Variations in Turbidity in Streams of the Bull Run Watershed, Oregon, Water Years 1989-90

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 93–4045

Prepared in cooperation with the
CITY OF PORTLAND WATER BUREAU AND
U.S. FOREST SERVICE

U.S. DEPARTMENT OF THE INTERIOR
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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

For additional information write to:

District Chief
U.S. Geological Survey, WRD
5400 MacArthur Blvd.
Vancouver, Washington 98661

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CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) as follows:

$$^{\circ}C = (^{\circ}F-32)/1.8.$$

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

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By Richard G. LaHusen

Abstract

In this study, turbidity is used to help explain spatial and temporal patterns of erosion and sediment transport.

Automated turbidity sampling in streams in the Bull Run watershed during water years 1989 and 1990, showed turbidity levels, in general, are remarkably low, with levels below 1 NTU (nephelometric turbidity unit) about 90 percent of the time. However, ephemeral increases in turbidity in streams of the Bull Run watershed occur in direct response to storms. Turbidity is caused by abundant organic particles as well as by materials eroded from unconsolidated geologic materials located along roads, stream channels, or stream banks. Seasonal and within-storm decreases in turbidity are attributed to depletion of accumulated particle supplies. During winter storms, erosion caused by rainfall intensities greater than 0.25 inches in 3 hours is sufficient to increase stream turbidities from less than 1 NTU to as much as 100 NTUs. Large-scale storms or floods cause persistent effects because mass erosion or scour of channel armor increases available sediment supply.

Spatial variability in turbidity is evident only during storms when erosion and sediment-transport processes are active. Parts of the Rhododendron Formation are particularly prone to channel and mass erosion during large storms. Eroding glacial deposits in sections of Log Creek affected by a 1964 dam-break flood also cause high stream turbidity relative to other streams in the watershed.

Analysis of characteristics of magnetic minerals in sediment sources and deposits was unproductive as a means to identify source areas of suspended sediment because high concentrations of magnetite in all samples of the volcanic rocks masked differences of less magnetic minerals in the samples.

INTRODUCTION

For more than a century, the federally administered forested watershed of the Bull Run River has served as the principal source of water for the metropolitan area of Portland, Oregon. Public Law 95-200, signed in 1977, allows the U.S. Forest Service (USFS) to conduct logging-related activities in the basin as long as the primary management objective for the production of "pure, clear, potable water" is not compromised. To insure compliance with the law, a monitoring program and specific water-quality standards were adopted by the USFS. The intent of the program was to prevent potential degradation of the water supply caused by land-use practices.

Water-quality standards were developed for five sampling locations called "key stations." The key stations include the headworks where water enters the supply system, Bull Run River, North Fork Bull Run River, South Fork Bull Run River, and Fir Creek, an unroaded, unlogged basin (fig. 1). Water samples collected daily at the headworks and weekly at the four key stations are analyzed for numerous water-quality parameters including turbidity.

One of the specific concerns of both citizens and watershed managers is potential degradation of water clarity owing to increased erosion resulting from land-use practices. The U.S. Geological Survey (USGS), in cooperation with the City of Portland Water Bureau and the USFS, conducted the 2-year study to obtain

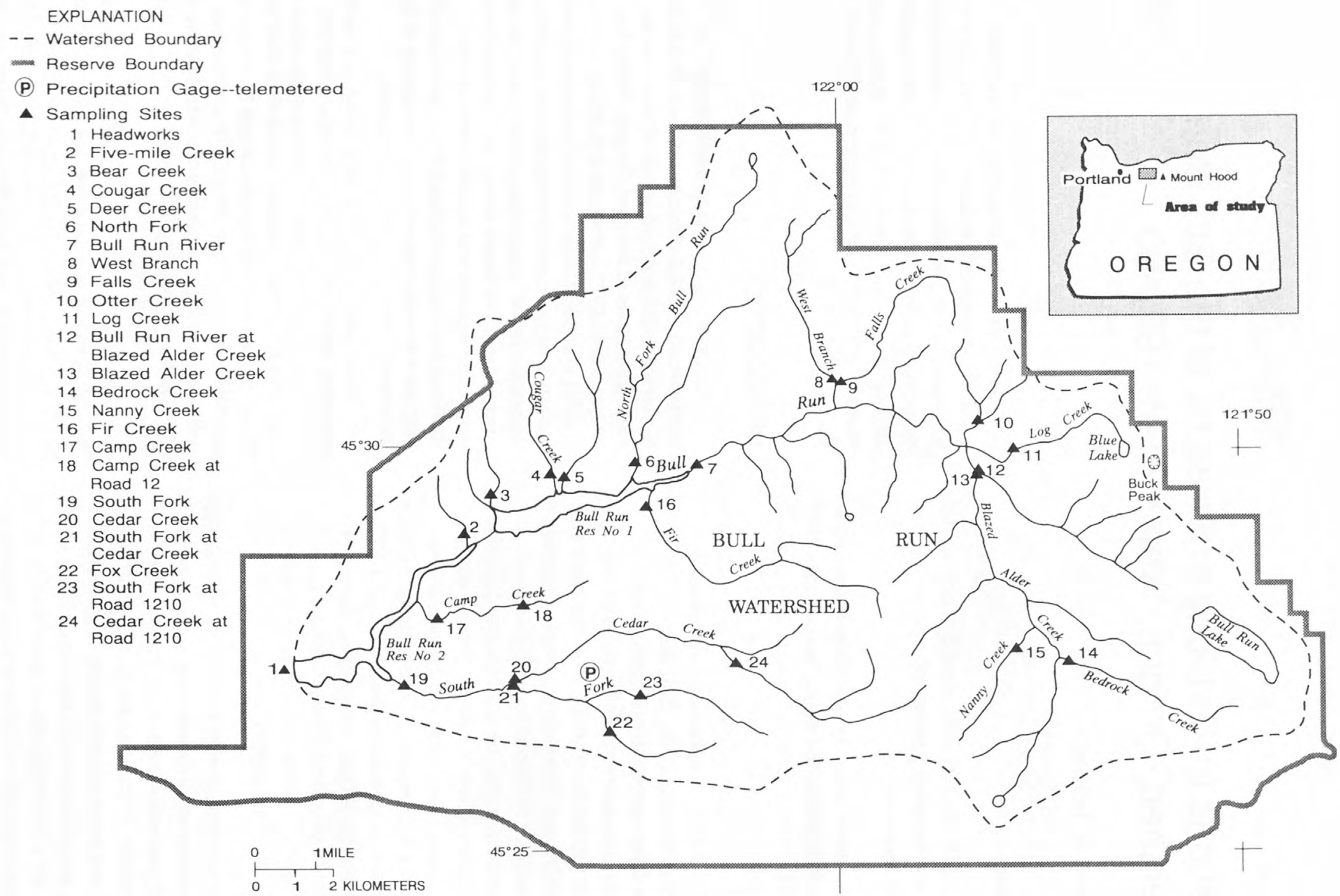

Figure 1. Location of streams and sampling sites in the Bull Run watershed.

information needed to improve water-quality monitoring programs and revise water-quality standards.

Turbidity, which is a measure of the scattering of light by suspended particles, is the parameter typically used as a measure of water clarity. Turbidity is of interest for several reasons. Water suppliers are legally required to monitor turbidity and provide users water with average turbidity levels below 1 NTU (nephelometric turbidity unit), and not exceeding 5 NTUs. In addition, turbidity measurements can be used to estimate suspended sediment concentrations (fig. 2) [Kunkle and Comer, 1971].

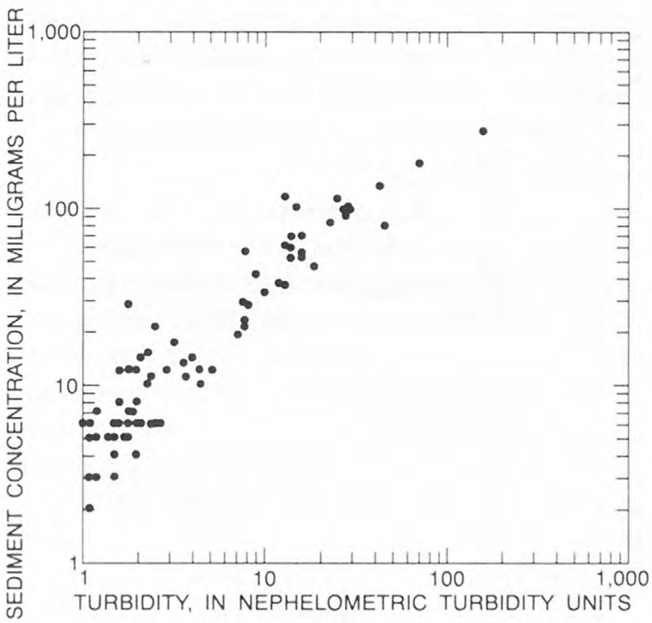

Figure 2. Relation between sediment concentration and turbidity for water samples collected in the Bull Run watershed.

Turbidity does not have a rigorous physical definition; accordingly, turbidity meters have a variety of optical designs. A replicatable reference solution of formazin is used to calibrate optical turbidity meters to obtain comparable measurements expressed in NTUs. Turbidity measurements may vary slightly among different instruments as a result of instrument design or because of coloration of water caused by dissolved materials (Austin, 1973).

Purpose and Scope

This report describes the methodology and results of a study of the sources and processes that cause variations in turbidity in streams in the Bull Run watershed. The study involved four components: (1) review of existing data, (2) field reconnaissance of erosion scars and sediment deposits, (3) turbidity monitoring, and (4) analysis of magnetic mineralogy of soils and sediment.

Approach

A review of the literature and water-quality data pertinent to erosion and sediment-transport processes in the Bull Run watershed was the first step in a multi-faceted approach to this study. Geologic and hydrologic reports from university, State, and Federal sources were analyzed to assses the state of knowledge of erosion and sediment-transport processes in the basin.

After review and analysis of pertinent information, a field reconnaissance of the watershed was done. Stream channels, hillslopes, roads, and timber-harvest units were inspected to locate recent erosion scars and sediment deposits.

A turbidity monitoring program was begun using manual and automated sampling methods. Turbidity was intermittently monitored by automated turbidity meters at 11 stream sampling stations (fig. 1). For this project, turbidity meters were modified for battery operation and equipped with radio-telemetry equipment to provide real-time information on turbidity, stream levels, and precipitation to the USGS office in Vancouver, Washington. By identifying storm periods, real-time telemetry allowed USGS personnel to collect point water samples at streams and roadside ditches to verify and augment the data collected by the automated sampling method. Automated sampling intervals varied from 1 hour during storms to 6 hours during periods between storms. Automated and manual sampling sites were selected to maximize the number of streams sampled, to sample different geologic formations, and to sample areas of different land use.

The final component of the study was an investigation of the magnetic properties of soils and sediment in the watershed. Analysis of magnetic characteristics of iron-bearing minerals in soils and sediment has been used to analyze sediment source areas in other watersheds (Oldfield, and others, 1979). In some cases, differences in characteristics of magnetic minerals contained in sediment and soils have allowed determination of source areas of deposits in reservoirs. The volcanic bedrock and derived sediment in the Bull Run watershed have an abundance of magnetic minerals making it a likely location to apply this technique.

Acknowledgments

Personnel of the City of Portland Water Bureau provided data on water quality and historical information relevant to this study. Employees of the USFS Columbia Gorge Ranger District also provided water-quality data as well as some precipitation data and valuable documentation of debris jam dynamics.

BASIN DESCRIPTION

Location

The Bull Run River watershed occupies 102 square miles of the Mount Hood National Forest. The basin is located 30 miles east of Portland, Oregon and 10 miles west of Mount Hood (fig. 1). Altitude in the basin ranges from 850 feet at the headworks dam site to 4,750 feet at Buck Peak on the northeast boundary of the basin.

Geology

Volcanic rocks underlie all parts of the watershed that drain into the municipal supply reservoirs (fig. 3). The lowermost rocks exposed in the basin consist of west-dipping flows of Miocene Columbia River Basalt, which are exposed in the bottom of steep inner canyons of the Bull Run River and parts of its major tributaries. These massive flows have been incised by the large streams in the watershed to form spectacular gorges and waterfalls. The loamy soils on the steep canyon walls are thin to nonexistent, whereas soil accumulations on gentler slopes have depths in excess of 4 feet. Natural slope-stability problems in this stratigraphic unit are limited to small soil slips and debris flows originating from steep canyon walls (Beaulieu, 1974).

In the western one-half of the watershed, the Columbia River Basalt is overlain by pyroclastic flow and mudflow breccias, tuffs, and andesites of the Rhododendron Formation, with local unconformity in the east. The assemblage of diverse flow deposits are exposed in the valley walls of the Bull Run River and its western tributaries. There is a wide variation in the degree of cementation and alteration in the Rhododendron Formation, ranging from platy andesite flows to moderately indurated breccias to small zones of hydrothermally altered, clay-rich tuffs (Beaulieu, 1974). Massive landslides in the Rhododendron Formation are topographically evident in the form of hummocky terrain, prominent headscarps, and disturbed drainages. The headscarps of such landslides occur predominantly at the contact between the Rhodedendron Formation and the overlying geologic units (Schulz, 1981).

Flows of Pliocene and Quaternary-age andesite and basaltic andesite overlie the previously described units throughout the watershed. Although massive to platy andesite flows form the greatest part of this unit, volcanic breccias and minor intrusions are also present. Extensive areas of thick talus have formed primarily in the eastern part of the watershed at altitudes above 2,500 feet (Beaulieu, 1974).

Evidence of glaciation in the watershed is limited to altitudes above 2,600 feet and is particularly apparent in north-facing drainages. Although moraines and glaciofluvial deposits can be found in numerous locations, they are not extensive. Glacial deposits in the watershed typically consist of unsorted cobbles and boulders in a silty sand matrix. Undercutting of these deposits has locally led to retrogressive failures similar to those occurring in talus slopes (Schulz, 1981).

Topography

Topography varies from low-relief lava flow surfaces to steep-walled canyons. Although some upland lava flows retain low relief, most of the west-dipping lava flows have been incised by down-cutting streams. Where massive flows of the Columbia River Basalt are exposed, less resistant materials overlying the basalt have been eroded preferentially to form broad, concave slopes on both sides of the lower Bull Run River and some of its major western tributaries.

