A Synoptic Approach for Analyzing Erosion as a Guide to Land-Use Planning

River-Quality Assessment of the Willamette River Basin, Oregon

U. S. DEPARTMENT OF THE INTERIOR
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GEOLOGICAL SURVEY CIRCULAR 715–L

Massive landslide near the headwaters of the Molalla River, a tributary to the Willamette River, Oregon. The landslide occurred on the lower slope during the winter of 1973 - 74 following the building of two log-hauling dirt roads associated with clear-cutting activity. Debris from the toe of the landslide now travels down the disrupted stream channel at right. Photograph taken September 6, 1974.

A SYNOPTIC APPROACH FOR ANALYZING EROSION AS A GUIDE TO LAND-USE PLANNING

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By William M. Brown III, Walter G. Hines, David A. Rickert, and Gary L. Beach

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FOREWORD

The American public has identified the enhancement and protection of river quality as an important national goal, and recent laws have given this commitment considerable force. As a consequence, a considerable investment has been made in the past few years to improve the quality of the Nation's rivers. Further improvements will require substantial expenditures and the consumption of large amounts of energy. For these reasons, it is important that alternative plans for river-quality management be scientifically assessed in terms of their relative ability to produce environmental benefits. To aid this endeavor, this circular series presents a case history of an intensive river-quality assessment in the Willamette River basin, Oregon.

The series examines approaches to and results of critical aspects of river-quality assessment. The first several circulars describe approaches for providing technically sound, timely information for river-basin planning and management. Specific topics include practical approaches to mathematical modeling, analysis of river hydrology, analysis of earth resources–river quality relations, and development of data-collection programs for assessing specific problems. The later circulars describe the application of approaches to existing or potential river-quality problems in the Willamette River basin. Specific topics include maintenance of high-level dissolved oxygen in the river, effects of reservoir release patterns on downstream river quality, algal growth potential, distribution of toxic metals, and the significance of erosion potential to proposed future land and water uses.

Each circular is the product of a study devoted to developing resource information for general use. The circulars are written to be informative and useful to informed laymen, resource planners, and resource scientists. This design stems from the recognition that the ultimate success of river-quality assessment depends on the clarity and utility of approaches and results as well as their basic scientific validity.

Individual circulars will be published in an alphabetical sequence in the Geological Survey Circular 715 series entitled "River-Quality Assessment of the Willamette River Basin, Oregon."

J. S. Cragwall, Jr.
Chief Hydrologist

Cover: *Willamette River as it winds through Portland, Oregon.*
Photograph taken by Hugh Ackroyd.

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CONVERSION FACTORS

[Factors for converting English units into the International System of Units (SI) are given below for four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units]

English	*Multiply by—*	*Metric (SI)*
in (inches)	2.540×10^{1}	mm (millimeters)
ft (feet)	3.048×10^{-1}	m (meters)
ft^2 (square feet)	9.290×10^{-2}	m^2 (square meters)
mi (statute miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
tons/acre/yr (tons per acre per year)	2.242	$t/hm^2/yr$ (tonnes per square hectometre per year
$tons/mi^2/yr$ (tons per square mile per year	3.502×10^{-1}	$t/km^2/yr$ (tonnes per square kilometer per year)

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ABSTRACT

A synoptic approach has been devised to delineate the relationships that exist between physiographic factors, land-use activities, and resultant erosional problems. The approach involves the development of an erosional-depositional province map and a numerical impact matrix for rating the potential for erosional problems. The province map is prepared by collating data on the natural terrain factors that exert the dominant controls on erosion and deposition in each basin. In addition, existing erosional and depositional features are identified and mapped from color-infrared, high-altitude aerial imagery. The axes of the impact matrix are composed of weighting values for the terrain factors used in developing the map and by a second set of values for the prevalent land-use activities. The body of the matrix is composed of composite erosional-impact ratings resulting from the product of the factor sets. Together the province map and problem matrix serve as practical tools for estimating the erosional impact of human activities on different types of terrain. The approach has been applied to the Molalla River basin, Oregon, and has proven useful for the recognition of problem areas. The same approach is currently being used by the State of Oregon (in the 208 assessment of nonpoint-source pollution under Public Law 92–500) to evaluate the impact of land-management practices on stream quality.

INTRODUCTION

Prior to about 1825, the character of the land in the Willamette River basin was controlled primarily by climate and natural terrain characteristics. In the past 150 years, man has greatly altered the natural equilibrium among these factors and thereby has become the dominant agent of land-surface change. However, the course of human alteration has been neither wholly planned nor regionally directed; instead, at various times, scattered areas of the basin have been changed to suit a myriad of purposes. This overlapping of human designs has ultimately caused severe environmental problems including massive land deformation and sediment-laden streams.

Some of the environmental problems (effects) can clearly be associated with the responsible land-surface changes (causes), but many land- and river-quality problems are far separated in time or space from the initial land alteration. The linkage between such problems and their causes is difficult if not impossible to detect from scattered observations of erosional processes and routine water-quality data. A holistic view of the basin is necessary to identify the causes of such problems and to develop adequate information for analysis and control.

This report describes the development and testing of an approach for synoptically viewing the land surface on a regional scale and for interpreting the observations to provide useful planning information. Another report (Meyers and others, 1978) illustrates the application of the approach to land-use planning in the Willamette River basin.

The basic approach is composed of four sequential steps:

1. Identification and mapping of erosional and depositional provinces. In this step, hypotheses are developed for selecting the major natural factors that control the erosional-depositional system. Criteria are then set for the selected factors and pertinent data are collated to enable the mapping of province boundaries onto a photomosaic base.

2. Mapping of existing erosional-depositional features. This is accomplished through interpretation of high-altitude aerial imagery, as verified by field checking and low-altitude aerial photographs. The features are mapped by symbol directly onto the erosional-depositional province map.

3. Analysis of land-use activities. The activities in the basin are identified from field-checked interpretation of color IR imagery. The verified activities are then evaluated and ranked according to the degree to which they disturb the terrain surface.
4. Development of an erosional problem matrix. This is done by developing order-of-magnitude estimates for the erosional impacts attributable to critical terrain factors and important land-use activities.

ACKNOWLEDGMENTS

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THE EROSIONAL-DEPOSITIONAL SYSTEM

The extent of erosion and the amount of sediment that is transported or deposited varies from one area to another depending on several natural factors and on man's use of the land. These elements must be placed in perspective to enable a meaningful analysis of land-surface change. To provide the necessary perspective, we will define sediment and establish a basic reference called the erosional-depositional system

DEFINITIONS

Sediment refers to fragmental particles of material that are moved about, suspended, or deposited by air, water, ice, or organisms. The particles originate from the mechanical and chemical breakdown of rocks and from biological activity. Sediment therefore includes both inorganic and organic particles. Table 1 lists the types and sizes of material generally reported by the U.S. Geological Survey as sediment.

The *erosional-depositional* system refers to the way sediment originates and moves from one place to another. The system comprises the three geological processes of erosion, transportation, and deposition. These processes are closely interrelated because erosion cannot occur without some transport of the eroded particles and because transported particles must eventually be deposited.

Erosion refers to the wearing away of the land surface. More specifically, erosion includes the detachment of sediment from the land surface by flowing water, water waves, wind, flowing ice (glaciers), gravity, and biological activity. Erosion also includes the dissolving of earth materials, principally by water.

In this report we are concerned primarily with two types of erosional processes, namely fluvial erosion and mass wasting. Fluvial erosion is the detachment and downslope movement of earth materials, primarily by flowing water. Rills and gullies are examples of features produced by fluvial erosion. In contrast, mass wasting is the downslope movement of earth materials primarily under the influence of gravity. Water as a "lubricant" is commonly involved in mass wasting but is not an active transporting agent. Landslides and debris flows are typical features resulting from mass wasting.

Transportation refers to the movement of sediment by traction, saltation, suspension, solution, and flotation. Traction is a rolling, sliding, dragging, or pushing mode of transport. Saltation refers to bouncing or skipping, such as the movement of sand particles in a breeze. Suspension refers to the transport of particles within a surrounding fluid; examples are silt in water and dust in air. Solution is the dissolving of materials by water, and flotation refers to movement on a fluid surface, such as leaves or twigs at the surface of a stream.

TABLE 1.—*Types and sizes of material generally reported as sediments by the U.S. Geological Survey*

Type of material	Size of material in average dimension (mm, millimeter; µm, micrometer)
Boulders	>256 mm
Cobbles	64–256 mm
Gravel	2.0–64 mm
Sand	62–2,000 µm
Silt	4–62 µm
Clay	0.24–4 µm
Colloids	0.05–0.24 µm
Biota	Phytoplankton, zooplankton—living organisms.
Organic remains.	Nonliving particles of organic matter.

Deposition refers to the settling of sediment and occurs when the transporting medium loses the energy required to move the particles, or when soluble matter precipitates from solution. For example, when a sediment-laden stream enters the still water of a lake or reservoir, the energy of the stream is dissipated and the sediment particles begin to settle. Also, when salt-laden water is evaporated from a marsh or a playa, the salt remains as a residual deposit. Deposition also refers to the accumulation of nonliving organic materials, such as the buildup of peat in a swamp or bog.

FACTORS CONTROLLING TERRAIN SURFACE STABILITY

The major environmental factors controlling terrain surface stability include climate, topography, geology, soils, and vegetation. In this section, the five factors are first discussed in the context of "natural" (unaltered) terrain conditions and then rediscussed with regard to how they are altered by man's use of the land.

ENVIRONMENTAL FACTORS

CLIMATE

The climatic factors that most affect the erosional-depositional system are precipitation, wind, and temperature. Precipitation, principally as rain and snow, provides the water that is the dominant universal agent of erosion and sediment transport. In arid regions, wind becomes an important erosional agent. Wind also generates water waves that contribute to shoreline erosion. Temperature and temperature fluctuations about the freezing point act in conjunction with water, plants, and animals to influence the rate of rock and soil weathering.

In arid and semiarid areas, protective vegetal cover is sparse. In such areas, raindrops break down aggregates of exposed soil and rock and disperse dislodged particles. These particles tend to clog soil porespace, thereby decreasing infiltration and increasing surface runoff. Fluvial erosion in the form of sheet-, rill-, and gully-erosion predominates.

In warm or temperate humid and semihumid areas, the vegetal cover is normally extensive. In these areas, most of the soils are rather permeable, and rainfall tends to readily infiltrate. Runoff occurs mostly in the form of shallow subsurface flow, becoming surface runoff only where the landscape is dissected by stream channels. Erosion is generally dominated by mass-wasting processes, particularly on hillslopes along bedding planes that are "lubricated" by subsurface water.

In alpine and subarctic regions, precipitation in the form of snow controls erosion by accumulation to form glaciers or by melting to provide surface and subsurface runoff.

Wind influences erosion primarily in areas having bare soils and unconsolidated geologic materials such as sand. Wind erosion is therefore generally greatest in arid and semiarid areas.

Temperature influences erosion in several ways. The freezing and thawing of water in joints and porespaces aids in the disintegration of rock and soil. Temperature partly controls biological activity and hence exerts a strong influence on the rate and extent of soil development and on the type and amount of vegetal cover. Temperature also affects the transporting capacity of water and together with wind influences the evaporation of soil moisture.

TOPOGRAPHY

The topographic elements that affect the erosional-depositional system include the orientation, steepness, and length of slope. The orientation of slope exposure determines to a considerable extent the impact of climatic forces on erosion. Slope steepness determines the susceptibility of rock and soil to downslope mass movement and controls the erosive power of running water. Slope length, together with slope steepness and soil properties, determines the potential rate and volume of runoff and thus the potential for fluvial erosion.

Because slope steepness largely determines the potential for both mass wasting and fluvial erosion, it is usually the most important single natural factor affecting the erosional-depositional system.

GEOLOGY

The near-surface properties of bedrock units are the most important geologic considerations in the erosional-depositional system. The degree of mechanical and chemical weathering of bedrock influences the size and abundance of transportable rock fragments, and the grain size, shape, and specific gravity of the fragments determine the force needed for dislodgment and transport. The orientation of bedding, foliation, and jointing planes with respect to land-surface slope greatly influences the susceptibility of rock units to downslope mass movement. The porosity, degree of fracturing, and the composition of rocks determine the rate of water infiltration, the potential for mineral dissolution, and the susceptibility to freeze-thaw action.

SOILS

Soils have a number of properties that influence the erosional-depositional system. Texture and structure largely determine the shear strength of soil particles and thus the degree of resistance to disintegration from the impact of raindrops and the force of overland flow. The porosity of a soil profile determines water-holding capacity, and permeability controls the rate of water infiltration. Together with soil depth and slope characteristics, porosity and permeability control the rate and volume of both surface and subsurface runoff and thus largely determine the potential for fluvial erosion and mass wasting.

The texture of soils is particularly significant in determining the susceptibility of minerals to erosion and mass-wasting. For example, coarse-grained gravelly and sandy soils, without clay, exhibit considerable frictional resistance to shear movement because of intergranular locking and the relatively heavier weight of the individual particles. On the other hand, very fine grained clay soils have molecular surface bonding when dry and exhibit considerable cohesive resistance to movement; however, when these soils are saturated, the molecular surface bonding between particles is largely disrupted by interstitial water. The intermediate textural materials, such as fine sands and silts, have neither the internal friction of the gravels and course sands because of greatly reduced grain size, nor the molecular surface-bonding (cohesive) property of clays. As a consequence, the fine sands and silts are readily susceptible to dislodgment by both wind and water. Silts, in particular, are highly susceptible to sheet and gulley erosion by running water and are prone to slump and flow when fully saturated.

VEGETATION

All vegetation, whether alive or dead, intercepts rainfall, retards the impact of running water and wind, and decreases insolation at the soil surface. The vegetal canopy and understory diminish the erosive force of raindrops and impede the velocity of runoff. In addition, the ground cover shields soil and rock particles from the tractive forces of flowing water and wind. Vegetal root systems add cohesion to the soil mantle and simultaneously increase its porosity and water-holding capacity. Vegetal root systems also retard gravitational slippage (mass wasting) of soil and rock masses.

EFFECTS FROM LAND USE

The impacts of man on the erosional-depositional system are often severe. Although some impacts are poorly understood, many can be readily recognized by examining how land-use activities disturb the five environmental factors (described above) that control terrain surface stability.

The effects of land use on regional climate are usually insignificant except in areas of intensive urban and industrial development. However, the impacts on local climatic conditions (microclimates) can be significant, particularly where land-use activities disturb dense vegetal cover. The removal of vegetation can cause local increases in insolation, soil temperature, wind velocity, and the soil-impact energy of raindrops. Also, the frequency and severity of freeze-thaw action may be increased, particularly if the land use removes the insulating layer of ground mulch.

Land use can affect topography by altering the steepness, length, and on occasion even the orientation of slope. Hillside road construction commonly results in cut-and-fill slopes that are steeper than the natural terrain. Agricultural terracing effectively breaks a long continuous slope into many short "stairsteps." Excavations and fills, such as those in extensive strip mining operations, occasionally change the orientation of slopes.

The principal effects of land use on geological conditions occur when (1) water is added to or extracted from permeable materials as by irrigation and pumping, (2) materials are covered by artificial fill, pavement, or debris that effectively creates a new surface, or (3) materials are excavated so new units are exposed to erosional agents.

The impacts of land use on soils are commonly similar to those on geologic materials. The soil characteristics most drastically altered are usually the water-related properties of porosity and permeability.

Land-use changes that affect vegetation commonly exert the greatest impacts on the erosional-depositional system. Many land uses such as agriculture, logging, construction, and mining call for the removal of natural vegetation with the consequent exposure of the underlying soil and rock to the agents of erosion. The extent and duration of such exposure and the type of cover which replaces the natural vegetation determine the type and severity of the erosional impact.

EROSIONAL-DEPOSITIONAL FEATURES

The interaction of environmental factors and man's activities create a variety of geomorphic features on the surface of the land. For example, when water flows over a disturbed soil on a long slope, it can create distinctive rills and gullies. In addition, when the slope gradient suddenly decreases, the water and its sediment load can cause the formation of alluvial fans or streambed deposits. In this example, the rills and gullies are erosional features representing the source areas of sediment, and the alluvial fans and streambed deposits are depositional features representing the sediment-receiving areas. Flowing water acts as the agent of sediment transport.

Rills, gullies, alluvial fans, and streambed deposits represent part of a large set of geomorphic features that may be readily classified in terms of the erosional-depositional system. Table 2 lists examples of selected erosional features, the primary agents that cause the erosion and transport the sediment, and the typical depositional features. The listing of features and agents in table 2 is cursory, but it serves to provide a format usable in any region for the compilation of detailed information on geomorphic features.

TABLE 2.—*Examples of erosional features, agents of erosion and sediment transport, and resultant depositional features*

Typical erosional feature(s)	Primary agent of erosion and sediment transport	Typical depositional feature(s)
Rill, gully	Land runoff	Alluvial fan, streambed, or flood-plain deposit
Streambank failure	Streamflow	Streambed deposit, deltaic deposit
Wave-cut cliff	Waves and currents	Beach, shelf deposit
Caves	Ground water	----------------
Deflation hollows	Wind	Sand dune, desert pavement
Cirque	Glaciers	Moraine
Landslide scarp	Gravity	Landslide lobe
Burrow holes	Biologic	Mounds

THE PROVINCE CONCEPT

A province can generally be defined as a terrain unit that, owing to its natural physical properties, exhibits characteristic types and rates of erosion and (or) deposition. In a broad sense, an erosional province is an association of distinctive landforms such as mountain peaks, ridges, and hill slopes generally subject to progressive erosion. Similarly, a depositional province is an association of distinctive landforms such as alluvial fans, flood plains, and marshlands generally subject to progressive accumulation (deposition) of sediments.

Such associations of landforms are readily apparent from a regional overview. For example, in the Willamette River basin (figs. 1 and 2), the western flank of the Cascade Range and the eastern flank of the Coast Range are dominated by erosional processes. In both areas the land surface owes much of its shape to the progressive removal of soil and rock. In contrast, the Willamette Valley is dominated by depositional processes. The flat to gently sloping plains that characterize the valley have resulted from progressive deposition of soil and geologic materials.

For application to environmental planning, it is necessary to further divide these regional physiographic divisions by analyzing the en-

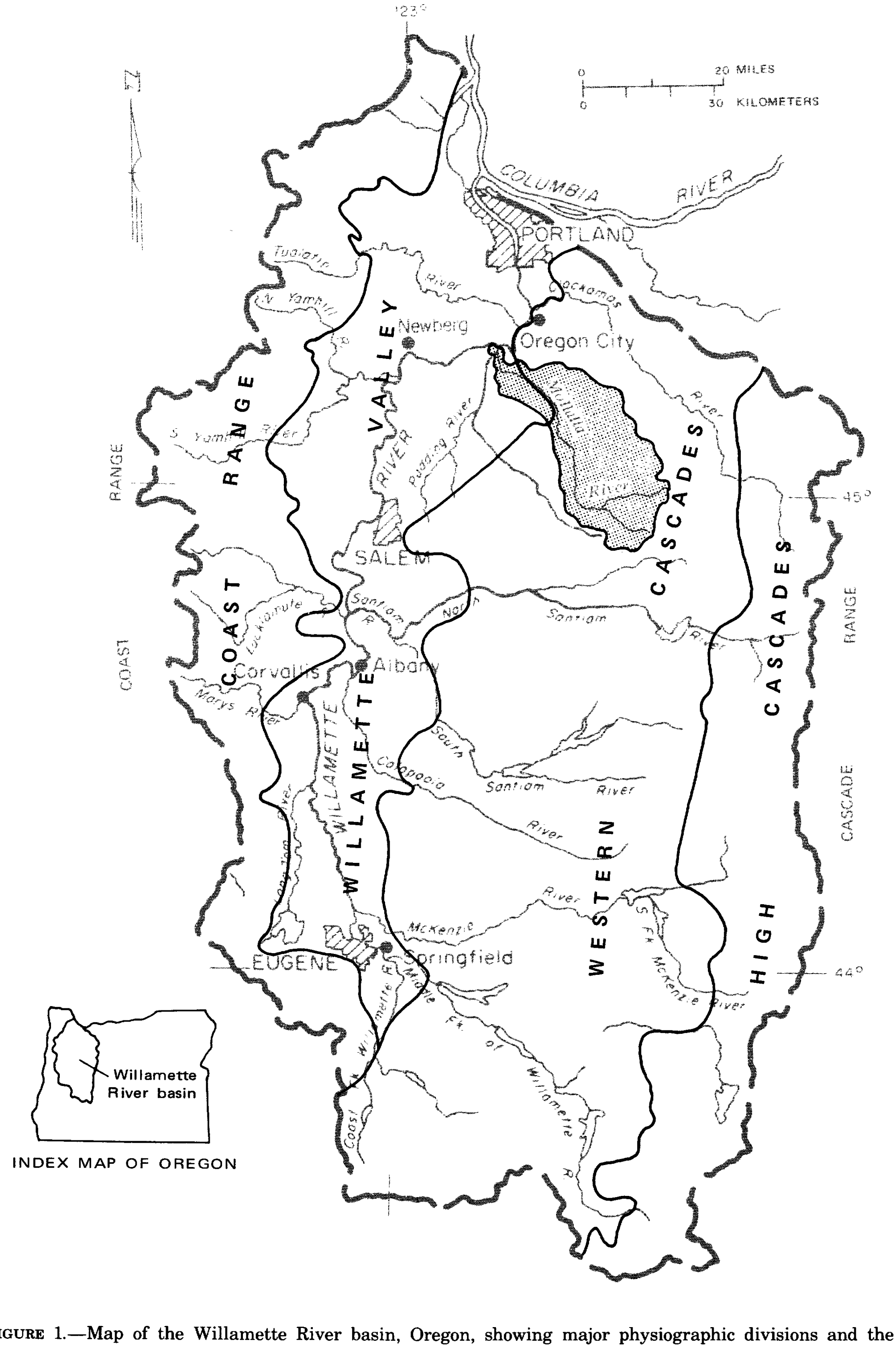


FIGURE 1.—Map of the Willamette River basin, Oregon, showing major physiographic divisions and the Molalla River basin (shaded).

