,490	396,810	34,490	63,840	290	298,190	0.56
June,	551,020	28,500	12,470	567,050	8,710	60,070	498,270	27,610	83,570	340	386,750	0.73
July,	629,150	29,040	5,830	652,360	9,090	67,820	575,450	28,680	57,460	400	488,910	0.92
August,	606,190	30,280	32,700	603,770	11,530	62,600	529,640	32,670	56,310	390	440,270	0.83
September,	273,150	26,720	28,320	271,550	9,600	23,150	238,800	34,490	47,020	220	157,070	0.30
October,	105,860	26,030	11,630	120,260	7,610	13,880[5]	98,770	21,180	21,960	90	55,540	0.11
November,	0	8,800	2,610	6,190	450	5,740[5]	0	0	0	0	0	0
December,	0	2,510	170	2,340	0	2,340	0	0	0	0	0	0
Total,	3,438,560	204,410	354,870[6]	3,288,100	76,870	425,360	2,785,860	219,980	400,530	1,970	2,163,380	4.08
Acre ft. per acre,	6.49	0.39	0.67	6.21	0.14	0.80	5.26	0.42	0.76	0.00	4.08	
Per cent Net Supply,	104.6	6.2	10.8	100.0	2.3	12.9	84.7	6.7	12.2	0.1	65.8	

1 Diversion amount from Banks Lake and Potholes Reservoir.
2 Reservoirs connected with distributing system only.
3 Diversions plus inflow from reservoirs and other sources less delivery to reservoirs.
4 Includes filling canal system.
5 Includes dewatering canal system.
6 Includes 267,050 A.F. feed to Potholes Reservoir or Potholes Canal system.

a Measured at Head of Lateral
b P.T. Farm Units - 1710 A.F., M & I - 260 A.F.
c Measured at Farm Turnout
d Includes 23,134 acres in water service contracts
* Lost to Project

412, 5-19-78
Page 1 of 6

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RHO-BWI-ST-6

Form 7-322 (July 1960)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MONTHLY WATER DISTRIBUTION

Project Main Canal (Banks Lake to Bifurcation) Area Irrigated 924 Acres Year 1977

QUANTITIES IN ACRE-FEET

153

MONTH	Diverted from Stream [1]	Inflow from Reservoirs and other sources	Delivered to Reservoirs [2]	Net Supply [3]	Main Canal Waste	Main Canal Losses	Delivered to Laterals [a]	Lateral Waste	Lateral Losses	Non-Irrigation Deliveries [b]	DELIVERED TO FARMS [c]	
											Total	Per Acre
January,	0	90	0	90	0	90	0	0	0	0	0	0
February,	0	0	0	0	0	0	0	0	0	0	0	0
March,	166,750	0	156,000	10,750[4]	0	10,630	120	0	40	0	80	0.09
April,	446,130	0	421,280	24,850	0	24,070	780	0	100	0	680	0.74
May,	350,370	0	334,580[5]	15,790	0	14,910	880	0	60	0	820	0.89
June,	390,850	2,210	375,210[5]	17,850	0	17,010	840	0	90	0	750	0.81
July,	455,670	320	436,630	19,360	0	18,460	900	0	100	0	800	0.86
August,	449,100	2,460	440,810	10,750	0	9,940	810	0	100	0	710	0.77
September,	207,650	2,890	218,510	-7,970	0	-8,300	330	0	40	0	290	0.31
October,	65,100	11,330	82,770	-6,340	0	-6,390	50	0	0	0	50	0.05
November,	0	2,180	1,710	470	0	470	0	0	0	0	0	0
December,	0	0	0	0	0	0	0	0	0	0	0	0
Total,	2,531,620	21,480	2,467,500[5]	85,600	0	80,890	4,710	0	530	0	4,180	4.52
Acre ft. per acre,				92.64		87.54	5.10		0.57		4.52	
Per cent Net Supply,				100.0		94.5	5.5		0.6		4.9	

RHO-BWI-ST-6

1 Diversion amount from Banks Lake.
2 Reservoirs connected with distributing system only (Billy Clapp Lake plus diversions to East Low and West Canals.)
3 Diversions plus inflow from reservoirs and other sources less delivery to reservoirs.
4 Includes filling canal system.
5 Includes 3,650 A.F. for diversion to Brook Lake for drought relief.

a Measured at Head of Lateral
b -0
c Measured at Farm Turnout

Form 7-322 (July 1960)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MONTHLY WATER DISTRIBUTION