In the upper basin there are numerous cirque basins, some of which contain lakes. The largest natural lake in the watershed is Bull Run Lake, which lies in a cirque and is impounded by a massive landslide deposit (Sherrod and Pickthorn, 1989). The principal drainage of the basin is the Bull Run River, which is fed by a dendritic network of short steep-gradient streams. Two manmade dams impound reservoirs on the lower sections of the Bull Run River.

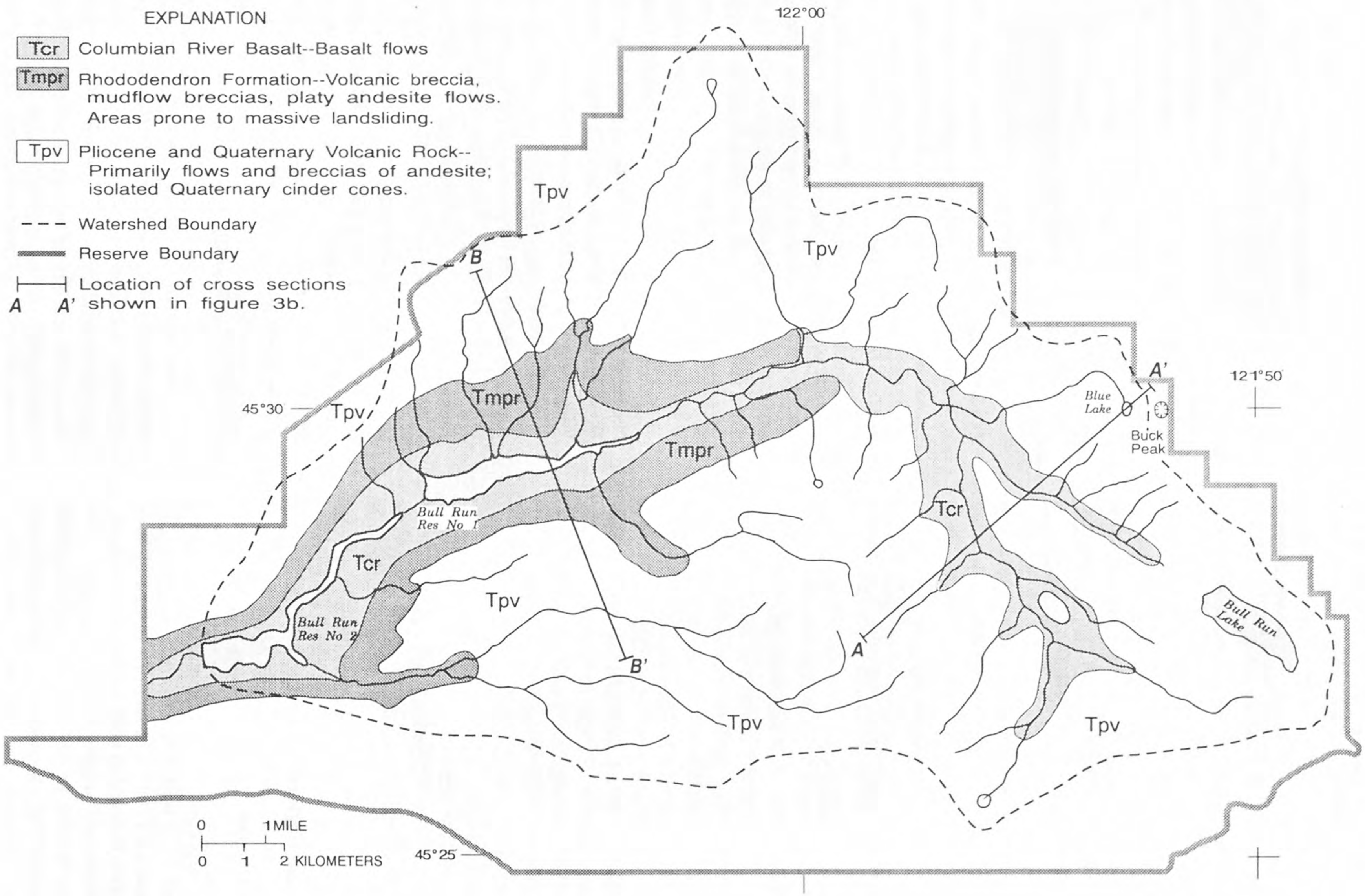

Figure 3a. Simplified geologic map of the Bull Run watershed. Adapted from Beaulieu, 1974.

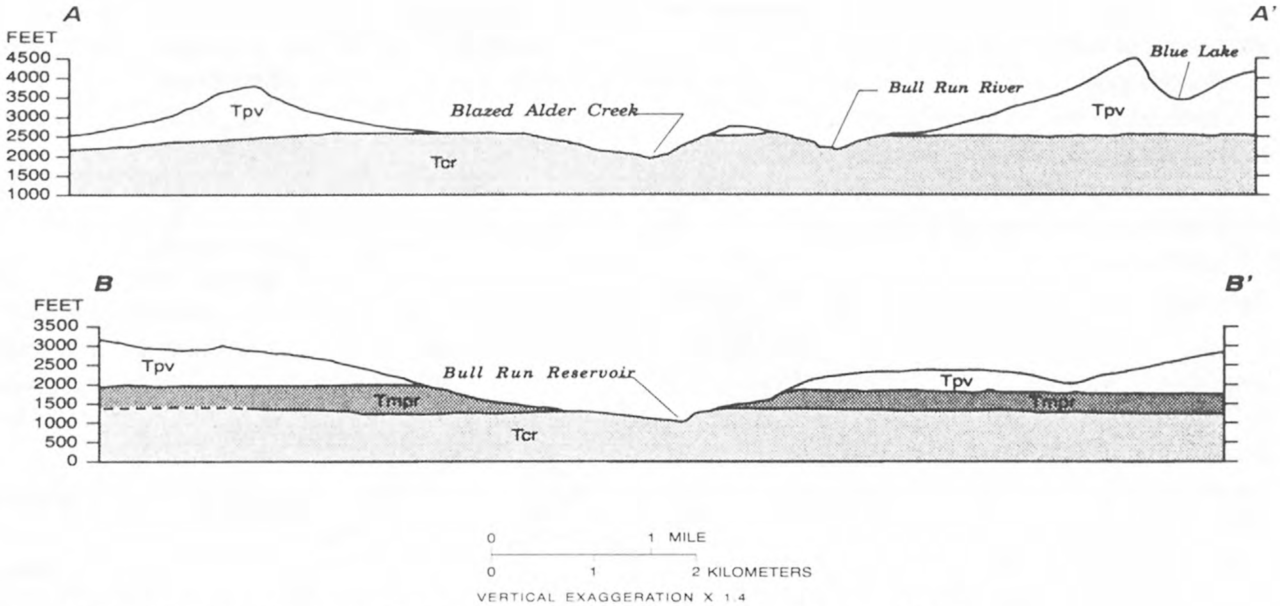

Figure 3b. Simplified geologic map of the Bull Run watershed. Adapted from Beaulieu, 1974.

Climate and Vegetation

The climate of the Bull Run watershed is controlled primarily by marine air masses. Seasonal moist, cool storms bring 70 to perhaps as much as 140 inches of annual precipitation to the basin. Strong orographic effects account for the wide variability of precipitation, which falls as both rain and snow. Summers typically are dry and warm, as high-pressure air masses predominate. Temperatures range annually from about 10 to 100 degrees Fahrenheit with an average of about 50 degrees Fahrenheit.

The basin is densely forested with evergreen conifers. Dominant tree species in the basin are Douglas fir, western hemlock, western red cedar, and grand fir. Understory vegetation is composed primarily of huckleberry, swordfern, oxalis, salal, and devil's club.

CAUSES OF TURBIDITY

Organic Particles

Visual inspections of water samples collected from streams in the Bull Run watershed revealed that suspended particles that cause turbidity in the Bull Run watershed are composed of both organic and inorganic materials. Abundant organic particles appear to include algae, mosses, or fauna from stream sources as well as forest litter that has fallen into or been washed into streams. The proportion of organic matter in water samples was determined by analyzing 84 streamflow samples that had turbidity levels greater than 1 NTU. Total sediment in each sample was determined by drying and weighing the sample. The organic matter was removed by oxidization with hydrogen peroxide, as described by Guy (1969). The remaining inorganic sediment was then redried and weighed. The organic fraction was calculated as the difference between the total and inorganic fractions.

The mean percentage of organic material causing stream turbidity was 64 percent of the total dry weight of suspended sediment. Variability of the organic fraction was high, as expressed by a standard deviation of 23 percent. Most of the variability is attributed to imprecision of the measurements of the low-concentration samples. The results are comparable to those of Beschta (1981), who found that coarse organic particles composed 10 to 50 percent of the bedload in several small, forested watersheds in western Oregon.

Erosion of Inorganic Particles

Inorganic or mineral particles originate predominantly from geologic materials as a result of erosion of hillslopes and stream channels. Erosion of geologic formations is a naturally occurring process that can be accelerated by human activities. Erosion processes can be classified into three general categories: surface erosion, mass erosion, and channel erosion.

All erosion processes depend on three environmental factors that control the rate of the processes as well as potential effects on stream turbidity. The first factor affecting erosion processes is erodibility of source material. On the basis of field inspection of erosion scars in the watershed, the most evident sources of readily erodible material appear to be "loose" geologic deposits, such as volcanic tuffs or breccias that are not welded or cemented into massive units. In addition, unconsolidated glacial drift and deposits of alluvial sediment also are susceptible to erosion, as are soils and subsoils formed by the weathering of more coherent geologic materials. The second factor common to all erosion processes is an energy source that is sufficient to detach particles at their source. The final factor is a transport process and route to deliver particles to stream channels. Principal transport processes are hillslope mass movements and water flow. Transport routes are along stream channels, streamside hillslopes, and roadside drainage ditches (Satterlund, 1972; Dunne and Leopold, 1978; Berglund, 1976).

The three elements of (1) source erodibility, (2) energy for particle detachment and (3) transport process collectively determine the occurrence of erosion and thus are essential to evaluation of any erosion-related phenomena such as stream turbidity. Particle sizes of suspended sediment and potential sediment sources also must be considered when assessing potential degradation of water clarity. Although silt and sand particles undoubtedly increase the turbidity of the swift, turbulent streams characteristic of the basin, turbidity is greatly attenuated by settling and dilution in the two reservoirs. A pulse of turbid streamflow with predominantly sand-sized particles derived from an eroding till deposit will not necessarily degrade clarity of the water supply because the sand quickly settles in the reservoirs. In contrast, clay-sized particles remain in suspension for weeks to months and thus represent the most severe threat to clarity of the water supply. The occurrence of very fine clay particles is minor in the Bull Run watershed (Beaulieu, 1974; Schulz, 1981).

REVIEW OF HISTORICAL DATA

Although water-quality data have been collected in the Bull Run watershed since the turn of the century, it was not until the 1970's that a regular monitoring program was begun for streams in the watershed. Since then, the City of Portland, USFS, and USGS have monitored water quality at numerous sites. One part of the monitoring program includes weekly turbidity measurements at four key stream stations used for water-quality standards compliance. In addition, turbidity is measured daily at a fifth key station at the headworks of the lower reservoir. A special task force was commissioned in 1988 to review the adequacy of the water-quality monitoring program. The task force acknowledged the exceptionally high quality of the Bull Run water supply but concluded, in part, that the monitoring program needed improvement, particularly because it did not incorporate flow-related water-quality effects (Aumen and others, 1989).

One noteworthy observation that can be made on examination of historical turbidity data is that recorded turbidity levels in the reservoirs appear to exceed those of the streams that feed into the reservoirs. This observation contrasts with an expected decrease of turbidity in the reservoirs as a result of settling and dilution of turbid streamflows. The disparity between historical stream and reservoir turbidity data is evident in water-quality standards. The standards were prepared by the USFS (U.S. Forest Service, 1987) as mandated by Public Law 95-200 and are used in a number of statistical tests to evaluate effects of land-use activities on water quality. These standards were derived from historical water-quality data and are indicative of the composition of those data. According to the standards, as shown in figure 4, turbidity for all four key streams is less than that of the reservoir headworks site. Contrary to the historical data and the standards, turbidity levels of the reservoirs typically were not greater than peak values of turbidity in the streams; rather, the historical weekly stream-sampling schedule did not effectively measure ephemeral turbidity increases that occur during storms. Some of the sediment delivered by streams was retained in suspension in the reservoirs where it was measured on a daily basis at the headworks. Consequently, existing turbidity data used to prescribe water-quality standards for the stream stations do not include representative measurements of peak stream turbidity.