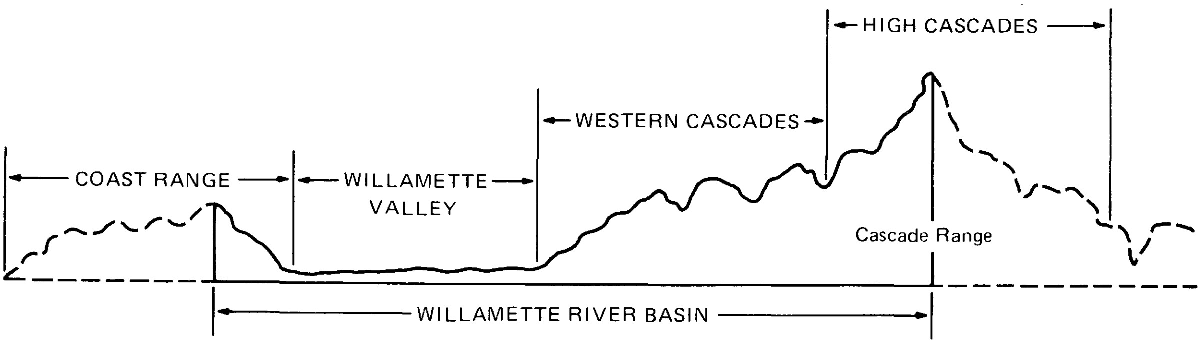


FIGURE 2.—Cross-sectional profile of the Willamette River basin illustrating relative relief dimensions of the major physiographic divisions. (Adapted from the Willamette Basin Task Force, 1969, Main Report, p. 14.)

vironmental factors that control terrain-surface stability. As previously described, the major natural factors that control surface stability are climate, topography, geology, soils, and vegetation. In order to identify the important erosional and depositional provinces of a basin, hypotheses must be developed to define the primary roles and interactions of these factors. Once the hypotheses have been developed and substantiated, they can be used to formulate specific criteria for the definition and mapping of erosional and depositional provinces.

Based on the province concept briefly outlined above, the remainder of the report describes a procedure for defining the relationships between critical environmental factors, land-use activities, and erosional-depositional problems. The premises of the procedure are as follows: (1) Climate and terrain properties determine the potential erodibility of land in its natural state, (2) land-use activities represent cultural disruptions of terrain surfaces, and (3) different combinations of climate, terrain properties, and land-use activities result in different types and severities of erosional-depositional problems.

Through application in a pilot study area, the procedure is used to first produce an erosional-depositional map and then to prepare an erosional-impact matrix for direct use by land-use and water-resource planners.

SELECTION OF A PILOT STUDY AREA

PRIMARY CONSIDERATIONS

Three primary considerations were used for selecting a basin as a pilot study area:

1. The basin needed to be representative of most of the types and ranges of terrain and land-use conditions found in the Willamette River basin. This would allow the pilot study to provide a detailed preview of the processes and problems to be encountered in the Willamette River basin as a whole.
2. The basin needed to be small so that the procedure could be applied in a short period of time. This factor was important because the procedure had never been completely tested. Application to a small pilot area would permit a timely evaluation of strengths and weaknesses and the opportunity for making changes prior to use on a regional scale.
3. The basin needed to be close to the project office in Portland. This was necessary to permit frequent field trips and periodic aerial observations. Such field work was considered essential for establishing the validity of interpretations derived from high-altitude imagery.

Based on these considerations, the Molalla River basin was selected as the pilot study area.

DESCRIPTION OF THE MOLALLA RIVER BASIN

The Molalla River basin occupies about 325 mi^2 (840 km^2) in the northeastern part of the Willamette River basin, Oregon (fig. 1). It is bounded by the Pudding River basin to the west, the Willamette River and Clackamas River basins to the north and east, and the North Santiam River basin to the south. The basin ranges in width from 6 mi (10 km) in the northwest to 15 mi (25 km) in the southeast and is about 36 mi (58 km) in length. Altitudes vary from about 50 ft (15 m) at the mouth of the Molalla River near

Canby to nearly 5,000 ft (1,525 m) at the eastern boundary.

The Molalla River basin includes parts of the Cascade Range and Willamette Valley physiographic provinces (see figs. 1 and 2). For purposes of this report, the term "uplands" refers to areas in the Cascade Range, and "lowlands" refers to those areas in the Willamette Valley.

The main stem of the Molalla River originates in the Western Cascade subdivision of the Cascade Range province at an altitude of about 2,600 ft (790 m). From this point the river flows westward to northwestward through deeply incised valleys which in places are 3,000 ft (915 m) below adjacent ridge tops. As the river leaves the confine of these steep-valley walls, it enters the transitional foothills section of the Western Cascades. There, the valley floor widens appreciably, although the channel is confined by Pleistocene terraces up to 100 ft (30 m) high (Hampton, 1972, p. 12). Past the town of Molalla, the river meanders in a broad flood plain before emptying into the Willamette River 16 mi (25 km) south of Portland.

Land use in the basin has been shaped primarily by the ready availability of timber, water and arable land. Consequently, the major industries are agriculture and forestry. Agricultural land is confined primarily to the valley floor and terraced benches in the northwest part of the basin at altitudes below 1,000 ft (300 m). Agricultural production is concentrated on grain crops and livestock. Most of the land above 1,000 ft (300 m) is managed by private timbering concerns and has been subjected to widespread clear-cut logging. In addition to agriculture and forestry, the basin is widely used for recreational purposes and is an important natural habitat for fish and wildlife.

Further details of the environmental character and land uses of the Molalla River basin are presented in subsequent sections that deal specifically with these topics.

DEVELOPMENT OF AN EROSIONAL-DEPOSITIONAL PROVINCE MAP

IDENTIFICATION OF PROVINCES

The development of an erosional-depositional province map can best be explained by showing the product and then describing the sequential steps involved in its production. The completed map for the Molalla River basin (plate 1) shows (1) the location of erosional-depositional provinces through use of boundary lines and large identifying symbols and (2) the location and character of erosional-depositional features through use of small symbols. The information was compiled on a photomosaic base (see Rickert and others, 1975) prepared from black-and-white imagery having a scale of 1:130,000 (Vickers and others, 1975). The photographs were taken during July 1973 by the U.S. National Aeronautics and Space Administration (NASA). (See section "Aerial Imagery".)

The first step in producing such a map is to select and integrate the environmental factors that exert the greatest control on terrain-surface stability.

IMPACT OF ENVIRONMENTAL FACTORS ON EROSION AND DEPOSITION—WORKING HYPOTHESES

The key to formulating meaningful criteria for the mapping of provinces is the derivation of working hypotheses that reflect the relative importance and interaction of critical environmental factors. For the Molalla River basin, the derivation of hypotheses was tempered by four considerations:

1. The primary objective of the study as a regional overview of the major processes and problems of the erosional-depositional system, rather than as a comprehensive geomorphic investigation suited for site-specific interpretations.
2. The need for a simple, practical product that can be used by planners and that is compatible with the 1:130,000-scale photomosaic base.
3. The large variability in the quality, quantity, and scale of existing earth-resource data and maps.
4. The extensive worldwide background of observations, publications, and knowledge concerning the functions, relationships, and relative importance of the major factors affecting the erosional-depositional system.

In concert, these four considerations dictated that the hypotheses be (1) general and not overly concerned with minor terrain anomalies or special, localized conditions, (2) suited to the identification of a small number of erosional and depositional provinces (not more than 10) to avoid confusion and clutter on the map, (3) compatible with the quality, quantity, and resolution of available earth-resource information, and (4) consistent with accepted scientific fact and reasoning.

Using these considerations as a guide, working hypotheses were derived for the five major environmental factors of climate, topography, geology, soils, and vegetation as they pertain to the Molalla River basin. The following sections treat the five factors one at a time. Each section first gives the geographical description of the factor and then states the working hypothesis used for developing province-defining criteria. Statement of the hypothesis is followed by complementary discussions on underlying rationales, substantiating information, and possible refinements.

CLIMATE

Geographical description—The Molalla basin has a modified, maritime temperature climate characterized by cool, wet winters and warm, dry summers. The effect of this seasonal variation is that only 10 percent of the total precipitation occurs between early May and late September. Moreover, the annual precipitation varies markedly with altitude from about 40 in (1,015 mm) in the lowlands to about 110 in (2,790 mm) near the basin headwaters (fig. 3).

The type of winter precipitation also varies with altitude. In the lowlands, low intensity rainfall of long duration is the rule. Snowfall is light and infrequent. In the uplands, owing primarily to orographic cooling, snowfall increases rapidly with increasing altitude. For example, along the windward slope of the Cascade Range province at 2,000 ft (610 m), about 10 percent of the precipitation occurs as snow. Above this altitude, the proportion occurring as snow increases about 10 percent for each 1,000-ft. (300 m) interval (Willamette Basin Task Force, 1969, Appendix B, p. II–10).

Because precipitation increases with altitude (orographic uplift), runoff trends to increase in a similar fashion (fig. 4). Annual runoff ranges from about 10 to 100 in (250 mm to 2,540 mm). Note by comparing figures 3 and 4 that runoff as a percentage of precipitation increases with altitude. The increased runoff can be traced in part to steeper slopes and thinner soils. During the annual cycle most of the runoff occurs (1) during the winter in direct response to the periods of greatest precipitation and (2) during the early spring when rainfall combines with snowmelt (Willamette Basin Task Force, 1969, Appendix A p.III–3). Average annual runoff for the Molalla River at Canby is about 1,100 ft^3/s (31 m^3/s). However, flow is only reasonably well sustained during the summer months, owing to the fact that the river heads in the Western Cascades, rather than in the perennial snowfields of the High Cascades.

Working hypothesis—The influence of precipitation and runoff on erosion can be considered constant throughout the Molalla River basin. Therefore, variation in precipitation and runoff need not be considered as factors for formulating province-defining criteria.

Rationale—The temperate, moist climate of the Molalla River basin produces a cyclical pattern of dry summers and wet winters. During the dry summer little overland runoff or erosion occurs. Most of the erosion occurs during the sustained wet periods. However, areal differences in erosion resulting from variations in the precipitation and runoff factors are relatively small. This occurs because the precipitation, although spatially variable in quality, is generally of low intensity.

Substantiation—"In the Willamette Basin rainfall is normally of low intensity. The gentle rains of long duration contribute toward a healing of disturbed locations unless the disturbance is continued or scars such as gullies become deeply ingrained." (Willamette Basin Task Force, 1969, Appendix G p.II–35).

Qualifications and possible refinements—Important departures sometimes occur from the assumed "constant" areal influence of precipitation and runoff. For example, in the uplands, heavy snowpacks are occasionally melted rapidly by sudden warm fronts accompanied by intense rainfall. In addition, a low pressure system may produce a storm of long duration having brief periods of intensive rainfall. Such situations can cause severe flooding and vastly accelerated erosion, particularly along streams, roads, escarpments, and on sloping terrain where bare soil is exposed.

For more detailed local studies, it might be desirable to distinguish precipitation-runoff zones. For example, one zone might be delineated at altitudes exceeding 3,000 ft (910 m) where the mean annual temperature is normally less than 50°F (10°C) and the annual precipitation generally exceeds 80 in (2,030 mm). Under these conditions, most of the winter precipitation falls as snow, and runoff is a very high percentage of the annual precipitation. Most of this terrain above an altitude of 3,000 ft (910 m) is subject to intensive erosion wherever the natural vegetation is removed and soil cover is destroyed.

For more detailed studies it might also be desirable to distinguish selected zones based on the yearly number of times that the soil profile freezes and thaws. If the number of freeze-thaw cycles is high, the resultant soil disturbance can lead to a considerable increase in the rate of erosion.

TOPOGRAPHY

Geographical description—The topography of the Molalla basin comprises flat to gently sloping

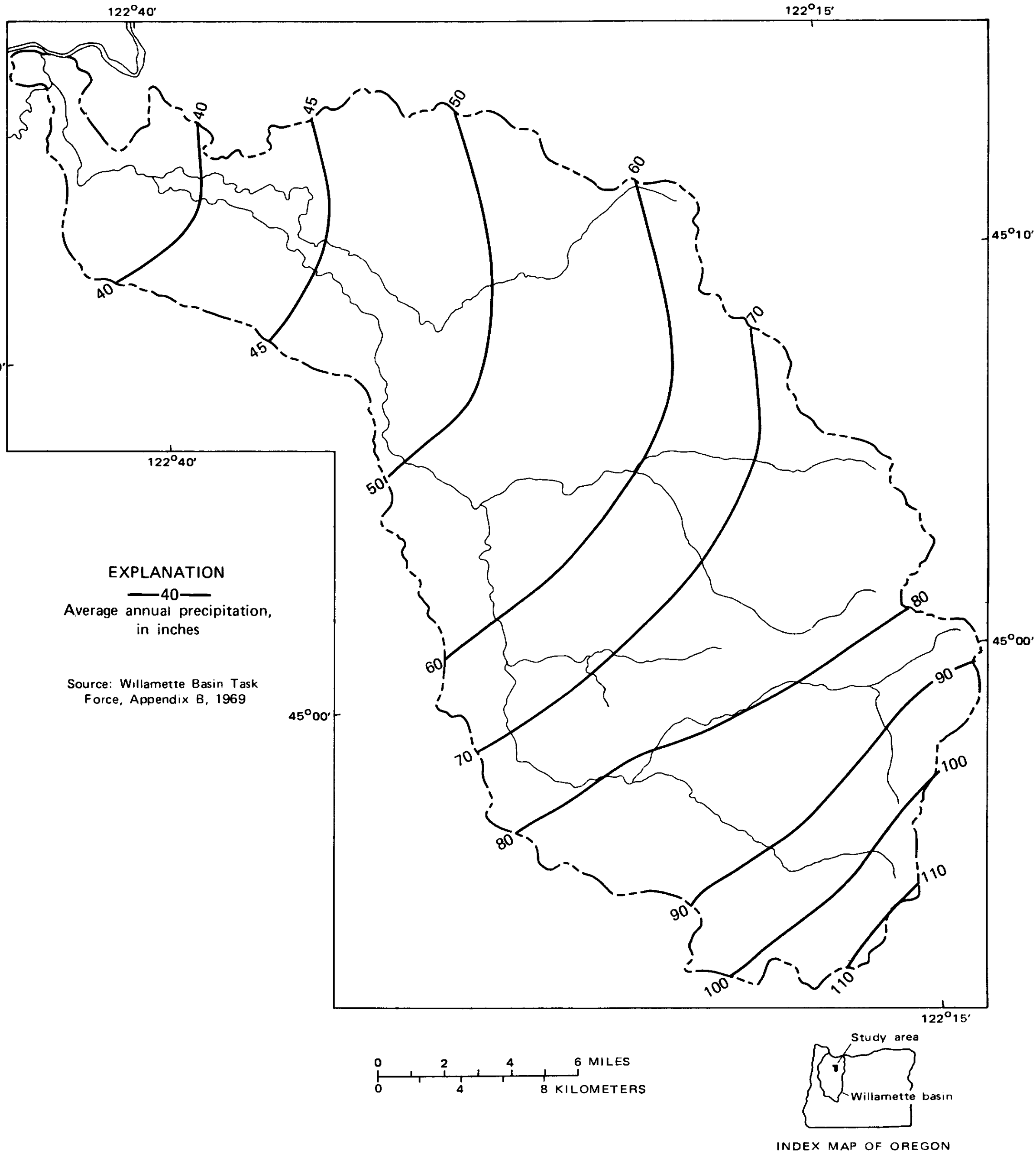


FIGURE 3.—Average annual precipitation in the Molalla River basin.

terrain in the western parts grading into steep, rugged terrain in the east. A major body of east-facing slopes occurs in the southwestern part of the basin along the west side of the Molalla River. Otherwise, the general aspect (orientation) of slopes is random throughout the basin.

Slope lengths vary widely throughout the basin, but with regard to erosion, these variations are not as important as slope steepness. Figure 5 is a slope-steepness map of the basin, which was compiled from a soils map published by the Oregon State Water Resources Board (1969). The figure shows that most of the land in the northwest part of the basin has slopes less than 12 per-

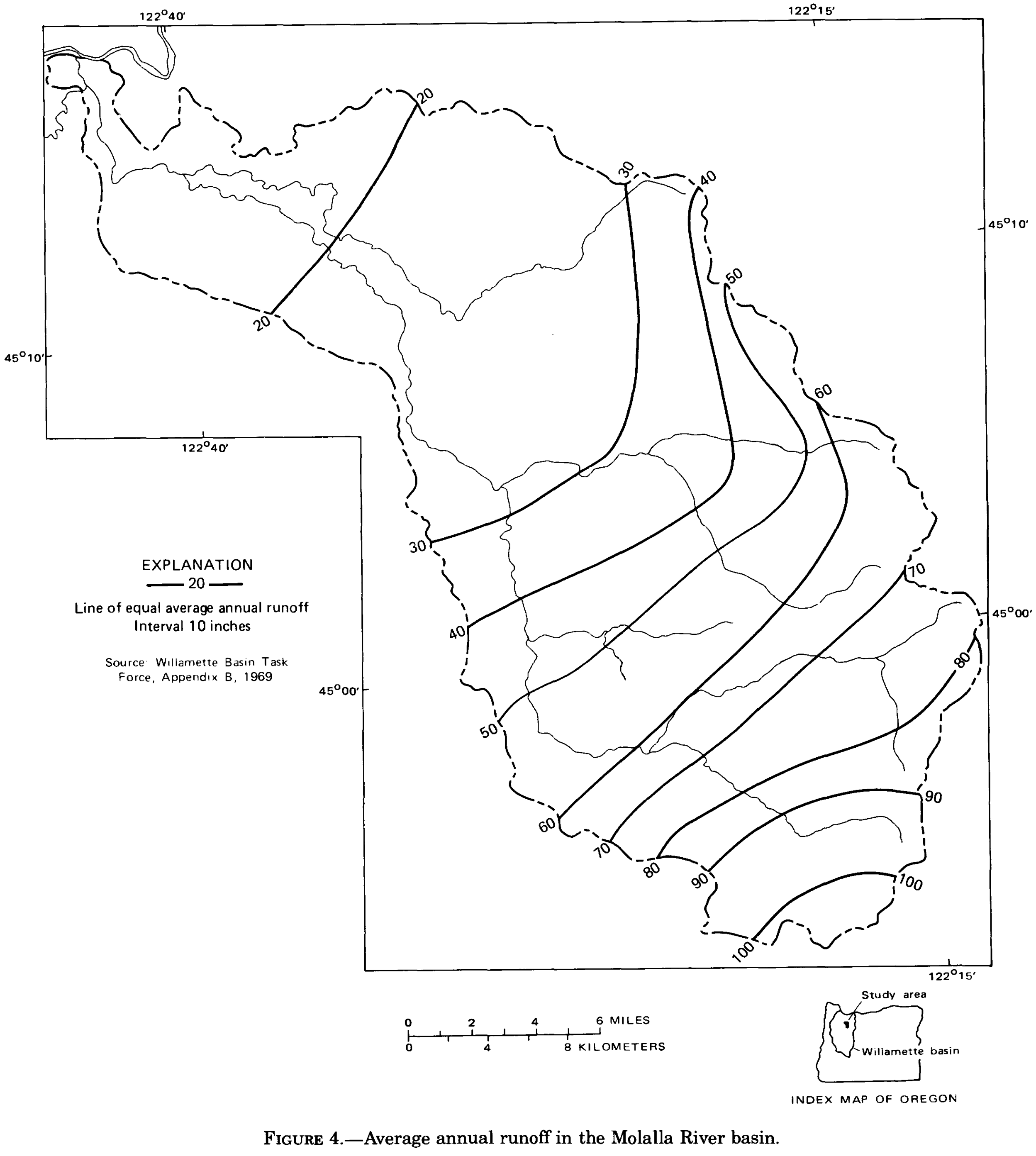


FIGURE 4.—Average annual runoff in the Molalla River basin.

cent, whereas nearly all the land in the southeast has slopes exceeding 12 percent.