Project West Canal Area Irrigated 213,410 Acres (d) Year 1977

QUANTITIES IN ACRE-FEET

MONTH	Diverted from Stream 1	Inflow from Reservoirs and other sources	Delivered to Reservoirs 2	Net Supply 3	Main Canal Waste *	Main Canal Losses	Delivered to Laterals a	Lateral Waste	Lateral Losses	Non-Irrigation Deliveries b	DELIVERED TO FARMS c	
											Total	Per Acre
January,	0	1,140	0	1,140	0	1,140	0	0	0	0	0	0
February,	0	2,390	0	2,390	0	2,390	0	0	-60	0	60	0
March,	61,730	2,820	20,370	44,180	1,330	12,250[4]	30,550	5,620	9,530	20	15,380	0.07
April,	207,970	3,090	29,150	181,910	3,100	9,340	169,470	12,240	28,040	120	129,070	0.60
May,	188,410	5,770	6,170	188,010	3,650	9,580	174,770	14,520	28,730	130	131,390	0.61
June,	214,690	6,290	3,320	217,660	3,010	10,900	203,750	11,690	40,510	140	151,410	0.71
July,	256,150	6,260	3,370	259,040	3,010	12,110	243,920	12,800	24,720	180	206,220	0.97
August,	248,990	5,360	5,920	248,430	4,320	20,200	223,910	15,090	23,130	180	185,510	0.87
September,	119,510	4,960	5,210	119,260	2,780	15,420	101,060	16,490	16,960	80	67,530	0.32
October,	40,360	2,350	2,550	40,160	1,560	6,510[5]	32,090	9,490	8,170	40	14,390	0.07
November,	0	1,430	0	1,430	0	1,430	0	0	0	0	0	0
December,	0	1,470	0	1,470	0	1,470	0	0	0	0	0	0
Total,	1,337,810	43,330	76,060[6]	1,305,080	22,820	102,740	1,179,520	97,940	179,730	890	900,960	4.22
Acre ft. per acre,	6.27	0.20	0.36	6.12	0.11	0.48	5.53	0.46	0.84	0.0	4.22	
Per cent Net Supply,	102.5	3.3	5.8	100.0	1.7	7.9	90.4	7.5	13.8	0.1	69.0	

1 Diversion amount to West Canal at Bifurcation
2 Reservoirs connected with distributing system only, (thru Winchester & Frenchman Wasteways.)
3 Diversion plus inflow from reservoirs and other sources less delivery to reservoirs.
4 Includes filling canal system.
5 Includes dewatering canal system.
6 Includes 49,810 A.F. feed to Potholes Reservoir.

a Measured at Head of Lateral
b P.T. Farm Units - 740 A.F., M & I - 150 A.F.
c Measured at Farm Turnout
d Includes 6,079 acres in water service contracts
* Lost to Project

412, 5-19-78

Form 7-322 (July 1960)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MONTHLY WATER DISTRIBUTION

Project East Low Canal Area Irrigated 127,989 Acres (d) Year 1977

QUANTITIES IN ACRE-FEET

MONTH	Diverted from Stream 1	Inflow from Reservoirs and other sources	Delivered to Reservoirs 2	Net Supply 3	Main Canal Waste	Main Canal Losses	Delivered to Laterals a	Lateral Waste	Lateral Losses	Non-Irrigation Deliveries b	DELIVERED TO FARMS c Total	Per Acre
January,	0	0	0	0	0	0	0	0	0	0	0	0
February,	0	0	0	0	0	0	0	0	0	0	0	0
March,	75,150	0	51,010	24,130	0	14,510[4]	9,620	2,170	3,470	10	3,970	0.03
April,	212,250	0	102,110	110,140	0	20,290	89,850	8,720	20,570	80	60,480	0.47
May,	144,140	0	23,260	120,880	0	12,110	108,770	9,940	27,450	150	71,230	0.56
June,	158,700	0	7,200	151,500	0	5,950	145,550	7,740	40,090	180	97,540	0.76
July,	180,480	0	2,460	178,020	0	14,690	163,330	7,110	31,820	190	124,210	0.97
August,	191,820	0	25,970	165,850	0	13,660	152,190	8,500	31,540	190	111,960	0.87
September,	99,000	0	23,110	75,890	0	9,460	66,430	9,460	20,020	130	36,820	0.29
October,	42,410	0	9,080	33,330	0	8,400[5]	24,930	6,260	10,000	50	8,620	0.07
November,	1,710	0	2,610	-900	0	-900	0	0	0	0	0	0
December,	0	0	10	-10	0	-10	0	0	0	0	0	0
Total,	1,105,660	0	246,820[6]	858,830	0	98,160	760,670	59,900	184,960	980	514,830	4.02
Acre ft. per acre,	8.64	0	1.93	6.71	0	0.77	5.94	0.47	1.45	0.01	4.02	
Per cent Net Supply,	128.7	0	28.7	100.0	0	11.4	88.6	7.0	21.5	0.1	59.9	

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1 Diversion amount to East Low Canal at Bifurcation.
2 Reservoirs connected with distributing system only (Potholes Reservoir & Scooteney Reservoir.)
3 Diversions plus inflow from reservoirs and other sources less delivery to reservoirs.
4 Includes filling canal system.
5 Includes dewatering canal system.
6 Includes 217,240 A.F. feed to Potholes Reservoir or Potholes Canal system.

a Measured at Head of Lateral
b P.T. Farm Units - 880 A.F., M & I - 100 A.F.
c Measured at Farm Turnout
d Includes 3,984 acres in water service contracts

Form 7-322 (July 1960)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MONTHLY WATER DISTRIBUTION