Although weekly stream-turbidity data do not serve as a source of information for the brief periods when turbidity-causing processes are active in streams, the historical record of daily headworks samples and weekly reservoir samples may adequately reflect

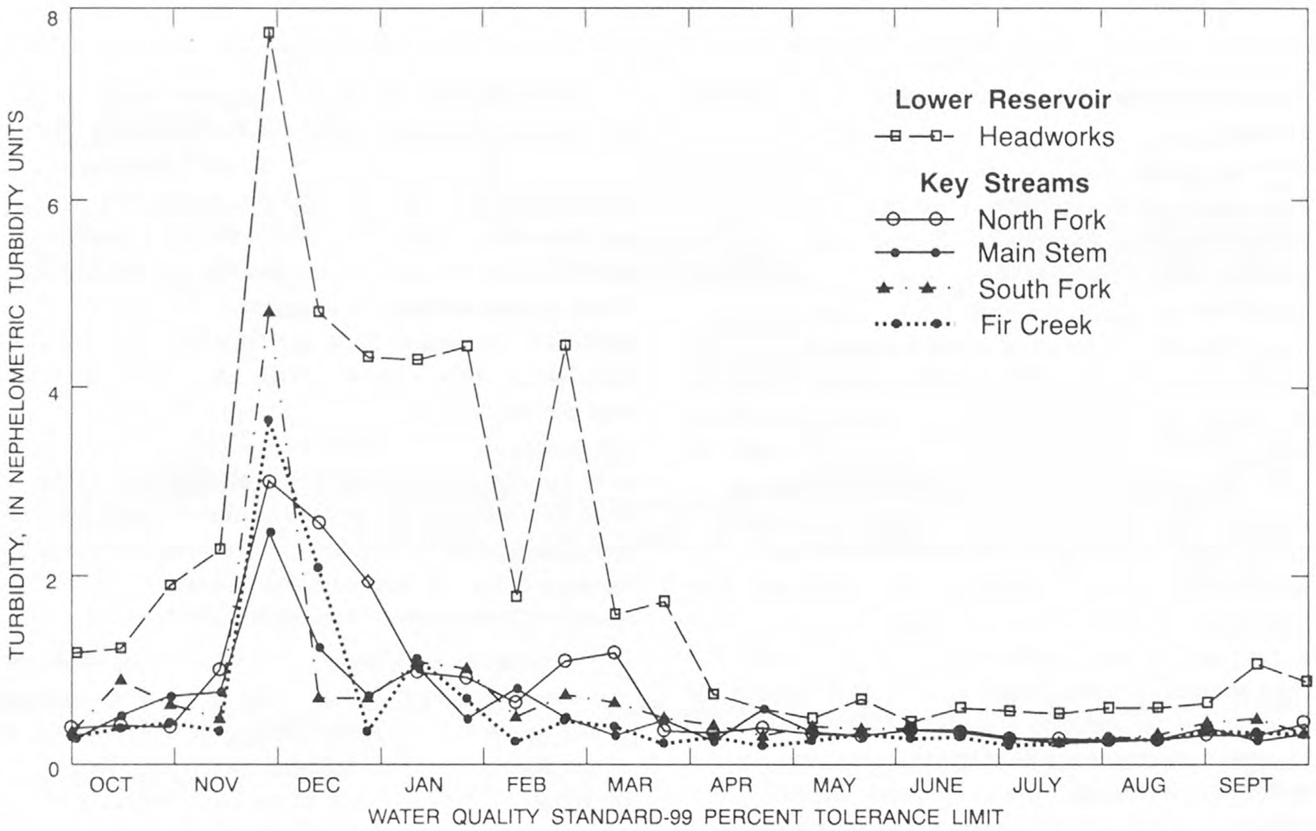

Figure 4. Turbidity standards for the four key stations and the headworks station.

water-quality variations in the reservoirs. The stream-turbidity data are useful for analyzing clear interstorm flow conditions and substantiating the need for establishing sampling protocols that can effectively monitor the transitory processes that cause variations in water clarity.

Additional evidence is available to support the premise that the dominant erosion and sediment-transport processes are active only during storms. The USGS, in cooperation with the City of Portland Water Bureau, studied water-quality variations at the four key stream stations from 1978 to 1983 (Rinella, 1987). Automated pumping samplers were installed during that period to collect water samples that were analyzed for suspended-sediment concentrations. Typically, samples were collected two to four times per day, but level-sensing switches automatically changed the sampling interval to 90 minutes during periods of high flows. Analysis of the data collected by this sampling protocol indicated that as much as 78 percent of the total suspended-sediment load at the four key stations was transported during only 3 or 4 days each year (Rinella, 1987).

A second element of Rinella's 1987 report was an examination of the relations between physical characteristics of the four key subbasins and water-quality variations. Multiple linear-regression equations were developed to relate annual suspended-sediment loads with basin climate, land use, topography, geology, and soils characteristics. On the basis of geologic hazards described by Beaulieu (1974), Rinella (1987, p. 12) hypothesized that differences in sediment concentrations between key stations are caused by the presence of easily erodible portions of the Rhododendron Formation within particular basins. A multiple regression analysis failed to verify the hypothesis, possibly because only annual total sediment loads for four large basins with mixed geologic and land-use characteristics were evaluated. The multiple-regression approach may be of greater value if applied to numerous individual storm peaks of numerous subbasins selected to isolate basin characteristics.

Observations made by Beaulieu (1974) also support the premise that large water-quality variations in the basin are highly event dependent. Beaulieu observed that unusually high flows significantly affected turbidity of the water supply by causing streamside slope failures. For example, he calculated that only a few tens of cubic yards of colloidal clay from a single slope failure was sufficient to increase turbidity for a prolonged period.

Schulz (1981) analyzed sediment sources by specifically investigating the relation between slope failures and geologic characteristics in the Bull Run watershed. He found that the morphology and distribution of mass movements in the basin are related to lithologic, structural, and stratigraphic variations in the bedrock. In particular, he found the greatest density of slump-earthflows on the Rhododendron Formation, whereas the density of debris avalanches is greatest on shallow soils found on steep canyon walls formed in Columbia River Basalt. Contacts between geologic units were found to be particularly susceptible to mass movements. Schulz also reported that zones of clay-rich material weathered from pyroclastic-flow and interflow breccias had increased incidence of mass movements.

FIELD RECONNAISSANCE

Field inspection of the watershed was done during both low-flow and high-flow conditions to locate recent erosion scars, sediment deposits, and actively eroding sites. The field reconnaissance included inspections of the reservoir shoreline during periods of low water, stream channels, roads, harvest units, and hillslopes.

Reservoir Shoreline

Since the establishment of the first water-supply reservoir on the Bull Run River in 1929, soils, forest litter, and sediment along the perimeter of each reservoir have been subjected to annual episodes of erosion by rainfall, streamflow, and wave action. After numerous cycles of scour and redeposition, much of the natural soil has been scoured away to expose a zone of resistant basalt along the upper shoreline. Downslope from this scoured zone lies a depositional zone, which is covered by a complex series of organic and mineral sediment deposits. Examination of trenches revealed that these deposits are predominantly conifer needles and silty sand that lack clay-sized particles. Fine sediment presumably remains in suspension long enough to be transported farther into the reservoirs. However, at extremely low reservoir levels, the shoreline deposits become exposed and eroded by streamflows and early season storms. Following such storms, eroded fine particles remain in suspension long enough to become a water-supply concern.

Examination of stream delta deposits in cutbanks and trenches also revealed a complex stratigraphy of organic and mineral layers. In contrast to shoreline sediment, sediment in upstream parts of the deltas is composed of boulders, cobbles, gravels, and sand that are not available for transport farther into the reservoirs. However, as in the case with shoreline sediment, finer sediment has been deposited on the distal portions of the deltas. During periods of extremely low pool levels, such deposits were observed to erode by incising streamflows. Erosion of deltas and shoreline deposits was observed to increase by down-cutting and lateral erosion of energetic storm-induced streamflows.

Logistical constraints of reservoir operation may make it difficult to avoid some delta and shoreline erosion, but effects of delta erosion might be reduced by an optimal management of reservoir pool levels. For example, during water year 1989, the upper reservoir was drawn down 56 feet and the lower reservoir was drawn down only 20 feet. During fall storms, turbid water was retained in the upper reservoir to refill the pool and allow suspended sediments to settle. Prior to the time that the upper reservoir filled, as shown by the vertical dashed line in figure 5, pulses of turbid water were retained in the upper reservoir and were not apparent at the headworks. Interestingly, turbidity appeared to decrease at the headworks during the refill period. This decrease is probably due to decreased delta erosion as pool levels rose and turbid flows were retained in the upper reservoir. After both reservoirs were full, increases in stream turbidity lasting only hours to days appeared greatly attenuated at the headworks several days later but persisted for as much as a month. Detailed analysis of in-reservoir processes is beyond the scope of this study, but focused studies on in-reservoir erosion, transport and sedimentation processes may be warranted to optimize reservoir operations.

Stream Channels

On the basis of field observations of erosion scars, the most evident sources of turbidity-causing particles are streamside sites. Evidence of recent, localized channel-bank erosion includes raveling stream banks and recently exposed roots. Such scarring tends to occur on unprotected banks, particularly on the outside of bends or where streamflows are deflected by debris into unconsolidated and unprotected banks. Erosion and transport of streambank materials greatly

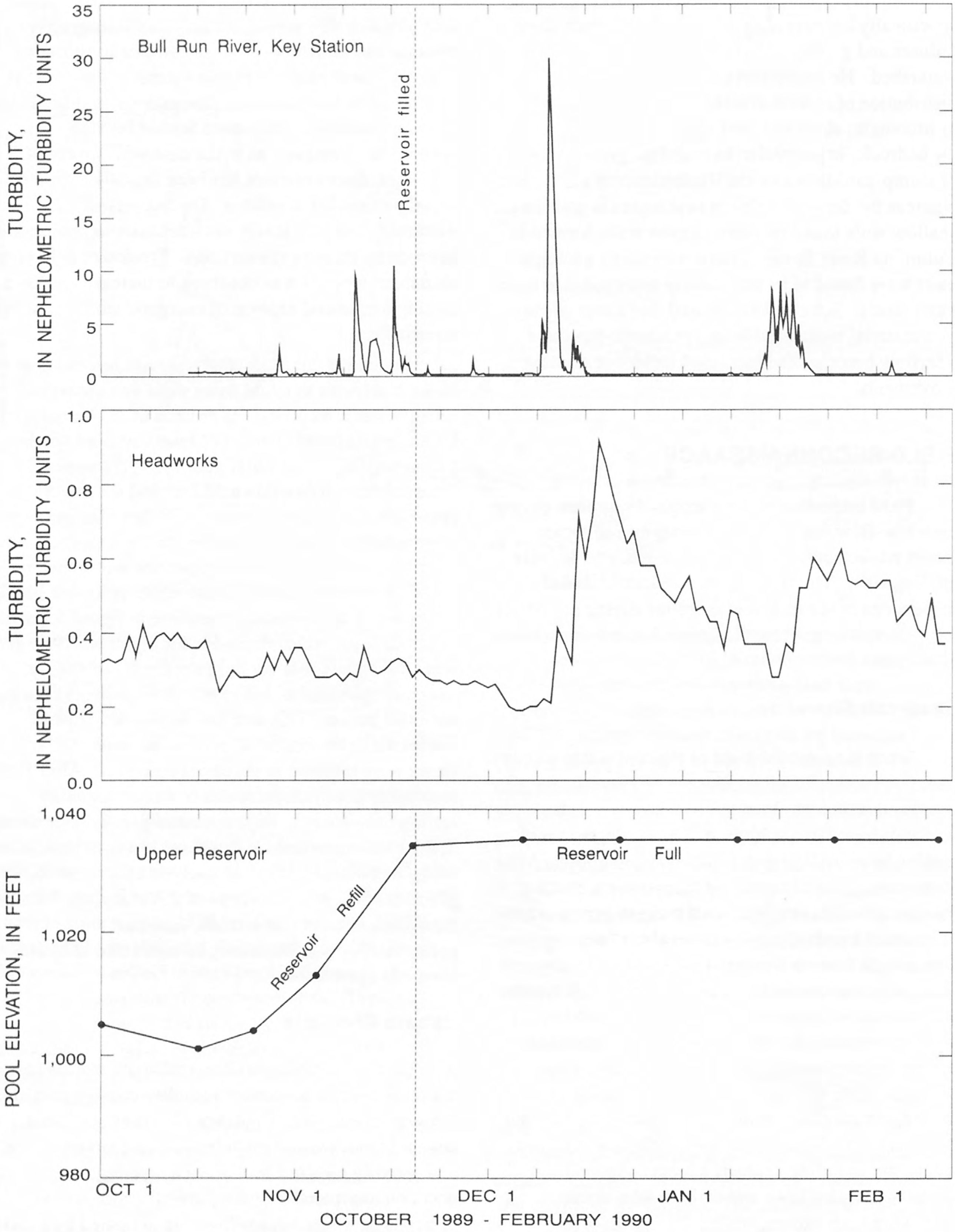

Figure 5. Turbidity at Bull Run River key station, headworks at lower reservoir and pool elevation of the upper reservoir from October 1, 1989 to February 10, 1990.

accelerates when streamflows rise to levels that allow erosive flows to contact unarmored bank materials.

Although stored fine-grained sediment is uncommon in the channels in the watershed, some streamside deposits do exist. Alluvial flood plains and terraces exist in the wide, relatively low-gradient valley bottoms that have formed in the Bull Run watershed by lateral erosion of relatively weak geologic formations. For example, erodible alluvial deposits are present adjacent to the small stream channels emptying into the north part of the upper reservoir: Five-mile Creek, Bear Creek, Deer Creek, and Cougar Creek. Cedar Creek, lower South Fork Bull Run River and the lower segment of Fir Creek also have relatively wide valley bottoms with erodible deposits (fig. 1). Sediment that has been deposited during high velocity streamflows in the Bull Run watershed typically consists of sand, gravel, cobbles, and boulders and lacks fine particles that may linger in suspension in reservoirs. However, weathering and soil genesis on old deposits gradually lead to accumulation of finer particles, which increases potential severity of downstream water-quality problems as these deposits erode during exceptional storms.

Narrow stream channels that have incised into massive basalt or andesite bedrock have steep rock banks that are not easily eroded. The main stem of the Bull Run River, Blazed Alder Creek, and the lower reaches of Nanny Creek are examples of such stream channels. Sediment within these channels appears to consist principally of volumes of coarse sediment stored behind ephemeral dams created by logs and other debris.

Debris jams are common in stream channels throughout the Bull Run watershed. They are important transient features that can affect turbidity by controlling the mode and rate of channel erosion processes. Pools created downstream from debris jams are sites where stream energy can dissipate in turbulent flow rather than by eroding channel beds and banks (Keller and Swanson, 1979). Coarse bed materials that accumulate behind debris jams may armor channels and decrease erosion in weak parent materials such as unconsolidated tuffs and breccias. The channel of Fir Creek is an example of a stream that has naturally developed a stepped sequence of debris jams and accumulations of coarse bed material that effectively armor the stream channel bottom through unconsolidated sections of the Rhododendron Formation.

The beneficial effects of debris jams are counteracted by detrimental effects such as bank erosion caused by deflection of streamflow into unprotected banks. Another detrimental effect is catastrophic failure of debris jams with consequent release of sediment and channel scour. Failure of debris jams appears to occur episodically throughout the Bull Run watershed (Nolan, 1984; Godbout, 1987). Nolan (1984) surveyed several debris jams in intermediate-sized streams in the basin in an effort to quantify bedload transport in steep forested streams. Reinspection of two of those debris jams in Cougar and Deer Creeks in 1989 revealed that both jams had failed with subsequent release of stored sediment. The sediment stored behind those jams consisted primarily of coarse sands, gravels, and cobbles. Evidently, fine silts and clays do not deposit behind jams but remain in suspension in swift turbulent flows typical of the Bull Run watershed. Although episodic debris jam disruption increases turbidity in streams, the relatively coarse material released is redeposited farther downstream or when flows reach the reservoirs. Active deposition of coarse bedload on the delta of Deer Creek was evident during the 1989-1990 study period as a recently fallen log became partly buried. Nolan (1984) documented recent changes in stream cross-sections and delta geometry at the mouth of Deer Creek as clear evidence of the sediment transport and deposition processes associated with a debris-jam failure. Examination of channels with documented jam failures and undergoing active channel adjustment indicated additional evidence of zones of bedload transport. In areas of active bedload transport, mobile boulders in the channel lack moss and appear relatively light in color compared to the darker surfaces of rocks that have been in place for longer periods of time.