Working hypothesis—A slope of 12 percent demarks the approximate boundary between upland terrain that is predominantly erosional and lowland terrain that is predominantly depositional.

Rationale.—The 12-percent slope gradient commonly marks the break in slope between the upland bedrock foothills and the lowland alluvial terraces. Thus, the 12-percent value serves as a general geomorphic boundary between these distinct terrain surfaces. Also, land surfaces with slopes of 12 percent or more tend to be nearly devoid of depressions that significantly retard the

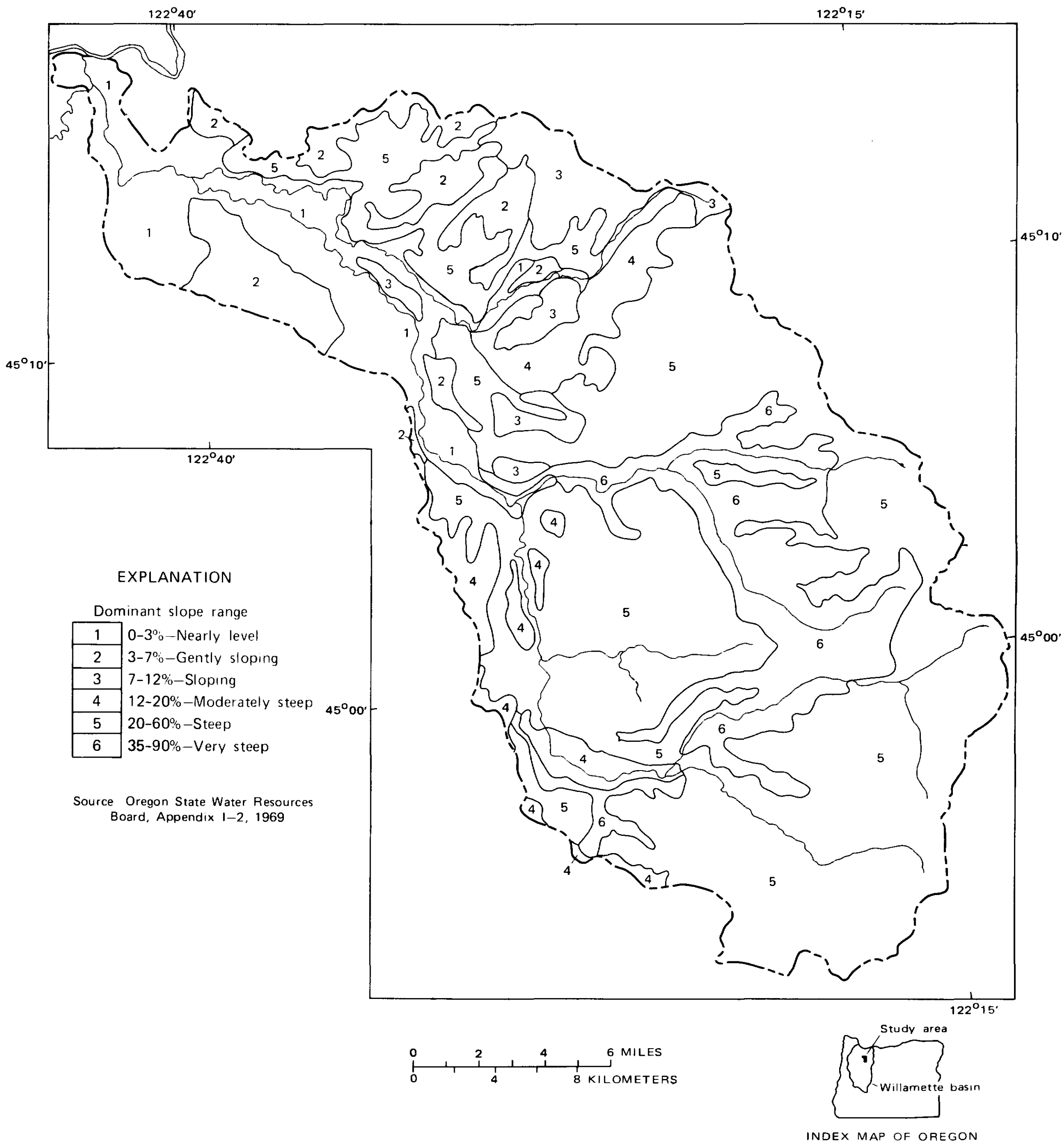


FIGURE 5.—Slope-steepness intervals of the Molalla River basin.

downslope movement of water and sediment. Furthermore, 12 percent is effectively the lowest gradient at which large-scale mass wasting can be observed from aerial photography of the basin. With regard to the impact of land use on the potential for accelerated erosion, the 12-percent gradient approximately marks the upper feasible limit in the basin for intensive urban development and sustained field crop cultivation.

Substantiation.—"Because a slope of 10 percent drops 10 feet in a 100-foot horizontal, temporary storage in the form of depressions which might hold silt would be nearly absent. For land slopes above 10 percent, stream channels also would tend to be nearly devoid of areas or depressions which could hold up sediment during its passage downhill. From a practical standpoint, therefore, a figure of about 10 percent probably would be a physical and economic limit beyond which construction would be especially harmful insofar as sediment production is concerned" (Leopold, 1968, p. 15).

Landslide and slope-stability maps and reports for areas along the Pacific coast and in the Pacific Northwest identify terrain with slopes of 15 percent as beginning to be susceptible to mass wasting and erosion-related problems. Examples are the publications by Brabb, Pampeyan, and Bonilla (1972) and Miller (1973).

In addition, available U.S. Soil Conservation Service maps published by the Oregon State Water Resources Board (1969) recognizes a 12-percent slope break as a general erosional-depositional boundary for soils and as a practical land-development boundary for the Willamette Basin.

Qualifications and possible refinements.—At slope steepnesses below 12 percent, some terrain may be susceptible to mass wasting or fluvial erosion depending on lithology, runoff, and the extent of surface-cover disruptions. For example, on the alluvial terraces, localized intensive erosion may occur when the soil cover is severely disturbed by construction or by agricultural practices.

Slope length is one of the factors that controls the depth of surface runoff and therefore is sometimes a critical element in determining the erosion potential of a particular area. However, because of the regional nature of this survey, slope length was not considered. At the 1:130,000 map scale, this omission was not considered serious because rates of erosion are more sensitive to slope steepness than slope length (Leopold, 1968). Nevertheless, in detailed large-scale studies, slope length should be considered as a possible controlling factor, particularly with regard to fluvial erosion.

Slope aspect (that is, the orientation of the slope relative to prevailing climatic forces) may also be important in local site-specific surveys. As a rule, slopes that face south and southwest are more prone to erosion than slopes facing other directions.

As to possible refinements, slope breaks at 20 and 60 percent seem to be critical. The 20-percent break is particularly important on terrain that is underlain by friable sedimentary rocks, such as certain shales and mudstones; by pyroclastic rocks, such as tuffs and breccias; and by loosely consolidated sediments. On slopes exceeding 20 percent, these lithologies are particularly susceptible to mass movement where toe support is removed by excavation or erosion, or where the rocks contain cohesive clays that lose shear strength upon saturation. The 60-percent break is critical because, regardless of lithology, this is approximately the angle of repose for angular rock materials. Therefore, for a more detailed study, the 20- and 60-percent slope breaks are recommended as additional erosional boundaries.

GEOLOGY

Geographical description.—The Molalla River basin is underlain primarily by volcanic rocks in its eastern and central parts and by alluvium and sedimentary rocks to the north and west (fig. 6 and table 3) (Wells and Peck, 1961; Beaulieu, 1971; Hampton, 1972).

Alluvium dominates the lowlands. The deposits include unconsolidated heterogeneous alluvium in the present flood plains and semiconsolidated nonmarine terrace deposits that flank the flood plains.

Nonmarine sedimentary rocks occur in the uplands in the northern part of the basin. These rocks consist of weakly coherent and predominantly inclined conglomerate, sandstone, and siltstone.

Igneous rocks dominate the uplands throughout the remainder of the basin (fig. 6 and table 3). The mapped units include (1) large areas of strongly coherent basaltic and andesitic layered rocks, (2) large areas of predominantly incoherent pyroclastic or hydrothermally altered rocks, (3) small areas of coherent intrusive rocks, and (4) small areas of undifferentiated pyroclastic rocks, volcanic breccias, and tuffs.

Working hypothesis.—The physiographic units (see fig. 1 and "Description of Molalla River Basin") and rock types that underlie the Molalla River basin can be categorized into four groups that reflect relative susceptibility to erosion (table 3). The lowlands of the basin are dominated by depositional processes, and the geologic deposits can be classified into (1) flood-plain alluvium and (2) valley terrace alluvium. The uplands (consist-

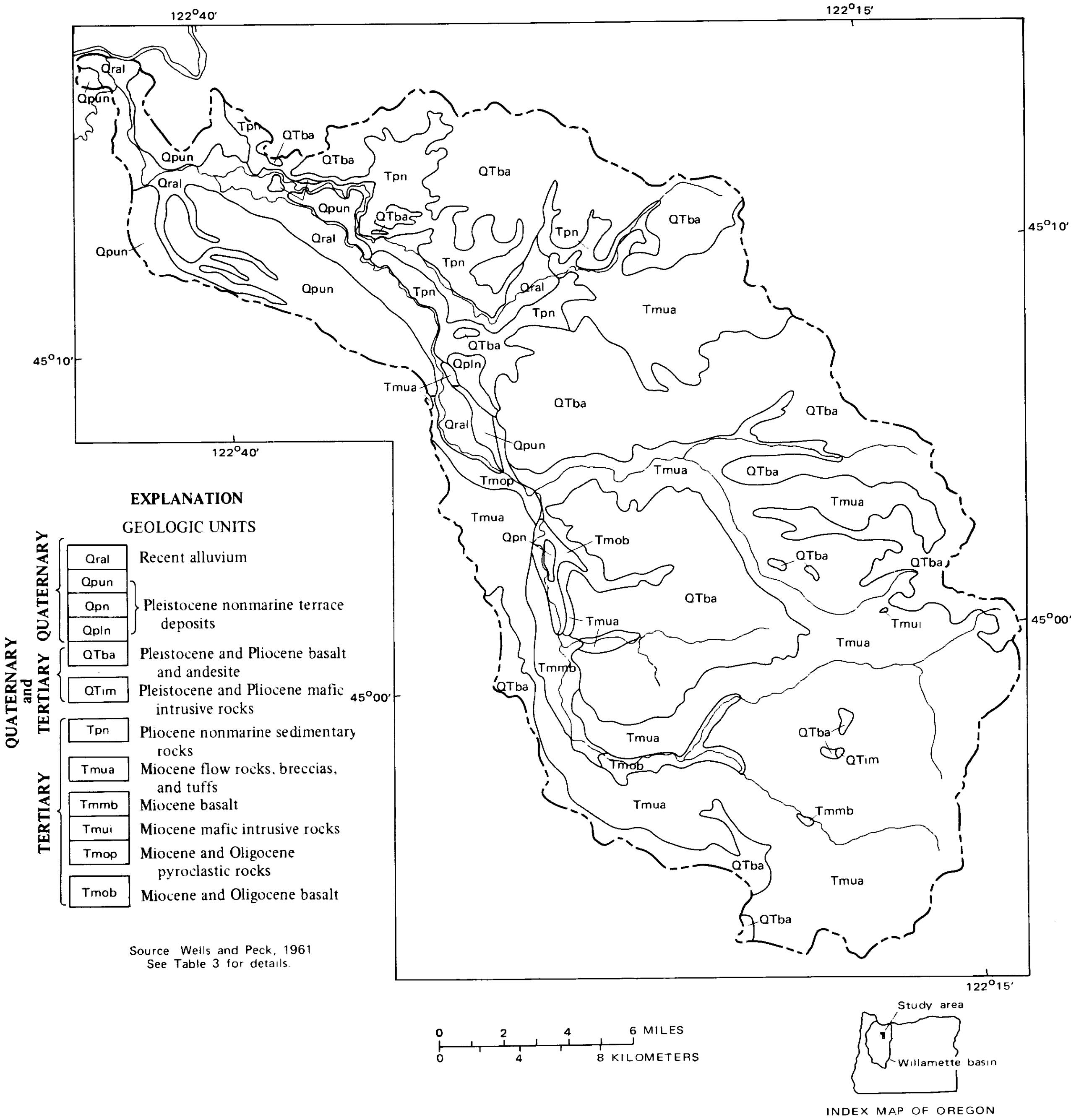


FIGURE 6.—Geologic map of the Molalla River basin. (See table 3 for a more detailed description of the geologic units.)

ing of foothills and mountains) are dominated by erosional processes, and the rocks can be classified into (3) competent bedrock units which are fairly resistant to mass wasting and (4) incompetent bedrock units which are prone to slope failure.

Rationale.—From a regional overview, the flood-plain and terrace-alluvium units compose virtually all the major depositional areas of the Molalla River basin. The two units differ lithologically in that the terrace deposits are semiconsolidated and Pleistocene in age, whereas the flood-plain deposits are unconsolidated and of Holocene age. The bulk of the deposition presently occurring in the basin takes place in the flood-plain unit. The deposition occurs primarily during periods of high runoff when gravel and silt are deposited by overbank flows and alluvial fans are formed at the toes of terraces. Active deposition on the terrace unit is less extensive and occurs primarily in areas where terraces abut the uplands.

The upland areas of the basin are dominated by erosional processes because slopes are steep and runoff is heavy. Fluvial erosion of soils in the form of sheet, rill, and gully erosion can occur on almost any sloping land (regardless of the competency of underlying bedrock) that has been stripped of its protective vegetal cover. In contrast, mass wasting occurs primarily where the slopes are steep and the geological materials are prone to shear failure when saturated. Therefore, to differentiate the potential for erosion in the uplands, it is necessary to group the geologic units with regard to their susceptibilities to mass wasting.

The layered lava and intrusive rocks of the uplands are strongly coherent, relatively resistant to mass wasting, and compose most of the higher ridges and steep peaks of the basin. These units can therefore be categorized as "competent bedrock." In contrast, upland sedimentary and pyroclastic rocks tend to have high contents of clay minerals that lose shear strength when saturated. On slopes greater than 12 percent, these rocks are prone to mass wasting. These sedimentary and pyroclastic rocks are thus weakly coherent and can be categorized as "incompetent bedrock."

Substantiation.—The relative susceptibility of the various bedrock units to mass movement has been recorded in many geologic reports on the Willamette Basin, particularly those dealing with the engineering and environmental geology of county-wide areas, such as Trimble (1963), Schlicker and Deacon (1967), and Beaulieu,

TABLE 3.—*Description of geologic units in the Molalla River basin*

Erosional group	Geologic units[1]	Lithology	Topographic expression
Flood plain alluvium.	Recent alluvium (Qral.)	Unconsolidated silt, sand, and gravel.	Channel deposits and flood plains peripheral to the main stem Molalla River; slopes average 0 to 3 percent.
Valley terrace alluvium.	Pleistocene non-marine terrace deposits (Qpun, Qpn, Qpln).	Semiconsolidated silt, sand, and gravel.	Terraces peripheral to the Molalla River and north of the town of Molalla; slopes average 0 to 12 percent.
Competent bedrock.	Pleistocene and Pliocene basalt and andesite (QTba).	Predominantly dense basalt and andesite flows.	Gentle to moderate sloping lower uplands, northwest Molalla River basin; average slope ≤12 percent.
			Ridges and resistant uplands; average slope >12 percent and commonly >35 percent.
	Miocene basalt (Tmmb).	Multiple basalt flows.	Middle Molalla River basin forming the stream channel and valley walls; average slope >12 percent and >35 percent along walls.
	Miocene and Oligocene basalt (Tmob).	Predominantly basalt flows, in some areas interbedded with breccia.	Middle Molalla River basin forming the stream channel and valley walls; average slope >12 percent and >35 percent along walls.
	Quaternary and Tertiary mafic intrusive rocks (QTim, Tmui).	Fine-grained andesite porphyry, diabase, and micronorite dikes and plugs.	South-central part of basin at peak of several uplands; average slopes >12 percent.
Incompetent bedrock.	Pliocene non-marine sedimentary rocks (Tpn).	Conglomerate with lenses of sandstone and siltstone.	Areas of local low slope <7 percent transitional to lower uplands with slopes ≤12 percent.
			Steep slopes along minor tributary valleys, lower Molalla River basin; slopes average >12 percent and >35 percent in many places.
	Miocene flow rocks, breccias, and tuffs (Tmua).	Predominantly breccias and tuffs with minor basalt and andesite flows.	Upper Molalla River basin, steep valley walls, and mountainous terrain; slopes average >12 percent and commonly >35 percent.
	Miocene and Oligocene pyroclastic rocks (Tmop).	Predominantly breccias and tuffs.	Lower uplands, western part of Molalla River basin; slopes >12 percent.

[1]Geologic units and map symbols from Wells and Peck (1961). For some units, different groupings and names have been given by Peck and others (1964), Beaulieu (1971), and Hampton (1972).

Hughes, and Mathiot (1974). Studies made in the Willamette Basin's H. J. Andrews Experimental Forest (Dyrness, 1967; Fredriksen, 1970; and Swanson and James, 1975) cite the particular susceptibility of pyroclastic rocks to landsliding (mass wasting).

Qualifications and possible refinements.—Although the lowland is dominated by depositional processes, some erosion does occur. For example, during flooding, unstabilized areas of the flood plains are subject to intensive erosion.

Another qualification is that the relatively erosion-resistant competent bedrock units may be subject to mass wasting at outcrops where underlain or surrounded by incompetent bedrock on steep slopes.

Moreover, although we have classified upland bedrock units on the basis of susceptibility to mass wasting, it is important to note that the processes of fluvial erosion and mass wasting are closely related. When mass movements like landslides occur, they generate large masses of loose rock, soil, and organic debris. The bare surface of such unstable areas permits fluvial erosion to occur at accelerated rates.

Where detailed geologic maps are available, more refinement of the working hypothesis may be warranted. Detailed geologic maps normally include recognition of old landslide deposits and other geomorphic features that give clues to the erodibility of rock units. For local studies, careful fieldwork would be necessary to insure the distinction of all important geologic units and their erosional properties.

SOILS

Geographical description.—With regard to their geographic distribution, the soils of the basin can be conveniently categorized into four general groups: (1) alluvial soils of the flood-plain lowlands; (2) alluvial soils of the valley terraces; (3) upland soils of the Cascade foothills; and (4) upland soils of the lower Cascade mountains. The general physical properties of these four groups are summarized in table 4, and the areal distributions of soil associations within the groups are shown in figure 7.

