Hydrogeologic Setting and Preliminary Estimates of Hydrologic Components for Bull Run Lake and the Bull Run Lake Drainage Basin, Multnomah and Clackamas Counties, Oregon

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4064

Prepared in cooperation with
CITY OF PORTLAND BUREAU OF WATER WORKS

Cover. Photograph shows Bull Run Lake, viewed southeastward towards Mount Hood. The scene was described by Woodward (Portland Oregonian, August 18, 1918):

> “The lake, clear, deep, and cold, ***, nestles like an emerald or turquoise with the changing lights or shadows at the base of these rocky, wooded slopes and above and beyond all, overlooking and reflected in its clear depths, lies snow-capped Mount Hood.”

Photograph credit: U.S. Forest Service, circa 1960.

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By DANIEL T. SNYDER and DORIE L. BROWNELL

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047.	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon	0.003785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow	
square foot (ft^2)	0.0929	square meter
cubic foot per second (ft^3 /s)	0.02832	cubic meter per second

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Hydrogeologic Setting and Preliminary Estimates of Hydrologic Components for Bull Run Lake and the Bull Run Lake Drainage Basin, Multnomah and Clackamas Counties, Oregon

By Daniel T. Snyder *and* Dorie L. Brownell

ABSTRACT

The hydrogeologic setting was described and preliminary estimates of hydrologic components prepared for the Bull Run Lake and for the Bull Run Lake drainage basin, in the Cascade Range of northwestern Oregon. The 0.73-square-mile lake and the 3.44-square-mile drainage basin lie within the Bull Run Watershed, the principal water supply for the Portland, Oregon, metropolitan area. During periods of high demand or low inflows to the watershed, the City of Portland Bureau of Water Works, releases water from Bull Run Lake to augment the supply.

Bull Run Lake is impounded by a natural dam formed by a landslide. Outflow of ground water from the lake through the landslide emerges as springflow at the toe of the landslide and forms the headwaters of the Bull Run River. The approximately 4,300-Mgal (million gallons) discharge of the Bull Run River measured below the springs during the 1993 water year is composed of (1) outflow of ground water from Bull Run Lake through the landslide (approximately 60 percent), (2) ground water originating from the contributing drainage area between the lake and the springs (approximately 34 percent), (3) streamflow from Bull Run Lake (approximately 5 percent), and (4) surface runoff (streamflow and overland flow) from the contributing drainage area between the lake and the springs (approximately 1 percent).

Estimated ranges for inflows to the Bull Run Lake drainage basin during the 1993 water year were about 3,400 to 9,200 Mgal from precipitation from rain and snow, and about 0 to 3,300 Mgal from fog drip. Estimated ranges for outflows from the lake basin, listed from largest to smallest, were about 1,800 to 3,400 Mgal for ground-water outflow through the landslide; about 600 to 1,800 Mgal for evapotranspiration from the land surface; about 170 to 410 Mgal for lake evaporation; and about 0 to 400 Mgal for streamflow from the lake. Ground-water outflow through the consolidated rocks could not be evaluated owing to the lack of data. The lake storage increased by a range of from about 1,700 to 1,900 Mgal. Changes in ground-water storage and soil-moisture storage could not be evaluated as a result of insufficient data.

Estimated inflows to Bull Run Lake from precipitation on the lake surface during the 1993 water year ranged from about 600 to 1,600 Mgal. Inflows from ground water and surface runoff could not be evaluated owing to the lack of data. Estimated ranges for outflows from the lake were about 1,800 to 3,400 Mgal from ground-water outflow through the landslide, about 170 to 410 Mgal from lake evaporation, and about 0 to 400 Mgal from streamflow. Outflow of ground water through the consolidated rocks could not be evaluated owing to the lack of data. Lake storage increased by a range of from about 1,700 to 1,900 Mgal.

Suggestions for further study include (1) evaluation of the surface-runoff component of inflow to the lake; (2) use of a cross-sectional ground-water flow model to estimate ground-water inflow, outflow, and storage; (3) additional data collection to reduce the uncertainties of the hydrologic components that have large relative uncertainties; and (4) determination of long-term trends for a wide range of climatic and hydrologic conditions.

INTRODUCTION

Since 1895, the Bull Run Watershed has been the primary water supply for the Portland, Oregon, metropolitan area. The City of Portland Bureau of Water Works (hereinafter "Portland Water Bureau") supplied water from the watershed to approximately 740,000 persons in 1994, about one-fourth of the population of Oregon. The watershed lies on the western side of the Cascade Range in northwestern Oregon, about 35 mi (miles) east of Portland (fig. 1). Within the lower part of the watershed are two manmade reservoirs (Bull Run Reservoirs 1 and 2) constructed for water storage, and within the upper part of the watershed is the naturally formed Bull Run Lake. A small manmade dam was constructed across the outlet channel of Bull Run Lake to increase storage and to aid in the controlled release of water from the lake. During periods of low inflows to the two reservoirs or during high demand, the Portland Water Bureau releases water from Bull Run Lake to augment the water supply in the reservoirs. The Portland Water Bureau has relied increasingly on water stored in Bull Run Lake to meet short-term water needs of the region because of increasing water demand and periods of extended drought.

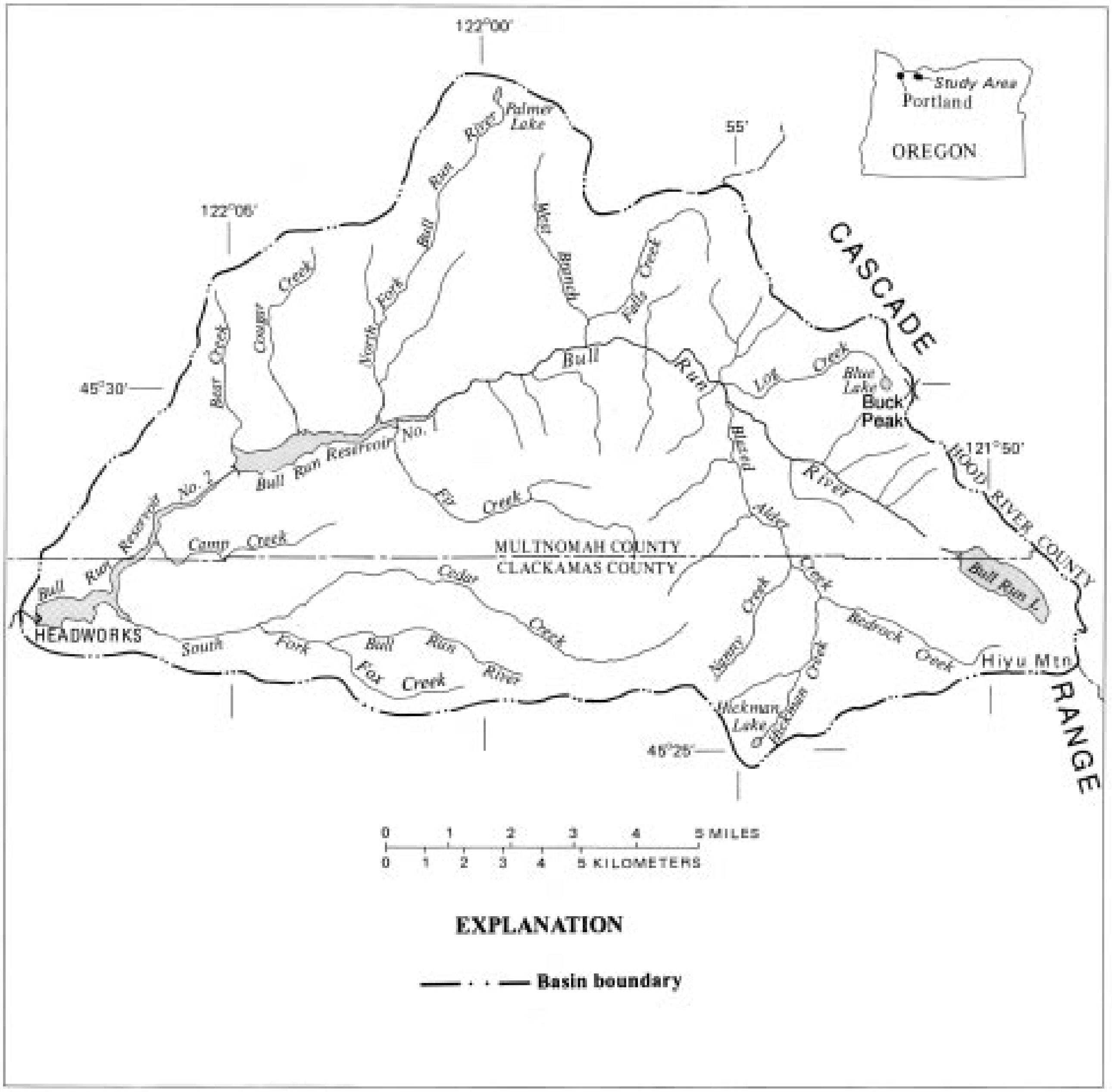


Figure 1. Location of the Bull Run Watershed.

This increased use, in conjunction with drought, has recently resulted in low water levels in Bull Run Lake.

The Portland Water Bureau and the U.S. Forest Service have recently completed an Environmental Assessment as part of an application to renew the City of Portland's Special-Use Authorization for Bull Run Lake (U.S. Forest Service, 1995a, 1995b, 1995c). The Environmental Assessment includes several management alternatives for utilization of Bull Run Lake for water supply. At issue in the permit reauthorization process is how the lake can continue to be used for augmentation of supply during peak demand periods while maintaining ecological processes and species diversity in the long term for the lake and surrounding habitats (U.S. Forest Service, 1995c). Bull Run Lake has provided an economical and reliable source of water in the past; therefore, it is important to determine how these uses can best be accommodated under various management alternatives. Answering these questions requires a more complete understanding of the hydrology of Bull Run Lake. To that end, in 1993 the U.S. Geological Survey (USGS), in cooperation with the Portland Water Bureau, began a preliminary study of the hydrology of Bull Run Lake.

Purpose and Scope

This report has two objectives: to characterize the hydrogeologic setting of Bull Run Lake and to develop an initial conceptual understanding of the hydrology of the lake. As part of this process, existing hydrologic data were assessed to determine their usefulness in estimating the hydrologic components and overall hydrologic budget of the lake and lake drainage basin. The results include suggestions for additional data collection that would lead to more accurate estimates of the hydrologic components, resulting in quantitative hydrologic budgets and providing a thorough understanding of the hydrology of Bull Run Lake.

Because of limitations in available hydrologic data, the estimates of the hydrologic components discussed in this report are limited to the 1993 water year. A water year is the 12-month period beginning October 1 and ending September 30 in the following year. The water year is designated by the calendar year in which it ends.

Approach

The characterization of the hydrogeologic setting of the Bull Run Lake drainage basin was developed using existing studies and descriptions of the geology, hydrology, and climate in the area. This information was used to develop a conceptual understanding of the hydrology of Bull Run Lake and to identify the inflows to and outflows from the lake and lake drainage basin. Existing data were used to calculate the hydrologic components of the lake and lake drainage basin for the 1993 water year. The conceptual model, the preliminary estimates of the hydrologic components, and the relative uncertainties of the hydrologic components were used to define additional data collection needs and to develop an approach for future work that would allow a more quantitative hydrologic analysis of the lake.

Description of Study Area

Bull Run Lake lies within the Bull Run Watershed, the principal water supply for the City of Portland, Oregon. The Bull Run Watershed is an officially designated management area of about 149 mi^2 (square miles) and includes nearly the entire 102 mi^2 of the Bull Run River drainage basin above the Headworks, the Portland Water Bureau facility where water is diverted to the Portland metropolitan area. The Bull Run River originates at a series of springs below Bull Run Lake at the eastern part of the watershed and flows westward (fig. 1). The river has two manmade reservoirs that were constructed to increase the water supply.

Physiography and Hydrography

Bull Run Lake is a naturally formed lake in a cirque-shaped basin within the U-shaped upper reaches of the Bull Run River Basin (fig. 2). Bull Run Lake is located in Multnomah and Clackamas Counties about 8.5 mi northwest of Mount Hood. A summary of the characteristics of the lake and its drainage basin is presented in table 1.

Bull Run Lake is in a deep basin surrounded by high ridges on three sides. Hiyu Mountain to the south is the highest point; it rises almost 1,500 ft (feet) above the lake to an altitude of 4,654 ft above sea level in less than 1 mi.

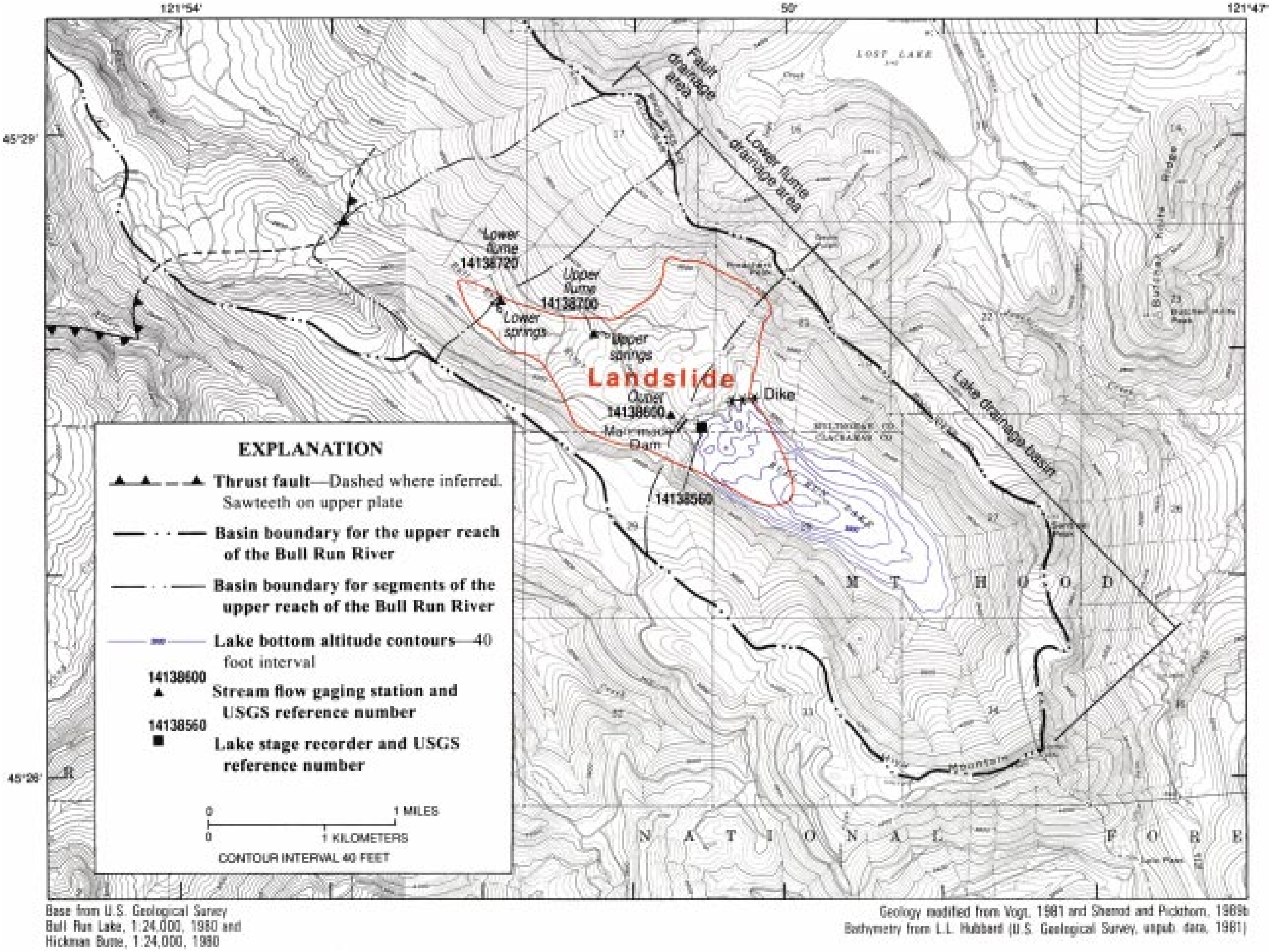


Figure 2. Topography, probable extent of landslide, and general features of the area around Bull Run Lake.

Table 1. Characteristics of Bull Run Lake and its drainage basin

[mi^2, square miles; mi, miles; Mgal, million gallons; ft, feet]

Characteristic	Measurements
Area:	
Bull Run Lake (at full pool)	0.73 mi^2
Contributing drainage basin (including Lake)	3.44 mi^2
Dimensions:	
Maximum length	1.5 mi
Maximum width	0.5 mi
Altitude (at full pool):	3,178 ft above sea level
Depth (at full pool):	
Maximum	273 ft
Mean	98 ft
Volume (at full pool):	
Usable storage	4,330 Mgal
Total storage	14,800 Mgal

Sentinel and Preachers Peaks, east and north of the lake respectively, are of similar height. At least nine small ephemeral streams drain to the lake from the steep canyon walls. These streams are all ungaged, and their contribution to the lake is unknown. The lake has a full pool altitude of 3,178 ft as the result of a manmade spillway. Measurements by the Portland Water Bureau show that lake stage varied from 3,143 to 3,178 ft during 1971 through 1992 (D.M. Bloem, City of Portland Bureau of Water Works, written commun., 1994). A lake stage recorder (station 14138560) with satellite telemetry was established at the lake by the USGS in October 1992 (fig. 2 and table 2).

The lake has one natural outlet along its northwestern side that was enlarged during construction of a manmade dam across the outlet. A gaging station (station 14138600) was established in the outlet to measure water discharge during releases by the Portland Water Bureau. The outlet channel runs about one-fourth mile northwestward and ends in a closed depression. Water entering this depression infiltrates the ground and may emerge as springs about one-half mile northwestward. A Parshall flume was installed in 1959 below the springs at an altitude of about 3,000 ft to measure discharge (station 14138700). Streamflow measurements made by the Portland Water Bureau between 1970 and 1993 show that the springs have a discharge ranging from 0 to about 72 ft^3/s (cubic feet per second) (D.M. Bloem, City of Portland Bureau of Water Works, written commun., 1994). For purposes of this report, these springs and the flume are referred to as the “upper springs” and “upper flume,” respectively.

About one-half mile downstream from the upper springs, another series of springs emerges along several hundred feet of the stream channel. These springs form the headwaters of the Bull Run River. A second Parshall flume was installed in 1959 and is just below the lowermost series of prominent springs at an altitude of about 2,720 ft. A continuous river-stage recorder (station 14138720) with satellite telemetry was established here by the USGS in October 1992. Measurements by the Portland Water Bureau during 1970 through 1992 show that discharge generally ranges from about 6 to 74 ft^3/s (D.M. Bloem, City of Portland Bureau of Water Works, written commun., 1994). In this report, this series of springs and the flume will be referred to as the “lower springs” and the “lower flume,” respectively.

During periods of high lake stage, stormflow, or releases from the lake, the stream channel between the upper flume and the lower springs may contain water. However, during low lake stage and extended dry periods, the stream channel may not contain any water beginning several hundred feet downstream from the upper flume to the lower springs.

Throughout this report, frequent references are made to the contributing drainage areas for Bull Run Lake; for the Bull Run River at the lower flume exclusive of the drainage basin for Bull Run Lake; and for the Bull Run River where it is crossed by a thrust fault exclusive of the drainage area above the lower flume. To avoid confusion, these drainage areas will be referred to as the “lake drainage basin”, the “lower flume drainage area,” and the “fault drainage area,” respectively (fig. 2).

