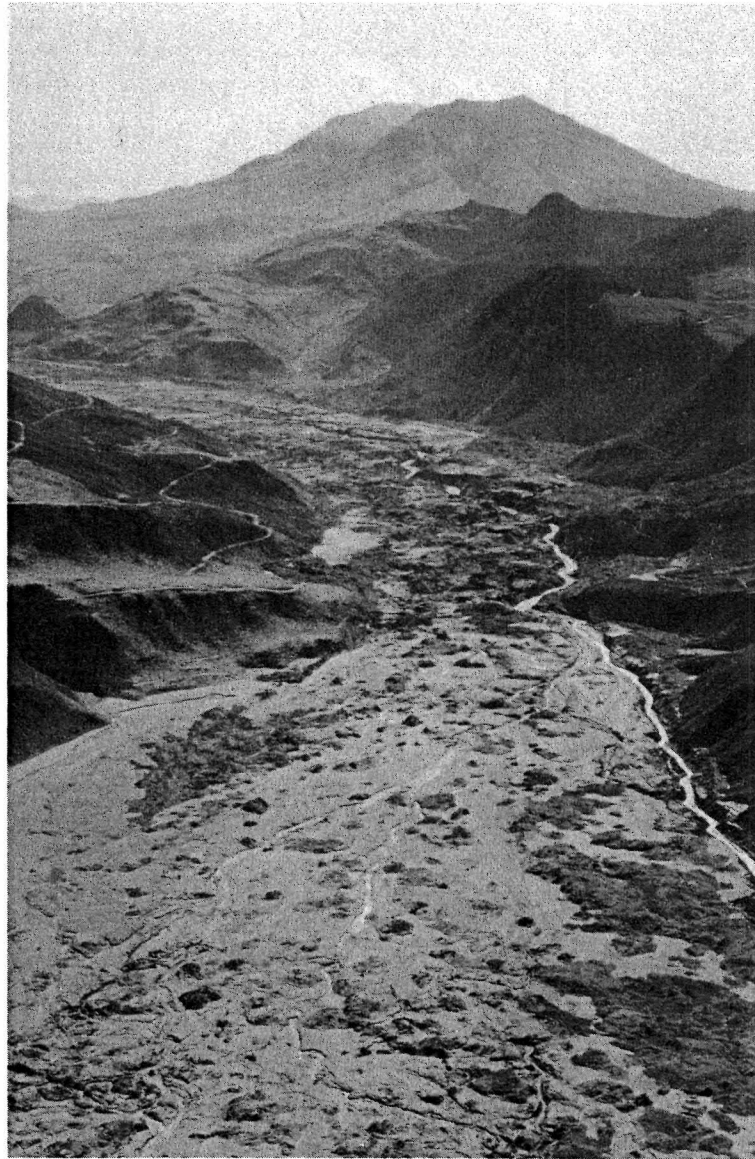


**Evolution of a Drainage Network:  
Remote Sensing Analysis of the North Fork Toutle River,  
Mount St. Helens, Washington**

by

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## ABSTRACT

The May 18, 1980 eruption of Mt. St. Helens and subsequent volcanic events inundated the upper 18 km of the North Fork Toutle River valley with a large ( $2.5 \times 10^9 \text{m}^3$ ) debris avalanche and several smaller pyroclastic flows and mudflows. The resultant hydrologic disruptions included displacement of the Spirit Lake basin and subsequent blockage of the lake at an elevation more than 60 m higher than its pre-eruption level; blockage of the major tributaries of the North Fork Toutle River resulting in new lake impoundments; and emplacement of a large hummocky debris avalanche deposit with numerous detention basins in the valley bottom. Additionally, the initial dewatering of the debris avalanche caused a fluid mudflow ( $12 \times 10^6 \text{m}^3$ ) that flooded along the lower Toutle and Cowlitz River valleys.

This project provided aerial surveillance, mapping and evaluation of the hydrologic conditions in the upper reaches of the North Fork Toutle River valley from October 1981 until January 1983. The purpose of the work was to assess the rate and mode of erosional and depositional development, and evaluate the potential for the occurrence of catastrophic events. During this period, major drainage network development occurred, and geomorphic trends of this evolutionary development were studied. A series of detailed hydrologic status maps were produced at a scale of 1:24,000 to depict the surface channel networks, major detention basins, and the location of mass movement areas and fluvial terraces.

A total of six interpretative maps were produced. The date of the first map was 13 October 1981. The dates selected for the subsequent maps were 24 November 1981, 11 and 16 December 1981, 06 February 1982, 05 March 1982, and 13 October 1982. These maps were specifically designed to illustrate the location, pattern, and density of fluvial and geomorphic features such that the maps could be examined either individually or through comparative analyses of two or more maps.

Examination of the maps reveals that significant hydrographic changes occurred following each storm event. The development and headward migration of gullies and streams progressed rapidly throughout the study area during the winter observation period (November 1981 to March 1982). Numerous outbreaks of ponds and lakes occurred within this time frame. Along the main stem of the North Fork Toutle River, a change from aggradational to degradational processes occurred during the summer months of 1982. Individual segments of the channel, however, appeared to defy this broad generalization as sections of the channel responded to mass movement occurrences, rate of discharge and erosional/depositional patterns. The most significant changes affecting the evolution of the drainage network occurred in February 1982. A series of high-intensity, long-duration storm events culminated on 20 February with the inundation of Jackson Lake, a resulting flood surge downriver, and the failure of the spillway located on the northern sediment retention dam.

The information provided by this project has yielded not only a visual assessment of the various temporal and spatial changes that can occur within a relatively short period of time, but an indication of the rates by which a pristine channel network can evolve. As such, the map products have provided valuable insights to planning and management officials concerned with the rates of landform change as well as the potential for future hydrologic hazards.

## FOREWORD

The Water Resources Research Institute, located on the Oregon State University campus, serves the State of Oregon. The Institute fosters, encourages and facilitates water resources research and education involving all aspects of the quality and quantity of water available for beneficial use. The Institute administers and coordinates statewide and regional programs of multidisciplinary research in water and related land resources. The Institute provides a necessary communications and coordination link between the agencies of local, state and federal government, as well as the private sector, and the broad research community at universities in the state on matters of water-related research. The Institute also coordinates the inter-disciplinary program of graduate education in water resources at Oregon State University.

It is Institute policy to make available the results of significant water-related research conducted in Oregon's universities and colleges. The Institute neither endorses nor rejects the findings of the authors of such research. It does recommend careful consideration of the accumulated facts by those concerned with the solution of water-related problems.

## ACKNOWLEDGEMENTS

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Members of the Oregon Army National Guard routinely flew low-altitude photographic missions over the study area. The imagery products derived from these missions was provided without charge and formed the basis by which the remote sensing analysis described in this report was conducted. Their imagery support for this project is gratefully acknowledged.

As several large-scale mapping projects exist within the Mount St. Helens impact zone, a coordination and cooperative effort was established between this project and the Water Resources Division of the U.S. Geological Survey. In particular, we extend our thanks and appreciation to Dr. Richard J. Janda for his support and encouragement.

Remote sensing interpretation and analysis of the acquired imagery was completed using the facilities of the Geographic Applications Laboratory located in the Geography Department of Oregon State University (OSU). David Welt of the OSU Cartographic Service provided immeasurable assistance in producing contact positive prints of the imagery as it arrived in negative strip rolls, furnishing competent cartographic advice and support, and supervising map reproduction.

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EVOLUTION OF A DRAINAGE NETWORK:  
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1. INTRODUCTION

Initial Justification

On May 18, 1980, Mt. St. Helens erupted explosively, blasting away the north flank of the mountain and clogging the North Fork Toutle River headwaters with an enormous debris avalanche. This debris avalanche, or hummocky lahar, filled the upper 18 km (11 mi) of the valley with an estimated 2.5 billion cubic meters of rock, ice, and organic debris. Spirit Lake was inundated by one lobe of the debris avalanche and its level was raised by approximately 60 m (200 ft). Within hours, entrained groundwater and melting ice liquified a portion of the fines on the surface of the debris avalanche and caused a major mudflow which yielded almost 12 million cubic meters of material to the lower Toutle and Cowlitz valleys. Considerable property damage in the valleys ensued in the process. The main valley lobe dammed several of the major tributary streams, causing lakes to form at the junctions of Coldwater, Castle, and Jackson Creeks. These lakes were filled quickly by runoff from rainfall producing storm events. As the channels along the lateral margins of the main lobe eroded, the new impounded lakes threatened to breach and cause extensive outburst flooding. In addition to these potential problems, rapid fluvial erosion of the main lobe was causing extensive sediment management problems downstream. As a result of these rapid developments, the U.S. Army Corps of Engineers embarked on a multifaceted sediment management plan along the lower Toutle and Cowlitz valleys, which included dredging, channel enlargement, levee construction, and the erection of two sediment retaining structures (U.S. Army Corps of Engineers, 1981a and 1981b).

Even as these corrective measures were being implemented, further modifications and physical adjustments to the impacted terrain surface continued to take place. For example, in December 1980 warm rains melted the snow accumulated higher in the basin and caused several small ponds and lakes to outburst. The cumulative effect yielded a flow event which rapidly eroded through the spillway of the sediment retaining structure that had been built across the upper North Fork Toutle River, and caused additional damage to the valley below. By the end of 1980, erosion had removed over 30 million cubic meters of sediment from the surface of the debris avalanche, mainly through the extension of the channel network. The rate at which the network was enlarging suggested that annual sediment yields of 20 to 40 million cubic meters should be expected until the basin reaches hydrologic equilibrium. Additionally, the major lakes produced by the avalanche blockage were approaching critical elevations and threatening to breach into the drainage network.

These rapidly changing hydrologic characteristics suggested the desirability of establishing a program to monitor the progressive changes. Hence, this mapping program was initiated. Through the facilities of the Geography Department at Oregon State University, maps were prepared from a variety of aerial photographic sources, and reproduced for distribution to concerned agencies and institutions.

### Potential Downstream Effects

Of immediate concern to all management and relief agencies was the potential for renewed mudflows or catastrophic flooding resulting from either meteorologic, volcanic, or depression outburst events; or more likely, a combination of the above causes. Agency programs focused upon climate and snowpack monitoring as well as volcanic

hazard prediction, while this project concentrated upon the hydrologic routing of potential flood waters in the upper reaches of the North Fork Toutle River.

The following chapters of this report focus upon the identification of problem areas and observed hydro-morphologic changes within the study area. However, because of the major threat to downstream reaches, it must be recognized that the results of this investigation can also be interpreted with regard to potential downstream effects. Three potentially critical downstream conditions were envisioned during the initial research design:

1. rapid increases in discharge from the headwater areas could result in overbank flows along the lower Toutle and Cowlitz valleys;
- 2) viscous mudflow events could cause channel blockage and upon breakup of the blockage, subsequent flash flooding along the Toutle valley; and
- 3) fluid mudflow events could cause rapid channel sedimentation as far as the Columbia River navigation channel, and a considerable loss of channel capacity along the lower Toutle and Cowlitz River valleys.

Estimates of cumulative flood losses by inundation and floodway destruction were prepared by the Federal Emergency Management Agency and the U.S. Geological Survey Water Resources Division. Additionally, constriction and siltation of the Columbia River navigation channel was studied by the U.S. Army Corps of Engineers. The total cost of potential downstream hazards exceeded one billion dollars. Therefore, an analysis of the hydrodynamic trends and tendencies of the erosional developments in the upper reaches of the North Fork Toutle River basin has significant implications with regard to the type and magnitude of potential downstream impacts. The nature, scale, detail, and timing of data produced by this study were designed to meet some of these anticipated needs.