In contrast to the pristine channel of Fir Creek, the channel structure of Log Creek was severely disturbed by a dam-break flood that occurred during an intense storm in 1964. A debris flow that resulted from that flood scoured portions of the Log Creek channel removing debris accumulations (figs. 6-8). Parts of that channel now exhibit erodible banks and lack pools that can dissipate the erosive energy of high level flows. Consequently, glacial deposits and talus slopes, which were destabilized, are still eroding more than 25 years after the channel-scouring flood. Log Creek provides a striking example of how the disturbance of natural structure in a channel has had a prolonged erosional consequence. Sand and silt particles, which predominate in the eroding banks of Log Creek, do not pose a major threat to the clarity of the municipal water supply because they rapidly settle in the reservoirs.

In addition to erosion from two dam-break floods (North Fork, 1972, and Log Creek, 1964), land-use activities in the Bull Run watershed have had other effects on stream channels. According to the USFS, 73 to 97 percent of forest blowdown in the Bull Run watershed during windstorms in 1973, 1976 and 1983 occurred adjacent to clearcuts (U.S. Forest Service, 1988). That increase in organic debris has resulted in the occurrence of numerous debris jams, particularly in upper basin streams such as Nanny and Bedrock Creeks (Godbout, 1987). Alterations in the natural occurrence of debris loads in channels have visibly accelerated erosion rates at some locations in the basin. Such effects are evident where addition or removal of debris has caused energetic streamflows to contact erodible channel-bank materials.

Roads

Unlike some other areas in the mountainous terrain of Oregon, the Bull Run watershed is affected little by roads (Brown and Krygier, 1971). The road system has been designed and maintained with the objective of preserving water quality. Paving of roads effectively prevents sediment production from the road surfaces (Reid and Dunne, 1984). Narrowness of the roads has minimized slope-disturbing cuts and fills and has limited the amount of impermeable surface contributing to runoff. Full vegetative cover along the roadside ditches effectively serves to dissipate the erosive energy of runoff, bind soil particles, and trap much of the sediment that gets into the ditches (Berglund, 1976). The erosion rates and transport of sediment from roads appear to be controlled principally by the amount of vegetation established on both roadcuts and roadside ditches. The location and maintenance of culverts appear to be effective in

Figure 6. Site of 1964 dam failure at Blue Lake and the head of the Log Creek channel. Photo by J.E. Costa 1989.

Figure 7. Scars remain on trees at margin of Log Creek as evidence of 1964 dam break flood and debris flow.

preventing erosion caused by concentrated road runoff or stream diversions.

Most roads in the basin upstream from the headworks site are located on stable ground such as lava flows or upland plains. At a few locations in exceptionally steep or weak lithologic units, incipient slope stability problems are evidenced by tension cracks and offset roadbeds. Settlement of organic road-fill material also has caused some road surface offsets and cracking. Water-quality hazards exist where fill failures have a high potential to deliver sediment to nearby streams. An example of one such site is the steep road fill perched above West Branch Falls Creek on Road 10.

Road construction during the study period was limited to only a few sites with little or no potential to transport sediment to streams. Several short sections of temporary roads were constructed to access timber sales in upland areas. Repairs to segments of some roads were completed during the study period. Inspection of those sites during storms revealed negligible effects on stream turbidity because highly turbid runoff from monitored sites did not flow into a stream. Rather, it was diverted to areas where sediment deposition and infiltration occurred.

The most visible sediment sources associated with roads are steep, unvegetated roadcuts, particularly near stream crossings. Erosion along roadcuts occurs as a result of ravel, frost heaving, sheet, rill, and small-scale mass erosion. The severity of ditch and roadcut erosion appears to depend on vegetative cover, amount of flow in ditches, steepness of the gully, and the erodibility of the gully bed and banks. Low-gradient ditches with well-established vegetative cover appear to serve as efficient sediment traps. In contrast, wherever a roadside ditch lacks vegetation and runs steeply into a nearby stream, eroded materials are transported efficiently and add to the sediment load of that stream. Steep ditches result in higher velocity flows and increased potential for erosion. Roadside ditches typically steepen as they drop into a stream, creating maximum erosion and sediment-delivery potential.

Timber-Harvest Units

Although about 20 percent of the Bull Run watershed has been logged, only a small part of that area was actively being logged during the study period. Recently logged tracts exist mostly in the upland areas where high winds damaged timber stands adjacent to clearcuts. These areas were included in the first of a 4-year timber salvage program designed to reduce fire hazards associated with blown down timber. Because of the upland location of the blowdown areas, the active harvest units had low potential to deliver sediment to streams. The exceptional efforts to minimize erosional effects of logging and the inherently stable characteristics of the upland lava plains also limited the potential for water-quality degradation. Typical yarding operations in the Bull Run watershed use cable or helicopter systems to maximize suspension of logs and minimize soil disturbance. Throughout the watershed, deep litter and organic duff layers protect the soil surface and promote rapid infiltration of rainfall. Even after light slash-burning operations, residual organic duff layers continue to provide some protection to the soil surface. However, hot slash burns and firebreaks cut around harvest units completely remove the organic surface layers, exposing the underlying mineral soil to the erosive effects of rainfall and surface runoff. Where such exposures occurred on streamside slopes,

Figure 8. Erosion of portions of Log Creek continues more than 25 years after a debris flow removed natural channel armor.

sediment transport occurred in rills leading to stream channels.

The most noticeable effect of logging operations is increased debris loading in streams caused by timber blowdown adjacent to clearcuts. Openings in the forest canopy created by logging have increased the incidence of timber blowdown (U.S. Forest Service, 1988). The blowdown of narrow streamside buffer zones with increased input of organic debris to streams is clearly evident at numerous locations in the basin and is a direct effect of logging activities.

Hillslopes

Because of their scarcity and heavy vegetative cover, hillslope erosion scars are not evident except for isolated debris-flow scars on steep canyon walls. The extensive aerial photo interpretation and field checking done by Schulz (1981) is a reference for an analysis of long-term hillslope stability.

Turbidity monitoring during the study period led to the discovery of a streamside slope failure. On January 9, 1989, intense rainfall and associated snowmelt caused high stream discharges in the watershed. The following day, a rapid and substantial increase in the turbidity of Fir Creek was measured. Turbidity levels increased from less than 1 NTU to more than 100 NTUs, a level in excess of the measuring capability of the onsite turbidimeter. Subsequent reconnaissance of Fir Creek revealed that a small soil-slip/debris flow had introduced less than 10 cubic yards of soil into the stream approximately 1 mile upstream of the key station gage house. The slope failure originated less than 200 feet above the stream in a clay-rich zone near the lithologic contact of the Rhododendron Formation and over-lying Pliocene volcanic rocks. Although most of the fine fractions of the deposit had been removed by increased streamflows, a deposit of coarse, angular clasts remains in the channel and sharply contrasts with the well-rounded bedload in the remainder of the channel. Subsequent streamflows continued to mobilize the landslide deposit, causing intermittent periods of elevated turbidity in the stream and a noticeable increase in the turbidity of Fir Creek in response to minor storms (fig. 9).

VARIATIONS IN TURBIDITY

Relation to Flow Phenomena

Hydrologic conditions during the study period were similar to average conditions. At the Bull Run River key station, total discharge for water years 1989 and 1990 was within 5 percent of the 23-year average and annual maximum discharges had recurrence intervals of about 1.5 years (Friday and Miller, 1984; Hubbard and others, 1989; Hubbard and others, 1990). Turbidity data collected during the study period indicate that increased turbidity in the streams of the Bull Run watershed is strongly related to storms. The relation between rainfall, discharge, and turbidity during storms is shown in figures 10-13. Although it is apparent that increases in turbidity accompany rapid increases in stream discharge, discharge alone is not adequate to fully interpret variations in turbidity (figs. 14-17). Lack of simple discharge-turbidity correlations can be attributed to numerous phenomena, including seasonal flushing flows, nonlinear responses to large storms, and hysteresis (Guy,1970; Porterfield, 1972; Paustian and Beschta, 1979). Interpretations of turbidity variations are improved compared to simple discharge-turbidity relations when periods of similar streamflow are segregated on the basis of these phenomena.

Interstorm Flows

Periods between intense rainfalls constitute most of the time in any year, and streamflows remain remarkably clear during these interstorm periods. Stream turbidity levels of 0.2 to 0.3 NTUs are typical, and levels rarely rise above 1 NTU during interstorm flow periods. Historical data collected at the key stations and turbidity data collected as part of this study indicate that this class of flow occurs about 90 percent of the time.

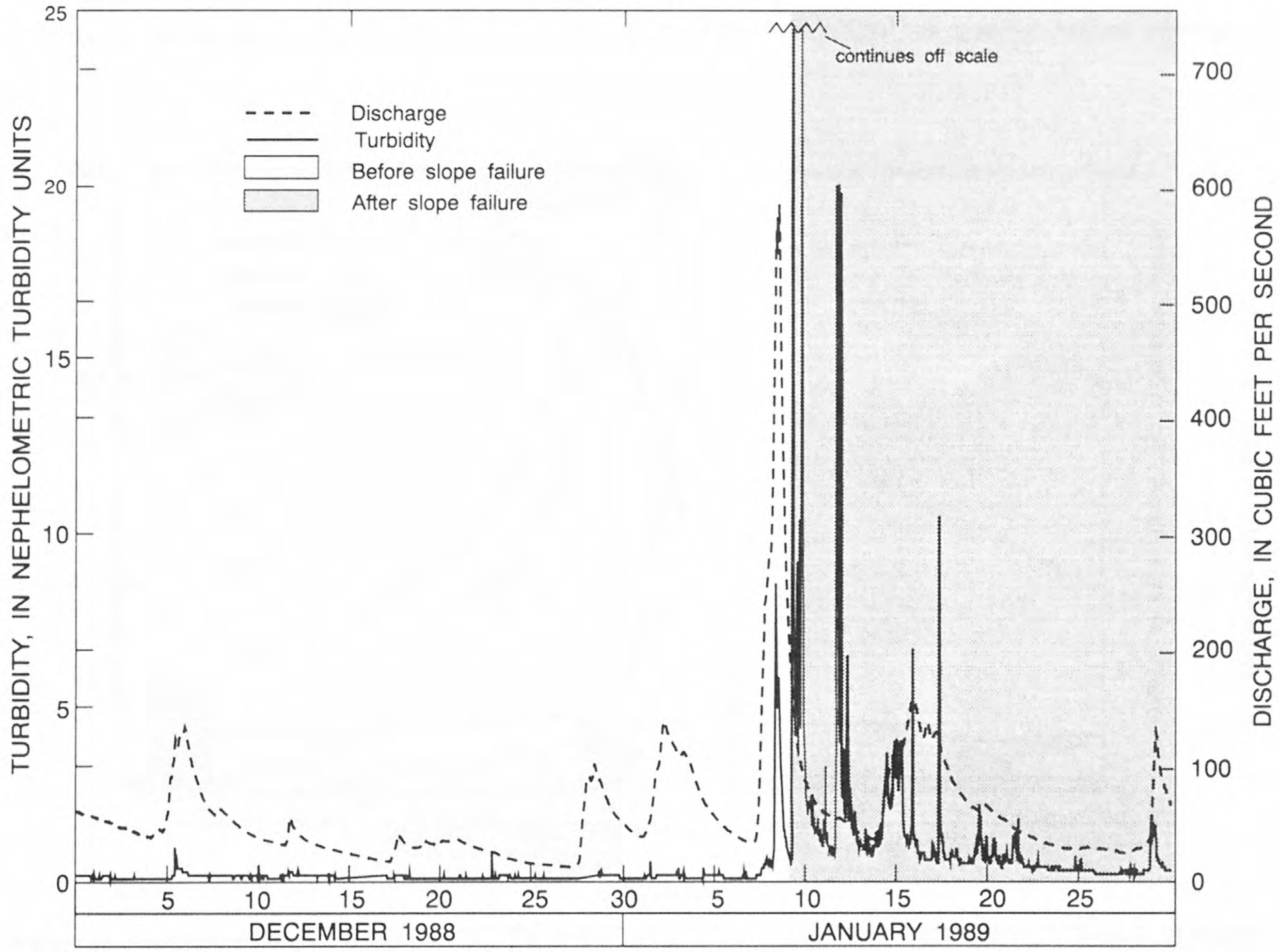

Figure 9. Turbidity and discharge, Fir Creek, December 1, 1988 to January 31, 1989.