Climate

The temperature and rainfall in the area of Bull Run Lake are typical of a maritime climate, which is characterized by wet, relatively cold winters and dry, cool summers. Most precipitation in this area is a result

Table 2. Locations of and selected data for hydrologic-data sites
[in, inches; yr, year; mi, miles; OR, Oregon; --, not applicable]

Index or station number [1]	Station name	Altitude (feet above sea level	Longitude	Latitude	Precipitation 1993 water year (in/yr.)	Average precipitation [2] (in/yr)	Distance from Bull Run Lake (mi)
	Lake stage and streamflow-gaging stations						
[3]14138560	Bull Run Lake near Brightwood, OR	[4]3,178	121˚50’34”	45˚27’39”	--	--	--
[3]14138600	Bull Run River at Lake Outlet, near Brightwood, OR	3,145	121˚50’44”	45˚27’42”	--	--	--
[5, 6]14138700	Bull Run River at Upper Flume, near Brightwood, OR	3,000	121˚51’16”	45˚28’5”	--	--	--
[5, 6]14138720	Bull Run River at Lower Flume, near Brightwood, OR	2,720	121˚51’55”	45˚28’5”	--	--	--
	Weather stations [7]						
35-0897	Bonneville Dam, OR	67	121˚57’	45˚38’	71.0	75.0	13.6
35-3402	Government Camp, OR	3,980	121˚45’	45˚18’	82.0	87.4	11.4
35-3770	Headworks, City of Portland Bureau of Water Works, OR	748	122˚ 9’	45˚27’	79.4	79.5	15.5
35-4003	Hood River Experiment Station, OR	500	121˚31’	45˚41’	29.6	30.7	22.0
35-6151	North Willamette Experiment Station, OR	150	122˚45’	45˚17’	40.8	41.7	46.2
35-6466	Parkdale 2NNE, OR	1,451	121˚34’	45˚33’	30.8	31.8	14.5
21D33S	Blazed Alder, OR	3,650	121˚52’	45˚25’	117.4	115.7	3.2
22D02S	North Fork, OR	3,120	122˚1’	45˚33’	138.0	132.4	11.2
21D04S	Red Hill, OR	4,400	121˚42’	45˚28’	105.3	103.6	6.5

[1] Index or station number: see figures 2 and 11 for location.
[2] For the period 1961–90.
[3] Source of data: Hubbard and others (1995).
[4] Altitude of full pool at Bull Run Lake.
[5] Source of data: U.S. Geological Survey (USGS) 1:24,000-scale topographic map for Bull Run Lake, Oregon, 1980.
[6] A high precision global positioning system (GPS) receiver using the Precise Positioning Service and Wide Area GPS Enhancements (WAGE) was used to determine the locations of the upper and lower flumes (stations 14138700 and 14138720) for comparison with locations derived using a 1:24,000-scale topographic map. Good agreement was found with regards to the position of the upper flume; however, the Bull Run River at the lower flume may actually be located about 450 feet east of the location indicated by the topographic map used for this table and throughout the maps in this report.
[7] Sources of data: U.S. Department of Commerce (1992–93); U.S. Soil Conservation Service (1988); and G.H. Taylor (Oregon Climate Service, Corvallis, Oregon, oral commun., 1995). Locations reported to the nearest minute.

of orographic effects associated with warm, moist air masses from the Pacific Ocean. When a marine air mass rises over the crest of the Cascade Range, prolonged periods of low- to moderate-intensity rain result (Rothacher and others, 1967). Average annual precipitation in the area of Bull Run Lake is about 104 in/yr (inches per year) (Taylor, 1993a). In the basin, snowpack ranges in maximum depth from 6 to 9 ft on the average (Franklin, 1972) and remains until spring, when snowmelt contributes to spring runoff. In addition, fog drip is believed to be a significant contribution to the hydrologic budget of the watershed (Harr, 1982; Ingwersen, 1985).

Land Use

Most of the Bull Run Watershed, including the entire drainage basin for Bull Run Lake, is federally owned and managed by the U.S. Forest Service as part of the Mount Hood National Forest. About 20 percent of the Bull Run Lake drainage basin is covered by the lake. The remaining area is forested, with small areas of rock talus along some steeper slopes. The area within the drainage basin for Bull Run Lake has not been logged, and contains no manmade structures or roads, except near the lake outlet and along the northwest corner of the lake. The remaining area around Bull Run Lake is virtually free of human disturbances.

Soils and Vegetation

The soils in the area around Bull Run Lake formed in colluvium and glacial till from underlying bedrock of andesite and basalt mixed with volcanic ash (Stephens, 1964; Green, 1983). The soils consist of deep, well-drained gravelly silt loams, which generally are underlain by glacial till or bedrock below a depth of 60 inches.

The areas around Bull Run Lake and along the upper reaches of the Bull Run River are densely forested with conifers such as Douglas fir, western hemlock, western red cedar, silver fir, noble fir, and grand fir. Many trees are of large diameter and are from 400 to 600 years old. The understory vegetation includes rhododendron, salal, and devil's club, which is common in wet areas. A few areas of bare talus slope and talus shrub communities occur on the steep slopes around the lake.

History

The area encompassed by the Bull Run River drainage basin was first set aside as the Bull Run Reserve, which was established in 1892 by Presidential Proclamation as the first National Forest Reserve in Oregon. This protected status helped the development of the Bull Run drainage basin as a water supply for the City of Portland. On January 2, 1895, water from the Bull Run Reserve flowed by pipeline into Portland for the first time and, subsequently, the reserve became the city's principal water supply (Short, 1983). In 1908, the Bull Run Reserve became part of the Oregon National Forest, which was renamed the Mount Hood National Forest in 1924. The present (1996) Bull Run Watershed was established in 1977 by Public Law 95–200 and consists of nearly the entire drainage basin of the Bull Run River and an adjacent buffer zone (U.S. Forest Service, 1995c).

The Klickitat Indian word for Bull Run Lake was Gohabedikt, meaning Loon Lake (Johnson and others, 1985). The lake was later named for the Bull Run River, which flowed through a region where escaped cattle ran wild in early pioneer years. The steady seepage of water from Bull Run Lake, which forms the headwaters of the Bull Run River, provided a dependable source of high-quality water. However, to meet increasing water demand, the City of Portland took several measures to increase storage at the lake and to decrease seepage from the lake. In 1915, a low timber-and-rockfill dam was installed across the natural outlet channel from Bull Run Lake, raising the maximum lake level approximately 10 ft to an altitude of 3,178 ft (City of Portland, 1915). This modification allowed controlled storage. During 1917–21, an earth-fill dike (fig. 2) was constructed along the northwest corner of the lake to prevent seepage of water through a shallow part of the lake where large sinkholes had been observed. The dike is about 500 ft long and isolates an area of the lake of about 0.01 mi^2. The dike's spillway is at an altitude of 3,178 ft. In an effort to reduce the rate of seepage, during 1919–1925, a blanket of rock and soil from nearby borrow pits was applied from a barge to the lake bottom near the dike (City of Portland, 1921, 1923, 1925). In 1921, the City of Portland received a special-use permit to operate Bull Run Lake as a dam and reservoir site.

In 1929, construction of the dam that impounds Reservoir 1 (fig. 1), also known as Lake Ben Morrow, was completed. Of 9,900 Mgal (million gallons) of total storage, including additional storage capacity added in 1954, 8,000 Mgal is usable (D.M. Bloem, City of Portland, Bureau of Water Works, oral commun., 1995). Reservoir 1 storage surpassed usable storage at Bull Run Lake—which previously had served as the sole reservoir in the watershed. By the 1950's, however, it was becoming increasingly difficult for the storage facilities to meet demand owing to growth of the metropolitan area and expansion of service to outlying water districts. To help meet this demand, repairs and improvements were made from 1957 to 1961 to the structures designed to increase storage at Bull Run Lake and to reduce seepage from the lake. The dike was repaired during this time, and several sink areas and areas of higher permeability were identified and sealed with bentonite clay by Shannon and Wilson, Inc. (1961).

A new concrete dam was constructed with improved outlets, including two gated conduits that allows lake drawdown to an altitude of 3,147 ft. The upper conduit is at an altitude of 3,158 ft, and the lower conduit is at an altitude of 3,147 ft. Usable storage at Bull Run Lake was increased from about 2,800 Mgal to 4,330 Mgal. Water from Bull Run Lake was used extensively to augment the water supply during 1958 and 1962.

In 1962, Reservoir 2 was completed, having 6,800 Mgal of total storage, 2,200 Mgal of which is usable (D.M. Bloem, City of Portland Bureau of Water Works, oral commun., 1995). With the addition of Reservoir 2, the Bull Run Watershed has provided a reliable supply of clean water to the Portland metropolitan area. However, drought and increased demand required water release from Bull Run Lake during every year between 1985 and 1992. In the summer of 1992, the lake was drawn down below the altitude of the lower conduit to more than 30 ft below maximum pool, and pumping was required to extract additional water. No water was released from Bull Run Lake by the Portland Water Bureau during the 1993 water year, except for an unknown quantity during an accidental release in March 1993.

Acknowledgments

Special acknowledgment is made to Douglas M. Bloem, City of Portland Bureau of Water Works, for his advice and knowledge with regard to the Bull Run Watershed. George H. Taylor, Oregon State Climatologist, provided assistance and data related to the climate of the study area. Finally, David R. Sherrod, U.S. Geological Survey Cascades Volcano Observatory, is gratefully acknowledged for his contributions with regard to the geology and hydrology of the Cascade Range.

HYDROGEOLOGIC SETTING

The hydrogeologic setting described in this report includes a review of the geology of the area as determined by existing surficial mapping. The formation of Bull Run Lake and a description of the natural dam impounding Bull Run Lake are discussed. Finally, the relation between the hydrogeologic setting and groundwater flow is examined.

Geology

The entire watershed is underlain by lava flows of the Columbia River Basalt Group (fig. 3; Sherrod and Scott, 1995), which have been folded and faulted (Wells and Peck, 1961; Wise, 1969; Vogt, 1981; Sherrod and Pickthorn, 1989a). These rocks have been covered by younger volcanic and volcaniclastic strata and unconsolidated surface deposits (Vogt, 1981). The area has been dissected by streams and scoured by glaciers, exposing the older rocks along the drainages.

The geology of the Bull Run Watershed has been studied by numerous investigators (including Sylvester, 1908; Williams, 1920; Barnes and Butler, 1930; Shannon and Wilson, Inc., 1961; Wise, 1969; Beaulieu, 1974). This investigation, however, relied primarily on the detailed geologic mapping and interpretation by Vogt (1981), who delineated the stratigraphy, areal extent, thickness, and structure of the Columbia River Basalt Group in the Bull Run Watershed, and Sherrod and Scott (1995), who mapped the geology of the southeastern part of the watershed.

Columbia River Basalt Group

The oldest rocks exposed in the Bull Run Watershed belong to the Columbia River Basalt Group (Vogt, 1981; Sherrod and Scott, 1995). The Columbia River Basalt Group is a sequence of flood basalts, of Miocene age, that entered from the east through a topographic low in the area of the present day Bull Run River (Wise, 1969; Beeson and Moran, 1979a; Vogt, 1981). The Columbia River Basalt Group is exposed westward from Bull Run Lake along the Bull Run River and Blazed Alder Creek as a result of downcutting by rivers through younger rocks (fig. 3).

The Columbia River Basalt Group comprises the Wanapum Basalt and underlying Grande Ronde Basalt within the watershed. Within the Grande Ronde Basalt, Vogt (1981) distinguished two units of fine-grained basalt on the basis of magnetic polarity of the rock—reversed-polarity unit 2 ($Tcgr_2$) and normal-polarity unit 2 ($Tcgn_2$). The Wanapum Basalt in the Bull Run Watershed consists of the Frenchman Springs member (Tcwf) and the Priest Rapids member (Tcwpr). Both the older Frenchman Springs member and the younger Priest Rapids member are fine-grained basalts.

The Priest Rapids member formed as an intracanyon flow following, and sometimes overflowing, the course of a former river channel eroded into the older units of the Columbia River Basalt Group (Vogt, 1981). It is exposed only in a limited extent within the watershed, along the Bull Run River southeast of the confluence with Blazed Alder Creek.

Folding of the Columbia River Basalt Group has formed the major structures in the Bull Run Watershed—a syncline and anticline, whose axes strike roughly northeast to southwest with a plunge gently to the southwest (Vogt, 1981) (fig. 3; and fig. 6 on page 18). The syncline (not present in the area encompassed by fig. 3) runs along or close to and parallel with the Bull Run River below Falls Creek (fig. 6 on page 18). The anticlinal axis crosses the Bull Run River about 2 mi northwest of Bull Run Lake (D.R. Sherrod, USGS, written commun., 1994); the lake is on the southeast-dipping limb of the anticline (Wells and Peck, 1961; Couch and Gemperle, 1979; Vogt, 1981). Vogt (1979, 1981) and Beeson and Moran (1979a) mapped a thrust fault along Blazed Alder Creek and the uppermost reach of the Bull Run River on the northwest limb of the anticline (fig. 3). This northeast striking thrust fault dips 12 degrees southeast and has produced at least 600 ft of vertical offset.

Younger Rocks

In the vicinity of Bull Run Lake, the Columbia River Basalt Group is unconformably overlain by Miocene through Pleistocene basalts and andesites. The andesite of Lolo Pass (Taop) may pinch out westward against the Bull Run anticline, which was formed before the andesite was extruded (Vogt, 1981), and may be the cause of the absence of the andesite near the crest or northwest of the anticline (fig. 3). The basalt of Bull Run Watershed (Tbbu) is present in only small areas southeast of the Bull Run anticline and is missing along the southwest slope of the ridge that separates Blazed Alder Creek and the Bull Run River. This condition may be due to pinching out or thinning eastward across the anticline—or perhaps erosion. The basaltic andesite (QTba), the remnants of the basalt near Lolo Pass (QTb), and the andesite of Hiyu Mountain (Qah) cap the northwest-trending ridge along the southwestern edge of Bull Run Lake.

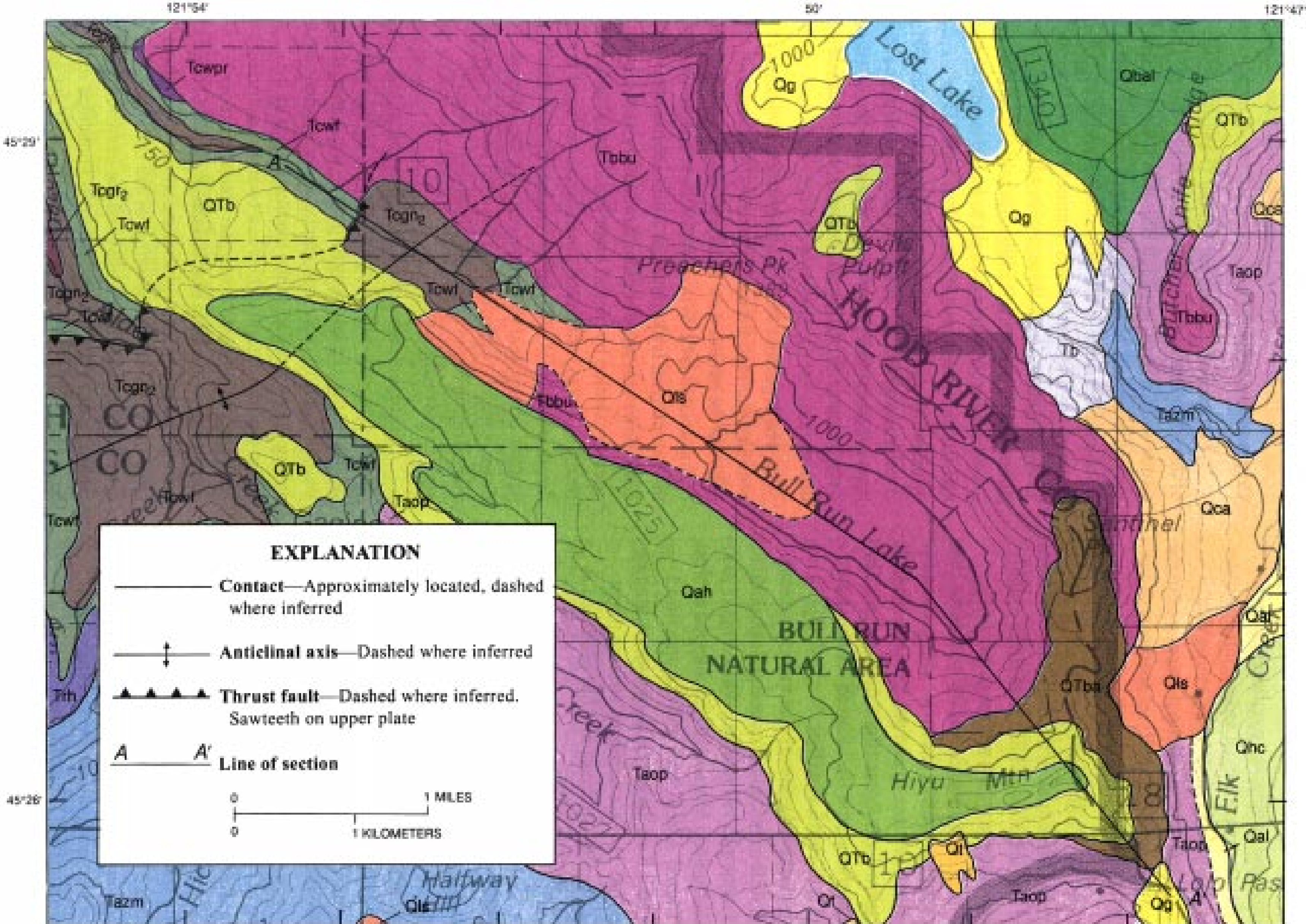
Formation of Bull Run Lake

Origin of the Lake

Pleistocene glaciers carved the U-shaped valley of the upper reaches of the Bull Run River Basin. The cirque-shaped basin in which Bull Run Lake is located may have been formed by a glacier that swept westward over the ridge at the southeastern end of the lake between Hiyu Mountain and Sentinel Peak (Sylvester, 1908; Williams, 1920; Wise, 1969; Allen, 1989; Sherrod and Pickthorn, 1989b). The altitude of the lowest glaciated area is thought to be between 2,000 and 3,000 ft (Beaulieu, 1974; Allen, 1989). The origin of the natural dam impounding Bull Run Lake is not known with certainty. Three mechanisms have been proposed to explain the formation of the natural dam: volcanic flows, glacial deposits, and landslide deposition.

The argument for a volcanic origin may have been first put forward by Sylvester (1908), who believed the natural dam was formed by a fissure-flow of unglaciated lava. Williams (1920) proposed that the natural dam is a composite feature formed by volcanic flows that were contemporaneously and subsequently mantled by glacial materials. Wise (1969) and Beaulieu (1974) attributed the dam to a series of lava flows. Beaulieu (1974), however, described scattered patches of morainal material overlying the volcanic flows, which he believed may have led to the mistaken identification of the entire unit as glacial debris by previous investigators.

The first reference to a glacial origin of the natural dam may be that of Van Winkle (1914) who suggested that the lake was formed by a morainal dam. Williams (1920) described glacial material uncovered during the excavation of the manmade dam as evidence that the natural dam was a composite structure consisting of volcanic flows and glacial material. According to Shannon and Wilson, Inc. (1961), the natural dam consists of glacial moraines; the authors cited the moraine-like lithology of the material (unsorted, angular fragments) and the occurrence of striated rock. They also indicate that landslides may have played a minor role in the formation of the natural dam. A glacial origin of the natural dam (at least in part) also is suggested by Allen (1989), who refers to morainal material on top of lava.