## 2. STUDY AREA

### Selection of the Study Area Boundary

When this project was initiated, selection of the study area boundary went through a sequence of developmental stages. The purpose of the project was to illustrate the successional changes of hydrologically related features in the impacted area of the upper North Fork Toutle River drainage basin resulting from the 18 May 1980 eruption of Mount St. Helens. Several factors were considered in determining the final study area boundary. Areas that were considered important for inclusion were:

- 1) the impact area between Mount St. Helens and Spirit Lake;
- 2) the upper watershed area immediately northwest of the volcanic crater;
- 3) the Castle Lake, Coldwater Lake, and Jackson Lake impoundment areas;
- 4) the South Coldwater Creek drainage system;
- 5) the main valley channel area of the North Fork Toutle River;  
and
- 6) the retention dam area immediately down-valley from the leading edge of the May 18th debris avalanche.

The study area boundary line finally selected was based on all of the above factors. For the most part, contour lines were used to approximate natural watershed boundary limits. In the western two-thirds of the study area, from a line drawn between Coldwater Lake and Castle Lake, the boundary line extended upslope one to two hundred meters from the impact zone. Thus, all the small lakes and small tributary streams formed or modified following the debris avalanche event were included. Contour lines were also used in the

upper one-third of the North Fork Toutle River such that, wherever feasible, a natural watershed boundary line was used; including the crest rim of the newly created Mount St. Helens crater. A dashed line was used to truncate Coldwater Lake and Spirit Lake since the most important areas of concern were the actual or potential lake outlet points. Finally, in completing the delineation of the study area boundary an arbitrary north-south line was drawn along the 122°30'W longitude line approximately 2.3 km (1.5 mi) west and immediately down-river from the sediment retention dams that had been constructed by the U.S. Army Corps of Engineers in the fall of 1980 (see interpretative maps, Appendix I).

#### Location and Description of the Study Area

The upper North Fork Toutle River study area is located in southwestern Washington approximately 75 km (47 mi) north-northeast of Vancouver, Washington (Fig. 1). Using a sonic digitizer, the total areal coverage of the project was computed to be 140 km<sup>2</sup> (54 mi<sup>2</sup>). The basic orientation of the study area is WNW-ESE, with the width ranging from 1.7 km (1.1 mi) near Elk Rock at its narrowest point, to a maximum width of 12.0 km (7.5 mi) extending along a line between the South Coldwater Creek drainage system east of Coldwater Lake to the southern rim of the Mount St. Helens crater. The mapping area has an approximate length of 29.5 km (18.3 mi). Elevations vary from 2,549 m (8,364 ft) at the crater rim, to 310 m (1,015 ft) at the western boundary line.



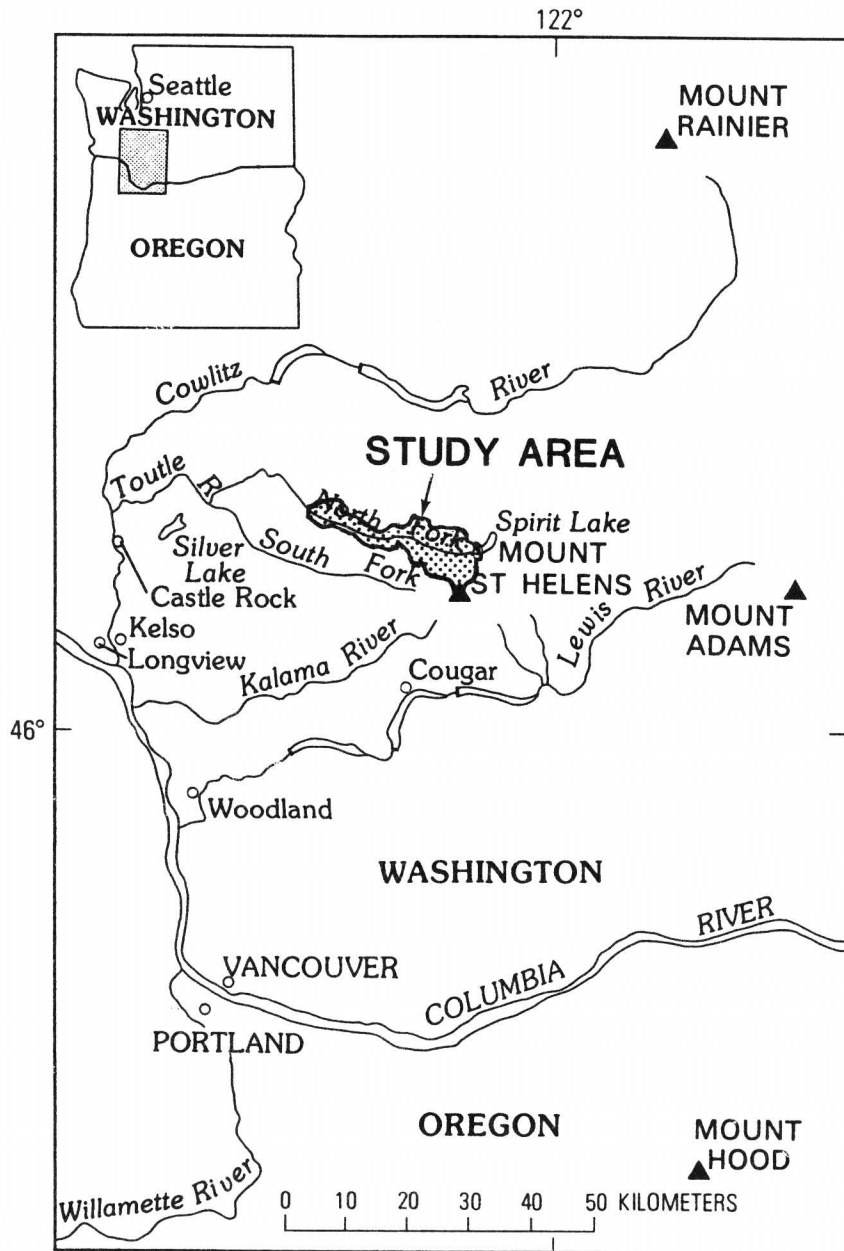


Figure 1. Geographic location of the North Fork Toutle River study area in southwestern Washington. (Adopted from Lipman and Mullineaux, 1981).

## Environmental Factors

### Climate

The climate of the study area is influenced by the barrier effects produced by the north-south orientation of the Cascade Range. The mountain range blocks or greatly modifies the westerly winds of marine air masses moving inland from the Pacific Ocean, and the easterly winds of continental air masses originating in the polar regions of Canada. Precipitation and temperature regimes are generally typical of a maritime climate associated with wet, relatively mild winters and dry, cool summers.

Mean annual precipitation ranges from approximately 2,030 mm (80 in) near the retention dams to over 3,550 mm (140 in) on the upper slopes of Mount St. Helens. The wet season begins in the fall, reaches a peak during the winter months (November-January), and then gradually decreases through spring. About 75 percent of the annual precipitation falls during the period October through March. July and August rainfall normally accounts for less than five percent of the annual precipitation (U.S. Forest Service, 1981).

Much of the annual precipitation in the study area occurs as snow. Snowpack increases with elevation such that the greatest amounts and longest duration periods occur above an elevation of 760 m (2,500 ft). The snow water content (i.e., water equivalency) ranges from 230 mm to 380 mm (9 in to 15 in). Under the treeless, post-eruptive conditions, snowpacks have generally had faster melt rates in the spring due to the almost total exposure to direct solar radiation. The presence of dense snowpacks has, in the past, contributed to the occasional occurrence of mudflows emanating from the crater or from the flanks of the volcano.

Below freezing temperatures occur on most nights between late October and early May. Temperature extremes, especially diurnal fluctuations, have probably been more severe because of the treeless, post-eruptive conditions. The climatically controlled activity of diurnal freeze-thaw events can therefore be viewed as one of the major erosional processes contributing to the downslope movement of sediment and the prevention of seedling establishment within the study area.

## Hydrology

The eruptive events of Mount St. Helens have significantly altered the hydrologic regime of the study area. Streams of the upper North Fork Toutle River drainage system are rapidly readjusting to the changes caused by the almost total devastation of all vegetative cover; especially to the now non-existent riparian cover. New channels have formed on the mudflow, debris flow, debris avalanche, and pyroclastic deposits. Hydrological modifications and adjustments have included the headward migration of gullies, stream capture, lake breaching, channel course changes, and extensive areas of channel braiding. These and other erosional and depositional processes can be expected to continue for decades until the channels readjust to the pre-eruption dynamic equilibrium status.

Severe bank and channel erosion can be expected to occur during the winter runoff season as flood waters erode and widen stream channels or create new channels around sites of debris concentrations, sediment accumulations, or man-made structures. The historic record shows that most of the peak flows occur between late November and early January during major rain-on-snow storm events. According to the Mount St. Helens Emergency Watershed Rehabilitation Report, more than 85 percent of the sediment yield will be from channel and gully

erosion processes during these critical winter months. The principal streams in the study area contributing to the growth, development, and sediment build-up of the North Fork Toutle River include: Coldwater, South Coldwater, Castle, Jackson, Maratta, Bear, Hoffstadt, and Deer Creeks.

In addition to the dramatic changes to the drainage systems, equally impressive changes have taken place with regard to the creation, maintenance, and destruction of lakes. As a direct result of the collapse of the north flank of the volcano, the water level of Spirit Lake was instantly raised by approximately 60 m (200 ft). The water level of Spirit Lake has continued to rise during the post-eruptive phase due to the blockage of its pre-eruptive drainage outlet. The Spirit Lake watershed is now a closed drainage basin.

The flow of debris and pyroclastic material down the North Fork Toutle River valley resulted in the formation of numerous new lakes and ponds. Two of these new lakes, Castle and Coldwater, have large inflow potentials but limited storage capacities. To prevent possible failure of these natural impoundments, the U.S. Army Corps of Engineers breached the lakes with spillways installed below the natural overtop elevations. Jackson Lake, at one time the fourth largest lake in the study area, was breached and almost totally drained in February 1982. This event was the direct result of the river undercutting a narrow debris blockage structure that had held back the water draining the Jackson Creek watershed. Dramatic changes and modifications such as these can be expected to continue into the near future, including the possible failure of the Spirit Lake debris dam blockage and a resulting catastrophic flood.

## Topography

The topography of the study area is typical of the Middle Cascade mountain range found in western Washington and Oregon. The platform upon which the younger volcanic cones rise, composed mainly of andesitic lavas and pyroclastic materials, is dominated by an uplifted accumulation of weathered basaltic flows. Much of the study area is characterized by ridge crests, separated by deep valleys with steep, moderately dissected sideslopes.

During the Pleistocene, mountain glaciers formed on Mount St. Helens and extended down the valleys for several kilometers. Although glacial features are in evidence, such as the U-shaped valley of upper Clearwater Creek and newly exposed morainal deposits, they do not constitute a pronounced set of features on the landscape. This evidence, coupled with the geologic record of frequent volcanic eruptions in the past 1,000 years (Crandell and Mullineaux, 1978), suggests that through the Pleistocene and Holocene periods modifications of the landforms by glacial erosion were either altered or buried as a result of frequent volcanic activity. A few alpine glaciers are still present on the upper slopes of Mount St. Helens, although the original source areas for most of these glaciers were removed during the catastrophic eruption of 1980.

The explosive eruption resulted in major landform changes not only to the shape of the mountain but to the surrounding terrain as well. Most of the topographic changes occurred to the area north of the mountain. The summit elevation of Mount St. Helens was lowered from 2,950 m (9,677 ft) to 2,549 m (8,364 ft), and a new crater, breached open to the north was formed (Lipman and Mullineaux, 1981, p. 134). Pyroclastic flow deposits now descend approximately 670 m (2,200 ft) from the crater floor to the broad, generally level pumice plain below. Inside the crater, a composite dacite dome has emerged from the volcanic vent and continues to grow with each new eruptive event.

The effects down-valley were no less dramatic. The massive debris avalanche and mudflow that followed the eruption raised the base level of the valley floor, dammed major tributaries, and created many new lakes. In other regions of the study area, instead of being destroyed, modified, or buried, topographic features such as rock outcrops and adjacent stream valleys long hidden by a dense fir forest cover were suddenly exposed to view and scientific examination. In short, rapid and dramatic changes to the assemblage of topographic features associated with the Mount St. Helens environment have become the norm rather than the exception.