The basic information from which table 4 and figure 7 were developed was taken from a report published by the Oregon State Water Resources Board (1969) (as derived from U.S. Soil Conservation Service data). For purposes of this circular, some minor modifications of the reported units were made. Specifically, because of their minor basinwide significance, the mountain peak and

TABLE 4.—*Description of geographic soil groups in the Molalla River basin*

Geographic Group	Description
Flood-plain soils	Flood-plain soils have formed from recently deposited sediments that border streams throughout the Molalla River valley. The soils occur on level to gently sloping terrain. Flood-plain soils are commonly shallow and include silty clays and silty to clayey loams. Most of the soils are well drained, but there are sizable areas of poorly drained soils where surface runoff can be substantial during periods of heavy rainfall.
Valley-terrace soils	Valley-terrace soils were developed under a mixed grass and tree cover from semiconsolidated sedimentary rocks within or bordering the Molalla River valley. The soils occur on level to gently sloping terrain. The soils are principally clayey loams, and depths range from deep to very deep depending on local relief and drainage. Most of the valley-terrace soils are well drained, but here too, there are sizable areas of poorly drained soils that give rise to substantial surface runoff during periods of heavy rainfall.
Cascade foothill soils	Soils of the Cascade foothills were formed under cover of mixed hardwood and coniferous forest from generally resistant volcanic rocks bordering the Molalla River valley. The soils occur on gentle to moderately steep slopes. The soils are principally clayey and silty-clay loams and depths range from shallow on the steeper slopes to moderately deep on the gentle slopes. The soils tend to have a well-developed structure that favors water infiltration and resists erosion.
Lower Cascade mountain soils	Soils of the lower Cascade mountains were formed under a coniferous forest cover from deeply weathered volcanic rocks. The soils occur on moderate to very steep terrain. The soils are principally clay loams and silty clay loams, and depths range from moderately deep on the more moderate slopes to shallow on the steepest slopes. The soils tend to absorb water rapidly and to resist erosion.

ridge soils were grouped with soils of the lower Cascade mountains.

Working hypothesis.—Under undisturbed conditions, the rates of soil erosion are generally similar and low throughout the basin.

Rationale.-With minor exceptions, the soils of the Molalla River basin have physical properties that (under natural conditions) render them (1) well drained and (2) suited to the growth of a dense vegetal cover. Thus, only where the natural drainage and cover conditions are disturbed, such as by man and fire, can slope and other geomorphic factors cause a significant increase in the rate of soil erosion.

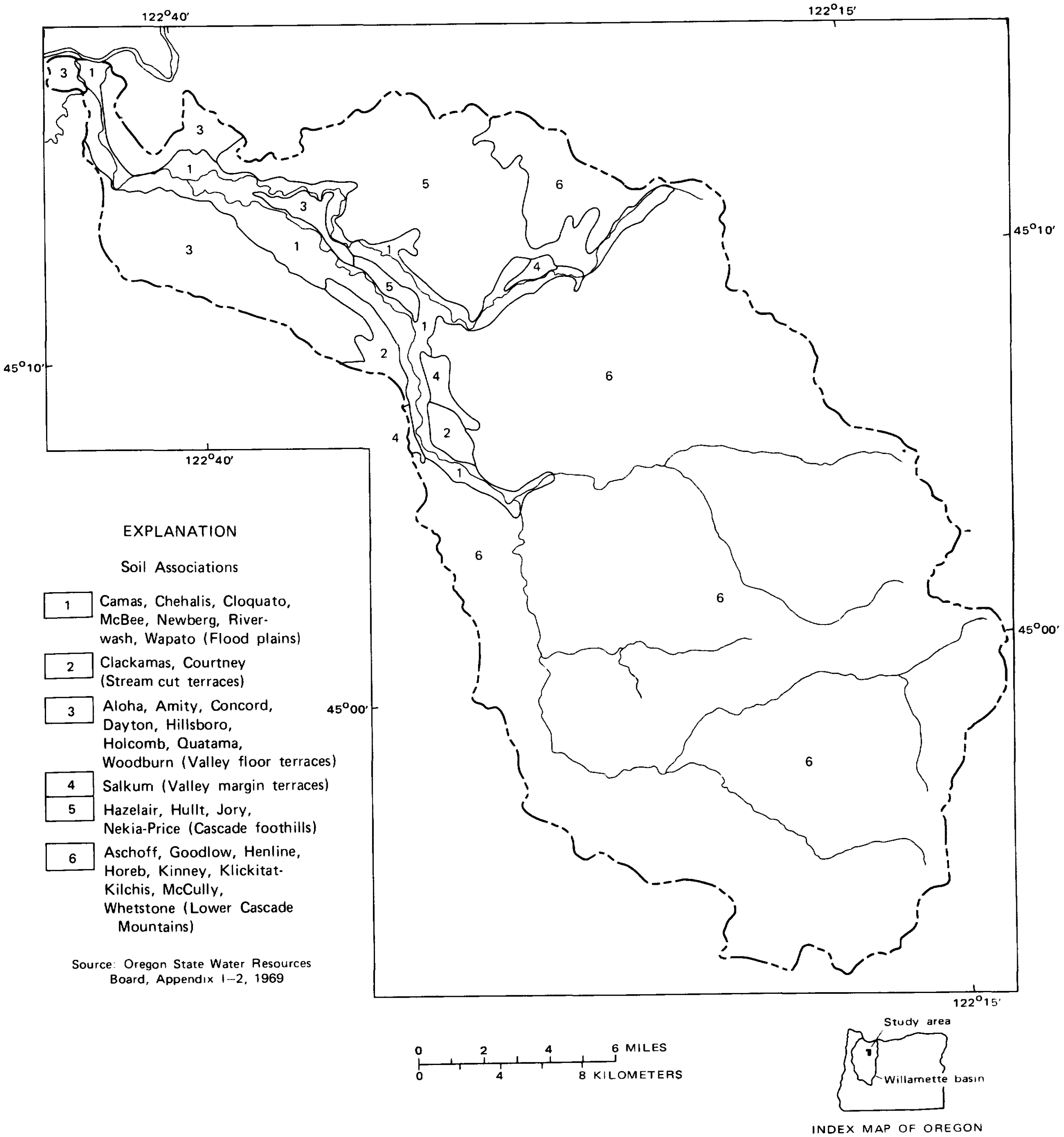


FIGURE 7.—Soil associations of the Molalla River basin.

Substantiation.–Three quotations from the Willamette Basin Task Force (Appendix A, 1969, p. II–17 to II–23) support the working hypothesis and rationale.

"In***the Cascades, there is little or no surface erosion in forested areas where the vegetative cover has not been disturbed."

"Despite steep slopes and heavy rainfall, surface erosion generally is not a serious problem in the foothill area. The well-developed soil structure favors water infiltration and resists erosion."

"Erosion from rainfall is generally not a problem on the valley floor soils, though there are some important local exceptions."

Qualifications and possible refinements.–Locally, some of the foothill areas of less than 1,000 ft (300 m) altitude were originally covered by hardwoods, brush, and grasses, and their soils have a slightly lighter texture than the clay loams of the conifer forest. Also, at altitudes of more than about 3,000 ft (915 m), shallow, stony loam soils have developed on the steeper mountain slopes. Both the lighter textured and the more coarsely textured soils are more susceptible to accelerated erosion when disturbed than are the predominant clay loams. However, the presence of these exceptions is not considered to be significant on a regional scale because of their limited areal extent. For detailed local studies, of course, it might be necessary to clearly distinguish all such soil differences.

In some terrain, periodic saturation of the upland soils that are underlain by impermeable clays or bedrock can lead to shallow mass soil movement. Such processes can, in local areas, lead to rates of erosion considerably higher than the generally uniform rate prevalent under undisturbed conditions (see "Working Hypothesis" above). The data needed to systematically define the potential for these shallow mass soil movements are presently not available. However, the potential for deep-seated mass wasting, which involves both soil and bedrock, has already been accounted for through consideration of bedrock "competence" (see table 3).

The deep alluvial soils of the gently sloping valleys and terraces are the primary exception to the basinwide predominance of forest loam soils. The valley terrace soils are generally resistant to erosion from rainfall, but there are some important local exceptions. One exception occurs where the level to gently sloping terrain of the terrace breaks to steeper slopes adjacent to flood plains. Erosion can be serious in such locations but only when the soils are left unprotected. A second exception occurs in localized areas where the soils are poorly drained. During winter, such soils give rise to substantial amounts of surface runoff and, if left unprotected, will erode.

Certain areas of the flood-plain soils are also poorly drained and therefore subject to erosion from overland flow. In addition, many flood-plain soils are subject to surface and channel erosion from stream overflow depending on the location, type of cover, and the nature of the overflow (Willamette Basin Task Force, Appendix A, 1969, p. II–22).

For more detailed studies, it would be prudent to group the valley terrace and flood-plain soils into relative categories of erosion potential. The delineation could be based on soil-drainage properties and on location with regard to breaks in slope and the potential for receiving stream overflow.

VEGETATION

Geographical description.–Historically, the wet-temperate climate of the Molalla River basin has supported a dense vegetal community, both in the lowlands and uplands, dominated by conifer forests composed primarily of Douglas fir. The native upland conifer forests also included hemlock, cedar, and white pine. Other native vegetation in the lowlands included alder (especially along streambanks), oak, and various shrubs and grasses. Alder and oak were the primary hardwoods found in the uplands, but they commonly occurred only in the foothills and at altitudes below 3,000 ft (915 m). (See Franklin and Dyrness, 1973.)

The natural vegetation of the Molalla River basin provided excellent cover and soil-holding properties, thus retarding land-surface erosion. This native vegetal cover has been greatly altered by human land-use activities during the last 150 years. Nearly all gently sloping flood-plain and terrace lands have been cleared and converted to agricultural crop and pasture land. About 80 percent of the forested uplands has been clearcut. Much of this clearcut area is characterized by barren or brushy slopes and immature, regenerating forest interlaced with logging roads.

Present-day vegetal patterns in the basin were examined on high-altitude, false color IR imagery. (See section "Interpretation and Mapping of Erosional and Depositional Features.") A cross section of the basin showing the 1973 conditions of vegetal cover is shown in figure 8.

Working hypothesis.–The extensive surface cover and soil-holding characteristics afforded by natural vegetation allow only minimal erosion. Only when vegetation is removed by man or by natural causes can severe erosional problems develop.

Rationale.–Except in areas that have been substantially altered by intensive land use (for example, road construction or tractor logging), the steeply sloping, most erodible terrain in the basin is covered by dense forest vegetation. The vegetal cover acts as an effective check against the initiation of rapid erosion.

Substantiation.–"the trees, brush, and grass that grow abundantly because of the moist, mild climate tend to protect the surface of the (Willamette) basin from rapid erosion" (Willamette Basin Task Force, Appendix B, 1969, p. IV–33).

"If vegetative density is high enough, it doesn't matter greatly whether or not the other elements (erosional) are conducive to high soils loss—the protection afforded by good cover will keep erosion to a minimum" (Willamette Basin Task Force, Appendix G, 1969, p. II–35).

Qualifications and possible refinements.–Besides the overhead canopy and soil-holding characteristics offered by large plants and trees, the extent of leaf litter and ground mulch is also important in controlling erosion. Unless artificially disturbed, forested areas in the basin normally have abundant leaf litter and ground mulch. However, other tree-covered areas may lack protective ground cover. For example, clean-tilled orchards without an understory cover crop may experience severe erosion despite a protective overhead canopy.

For site-specific studies, therefore, it may be important to examine both vegetal canopy and ground-cover conditions to interpret the potential for erosion.

PROVINCE-DEFINING CRITERIA

A primary objective of the province concept is to provide a basis for delineating the erosional and depositional potentials of land in its natural state. Once the potentials are delineated, an evaluation can be made of the impact of man on the erosion

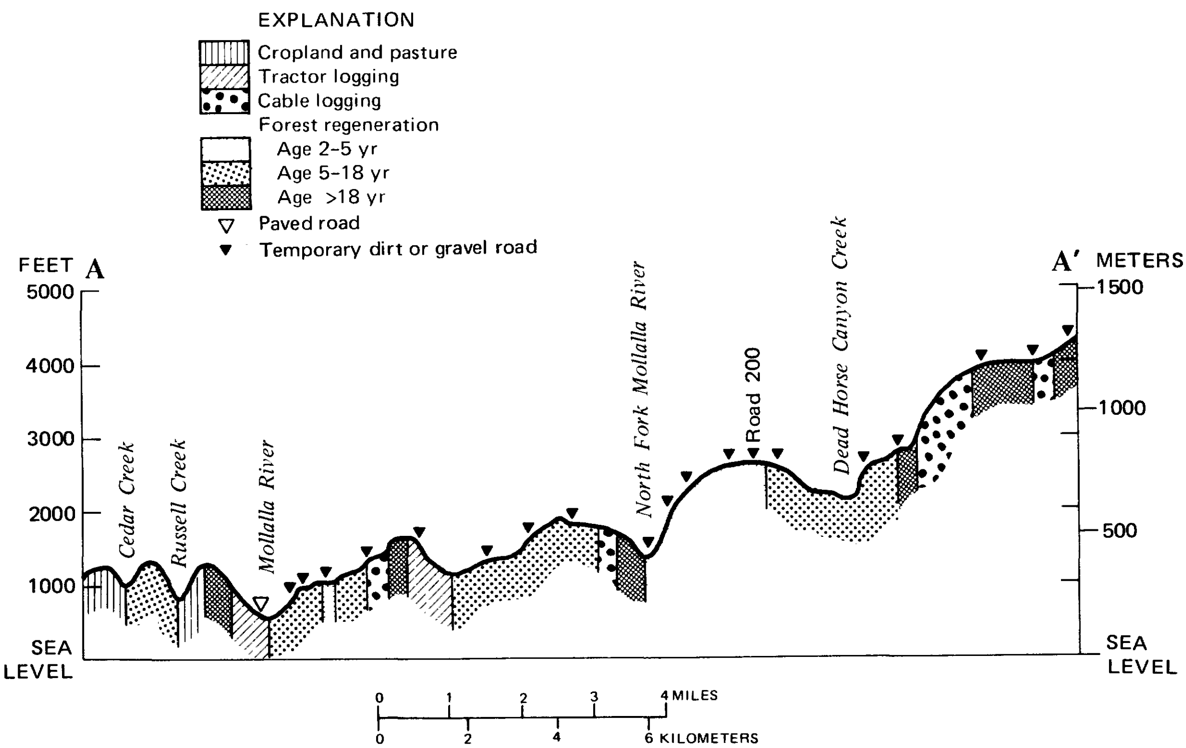


FIGURE 8.—Cross-sectional diagram of the Molalla River basin showing 1973 conditions of vegetal covering. See plate 1 for location.

and deposition that is occurring in a particular basin.

The preceding sections have examined the major environmental factors that control terrain-surface stability as to their relative impact on erosion in the Molalla River basin. Of the five factors, climate and soils are both considered to exert relatively homogeneous impacts on erosion throughout the basin. In addition, natural vegetation exerts a homogeneous impact by preventing the occurrence of accelerated erosion. Natural vegetation becomes a variable factor in basinwide erosion only through its removal; consequently, in "Development of an Erosional Impact Matrix" we treat vegetation as a proxy for land use.

Of the five original factors, topography (slope steepness) and geology exert the most widely variable impacts on basinwide erosion. Thus, the working hypotheses for these factors contain the criteria needed to define regional scale erosional-depositional provinces for the Molalla River basin. These criteria have been used to synthesize the basic information presented on slope steepness (fig. 5) and geology (fig. 6) into generalized factor maps for slope steepness (fig. 9) and geology (fig. 10). In turn, the generalized maps have been composited to delineate four eroerosional and two depositional provinces. (See plate 1.)

Table 5 summarizes the province-defining process by restating the criteria and by identifying the six provinces and their mapping symbols. In addition, the table includes pertinent information on the erosional, transportational, and depositional activities, as well as the physical character of each province. The combined information was developed over a 3-year period from analysis of available earth-resource data, review of geomorphic literature, consultation with local scientists and planners, field-checked interpretation of color IR imagery, and professional judgments by the project staff.

DELINEATION OF BOUNDARIES

The erosional-depositional map of the Molalla River basin (plate 1) was prepared by compositing the generalized slope and geologic maps (figs. 9 and 10) onto a 1:130,000-scale photomosaic base (Vickers and others, 1975). By using an overlay approach and a reflecting projector, the generalized geologic map was optically enlarged to the scale of the photomosaic base. Flood-plain and terrace-alluvium deposits were then outlined to identify the depositional provinces V_1 and V_2 (table 5). Next, the upland competent and incompetent bedrock units were outlined. Finally, the generalized slope map was scale matched to the photomosaic base. The 12-percent slope break was used to separate the competent and incompetent bedrock units into ≤ 12 and >12 percent slope groups. This resulted in the delineation of the four erosional provinces identified as C_1, C_2, I_1, and I_2 (plate 1 and table 5).

Throughout the overlay procedure, aerial photographs and 1:24,000- and 1:62,500-scale topographic maps were used to make fine adjustments in the province boundary lines. This was necessary because the slope and geologic information was generalized from maps of various scales that did not strictly conform with the semicontrolled 1:130,000-scale photomosaic base. For this reason, the erosional and depositional provinces shown on plate 1 are regional in nature. For site-specific studies (particularly in areas proximate to boundary lines), interested parties may wish to refine the boundary lines through additional fieldwork and the preparation of more detailed maps for slope and geology.

IDENTIFICATION AND DESCRIPTION OF EROSIONAL-DEPOSITIONAL FEATURES

The second step in producing a province map is the identification and mapping of existing erosional-depositional features. Inclusion of the features on the map serves several purposes. First, the features indicate the general basinwide patterns of land deformation and thereby provide a direct visual statement of land-surface quality. Second, by showing the location and density of disturbed, unstable surfaces, the mapping identifies the major sediment sources in the basin. Thus, in conjunction with the erosional-depositional provinces and observable land-use activities (see plate 1), the mapped features provide a basis for interpreting the spatial impact of man's activities on both land and river quality.

Erosional and depositional features in the Molalla River basin were identified through intensive analysis of stereoscopically paired color-IR images (scale 1:130,000). The images were magnified and perused on a scanning stereoscope, and descriptive notes were made regarding prominent features, land-use associations, and patterns of vegetation. Next, in selected areas, the descriptive notes and preliminary feature identifications were checked and verified through field observations, ground-level color and color-IR photography, and low-level aerial photography.