Base from U.S. Geological Survey
Mt. Hood, 1:100,000, 1984

CONTOUR INTERVAL 50 METERS

Geology modified from Sherrod
and Scott, 1995; Vogt, 1981

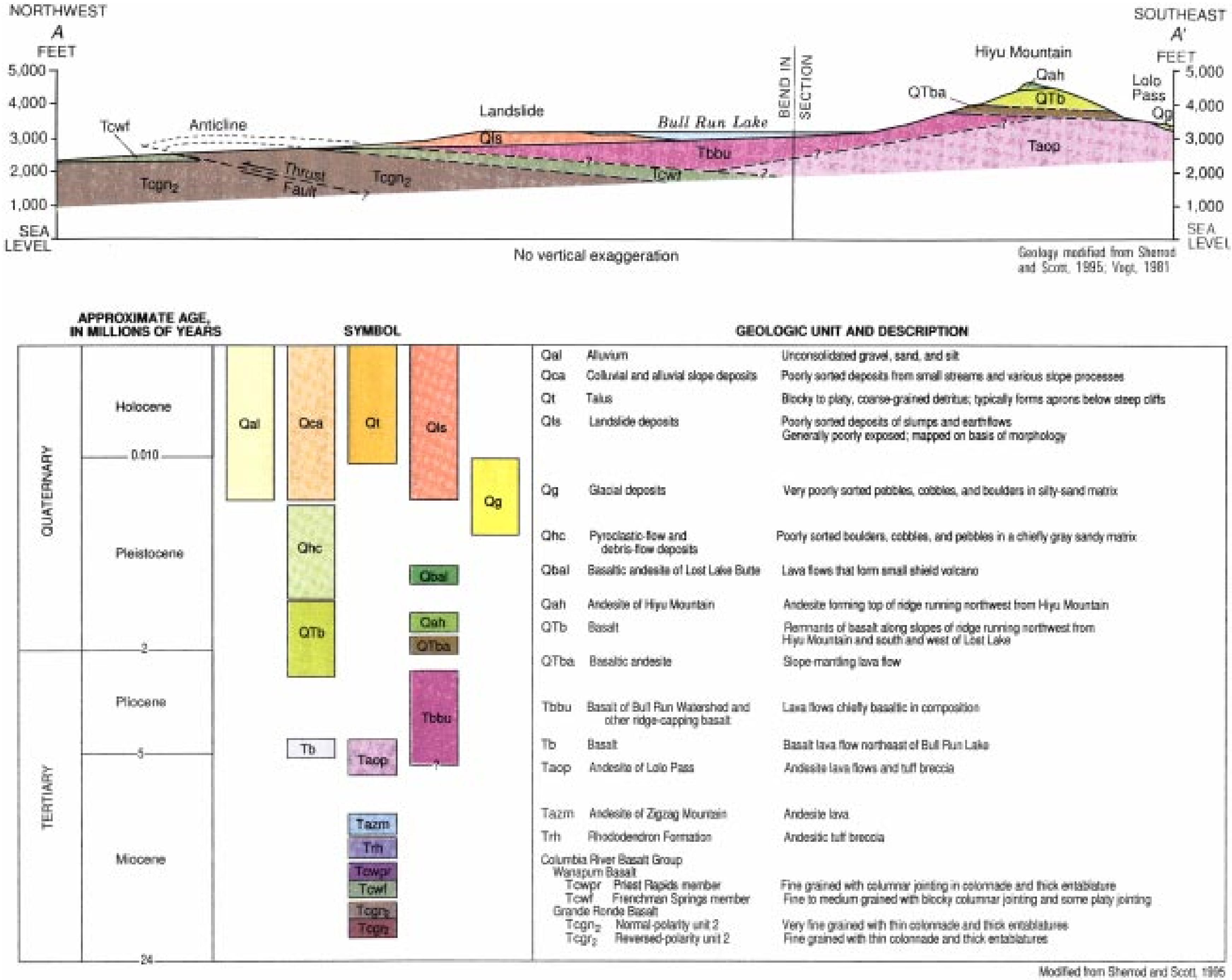


Figure 3. Geologic features of the Bull Run Lake area.

Shannon and Wilson, Inc. (1961) cite a report discussing conditions observed in 1913 and 1914 that suggested the natural dam was formed by two rock slides, from Preacher's Rock (Preachers Peak in fig. 2) and from the northwest-trending ridge near the westernmost corner of Bull Run Lake. Sherrod and Pickthorn (1989b) describe the natural dam as a landslide originating from the canyon wall near Preachers Peak, which resulted in a hummocky terrain underlain by broken basalt. The authors attribute the resulting irregular terrain and apparent fresh lava as the reason the landslide was misinterpreted as a volcanic feature. They also indicate that the landslide must be latest Pleistocene or Holocene, because it is unglaciated.

Evidence of landslides in the Bull Run Watershed has been observed by Beaulieu (1974), who noted a series of massive landslides of Quaternary age, and by Schulz (1981). As seen in figure 2, the natural dam and immediate area around the northwest end of Bull Run Lake fits Beaulieu's (1974, p. 29) description of the appearance of massive landslides in the Bull Run Watershed:

> Areas of massive landsliding are characterized by a variety of topographic features. Basically the downslope movement of material disrupts the terrain so that the ground surface is irregular to hummocky and the drainage is deranged. Springs, swampy areas, and sag ponds are common. Outcrops are rare and scattered and generally consist of broken rock delivered from higher on the slopes.
>
> Viewing the slide as a whole, the slope is gentle relative to the intact surrounding terrain. Where depth of failure is relatively great, the headscarp bounding the upper edge of the slide is commonly concave.

Of all the theories regarding the origin of Bull Run Lake, the "landslide theory" best accounts for the observations of previous investigators. The diverse rock material composing the natural dam; its unsorted and angular character, including the juxtaposition of large blocks and boulders in close proximity to finer-grained materials; the hummocky nature of the surface; and the break in the uniformly sloping valley wall below Preachers Peak are all best explained by a landslide process.

The topography of the area along the southwestern valley wall at the northwestern end of Bull Run Lake may indicate an additional landslide source for part of the natural dam. The fact that there is a relatively gentle slope between the 3,200- and 3,400-foot contours along the base of the ridge at this site (fig. 2) is inconsistent with the steeper slopes farther to the northwest and the southeast. This may lend support to the theory that another landslide occurred in this area, as proposed in the report describing conditions observed in 1913 and 1914 cited by Shannon and Wilson, Inc. (1961). For the purposes of this report, the natural dam will be considered to be the result of one or more landslides until further evidence can be found to substantiate an alternative origin.

The age of the natural dam is bounded by the period of the last glaciation and the age of the oldest lake sediments. Sherrod and Pickthorn (1989b) report that the landslide was unglaciated, indicating a maximum age of less than 15,000 years (Allen, 1989). The oldest lake bottom sediments penetrated during a study by Raymond (1983) were ash deposits from the eruption of Mount Mazama. The climactic eruption of Mount Mazama occurred about 6,900 years ago (Bacon and Lanphere, 1990). Raymond was unable to penetrate through the ash layer, however, and did not reach the consolidated rocks underlying the sediments. The minimum age of the lake is, therefore, greater than 6,900 years.

Description of the Natural Dam

The extent of the landslide was first delineated by Sherrod and Pickthorn (1989b). However, no description was given to the extent of the landslide under the surface of the lake, because detailed topography of the lake bottom was lacking. To estimate the probable geometry of the landslide material, a section along the Bull Run River drainage basin that follows the channel of the Bull Run River across the surface of the landslide and along the bottom of Bull Run Lake was used. Figure 4 is a vertically exaggerated section along the central part of the section (A–A') indicated in figure 3. The section in figure 4 was prepared by using contours from the USGS 1:24,000-scale topographic map for Bull Run Lake and lake bottom topography determined by L.L. Hubbard (USGS, unpub. data, 1981) (fig. 2).

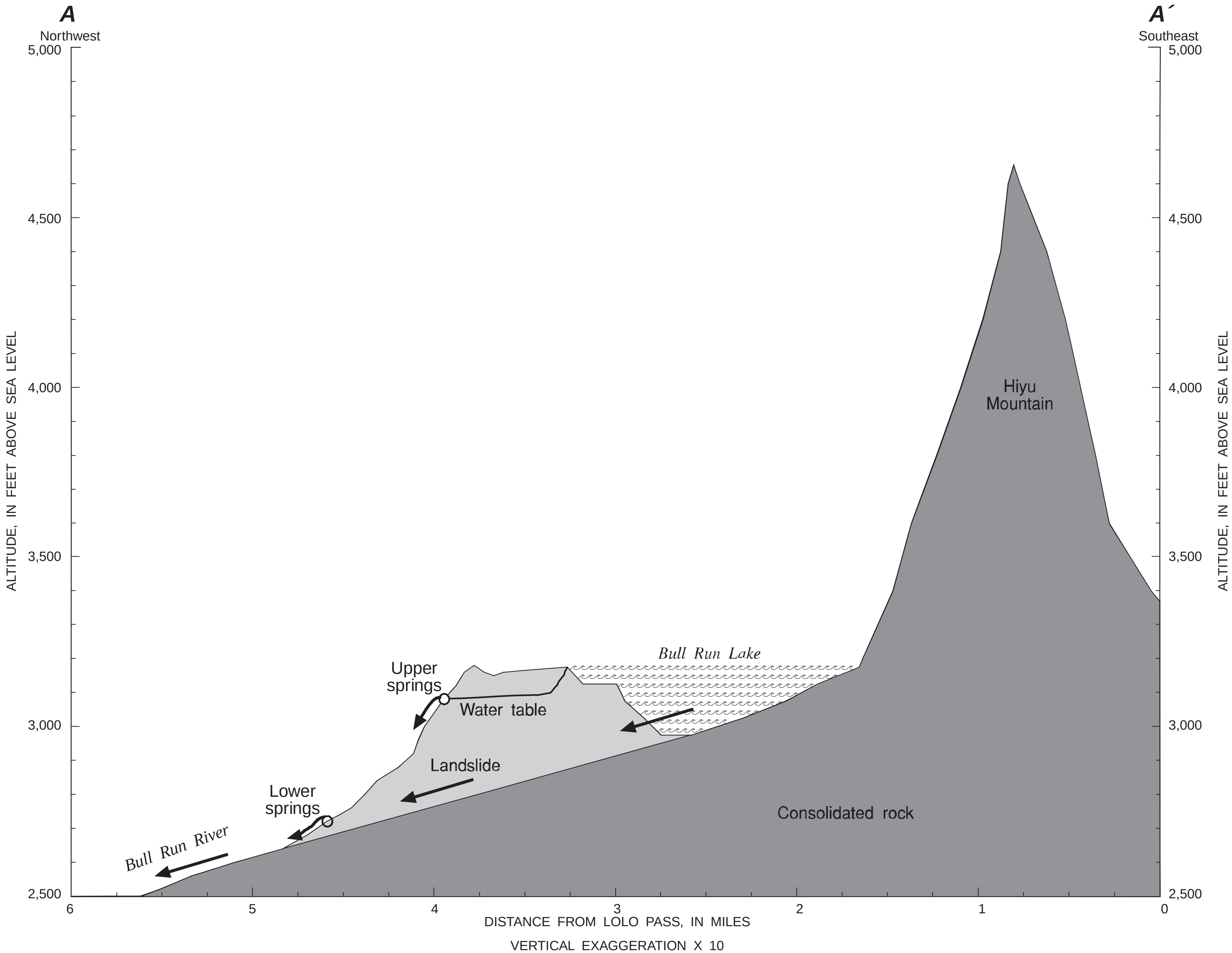


Figure 4. Diagrammatic section along the Bull Run River drainage basin showing landslide and conceptualized ground-water flow. (See figure 3 for location of section.)

It is assumed that the break in slope along the northwestern lake bottom near the deepest part of the lake represents the southwestern extent of the landslide into the lake. The preexisting land surface underlying the landslide was estimated by projecting the line of the slope from the deepest part of the lake to the point at which there is a break in slope near the lower springs (figs. 2 and 4). This estimation results in extending the landslide down drainage a short distance along the immediate channel of the Bull Run River; that assumption is consistent with the change from a broad gentle topography to a steeper canyon along the river. A map of the probable areal extent of the landslide is presented in figure 2.

The dimensions of the landslide as delineated above are as follows: width, as much as 2 mi, length, about 1 mi, and maximum thickness, more than 350 ft. The total volume of the landslide is about 3.9 billion cubic feet. The area covered by the landslide is about 1.1 mi^2, resulting in an average thickness of about 130 ft. Estimates of the percent saturation and volume of water contained within the landslide can be made by using the volume and geometry of the landslide, estimating the position of the water table (the top of the zone of saturation) within the landslide, and estimating a value of porosity for the landslide material. On the basis of the configuration of the water table shown in figure 4, the saturated volume of the landslide is about 3.4 billion cubic feet. The landslide is therefore about 87 percent saturated. The volume of water in the saturated part of the landslide is dependent on the porosity of the landslide material. The porosity of landslides can be quite variable and may range from 15 to 45 percent (R.L. Schuster, USGS, oral commun., 1994). Assuming an average porosity of 0.30 for the landslide material, the volume of water within the saturated zone of the landslide is about 7,600 Mgal.

Ground-Water Flow System

The discussion of ground-water flow is in two parts: (1) flow through the unconsolidated landslide deposits that impound Bull Run Lake and (2) flow through the consolidated rocks (andesites and basalts) that form the drainage basin and underlie Bull Run Lake and the landslide deposits (figs. 3 and 4).

Flow Within the Landslide

Bull Run Lake loses water by seepage through the lake bottom; the seepage eventually emerges as springs farther down the drainage northwest of the lake (Sylvester, 1908; Williams, 1920; Shannon and Wilson, Inc., 1961). About one-third of the lake bottom closest to the natural dam is formed by the landslide (fig. 2). The consolidated rocks, consisting of basalt and andesite, underlie the landslide and form the remaining part of the lake bottom (figs. 3 and 4). Ground-water outflow from the lake is primarily through the unconsolidated landslide material. Landslides have a wide range of values for hydraulic conductivity (a measure of the rate at which water can move through a permeable medium). It is probable, however, that the hydraulic conductivity of the landslide is several orders of magnitude greater than that of the underlying consolidated rocks. The difference in hydraulic conductivity between the two media acts to retard the downward vertical flow of water into the consolidated rocks, and the net effect is that most water that percolates through the lake bottom into the landslide probably flows laterally within this material above the contact of the landslide with the consolidated rocks (fig. 4). The water eventually emerges as contact springs ("lower springs" in fig. 4) at the toe of the landslide in the vicinity of the lower flume.

The outflow of water from the lake through the landslide is related to the hydraulic characteristics of both the landslide material and the lake bottom sediments. Observations of sinkholes within the shallow area of the lake near the natural dam prompted the Portland Water Bureau to isolate part of the lake by a dike, fill some sinkholes, and deposit bentonite clay on some areas of the lake bottom to reduce seepage losses (City of Portland, 1921, 1923, 1925; Shannon and Wilson, Inc., 1961; Short, 1983; D.M. Bloem, City of Portland Bureau of Water Works, oral commun., 1993). The natural deposition of lake sediments also can reduce the outflow of ground water through the lake bottom. No information could be found describing the thickness or hydraulic characteristics of the sediments on the lake bottom. However, Raymond (1983) collected several cores from the deeper parts of the lake, the longest of which was about 12 ft. The cores consist of an organic-rich mud with some clay and end at a layer of volcanic ash deposited by the eruption of Mount Mazama. The lake substrate also has been described as dominated by boulders and cobble near an altitude of 3,178 ft and changing with increasing depth to sand and silt at and below 3,148 ft (Beak Consultants, Inc., 1993).

The presence of a deep water table adjacent to the lake is indicated by information derived from wells drilled in the landslide. During a study of the lake in 1960, two wells were drilled in the landslide less than 150 ft from the lakeshore (Shannon and Wilson, Inc., 1961). Neither well reached water at a depth of 80 ft below the level of the lake. Water pumped into the wells at a rate of 15 gallons per minute could maintain only a 2-ft head in the wells (Shannon and Wilson, Inc., 1961). One well produced a small amount of water at 100 ft below lake level. The great depth of the water table within the landslide adjacent to the lake could be the result of high hydraulic conductivity of the landslide material or low hydraulic conductivity of the lakebed sediments. An attempt to locate and determine the condition of these wells during the current study was unsuccessful.

A series of seeps forming the upper springs is on the western slope of the landslide at an altitude of about 3,060 ft. The origin of the flow from the upper springs may be the intersection of the water table with the land surface along the upper west slope of the landslide (fig. 4). This theory is supported by observations that minimum discharges at the upper springs appear to be strongly correlated to lake stage. That is, the smallest discharge at the upper springs for a given lake stage is directly proportional to the lake stage. These minimum discharges probably represent only seepage from the lake, that is, without contributions from surface runoff (streamflow and overland flow) or the release of water from the lake through the manmade dam. Discharge at the upper springs is zero only when the altitude of the lake is less than 3,158 ft. These observations indicate that a hydraulic connection may exist between the upper springs and the lake through the water table. However, an alternative conceptualization might be that the upper springs are the result of a perched water body that is sustained by leakage from the lake. Beneath the perched water body, a variably saturated zone may exist in which water movement is predominantly downward until the water table is encountered at some point above the contact between the landslide materials and the underlying consolidated rocks. This conceptualization is supported by the apparent lack of seepage along the northwestern face of the landslide between the upper and lower springs during low lake stage and extended dry periods such as were observed between November 8 and 10, 1993.

The infiltration of precipitation and surface runoff from an area near the top of the landslide may result in rapid increases in discharge at the upper springs. Surface runoff collects in the closed depression at the western end of the outlet channel from the lake, about one-fourth mile northwest of the manmade dam. This closed depression, which acts to focus recharge to the water table, also receives water that is released from the lake by the Portland Water Bureau. Water that infiltrates through the ground in this area may serve to raise the water table—resulting in an increase in discharge at the upper springs. The water initially discharging from the upper springs following a recharge event at the closed depression, however, may not be the water that infiltrates at the closed depression. After the infiltrating water has moved through the subsurface from the closed depression to the upper springs, the discharge of the upper springs may consist of the water that infiltrates at the closed depression. This is supported by the observation that an increase in discharge at the upper springs occurs almost immediately, whereas the temperature of the upper springs takes about 1 day to reflect the temperature of the water released from the lake as it infiltrates at the closed depression (D.M. Bloem, City of Portland Bureau of Water Works, oral commun., 1994).

Flow Within the Consolidated Rocks

A conceptual ground-water-flow diagram, or flow net, was constructed to show hypothetical ground-water flow within the consolidated rocks. Figure 5 shows a northwest-southeast section along the Bull Run River drainage basin depicting the steady-state ground-water flow system. The flow net is based only on empirical information owing to the lack of data regarding water levels and ground-water flow lines within the consolidated rocks and the hydraulic properties of the consolidated rocks.