Project Potholes Canal Area Irrigated 187,535 Acres (d) Year 1977

QUANTITIES IN ACRE-FEET

MONTH	Diverted from Stream 1	Inflow from Reservoirs and other sources	Delivered to Reservoirs 2	Net Supply 3	Main Canal Waste *	Main Canal Losses	Delivered to Laterals a	Lateral Waste	Lateral Losses	Non-Irrigation Deliveries b	DELIVERED TO FARMS c Total	Per Acre
January,	0	1,050	1,590	-540	0	-540	0	0	0	0	0	0
February,	4,480	1,120	1,990	3,610	0	-3,610[4]	0	0	0	0	0	0
March,	48,540	3,380	2,210	49,710	7,160	16,820[4]	26,100	3,660	3,770	0	18,740	0.10
April,	135,370	13,410	1,070	147,710	6,860	20,670	121,630	8,450	4,980	10	108,190	0.58
May,	121,550	15,290	0	136,840	7,720	17,890	112,390	10,030	7,600	10	94,750	0.50
June,	160,170	16,340	130	176,380	5,700	26,210	148,130	8,180	2,880	20	137,050	0.73
July,	173,480	17,400	0	190,880	6,080	22,560	167,300	8,770	820	30	157,680	0.84
August,	157,090	19,020	810	175,300	7,210	18,800	152,730	9,080	1,540	20	142,090	0.76
September,	65,500	17,890	0	83,390	6,820	6,570	70,980	8,540	10,000	10	52,430	0.28
October,	40,760	11,810	0	52,570	6,050	5,360[5]	41,700	5,430	3,790	0	32,480	0.17
November,	0	5,190	0	5,190	450	4,740[5]	0	0	0	0	0	0
December,	0	1,040	160	880	0	880	0	0	0	0	0	0
Total,	906,940	122,940	7,960	1,021,920[6]	54,050	143,570	840,960	62,140	35,310	100	743,410	3.96
Acre ft. per acre,	4.84	0.66	0.04	5.45	0.29	0.77	4.48	0.33	0.19	0.0	3.96	
Per cent Net Supply,	88.7	12.0	0.8	100.0	5.3	14.0	82.3	6.1	3.5	0.0	72.7	

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RHO-BWI-ST-6

1 Diversion amount from Potholes Reservoir
2 Reservoirs connected with distributing system only. (Scooteney Reservoir)
3 Diversion plus inflow from reservoirs and other sources less delivery to reservoirs.
4 Includes filling canal system.
5 Includes dewatering canal system.
6 Includes 5,220 A.F. feed to Potholes Canal system.

a Measured at Head of Lateral
b P.T. Farm Units - 90 A.F., M & I - 10 A.F.
c Measured at Farm Turnout
d Includes 13,071 acres in water service contracts
* Lost to Project

Form 7-322 (July 1960)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MONTHLY WATER DISTRIBUTION

Project Columbia Basin (Blocks 2 & 3) Area Irrigated 4,114 Acres Year 1977

QUANTITIES IN ACRE-FEET

MONTH	Diverted from Stream 1	Inflow from Reservoirs and other sources	Delivered to Reservoirs 2	Net Supply 3	Main Canal Waste	Main Canal Losses	Delivered to Laterals a	Lateral Waste	Lateral Losses	Non-Irrigation Deliveries b	DELIVERED TO FARMS c Total	Per Acre
January,	0			0			0	0	0	0	0	0
February,	0			0			0	0	0	0	0	0
March,	1,220			1,220			1,220	240	210	20	750	0.18
April,	3,720			3,720			3,720	470	280	90	2,880	0.70
May,	3,530			3,530			3,530	560	180	90	2,700	0.66
June,	4,510			4,510			4,510	590	310	110	3,500	0.85
July,	4,910			4,910			4,910	570	440	120	3,780	0.92
August,	4,290			4,290			4,290	670	300	100	3,220	0.78
September,	2,310			2,310			2,310	530	140	60	1,580	0.38
October,	720			720			720	270	60	30	360	0.09
November,	0			0			0	0	0	0	0	0
December,	0			0			0	0	0	0	0	0
Total,	25,210			25,210			25,210	3,900	1,920	620	18,770	4.56
Acre ft. per acre,	6.13			6.13			6.13	0.95	0.47	0.15	4.56	
Per cent Net Supply,	100.0			100.0			100.0	15.5	7.6	2.5	74.5	

1 Diversion amount from Snake and Columbia Rivers at Burbank

a Measured at Head of Lateral
b P.T. Farm Units - 620 A.F., M & I - 0
c Measured at Farm Turnouts

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APPENDIX D

STREAM REACH INVENTORIES

COLUMBIA RIVER

PRIMARY DRAINAGE	STATION	MILE	GAUGED FLOW (AF/YR)	YEARS OF RECORD	KNOWN INPUTS (OVER REACH)			KNOWN WITHDRAWALS (OVER REACH)			DIFFERENCE BETWEEN GAUGES (AF/YR)	NET (INPUTS MINUS WITHDRAWALS) (1)	AVAILABLE FOR (2) RECHARGE	ERROR FACTOR (%) (3)	REMARKS
					NAME	MILE	AF/YR	NAME	MILE	AF/YR					
COLUMBIA	GRAND COULEE DAM	596.3	80,060,000	64	—	—	—	—	—	—	—	—	—	10	UNADJUSTED
COLUMBIA	BRIDGEPORT	544.0	83,320,000	25	NESPELEM R. FOSTER CR.	582.1 544.6	<100,000 (4) <100,000 (4)	—	—	—	3,260,000	<+200,000	+3,060,000+	10	UNADJUSTED
COLUMBIA	WELLS DAM	515.9	87,450,000	24	OKANOGAN R. METHOW R.	533.5 523.9	2,273,000 1,172,000	—	—	—	4,130,000	+3,445,000	+685,000	10	UNADJUSTED
COLUMBIA	ROCKY REACH DAM	473.4	86,800,000	17	CHELAN R. ENTIAT R.	503.3 483.7	1,495,000 281,000	—	—	—	650,000	+1,776,000	-1,126,000	10	UNADJUSTED
COLUMBIA	BELOW ROCK ISLAND DAM	452.4	88,460,000	50	WENATCHEE R.	468.7	2,478,000	—	—	—	1,660,000	+2,478,000	-818,000	10	UNADJUSTED
COLUMBIA	BELOW PRIEST RAPIDS DAM	394.5	87,230,000	60	MOSES COULEE CRAB CR.	447.9 410.8	? <200,000	—	—	—	1,230,000	<200,000	-1,030,000+	5	FLOW IN CRAB CREEK SHOWS INCREASING TREND, CORRESPONDING WITH IRRIGATION DEVELOPMENT IN BIG BEND SUB-BASIN
COLUMBIA	McNARY DAM	292.0	134,200,000	27	YAKIMA R. SNAKE R. WALLA WALLA R. RETURN FLOW	335.2 324.2 314.6	2,500,000 (4) 40,900,000 431,800 225,000	—	—	—	46,970,000	+44,056,000	+2,914,000	POWER OUTPUT AT McNARY DAM	YAKIMA RIVER INFLOW BASED ON AVERAGE OF RECORDS FOR PAST 15 YEARS
COLUMBIA	THE DALLES	188.9	140,600,000	99	UMATILLA R. WILLOW CR. JOHN DAY R.		319,500 20,580 1,448,000	—	—	—	+6,400,000	+1,788,000	+4,612,000	15	SEVERAL SMALL EPHEMERAL DRAINAGES INPUT ALONG REACH