## Geology and Geomorphology

Volcanic activity has dominated the bedrock development and geomorphic processes within the study area for thousands of years. Together, both endogenic and exogenic processes have left an indelible record on the landscape. Ancestral Mount St. Helens has produced numerous explosive eruptions as evidenced by outcrops of pumice layers, pyroclastic flow deposits, and mudflow deposits (Crandell and Mullineaux, 1978). However, the unprecedented and catastrophic failure of the northern flank on May 18, 1980, resulted in one of the largest mass movements in recorded history (Lipman and Mullineaux, 1981, p. 344).

Mount St. Helens is one of 15 major stratovolcanoes located within the physiographic province of the Cascade Range. Geologic and geomorphic evidence suggests that the mountain is one of the youngest, most active, and compositionally one of the most diverse of these major volcanoes. The level of volcanic activity appears to be tied to plate tectonics and is governed by the rate at which the Juan de Fuca plate is plunging under the North American plate at the subduction zone located off the Washington coast (Decker and Decker, 1981, p. 71; Lipman and Mullineaux, 1981, p. 120).

Preceded by a swarm of shallow earthquakes in March 1980, the volcano came to life following a dormant period that had lasted since 1857. As the level of seismic activity continued, tiltmeter measurements revealed the development of a summit graben (zone of downfaulting across the summit) accompanied by a bulge (uplift and expansion) on the high north flank of the mountain. At 8:32 PDT on May 18, 1980, a 5+ magnitude earthquake centered below the northern flank set into motion the devastating rockslide-debris avalanche in which 2.5-3 cubic kilometers of volcanic rock and glacier ice was displaced 25 km (15 mi) from the source area (Lipman and Mullineaux, 1981). The gravitational slide cascaded rapidly down the slope of the mountain before impacting Spirit Lake and moving into the North Fork Toutle River drainage system. Pyroclastic flow deposits in the upper half of the study area range from sheet-like masses to narrow, elongated tongues and lobes. Interspersed throughout this area are phreatic-explosion pits. These craters formed when hot pyroclastic flows and debris flows covered water in streams, ponds, and springs. Whenever and wherever water flashed to steam, an upward-directed explosion was produced.

Destructive lahars (mudflows) and debris flows commonly accompany pyroclastic eruptions on stratovolcanoes. The most voluminous lahar/debris flow originated by slumping and flowage of water-saturated hummocky deposits of the rockslide-debris avalanche in the upper North Fork Toutle River valley. West of the pyroclastic flow deposits, the U.S. Geological Survey has identified and mapped three principal depositional units (Lipman and Mullineaux, 1981). From the Pumice Plain to approximately Castle Lake, the "North Toutle" unit, designated (dn), consists of irregular hummocky debris and closed depressions, typically 20-70 m (65-230 ft) thick. This unit initially contained large blocks of glacier ice that have subsequently melted. Marginal levees are as high as 30 m (100 ft).

The next unit stretches from the Castle-Coldwater Lake area to approximately 1.6 km (1 mi) east-southeast of the present retention

dams. This "Mudflow" unit (dmf) is characterized by thin discontinuous mudflow deposits on the surface of the debris avalanche (dn). At the distal terminous of this unit, there are jumbled masses of wood debris incorporated into a matrix of organic rich soil. It is at this point that the true lahar emerged. The "Mudflow Deposits" unit (mf) extends beyond the western boundary of the study area. This unit was characterized by rapid movement, a higher water content ratio to the flow, and the commencement of a series of branching and coalescing channel networks in which numerous islands were left unaffected by the mudflow surge.

Upon this devastated, post-eruptive stage, a myriad of complex and interrelated geomorphic processes immediately began operating to further modify these landform features. For example, slope instability remains a major problem in the study area, especially in the upper reaches above the Elk Rock narrows. Various mass wasting processes have led to the downslope movement of debris material. This eroded and displaced material frequently impacts evolving drainage networks. These persistent and reoccurring types of mass movement have included; debris avalanches and debris flows, slump/earthflows, mudflows emanating from the crater or from the flanks of the mountain, and cutback and fillslope failures along existing or newly constructed roads. By far the most important mass wasting process, in terms of channel evolution and direct sediment production input to streams and rivers, is from bank failures caused by channel undercutting and/or groundwater sapping. The streams and rivers must continuously adjust to these massive inputs of sediment and debris. The capacity of the streams and rivers to remove the material can influence the rate of future fluvial erosion and mass movement events.

One of the most serious and pressing problems within the study area concerns our understanding of fluvial geomorphic processes. Hydrologic conditions are changing almost daily. Channel modifications involving aggradational and degradational processes ostensibly



appear to defy explanation. What is apparent is that within the upper North Fork Toutle River watershed, there is an annual sediment production cycle that is closely tied to periods of peak runoff. The greatest amount of erosion and sediment transport takes place following rainfall from winter storm events and during the spring snowmelt period. The magnitude and frequency of mass movement and fluvial erosional processes can be expected to continue at comparatively high levels for many more years, till such time that vegetation cover once again begins to help stabilize the area.

## Vegetation

Except for a few acres of vegetative cover located in the vicinity of the retention dams and along the side-slopes of the western study area boundary, all of the vegetation was destroyed by the various eruption processes. Douglas fir had been the predominant species found below 1,065 m (3,500 ft) elevation. This area of the Western Cascades is generally characteristic of the western hemlock zone in which western hemlock and western red cedar are considered to be the climax species (Franklin and Dyrness, 1973). While hardwoods did not represent a significant percentage of the total vegetative cover, alder, maple, willow, and cottonwood had been present along the banks of the larger streams.

As part of a watershed rehabilitation project, grass seeding and fertilizing was begun in the fall of 1980. Approximately 4,915 ha (12,150 ac) of impacted State and private lands were grass seeded and fertilized in the North Fork Toutle River drainage, including portions of the study area, by the U.S. Soil Conservation Service (SCS). The efforts have been met with only limited success. An evaluation by SCS in May, 1981 showed that only about 15 percent of

the seeded area had grass cover. The flight lines flown by the helicopters during this seeding project appear as linear bands on low-altitude air photos. These distinctively darker bands indicate where the vegetation cover has begun to take hold within the floodplain. Revegetation of riparian zones and side-slopes have been planned for the future.

Natural pioneer species have already begun the slow but inexorable process of reoccupying the devastated area. Successional patterns can only be estimated, however. Vegetation re-establishment will probably follow the grass, forb, shrub, deciduous tree, conifer tree sequence depending upon the site conditions, amount of surficial erosion and mass wasting processes taking place, and interventions by man. The establishment of trees will depend especially on site locations that are protected from unstable or adverse environmental elements. Once established, vegetation will then probably radiate outward from these source areas. Some areas can, nevertheless, be expected to remain barren and non-productive for a considerable period of time.

### Cultural Features

Although the study area has had only a few direct impacts by man since the May 18th eruption in 1980, several construction projects operate to change the hydro-morphologic processes at work within the study area. Several of the effects resulting from human intervention will be discussed later in the "Major Observations" section of this report. Discussion here will be limited to describing the principal cultural activities and resulting features that have in some way modified the configuration of the post-eruption landscape.

Until the summer of 1982, the only road in operation within the river valley was from the retention dam area along the western boundary line to approximately 122°22.5'W longitude (1.5 km west of Elk Rock). This road was built and used primarily by the U.S. Army Corps of Engineers in constructing the debris/sediment retention structures (designated DRS N-1) across the North Fork Toutle River immediately below the western most extension of the debris avalanche. A visitor parking area and viewing facility has subsequently been established at the base of the hill separating the two retention dam structures. During the late summer and early fall of 1982, a road was constructed that entered the study area from the east, then crossed the pumice plain to its termination point located atop the debris blockage of Spirit Lake. This temporary road (formerly USFS Road 100) was constructed to allow access of heavy equipment and supplies used by the U.S. Army Corps of Engineers to pump water from Spirit Lake. The location of these two roads appear on the 12 October 1982 map (see Appendix I). There is currently no direct access by road to Spirit Lake and the upper North Fork Toutle River debris avalanche from the Elk Rock area (approximately 122°22.5'W longitude).

Besides the two roads presently located within the river valley, and a few temporary roads constructed along the upslope margins of the study area by logging companies to salvage downed timber, the principal long-term modifications to the drainage system and the new landform assemblage have been made by the U.S. Army Corps of Engineers. The retention dams near the western boundary line were constructed to trap sediment in transport and thereby retard sediment buildup further downriver in the Toutle, Cowlitz, and Columbia River drainage systems. The pumping station and excavated trench located near the southwest corner of Spirit Lake were built in an effort to help lower the rapidly rising lake level (and thereby relieve the hydraulic pressure building on the tenuously empounded debris dam), as well as to prevent the possible collapse of the blockage area due to either piping or lake over-topping.

The final comment regarding cultural features concerns future modifications that are likely to occur within the study area. Since the establishment of the blast-area as the Mount St. Helens National Volcanic Monument, planning has been underway by the U.S. Forest Service, U.S. Geological Survey, and other federal and state agencies to provide a permanent visitor center within the impact zone. The proposed facility, replete with access road, parking area, building for displays, and restrooms is to be located at an appropriate location along Johnston Ridge. In addition, hiking trails, including one to Harry's Ridge overlooking and immediately west of Spirit Lake, are also to be constructed.

### 3. METHODOLOGY

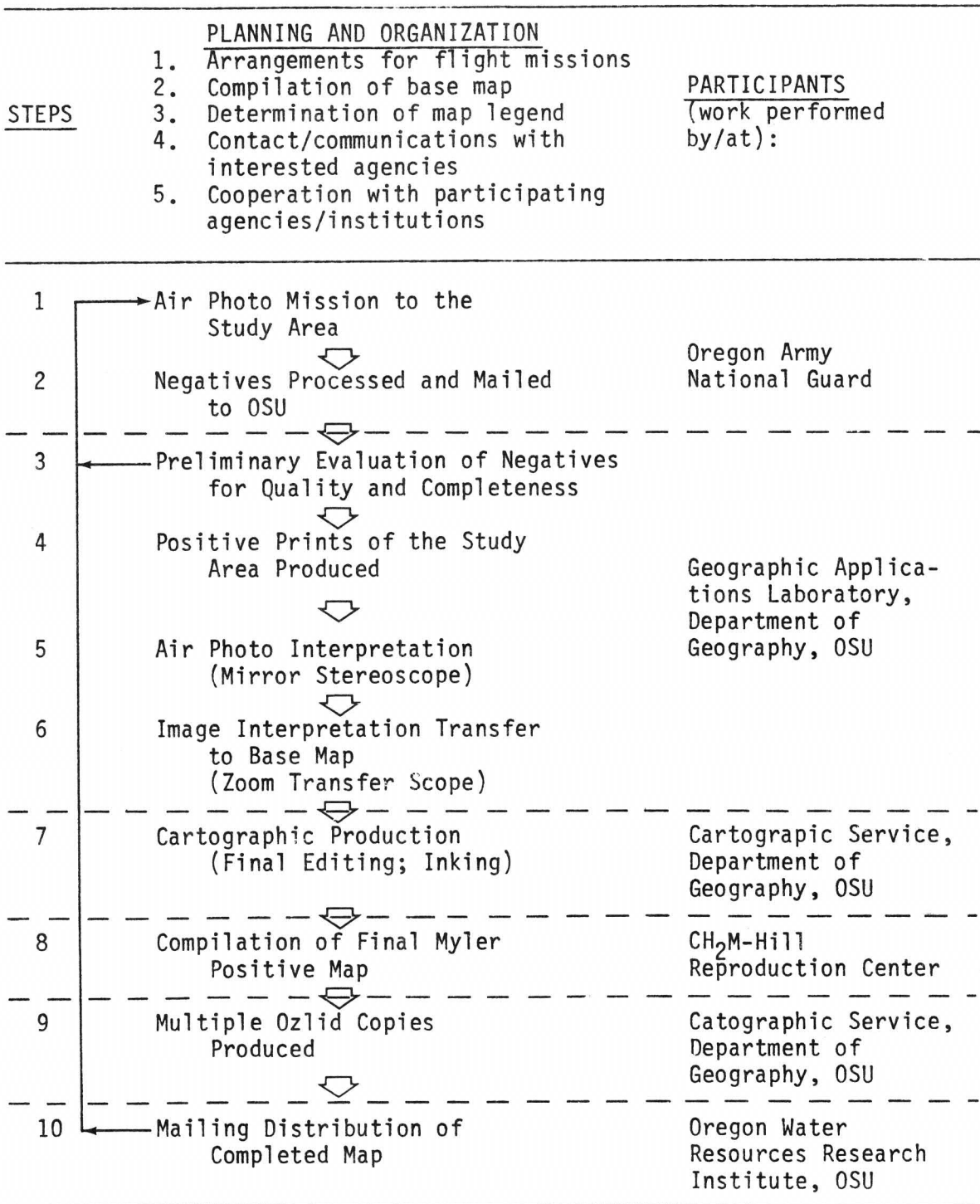
The purpose of this remote sensing project was to interpret, map, and analyze both the spatial and temporal changes that have occurred to the hydro-morphologic characteristics of the upper North Fork Toutle River drainage system. In order to accomplish these objectives, the project was divided into three chronological phases (Table 1). Phase one consisted principally of planning and organizing the project such that the desired map projects would be produced in a timely and utilitarian manner. Decisions made and tasks accomplished during this phase included: (1) arrangement for periodic flights over the study area for the purpose of air photo acquisition; (2) compilation of a base map to be used in delineating the interpreted features; (3) determination of key features to be interpreted; and (4) coordination with organizations who were either interested in receiving copies of the map series, or who would be acting as participants under phase two.