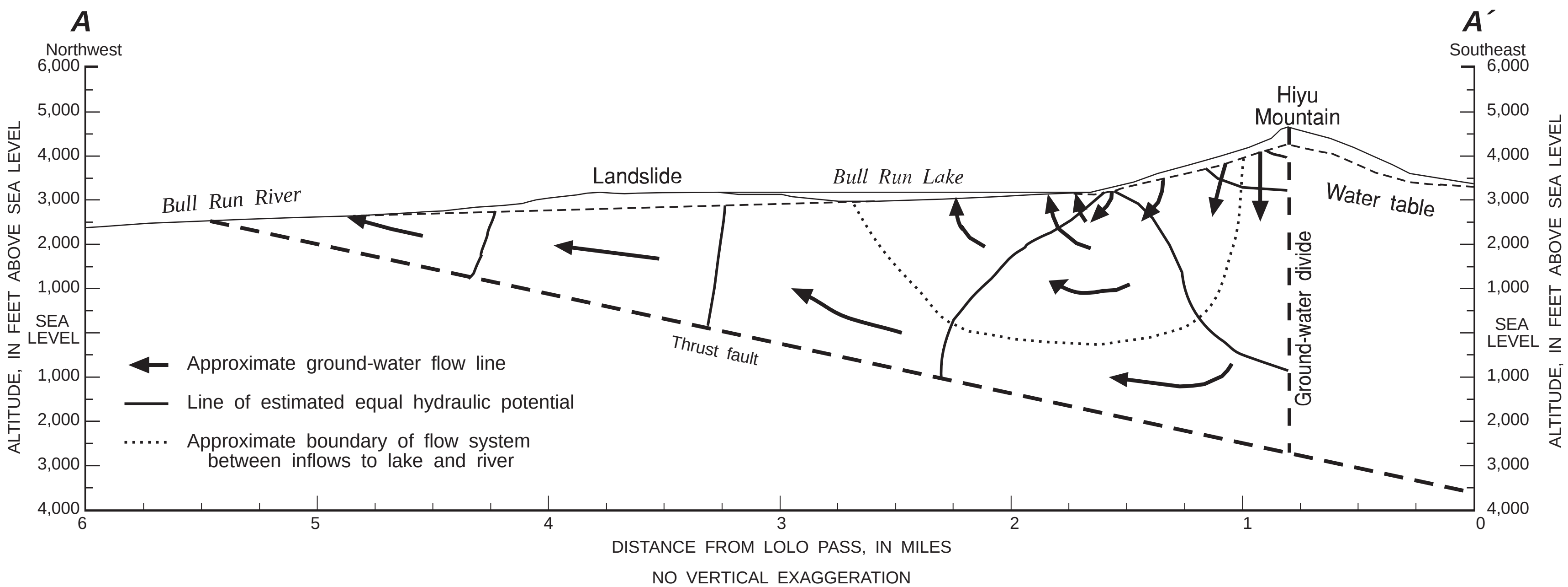


Figure 5. Diagrammatic section along the Bull Run River drainage basin showing hypothetical ground-water flow in the consolidated rocks. (See figure 3 for location of section.)

Equipotential lines (lines of equal head) were first estimated, and ground-water flow lines were drawn perpendicular to the equipotential lines at intervals representing approximately equal recharge along the northwestern slope of Hiyu Mountain. The flow net was drawn using the assumption that the consolidated rocks are isotropic (vertical hydraulic conductivity equals horizontal hydraulic conductivity) and homogeneous. Figure 5 shows the general conceptualization of ground-water flow—it is not intended to determine actual quantities of ground-water flow.

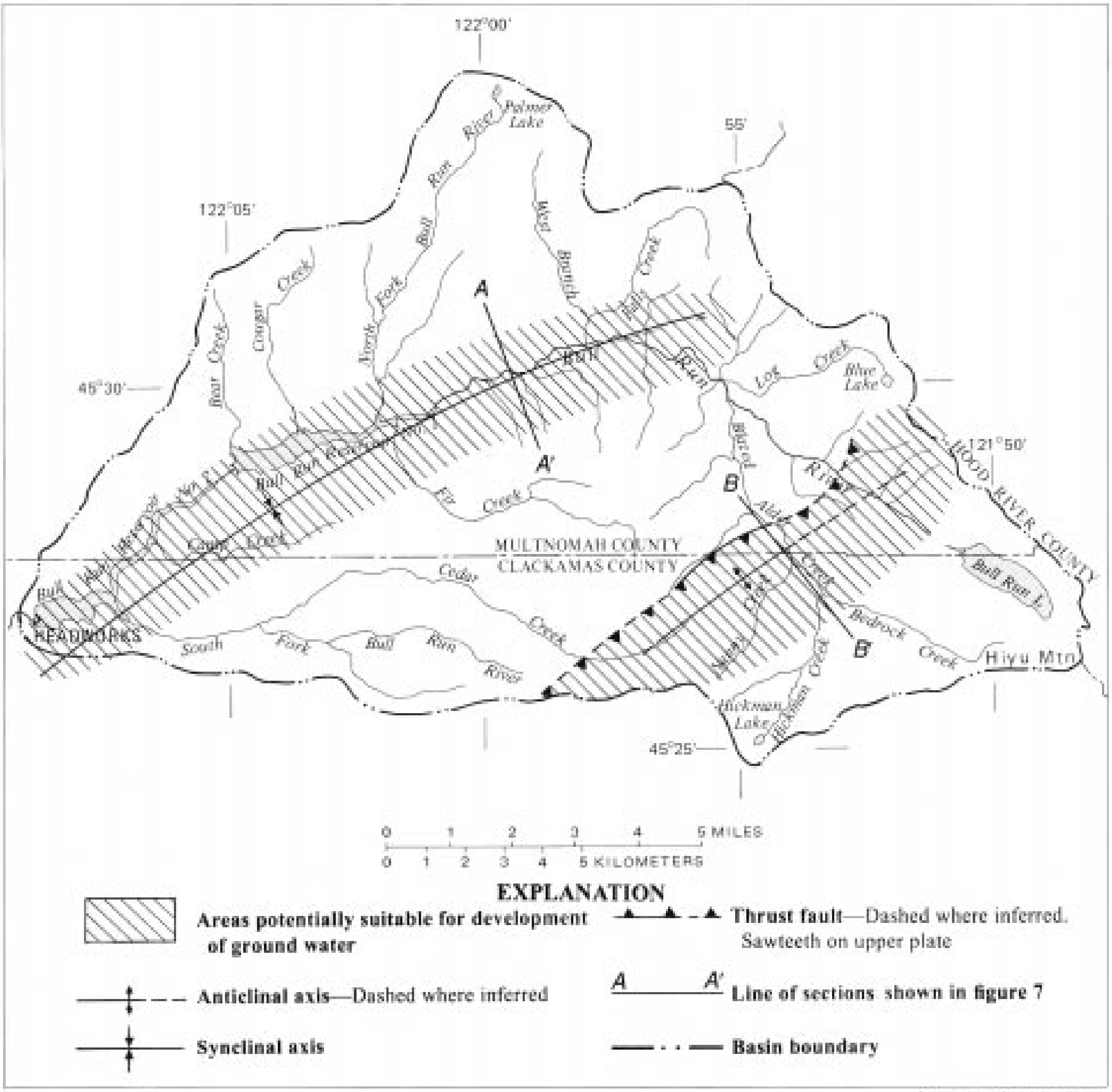
It was assumed that the thrust fault that intersects the land surface about 2 mi northwest of Bull Run Lake (fig. 3) continues beneath the lake at a constant dip to the southeast. The thrust fault was conceptualized as an impermeable barrier to ground-water flow. This decision was based on the observations of Beeson and others (1982), who stated that the thrust zone contains more than 300 ft of massive tectonic breccia that appears to be impermeable and is likely a barrier to the movement of water. A vertical ground-water divide (across which there is no ground-water flow) probably exists beneath the surface-water divide along the topographically high ridges south of Bull Run Lake (fig. 2). The influences of the lake sediments and the landslide material on the ground-water flow system were not considered in the analysis. It was assumed that little or no ground water flows between the landslide and the consolidated rocks. Buried, compacted soils beneath the landslide material probably limit ground-water flow between the consolidated rocks and the overlying landslide material. Also, large downward vertical hydraulic gradients probably exist in the landslide material owing to local recharge and the infiltration of lake water, further limiting the likelihood of upward leakage into the landslide material from the consolidated rocks.

Water infiltrating along the northwestern slopes of Hiyu Mountain moves downward from the land surface through the unsaturated zone to the water table. After the water enters the ground-water flow system, it moves downward from areas of high hydraulic head to areas of low hydraulic head. Some of the water enters Bull Run Lake along the lake bottom, with a greater inflow generally expected to occur nearer the southeastern shoreline than in deeper parts of the lake (Winter, 1976; Winter and Woo, 1990), as represented by the greater density of ground-water flow lines. The remaining ground water flows beneath Bull Run Lake and moves upward as the thickness of the consolidated rocks decreases as a result of the dip of the fault plane. Ground water discharges to the Bull Run River in the area between the western toe of the landslide and the intersection of the fault plane with the land surface. The boundary separating the part of the flow system discharging to the lake from the part of the flow system discharging to the river is shown in figure 5. Note that, in this conceptualization, there is no ground-water outflow from Bull Run Lake through the consolidated rocks; however, this is only one of many conceptualizations possible. Other conceptualizations are possible that might have differences with regard to features such as the proportions of flow between the lake and river, the depth of circulation of the local flow system to the lake, or the parts of the lake bottom which are gaining or losing water to the ground-water system. For a detailed discussion of the interaction of lakes and ground water, the reader is referred to works by Winter (1976, 1978a, 1978b) and Winter and Woo (1990).

Implications for the Use of Ground Water in the Bull Run Watershed

During the review of work pertaining to the hydrogeologic setting of Bull Run Lake, several aspects concerning the possible use of ground water in the Bull Run Watershed became apparent and are presented here. Tectonic structures within the rocks of the Columbia River Basalt Group and the occurrence of ancient alluvial deposits may represent opportunities for the use of ground water to supplement surface-water storage in the Bull Run Watershed. Ground water is present throughout the watershed; however, certain areas may more readily lend themselves to development of the ground-water resources.

Aquifers resulting from the storage of ground water behind structural barriers such as faults or anticlines have been suggested and developed for ground-water utilization (Newcomb, 1959, 1961a, 1961b, 1969, 1982; Beeson and others, 1982). Similar structures exist in the vicinity of Bull Run Lake and Blazed Alder Creek (figs. 6 and 7) (Vogt, 1981).



Geology modified from Sherrod and Scott, 1995; Vogt, 1981

Figure 6. Areas within the Bull Run Watershed potentially suitable for the development of ground water.

In addition, the Bull Run River, between Falls Creek and the Headworks, flows along the axis of a syncline in the Columbia River Basalt Group (Vogt, 1981) that may provide a readily available supply of water from deep wells (fig. 7) (Newcomb, 1961a; Beeson and others, 1982).

Alluvial sediments deposited along the former course of the ancestral Columbia River may underlie the Columbia River Basalt Group along the axis of the syncline in the Bull Run Watershed (fig. 7) and may be suitable for development (Beeson and others, 1982). In addition, within the Bull Run Watershed, part of the Priest Rapids member of the Columbia River Basalt Group also apparently formed an intracanyon flow that followed the paleochannel of a westward flowing river (Vogt, 1981; Tolan and Beeson, 1984; Tolan and others, 1984). The alluvial material, the 350-foot-thick palagonite at the base of the formation, or both may form a useful aquifer.

Ground water tapped by wells near the Bull Run River or its tributaries could be pumped directly into the river or streams. Pumping of wells could start when surface-water reservoirs begin to be drawn down. Pumpage would stop when the surface-water reservoirs are refilling or full, at which time the ground-water system would have an opportunity to be

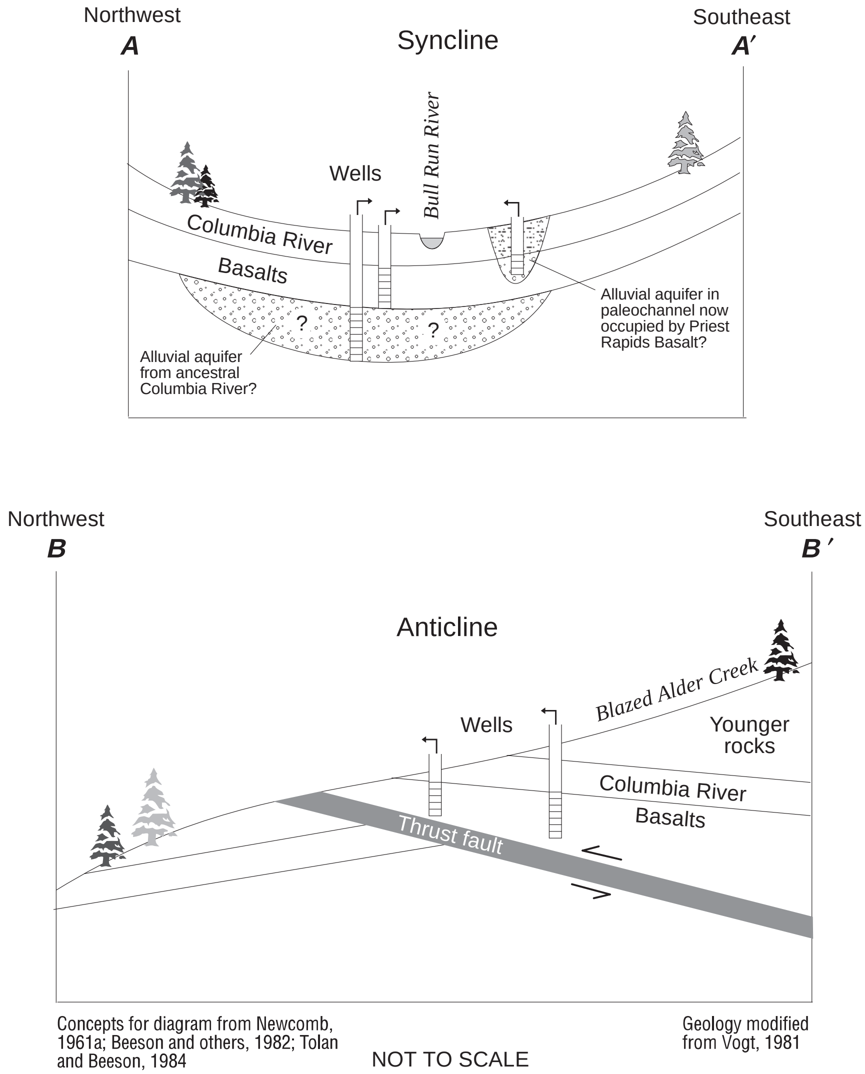


Figure 7. Diagrammatic sections across the Bull Run River drainage basin and along Blazed Alder Creek drainage basin showing areas within the Bull Run Watershed potentially suitable for the development of ground water. (See figure 6 for section locations.)

recharged. It may be necessary to accelerate recharge of the ground-water system and restore ground-water levels through the use of artificial recharge by injecting excess winter surface runoff into wells (see Foxworthy and Bryant, 1967, for example).

Suggestions for future work include detailed site evaluation; exploratory drilling; determination of hydraulic characteristics; modeling of discharge capacity, effects on streamflow, and optimization of pumpage; and development of a pilot study. See Newcomb (1961a) for a discussion of examples, test and production well design, approximate costs, benefits, and possible disadvantages.

PRELIMINARY ESTIMATES OF HYDROLOGIC COMPONENTS

The hydrologic budget of a lake or lake basin is an expression of the conservation of water mass of the hydrologic components. Simply stated, the difference between the hydrologic components that constitute the inflows and outflows of water during a given time period must equal the change in lake storage over the same time period:

$$\text{inflows} - \text{outflows} = \text{change in storage}.$$

Figure 8 shows a conceptualization of the hydrologic components for Bull Run Lake. The equation describing the hydrologic budget for Bull Run Lake is:

$$(P_L + GW_I + SF_I + OF_I) - (E_L + GW_O + SF_O) = \Delta S_L \quad (1)$$

where

inflows:

P_L = precipitation on the lake surface,
GW_I = ground-water inflow to the lake,
SF_I = streamflow to the lake,
OF_I = overland flow to the lake,

outflows:

E_L = evaporation from the lake surface,
GW_O = ground-water outflow from the lake,
SF_O = streamflow from the lake, and

storage:

ΔS_L = change in lake storage.

Existing data for Bull Run Lake were inadequate to independently evaluate the GW_I, SF_I, OF_I, or GW_O components. As a consequence, the approach used in this study was to first determine the hydrologic components for the drainage basin contributing to Bull Run Lake and then to evaluate their usefulness in the analysis of the hydrologic components for Bull Run Lake.

The equation describing the hydrologic budget for the Bull Run Lake drainage basin is similar to that of the lake; it stipulates that the inflows minus the outflows must equal the change in storage components for the basin. However, because the lake's drainage basin is, by definition, surrounded by a surface-water divide, there is no inflow from streamflow or overland flow. If it is also assumed that a ground-water divide is coincident with the surface-water divide along the boundary of the lake basin, then ground-water inflow can be neglected. Figure 9 shows a conceptualization of the hydrologic components for the lake basin. Precipitation on the lake surface from rain and snow is considered separately from precipitation on the land surface, which also includes precipitation resulting from fog drip from the forest canopy. The equation summarizing the hydrologic budget for the Bull Run Lake drainage basin is:

$$(P_L + P_{LS}) - (E_L + ET_{LS} + GW_{OL} + GW_{OC} + SF_O) = (\Delta S_L + \Delta S_{SM} + \Delta S_{GW}) \quad (2)$$

where

inflows:

P_L = precipitation on the lake surface,
P_{LS} = precipitation on the land surface,

outflows:

E_L = evaporation from the lake surface,
ET_{LS} = evapotranspiration from the land surface,
GW_{OL} = ground-water outflow from the lake basin, through landslide,
GW_{OC} = ground-water outflow from the lake basin, through consolidated rocks,
SF_O = streamflow from the lake, storage:
ΔS_L = change in lake storage,
ΔS_{SM} = change in soil-moisture storage, and
ΔS_{GW} = change in ground-water storage.

Each component of the hydrologic budget will be considered below.

Associated with each budget term is an uncertainty that represents the inherent errors in measurement and interpretation (Winter, 1981). Measurement errors result from attempts to measure a quantity at a point using imperfect instruments and from inadequate sampling design and data-collection methods. Interpretation errors result from inaccurate estimates of temporally and spatially variable quantities based on point data and from improper selection of techniques for data analysis. Many of the hydrologic components have several sources of error. The total uncertainty can be calculated by using two methods: a "typical" and "worst possible." The typical uncertainty assumes that the errors are independent and, therefore, that there is some compensation for measurements that are too high with those that are too low (Winter, 1981). The typical uncertainty is calculated as the square root of the sum of squares of the errors. The worst possible uncertainty assumes that the errors are additive and is calculated as the sum of the errors. For the purposes of this study, the total uncertainty was calculated using the method of worst possible uncertainty for hydrologic components that have several sources of error.