(1) FOUND BY SUBTRACTING UPSTREAM GAUGED FLOW FROM THE GAUGED FLOW OF THE STATION UNDER CONSIDERATION.

(2) NEGATIVE VALUES INDICATE POSSIBLE STREAM LOSSES TO GROUND WATER. POSITIVE VALUES INDICATE POSSIBLE DISCHARGE OF GROUND WATER TO THE STREAM.

(3) INDICATES THAT 95 PERCENT OF THE DAILY DISCHARGES WERE RECORDED WITHIN THE SPECIFIED LEVEL OF ACCURACY.

(4) ESTIMATED FROM EITHER ANNUAL MAXIMUM DISCHARGE AT CREST-STAGE PARTIAL-RECORD STATIONS DURING WATER YEAR 1977 OR FROM ANNUAL AVERAGES USING OTHER SOURCES. PROBABLE ACCURACY WITHIN ONE ORDER OF MAGNITUDE.

YAKIMA RIVER

PRIMARY DRAINAGE	STATION	MILE	GAUGED FLOW (AF/YR)	YEARS OF RECORD	KNOWN INPUTS (OVER REACH)			KNOWN WITHDRAWALS (OVER REACH)			DIFFERENCE BETWEEN GAUGES (AF/YR)	NET (INPUTS MINUS WITHDRAWALS) (1)	AVAILABLE FOR (2) RECHARGE	ERROR FACTOR (%) (3)	REMARKS
					NAME	MILE	AF/YR	NAME	MILE	AF/YR					
YAKIMA	MARTIN	214.4	244,900	74	—	—	—	—	—	—	—	—	—	10	ADJUSTED FOR STORAGE SINCE 1906. FLOW REGULATED BY KEECHELUS LAKE
YAKIMA	CLE ELUM	183.1	1,478,000 (1,280,000*)	71	KACHESS R. CLE ELUM R.	203.5 185.6	213,000 676,000	—	—	—	1,234,000	+889,000	+345,000	15	ADJUSTED. SOME DIVERSIONS ABOVE STATION FOR IRRIGATION
YAKIMA	UMTANUM	140.4	(1,880,000*)	72	TEANAWAY R. NANEUM R. + WILSON CR. RETURN FLOWS	176.1 147.0	TRIBUTARY INFLOW = 550,000* 170,000*	PROJECT + PRIVATE DIVERSIONS IN KITTITAS VALLEY	—	435,000*	600,000*	+285,000*	+315,000*	5	IRRIGATION OF ABOUT 150,000 ACRES. BALANCE BASED ON ESTIMATES BY USBR
YAKIMA	UNION GAP	107.3	—	12	NACHES R. RETURN FLOW	116.3 —	1,262,000 (1,125,000*) 490,000*	ROZA IRRIG. ROZA POWER PRIVATE DIV.	— — —	364,000* 490,000* 65,000*	—	696,000*	—	—	BALANCE ESTIMATES BASED ON USBR DATA
YAKIMA	PARKER	103.8	(1,800,000*)	52	TRIBUTARIES RETURN FLOWS	— —	1,305,000* 625,000*	UMTANUM TO UNION GAP SUNNYSIDE WAPATO	— — —	919,000* 440,000* 650,000*	-80,000*	-79,000*	-1,000*	10	BALANCE PERFORMED BETWEEN UMTANUM AND PARKER. ESTIMATES BASED ON USBR DATA
YAKIMA	MABTON	59.8	—	7	ROZA WASTEWAY SATUS CR. SULPHUR CR.WW	98.0 80.4 69.6 61.0	—	SNIPES MTN. LATERAL	78.3	—	—	—	—	15	RECORD TOO SHORT TO PROVIDE MEANINGFUL AVERAGES
YAKIMA	KIONA	29.9	2,636,000 (4) (2,555,000*)	83	IRRIGATION RETURN FLOWS TOPPENISH CR. POWER RETURN FLOWS	— —	1,075,000* 555,000*	CHANDLER CANAL KIONA CANAL KENNEWICK CANAL	47.1 34.9 —	785,000* 90,000*	755,000*	+755,000	0	10	BALANCE ESTIMATES BASED ON USBR DATA
YAKIMA	RICHLAND	0	(2,400,000*)	—	—	—	—	COLUMBIA CANAL AND OTHER DIVERSIONS	—	115,000*	—	—	—	—	BALANCE ESTIMATES BASED ON USBR DATA

* STATISTIC FROM OR COMPUTED FROM UNITED STATES BUREAU OF RECLAMATION ESTIMATES FOR WATER BALANCE IN THE YAKIMA PROJECT.

(1) FOUND BY SUBTRACTING UPSTREAM GAUGED FLOW FROM THE GAUGED FLOW OF THE STATION UNDER CONSIDERATION.