Table 1. Major Phases of the Remote Sensing Project

Phase #	Description	Date
1	Planning and Organization	Sept. - Oct. 1981
2	Interpretative Mapping	Oct. 1981 - Dec. 1982
3	Analysis and Preparation of Final Report	Jan. - Apr. 1983

Under phase two, a specified minimum number of sequential steps were required of the principal investigators and several of the other participants in order to generate the desired map products. A generalized flow diagram of phase two is presented in Figure 2. Included in the diagram are each of the major steps required to successfully complete an interpretative map, as well as relationship and responsibility of each participant. A summary discussion regarding the method-

Figure 2. Generalized Flow Diagram of the Remote Sensing Interpretation, Mapping, and Analysis Project.



ological approach adopted for each of these key procedural steps will be presented in the following sub-sections of the report.

Phase three was designated as a period of review and analysis of the completed map products. Under this phase, several months were allocated such that major observations regarding identified hydro-morphologic changes could be assessed and the final report prepared for distribution.

### Compilation of the Base Map

Through the efforts of the State Resident Cartographer, Glen Ireland, advance sheets from the 7.5 minute topographic quadrangle map series were acquired from the U.S. Geological Survey. These preliminary draft quadrangles, at a scale of 1:24,000, were prepared by the Topographic Division of the U.S. Geological Survey from imagery acquired in September 1980. The following listed quadrangles formed the basis for the base map that was used throughout the course of this project:

- Cougar NE
- Elk Rock SE
- Elk Rock SW
- Mt. St. Helens NW
- Spirit Lake SW

The base map was prepared during the months of September and October, 1981. Individual sheets were mosaicked together to form a composite map of the study area. Determination of the study area boundary was discussed with each of the intended map users before the base map was prepared.

Once the topographic map sheets were mosaicked together, areas outside the study area were masked-out on the topographic mylar positive. In addition to this separate, positive overlay separates were

then prepared of the study area boundary line and of the title/legend lettering. These three permanent separates, coupled with the inked interpretative map overlay, were then combined in negative form to produce the completed composite mylar map later used in ozlid reproduction.

### List of Interpretative Features

Included within the planning and organizational phase of this project was the identification of features to be interpreted from the acquired imagery. Keeping in mind the limitations imposed by the mapping scale, the resolution quality of the imagery, and the purpose of the project, the list of features to be interpreted went through a series of modifications. A variety of features were considered for possible adoption. The list of features finally agreed upon was based on the views of the principal investigators, cooperators, and several of the intended users.

The list of features used in producing the first interpretative map did not remain fixed. As new maps were prepared, several refinements and changes were made in an effort to continuously improve the quality of each map product. Table 2 summarizes the various physical features that were used in completing each of the interpretative maps.

Inclusion of these selected physical features served several purposes. First, by identifying the spatial pattern of the features within the study area, a visual summary statement could be made as to hydro-morphologic characteristics that existed at the time of imagery acquisition. Second, by showing the location, pattern, and density features, identification regarding source areas responsible for major sediment production (i.e., where in-channel storage of sediment was




Table 2. Summary of Features Used in Each Interpretative Map.

Map Legend Category	Categories Used Per Map					
	10/13/81	11/24/81	12/11 &16/81	2/6/82	3/5/82	10/13/82
Active channels	x	x	x	x	x	x
Inactive channels	x	x	x	x	x	x
Standing water	x	x	x	x	x	x
Floodplain	x	x	x	x	x	x
Terraces	x	x	x	x	x	x
Mass movements		x	x	x	x	x
Spring			x	x	x	x
Snow cover boundary			x			
Escarpments/waterfalls				x	x	x
Study area boundary			x	x	x	x
Limit of air photo coverage			x	x	x	x

taking place, or areas that were prone to mass movements) could be inferred. Third, and perhaps most important, when the series of maps are compared, assessments could be made concerning the rates of change per feature or area over time. In short, the evolutionary history of the rapidly changing drainage network could be documented and inferences from these manifest changes deduced.

The following briefly identifies each of the map legend categories adopted and used during the course of this project, its corresponding mapping symbol, and finally a working, descriptive definition.

Active channels ()

- Indicates the presence of water flowing in a defined channel.
- Inclusive of all bodies of flowing water ranging in size from gullies to rivers.
- These linear features generally have a dark color tone on the imagery, but also appear as shades of gray depending upon the channel depth and the amount of suspended sediment present in the water flow.

- Synonymous with perennial streams and rivers.

### Inactive channels (←==→)

- Indicates the presence of a defined channel but without water flow.
- Size of feature is generally restricted to gullies and small streams.
- These linear landform features indicate where channels have been formed, and where water would flow and have flowed during rainfall producing storm events, snowmelt, and lake capture.
- Clues used in interpreting these features include: size, pattern, shape, and shadows.
- During those months when snow cover obscured the surface, especially at higher elevations, the location of inactive channels were either inferred from the patterns present or were not mapped.
- These channels are dry for a large part of the year.
- Synonymous with intermittent and ephemeral streams.

### Standing water ( ● )

- A body of water entirely surrounded by land; i.e., an accumulation of water collected in a natural depression on the earth's surface.
- A surface outlet may or may not be present.
- No differentiation is made as to size and depth of the standing water body.
- Depressions (either moist or dry) in which the water is no longer present due to groundwater seepage, piping, or evaporation were not mapped.
- These areal features generally appear black on the imagery, but occasionally as shades of gray depending upon their depth, presence of suspended sediment, or biological activity.
- Includes all lakes, ponds, pools, and reservoirs located within the study area where surface water is being stored.

### Floodplain ( )

- Region of entrenchment or confinement in which the stream or river is shifting back and forth, eroding steep side-wall embankments.
- That portion of the valley which could be covered with water when the stream or river overflows its channel banks during flood stage or periods of peak discharge.
- The nearly level land situated on either side of a channel which is subject to overflow flooding and deposition of sediments.
- Included within the floodplain are indicator features such as braided channels, terraces, and steep to nearly vertical embankments.
- The symbol used has tick marks on the outside rather than on the inside of the solid line because of the number of active channels that may be present during periods of high discharge.

### Terraces ( )

- A shelf or bench, relatively flat and horizontal, sometimes slightly inclined toward the channel, that lies along the side of a valley.
- Generally located within the floodplain, terraces indicate the former level of the active channel left standing above the current channel due to the degradation or downcutting of the stream or river.
- Terraces are bounded above and below by rather abrupt slopes.
- Differentiation as to height above the current active channel and type or composition of terrace depositional material were not made.

### Mass movements ( )

- The downward movement of material on a slope due, in large part, to the influence of gravity. Water is usually involved as a major triggering mechanism, but not as an active transporting agent.
- Mapped areas are of recently rapid mass movement occurrences or of unstable areas indicative of slow displacement rates.

- Undifferentiated as to type; the major mass movement categories present in the study area include stream bank failures, slump/-earthflows, and debris flows. Excluded from this broad category are such process/features as creep, solifluction lobes, talus cones, and snow avalanches.
- Identified by: (1) recently displaced material that accumulates in valleys, depressions, and stream channels - light gray in tone when compared to the darker tonal characteristic of stable areas; (2) large tension cracks--usually crescent-shaped--that are situated on steep upslope surfaces and ridge fronts; (3) presence of hummocky topography with undrained or poorly drained depressions; and (4) changes in tone near the edges of embankments which may indicate moisture differences in the sub-soil.
- The "M" symbol was added to the 06 February 1982 map in order to delineate areas too small or narrow for the area symbol.

#### Spring ( o w )

- Point source of water seepage issuing naturally out of the earth; occurs where the groundwater table intersects the earth surface.
- Preponderance of springs in the study area are located along the margins of the debris flow/debris avalanche deposits.
- Springs are most conspicuous and identifiable when snow of one meter or less in depth is present to provide a sharp contrast between snow (white) and spring point of origin (black).
- Undifferentiated as to being either permanent or intermittent.

#### Snow cover boundary ( ↖ ↗ )

- Lower limit of snow cover at the time of imagery acquisition.
- Distinguished from bare ground surfaces and water bodies by tonal differences (white vs. black to shades of gray).
- This category was used only for the 11 & 16 December 1981 map due to the excessive amount of time necessary to delineate snow cover areas.

#### Escarpments/Waterfalls ( U )

- Escarpment refers to a steep slope interrupting the general continuity of the landscape; i.e., a significant break in slope gradient--a "knickpoint" or "step".

- Waterfall refers to a steep, more or less perpendicular descent of a stream or river; i.e., a point at which the course of a stream or river is markedly and suddenly interrupted.
- Rapids on streams and rivers were not identified.
- Identification was made principally through analysis of relief differences and the extent of shadows.
- Distinction as to the presence or absence of water flow can be made using the active and inactive channel symbol were it intersects the escarpment/waterfall symbol.

#### Study area boundary ( )

- A 2 mm thick line is used to distinguish the border of the study area and the corresponding extent of topographic (contour) coverage.
- The upper extent of the study area (east) generally utilizes natural watershed boundary lines (e.g., Mount St. Helens crater); in the lower portion of the study area (west) the boundary line extends upslope several hundred meters from the valley floor-side slope interface.
- Dashed lines extend across Spirit Lake and Coldwater Lake, thus truncating and excluding the upper portions of these two water bodies.

#### Limit of air photo coverage ( )

- This symbol is used to indicate the actual extent of photo coverage in the study area for that particular date.
- Orientation of the symbol indicates the flight-line direction of the aircraft.
- Because the flights were flown at low altitudes utilizing a large scale photo format, total study area coverage was not completed for any flight mission.

#### Roads ( )

- At the last moment, the road category was added to the final map dated 12 October 1982.
- The road symbol was not added to the map legend.

- Two roads are identified: the main road associated with the retention dams and the access road (former USFS Road 100) to Spirit Lake.