Descriptions of the selected erosional-depositional features are presented below, along with the identifying map symbols used on plate 1. Details of the technique by which the features were identified and mapped are given in the section "Interpretation and Mapping of Erosional and Depositional Features." The techniques when

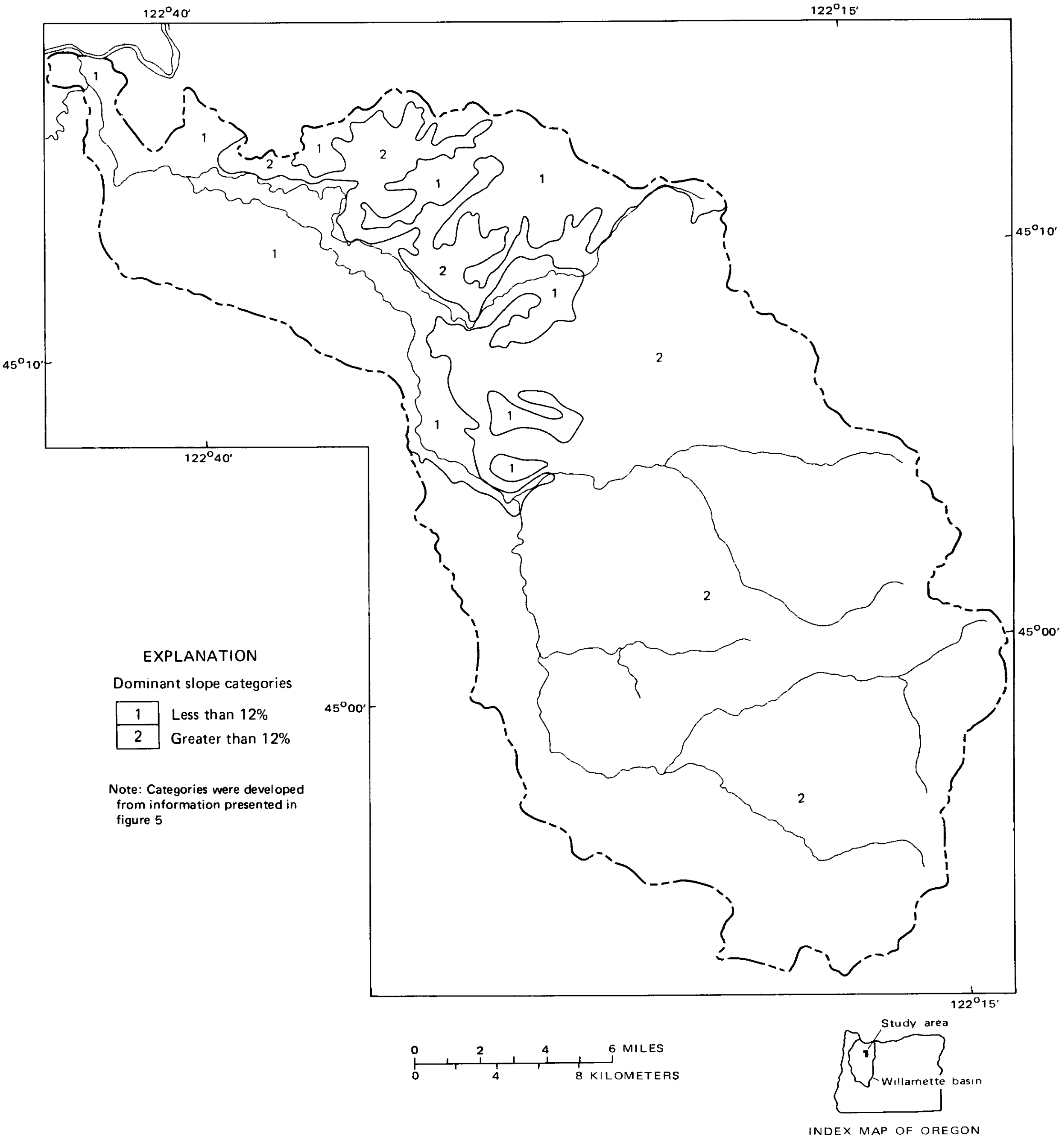


FIGURE 9.—Generalized slope-steepness categories of the Molalla River basin.

used at the 1:130,000 scale cannot effectively distinguish all the types of erosional and depositional features defined in the geomorphic literature. For example, it was not possible to distinguish among all the different types of formally defined landslides. Therefore, the descriptions given below, although generally consistent with accepted geomorphic terminology, have been generalized to provide working definitions compatible with the photointerpretive technique. It is also important to note that the technique does not permit identification of old features which have become partially stabilized and covered with vegetation. Examples of such

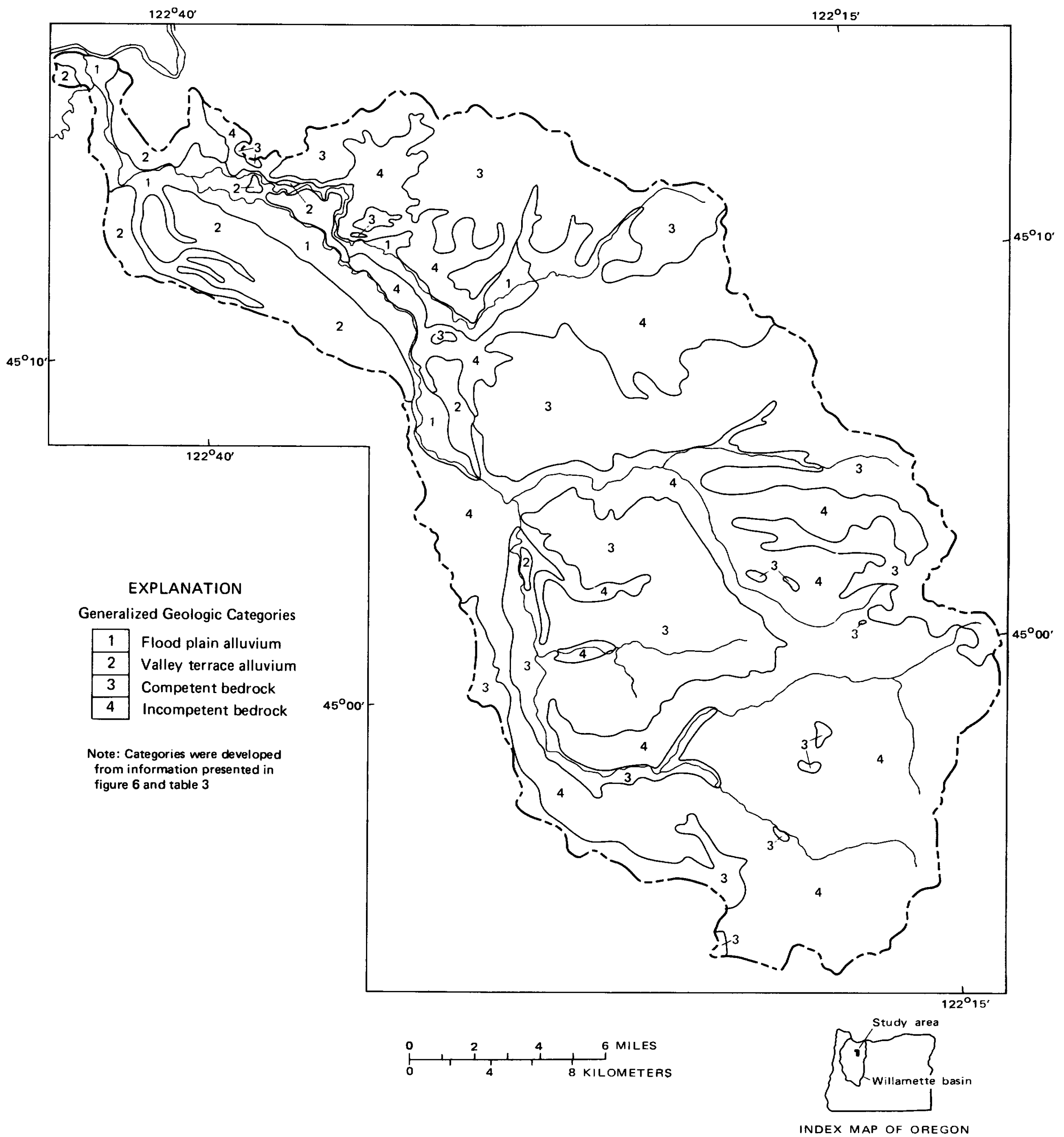


FIGURE 10.—Generalized geologic map of the Molalla River basin.

TABLE 5.—*Mapping criteria and physical characteristics of erosional and depositional provinces in the Molalla River basin*

Provinces: Name	Provinces: Symbol	Slope (percent)	Geologic units[1]	Erodibility of geologic units	Types and sources of sediments entering streams	Deposition
			Erosional provinces			
Incompetent sloping uplands.	I_1	≤12	Pliocene nonmarine sedimentary rocks (Tpn); Miocene flow rocks, breccias, and tuffs (Tmua); Miocene and Oligocene pyroclastic rocks (Tmop).	Moderate to very high: Most of these units are prone to mass movement on slopes between 12 and 60 percent, particularly where linear planes of weakness (such as bedding planes and joints) are inclined downslope. Units of tuff with swelling clays are particularly prone to mass movement and are highly susceptible to fluvial erosion.	Shale, mudstone, and pyroclastic units will contribute large loads of fine suspended sediments and induce turbidity. Breccias may contribute boulder-sized materials (bedload) from mass-wasting processes.	Mass-wasting debris in numerous locations; also streambed deposits and debris jams are common in some areas.
Incompetent steep uplands.	I_2	>12				
Competent sloping uplands.	C_1	≤12	Pleistocene and Pliocene basalt and andesite (QTba); Miocene basalt (Tmmb); Miocene and Oligocene basalt (Tmob); Quaternary and Tertiary mafic intrusive rocks (QTim, Tmui).	Low to moderate: These units are not generally prone to deep-seated mass movement on slopes under 60 percent, except at the edge of outcrops where underlain or surrounded by incompetent bedrock which is susceptible to mass movement. Where layered lava rocks are inclined downslope and have tuff interbeds, there is high potential for slides and rockfall. Deep clay residuum is prone to soil slump. Rockfalls and debris flows are common on slopes near 60 percent.	In most areas, units contribute small loads of predominantly cobble- and boulder-sized materials as bedload. Where competent units are underlain or interbedded with tuffs, pyroclastics, or sedimentary units, moderate to large quantities of fine sediments can be added to the suspended load.	Some mass-wasting debris in localized areas; also, localized streambed deposits and debris jams.
Competent steep uplands.	C_2	>12				
			Depositional provinces			
Valley flood plain.	V_1	≤3	Recent alluvium (Qral).	Normally low, except during flooding, when sandy soils are subject to scour (particularly in swales) due to concentrated flow. Channel changes due to flooding predominantly occur in the braided reaches of the flood plains.	Coarse sands and gravels resulting from scour of streambed deposits and bank erosion contribute to bedload. Flood-plain clays and silts derived from streambank failures and floodwater erosion contribute to suspended load.	Subject to overbank silt deposition and gravel splays during floods; in channelways, depositional bars occur at inside curve of meanders and at, or near, obstructions.
Valley terrace.	V_2	≤12	Pleistocene nonmarine terrace deposits (Qpun, Qpn, Qpln).	Low to moderate, depending upon location of terrace scarps in relation to existing drainageways. Moderate to very high where river meanders undercut valley-floor terraces composed of bedded silts and clays or where bank sloughing of valley-floor terrace scarps occurs.	Clay and silt deposits near drainageways will contribute to suspended load. Some bedload will be contributed by gravel terraces and old gravel outwash fans during flood conditions.	Small alluvial fans and colluvium deposits occur at breaks of slopes. Occasional landslide debris from foothills and valley buttes can occur immediately upslope of terraces.

[1]See table 3 for description of lithology, topographic expression, and bibliographic sources of information.

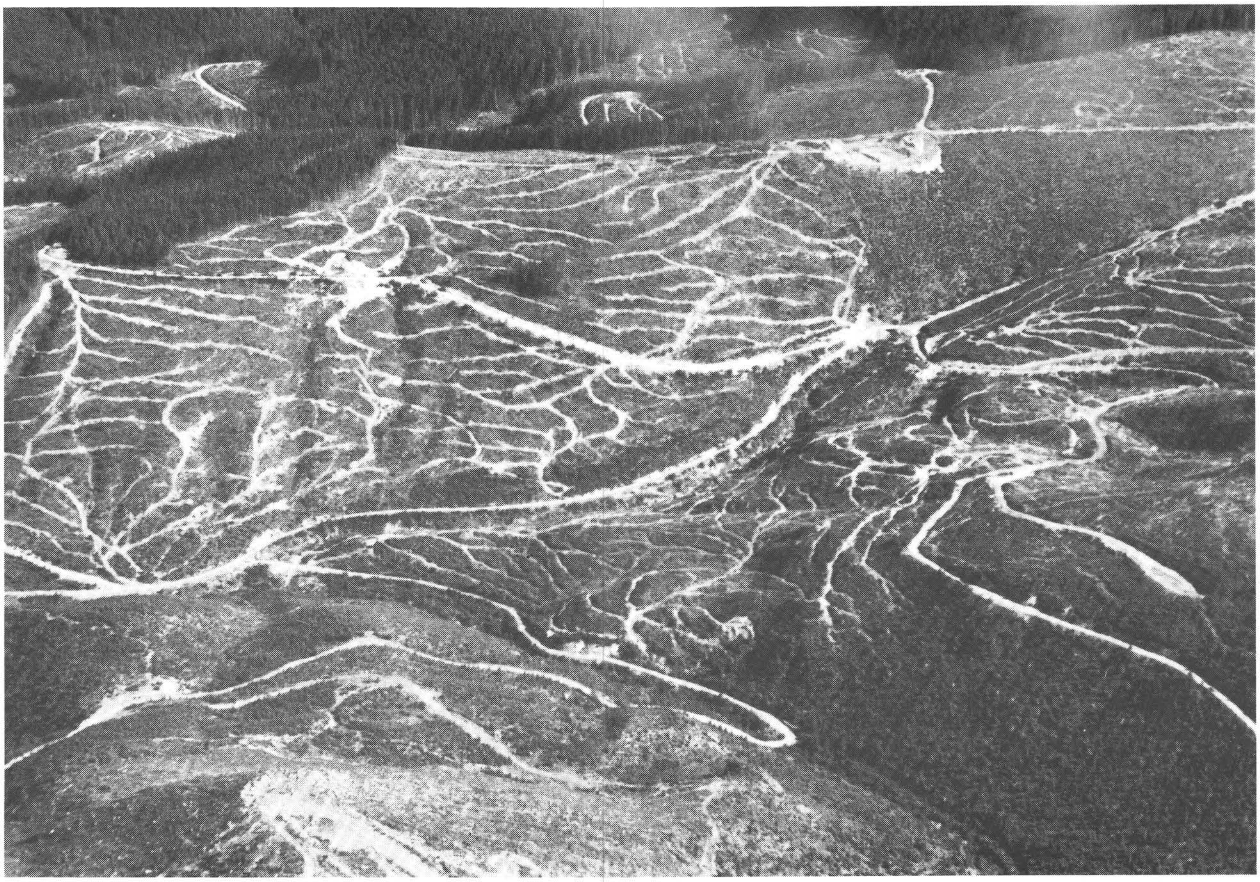


FIGURE 11.—Example of sheet and rill erosion surfaces in the Molalla River basin. Photograph taken August 29, 1974.

features are old landslide deposits and stabilized alluvial fans.

EROSIONAL FEATURES

SHEET AND RILL—(R)

Sheet and rill erosion result from the erosive flow of storm runoff moving as thin sheets of water down a sloping surface of relatively soft materials. Although generally inconspicuous during early stages of development, sheet and rill erosion represent major types of fluvial erosion in the Molalla River basin.

Sheet erosion is the generally uniform removal of soil by overland runoff. The resulting scarred surface is characterized by numerous small channelways that change in shape and size with each succeeding wave of runoff (fig. 11). Rill erosion refers to a slightly later stage wherein a number of the tiny channelways are deepened into conspicuous small rivulets. As opposed to gullies, these shallow rills are easily obliterated by tillage. Sheet and rill erosion are recognized on the aerial imagery by (1) the appearance of "galled spots" in bare fields, (2) the deposition of sediment at the edges of fields, and (3) by the development of small fans at the bases of slopes.

In the Molalla River basin, sheet and rill erosion occur primarily on dirt roads and on road cuts and fills. Sheet and rill erosion may also occur on clear-cut lands scarred by tractor and cable logging (fig. 12) or on other newly exposed (devegetated) surfaces. Sheet and rill erosion also occur on the surface of mass-wasting features such as landslides. To avoid excessive clutter, only the more obvious examples are identified on plate 1.

EARTH FLOW AND DEBRIS FLOW—(E)

An earth flow is a relatively shallow mass of dominantly fine particles that becomes lubricated and weighted by water and then moves rapidly downslope under the influence of gravity. An

FIGURE 12.—Typical landscapes resulting from cable (A)- and tractor (B)-logging practices in the Molalla River basin. Tractor logging is evident in upper right of picture. Photograph taken May 9, 1977.

earth flow typically is long and narrow, and its shape conforms somewhat to the canyon or channel through which it flows. An earth flow is distinguished by its continuity of movement throughout its length and its tendency to build a fan or debris lobe where it reaches the toe of the slope. This description of earth flows is a working definition which includes mudflows and other shallow mass movements of fine-grained materials associated with both gravity and water. (See Sharpe, 1960, p. 56)

A debris flow (fig. 13) is similar to an earth flow in its form and processes of movement. However, debris flows are composed dominantly of coarse rock fragments rather than fine sediment particles. In addition, debris flows tend to occur on steeper slopes than earth flows and to exhibit higher rates of movement.

Earth flows and debris flows are not effectively differentiated by the photointerpretive techniques used in this study. Therefore, for purposes of mapping, the two are identical as one feature and represented by one symbol (E).

Earth and debris flows are common in the eastern part of the basin where there are accumulations of volcanic ash, cinders, and blocks on steep slopes and in narrow canyons.

LANDSLIDE—(L)

A landslide (fig. 14) is a relatively dry mass of earth, rock, or mixture of the two that moves intermittently or continuously downslope under the influence of gravity (Sharpe, 1960, p. 64). By this definition, a landslide is a general type of feature that includes earth slides and debris slides. Landslides may be distinguished by a number of characteristics, including abrupt and irregular changes in the drainage pattern, disturbed vegetation, hummocky irregular surfaces, and steep scarps at the upper edge of the feature. As differentiated from earth and debris flows, landslides are generally deeper, contain less water, and are

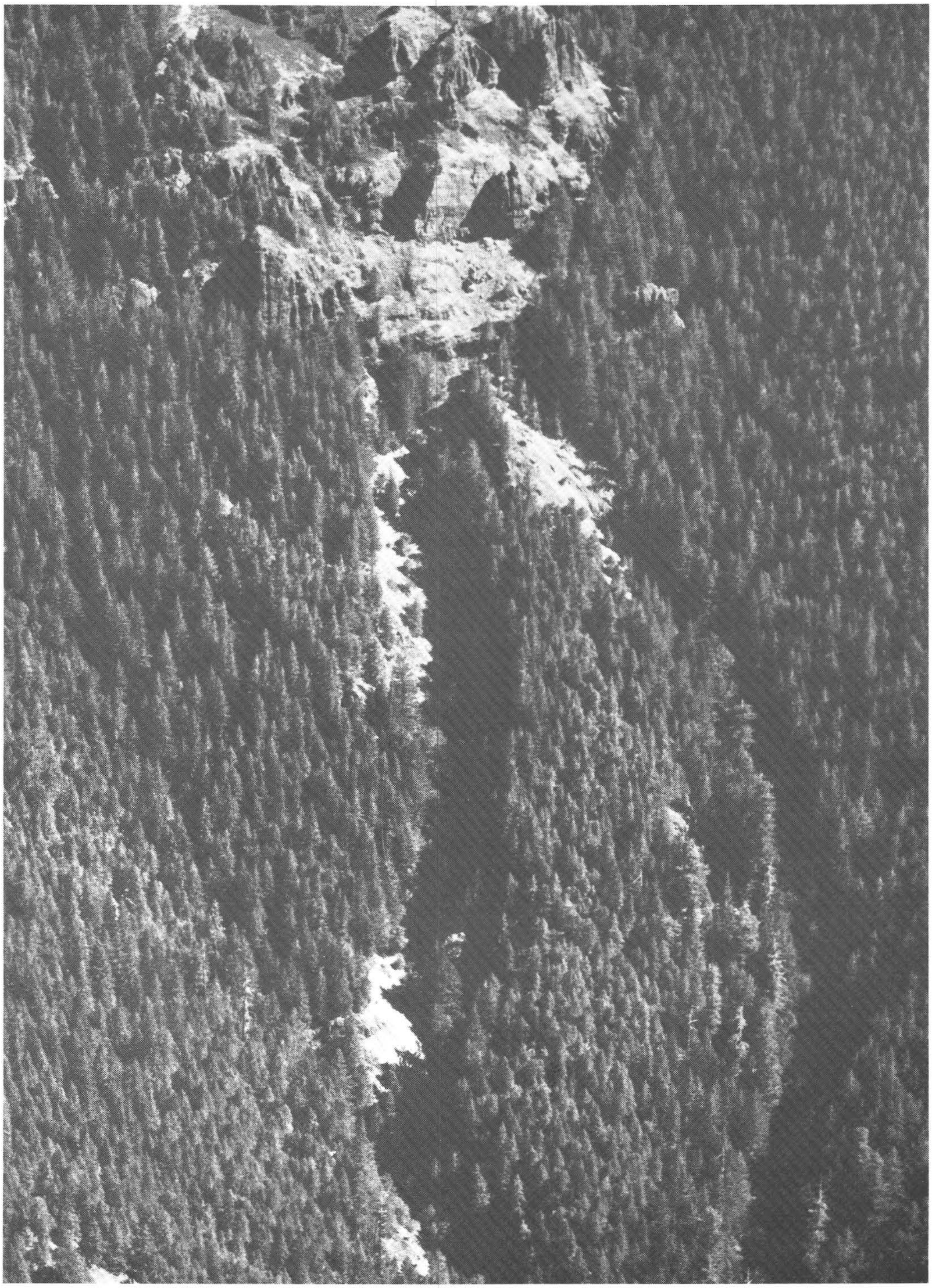


FIGURE 13.—Debris flow emanating from volcanic cliffs that have partly disintegrated into coarse rock fragments. Photograph taken September 6, 1974. Compare with landslide shown in figure 14.

not necessarily confined to narrow canyons and channelways. Rockslides and rockfalls are sometimes categorized as landslides, but in this study are included under "talus."