(2) NEGATIVE VALUES INDICATE POSSIBLE STREAM LOSSES TO GROUND WATER. POSITIVE VALUES INDICATE POSSIBLE DISCHARGE OF GROUND WATER TO THE STREAM.

(3) INDICATES THAT 95 PERCENT OF THE DAILY DISCHARGES WERE RECORDED WITHIN THE SPECIFIED LEVEL OF ACCURACY.

(4) ESTIMATED FROM EITHER ANNUAL MAXIMUM DISCHARGE AT CREST-STAGE PARTIAL-RECORD STATIONS DURING WATER YEAR 1977 OR FROM ANNUAL AVERAGES USING OTHER SOURCES. PROBABLE ACCURACY WITHIN ONE ORDER OF MAGNITUDE.

SNAKE RIVER

PRIMARY DRAINAGE	STATION	MILE	GAUGED FLOW (AF/YR)	YEARS OF RECORD	KNOWN INPUTS (OVER REACH)			KNOWN WITHDRAWALS (OVER REACH)			DIFFERENCE BETWEEN GAUGES (AF/YR)	NET (INPUTS MINUS WITHDRAWALS) (1)	AVAILABLE FOR RECHARGE (2)	ERROR FACTOR (%) (3)	REMARKS
					NAME	MILE	AF/YR	NAME	MILE	AF/YR					
SNAKE	HELLS CANYON DAM	247.0	15,870,000	12	—	—	—	—	—	—	—	—	—	10	
SNAKE	ANATONE	167.2	26,300,000	19	SALMON R. GRANDE RONDE IMNAHA R.	168.7	8,158,000	—	—	—	10,430,000	+10,785,500	355,500	10	
SNAKE	ICE HARBOR DAM	9.7	40,900,000	22	ASOTIN CR. CLEARWATER R. TUCANNON R. PALOUSE R.	145.3 139.3 62.2 59.5	55,930 11,260,000 129,000 448,500	—	—	—	14,600,000	+11,893,430	-2,706,570	—	

(1) FOUND BY SUBTRACTING UPSTREAM GAUGED FLOW FROM THE GAUGED FLOW OF THE STATION UNDER CONSIDERATION.

(2) NEGATIVE VALUES INDICATE POSSIBLE STREAM LOSSES TO GROUND WATER. POSITIVE VALUES INDICATE POSSIBLE DISCHARGE OF GROUND WATER TO THE STREAM.

(3) INDICATES THAT 95 PERCENT OF THE DAILY DISCHARGES WERE RECORDED WITHIN THE SPECIFIED LEVEL OF ACCURACY.

(4) ESTIMATED FROM EITHER ANNUAL MAXIMUM DISCHARGE AT CREST-STAGE PARTIAL-RECORD STATIONS DURING WATER YEAR 1977 OR FROM ANNUAL AVERAGES USING OTHER SOURCES. PROBABLE ACCURACY WITHIN ONE ORDER OF MAGNITUDE.

WALLA WALLA RIVER

PRIMARY DRAINAGE	STATION	MILE	GAUGED FLOW (AF/YR)	YEARS OF RECORD	KNOWN INPUTS (OVER REACH)			KNOWN WITHDRAWALS (OVER REACH)			DIFFERENCE BETWEEN GAUGES (AF/YR)	NET (INPUTS MINUS WITHDRAWALS) (1)	AVAILABLE FOR RECHARGE (2)	ERROR FACTOR (%) (3)	REMARKS
					NAME	MILE	AF/YR	NAME	MILE	AF/YR					
WALLA WALLA	SOUTH FORK MILTON, OR.	---	129,000	56	—	—	—	—	—	—	—	—	—	10	
WALLA WALLA	NORTH FORK MILTON-FREEWATER, OR	—	39,990	8	—	—	—	—	—	—	—	—	—	10	
WALLA WALLA	NEAR TOUCHET	18.2	431,800	26	MILL CR. TOUCHET R. CONFLUENCE	33.6 21.6	75,000 (4) 169,500 169,000 (4)	—	—	—	—	+413,500	-18,300	10	

(1) FOUND BY SUBTRACTING UPSTREAM GAUGED FLOW FROM THE GAUGED FLOW OF THE STATION UNDER CONSIDERATION.

(2) NEGATIVE VALUES INDICATE POSSIBLE STREAM LOSSES TO GROUND WATER. POSITIVE VALUES INDICATE POSSIBLE DISCHARGE OF GROUND WATER TO THE STREAM.

(3) INDICATES THAT 95 PERCENT OF THE DAILY DISCHARGES WERE RECORDED WITHIN THE SPECIFIED LEVEL OF ACCURACY.

(4) ESTIMATED FROM EITHER ANNUAL MAXIMUM DISCHARGE AT CREST-STAGE PARTIAL-RECORD STATIONS DURING WATER YEAR 1977 OR FROM ANNUAL AVERAGES USING OTHER SOURCES. PROBABLE ACCURACY WITHIN ONE ORDER OF MAGNITUDE.