Low-Altitude, Large-Scale Aerial Photography

Arrangements for monthly flight missions to the study area for the purpose of imagery acquisition was arranged through the Office of Operations and Training of the Oregon Army National Guard. Decisions made prior to the initiation of these flights included: determination of flight line locations, film type, film filter use, film format, imagery scale, overflight conditions, and acquisition times (Table 3).

Most of the flights were flown utilizing a KA-76 camera with a 152 mm (6 in) lens. The camera platform for these missions was a U.S. Army OV-10 Mohawk aircraft. This aircraft has the capability of

Table 3. Imagery Requirements and Specifications

Imagery Requirements	Specifications
Flight line location	(1) Mount St. Helens to Spirit Lake (N-S).  (2) Spirit Lake to western study area boundary; including coverage of retention dam, Castle Lake, and Coldwater Lake (E-W).
Film type	Panchromatic (Kodak 2443).
Film filter	Minus-blue (yellow).
Film format	115 x 115 mm (4.5 x 4.5 in); vertical-simultaneous acquisition with 60% overlap.
Imagery scale	Approximately 1:10,000; range 1:10,000-1:20,000.
Overflight conditions	No wind blown dust or cloud obscuration.
Acquisition times	1000-1400 local.

flying at low altitudes under existing cloud coverage or other adverse weather conditions when flights by other aircraft would normally not be possible.

The film type was limited to black and white, panchromatic film in a 115 x 115 mm (4.5 x 4.5 in.) format. Vertical negatives were taken with 60 percent overlap in order to provide for stereoscopic analysis (i.e., for viewing in three-dimensional relief). The image scale was approximately 1:10,000, but ranged from this large scale format to a smaller scale of 1:20,000 depending upon the flight altitude and/or camera lens used. Once the continuous negative rolls were developed at the Oregon National Guard facility, they were sent to the Geography Department at Oregon State University for assessment as to image quality and adequacy of coverage. Table 4 summarizes the aerial photography acquired before and during the project period.

Examination of the six complete maps reveals that the study area at no time received complete air photo coverage. This was principally because: (1) the flights were flown at low altitudes thus necessitating the generation of a vast number of negatives to provide even minimal coverage of the study area; (2) the limited amount of flight time available for the over-flight; and (3) the occasional occurrence of adverse weather conditions or mechanical malfunction of the equipment. In addition to the problems associated with obtaining adequate air photo coverage, the quality of the acquired air photos were also found to suffer from tonal variations and processing inconsistencies. The photos taken on 13 October 1981 provided the basis for the first interpretative map of the study area.

#### Stereophoto Interpretation

The imagery was interpreted stereoscopically utilizing a Dietzgen mirror stereoscope. Binocular lens of 3x magnification

Table 4. Summary of Air Photo Acquisition

(Source: Oregon Army National Guard and Dr. Charles L. Rosenfeld, OSU)

Date	Scale	Film Type	Areal Coverage
6/30/80	1:20,000	B/W	Spirit Lake to South Fork Toutle River junction (initial conditions)
10/30/80	1:20,000	B/W	North Fork Toutle River
11/5/80	1:20,000	B/W	Upper N.F. Toutle River down to retention dam
12/30/80	1:10,000	B/W	Retention dam site after breaching N.F. Toutle River to S.F. Toutle River junction (effects of Winter '80-'81 storms)
9/9/81	1:16,000	B/W	Upper N.F. Toutle River down to retention dam
9/21/81	Variable	Color	Hand-held slides of various N.F. Toutle River sites
*10/13/81	1:20,000	B/W	N.F. Toutle River
11/4/81	1:20,000	B/W	N.F. Toutle River (camera malfunction)
*11/24/81	1:20,000	B/W	Upper N.F. Toutle River/Coldwater Lake to retention dam
11/27/81	1:14,000	B/W	Spirit Lake to Coldwater Lake
*12/11/81	1:10,000	B/W	Upper N.F. Toutle River; retention dam to Mount St. Helens
*12/16/81	1:20,000	B/W	Upper N.F. Toutle River; retention dam to Spirit Lake; Spirit Lake to Mount St. Helens
*2/6/81	1:20,000	B/W	Upper N.F. Toutle River; retention dam to Spirit Lake; Spirit Lake to Mount St. Helens
*3/5/82	1:18,925	B/W	Upper N.F. Toutle River; retention dam to Spirit Lake; Spirit Lake to Mount St. Helens
3/18/82	1:9,000	B/W	Upper N.F. Toutle River; retention dam to Spirit Lake; Spirit Lake to Mount St. Helens
3/18/82	1:19,000	B/W	Upper N.F. Toutle River; retention dam to Spirit Lake; Spirit Lake to Mount St. Helens
3/23/82	1:9,550	B/W	Upper N.F. Toutle River from Castle Lake to retention dam
4/7/82	1:9,800	B/W	Upper N.F. Toutle River from Spirit Lake to retention dam
5/1/82	1:9,570	B/W	Upper N.F. Toutle River from Spirit Lake to retention dam
8/17/82	—	B/W	Upper N.F. Toutle River from Spirit Lake to retention dam
*10/13/82	1:10,000	B/W	Upper N.F. Toutle River from Spirit Lake to retention dam
12/10/82	—	B/W	Upper N.F. Toutle River from Spirit Lake to retention dam
12/30/82	—	B/W	Upper N.F. Toutle River from Spirit Lake to retention dam

\* Imagery data used in producing an interpretative map.



ensured definitive coverage of subtle relief differences. Omnichrome colored pencils were used to differentiate the various categories listed in the map legend.

Identification of the various features was facilitated by observing recognizable similarities and differences as they appeared on the imagery. The clues used in the development of mental signature keys associated with each category was based upon the characteristics of size, shape, shadow, tone (or color), texture, and pattern (Bowden and Pruitt, 1975). Ground truthing experience acquired by the interpreter contributed significantly to the accuracy and ease of feature determinations. The addition of stereoscopic vision also made most features easier to recognize and differentiate. Once the features were identified, a colored point or line symbol was placed directly onto a positive print of the imagery. When the interpretative phase was complete, the information was then transferred to a base map overlay utilizing a zoom transfer scope.

#### Photo Transfer and Registry

Because the base map and photographs used in this project were of different scales (map 1:24,000; imagery 1:10,000-1:20,000), transfer of the interpreted information from the photographs to the base map was facilitated by employing a Bausch and Lomb Zoom Transfer Scope. This instrument can be used to optically superimpose a view of an image with that of a map. By using a 4x map lens and adjusting the magnification of the two views, the image scale was matched to the scale of the base map.

Difficulties in matching the image and map arose in those situations where significant vertical relief differences occurred over short horizontal distances. In these situations, the image had to be

constantly adjusted to match the contours appearing on the base map. An additional problem in transferring the interpreted information occurred where there were few contour lines available on the base map for reference purposes. Contour lines and other topographic map symbols were constantly used in the transfer step for the purpose of orientation and precise matching of the image with the base map. However, numerous modifications to the terrain configuration have taken place since 1980 when the topographic base map was photogrammetrically produced. In those situations where significant landform changes had occurred, or where the existing map contours were widely spaced indicating gentle slopes lacking in depressions, hills, and streams, matching the image to the map become a more difficult and time consuming task. Finally, difficulties encountered in the transfer step were compounded whenever the aircraft changed altitude, or under clear air turbulence situations, the aircraft pitched, yawed, or rolled during the photo run.

Prior to transferring the interpreted information, a blank mylar sheet was registered to a mylar positive of the mosaicked base map. Onto this blank mylar sheet, a 6H pencil was used to accurately locate and match the colored interpreted symbols derived from the air photo interpretation step. To the degree possible, the exact spatial distribution of each feature (e.g., the extent of surface water flowing in the floodplain), was transferred onto the base map overlay. Once the penciled overlay separate was completed, the transferred information was then registered to the base map negative for final cartographic editing and inking.

### Map Reproduction and Distribution

After the interpretative map separate was inked, the various negative and positive separates were taken to the CH<sub>2</sub>M-Hill

Reproduction Center where a final composite mylar positive map was produced. Sub-contracting was necessary because of the large dimensional size of the base map (122 x 70 cm; 48 x 28 in). Numerous time delays were encountered at this step of the project because of scheduling problems at the sub-contractor facility.

When the composite map was returned, multiple ozlid copies were produced. Several copies, including the original, were retained in the OSU Geography Department as part of the project's archival collection. The balance of the reproduced copies were sent to the Oregon Water Resources Research Institute (WRI). From there the completed map was distributed to cooperators and other interested parties.

#### Initial Mailings and Questionnaire

During the planning and organizational phase of this project, numerous federal, state, and private agencies and institutions were contacted concerning their respective interest in receiving the mapped products from this project; a chronology of maps specifically designed to depict the hydrologic changes occurring on the upper North Fork Toutle River debris avalanche. In December 1981, a questionnaire form was prepared and mailed out with the first completed map product dated 13 October 1981. Interested agencies and persons who responded to the questionnaire were placed on a mailing distribution list. This phase of the project was coordinated under the auspices of Dr. Peter C. Klingeman, director of the Oregon Water Resources Research Institute. A complete list of those agencies and persons who have received one or all of the completed maps appears in Appendix II.

### Suggested Improvements from Users

Since the initiation of this project, numerous general comments and suggestions have been received concerning: (1) the hydro-morphologic features being interpreted; (2) the presentation of interpretative data on the base map; and (3) recommendations for cartographic improvements. These various observations and comments were sent either directly to the principal investigators or were received indirectly through the WRRRI office.

Examination of the interpretative maps (Appendix I) will disclose that a significant number of changes and improvements in the map products have occurred subsequent to the completion of the first map. Of the many substantive changes that have been implemented during the course of this project, the greatest number of changes were associated with the production of the 11 and 16 December 1981 map -- the direct result of user feedback. The following listed changes and improvements to the map products, for example, were received in time to be incorporated into the December 1981 map:

- (1) A new title, at a larger letter point size, that more accurately defined the study area.
- (2) Incorporation of geographic coordinate reference systems (i.e., township/range and latitude/longitude ticks).
- (3) A new bar scale and correction of the contour interval (i.e., 40 feet).
- (4) Inclusion of a north arrow.
- (5) Expansion of the legend to include: "Study area boundary," and "Limit of air photo coverage."
- (6) The addition of two new categories to the legend: "Springs" and "Snow cover boundary." Note: Because of time limitations required in completing the map products, the "Snow cover boundary" category was dropped from subsequent maps.
- (7) Inclusion of several named landform features for orientation purposes; i.e., Retainment Dam, Coldwater Lake, Castle Lake, Spirit Lake, and Mt. St. Helens.

In addition to these noted changes and improvements to the map products, several other modifications were instituted during the course of the project. For example, rather than using a zip-a-tone pattern to denote terraces (which did not reproduce satisfactorily), later maps were produced using stippled dot points to delineate these landform features. An "M" was added to those areas of mass movement occurrence that were too small or narrow for inclusion of the mass movement symbol. The symbol "U" was added to the February 1982 map to indicate the location of major escarpments and/or waterfalls. The purpose of this symbol was to indicate the headward migration of knickpoints over time.

When specific requests or recommendations were received concerning the interpretation of features, these were also incorporated into the project framework whenever feasible. For example, the U.S. Geological Survey requested that, if possible, they would like to see greater emphasis placed on identifying the location of all channel terraces and mass movements. Beginning in February 1982 these maps thus reflect an increased emphasis on interpreting the spatial distribution of all terraces, and of active and recently active mass movement events. Because of limitations imposed by the mapping scale (1:24,000), no attempt was made to differentiate the type or relative height of terraces, nor to distinguish amongst the various mass movement types occurring within the study area, such as streambank failures and slump/earthflow occurrences.