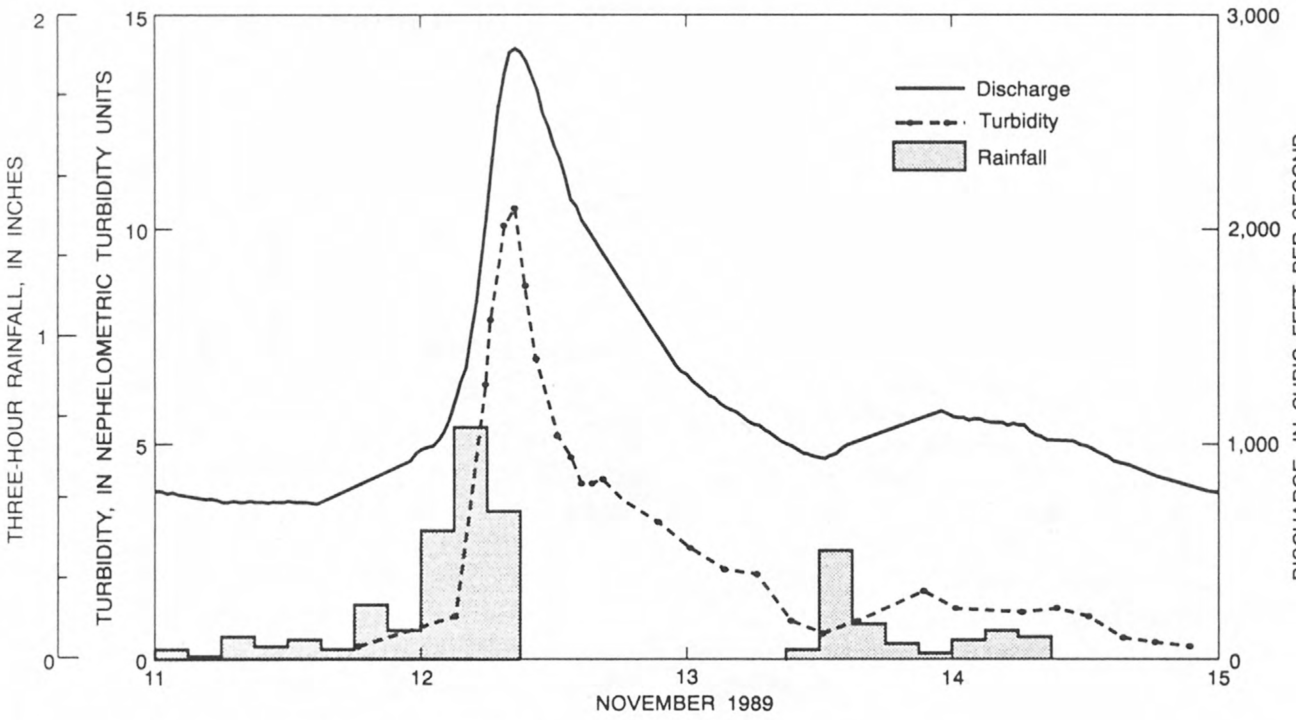

Figure 10. Rainfall, discharge and turbidity, Bull Run River, November 11-14, 1989.

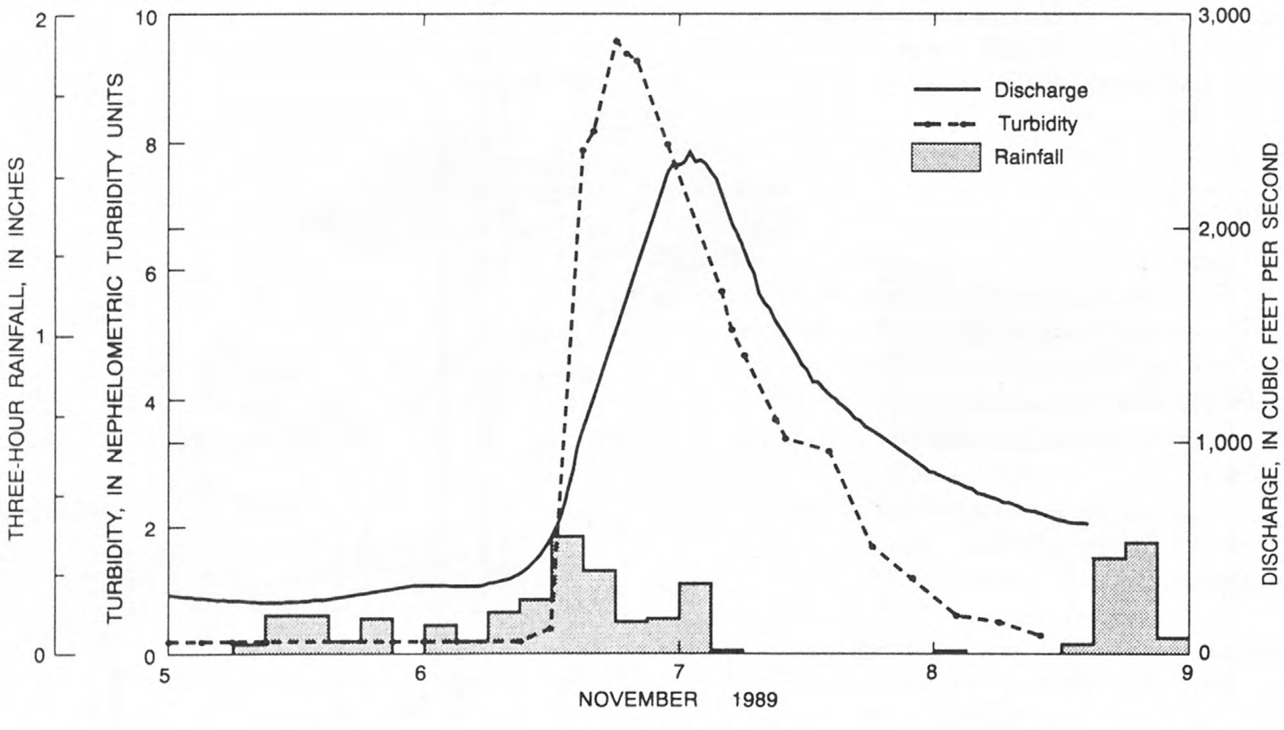

Figure 11. Rainfall, discharge and turbidity, Bull Run River, November 5-8, 1989.

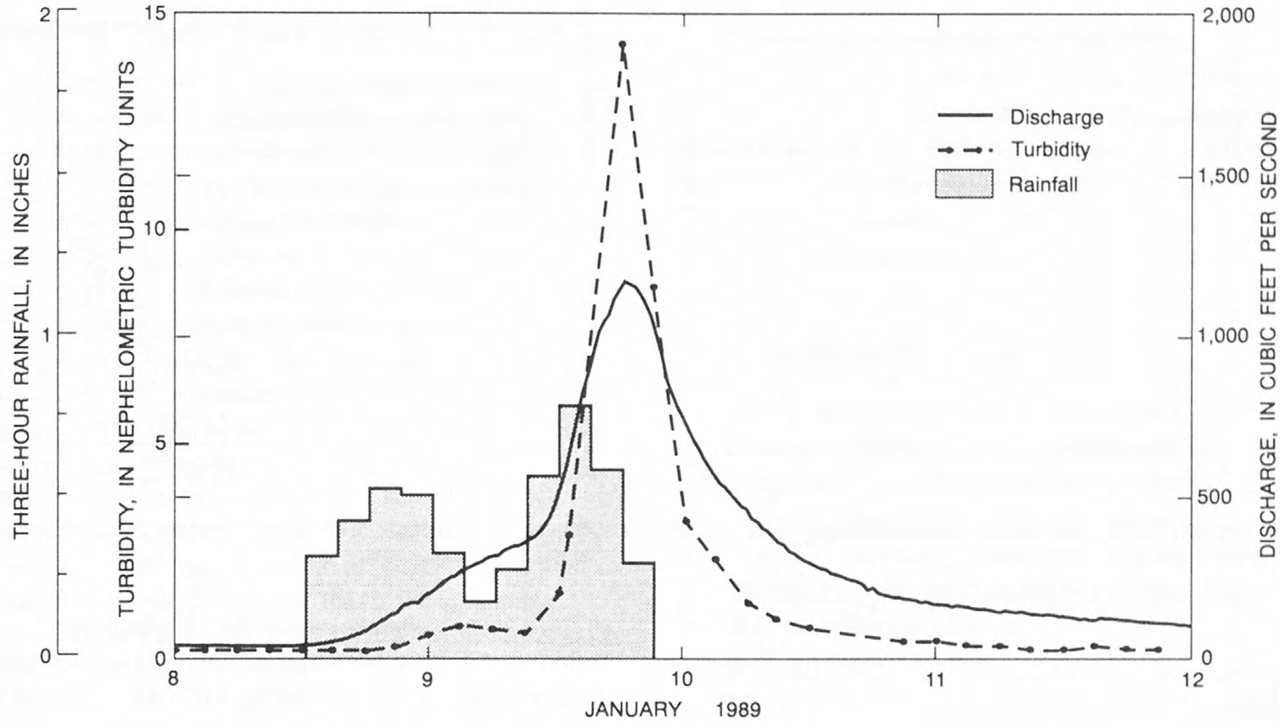

Figure 12. Rainfall, discharge and turbidity, Blazed Alder Creek, January 8-11, 1989.

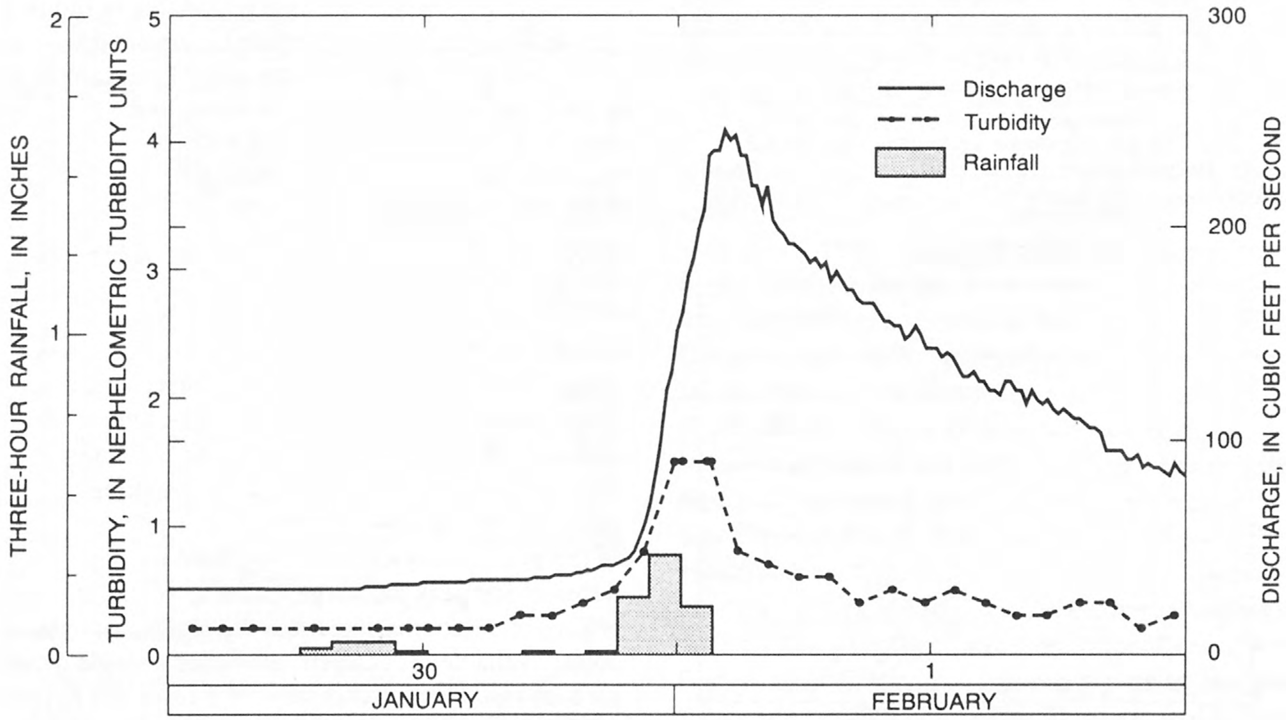

Figure 13. Rainfall, discharge and turbidity, Log Creek, January 29 to February 1, 1989.

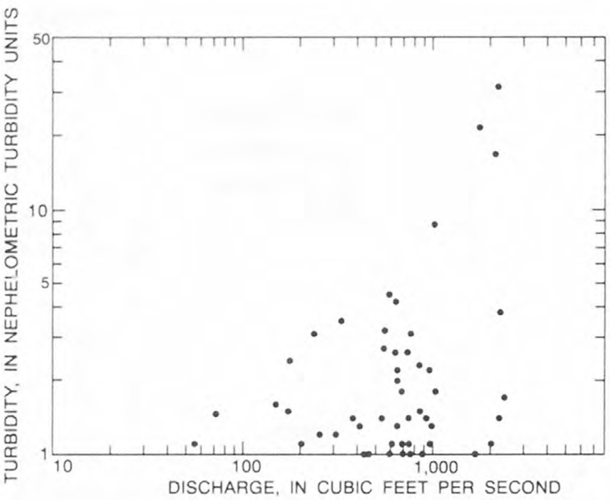

Figure 14. Relation of turbidity and discharge, Blazed Alder Creek, water year 1990.

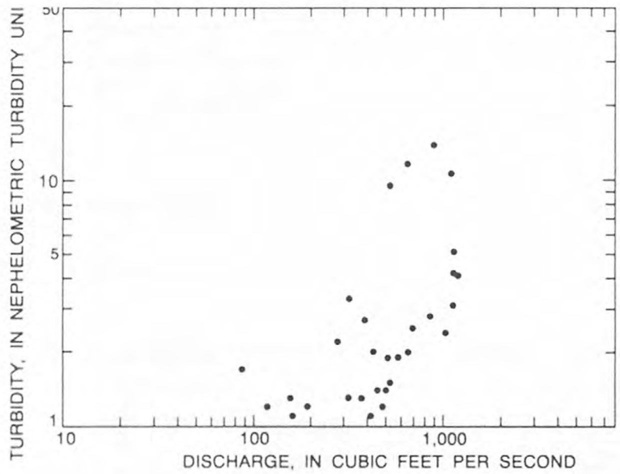

Figure 15. Relation of turbidity and discharge, Bull Run River above confluence with Blazed Alder Creek, water year 1990.

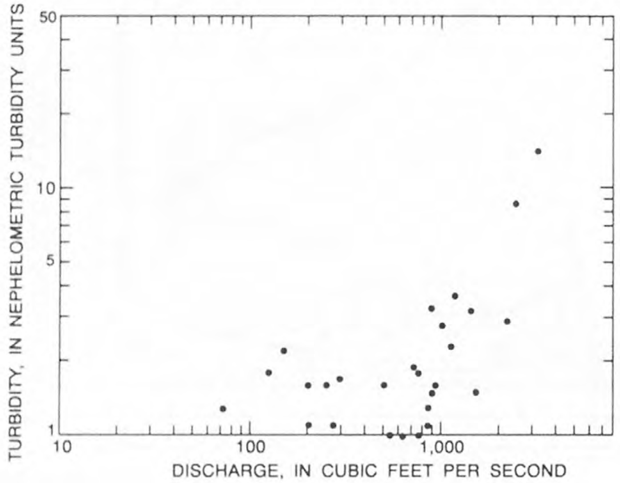

Figure 16. Relation of turbidity and discharge, Blazed Alder Creek, water year 1989.