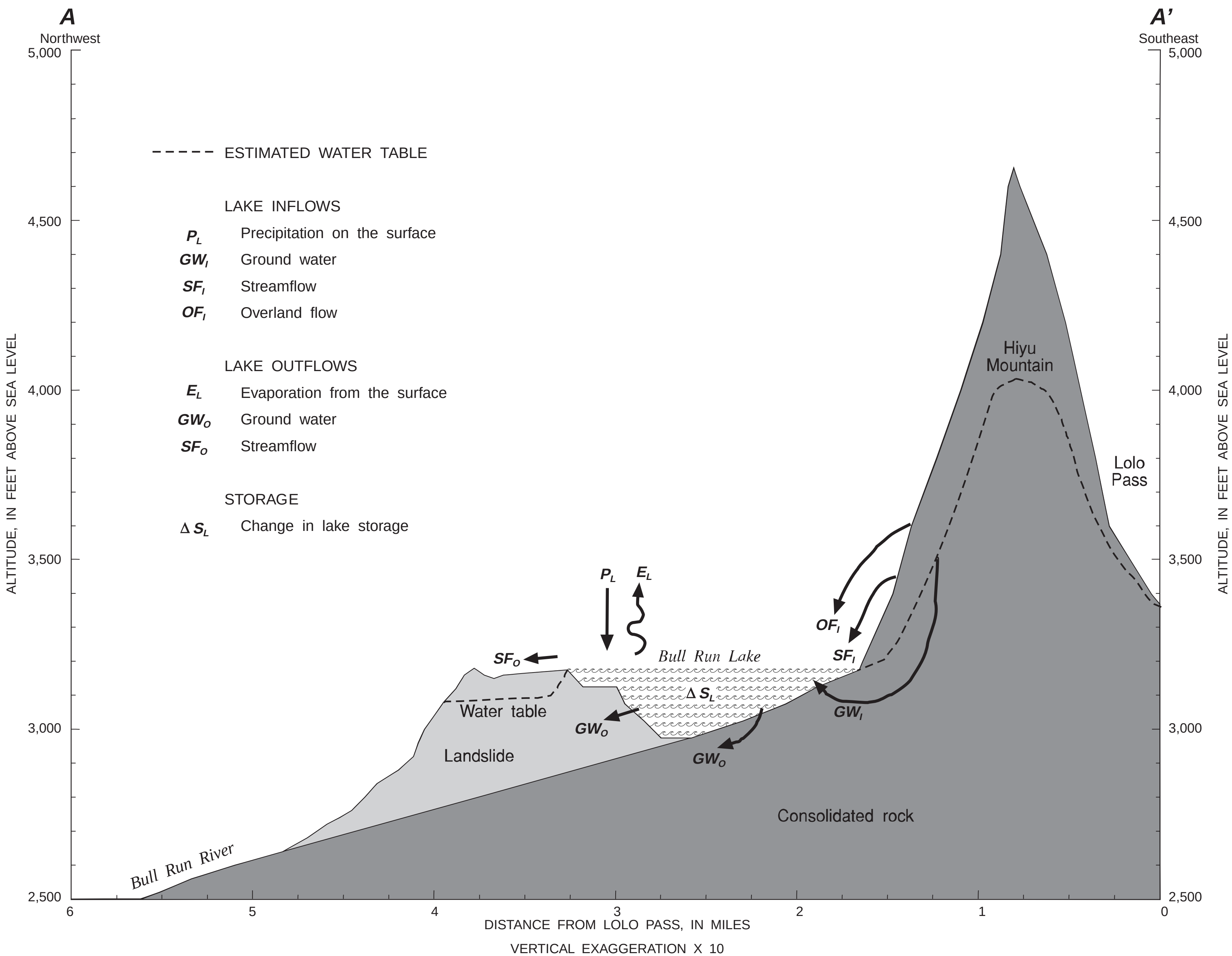


Figure 8. Diagrammatic section along the Bull Run River drainage basin showing conceptualized hydrologic budget terms for Bull Run Lake. (See figure 3 for location of section.)

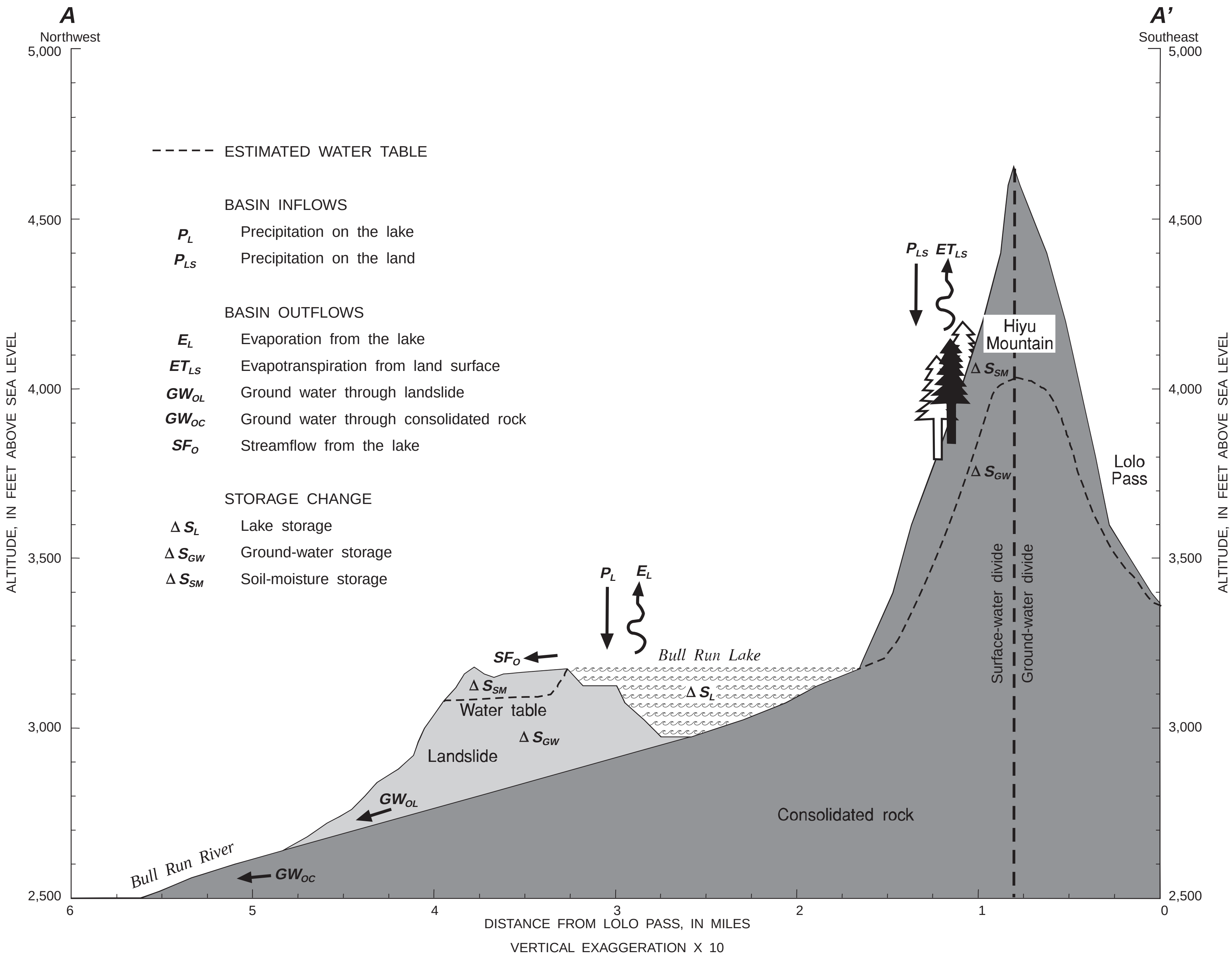


Figure 9. Diagrammatic section along the Bull Run River drainage basin showing conceptualized hydrologic budget terms for Bull Run Lake drainage basin. (See figure 3 for location of section.)

The uncertainty of each of the hydrologic components is estimated and used to determine a range of values for each component. The information will be useful in determining the reliability of the value estimated for each component. It can also help to guide future data-collection efforts by identifying which components have the greatest uncertainty relative to one another.

Water Inflows to the Bull Run Lake Drainage Basin

Inflow to the Bull Run Lake drainage basin consists of precipitation from rain and snow on the lake surface and on the land surface and of fog drip from the forest canopy onto the land surface. However, because of the possible importance of fog drip from the forest canopy onto the land surface, this inflow will be considered separately. No current precipitation data are available for Bull Run Lake. Data from nearby climatic stations were used to interpolate the amount of precipitation from rain and snow. Fog drip was estimated by using information from a study in another part of the Bull Run Watershed.

Precipitation on the Lake Surface

Precipitation on the Bull Run Lake surface is in the form of rain and snow. The amount of precipitation was calculated by using the average annual precipitation scaled to the 1993 water year. The estimate of average annual precipitation used in this study is the spatial distribution determined for the 1961–90 period by Taylor (1993a) using the PRISM model (Daly and Neilson, 1992; Daly and others, 1994). Average annual precipitation from rain and snow in the drainage basin of Bull Run Lake ranges from about 95 to 115 in/yr, with an area-weighted mean of about 104 in/yr for the drainage basin and about 103 in/yr for the lake (fig. 10). This range was scaled by the ratio of the annual precipitation during the 1993 water year to the average annual precipitation, as indexed by the nine nearest climatic stations (fig. 11 and table 2). For each index station, the ratio of the precipitation during the 1993 water year to the average annual precipitation during the period 1961–90 was weighted by multiplying by the inverse of the squared distance between the station and Bull Run Lake. These weighted ratios were summed and then divided by the sum of the inverse of the squared distance between each station and Bull Run Lake. Precipitation at Bull Run Lake during the 1993 water year was about 101 percent of the 1961–90 annual average. The volume of precipitation contributed to the lake during the 1993 water year was calculated as the sum of the precipitation on the lake surface within each contour band. The average rate of precipitation during the 1993 water year within each contour band was multiplied by the mean surface area of the lake subtended by each contour band. The mean surface area of the lake was determined from an analysis of the relation between lake stage and surface area (fig. 12) calculated by using the lake bottom topography. The mean lake stage during the 1993 water year was 3,157 ft, corresponding to a surface area of about 0.62 mi^2.

Uncertainty in the estimate of the amount of precipitation from rain and snow on the lake surface can arise from errors associated with the precipitation measurement using gages at climatic stations and from the method of regionalization of the precipitation distribution in the Bull Run Lake area. Winter (1981) provides examples of estimates for the uncertainty in the various components involved with the commonly used methods for the measurement and interpolation of precipitation. Assuming a worst possible estimate for precipitation results in an overall uncertainty of 30 percent.The current study includes additional uncertainty associated with the estimation of precipitation using the PRISM model, which was calculated as 16 percent for northern Oregon (Daly and others, 1994). A worst possible estimate of the total uncertainty of 46 percent was used in the calculation of the volumes of precipitation presented in table 3.

Precipitation on Land Surface

Precipitation in this study includes moisture deposited from the atmosphere onto the ground or forest canopy and consists of rain, snow, and fog drip.

Rain and Snow

Precipitation from rain and snow on the land surface was calculated in a manner similar to that for precipitation on the lake surface. Average annual precipitation from rain and snow on the land surface of the drainage basin of Bull Run Lake has an area-weighted mean of about 105 in/yr.

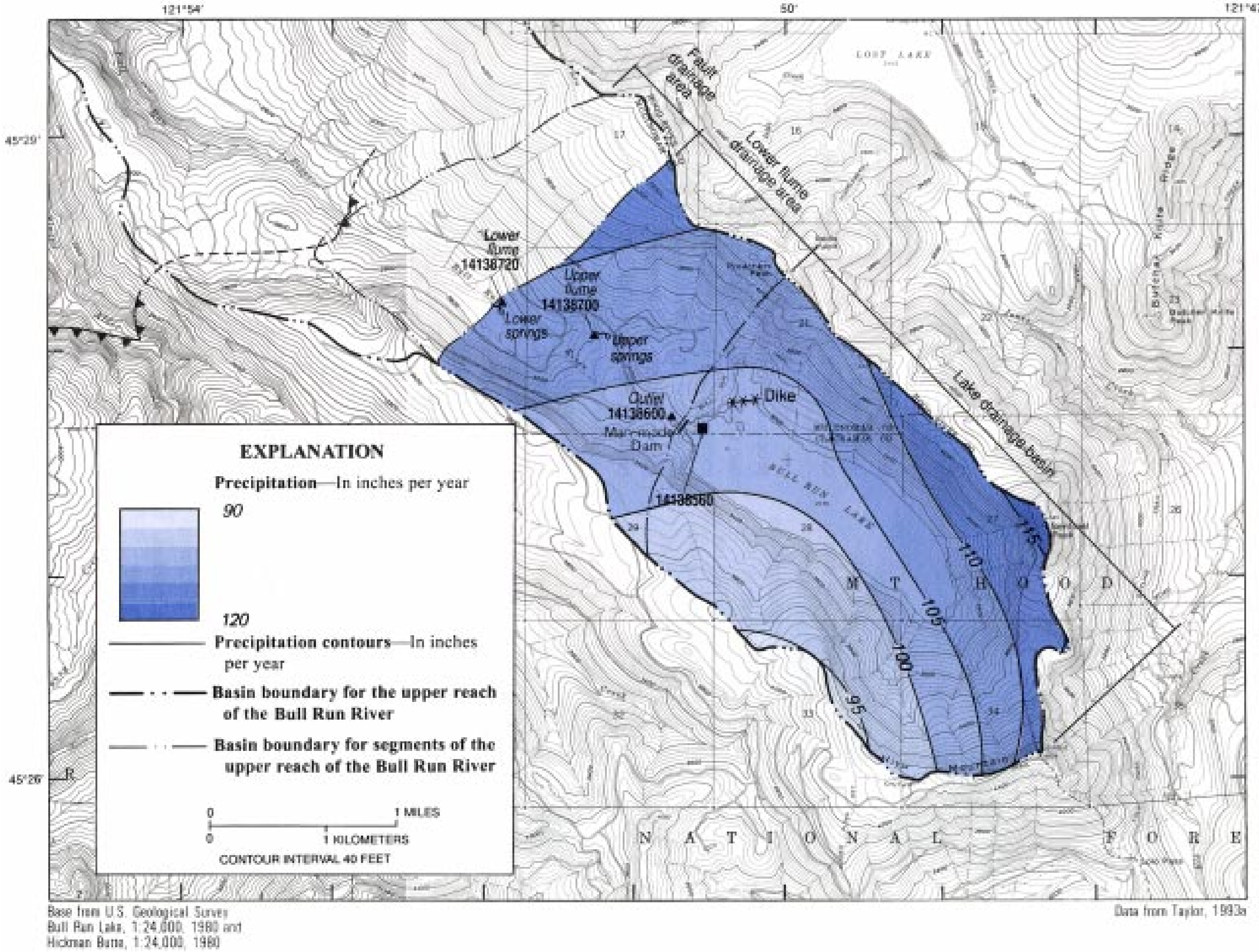


Figure 10. Estimated average annual precipitation distribution from rain and snow in the vicinity of Bull Run Lake for the period 1961–90.

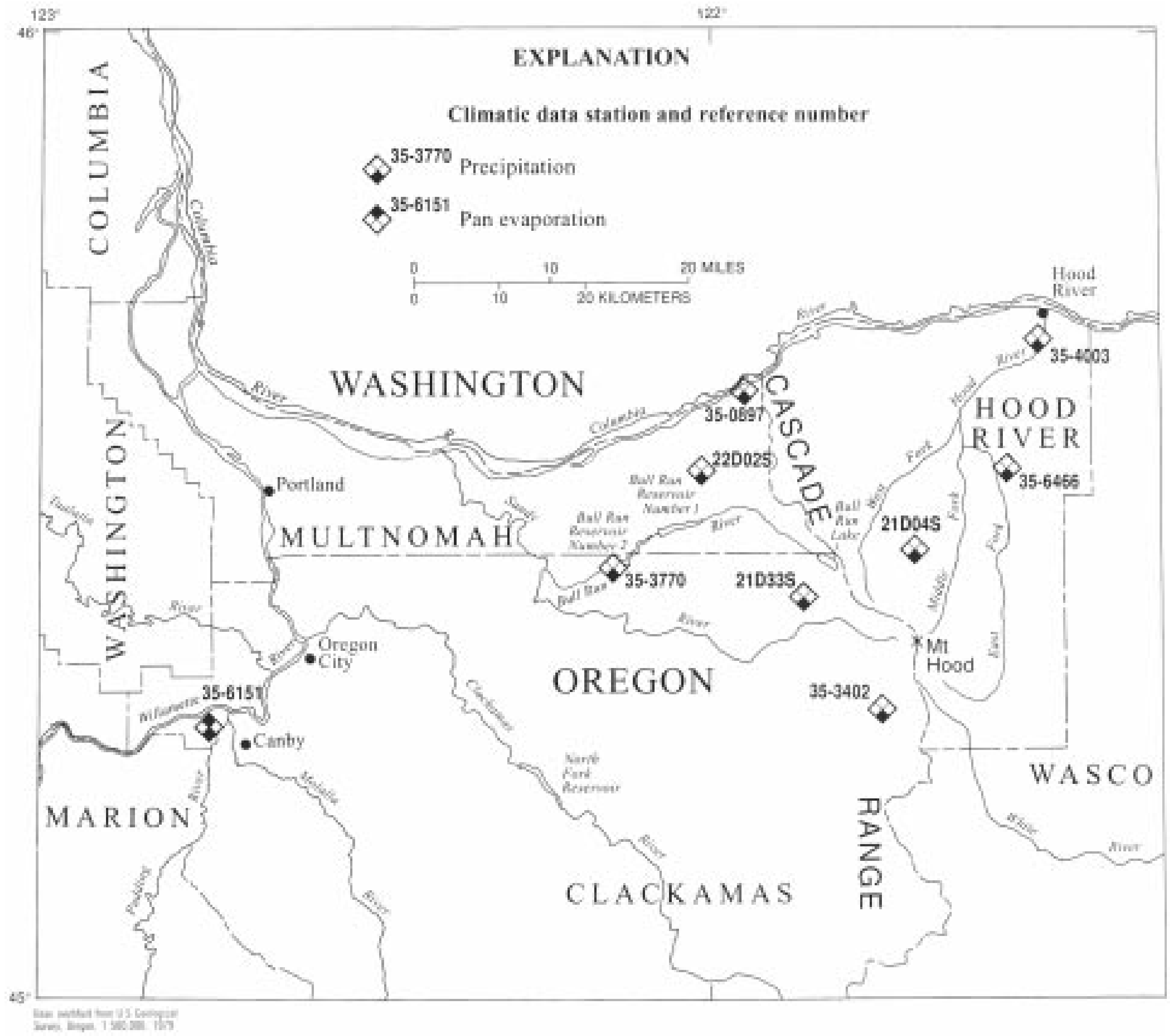


Figure 11. Location of climatic data stations.

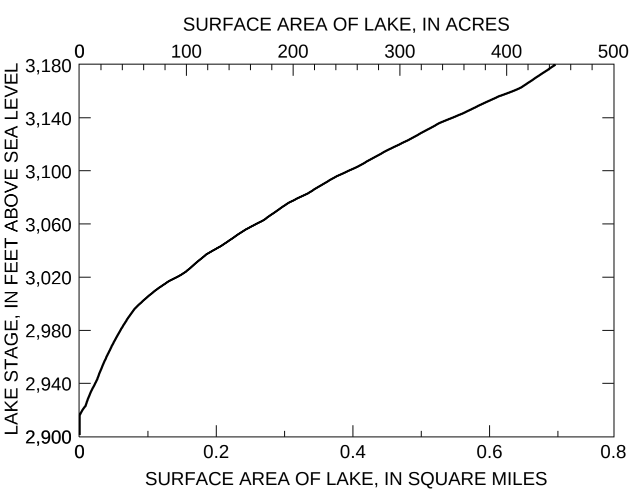


Figure 12. Relation between lake stage and surface area at Bull Run Lake. (Data modified from L.L. Hubbard, U.S. Geological Survey, unpub. data, 1981.)

This value was scaled by 101 percent, the ratio of the annual precipitation during the 1993 water year to the average annual precipitation, as indexed by the nine nearest climatic stations (fig. 11 and table 2). A total uncertainty of 46 percent was used in the calculation of the volumes of precipitation from rain and snow on the land surface which are presented in table 3.