#### 4. MAJOR OBSERVATIONS OF DRAINAGE NETWORK EVOLUTION

The massive pyroclastic, debris avalanche, and mudflow deposits which inundated the upper North Fork Toutle River valley on 18 May 1980 remains extremely unstable. The entire study area is indicative of a hydro-morphologic assemblage of features and processes in disequilibrium. Runoff from rainfall and snowmelt is the continuing agent responsible for the rapid alterations in the surface drainage network. Extensive areas of the watershed are experiencing stream-bank erosion, channel shifting, or alternating degradation/aggradation processes. The river course through the debris deposits remains extensively braided. Individual channel braids shift rapidly and continuously, converging and diverging, as the drainage network continues to evolve. The erosion, transport, and deposition of sediment in the study area thus reflects the dynamic character of the hydrologic and geomorphic processes operating to readjust the present landform configuration back to the pre-eruption equilibrium balance between slope gradient, volume and velocity of flow, and sediment load.

This section will explore and generate selected observations of these rapidly changing physical conditions. Thus far, only limited quantitative analyses have been performed. The basis for these observations will be predicated primarily upon qualitative, subjective assessments of the hydro-morphologic characteristics as derived from remote sensing analysis techniques and as cartographically represented on the completed maps. Interspersed throughout these discussions will be background information collected and generally assessed by field crews of the U.S. Geological Survey (USGS). It is left to the users of these products to cull the various environmental parameters that await further elaboration and detailed examination.

The following two sub-sections have been organized to provide summary descriptions and observations of the products derived from this project. The first section briefly abstracts each of the com-

pleted interpretative map products with regard to drainage network evolution. The six completed maps in Appendix I have been photographically reduced from their original 1:24,000 map scale down to 1:72,000 for inclusion in this report. The second section focuses on a particular set of hydro-morphologic processes as observed and characterized from several selected reaches of the study area. Because these two sections have been written independently of the other, some redundancy in the observational comments will be noted.

### Discussion of the Interpretative Map Products

13 October 1981

The first map in this interpretative map series revealed the general spatial relationship (or status) of hydro-morphologic features and set the stage for future comparative assessments. Although a few small runoff events had occurred prior to the air photo acquisition flight, most developed tributary streams were not flowing with water. The map indicates a propensity toward inactive or intermittent stream channels. The density of channels is considered to be low. Active or perennial stream channels were principally confined to the main stem of the North Fork Toutle River, or to tributary streams emanating from the larger lakes. The cartographic line-work for active channels indicates the linear distribution, and to the degree possible, the actual areal coverage of the braiding river system. Within the floodplain, the location of observable terraces were primarily limited to those of large areal extent, and/or height (greater than 1 m; 3 ft) above the active channel floor.

The physical conditions and geographical expanse of Spirit, Coldwater, and Castle Lakes were not available from the imagery.



Only partial coverage of Jackson Lake and the retention reservoirs are indicated. This map clearly illustrates that certain areas, primarily because of the lithologic composition and structure of the debris avalanche deposits, have a high concentration of lakes and ponds present. One such area, for example, is located south of Elk Rock and northwest of Jackson Lake. These areas are characterized by their general lack of integrated drainage systems and a proclivity towards closed depressions.

Note the highly braided pattern of the river immediately upstream from the retention dam structure. As of October 1981, the southern half of the reservoir/sediment storage area has been partially filled with sediment and debris. Suspended sediment (and bedload during peak discharge events) is either cascading directly over the spillway or is in-filling the balance of the southern reservoir via a delta-shaped alluvial fan feature. Based upon cross-sectional transects conducted by the USGS, the location of the retention dam structure(s), represents both in terms of time and space, the transition zone between aggradation which is generally taking place upriver, and degradation or scouring which is generally taking place downriver.

24 November 1981

The large-scale imagery acquired on 24 November 1981 provided coverage for only the western half of the study area. Two flight lines were flown. One flight line was generally centered on the south to southwestern half of the valley, while the second covered the north to northeastern half. There was sufficient overlap to maintain continuous coverage except near the retention dam structures where the flightlines diverged.

One of the most notable differences between the October and November maps is the change in the amount of discharge flowing in the North Fork Toutle River floodplain. In some stretches of the river there is a nearly continuous flood of water situated within the narrow confines of the evolving floodplain. Hundreds of temporary, continuously changing islands are located throughout the braided river reach. Another major change is the location of the main stem of the river near Jackson Lake. Sometime between 13 October and 24 November 1981, the principal channel flow shifted from the north side of the valley to the south side. Input from the north channel, nevertheless, appears to have remained significant in terms of rate of flow (cfs). Other changes that are evident with regard to moving water include: the change from a preponderance of intermittent dry channels to those with water flow; a slight widening of the floodplains especially along the outside bend where the river changes direction--a direct result of riverbank undercutting and corresponding bank failures; and the apparent reduction of previously identified terraces or the existence of new terraces where none had previously been present in October. Careful examination and comparative analyses will also reveal that there are evidences of stream capture, and 180 degree changes in stream course direction within the debris avalanche and mudflow deposits.

No less dramatic are the numerous changes that have taken place with regard to standing water bodies. Not only has the total number of lakes and ponds increased, but their size or areal extent when compared to the October map has generally increased as well. A notable exception to this trend is the reduction in total water volume temporarily being stored behind the southern retention dam structure. Sediment input and changes in channel flow direction has significantly altered the reservoir storage area. The direction of sediment input is toward the northwest. Each new discharge pulse contributes to the sediment buildup and the corresponding loss of surface water storage. The northern dam structure and reservoir, not

directly associated with the main river flow, appears to be little altered due to sediment input and peak discharge flow events.

The linear, NW-SE oriented feature appearing in (Sec. 33, T10N, R3E) is part of a diversion channel ditch that was also constructed by the U.S. Army Corps of Engineers. Its purpose was to divert water into the northern reservoir system during periods of peak discharge storm events. All of these various identifiable changes, the direct and immediate result of runoff from the first winter storms of 1981-82, were just a prelude to the diverse variety of alterations that were to occur within the next few months.

11 & 16 December 1981

The December map introduced a number of observable modifications to the basic design of the map, as well as the addition of new interpretation categories. Most of these improvements were discussed earlier in this report. In order to produce a map with nearly complete coverage of the entire designated study area, imagery from two separate flights were combined. As the footnote on the map indicates, interpretation of surface hydro-morphologic features was based principally on imagery acquired on 16 December 1981. The 11 December 1981 imagery was incorporated into the final map in order to provide supplemental coverage of areas that were not covered by the later, larger-scale imagery. For the first time, complete coverage was made not only of Spirit Lake, Coldwater Lake, and Castle Lake, but of the retention dam storage areas as well.

The runoff effects of the early winter storms are clearly evident on this map. The discharge volume of the North Fork Toutle River is slightly less than was indicated on the 24 November 1981 map, but the spatial pattern still indicates a rather high discharge flow rate. At the time of imagery acquisition, snow blanketed much of

the land surface. The elevation of the lower snow cover boundary was approximately 670 m (2,200 ft). Only the lower western half of the study area was snow free. Changes in climatic conditions were reflected in the slight variation of snow cover when the two imagery dates were compared. These observable differences suggest that there may have been increased runoff due to rain on snow or snowmelt when a warm air mass moved into the region within the five day span of time between imagery flights. It should be pointed out that the triangular-shaped area between Mount St. Helens, Spirit Lake, and Castle Lake does not accurately represent the actual number of inactive channels present. Depth of snow cover at this higher elevation precluded a complete identification of smaller channels. Thus, only the larger, deeper channels not buried by snow and hidden from view were mapped.

The eastern half of the December map has several interesting features of note. First, South Coldwater Creek provided a superb example of a braided channel network. The exact location of these channel flow lines was enhanced by the contrast provided by the snow cover (Fig. 3). Second, an imaginary line between Coldwater and Castle Lakes marks the approximate location of where the groundwater from the upper debris avalanche intersects the land surface. Here, numerous stream channels within a short drop in elevation and slope gradient show a transition from dry channel beds to streams with flowing water. Third, on no other map was the number of positively identifiable springs more prolific. Case in point are the many springs located on the north side of Johnston Ridge. Again, interpretation of these features was greatly aided by the presence of snow on the ground. Fourth, the spatial distribution and areal extent of the primary and secondary lakes located within the study area are clearly defined for the first time. Future analyses associated with the changes in lake levels (e.g., Spirit Lake) and the presence or absence of lakes and ponds makes this map particularly important when compared and contrasted with later interpretative maps in this series. Note the second major dominance area for lakes and ponds immed-



Figure 3. An example of stream braiding in the lower South Coldwater Creek watershed. This aggrading stream reach exhibits the characteristics typical of a braided stream network in which hundreds of channel links divide, subdivide, and reunite repeatedly. The snow cover serves to enhance the myriad of anastomosing channels. Coldwater Lake is the dark feature at the top of the photo. The photo date is 11 December 1981 (Oregon Army National Guard).

ately south-southwest of Coldwater Lake (S1/2, Sec. 2 and N1/2, Sec. 11, T9N, R4E).

By the time the imagery for this map was flown, the U.S. Army Corps of Engineers had completed the dredging of overflow escape channels for Coldwater and Castle Lakes. The purpose of these new channels was to prevent the disastrous downstream flooding that would result if the collapse of these natural debris dams were to take place due to over-topping of the blockage areas.

Included among the most interesting of the hydro-morphologic features located in the western half of the map is: (1) the large braided reach of the river situated northeast of Jackson Lake; and (2) the retention dam area. The braided reach of the river reveals the spatial configuration of the bifurcation taking place to the main river channel flow. Once the river enters the area, which is characterized by an increased slope gradient and the lack of channel-bounding escarpments, the water flow fans out over a large, generally unobstructed planar terrain surface. By this date, the bulk of the braided river flow had shifted southward in response to sediment deposition patterns. This is a prime example of sediment being placed into temporary in-channel and near-channel storage rather than immediately being flushed through the river system. Further elucidation of this unique area will be made later in this chapter of the report.

As of mid-December, there is still little observable alterations to the general character of the north reservoir. The south reservoir, however, has continued to evolve hydro-morphologically. Sediment has completely filled the storage area behind the south dam structure. The main channel has become more confined and less braided. This may be due in part to the lower volume of discharge taking place at this particular time. A small off-shoot from the main channel has recently breached the road/levee that had separated the two reservoir systems, and now water and entrained sediment is

beginning to enter the northern reservoir storage area; an ominous sign of events to come.

06 February 1982

A map for January was unobtainable due to adverse weather conditions that prevailed throughout the month, and to mechanical difficulties with the aircraft. During the interim between maps, the Mount St. Helens region experienced an almost continuous series of storm events. Rainfall and snowfall, relatively warm and cold temperatures alternated throughout much of the study area; especially in the transitional middle section near Coldwater and Castle Lakes. Between January 22 and 24, a warm front from off the Pacific produced the largest discharge peaks since the debris deposits were implaced within the North Fork Toutle River valley. Although the precipitation that fell was only in the range of 85 to 126 mm (3.3 to 5.0 in), runoff was augmented by high antecedent moisture conditions and snowmelt. This two-month period can be characterized as experiencing persistently high stream discharge rates and rapid, but localized, changes in channel geometry.

Single, rather than multiple, large-scale flight lines resulted in their being no aerial coverage of the Spirit Lake area. Further down-valley, cross-flight lines allowed for the interpretation of the outlet points of Coldwater and Castle Lakes. The highly braided nature that had so characterized South Coldwater Creek in December has been significantly transformed. Rather than hundreds of small diverging and converging channels, only a few interconnecting stream links remain. Of particular note in this area is the classic delta feature that was observed to be developing where South Coldwater Creek empties into Coldwater Lake.

Areas experiencing recent mass movement occurrences are substantially greater than had previously been observed and mapped. The most prominent type of mass movement is steambank erosion due to the lateral expansive growth of the floodplains, and large areas of instability characterized by saturated, slow-to-rapid moving debris flows or slump/earth flows.

Throughout the study area, the total length and density of streams and gullies has increased significantly when compared to the previous maps. The runoff experienced in the past two months has contributed not only to the headward migration of knickpoints and amphitheater-shaped head scarps of established channels, but to the continuing evolution of new channels produced principally from processes involving fluvial erosion.