The landslides identified on plate 1 assume many shapes and sizes. Most of the slides occur on steep deforested terrain in the south and southeastern parts of the basin.

TALUS—(T)

Talus is an accumulation of coarse rock fragments that moves slowly downslope under the influence of gravity. In general, talus assumes slopes between 20 and 40 percent, depending primarily on the size and shape of the rock fragments. Talus is commonly found on hillsides in the form of rockslides (fig. 15) or at the base of cliffs as rockfalls.

Talus is most prevalent in the south-central part of the basin where the weathering of exposed volcanic rocks provides the fragmented materials.

STREAMBANK FAILURE—(B)

A streambank failure is a collapse of earth materials directly into a stream (fig. 16). Such failures usually occur on the outside bends of streams where flowing water undercuts the base of loosely consolidated alluvium or highly weathered bedrock.

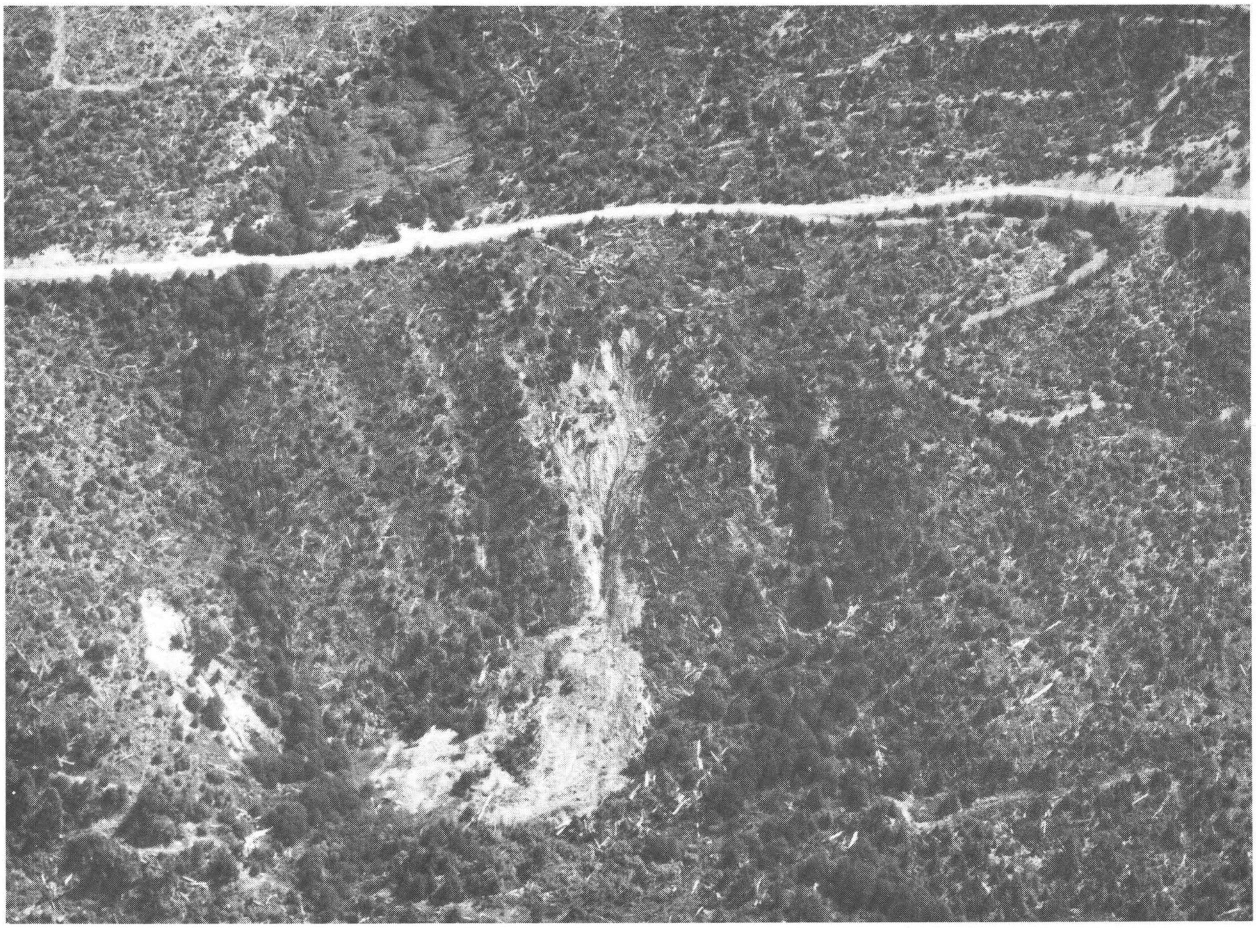


FIGURE 14.—Typical landslide in the Molalla River basin. Photograph taken September 6, 1974. Compare with debris flow shown in figure 13.

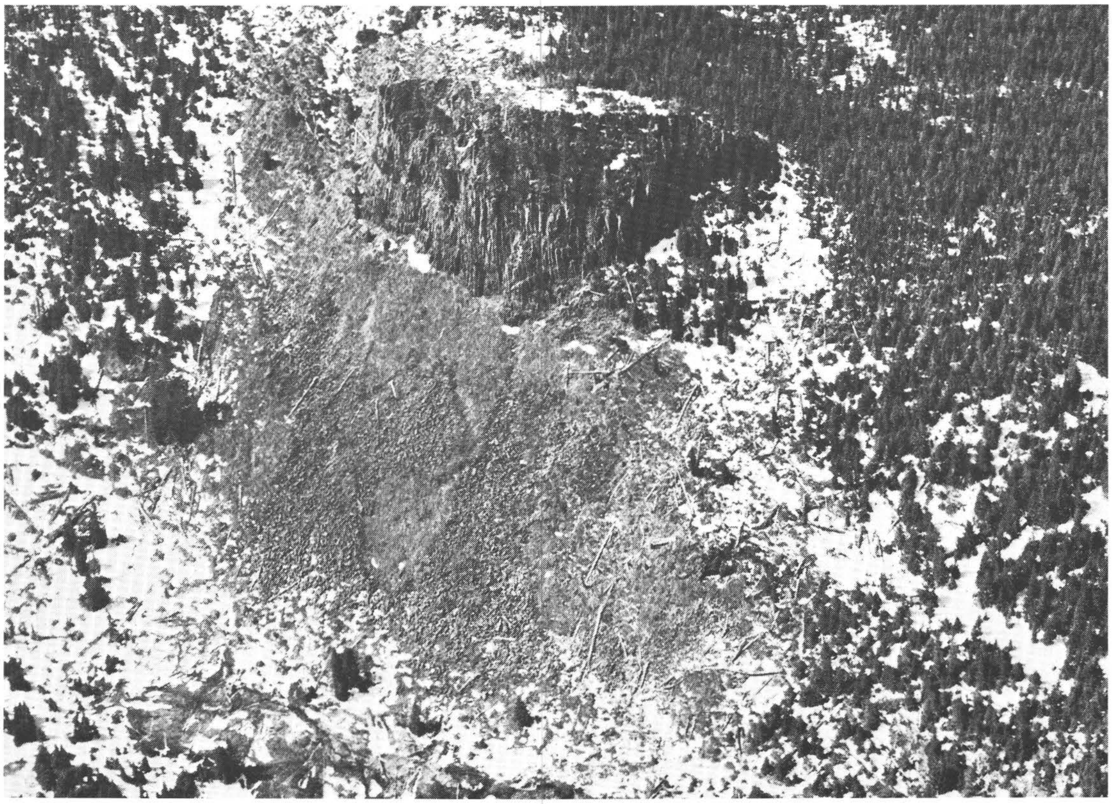


FIGURE 15.—Talus accumulation on hillslope below volcanic cliff in the Molalla River basin. Photograph taken May 9, 1977.

Streambank failures are most common in streams that are subject to unnaturally high influxes of sediment and debris. These influxes often cause instabilities in the sediment-transport regimen which, in turn, lead to streambed aggradation, channel shifts, and inevitably to streambank erosion.

DEPOSITIONAL FEATURES

STREAMBED DEPOSIT—(S)

A streambed deposit (fig. 17) consists of alluvial materials stored in a stream channel and subject to downstream movement during periods of high flow. The materials commonly are deposited in the form of sand and gravel bars. Individual particles may be moved and redeposited many times until they are ultimately discharged or otherwise removed from the streambed.

Streambed deposits occur in channels throughout the basin, but particularly in the lower gradient reaches of the valleys and flood plains.

MARSHLAND—(M)

For purposes of this study, a marshland is synonomous with wetlands and is a depression characterized by abundant vegetation growing in shallow, stagnant water (fig. 18). The water in marshlands is maintained by ground-water seepage and surface runoff. The surface runoff occasionally transports fine-grained sediments such as clay, silt, and organic material into the depression. This is prevalent especially during periods of overbank flooding of adjacent stream channels.

In the Molalla River basin, most marshlands are associated with sloughs, oxbow lakes, and backwater areas of the alluvial flood plains.

MANMADE FEATURES

Besides the "natural" features described above, there are several types of manmade features that may be important to the erosional-depositional system. Such features include landfills, roadfills, levies, earth dams, and various types of excavations. Although there are examples of each of

FIGURE 16.—Streambank failure (see arrow) along the Molalla River northwest of the town of Molalla. Photograph taken September 5, 1974.

these features in the Molalla River basin, excavations are the most prominent type of manmade feature.

EXCAVATION—(X)

An excavation is an artificial depression in the land surface formed by the removal of rock and soil. Most of the excavations in the Molalla Basin are gravel pits and rock quarries (fig. 19). The gravel pits are commonly located in or adjacent to stream channels and can result in the introduction of sediment into the streams. These excavations may also serve as periodic depositional sites for streamborne sediments. The rock quarries serve primarily as depositional areas for sediment from adjacent hillsides.

The gravel pit excavations occur primarily in the alluvial flood-plain deposits of the main-stem Molalla River. The rock quarry excavations are most common in the central part of the basin (see plate 1).

USE OF MAP FOR DESCRIBING THE EROSIONAL-DEPOSITIONAL SYSTEM

The six provinces identified in table 5 and delineated on plate 1 reflect distinctive differences in erosional-depositional processes and features. Although the provinces are distinct, there is a definite, logical interconnection among them. Obviously, much of the sediment derived from the erosional provinces must pass through or come to rest in the depositional provinces. It is instructive, therefore, to describe the provinces in a sequence that begins with the upland units.

The incompetent bedrock provinces (I_1 and I_2) contain a large share of the active erosional fea-

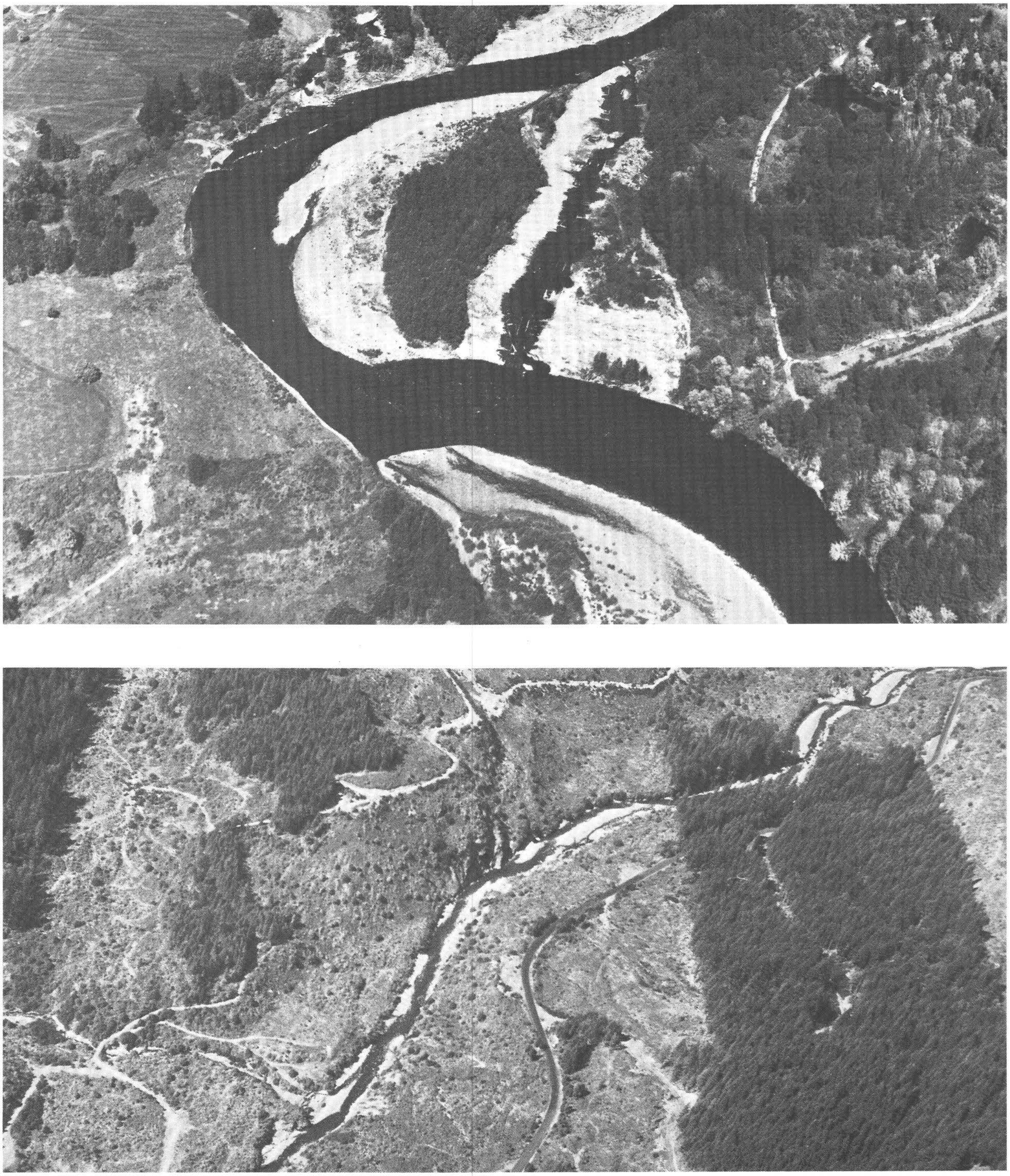


FIGURE 17.—Streambed deposits in the Molalla River basin. Upper, Flood-plain reach, photograph taken May 9, 1977. Lower, Upland stream, photograph taken September 6, 1974.

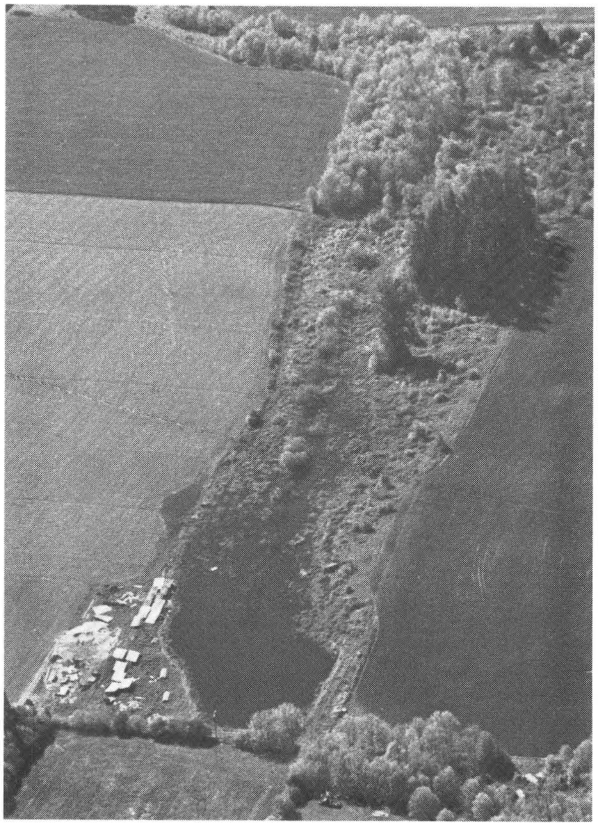


FIGURE 18.—Typical marshland in the Molalla River basin. Photograph taken May 9, 1977.

tures in the basin. The erosional susceptibility is greatest in the I_2 province where slopes commonly exceed 60 percent. Erosional features are also prevalent in locations where the incompetent bedrock abuts a more resistant (competent) bedrock or where the bedding planes of the underlying rock dip parallel to the land-surface slope (see table 5).

A large part of the sediment that is transported in the I_2 province is initially derived from mass-wasting features such as landslides, earth flows, and debris flows. However, the increased density of such features causes an acceleration of fluvial erosion because they increase the amount of exposed, unstable earth that is subject to sheet and rill erosion. Once set into motion, the sediment in the I_2 province moves rapidly downgradient into stream channels. This is particularly prevalent in those areas of the province where clearcutting has occurred (fig. 20).

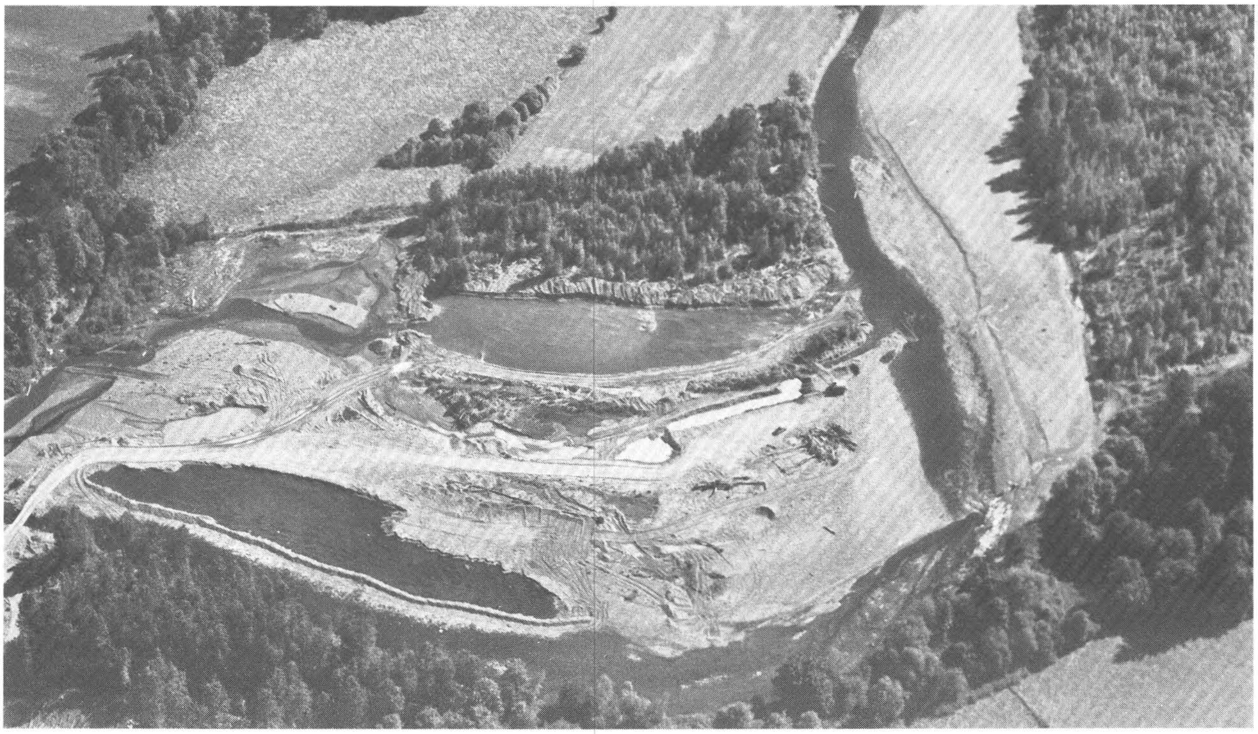
By comparison with the I_1 and I_2 provinces, the competent upland provinces (C_1 and C_2) exhibit few major erosional features. Although the C_1 and C_2 provinces are relatively resistant to mass wasting, their resistance decreases with increasing slope. Most of the sediment that moves in these provinces is derived from shallow landslides and from sheet and rill erosion. Much of the resultant sediment moves readily into stream channels because the natural restraint of vegetal cover is commonly lacking (fig. 21).