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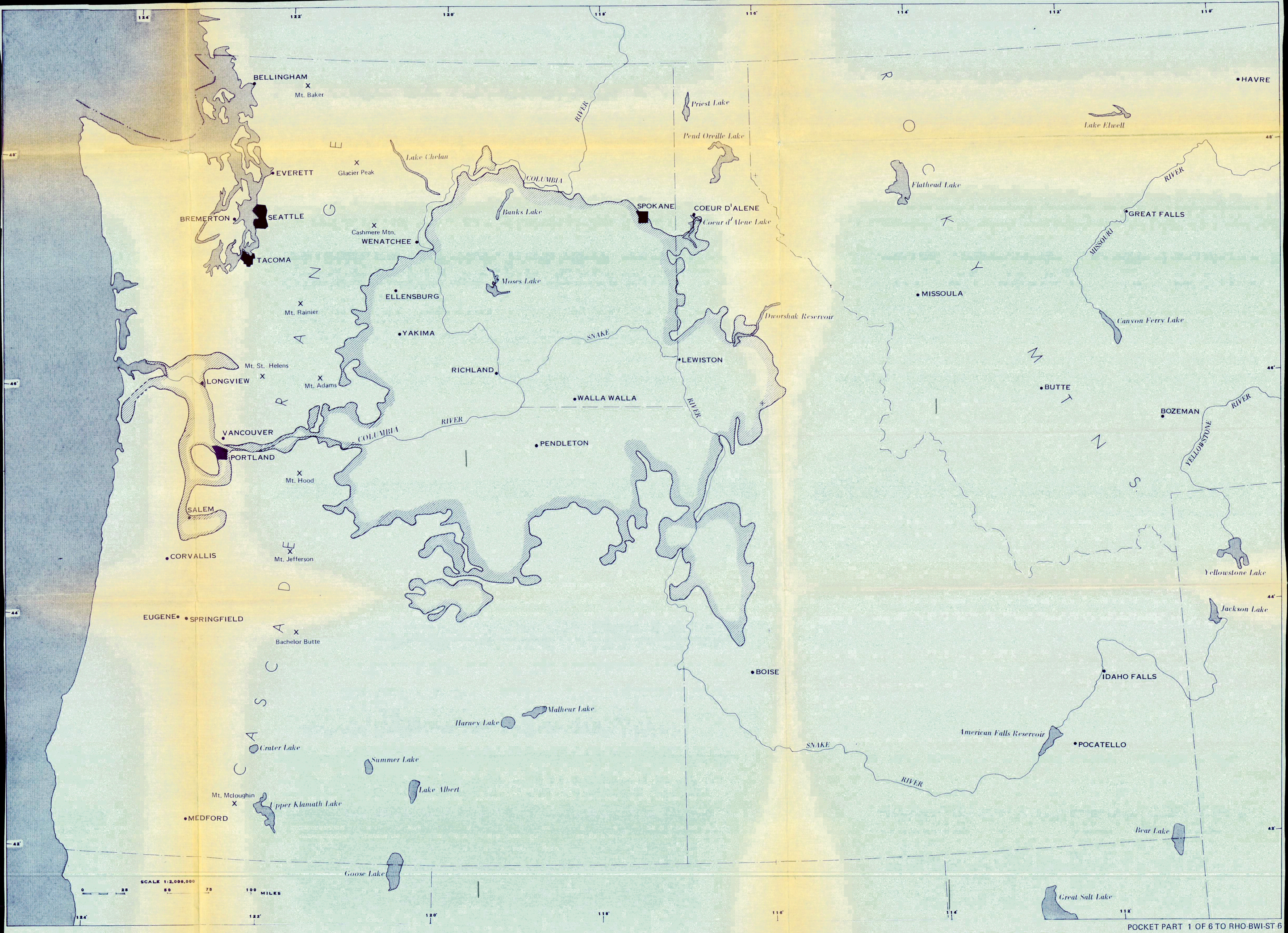