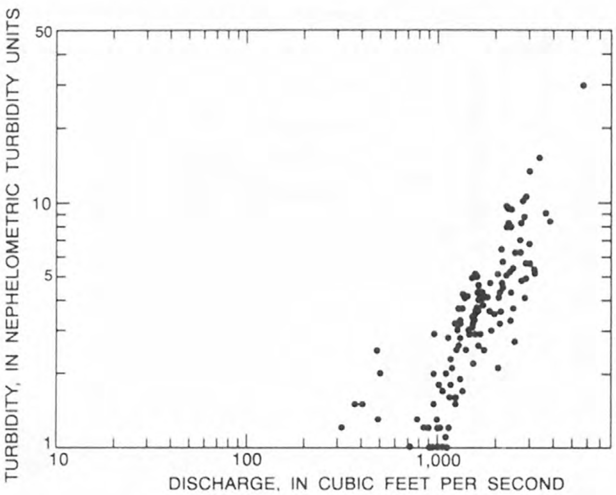

Figure 17. Relation of turbidity and discharge, Bull Run River at the key station, water year 1990.

Hysteresis simply means that the discharge-turbidity relation differs between periods of rising and falling stream levels. Hysteresis has been attributed to differences in timing of turbidity peaks and discharge peaks (Marcus, 1989; Heidel, 1956) and to depletion of sediment supplies during a storm (VanSickle and Beschta, 1983). The effect can be observed in figures 10 and 11, which illustrate storm hydrographs of the Bull Run River. Note that the peak turbidity in figure 11 preceded the peak in discharge and that turbidity is greater for equal discharges while the stream discharge is increasing compared to decreasing. For example, at a discharge of 2,000 ft^3/s on the rising limb of the hydrograph, turbidity is 8.8 NTUs whereas at a discharge of 2,000 ft^3/s on the falling limb, turbidity is 5.1 NTUs. Hysteresis is also evident in figure 10 for a hydrograph with more coincident peaks in discharge and turbidity. Again at 2,000 ft^3/s, turbidity is 6.3 NTUs on the rising hydrograph and 4.1 NTUs while the streamflow is receding. The hysteresis phenomenon complicates simple attempts to construct a rating curve between instantaneous discharge and turbidity measurements. The relation can be improved by identifying hysteresis in the data and adopting analytical methods that account for the phenomenon. In this study, analyses were completed using peak turbidity and peak discharge values to avoid hysteresis effects. This approach reduces the number of data points available for analysis, providing a single datum for each storm peak. Alternatively, Brown and Krygier (1971) avoided hysteresis effects by using only those data from the rising part of stormflows above a certain magnitude in an analysis of sediment transport in several Western Oregon streams.

Seasonal Flushing Flows

The first few storms occurring at the onset of the rainy season are characterized by disproportionately high turbidity compared with flows of similar magnitude occurring later in the season. Relatively small early season flows have higher turbidities than subsequent larger flows, as shown in figure 18. These early-season turbid flows have been attributed to a channel-flushing process whereby sediment that accumulated during low-flow periods is mobilized and depleted by early season stormflows (VanSickle and Beschta, 1983). The material transported by flushing flows includes abundant organic matter as well as soil material that accumulated in channel margins and roadside ditches. Turbidity appears to increase as a result of minor increases in streamflow early in the flushing period. The end of the flushing period is indicated by a decreased ratio of peak turbidity to peak flow during low-intensity rainfall.

Seasonal flushing effects alter the direct relation between streamflow and turbidity and need to be considered in sediment-transport studies. The seasonal effect has been incorporated into a sediment-transport model by VanSickle and Beschta (1983) by including a model component that accounts for sediment storage and depletion variations over time. Another analytical technique is multiple-regression analysis using a seasonally fluctuating independent variable such as air temperature or month (Guy, 1964).

During early season stormflows, the low water levels in the water-supply reservoirs expose stream deltas and sediment. Consequently, early-season flows erode shoreline and delta deposits and increase reservoir turbidity. Turbidity of streamflows measured above and below reservoir deltas showed that stream turbidity increased from an average of 2 NTU's to an average of 8 NTU's and as much as 25 NTU's as streams were observed cutting into the exposed deltas in the upper reservoir. Although typical early-season storms produce relatively low stream discharges, their effects on reservoir turbidity are of concern because attenuation of turbidity by reservoir dilution is less than that for subsequent flows.

Winter Stormflows

Winter storms that occur after early-season flushing flows appear to require a minimum threshold of rainfall intensity to cause increased turbidity in streams. Rainfall intensities greater than 0.25 inches in a 3-hour period are sufficient to temporarily raise stream turbidity to levels of 1 NTU to 30 NTUs. During winter stormflows, turbidity and streamflows increase rapidly in response to such high-intensity rainfall (figs. 10-13). Peak turbidity levels occur after rainfall peaks but often precede peaks in streamflow. Turbidity quickly falls to interstorm levels after rainfall stops; however, recession of stream discharge is slower.

Large Stormflows

Storms and floods that produce streamside landslides or debris-jam failures and channel scour cause large and persistent increases in turbidity. Such storms cause deviations in discharge-turbidity relations. The previously discussed Log Creek dam-break flood of 1964 is an example of a persistent effect caused by an exceptional event.

A similar incident occurred during a large storm in 1972 when another dam-break flood caused a debris flow in the North Fork Bull Run River. The large flood and debris flow eroded parts of a large, inactive landslide at the upper contact of the Rhododendron Formation. Erosion at that site delivered tens of cubic yards of colloidal clay to the North Fork and caused a persistent turbidity problem in the municipal water supply. Installation of revetments to channelize the streamflow and prevent additional erosion was necessary to alleviate the problem.

A naturally occurring example of a persistent response to a storm resulted when an intense winter storm caused a debris flow that ran into Fir Creek on January 10, 1990. About 10 cubic yards of sediment were deposited into the stream channel and caused a large and persistent increase in turbidity of that stream. Unlike most turbidity increases associated with low-intensity storms, the secondary pulse in turbidity in Fir Creek shown in figure 19 occurred well after the cessation of rainfall and peak discharge. The delayed response was caused by a streamside debris flow that was discovered by field reconnaissance. A second example of a delayed turbidity response also occurred after the January 9, 1989 storm in the upper reaches of the Bull Run River upstream from its confluence with Blazed Alder Creek. The secondary peak in turbidity shown in figure 20 occurred on the morning of January 10, hours after cessation of rainfall and recession of peak streamflow, and could have been caused by minor streamside slope failures or bank failure.

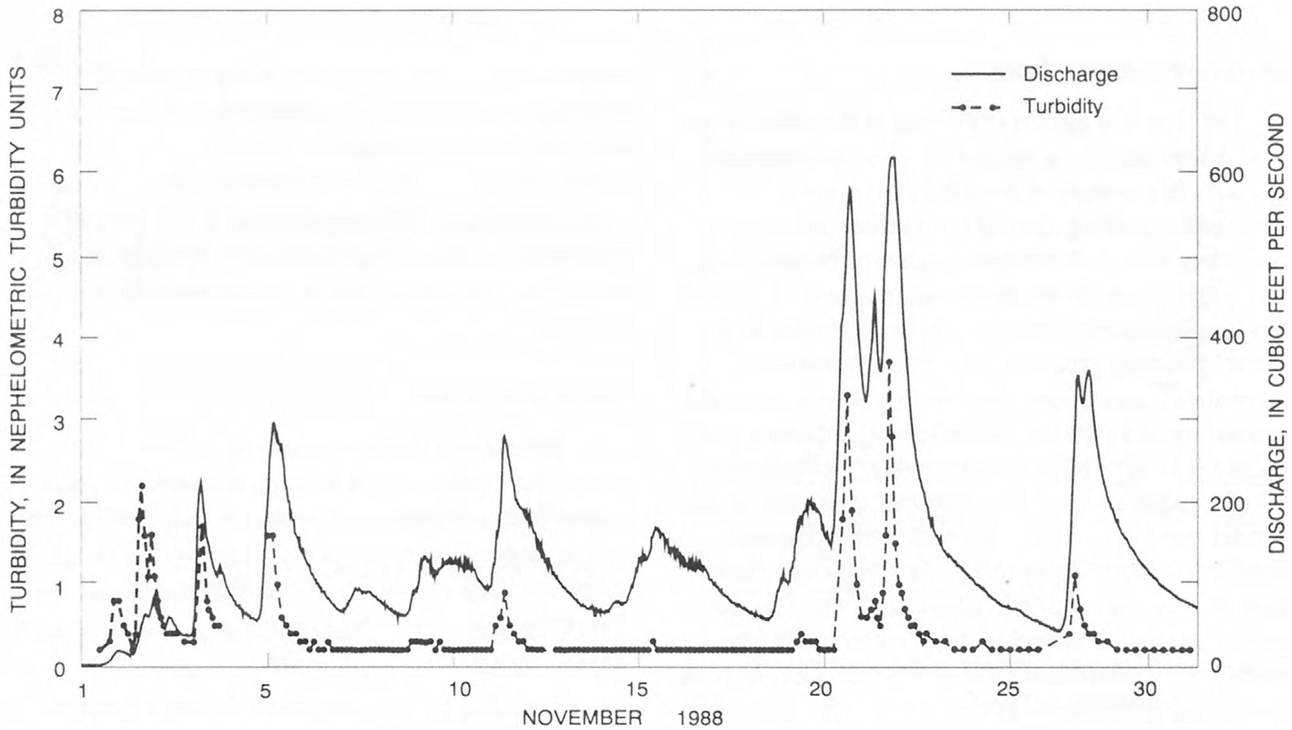

Figure 18. Turbidity and discharge, Blazed Alder Creek, November 1-30, 1988.

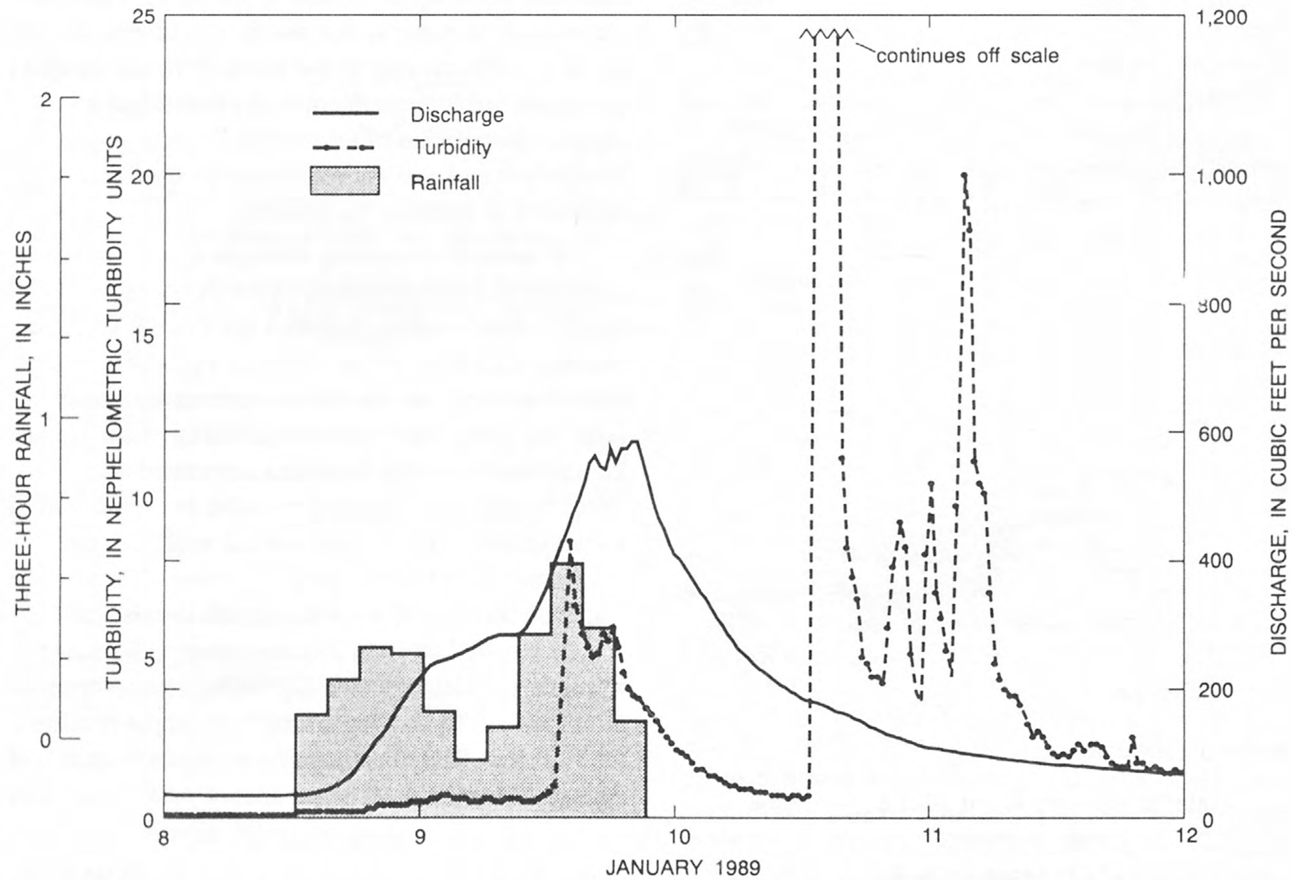

Figure 19. Rainfall, discharge Fir Creek, January, 8-11, 1989. Delayed peak in turbidity due to streamside landslide occurred almost 24 hours after the discharge peak.