The valley terrace province (V_2) exhibits few major erosional features (fig. 22). Consisting largely of gently sloping terrain covered with grasses, the province is relatively free of mass-wasting processes and is little marked by fluvial erosion. Locally, moderate erosion results from oversteepened slopes and from streambank failures where the terraces abut the Molalla River flood plain.

The valley flood plain province (V_1) exhibits numerous, active erosional and depositional features (fig. 23). As the receiving area for sediment derived from the uplands and terraces, the surface of the province changes rapidly to accommodate the excessive sediment loads. Channel aggradation is virtually continuous along the Molalla River from Glen Avon to the Willamette River (plate 1). The aggradation contributes to lateral cutting by the Molalla which, in many locations, induces severe streambank erosion.

The above overview of erosional and depositional activities in each province is useful for deriving generalities regarding land-surface conditions. The surface condition, implied in the occurrence and severity of active erosional and depositional features, are severely degraded in the I_2 and V_1 provinces. In contrast, the remainder of the basin is relatively free of major erosional and depositional disturbances.

The density of erosional features in the I_2 province is greatest in areas of human-altered terrain. This suggests that the predominant land-use activities, namely large-scale clear-cut logging and related roadbuilding, are largely responsible for



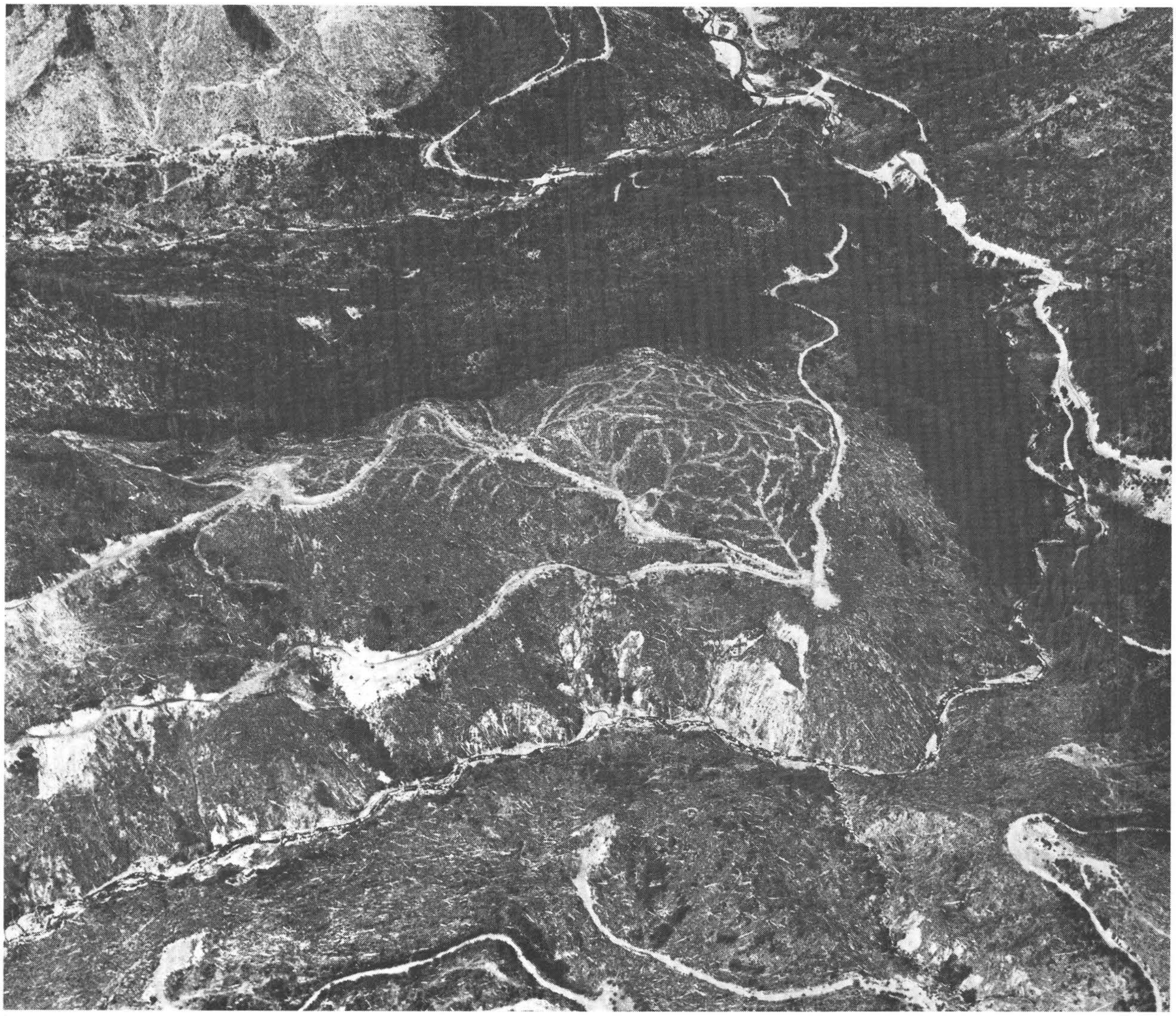


FIGURE 20.—Overview of clear-cut terrain in the incompetent steep uplands province (I_2) of the Molalla River basin. Note large landslides along the stream course. Photograph taken September 5, 1974.

the erosional features. Furthermore, it follows that the extension of similar land-use activities into unaltered parts of the I_2 province will cause similar erosional disturbances unless adequate protective measures are taken. The erosion potential for unaltered areas of the province is very high because the forested lands have steeper slopes than the areas already logged. The undisturbed lands presently have a precarious natural stability that will easily be disrupted by all but the most careful logging and roadbuilding practices.

FIGURE 19.—Examples of excavations in the Molalla River basin. Upper, Excavation in volcanic rock, North Fork Molalla River basin. Note the debris cast downslope from the excavation. Photograph taken September 6, 1974. Lower, Open-pit gravel mine adjacent to the main channel of the Molalla River near Canby. Photograph taken September 5, 1974.

The existing disturbances in the I_2 province have caused accelerated deposition in downslope stream channels. Geographically, a funnellike system exists wherein sedimentary debris, primarily transported from widespread sources in the I_2 province, is ultimately confined to the main stem of the Molalla River as it flows through the V_1 province. The consequences in the V_1 province include (1) at least a temporary increase in flood

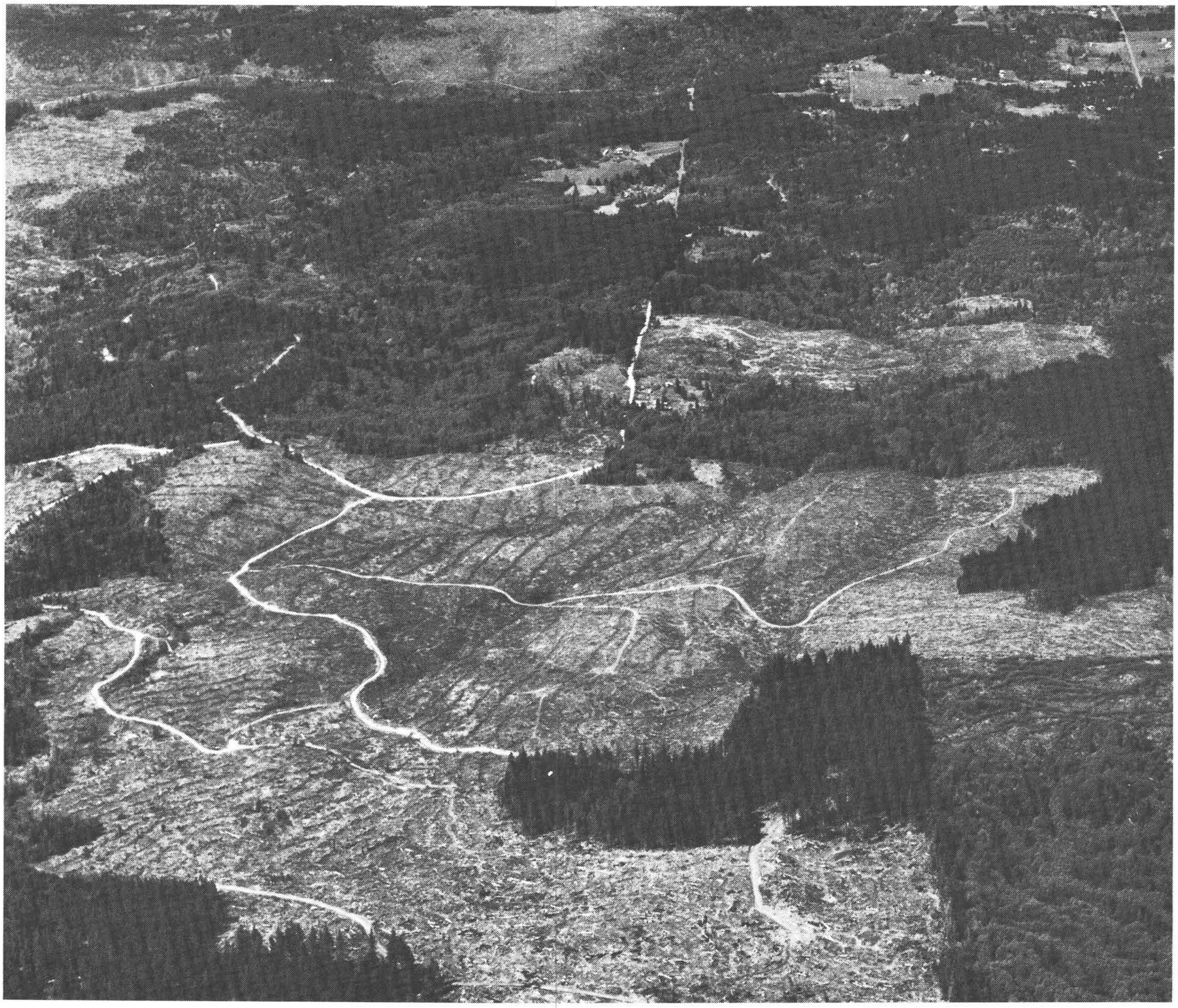


FIGURE 21.—Overview of clear-cut terrain in the competent steep uplands province (C_2) of the Molalla River basin. Photograph taken May 9, 1977.

potential resulting from a reduced channel capacity to carry floodflows and (2) erosion of floodplain lands as the river attempts to widen its channel to accommodate the transport of excess debris.

DEVELOPMENT OF AN EROSIONAL IMPACT MATRIX

The province map (plate 1) with accompanying features provides a basic tool for examining the basinwide condition of the erosional-depositional system. However, the utility of the map for environmental planning can be greatly enhanced through conjunctive use of a scheme for ranking the erodibility of different land surfaces within each province. The scheme developed for this purpose is the erosional-impact matrix (table 6). The matrix provides a systematic basis for making predictive estimates of the relative impact, in terms of erosion, of human activity on different types of terrain (provinces).

The horizontal axis of the matrix (table 6) is composed of order-of-magnitude factors for geology and slope, and the vertical axis of erosional-impact factors for selected land-use activities. The inclusion of these factors follows from previous discussions where we indicated that (1) geology and slope are the province-defining factors in the Molalla River basin and (2) the degree to which

FIGURE 22.—Terrain typical of the valley terrace province (V_2) in the Molalla River basin. Arrow denotes location of terrace scarp. Photograph taken May 9, 1977.

land-use activities accelerate erosion depends primarily on the extent and degree of vegetal disruption.

The body of the matrix contains order-of-magnitude "erosional impact ratings" that represent the products of the three sets of factors. Each rating is intended to approximate the average annual production of sediment resulting from application of the specified land use on the identified type of terrain. The estimated production values range from $<10^3$ to $>10^3$ tons per acre per year (tons/acre/yr) ($\sim<10^3-{>}10^3$ t/hm^2/yr).

In the matrix, the four geologic groups on the horizontal axis are identical to those used to define the erosional-depositional provinces on plate 1. In contrast, the matrix includes six slope-gradient intervals rather than the two intervals (≤ 12 and >12 percent) used in delineating the provinces in plate 1. Thus, in areas having detailed slope data, the matrix provides a means for making better site-specific estimates of sediment production than are possible from the regional scale (1:130,000) map. The 20 individual land-use activities on the vertical axis were selected on the basis of their prevalence and socioeconomic importance in the basin. As shown in table 7, the 20 activities compose five major categories of land use. The rationale for developing the erosional factors and impact ratings is based on the concept that order-of-magnitude differences in annual sediment production can be attributed to distinctive couplings of climate, terrain, and land use. The basis of the concept and the data used to formulate the matrix are contained in several publications but most importantly in those by Ursic and Dendy (1965), Wolman (1967), Judson (1968), and Robinson (1973). The type of information available from these papers is illustrated in figures 24 and 25.

In formulating the matrix, the following process was used to develop the order-of-magnitude factors:

1. A "standard" Willamette basin climatic, terrain, land-use condition was established. The

FIGURE 23.—View northwesterly along the Molalla River north of the town of Molalla showing terrain typical of the valley flood plain province (V_1). Photograph taken May 9, 1977.

purpose of the "standard" was to define a quantitative beginning point around which the matrix could be expanded. The defined "standard" condition has the following properties: (a) climate—temperate, marine west coast with sustained low intensity rainfall and annual precipitation averaging 35 to 80 in (890 to 2,030 mm), (b) terrain—permeable, moderately erodible clay loam soil on a slope of 7 to 12 percent, (c) land use—agricultural row crops.

2. Based on the "standard" condition, values were assigned to the empirical coefficients of the Universal Soil Loss Equation (Musgrave, 1947; Chow, 1964) presented below. An "erosional-impact rating" (equivalent to A in the equation) of 10° was established for the "standard."

$$A = RKLSCP$$

where A = average annual soil loss, in tons per acre,
R = rainfall coefficient,

TABLE 6.—*Matrix for estimating interactive erosional impact of land-use activities with terrain properties of geology and slope, Molalla River basin, Oreg.*

[Unshaded box] Ratings of 10^{-2} or less reflect low erosional impact. [Light shading] Ratings from 10^{-1} to 10^{1} reflect moderate erosional impact. [Dark shading] Ratings of 10^{2} or greater reflect major erosional impact.

Land-use activity	Land-use–erosional factor[3]										
Slope (percent)		0–3	3–7	7–12		12–20		20–60		>60	
Slope-erosional factor		10^{-2}	10^{-1}	10^{0}		10^{1}		10^{2}		10^{3}	
Geologic group[1]		V_1/V_2	V_2/I_1	C_1	V_2/I_1	C_2	I_2	C_2	I_2	C_2	I_2
Geologic-erosional factor		10^{0}	10^{0}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{-1}	10^{0}
Product[2]		10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}
		Erosional-impact rating[4]									
Mature forest	10^{-3}	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}
Managed silviculture or nursery	10^{-3}	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}
Forest regrowth or mixed woods and shrubs	10^{-2}	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}
Helicopter or balloon logging	10^{-2}	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}
Metropolitan (developed)	10^{-2}	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}
Orchard with ground cover	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}
Pasture or grassland (light grazing)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}
Semirural (developed with light farming)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}
Paved roads (well maintained)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}
Cable logging	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}
Powerlines (dirt maintenance road)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}
Cropland	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}
Orchard without ground cover	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}
Pasture or grassland (heavy grazing)	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}
Gravel roads	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}
Tractor logging	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}
Fallow agricultural land	10^{1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}	10^{3}	$>10^{3}$
Light construction and excavation	10^{1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}	10^{3}	$>10^{3}$
Temporary dirt roads (poorly maintained)	10^{2}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}	10^{3}	$>10^{3}$	$>10^{3}$	$>10^{3}$
Heavy construction and excavation	10^{2}	10^{0}	10^{1}	10^{1}	10^{2}	10^{2}	10^{3}	10^{3}	$>10^{3}$	$>10^{3}$	$>10^{3}$

[1] V—Surficial, weakly coherent, alluvial deposits readily eroded by water. (V_1—≤3 percent slope; V_2—≤12 percent slope). I—Incompetent, or weakly coherent, bedrock such as shales and tuffs readily eroded by water and (or) prone to mass movement on steep slopes (I_1—≤12 percent slope; I_2—>12 percent slope). C—Competent, or strongly coherent, bedrock such as layered lava flow rocks and igneous intrusives not readily eroded by water, nor generally prone to mass movement except for rockslides and rockfalls from very steep slopes and cliffs (C_1—≤12 percent slope; C_2—>12 percent slope).

[2] Product of slope- and geologic-erosional factors.

[3] See table 7 for details.

[4] Ratings are the product of land use-, slope-, and geologic-erosional factors. The ratings roughly approximate the average annual order-of-magnitude sediment production in tons/acre/year.

K = soil-erodibility coefficient,
L = slope-length coefficient,
S = slope-steepness coefficient, and
C and P = coefficients related to land-use activity and conservation practice.

Coefficients for the equation have been developed from long experience with fluvial erosion of "test plots" in the South, Southeast, and Midwest United States. For application to the "standard" Willamette Basin condition, it was necessary to reduce the rainfall coefficient (R) (and thus A) by an order of magnitude. This was done to compensate for the mild sustained rains of the Willamette Basin that, although similar in average annual total, do not cause as much fluvial erosion as the intense thunderstorm-type precipitation experienced in most of the "test plot" regions.

3. Land-use activities (table 7) were grouped in an erosional-impact hierachy based on the relative tendency of each activity to disrupt natural vegetation and soil conditions. Each activity was assigned an order-of-mangitude "activity weighting factor" based upon (a) experience with the C and P coefficients of the Universal Soil Loss Equation and (b) sediment production and sediment yield data reported by the investigators listed in table 7.
4. For the slope increments of 0–3, 3–7, 7–12, and 12–20, the erosional-impact matrix was expanded about the 10^{0} "standard" by adjusting the S coefficient of the Universal Soil Loss Equation. The 20-percent slope represents the approximate upper limit of experience and utility of the equation. In the upper part of the 12–20 percent range, mass-wasting phenomena, rather than fluval erosion, begin to dominate in the climatic and vegetal regime of the Willamette Basin.
5. To estimate the increased erosional impact of

TABLE 7.—*Relative erosional-impact factors associated with selected land-use activities in the Molalla River basin, Oregon*

Land-use activity[1]	Land-use–erosional impact factor[2]	Remarks	References utilized in deriving land-use–erosional impact factor
Construction and excavation:			
Heavy—subdivision construction, commercial excavation, strip mining.	10^2	Construction activities remove vegetation, deeply disturb soils, artificially steepen slopes, and cause compaction and increased runoff. Of all land-use activities, construction activities are associated with the highest rates of erosion, although only for the period of the time during which construction is active. Mass wasting and fluvial erosion are both active.	Knott (1973); Guy (1970); Wolman (1967).
Light—single dwelling construction, gravel pit excavation, pipeline excavation.	10^1		
Urban:			
Metropolitan to suburban—dense residential, industrial, or commercial development with greater than 50 percent of the area impervious and sewered.	10^{-2}	Developed urban areas commonly have only minimal local erosion problems except when developments are located in steep terrain where mass wasting may be triggered. However, the imperviousness of urban areas causes increased runoff and flood peaks that can cause severe erosion down stream, particularly in stream channels. Because of the wide range of land-surface conditions prevailing with urban land use, erosion rates are perhaps more variable than for many of the other uses listed in this table.	Leopold (1968); Guy (1970); Knott (1973).
Semirural—scattered residences on large vegetated lots with less than 25 percent of area impervious and sewered.	10^{-1}		
Agricultural:			
Fallow (bare soil).	10^1	Fluvial erosion is the cause of most sediment production in agricultural areas, except on steeper lands (>12 percent) used for orchards and pasture where mass wasting may also be significant in areas of incompetent rock and unstable soils.	Ursic and Dendy (1965); Wolman (1967); Robinson (1973).
Cropland (row crops).	10^0		
Orchard, without ground cover crop.	10^0		
Orchard with ground-cover crop.	10^{-1}		
Pasture or grasslands (heavy grazing).	10^0		
Pasture or grasslands (light grazing).	10^{-1}		
Forestry and logging:			
Ten-year-old regrowth or mixed woods and shrubs (old logging roads partially overgrown).	10^{-2}	Logging activities remove vegetation, disturb soils, artificially steepen slopes, and cause compaction in areas worked by tractors. Where logs are skidded, soil is laid bare, compacted, and channels formed for rapid runoff. Roads are the most disruptive of all logging practices, particularly in areas of incompetent rock and unstable soils. (Note that the estimated impact factors for forestry practices are significantly lower than for construction. This apparent anomaly is due to our assumption, for comparative purposes, of a standard 7–12-percent slope.) Most logging activities occur on slopes between 20 and 60 percent and consequently cause greater impacts per unit area than indicated here. (See table 6.)	Ursic and Dendy (1965); Dyrness (1976); Fredricksen (1970); Megahan and Kidd (1972); Kidd and Kochenderfer (1973).
Mature forest (no roads).	10^{-3}		
Managed silviculture, mature nursery.	10^{-3}		
Tractor logging (10–20 lineal mi/mi² of logging roads).	10^0		
Cable logging (1–4 lineal mi/mi² of logging roads).	10^{-1}		
Helicopter or balloon logging (1 lineal mi/mi²) of logging roads).	10^{-2}		

mass-wasting phenomena on slopes >12 percent, weighting factors of 10^1, 10^2, and 10^3 were assigned, respectively to the slope intervals of 12–20, 20–60, and >60 percent.