Fog Drip

Fog drip is the moisture in the atmosphere that condenses onto the forest canopy and falls to the ground. The contribution from fog drip to the total precipitation in part of the Bull Run Watershed was investigated by Harr (1982). The study was conducted in the Fox Creek experimental watersheds, which are about

Table 3. Precipitation from rain and snow and from fog drip for the 1993 water year

[mi^2, square miles; in, inches; yr, year; Mgal, million gallons; volumetric values rounded to two significant figures]

Location	Area (mi^2)	Rate of precipitation (in/yr)	Volume of precipitation (Mgal/yr)
Precipitation from rain and snow			
On the Bull Run Lake surface [1]	0.62	56–152	600–1,600
On the land surface within the Bull Run Lake drainage basin [1]	2.82	57–155	2,800–7,600
Total for Bull Run Lake drainage basin	3.44	57–153	3,400–9,200
Lower flume drainage area	1.64	57–155	1,600–4,400
Precipitation from fog drip			
On the Bull Run Lake surface [2]	0.73	0	0
On the land surface within the Bull Run Lake drainage basin [2]	2.71	0–70	0–3,300
Total for Bull Run Lake drainage basin	3.44	0–54	0–3,300
Lower flume drainage area	1.64	0–70	0–2,000

[1] At mean lake stage during the 1993 water year—3,157 feet above sea level.

[2] At full pool—3,178 feet above sea level.

10 mi east of Bull Run Lake and are very similar to the area around the lake. The watersheds range in altitude from 2,800 to 3,500 ft, have an average annual precipitation (rain and snow) of about 113 in/yr (Harr, 1982), and consist of old growth Douglas fir and western hemlock mixed with Pacific silver fir. Harr (1982) measured net precipitation using a series of eight 80-ft-long collector troughs. Two troughs were randomly located in each of two areas logged by clearcut and in each of two unlogged areas. Net precipitation was measured for each trough and compared to precipitation measured in a standard rain gage in a nearby clearing. For the 1980 water year, Harr (1982) found that fog drip amounted to about 35 in/yr, whereas precipitation from rain and snow totaled 79 in/yr.

Unfortunately, no additional work has been done to delineate the spatial distribution of fog drip within the Bull Run Watershed, quantify the amount of variation in fog drip from year to year, or determine if fog drip can be estimated as a percentage of the average annual precipitation from rain and snow. Harr (1982) chose to use the value of 35 in/yr, rather than a value scaled to precipitation (rain and snow), to explain discrepancies in the water yield calculated for the Bull Run Watershed by Luchin (1973) and for streamflow anomalies for the Fox Creek watersheds. Therefore, the value of 35 in/yr will be used as an estimate of fog drip for the forested area around Bull Run Lake. However, the value of 35 in/yr may be unreasonably large (Antonius Laenen, USGS, oral commun., 1994; G.L. Gallino, USGS, oral commun., 1995). Because data regarding uncertainty of fog drip measurements do not exist, a value of 100 percent was assumed. The forested area around Bull Run Lake was calculated as the area of the lake drainage basin minus the area of the lake at full pool. No fog drip was assumed to contribute directly to the lake owing to the lack of forest canopy over the lake. Table 3 summarizes the estimated contribution of fog drip to the Bull Run Lake drainage basin.

Water Outflows from the Bull Run Lake Drainage Basin

The outflow of water from the lake basin consists of evaporation from the lake, evapotranspiration from the land surface, ground-water outflow through the landslide, ground-water outflow through the consolidated rocks, and streamflow from Bull Run Lake resulting from the release of water from the lake. No data could be found regarding evaporation or evapotranspiration from the area of Bull Run Lake. Evaporation from the lake was estimated by using pan evaporation data collected at a climatic station outside the watershed. Evapotranspiration was estimated by comparison with studies on a watershed with similar basin characteristics. Outflow of ground water through the landslide was estimated by using a lake stage-seepage relation established at the lower flume. Ground-water outflow through the consolidated rocks could not be estimated owing to a lack of data. Streamflow from the lake attributable to the release of water through the lower conduit was estimated by an analysis of the discharge of the Bull Run River at the lower flume.

Evaporation from the Lake

Estimates of lake evaporation were based on daily Class A evaporation pan data from the North Willamette Experiment Station (station 35–6151) 46 mi west of Bull Run Lake (fig. 11 and table 2). During the 1993 water year, total pan evaporation was 36.4 inches. The volume of evaporation from a pan is generally considered to be larger than that from a lake, primarily because of differences in water temperature in the pan and lake, and because of differences in air circulation. A pan coefficient can be used to relate pan evaporation to lake evaporation. A pan coefficient of 0.73 for the location of Bull Run Lake was determined from a map of annual pan coefficients for the United States (Farnsworth and others, 1982). The estimated pan evaporation expected at Bull Run Lake is probably less than that measured at the North Willamette Experiment Station. Bull Run Lake is situated in a sheltered basin at an altitude that is 3,000 ft higher, probably resulting in cooler average temperatures and higher average humidities. Winter (1981) provides examples of estimates for the uncertainty in the various components involved with the commonly used methods for the measurement and interpolation of evaporation using evaporation pans. Assuming a worst possible estimate for evaporation results in an overall uncertainty of 40 percent. The volume of evaporation, calculated by multiplying the estimated annual lake evaporation by the mean surface area of the lake during the 1993 water year and applying the uncertainty in the measurement, was estimated to range from about 170 to 410 Mgal for the 1993 water year.

Evapotranspiration from the Land Surface

An area similar to the Bull Run Lake drainage basin is the H.J. Andrews Experimental Forest, which is considered a benchmark for watersheds within Douglas fir forests on the western slopes of the Oregon Cascade Range (Rothacher and others, 1967). The forest consists of old-growth Douglas fir mixed with western hemlock, western red cedar, and true firs, with an understory of rhododendron, vine maple, and Pacific yew. Rothacher and others (1967) calculated evapotranspiration in three small watersheds within the H.J. Andrews Experimental Forest that range in altitude from 1,450 to 3,550 ft. The rate of evapotranspiration was estimated as 21 in/yr for the period 1959–62, during which the average annual precipitation was 92 in/yr. Waring and Schlesinger (1985) calculated evapotranspiration rates of 29 in/yr for 66 inches precipitation in 1973, and 21 in/yr for 120 inches precipitation in 1974 for sites in the H.J. Andrews Experimental Forest. Results of these two studies yield an estimated average annual evapotranspiration of 23 in/yr.

Fritschen and others (1977) installed and monitored a single 92-ft Douglas fir in a weighing lysimeter in the Cedar River watershed. The watershed is 40 mi southeast of Seattle, Washington, at an altitude of 700 ft and is forested with Douglas fir and hemlock. The results for the single tree were translated to an area basis for a stand of similar trees and yielded an evapotranspiration rate of 24 in/yr, for a period with an average precipitation of 55 in/yr (Fritschen and others, 1977).

On the basis of the evapotranspiration studies discussed above, the value of 24 in/yr was selected for use in the current study to estimate the rate of evapotranspiration of the forested areas within the Bull Run Lake drainage basin. The estimate of evapotranspiration from the land surface has a large uncertainty because it was derived entirely by comparison with studies performed outside of the Bull Run Watershed. It is likely that the actual evapotranspiration is within 12 in/yr of the 24 in/yr value used as the estimate of evapotranspiration around Bull Run Lake. Therefore, an uncertainty of 50 percent will be used. Using the estimates of the rate of evapotranspiration and its associated uncertainty results in an estimate of the outflow from the Bull Run Lake drainage basin that ranges from 600 to 1,800 Mgal.

Ground-Water Outflow

Ground-water outflow was separated into two components: outflow of ground water from Bull Run Lake through the natural dam formed by the landslide and outflow of ground water through the consolidated rocks underlying the entire Bull Run Lake drainage basin.

Outflow through the Landslide

The discharge of the Bull Run River at the lower flume is derived from several sources of water: ground-water outflow from Bull Run Lake through the landslide, baseflow from ground water originating in the lower flume drainage area (the drainage area contributing to the Bull Run River at the lower flume exclusive of the lake drainage basin as shown in fig. 2), surface runoff from the lower flume drainage area, and streamflow from Bull Run Lake. In this report, the term "baseflow" will be used to describe the ground-water outflow originating in the lower flume drainage area.

From Darcy's law, the rate of ground-water outflow through the landslide from the lake is a function of the hydraulic gradient, the surface area through which the water seeps, and the hydraulic conductivity of the conducting material. The value of these three properties may each be a function of lake stage. The hydraulic gradient is directly proportional to hydraulic head, as represented by the lake stage. The area of the lake bottom through which water seeps increases as lake stage increases. The average hydraulic conductivity of the lake bottom sediments may decrease with lake depth at a given stage as sediment thickness increases and sediment particle size decreases.

The stage of Bull Run Lake and discharge of the Bull Run River at the lower flume is illustrated in figures 13 and 14 for continuous daily mean stage and discharge data collected from October 1, 1992, through June 8, 1994. An estimate of the lake stage-stream discharge relation can be developed by plotting discharge at the lower flume as a function of lake stage (fig. 15). For a given altitude of the lake surface, the smallest stream discharge should represent flows that contain the greatest proportion of ground-water outflow from Bull Run Lake through the landslide. If, at these times, surface runoff and baseflow from the lower flume drainage area and streamflow from Bull Run Lake are assumed to be negligible, the entire discharge is presupposed to be due to the outflow of ground water from the lake. These points should define a curve that empirically describes the relationship between lake level and ground-water outflow from the lake. To adequately define the lower limit of

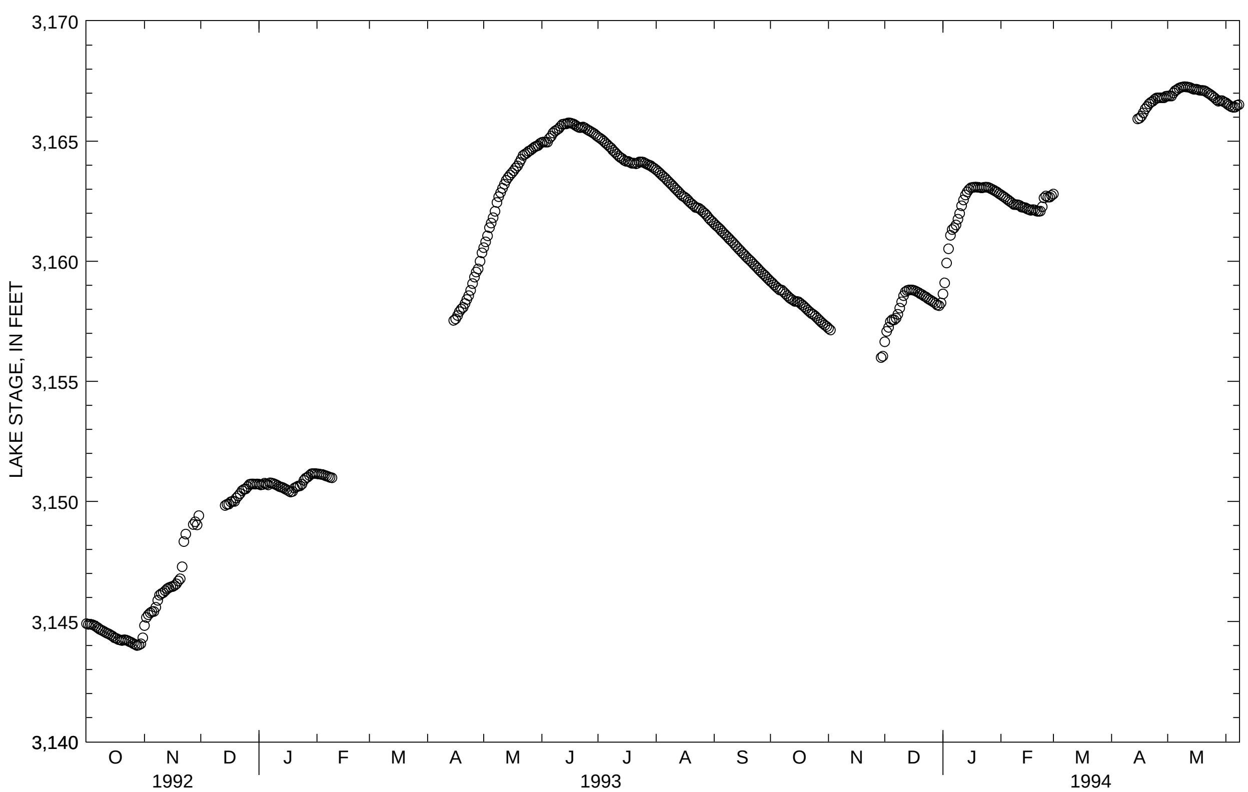


Figure 13. Daily mean stage of Bull Run Lake for the period October 1, 1992, through June 8, 1994.

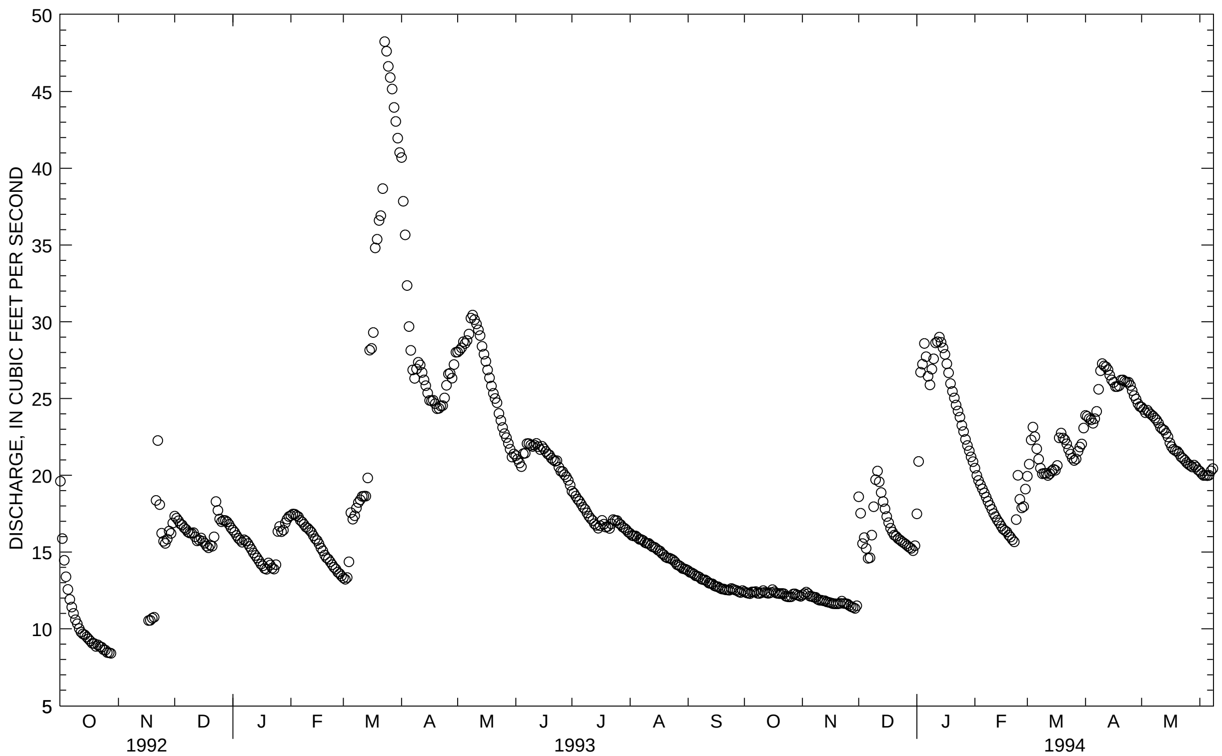


Figure 14. Daily mean discharge of the Bull Run River at the lower flume for the period October 1, 1992, through June 8, 1994.

the curve in figure 15, a long record of data covering a large range of lake stages is needed, especially for periods when contributions from surface runoff and baseflow from the lower flume drainage area, and streamflow from the lake are small. However, only data from October 1, 1992, through June 8, 1994 were used for this analysis. Therefore, a linear relation between lake stage and ground-water outflow is assumed because of the lack of sufficient data to indicate otherwise. The line with the smallest slope was estimated by a visual best fit through the data points representing the smallest discharge for a given lake stage. The empirically derived equation for the line describing the relation between lake stage and ground-water outflow from Bull Run Lake through the landslide is:

$$GW_{OL} = 0.2467L - 767.3 \qquad (3)$$

where

GW_{OL} = discharge to Bull Run River at lower flume in ft^3/s, and

L = altitude of the lake surface in feet above sea level.

The equation is not necessarily valid for lake stages outside the range of those used to develop the relation (3,144 to 3,167 ft).

Using the lake stage data and equation 3, estimates of the daily mean ground-water outflow from the lake through the landslide were calculated. Uncertainty in the estimate of outflow through the landslide is a result of the combination of errors in the determination of the stage-seepage relation and in the collection of the data. Winter (1981) states that the error in measured discharge of flumes is about 5 percent. The uncertainty in the measurement of lake stage, using a manometer gage, is about ± 0.02 ft at Bull Run Lake (G.L. Gallino, USGS, written commun., 1995). That uncertainty is about 0.1 percent of the range of variation in lake stage historically observed at the lake. The uncertainty in the stage-seepage relation was estimated as about 25 percent on the basis of the possible relations that could have been used to describe the empirical relation between stage of Bull Run Lake and discharge of the Bull Run River at the lower flume (fig. 15). The total worst case uncertainty estimated for the ground-water outflow from Bull Run Lake through the landslide is about 30 percent. The total ground-water outflow from the lake through the landslide for the 1993 water year was calculated, using the sum of the estimates of daily mean discharge and applying the uncertainty in the measurement, and ranged from about 1,800 to 3,400 Mgal.

An underestimate of the ground-water outflow from the lake through the landslide could arise from the possibility that the streamflow-gaging station at the lower flume is not measuring all of the ground-water outflow through the landslide. The gaging station may be above the contact of the toe of the landslide with the underlying consolidated rocks. Ground-water outflow from the lake through the landslide may discharge to the river downstream from the gaging station. Shannon and Wilson, Inc. (1961) stated that, for this reason, perhaps only a small part of the discharge of ground water from the lake is measured at the lower flume.

Ground-water outflow from the lake through the landslide (calculated as the mean of the range of flow volumes for ground-water outflow from Bull Run Lake through the landslide) was subtracted from the total discharge at the lower flume to yield the discharge owing to surface runoff and baseflow within the lower flume drainage area and streamflow from the lake. A baseflow recession analysis was performed on the resulting discharge data to separate the ground-water outflow and surface-runoff components of discharge from the lower flume drainage area.