AREAL EXTENT OF THE COLUMBIA RIVER BASALT GROUP OUTCROP

Plate 1

CANADA
VANCOUVER ISLAND
PACIFIC OCEAN
IDAHO
OREGON
STRAIT OF JUAN DE FUCA
SAN JUAN
ORCAS ISLAND
VICTORIA
BELLINGHAM
EVERETT
LAKE WASHINGTON
BREMERTON
TACOMA
ELLENSBURG
WENATCHEE
Waterville
Davenport
Ritzville
COLFAX
PULLMAN
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SKAMANIA
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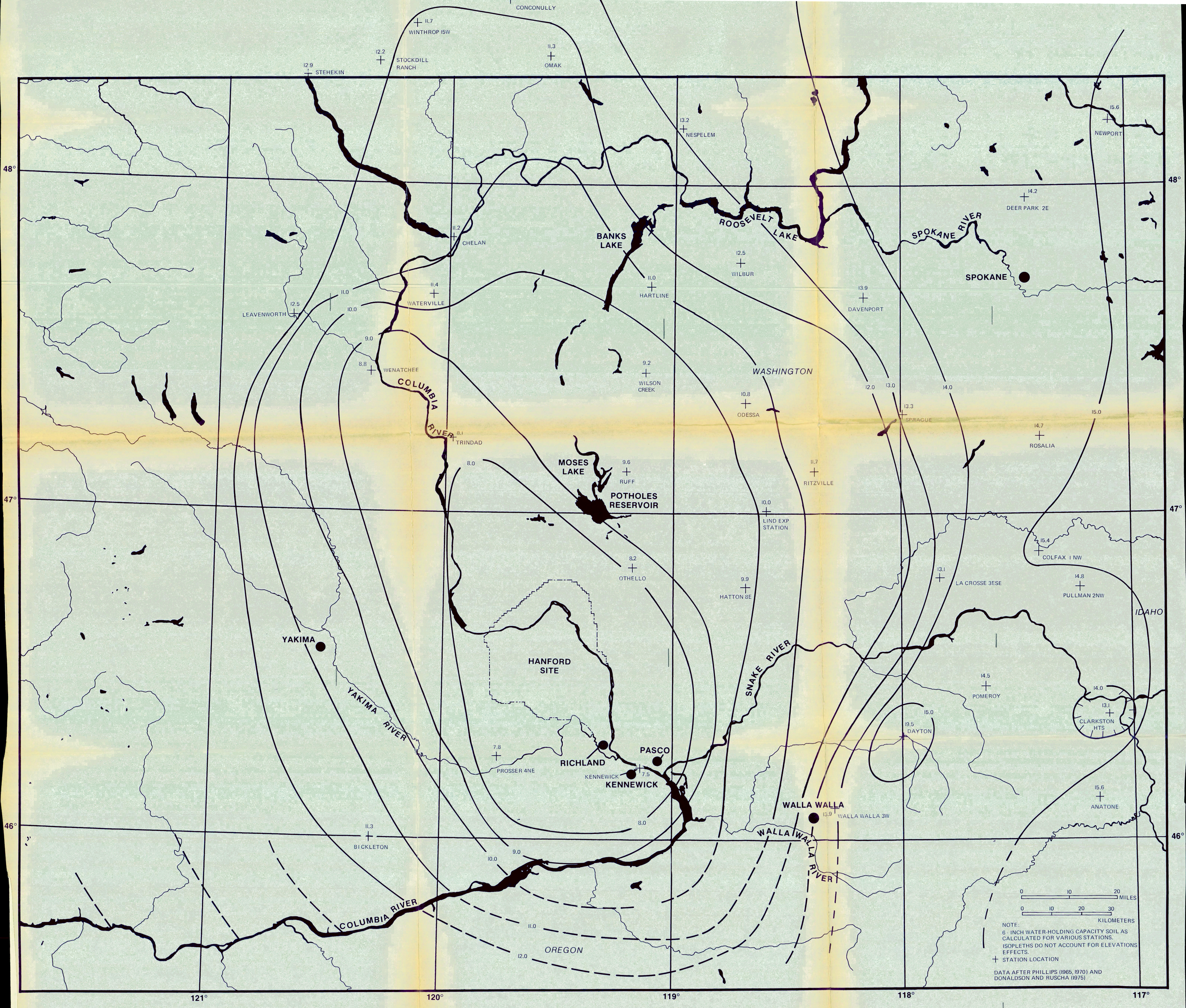
KITTITAS
CHELAN
GRAYS HARBOR
MASON
KITSAP
JEFFERSON
CLALLAM
ISLAND
SKAGIT
WHATCOM
SNOHOMISH
KING
Cape Flattery
Point of Arches
Cape Alava
Hoh Head
Point Grenville
Point Brown
Point Chehalis
Cape Shoalwater
Leadbetter Point
Cape Disappointment
COLUMBIA RIVER
Isohyetal analysis prepared by the U.S. Weather Bureau River Forecast Center, Portland, Oregon using adjusted climatological data (1930 – 57) and values derived by correlation with physiographic factors.
UNITED STATES DEPARTMENT OF AGRICULTURE (1965)
Mean Annual Precipitation
1930 - 1957
STATE OF WASHINGTON
10 0 10 20 30 40
Scale in Miles
POCKET PART 2 OF 6 TO RHO-BWI-ST-6
PLATE 2



PRELIMINARY ACTUAL EVAPOTRANSPIRATION MAP- COLUMBIA PLATEAU

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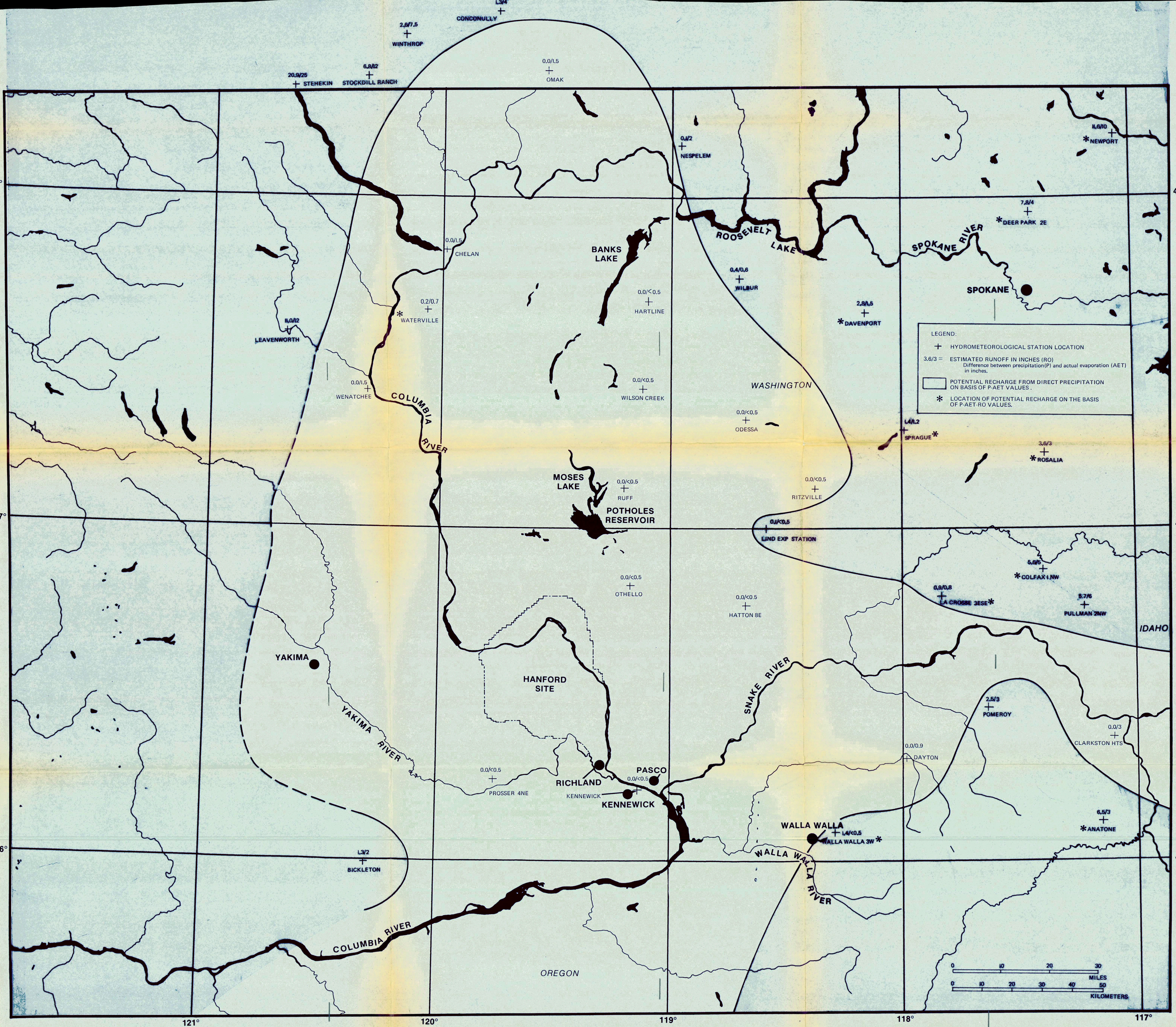
PLATE 3