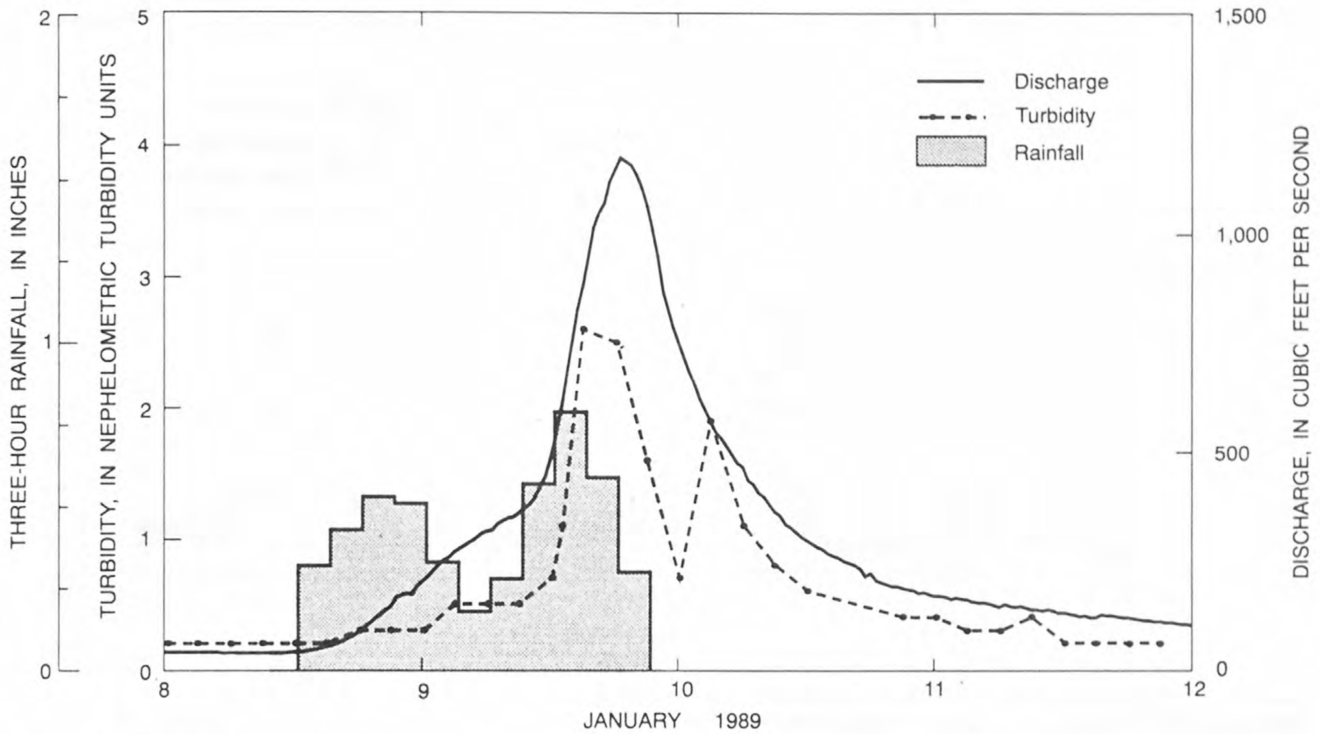

Figure 20. Rainfall, discharge and turbidity, Bull Run River above confluence with Blazed Alder Creek, January, 8-11, 1989. A secondary peak in turbidity occurred almost 10 hours after the peak discharge.

Relation to Geology

Turbidity of water samples collected during winter storms varied with storm intensity and also with differences in the erodibility of different geologic units. No differences in stream turbidity were apparent between sampling sites for streamflows occurring during interstorm periods. During stormflows, however, differences in stream turbidity between sites became apparent.

The turbidity of Log Creek typically exceeded that of other streams in the basin during seasonal flushing flows and also during some winter storms (figs. 21-23). This response was caused by raveling and undercutting of channel banks of unconsolidated glacial till that have not healed following the dam-break flood and debris flow in 1964.

Rocks and soils associated with the Rhododendron Formation appeared to contribute disproportionately to peak turbidity levels, particularly during large winter storms. Relatively high peak turbidity in streams flowing through the Rhododendron Formation appears to be caused by the presence of erodible banks, which contrast with the hard rock banks of most of the overlying and underlying geologic formations.

The difference between the mean turbidity peaks measured in streams that flow through the Rhododendron Formation and streams that do not were investigated by using a Wilcoxon-Mann-Whitney rank sum test (Iman and Conover, 1983). This nonparametric test was chosen because it accommodates small samples with nonnormal distribution. The test was applied to turbidity data for storms that produced the annual maximum discharges during water years 1989 and 1990. The rank sum test affirmed, with more than a 99.5-percent confidence level, that mean peak turbidity in streams flowing through the Rhododendron Formation is greater than mean peak turbidity in streams that do not flow through the formation (table 1).

Relation to Flow Discharge and Duration

In this study, turbidity is used to help explain spatial patterns of erosion and sediment transport. Temporal patterns of turbidity variations also are conspicuous in the data. During most of the historical water-quality monitoring done in streams of the Bull Run watershed, streams were sampled at regular time intervals. Such a sampling approach precludes accurate evaluation of stream turbidity caused by

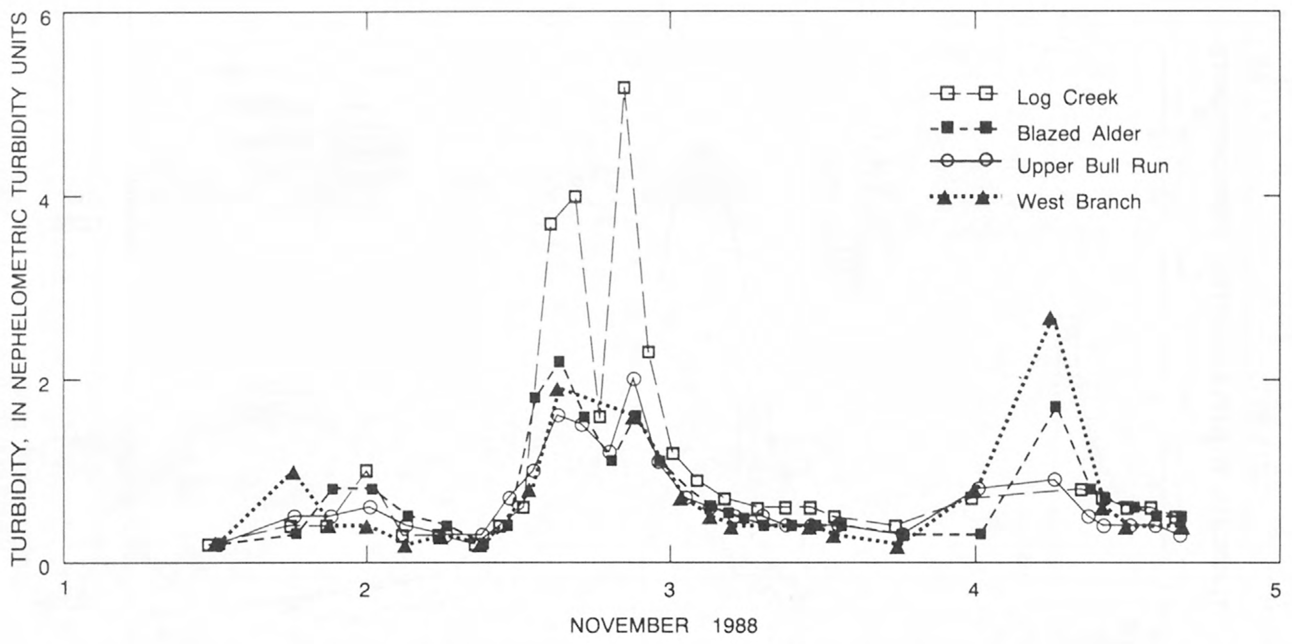

Figure 21. Turbidity at Log Creek, Blazed Alder Creek, upper Bull Run River and West Branch Falls Creek, November 1-4, 1988.

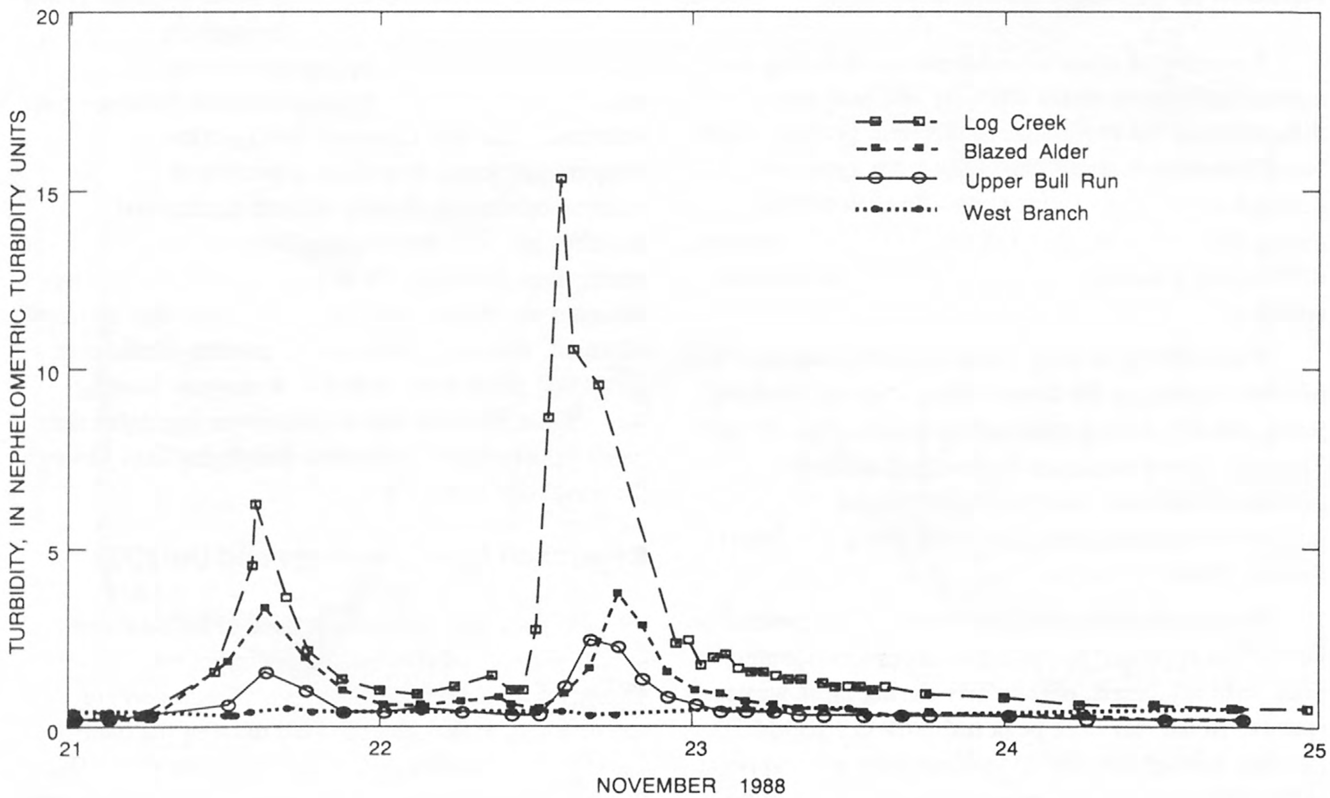

Figure 22. Turbidity at Log Creek, Blazed Alder Creek, upper Bull Run River, and West Branch Falls Creek, November 21-24, 1988.

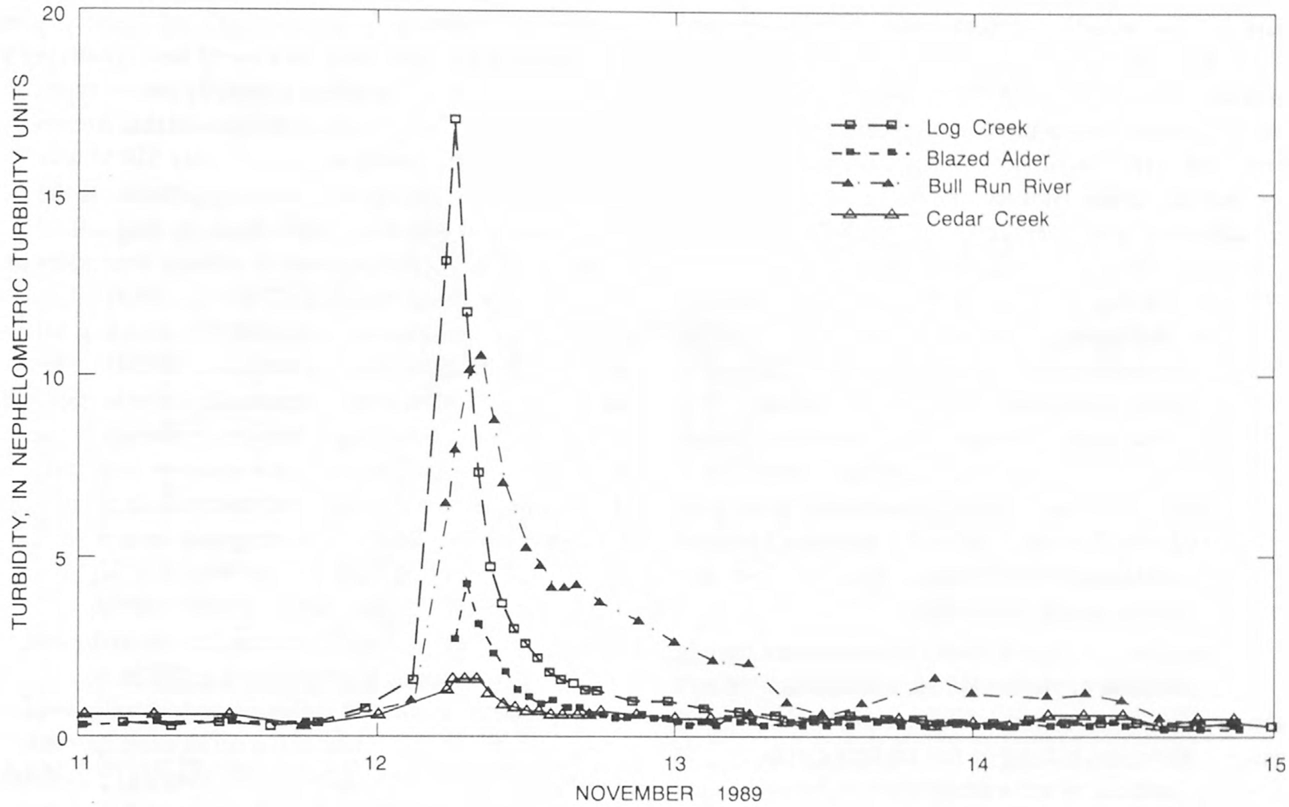

Figure 23. Turbidity at Log Creek, Blazed Alder Creek, Bull Run River (key) and Cedar Creek, November 11-14, 1989.