Despite the frequent occurrence of runoff pulses through the established drainage system, only a few alterations have occurred with regard to the retention dam area since mid-December. First, the floodplain immediately up-river from the south dam spillway has widened. Second, the north flowing splinter from the main stem was not observed to be discharging into the northern reservoir. Rather, the secondary stream was looping backward along the south dam face. Finally, the braided river pattern continues to persist in the sediment-filled south reservoir storage area.

05 March 1982

This map illustrates the most dramatic and significant changes that have yet occurred with regard to the spatial character and evolutionary development of the hydro-morphologic features in the study area. The north retention dam was breached, numerous lake and pond breakouts coincided with periods of peak discharge, areas of recent



mass movement occurrences increased significantly, and the main stem of the North Fork Toutle River spilled out of its normally confined floodplain channel in several locations. As a direct result of these multiple transformations, large areas of the study area have lost their primary chaotic, hummocky microtopography appearance, and have acquired a physiographic character similar to those of maturely integrated arid and semi-arid landscapes that are devoid of vegetative cover.

A series of major storms began on February 13 and culminated on February 20. Instantaneous peak discharges exceeded the previous high recorded on January 24. Similar to the January weather pattern, but of greater intensity and longer duration, discharges during the February series of winter storms were produced by a combination of rainfall and snowmelt. The March map reflects, in part, these continued high discharge rates.

The filling and breaching of lakes and ponds on or adjacent to the hummocky debris deposits continued to be a major process in the development of a more integrated drainage network. The lake and pond breakouts appear to occur mostly during or immediately following periods of high discharge. The USGS suggests that the two largest breakouts occurred on the recession from the February 13 flood and during the peak stage of the February 20 flood. These breakouts occurred from ponds along the northern margin of the debris avalanche deposit (compare the February and March maps, Sec. 12-13, T9N, R4E), and from Jackson Lake. The ponds were probably breached by the rapid headward migration of streams and gullies. Piping may also have been a contributing factor. Jackson Lake was inundated by the main flow of the river as the blockage material impounding the lake was removed by repeated and concentrated bank failures. After the peak surge, the river once again retreated to its former channel course leaving behind tons of sediment in the former lake bottom.

The March map reveals that channel aggradation and extensive areas of bank erosion occurred during and after the series of late February storm events. The braided area north of Jackson Lake continues to indicate a dominance towards aggradation processes. Escarpments bordering the major channels appear to be persisting in their progressive retreat primarily through the erosional processes of slumping collapse, followed by saturated flowage of the materials. In some tributary channels, mudflows were generated that may have moved downslope as hyperconcentrated, channelized stream flows. These processes are indicative of the large areas of frequent and persistent mass movement occurrences that are indicated on this map.

Channel modifications immediately down-valley from the Elk Rock narrows reached levels that caused perhaps as much as 30-50 percent of the flow in the North Fork Toutle River to spill out of its normal channel bed and into a gully network that had been a tributary to Bear Creek. This deflection of the river flow to the north, left in its wake a wide gully floodplain and numerous standing terraces.

Prior to this flood surge, Bear Creek and Hoffstadt Creek had been the principal sources for water draining into the north reservoir storage area. When the flood discharge entered the north reservoir, the sudden surge exceeded the design capacity of the north dam spillway resulting in its failure during the afternoon of February 20. Water and water-saturated fine sediment from the reservoir storage area rapidly swept through the spillway breach. The sediment stored behind the dam probably experienced some liquefaction movement as well as a series of headward-working slump-flows. Much of this displaced material was readily incorporated into the stream flow and transported further downstream.

The morphological features observable on the March map reflect the aftermath of these hydrologically-induced series of events. For example, the north reservoir has been completely drained of its

standing surface water, numerous gullies and terraces are present in the storage area where previously there had been none, and a tributary stream network from the main stem of the river once again drains into the north sediment storage area and out through the north dam spillway. A more detailed discussion of these radical events is covered later in this section of the report.

13 October 1982

The last interpretative map in this project series is also the most definitive. Unincumbered by snow cover, cloud cover, and impenetrable dark shadows, the October 1982 map represents the most accurate and detailed evaluation to date. Every effort was made to stretch to the limits, the restraints imposed by the imagery and map scales. The most regrettable factor regarding this map was the lack of aerial coverage for the Coldwater Lake outlet area.

Comparative analysis with the previously completed maps indicates that there is a preponderance of inactive channels dispersed throughout the area. This is especially the case in the region lying between Mount St. Helens and Spirit Lake. Even the main stems of the North Fork Toutle River reflect the lower flow rates that have persisted from late spring and on through the summer months. Except where groundwater seepage or springs intersect the land surface, most low order tributary streams have probably received little or no runoff since May. One notable change during the summer months has been the switch from aggradation to degradation processes in the braided reach of the river. During the interim between the March and October 1982 maps, the river has gradually become incised into previous deposits of alluvium, debris avalanche and pyroclastic flow material. Although the amount of precipitation input has been slight immediately prior to the imagery acquisition date, there remain large areas of recently active or potentially active mass movements.

In the Spirit Lake area, numerous changes can be discerned. Comparison of the December 1981 and October 1982 maps reveals a substantial difference in the surface elevation of Spirit Lake. Many acres of former shoreline have been inundated as the lake continues to rise in response to runoff. Along the western border of the lake, a drainage ditch constructed by the U.S. Army Corps of Engineers is nearing completion. From a nearby pumping station, water will be released into this controlled aqueduct in an effort to maintain or to at least slow the rate of lake level rise.

At the opposite end of the study area, the breached conditions of the retention dams no longer allow them to serve as sediment sinks. Examination of the map shows that the south retention dam structure has been breached near the southern end. An alluvial fan feature has developed west of the breach. During high flow conditions, excess runoff is now contributing to the total Deer Creek discharge rates. The depositional pattern of the feature would indicate that it is moving westward with each new peak flow event. The river channel behind the south dam is now partially incised as the river continues to cut down through the dam structure removing stored sediment in the process. The south dam has now been partially buried on the down-flow side with sediment accumulations that overtopped the structure. The braided area behind the former south reservoir area has increased in areal extent. Erosion in the braided area has been taking place in the north and northeast quadrants; especially where the floodplain abuts the construction access road.

Discussion of Drainage Network Evolution  
in Selected Reaches of the Study Area

Hydro-Morphologic Changes at the Sediment Retention Dam Site

During the summer and early fall of 1980, the U.S. Army Corps of Engineers constructed two adjacent sediment/debris retention structures across the North Fork Toutle River valley (designated DRS N-1). The dams are located between the distal end of the mudflow/debris avalanche deposits and Camp Baker. The purpose of these structures was to retain a large quantity of sediment and erosional debris close to the mountain in order to lessen the immediate effects and problems associated with excessive sediment deposition further down-river. By late December 1980 (less than three months after completion), the southern storage area had been filled with approximately  $8 \times 10^6 \text{ m}^3$  of sediment and debris (Lehre, Collins, and Dunne, 1981, p. 222). During peak runoff conditions, sediment was being transported directly through the south spillway. The following sequence of maps chronicles the rapid changes that transpired in this particular reach of the river during the 1981-82 water year, including: channel characteristics associated with aggradational processes; the February 1982 failure of the north dam spillway; and accelerated erosion resulting from multiple breaches in the dam structures. Due to limited air photo coverage, the 13 October 1981 map (Fig. 4) includes an interpretation of only the southern half of the retention dam site. Sediment deposits have partially filled the designated storage area. Suspended sediment and bedload is cascading unimpeded over the spillway.

A braided river pattern with anastomosing channels characterize the surface of the storage area. Off-shoots from the main stem of the river are in the process of filling in the northwest quadrant of

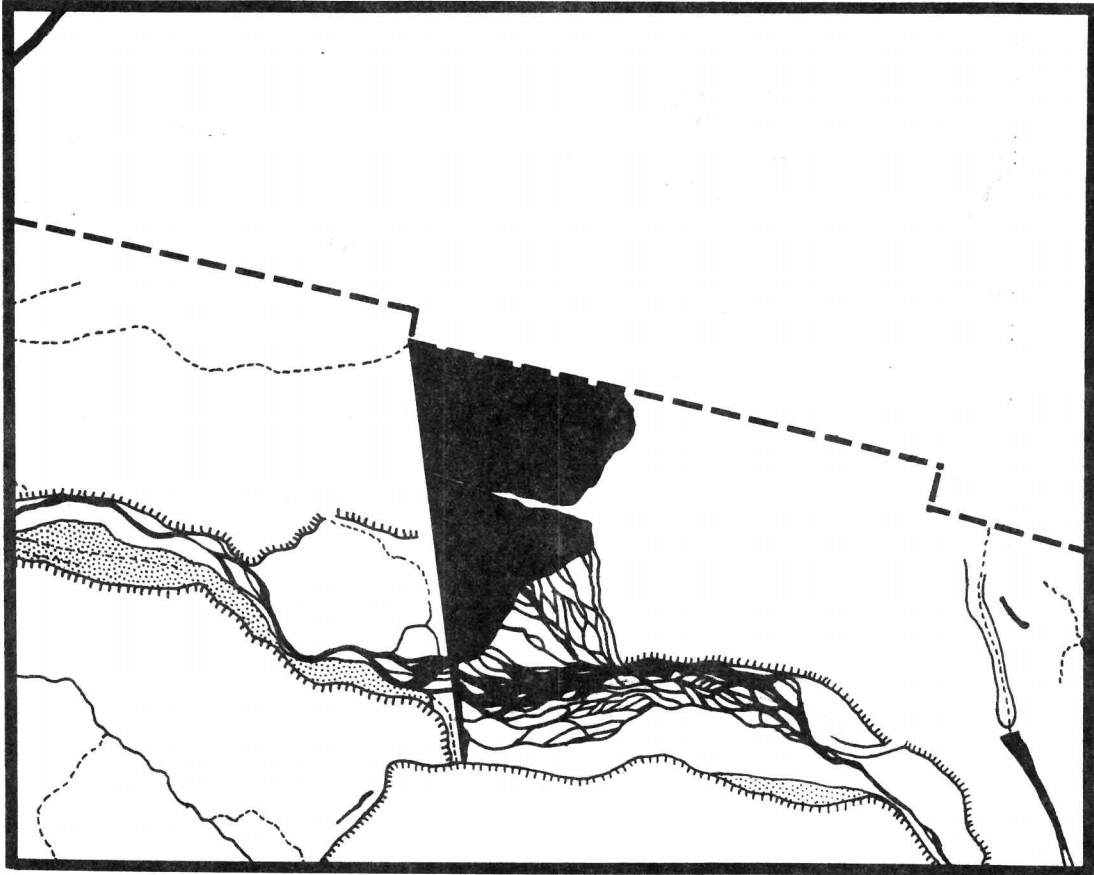


Figure 4. Physical appearance of the retention dam area on 13 October 1981.

the storage area and thereby reducing the remaining surface water storage capacity. An alluvial fan-shaped feature is present indicating that there is a change in the channel slope which encourages deposition. The location of the access road and levee situated between the north and south storage areas is also indicated on the map.

The 24 November 1981 map (Fig. 5) suggests an increase in the volume of river discharge since the preceding map date. The increased discharge is in direct response to runoff from the first rainfall producing storms of the fall season. The braided pattern of the river has extended headward approximately 275 m (900 ft). The direction of sediment input continues to be toward the northwest quadrant. Each new runoff pulse contributes to the buildup of sediment and the corresponding loss of surface water storage. Surface water storage behind the south dam structure has nearly been eliminated. Except for a small gap between flightlines, the location of both dam structures and relationship of their respective storage areas are shown for the first time. The 11 and 16 December 1981 map (Fig. 6) shows the large reservoir situated behind the northern dam, while the southern dam where the main river flow is occurring, has been completely filled in with sediment. A small off-shoot branch from the main stem of the river continues to flow in a northerly direction towards the northern reservoir. The road/levee separating the two catchment areas has recently been breached. Small quantities of discharge and sediment are entering the north reservoir at the breached point. The surface height of the north reservoir appears to have increased on the order of approximately .5 to 1 m (1.6 to 3.3 ft). Note the change in the spatial distribution of terraces immediately west of the south spillway. Portions of the stored sediment have been eroded away by the meandering river channel and transported further down-river.