GENERALIZED HYDROMETEOROLOGICAL BALANCE - COLUMBIA PLATEAU

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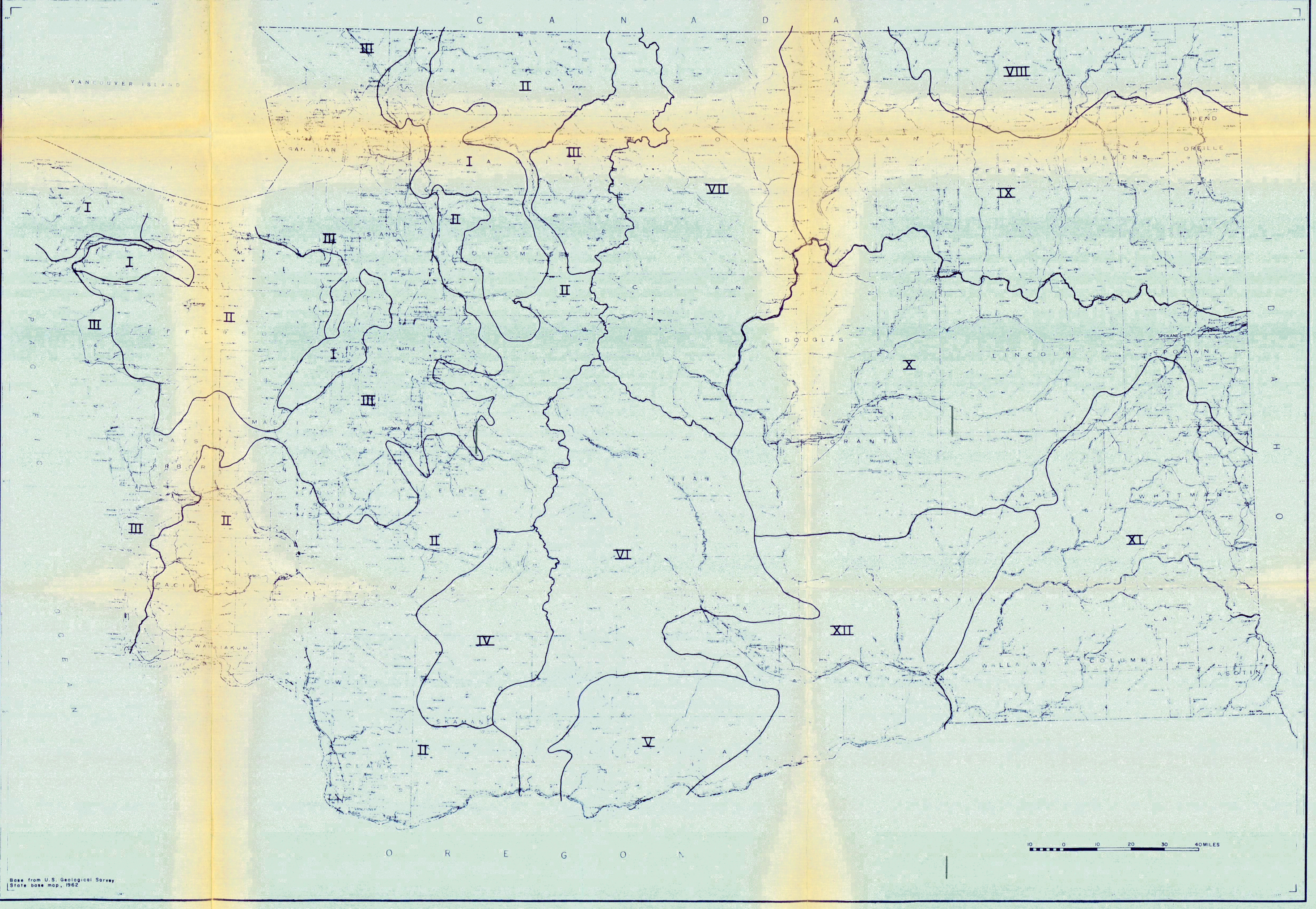
PLATE 4



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POCKET PART 5 OF 6 TO RHO-BWI-ST-6

Plate 5

PRELIMINARY REACH INVENTORY MAP