Table 1. Wilcoxon-Mann-Whitney rank sum test data

Upstream from Rhododendron Formation			Downstream from Rhododendron Formation		
Station	Turbidity	Rank	Station	Turbidity	Rank
Peak turbidity values — January 9, 1989, 18:00 to 20:00					
9	4.4	1	16	7.8	4
10	4.8	2	17	13	8
18	6.7	3	4	13	8
8	8.0	5	5	13	8
13	12	6	6	16	10
			3	22	11
			19	28	12
Significant difference in mean peak turbidity at 99.5-percent confidence level.					
Peak turbidity values — December 4, 1989, 17:00 to 19:00					
24	8.2	1	7	13	5
10	8.6	2	17	18	7
11	12	3.5	19	26	10
18	12	3.5	5	27	11
12	15	6	3	30	12.5
8	21	8	5	30	12.5
22	23	9	4	36	14
			6	39	15
			16	10	16
Significant difference in mean peak turbidity at 99.9-percent confidence level.					

stormflows. Potential effects of storms might better be identified by including effects of stream discharge and duration in addition to turbidity. The importance of including discharge and duration can be realized quickly by comparing the potential effects of a single stormflow with that of typical interstorm streamflow. For instance, at the Bull Run River key station, the turbidity during an average annual peak flow of 6,000 ft^3/s is 15 NTUs. Median interstorm turbidity is 0.2 NTUs and median discharge is 250 ft^3/s at that station. Therefore, the annual peak storm turbidity is 75 times greater than median interstorm turbidity, and annual peak discharge is 24 times greater than median interstorm discharge. The product of these two factors, 1,800, can be used to compare the relative inputs of turbid water to the water-supply reservoirs. If the peak flow lasted only 3 hours, it takes 7.5 months (3 hours x 1,800 = 5,400 hours) of interstorm flow to deliver an equivalent input to the reservoirs.

Inputs for seasonal flushing flows amount to only 10 percent of the total annual load and are limited by the low discharges of streamflows early in the rainy season. However, effects of fall flushes can be important because of delta erosion and reduced dilution in the reservoirs. An additional10 percent of the annual load was delivered during interstorm periods, and the remaining 80 percent was delivered to the reservoirs by the peaks of winter stormflows. More than one-half of that quantity was delivered during each annual maximum flow.

MAGNETIC MINERALOGY

Surface and subsurface soil horizons in different lithologic units and stream and reservoir sediment were sampled and analyzed for a variety of magnetic properties to help determine sources of turbidity-causing minerals. The following properties were measured on the samples: (1) magnetic susceptibility, (2) saturated isothermal remnant magnetization (SIRM), (3) coercivity of remnance, and (4) Curie temperature. Magnetic mass susceptibility, X, is a parameter that describes the tendency for a sample to become magnetized while in an applied magnetic field. It varies primarily with the concentration and to a lesser degree with type of magnetic minerals in a sample. SIRM is a parameter that describes the tendency for a sample to remain magnetized after being removed from a strong magnetic field that caused complete magnetization of the sample. SIRM depends primarily on the concentration of magnetic minerals in a sample and to a lesser extent on the type of minerals in the sample. Coercivity of remnance, or back coercivity, is a parameter that describes the ease of demagnetizing a sample. Coercivity depends primarily on the type of mineral in a sample. Initial tests showed that coercivity and SIRM were closely related, so only SIRM was measured for all samples. Curie temperature is the temperature at which a sample loses its magnetic properties. Curie temperature is entirely dependent on the type of mineral sampled (Oldfield, 1983). An additional parameter was calculated by dividing SIRM by susceptibility to obtain a measure, SIRM/X, that minimizes the effects of concentration of minerals and accentuates the differences between minerals in the samples. Results of the tests for samples collected from soils, stream deposits and reservoir deposits are shown in figures 24-27. The magnetic tests revealed that all samples had high concentrations of highly magnetic magnetite that dominated the readings. Differences between soil horizons, stream sediment, and reservoir sediment are evident in SIRM and susceptibility because of differing concentrations of magnetic minerals. Those differences are expected because of natural pedogenic (soil-forming) processes and particle-sorting processes in the fluvial system. Such differences are not useful in differentiating sediment sources.

The remaining parameters, SIRM/X and Curie temperature, are most useful in revealing differences in samples due to differences in magnetic minerals. The values for SIRM/X and Curie temperature were dominated by the effects of high concentrations of magnetite, which prevented discrimination of mineralogic diversity of less magnetic minerals.

IMPLICATIONS FOR MONITORING TURBIDITY

An important improvement to the stream water-quality monitoring program could be made by incorporating sampling and analytical techniques that take into account the event-dependent nature of erosion and sediment-transport processes in the watershed. For example, in this study, automated monitoring and telemetry were used to collect data and notify personnel during periods of increased turbidity. Data were then separated into four flow classes to facilitate analysis of similar periods. A similar process-oriented approach might be suitable in revising sampling protocols as well as revising statistical tests used to evaluate turbidity data.

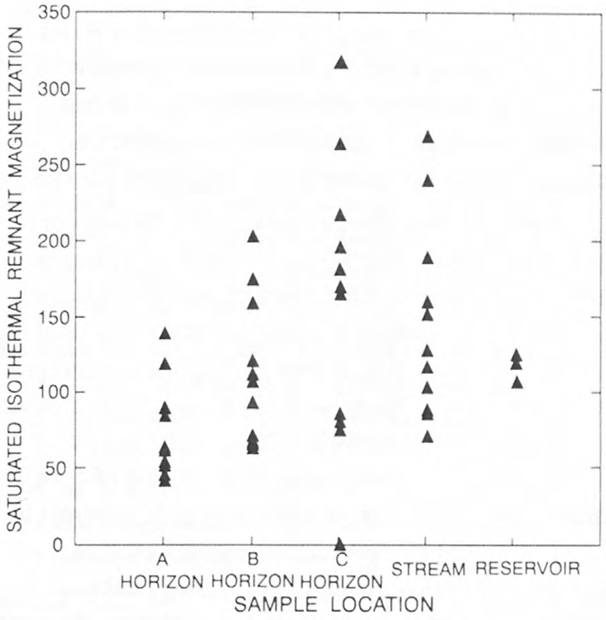

Figure 24. Relation of saturated isothermal remnant magnetization and sample source. Sources: (1) A horizon soil, (2) B horizon soil, (3) C horizon soil, (4) stream sediment (5) reservoir sediment.

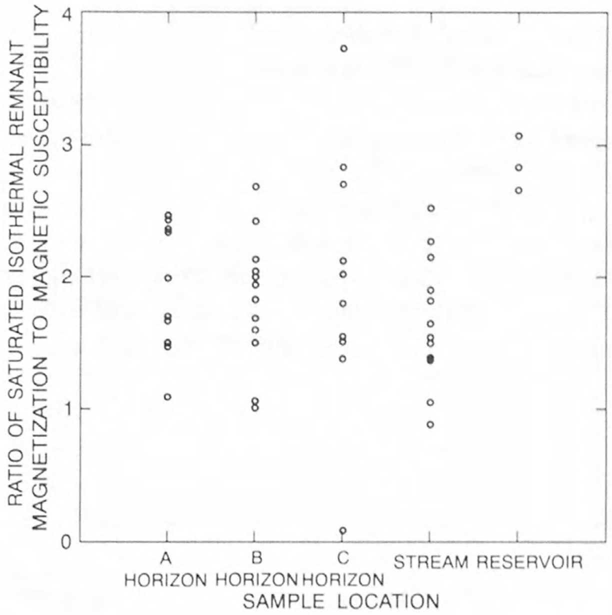

Figure 26. Relation of SIRM/X ratio and sample source. Sources: (1) A horizon soil, (2) B horizon soil, (3) C horizon soil, (4) stream sediment (5) near-shore reservoir sediment.

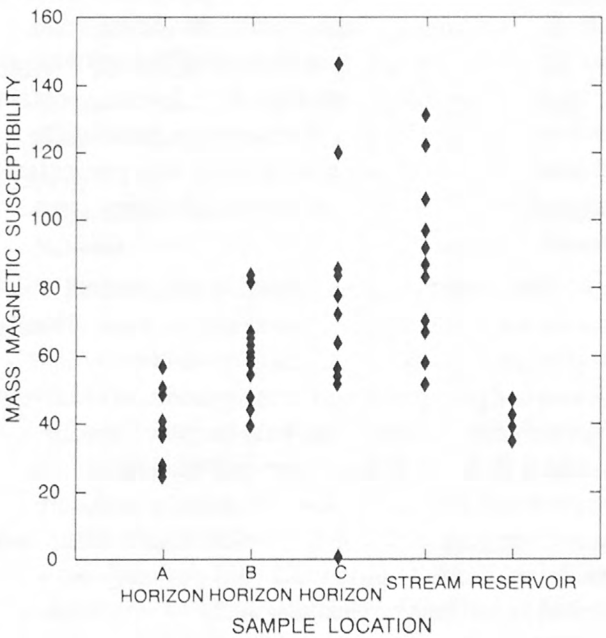

Figure 25. Relation of mass magnetic susceptibility and sample source. Sources: (1) A horizon soil, (2) B horizon soil, (3) C horizon soil, (4) stream sediment (5) near-shore reservoir sediment.

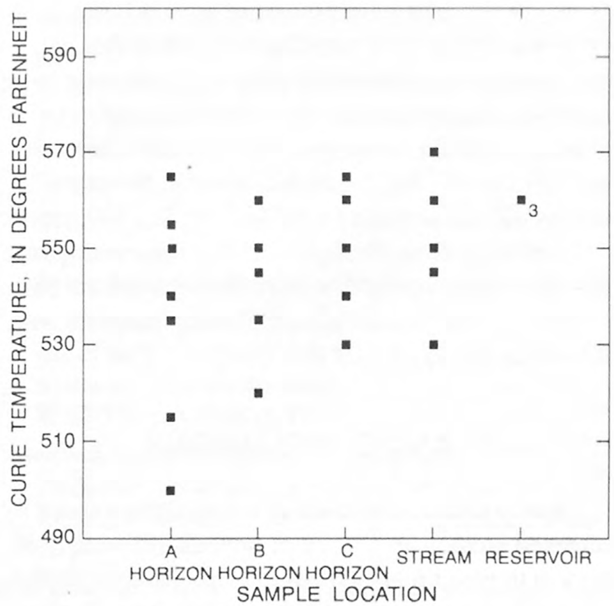

Figure 27. Relation of Curie temperature and sample source. Sources: (1) A horizon soil, (2) B horizon soil, (3) C horizon soil, (4) stream sediment (5) near-shore reservoir sediment.

Effects of hysteresis can be reduced if an alternative method is used to evaluate water-quality data. Currently, instantaneous values of turbidity are used for standards-compliance assessment without regard for their timing relative to a storm hydrograph. Improved interpretation of water-quality variations might result from evaluating turbidity peaks relative to water-discharge peaks or integrating turbidity and discharge over a storm hydrograph. Peak discharge as an indicator of storm intensity may not be ideal because snowmelt and variations in rainfall intensity and duration also affect discharge, erosion, and sediment transport. Additional storm-event variables possibly useful as indicators of storm intensity include rainfall intensity, the rate of change of stream discharge, and the ratio of peak flow to total storm discharge (Guy, 1964).

Variations in turbidity caused by episodic events such as the landslide in Fir Creek basin have important implications for the water-quality monitoring program. Fir Creek Basin has been excluded from management activities to serve as the only control basin for paired-basin analyses. Paired-basin studies require establishing a correlation between basins before and after a treatment is applied to one basin (Ponce and others, 1982). The paired-basin approach is not appropriate for stream turbidity in the Bull Run watershed because historical data are inadequate to establish a correlation before treatment (logging) of other basins in the watershed. Furthermore, turbidity data collected by this study indicate that the key stations did not respond to the January 9, 1989, storm in a similar fashion. Such variations in storm response between basins require that more than one control basin be used for comparison in a monitoring program (Brown and Krygier, 1971).

SUMMARY AND CONCLUSIONS

The potential reduction in water clarity caused by increased erosion as a result of land disturbance is of concern to water managers of the Bull Run watershed, the principal source of water for metropolitan Portland, Oregon. A 2-year study was conducted to obtain information that could be used to guide decisions regarding monitoring of water turbidity and, if necessary, revision of water-quality standards for the watershed.

Inspection of daily records of turbidity at the lower dam headworks showed that event-driven increases in stream turbidity were not adequately documented by the historical weekly stream water-quality sampling program. Automated turbidity-monitoring equipment with real-time data access allowed investigators to augment data-collection activities with point sampling during storm periods.

Turbidity monitoring showed that 90 percent of the time streamflows remained remarkably clear with turbidity less than 1 NTU. Stream turbidity greater than 1 NTU was found to occur rapidly when rainfall intensities exceeded 0.25 inch in 3 hours. This rapid rise is consistent with erosion of sediment at sources in or close to stream channels. Rapid increases in turbidity are attributed primarily to erosion of bare streambanks and roadcuts and ditches. In contrast to turbidity caused by surface and channel erosion, turbidity peaks that substantially lagged peaks in rainfall and discharge are attributed to streamside slope failures.

Field reconnaissance revealed that the most visible sites of erosion are stream channels, streambanks, and roadside ditches. Loose, unconsolidated deposits such as glacial tills, volcanic tuffs, and breccias were identified as active sources of turbidity-causing suspended sediment. Some wide, low-gradient channel segments formed by backwasting of the Rhododendron Formation were found to contain easily erodible sediment. Furthermore, parts of the Rhododendron Formation were found to be particularly susceptible to mass erosion during infrequent large storms.

The incidence of mass erosion and channel erosion will undoubtedly be increased by exceptionally large storms. Runoff from such storms can initiate serious and potentially persistent episodes of relatively high turbidity. Much of the total length of stream channels in the Bull Run watershed has incised into massive and competent flows of andesite or basalt. Accordingly, episodes of streamside mass wasting and associated turbidity production will probably be limited to sections of channels in the Rhododendron Formation where many incipient slumps are evident and altered clay zones can supply a persistent source of suspendable colloidal particles. As seen in severely disturbed sections of Log Creek and the North Fork Bull Run River, accelerated erosion of unconsolidated and unprotected banks can persist for prolonged periods unless channel revetments are installed.

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