The baseflow component of the discharge of the Bull Run River at the lower flume was calculated by

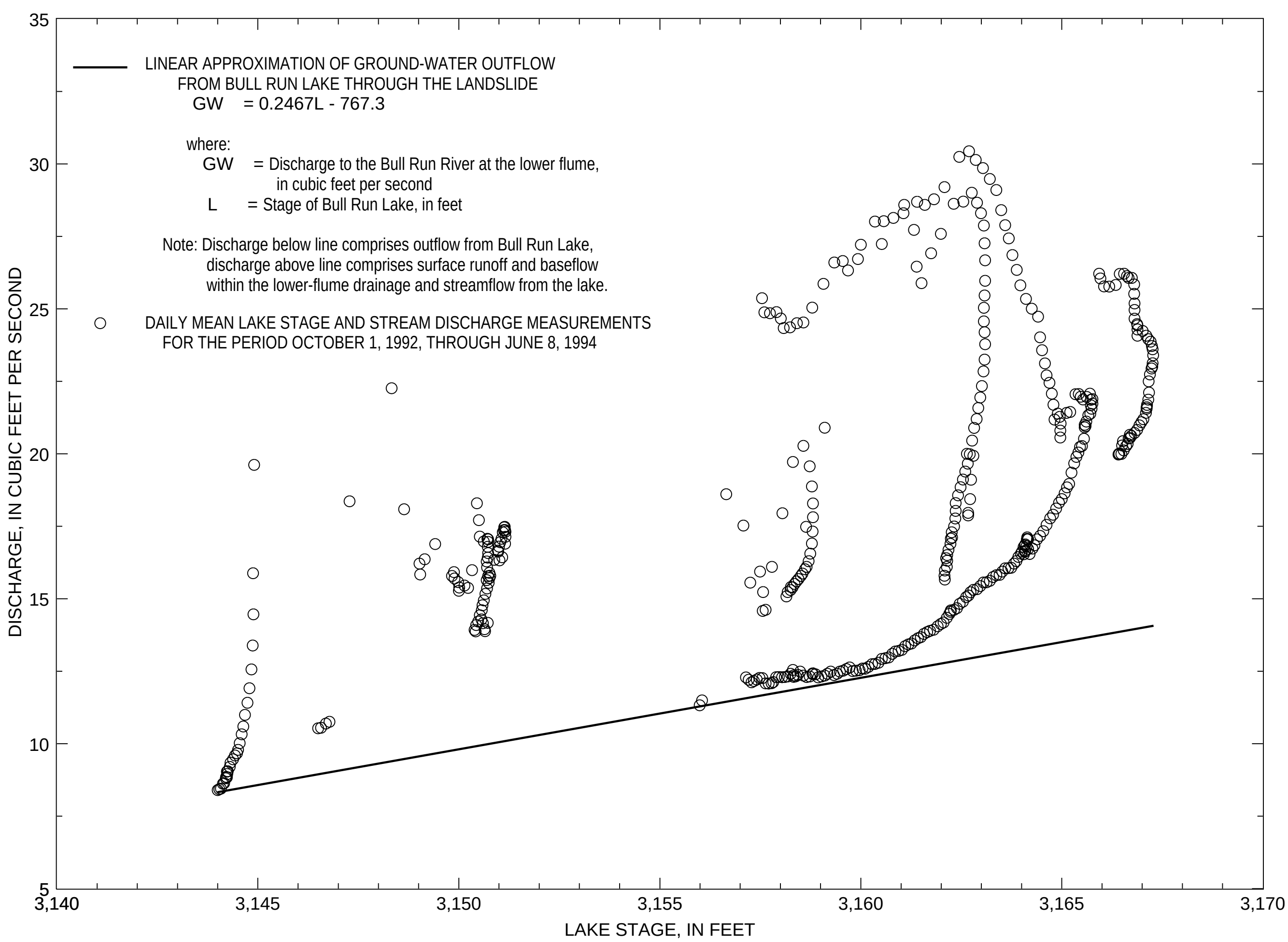


Figure 15. Relation between stage of Bull Run Lake and discharge of the Bull Run River at the lower flume.

using the programs of Rutledge (1993; Rutledge and Daniel, 1994), who developed a mathematical expression for recession of baseflow. The recession program determines the master recession curve of streamflow recession during time periods when all flow can be considered to be baseflow. To meet this requirement, the outflow of ground water from the lake, as calculated by using lake stage, was subtracted from the streamflow record prior to analysis. Rutledge (1993) used the empirical relation of Linsley and others (1982) to determine the length of time following a recharge event, such as precipitation or snowmelt, that surface runoff and interflow may contribute to streamflow:

$$N = A^{0.2} \quad (4)$$

where

N is the number of days after the recharge peak, and

A is drainage area in square miles.

The area of the lower flume drainage area is 1.64 mi^2 (fig. 2). Thus, the number of days after a recharge event that surface runoff and interflow may be significant is 1.1 days; however, the programs of Rutledge (1993) rounded the 1.1-day value to the next highest integer. Therefore, discharge data within 2 days of a recharge event were not used in the calculation of the master recession curve.

Recharge for each peak in the streamflow record was estimated by using the recession-curve displacement method (or Rorabaugh method). This method is based on the upward shift in the recession curve of ground-water discharge that occurs as a result of recharge (Rutledge, 1993). The daily record of baseflow was estimated by using streamflow partitioning. Baseflow was assumed to be equal to streamflow during periods not influenced by surface runoff; linear interpolation was used to estimate baseflow for the remaining periods (Rutledge, 1993). The surface runoff component from the lower flume drainage area was calculated as the residual discharge—the component of discharge remaining after ground-water outflow through the landslide and baseflow have been subtracted. Snowmelt runoff was not treated separately and may inadvertently be attributed to baseflow. Such an error could result in an increase of the uncertainty of the baseflow and surface-runoff estimates. Figure 16 shows the total discharge and the proportion of each flow component—ground-water outflow from the lake through the landslide, baseflow and surface runoff from the lower flume drainage area, and streamflow from Bull Run Lake. Tables 4 and 5 summarize the results.

During March of 1993, an unintentional release of water from Bull Run Lake took place (see section titled “Streamflow from the Lake”). It is believed that the entire volume of water released as streamflow infiltrated the landslide material and contributed to the discharge of the Bull Run River at the lower springs. The daily volume of the release was estimated by using the discharge record of the Bull Run River at the lower flume. Surface runoff was calculated for only part of this period.

Estimated ground-water outflow from Bull Run Lake through the landslide varied by less than 6 ft^3/s during the period of record (table 4). During that period, lake levels were near record lows. The lake, however, did not reach maximum pool during this period, and therefore the full range of possible ground-water outflow values probably was not observed.

During summer and fall, the discharge of the Bull Run River at the lower flume is primarily composed of ground-water outflow from Bull Run Lake through the landslide (fig. 16). Baseflow is a significant source of discharge during the winter and spring. Surface runoff is generally of short duration during and following precipitation events and contributes only a small amount of flow to the total discharge. Streamflow from Bull Run Lake occurs only during the release of water by the Portland Water Bureau.

The graph showing the proportion of flow components that compose the discharge at the lower flume (fig. 16) may prove useful in determining how each flow component contributes to the water quality of the Bull Run River. For example, during several periods of extended baseflow recessions, discharge at the lower flume consists almost exclusively of ground-water outflow from the lake. These periods are suitable for the determination of water quality of ground-water outflow from the lake, such as constituent concentration, constituent load, or temperature. The change in water quality that is a result of the influx of surface runoff and baseflow following a storm, or from inflow of water released from Bull Run Lake, could then be determined.

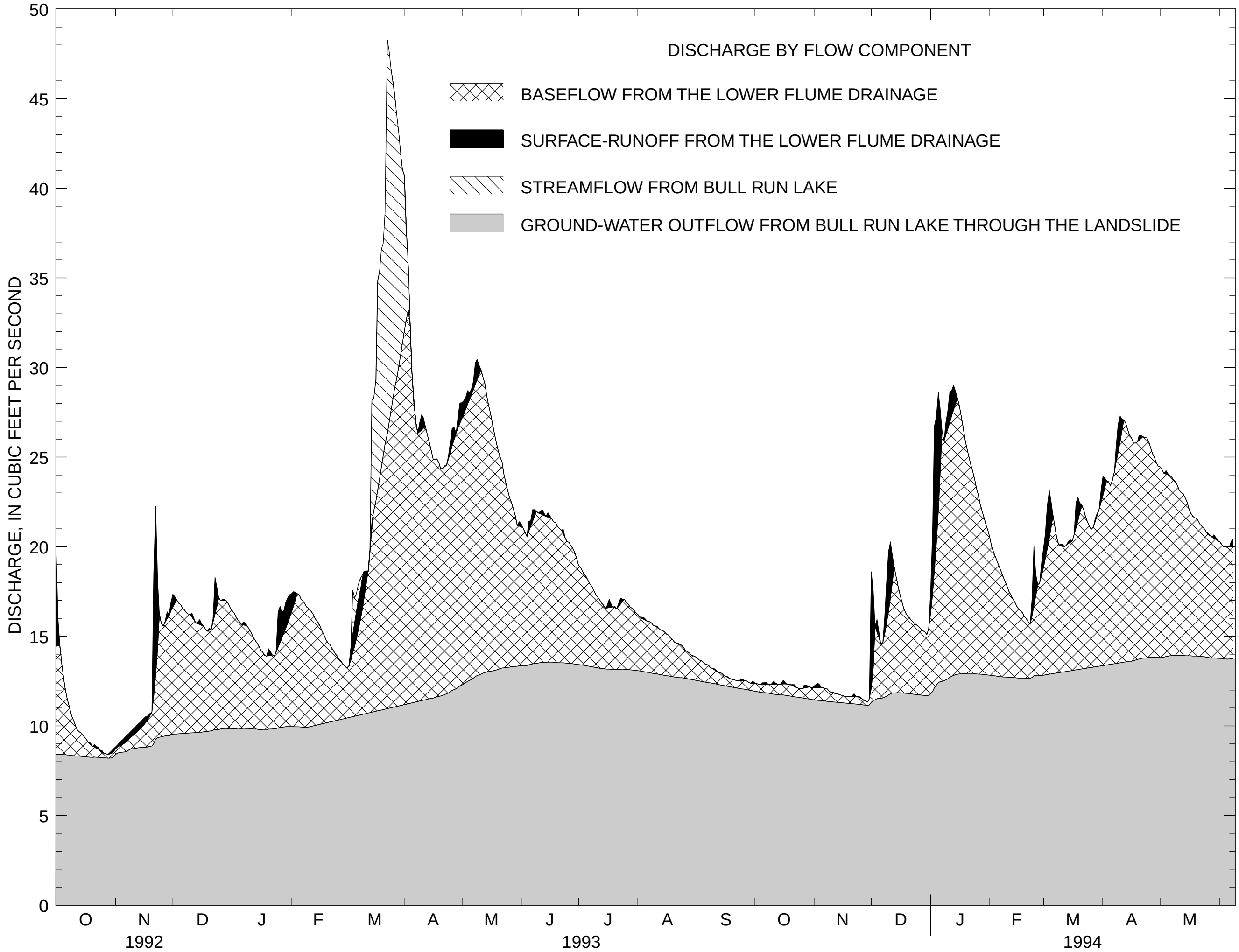


Figure 16. Daily mean discharge of the Bull Run River at the lower flume by flow component.

Table 4. Summary of mean daily discharge of the Bull Run River at the lower flume by flow component for the period October 1, 1992, to June 8, 1994

Flow component	Minimum	Mean	Maximum
		Mean daily discharge in cubic feet per second	
Total discharge	8.4	19	48
Ground-water outflow from Bull Run Lake through landslide	8.2	12	14
Baseflow from lower flume drainage area	0.2	6.2	22
Surface runoff from lower flume drainage area	0	0.3	9.4
Streamflow from Bull Run Lake	0	0.4	22
		Percentage of total mean daily discharge	
Ground-water outflow from Bull Run Lake through landslide	23	68	98
Baseflow from lower flume drainage area	2	29	65
Surface runoff from lower flume drainage area	0	2	42
Streamflow from Bull Run Lake	0	1	45

Table 5. Summary of annual discharge of the Bull Run River at the lower flume by flow component for the 1993 water year
[Mgal, million gallons]

Flow component	Total (Mgal)	Percentage of total
Ground-water outflow from Bull Run Lake through landslide [1]	2,600	60
Baseflow from lower flume drainage area	1,450	34
Surface runoff from lower flume drainage area	50	1
Streamflow from Bull Run Lake [2]	200	5
Total discharge	4,300	100

[1] Calculated by using the mean of the range of flow volumes for ground-water outflow from Bull Run Lake through the landslide.

[2] Calculated by using the mean of the range of flow volumes for streamflow from Bull Run Lake.

Outflow through the Consolidated Rocks

As previously discussed, a northeast striking thrust fault in the Columbia River Basalt Group, containing a massive impermeable tectonic breccia, crosses the Bull Run River about 1 mi downstream from the lower flume and dips to the southeast (Vogt, 1981). Newcomb (1959, 1961a,1961b, 1969, 1982) described and discussed similar structures in the Columbia River Basalt Group that also may act as barriers to the lateral flow of water. The thrust fault may cause the outflow of ground water from the Bull Run Lake drainage basin through the consolidated rocks to emerge at the surface east of this fault, either as springs or as direct discharge to the Bull Run River (fig. 17). Measurements of stream discharge taken along the Bull Run River during November 10, 1993 had a net increase of about 6 ft^3/s (38 percent) from

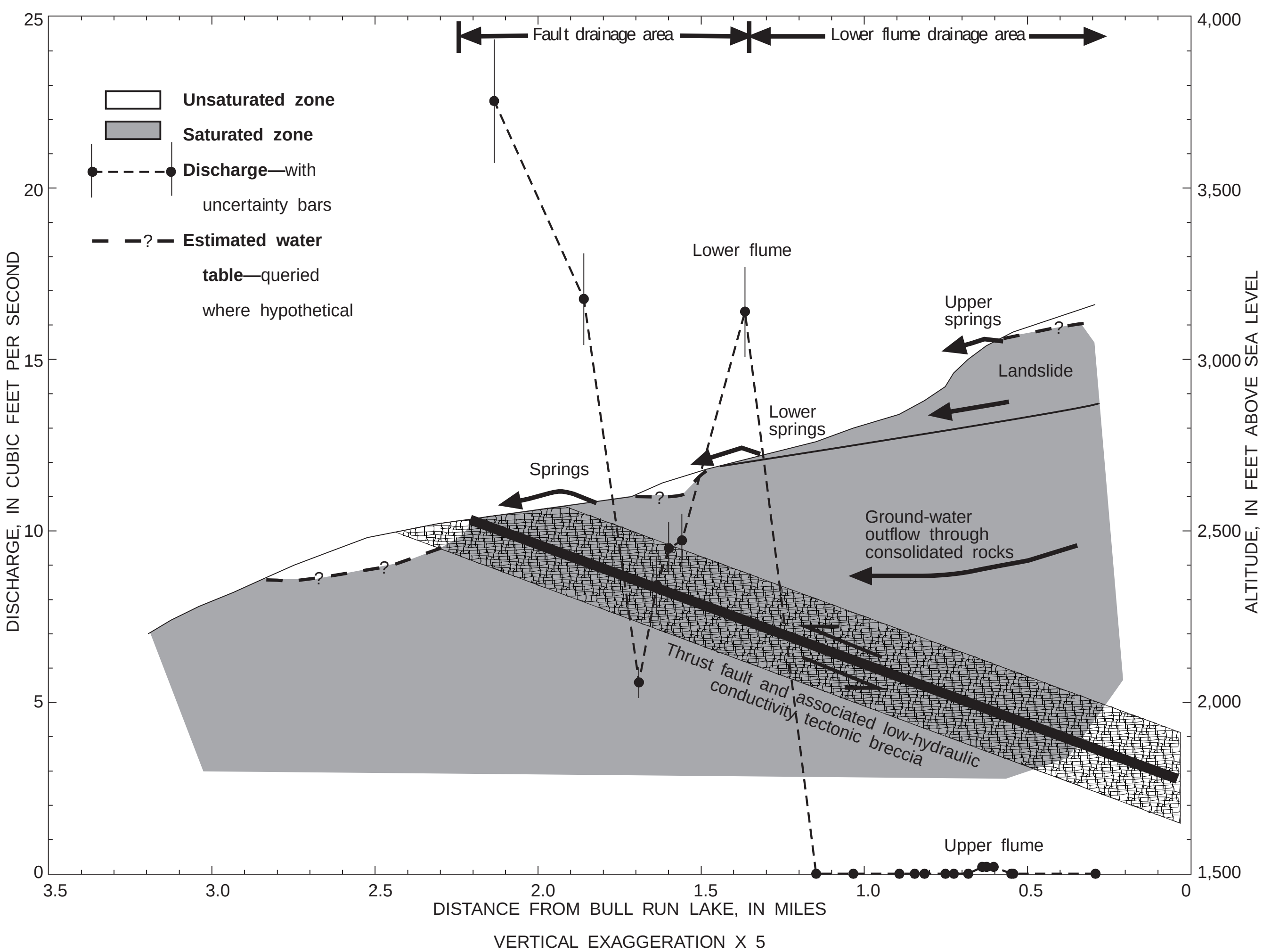


Figure 17. Discharge profile of the Bull Run River and diagrammatic section along the Bull Run River drainage basin for November 10, 1993.

the lower flume to the vicinity of the thrust fault, a distance of about 0.8 mi (fig. 17) (Hubbard and others, 1995, p. 443–444). Several springs were observed along this reach of river at that time. The increase in discharge may be attributable to baseflow from the fault drainage area (the contributing drainage to the Bull Run River between the lower flume and the intersection of the river with the fault as shown in fig. 2) and ground-water outflow through the consolidated rocks. However, there is insufficient information to estimate the outflow of ground water through the consolidated rocks during the 1993 water year.

Streamflow from the Lake

Streamflow directly from Bull Run Lake occurs only when the lake level exceeds the altitude of the spillway on the dike or when water is released by the Portland Water Bureau through the conduits in the manmade dam. Streamflow over the spillway did not occur during the 1993 water year. An accidental release of water from Bull Run Lake through the lower conduit, however, took place during March 1993. On March 31, 1993, Portland Water Bureau personnel observed that water was ponding in the closed depression below the outlet channel, about one-fourth mile northwest of the manmade dam. An inspection tour on April 1, 1993 found that the valve controlling the lower conduit was open, and the valve was subsequently closed (D.M. Bloem, City of Portland Bureau of Water Works, written commun., 1995). Portland Water Bureau personnel did not observe any ponded water in the closed depression below the outlet channel during a maintenance trip to the lake on March 3, 1993, indicating that the release of water may have taken place after that time.

An estimate of the volume of water released from the lake through the lower conduit was made using the discharge record of the Bull Run River at the lower flume. It was assumed the conduit was open from March 3 to April 1, 1993 (fig. 16), and that all of the water released from the lake discharged at the lower flume. If, however, the accidental release from the lake occurred only during the 2 days actually observed by Portland Water Bureau personnel, the total discharge may have been negligible. A value of 100 percent was used to represent this uncertainty. Using this uncertainty results in an estimate of streamflow owing to the release of water through the conduit as a range from 0 to 400 Mgal.

Change in Storage

Bull Run Lake

Change in storage of Bull Run Lake for the 1993 water year was estimated by using the relation between lake stage and lake volume (fig. 18) calculated from lake bottom topography. Lake stage was 3,144.9 ft on October 1, 1992, and 3,159.2 ft on September 30, 1993, an increase of 14.3 ft. Lake storage increased from 10,000 Mgal to 11,800 Mgal. The uncertainty associated with the change in lake storage is a function of the measurement of the lake stage and of the lake stage-volume relation determined for the lake. The uncertainty due to the measurement of lake stage is about 0.02 ft, and the resulting uncertainty would be less than 0.1 percent. The lake stage-volume relation was assumed to have an uncertainty of about 5 percent. Using this uncertainty results in an increase in lake storage that ranges from about 1,700 to 1,900 Mgal.

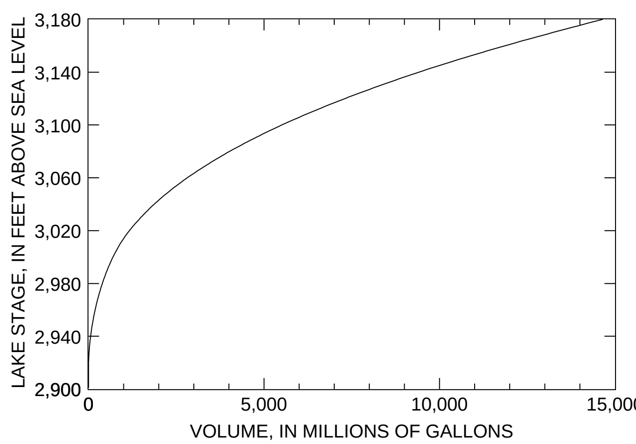


Figure 18. Relation between lake stage and volume of water at Bull Run Lake. (Modified from L.L. Hubbard, U.S. Geological Survey, unpub. data, 1981.)