6. On the basis of empirical observation and professional judgment, the geologic units defined on plate 1 were ranked as to their susceptibility to mass wasting. Order-of-

TABLE 7.—*Relative erosional-impact factors associated with selected land-use activities in the Molalla River basin, Oregon—Continued*

Land-use activity[1]	Land-use—erosional impact factor[2]	Remarks	References utilized in deriving land-use—erosional impact factor
Roads:			
Temporary dirt roads (no improved drainage or maintenance).	10^2	Because of the increased runoff from paved or compacted road surfaces and artificially steepened slopes associated with cuts, roads and peripheral rights of way are prone to high rates of erosion. Mass wasting is prevalent along cuts, and sheet and rill erosion is common on exposed, steepened cut-and-fill slopes. Roads with good maintenance and drainage may have significantly lower impact factors than shown here.	Fredricksen (1970); Kidd and Kochenderfer (1973); Sommer (1973); Megahan and Kidd (1972).
Gravel roads (some drainage and maintenance).	10^0		
Paved roads (substantial drainage and maintenance).	10^{-1}		
Powerlines (utility road along ridge lines, minimal cut and fill).	10^{-1}		

[1]Land-use activities were chosen on the basis of their prevalence and economic and social importance in the basin.
[2]For comparative purposes, factors have been adjusted to reflect a "standard" terrain condition (see text for discussion). The factors are intended to summarize the relative erosional impact of different land-use activities.

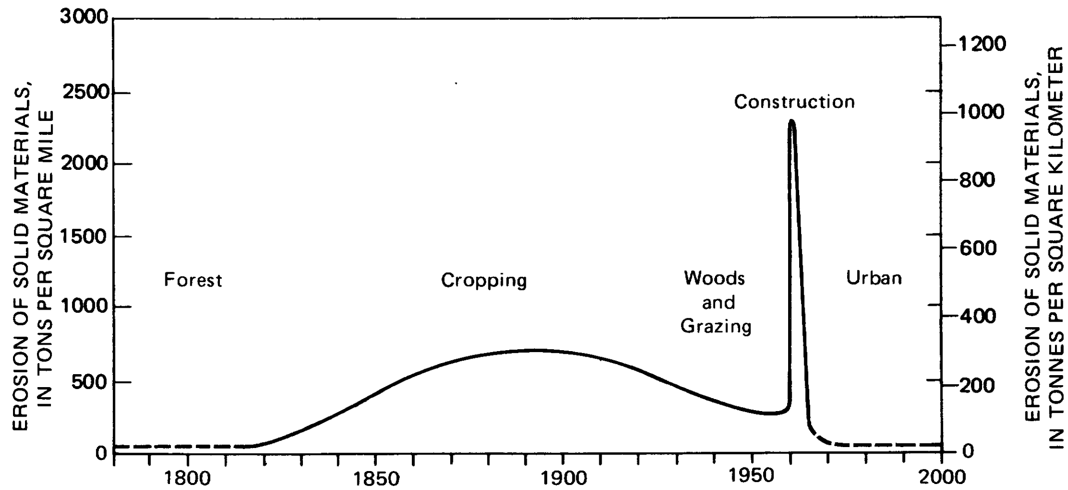


FIGURE 24.—Sequence of land-use changes and sediment yields beginning prior to the advent of extensive farming and continuing through a period of construction and subsequent urban landscape. Based on experience in the Middle Atlantic region of the United States. (After Wolman, 1967.)

magnitude weighting factors were assigned as shown on the horizontal axis of the matrix.

7. The weighting factors for slope, geology, and land use were multiplied, and the calculated "erosional-impact ratings" were placed in the appropriate position in the matrix body.
8. Finally, the matrix was checked for internal consistency and "fine tuned" to be compatible with results of sediment production and yield data in the Pacific Northwest. The yield data used to develop values reported in table 7 were gleaned from studies (see references, table 7) on small drainage basins and, therefore, should closely approximate sediment production values. Because the ratings are reported as order of magnitude, this estimation process should produce useful qualitative data.

The erosional-impact matrix presented in table 6 is, thus, the intergrated result of reported data, empirical observation, and professional judgment. The ratings must be considered as approximations rather than exact numbers that are

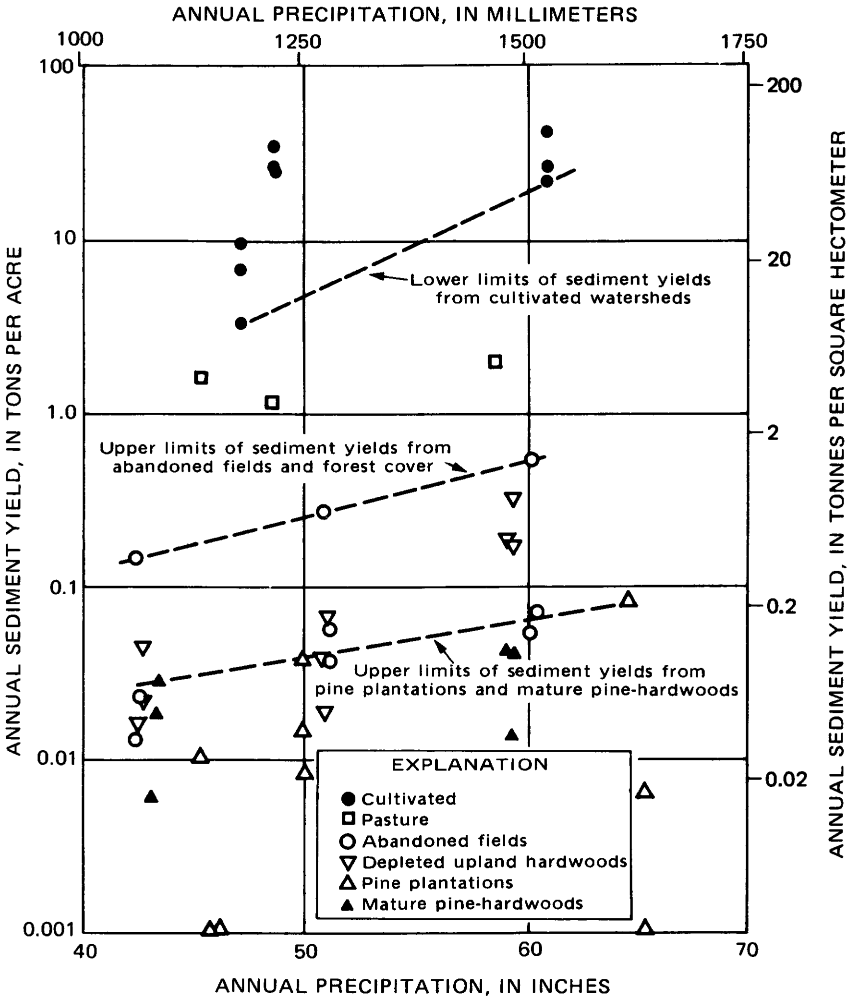


FIGURE 25.—Sediment yields from small watersheds in northern Mississippi under various land-use and precipitation regimens. (Adapted from Ursic and Dendy, 1965.)

rigorously quantifiable and verifiable. However, their rough equivalency with the notion of "sediment production potential" gives the ratings a meaningful conceptual and empirical basis not possible with an arbitrary ranking scheme.

APPLICATION TO PLANNING

In conjunction with the erosional-depositional province map, the completed matrix provides a means for making tentative estimates of the erosional impact of human activities on various lands in the basin. The following sequence of steps provides a guide for using the map and matrix:

1. Locate the parcel of land for which a particular land-use activity, or set of activities, has been proposed.
2. Identify the province in which the proposed activity would occur and examine the prevailing patterns of land-use activities and erosional features. The existence, or absence, of erosional features and their type will indicate to some degree the possible magnitude of erosional impact in terms of land deformation that would be generated by the proposed change in land-use activity.
3. Note the prevailing geologic and slope conditions for the area in question by cross referencing (a) the province (for example, I_2) within which the parcel of land is enclosed

with (b) the geologic and slope criteria shown in table 6.

4. Enter the matrix body under the specified combination of slope, geology, and land-use activity. Note the appropriate erosional-impact number or range of numbers. An impact rated below 10^{-1} indicates minimal potential for erosion. Impacts in the 10^{-1} to 10^{1} range indicate that moderate to high erosion could be generated and hence that management (conservation) practices may be required. Impact ratings of $>10^{2}$ indicate that high to extraordinary erosional impacts are likely to be generated and that the proposed land-use activity should be questioned.

The erosional-impact ratings in table 6 were developed as guidelines for regional planning purposes. High impact ratings do not necessarily mean that a proposed land-use cannot be reasonably undertaken provided stringent conservation and engineering practices are applied. Final judgments as to land-use suitability, particularly for lands receiving ratings of above 10^{1}, should be based on detail site investigations.

CONCLUSIONS

USE OF THE MAP AND MATRIX TOOLS

The erosional province map and impact matrix were initially developed as tools for land-use planning. However, these tools also provide a practical framework for the (1) selection of land-management activities to protect stream quality in accordance with Section 208 of Public Law 92–500 (Federal Water Pollution Control Act Amendments of 1972) and (2) development of improved data-collection systems for defining the relationships of human activities to land and water quality.

With regard to Public Law 92–500, Oregon is presently using the approach described in this circular for conducting a statewide 208 assessment of land-management activities. Over a 2-year period, erosional-depositional province maps will be prepared for selected critical basins in the various physiographic regions of the State. Once completed, the tools will guide the selection and application of activities on each type of terrain in each region. Then, over time, the effectiveness of applied activities will be monitored through interpretation of updated aerial imagery and the collation of new stream-quality data.

As a basis for designing data-collection programs, the map and matrix serve to show where erosional and depositional problems are most prevalent and also where new problems are most likely to occur. Areas mapped as having severe erosional problems will probably be prominent sources of land-runoff pollution. In such areas, sediment will commonly be the major water-quality concern. In addition, plant nutrients, pesticides, and metals will also tend to move into streams by virtue of their attachment to sediment particles. Thus, by using a province map, data programs can be spatially designed to better define the cause-effect relationships of land and water quality. Moreover, an erosional-impact matrix provides helpful collaborative information for selecting baseline and other comparative areas. Once the spatial framework of a data program is defined, the optimum timing and frequency of sampling can be readily determined through analysis of climatic and streamflow records.

Thus, the erosional-potential map and matrix are useful tools for (1) immediate land-use planning, (2) the selection and monitoring of land-management activities, and (3) the design of data-collection programs to assess land and water quality. For all three purposes, the tools are flexible, because through interpretation of aerial photographs, they can be regularly updated to provide information under rapidly changing conditions.

MODIFICATION AND FUTURE DEVELOPMENT OF THE EROSION-POTENTIAL CONCEPT

MODIFICATION

As noted in the factor section on "Soils," the soils of the Molalla River basin lowlands could be categorized into groups that reflect relative susceptibilities to erosion. Such a grouping of lowland soils was not pursued in this study, because the described province concept treats the lowlands as depositional areas and thereby deemphasizes concern about erosion.

In future basin studies, it might be desirable to modify the province concept to accommodate the delineation of relative erosion potentials within the lowland areas. The modification would require that the province concept be changed from one which emphasized the separation of erosional and depositional areas to one which emphasized the relative ranking of erosion potential throughout each basin. The envisioned procedure would still begin with a precursory landform analysis to separate uplands from lowlands. The second step would be the development of working hypotheses for the five environmental factors of climate, topography, geology, soils, and vegetation to identify relevant erosional provinces in the uplands, and then the development of a similar set of hypotheses to identify erosional provinces in the lowlands.

The initial division of a basin into uplands and lowlands is deemed necessary because the five environmental factors assume different degrees of importance in the two types of terrain. For example, in upland areas where slopes commonly exceed 20 percent, the effect on erosion potential of slight to moderate differences in the physical and chemical properties of soils would probably be overwhelmed by areal differences in slope. In contrast, in the lowlands where slope gradients are low, differences in soil characteristics may be the primary determinant of the relative erosion potential of different areas.

In summary, we are suggesting for basins having large areas of lowlands that the framework developed in this study be modified from an erosional and depositional province concept to a relative erosion-potential concept which treats uplands and lowlands in a separate but similar manner.

FUTURE DEVELOPMENT

At present, resource analysts critically need a unified interpretive framework for analyzing and explaining watershed-erosion problems. Such a framework is needed to provide (1) a means for understanding and quantifying the amounts, sizes, timing, and spatial distribution of sediments that enter stream systems and (2) a better explanatory context for the detailed synoptic observations now available from remote-sensing imagery. The authors believe the concepts developed in this report provide the beginning for such an interpretive framework. However, we recognize that much work will be needed to mold the concepts into a framework that is readily applicable to all types of terrain and all categories of land use. Several of the authors are presently working to improve and generalize the erosional-impact matrix. The immediate goal is to couple the matrix with a climatic-hydrologic classification scheme so it can be quickly applied to virtually any watershed of interest. A long term goal is the development of a more refined and universal watershed-erosion classification scheme that would incorporate detailed descriptions of climatic, terrain, and land-use factors in a seasonal (rather than average annual) time frame.

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SUPPLEMENTAL INFORMATION

AERIAL IMAGERY

In 1966, the Earth Resources Observation System (EROS) Program was conceived as an experiment in gathering and disseminating earth-resources information from high-altitude aircraft and satellites. The program was initiated by the National Aeronautics and Space Administration (NASA), with the cooperation of the Department of the Interior, certain Federal research agencies, and several colleges and universities.

In 1973, the U.S. Geological Survey and Oregon State University (within the framework of the EROS Program) negotiated with NASA for high-altitude photography of the Willamette River basin. The NASA-Ames Research Center, Moffett Field, Calif., made the flights using the Lockheed U–2 on July 3, 17, and 26. Details of the flights, including flight line locations are available on request from the U.S. Geological Survey, Portland, Oreg.

During each of the three flights, all or part of the Willamette River basin was photographed by two cameras from an altitude of 65,000 ft. (19,800 m) above mean sea level (msl). One camera, having a lens focal length of 6 in (15 cm), obtained 9 × 9 in (23 × 23 cm) transparencies on a continuous film strip. The images provided stereoscopic coverage (60 percent overlap) at an approximate scale of 1:300,000 of the Willamette River basin. The second camera, having a lens forcal length of 24 in (61 cm), obtained 9 × 18-in (23 × 46-cm) transparencies on a continuous film strip of the Willamette River. These images provided coverage at an approximate scale of 1:32,500.

Presently the imagery is on file at the U.S. Geological Survey office in Portland, Oreg.; the ERSAL office, Oregon State University, Corvallis; the NASA-Ames office, Moffett Field, Calif.; and the EROS Data Center, Sioux Falls, S. Dak.

During the present study, the imagery served two primary purposes: (1) Color IR imagery at both the 1:32,500 and 1:130,000 scales was used to identify or map erosional-depositional features, terrain properties, and land-use patterns, and (2) black and white imagery at the 1:130,000 scale was used to construct semicontrolled photomosaic base maps of the Molalla (plate 1) and Willamette River basins (Vickers and others, 1975; Rickert and others, 1976). The interpretive use of the color IR imagery is described below.

INTERPRETATION AND MAPPING OF EROSIONAL AND DEPOSITIONAL FEATURES

PROPERTIES OF THE COLOR IR IMAGERY

The imagery obtained for the Willamette River basin represented a special band of 510–900 nanometers on Kodak Aerochrome Infrared, Type 2443 film, a modified version of Type 8443[1]. With respect to the mapping of erosional-depositional features, the false-color IR, stereoscopically paired, vertical aerial images have the following important properties:

1. Any part of the land surface that is barren of vegetation contrasts sharply with vegetated terrain. In general, bare soils and rocks, such as those exposed on gully walls or on landslide scarps, appear as white or gray patterns in a field of red (representing the vegetation).
2. The distinctions among various features were readily apparent because of the extraordinary resolution of the imagery. Many of the mapped features were verified by field checks on the ground and by observations from low-altitude, light aircraft. These checks showed that the quality of the images was sufficient to assure a high level of confidence in the identification of a feature.
3. Identification of features was further enhanced by the format of the film. Sufficient overlap (60 percent) and sidelap (30 percent) provided on the continuous-strip imagery allowed different views of the same feature. The ability to move rapidly from one point to another on the strip was also beneficial for comparative purposes.

CHOICE AND ASSESSMENT OF FEATURES

Erosional and depositional features for the Molalla River basin were chosen primarily on the basis of an intensive review of the 1:130,000-scale color IR images taken on July 3, 1973. Each of the images was analyzed in detail, and descriptive notes were made regarding erosional-depositional features and processes, land-use associations, vegetation patterns, and a variety of related items. In addition to providing an identification of erosional-depositional features, the analysis

[1] Use of commercial names is this report is for descriptive purposes only and does not constitute an endorsement of products by the U.S. Geological Survey.

served to develop a general understanding of basin-wide land-surface forms and processes.

On the basis of the review and from staff discussions, 10 features were finally selected for mapping on plate 1. The following restrictions apply to the interpretation and mapping of the features:

1. The small set of generalized features was chosen in order that the mapping would be reasonably compatible with the 1:130,000-scale photomosaic base and that excessive clutter could be avoided. That is, the features were generalized in an effort to add simplicity to the explanation and use of the map.
2. Only those features were mapped that could be perceived by the analyst's unaided eye on the 1:130,000-scale color IR imagery. Once a feature was detected, its identity, magnitude, and degree of activity was stereoscopically verified by higher magnification of the IR imagery, and sometimes by field checking. Commonly, sites where erosional and depositional features occurred were too closely spaced to be mapped exactly at the selected regional scale. For local studies, more detailed investigations at each site are suggested.
3. In general, the minimum size of the mapped features is on the order of 2,500 ft^2 (230 m^2). However, the identification of features is based upon factors other than size. For example, gullies may be readily resolved because of their "linear" character. Similarly, sheet and rill erosion surfaces can be inferred from the white, "galled" spots evident on the color IR photographs.
4. The features were mapped to indicate the dominant process at each site. However, at many sites, more than one process may be active. For example, a gully may be superimposed on a landslide deposit, or an artificial fill may be superimposed on a marshland.
5. Some of the mapped sites were transitional; that is, a site of erosion during a given year might be obliterated or changed by natural or artificial means by the next year. Therefore, the mapped sites pertain only to the study period, June 1973–June 1974, and do not reflect changes since June 1974. However, some of the mapped types of erosional and depositional features remain active over a period of years and many are probably still active (1979).