Soil Moisture

The change in soil-moisture storage is often assumed to be negligible over the course of a water year, because depletion of soil-moisture storage is assumed to be equalled by replenishment through the infiltration of precipitation. Though this assumption is generally valid when averaged over many years, variations during any single year could be significant. There was insufficient information to calculate the change in soil moisture within the Bull Run Lake drainage basin during the 1993 water year.

Ground Water

The depletion of ground-water storage is often assumed to be equalled by replenishment through the infiltration of precipitation. Though this assumption is generally valid when averaged over many years, variations during any single year could be significant. During the 1993 water year, the lake stage rose 14.3 ft; therefore, it is likely that ground-water levels rose proportionally within both the landslide and consolidated rocks adjacent to the lake, causing an increase in ground-water storage. There is, however, insufficient information to estimate the change in volume of the ground-water storage within the Bull Run Lake drainage basin.

Discussion of Hydrologic Components for the Bull Run Lake Drainage Basin

The hydrologic budget for the Bull Run Lake drainage basin was not evaluated owing to the lack of information on several hydrologic components and the large uncertainties associated with some of the other components. A summary of the hydrologic components for the Bull Run Lake drainage basin for the 1993 water year is presented in table 6. Precipitation from rain and snow is the largest component of inflow to the basin, followed by fog drip. Outflow from the lake drainage basin, listed in order of decreasing volume, consists of ground-water outflow from the lake through the landslide, evapotranspiration from the land surface, lake evaporation, and streamflow from the lake. Ground-water outflow through the consolidated rocks could not be evaluated owing to lack of data. Lake storage increased and ground-water storage may also have increased but by an unknown amount. Soil-moisture storage could not be evaluated owing to insufficient data. It should be noted that the lake stage was still recovering from drought and water releases during water years prior to 1993. If the lake had been at a higher stage than it was during the 1993 water year, ground-water outflow from the lake through the landslide would probably have been greater.

A comparison of the uncertainties of the hydrologic components for the Bull Run Lake drainage basin demonstrates that the largest uncertainties, as measured by the range of volume for an inflow or outflow component, are associated with the inflow components—precipitation from rain and snow and from fog drip (table 6). The uncertainties of the outflow components are significantly smaller; the component of ground-water outflow through the landslide has the most uncertainty, followed by evapotranspiration.

Discussion of Hydrologic Components for Bull Run Lake

Necessary data at Bull Run Lake were lacking to independently evaluate the inflow components, ground water or surface runoff (consisting of streamflow and overland flow), as well as the outflow from ground water. In addition, large uncertainties are associated with some of the other components. As a consequence, the hydrologic budget for Bull Run Lake could not be

Table 6. Hydrologic components for Bull Run Lake drainage basin for the 1993 water year

[Mgal, million gallons; volumetric values rounded to two significant figures]

Flow Component	Component Abbreviation	Range of flow volumes (Mgal)
Inflows:		
Precipitation on the lake surface (rain and snow)	P_L	600–1,600
Precipitation on the land surface	P_{LS}	
Rain and snow		2,800–7,600
Fog drip		0–3,300
Outflows:		
Lake evaporation	E_L	170–410
Evapotranspiration	ET_{LS}	600–1,800
Ground water, through landslide	GW_{OL}	1,800–3,400
Ground water, through consolidated rocks	GW_{OC}	Unknown
Streamflow from the lake	SF_O	0–400
Change in storage:		
Lake	ΔS_L	1,700–1,900
Soil moisture	ΔS_{SM}	Unknown
Ground water	ΔS_{GW}	Unknown

evaluated. A summary of the hydrologic components for Bull Run Lake for the 1993 water year is presented in table 7. Of the inflows to the lake, only the precipitation on the lake surface from rain and snow was estimated. Because of the lack of piezometers or wells in the Bull Run Lake drainage basin and the lack of gages on any of the streams tributary to the lake, there were insufficient data to estimate the inflow from ground water or surface runoff. Outflows from the lake that were estimated, listed in order of decreasing volume, consist of ground-water outflow through the landslide, lake evaporation, and streamflow. Ground-water outflow through the consolidated rocks could not be evaluated owing to lack of data. Lake storage increased during the 1993 water year. As discussed above, the lake stage was still recovering from drought and water releases during water years prior to 1993. If the lake had been at a higher stage than it was, ground-water outflow from the lake through the landslide would probably have been greater, and the change in lake storage probably would have been smaller.

Table 7. Hydrologic components for Bull Run Lake for the 1993 water year

[Mgal, million gallons; volumetric values rounded to two significant figures]

Flow Component	Component Abbreviation	Range of flow volumes (Mgal)
Inflows:		
Precipitation on the lake surface (rain and snow)	P_L	600–1,600
Ground-water inflow to the lake	GW_I	Unknown
Streamflow to the lake	SF_I	Unknown
Overland flow to the lake	OF_I	Unknown
Outflows:		
Lake evaporation	E_L	170–410
Ground water, through landslide	GW_O	1,800–3,400
Ground water, through consolidated rocks		Unknown
Streamflow from the lake	SF_O	0–400
Change in Storage:		
Lake	ΔS_L	1,700–1,900

Among the hydrologic components estimated for Bull Run Lake, the largest uncertainties are in the estimates of ground-water outflow through the landslide and precipitation on the lake surface followed by streamflow from the lake, lake evaporation, and the change in lake storage.

SUGGESTIONS FOR FURTHER STUDY

The approach for the work described in this report relied on existing data to evaluate the hydrologic components of Bull Run Lake and the Bull Run Lake drainage basin. Future data-collection efforts that would facilitate the development of a quantitative hydrologic budget for Bull Run Lake could include (1) evaluation of the surface-runoff component of inflow to the lake; (2) use of a cross-sectional ground-water flow model to estimate ground-water inflow, outflow, and storage; (3) additional data collection to reduce the uncertainties of the hydrologic components having large relative uncertainties; and (4) determination of long-term trends.

Methods

A study of Bull Run Lake could be designed to refine estimates of many of the components of the hydrologic budget. Each component is discussed below. Emphasis would be placed on evaluating the hydrologic components for which there is currently insufficient data and those components contributing the largest uncertainty to the hydrologic budget. Reductions in small uncertainties of large components may provide greater benefits than efforts designed to reduce large uncertainties in small components. This is because small budget components with a large percentage of uncertainty may not represent large water volumes, but a small percentage of uncertainty in a large budget component can involve a considerable quantity of water (Winter, 1981).

Inflow to the lake from direct precipitation on the lake surface can be determined by using a continuous recording rain gage established at the lake. The accurate measurement of the inflow components to the lake, consisting of ground water and surface runoff, can require a substantial commitment of resources including instrumentation, manpower, and money. However, these components could be estimated efficiently by using a mathematical model to simulate these processes and would require only a modest data-collection effort. To further reduce the data-collection effort and cost, the model can be applied to one or more subbasins within the drainage basin and the results extrapolated to the entire basin contributing to the lake.

A mathematical model that could be used to determine the quantity of inflow from surface runoff and ground water is the Deep Percolation Model for Estimating Ground-Water Recharge (DPM). The computer model was developed by Bauer and Vaccaro (1987, 1990) to estimate long-term average ground-water recharge from precipitation in areas with variable weather, soils, and land uses. The model is based on practical and relatively easily implemented physical relations and estimates the components of the hydrologic budget for a basin, including changes in soil moisture, soil evaporation, plant transpiration, surface-water runoff, snow cover, and interception and evaporation of precipitation from the vegetation. The major factors that control recharge from precipitation are simulated on a daily basis and summarized for each month and year. The DPM could be useful in providing information for the development of monthly water budgets, which would otherwise not be feasible without measuring changes in soil-moisture and ground-water storage.

Subbasins to be modeled using the DPM could be selected on the basis of the following criteria: (1) well-defined surface-water drainage divides; (2) distinct streamflow channel(s); (3) representative climatic, hydrologic, physiographic, geologic, and biologic conditions for the drainage basin of the lake; and (4) accessibility during all seasons. The data requirements for the DPM include climate, land-surface altitude, soil information, and vegetation properties. Though not required, streamflow measurements, baseflow estimates, and information describing the slope and aspect of the land surface could be used in the DPM for increased reliability. Climatic data required include daily precipitation (rain, snow, and fog drip), daily minimum and maximum temperatures, daily percentage of possible sunshine, and solar radiation.

The data-collection needs to support use of the DPM are relatively modest. The continuous-recording rain gage, designed to measure direct precipitation, could be supplemented by storage rain gages at different areas around the lake to provide a representative estimate of precipitation with respect to spatial distribution, including aspect and altitude. In order to measure the amount of fog drip within the area of Bull Run Lake, a continuous-recording fog-drip (or throughfall) collection station as described by Harr (1982) or W.R. Bidlake (USGS, written commun., 1995) could be established under the forest canopy in one or more locations around the lake. A continuous-recording temperature station could be established at the lake to determine daily minimum, maximum, and mean temperatures. A continuous-recording stream-stage station could be established at the mouth of each stream in the subbasin(s) selected for use with the DPM.

The DPM calculates ground-water recharge. However, as discussed in the section “Flow Within the Consolidated Rocks,” a part of the recharge flows to the Bull Run River and not to Bull Run Lake. A cross-sectional ground-water flow model could help to accurately determine the amount and distribution of recharge that enters the lake. The model would consist of a mathematical representation of ground-water flow in two dimensions to identify flow along a cross section of part of the lake basin. The USGS modular three-dimensional finite-difference ground-water flow model by McDonald and Harbaugh (1988) (commonly known as MODFLOW) and the USGS three-dimensional particle tracking post-processing programs developed by Pollock (1994) (commonly known as MODPATH) may be suitable for modeling the hydrologic setting at Bull Run Lake. The cross-sectional model could help to provide information on the amount and location of ground-water inflow to and ground-water outflow from the lake, assuming certain information about recharge, the geometry, and hydraulic characteristics of the geologic units (see Winter, 1976, and Forster and Smith, 1988, for example). Bracketing these values can yield a set of possible results that may be useful in determining the relative magnitude of the ground-water inflow and outflow components, through the landslide and the consolidated rocks, and the change in ground-water storage.

This information may provide useful insights that could aid in guiding the data-collection efforts.

The cross-sectional model requires information on the spatial distribution of the hydraulic properties of the rock materials and the distribution of hydraulic heads or gradients. This information can be determined by placing a series of piezometer nests along the shoreline of the lake and along the adjacent slope. Each piezometer nest could consist of two piezometers, one shallow and one deep. This combination could help to determine the hydraulic gradients with depth. A row of three piezometer nests consisting of a piezometer nest at the lakeshore, 25 percent upslope from the lake, and 75 percent upslope from the lake could be installed to determine the altitude of the water table and the change in hydraulic gradients with depth at the shoreline and upslope. An identical set of piezometers could be placed parallel to the first set but would be separated by several hundred feet to help establish the spatial distribution of the water table. Slug tests can be used to estimate the hydraulic properties of the rock materials.

Outflow from lake evaporation can be estimated by using the pan-evaporation station at the Headworks climatological station (station 35-3770), which could be cleaned and maintained at regular intervals. A correlation could be sought to adjust pan evaporation at the Headworks to Bull Run Lake, which is at an altitude 2,400 ft higher than the Headworks. The uncertainty associated with the estimate of evaporation from the lake was small relative to the uncertainties of the other hydrologic components during the 1993 water year; therefore, it is not suggested that a pan-evaporation station, which would require a substantial commitment of resources, be established at the lake.

Ground-water outflow from Bull Run Lake through the landslide represents the largest quantified outflow component. The seepage-stage relation developed in the section, “Outflow through the Landslide,” provides a means for estimating the quantity of outflow. This relation can be updated as additional data on lake stage and discharge at the lower flume becomes available, especially for higher lake stages. It may also be beneficial to perform a regression analysis with the smallest stream discharge at each lake stage as the response variable. Explanatory variables could consist of lake stage, surface area of lake-bottom landslide material (a function of lake stage), thickness and hydraulic conductivity of lake sediments (also a function of lake stage), and any other relevant factors. The resulting regression equation could be used as an aid to estimate ground-water outflow from the lake for a given set of conditions. Additional information could be gained from the measurement of water levels within one or two piezometers placed in the landslide to address the effects of recharge not derived from outflow from the lake.

Ground-water outflow through the landslide might also be determined by using stable isotopes of water, including deuterium and oxygen-18. These naturally occurring isotopes (already present in water) could be used to determine the source of water in the Bull Run River and the interaction of ground water with Bull Run Lake if the characteristics of each isotopic source are significantly different (Turner and others, 1987; Krabbenhoft and others, 1990).

Change in ground-water storage can be determined by using the information from the piezometer nests installed within the subbasin(s) and in the landslide to estimate change in saturated volume of the subsurface material or through the use of the cross-sectional ground-water flow model. Slug tests can be used to estimate the specific yield, which can then be used to calculate the change in ground-water volume.

As previously discussed, the gaging station at the lower flume may be above the toe of the landslide rather than below it and, therefore, may not be measuring some of the ground-water outflow through the landslide from the lake. In addition, the thrust fault mapped by Vogt (1981), about 1 mi downstream of the lower flume, can act as a barrier to ground-water flow and cause ground water in the consolidated rocks to discharge to the Bull Run River at the fault (see the section, “Flow within the Consolidated Rocks”). To better estimate the ground-water outflow from the lake and from the consolidated rocks, several sets of discharge measurements could be made along the river below the lower flume to some point below the thrust fault. Also, a temporary gaging station could be established along this reach of the river in order to determine if a correction factor can be used to adjust measurements at the gaging station to estimate ground-water flow through the landslide. A similar suggestion was made by Shannon and Wilson, Inc. (1961). Field reconnaissance or field mapping may be required to accurately locate the toe of the landslide and the location of the thrust fault where it crosses the Bull Run River.

A long-term data-collection program could be established to identify trends over a wide range of climate and hydrologic conditions, including extremes in precipitation and lake level. These two conditions most influence the hydrologic budget of the lake; precipitation because of its contribution to inflow to the lake resulting from direct precipitation, surface runoff, and ground water; lake level because of the direct proportionality between lake level and ground-water outflow through the landslide. At a minimum, this program might consist of monitoring precipitation at the lake, lake stage, and streamflow below the natural dam on a continuous basis. The long-term data could help reduce the uncertainties of the components of the hydrologic budget, because errors in averaging short-term data are considerably greater than those in long-term data (Winter, 1981).

SUMMARY

Bull Run Lake lies within the Bull Run Watershed, the principal water supply for the Portland, Oregon, metropolitan area.The naturally formed 0.73 mi^2 (square miles) lake lies within a 3.44 mi^2 drainage basin in the upper eastern reaches of the Bull Run River Basin. During periods of low inflows to the watershed or during high demand, the City of Portland, Bureau of Water Works (Portland Water Bureau), releases water from Bull Run Lake to augment the water supply. The increasing demand, coupled with drought periods, has resulted in low water levels in Bull Run Lake. To aid in the development of a conceptual understanding of the hydrology of Bull Run Lake, the hydrogeologic setting of the lake was studied, and preliminary estimates of the hydrologic components of the lake and lake drainage basin were made using existing hydrologic data.

Bull Run Lake is impounded by a natural dam resulting from a landslide that forms part of the lake bottom. Ground-water outflow from the lake through the landslide eventually emerges as springs at the toe of the landslide. A part of the water that enters the ground-water flow system through the consolidated rocks on the slopes above Bull Run Lake enters the lake. The remaining ground water flows through the consolidated rocks and discharges to the Bull Run River.

Two areas of spring discharge are on the landslide. An upper set of springs is near the top and center of the landslide. The discharge from the upper springs is probably the result of the water table intersecting the land surface along the upper west slope of the landslide. The spring discharge also may be supplemented by baseflow and surface-water runoff collected in a small closed depression on the landslide and by water released from Bull Run Lake by the City of Portland Bureau of Water Works (Portland Water Bureau). A lower set of springs is at the downstream toe of the landslide and forms the headwaters of the Bull Run River. The approximately 4,300-Mgal (million gallon) discharge of the Bull Run River measured at the lower flume just below the lower springs during the 1993 water year is composed of (1) outflow of ground water from Bull Run Lake through the landslide (approximately 60 percent), (2) ground water originating from the contributing drainage area between the lake and the springs (approximately 34 percent), (3) streamflow from Bull Run Lake (approximately 5 percent), and (4) surface runoff (streamflow and overland flow) from the contributing drainage area between the lake and the springs (approximately 1 percent).

The hydrologic components were estimated for the Bull Run Lake drainage basin for the 1993 water year. Inflows of water to the lake basin consist of precipitation on the lake surface and on the land surface. Data from nearby climatic stations were used to estimate the amount of precipitation from rain and snow. Fog drip was estimated by using information from a study in a nearby part of the Bull Run Watershed. Outflows of water from the lake basin consist of evaporation from the lake, evapotranspiration from the land surface, ground-water outflow from the lake through the landslide, ground-water outflow from the land surface through the consolidated rocks, and streamflow from the lake. Evaporation from the lake was estimated by using pan-evaporation data collected at a climatic station outside the watershed. Evapotranspiration was estimated by comparison with studies on a watershed with similar basin characteristics. Outflow of ground water through the landslide was estimated by using a lake stage-seepage relation established at the lower flume. Ground-water outflow through the consolidated rocks could not be estimated owing to the lack of existing data. Streamflow from the lake during an accidental release of water was estimated by an analysis of the discharge record of the Bull Run River at the lower flume. Change in lake storage was determined by using a relation between lake stage and lake volume. Change in storage of soil moisture and ground water could not be estimated owing to insufficient data.

Estimated ranges for inflows to the Bull Run Lake drainage basin during the 1993 water year were about 3,400 to 9,200 Mgal from precipitation from rain and snow, and about 0 to 3,300 Mgal from fog drip. Estimated ranges for outflows from the lake basin, listed from largest to smallest, were about 1,800 to 3,400 Mgal for ground-water outflow through the landslide; about 600 to 1,800 Mgal for evapotranspiration from the land surface; about 170 to 410 Mgal for lake evaporation; and about 0 to 400 Mgal for streamflow from the lake. Ground-water outflow through the consolidated rocks could not be evaluated owing to the lack of data. The lake storage increased by a range of from about 1,700 to 1,900 Mgal. Changes in ground-water storage and soil-moisture storage could not be evaluated owing to insufficient data.

Estimated inflows to Bull Run Lake from precipitation on the lake surface during the 1993 water year ranged from about 600 to 1,600 Mgal. Inflows from ground water and surface runoff could not be evaluated owing to the lack of data. Estimated ranges for outflows from the lake were about 1,800 to 3,400 Mgal from ground-water outflow through the landslide, about 170 to 410 Mgal from lake evaporation, and about 0 to 400 Mgal from streamflow. Outflow of ground water through the consolidated rocks could not be evaluated owing to the lack of data. Lake storage increased by a range of from about 1,700 to 1,900 Mgal.

Suggestions for further study include (1) evaluation of the surface-runoff component of inflow to the lake; (2) use of a cross-sectional ground-water flow model to estimate ground-water inflow, outflow, and storage; (3) additional data collection to reduce the uncertainties of the hydrologic components that have large relative uncertainties; and (4) determination of long-term trends for a wide range of climatic and hydrologic conditions.

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