The 06 February 1982 map (Fig. 7) indicates that the width of the floodplain behind the south structure has increased to the north

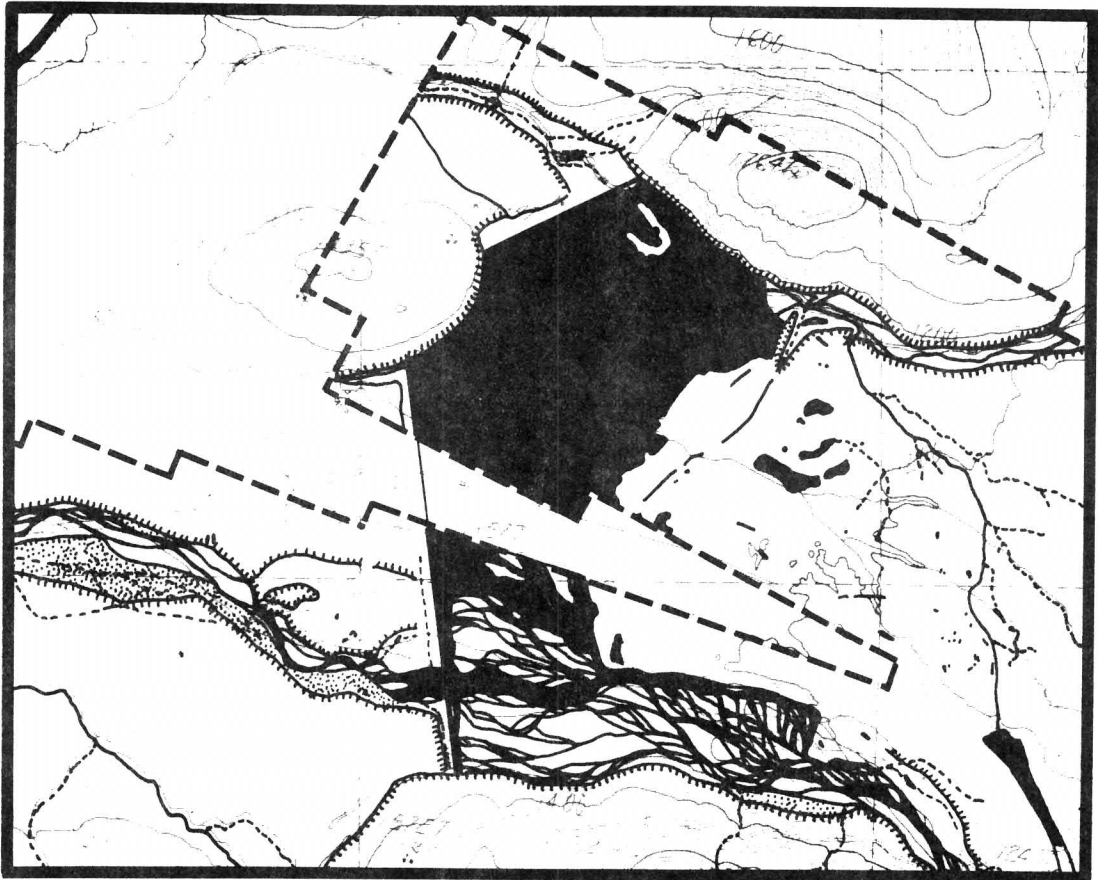


Figure 5. Physical appearance of the retention dam area on 24 November 1981.



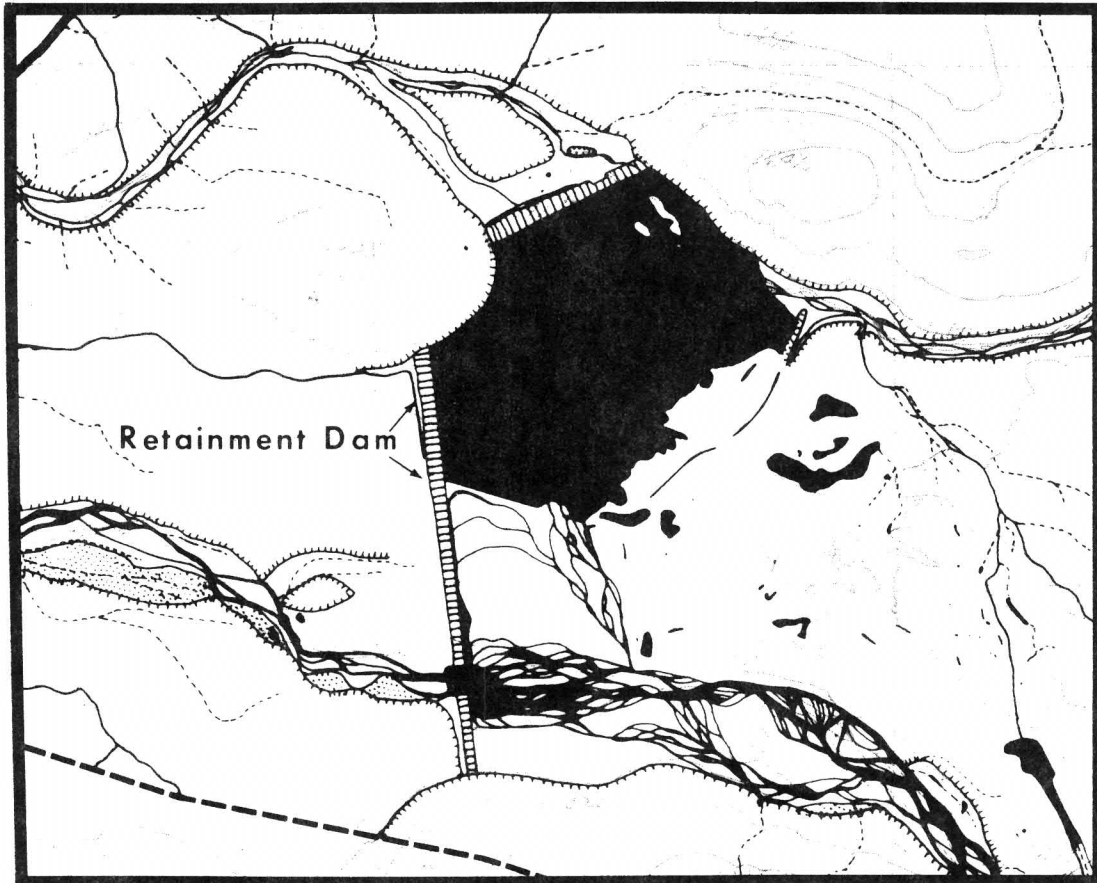


Figure 6. Physical appearance of the retention dam area on 11 and 16 December 1981.

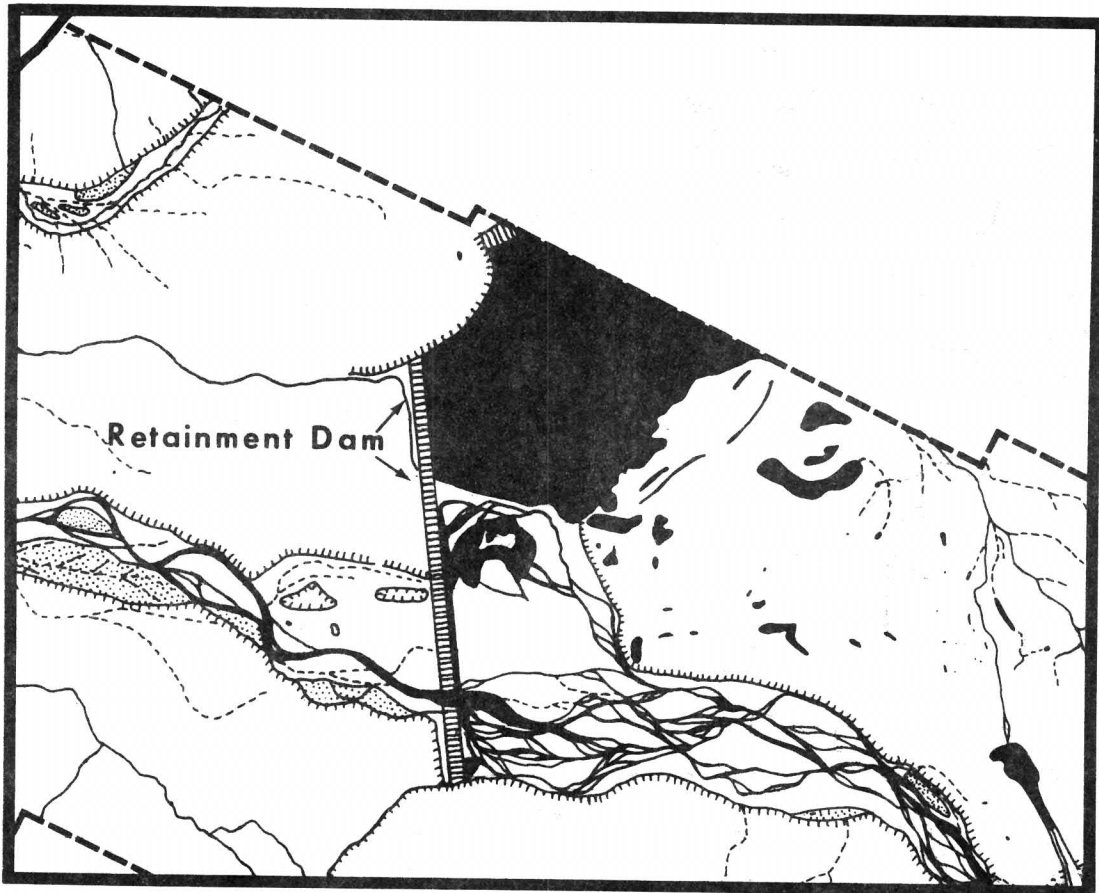


Figure 7. Physical appearance of the retention dam area on 06 February 1982.

by approximately 45 m (150 ft). This growth appears to be in response to lateral erosion resulting from the growth and extension of in-channel sediment storage. The area of channel braiding extends across the entire breadth of the floodplain. The break between the two storage areas has been plugged. The small north flowing branch of the river is now looping back along the south dam structure. An area of temporary shallow, water storage south of the access road/levee is also indicated on this map.

The most significant changes to the hydro-morphologic character of this particular reach of the river valley are illustrated on the 05 March 1982 map (Fig. 8). The substantially altered configuration of features are the direct result of: (1) peak discharge rates following a sustained period of precipitation in February 1982; and (2) major upriver channel changes. The north dam spillway failed on 20 February 1982 when a flood surge entered the north reservoir storage area from Bear and Hoffstadt Creeks. The flood surge originated west of the Elk Rock area (SW1/4, Sec. 1, T9N, R3E) when the peak runoff flow (perhaps as much as 30 to 50 percent of the total river discharge) bifurcated northward into a developing gully system that was a tributary to Bear Creek (Fig. 9, bottom). The possibility of such a sequence of events occurring was indicated as early as mid-December 1981 when a small stream flow was shown originating at the flood-stage bifurcation point (Fig. 9, top). The collapse of the north spillway resulted in the rapid drainage of the stored water and the initiation of a multiple series of interrelated erosional processes. These associated processes probably included: liquefaction movement of super-saturated fine to coarse grained sediments; the occurrence of slump/earthflows resulting from the removal of toe-support as the ensuing erosional channel developed; and the clearly identifiable development of headward migrating gully systems. As the new channel continued to cut down through the spillway, distinctively large terraces were produced. Within the main channel, a knickpoint of considerable height is observed

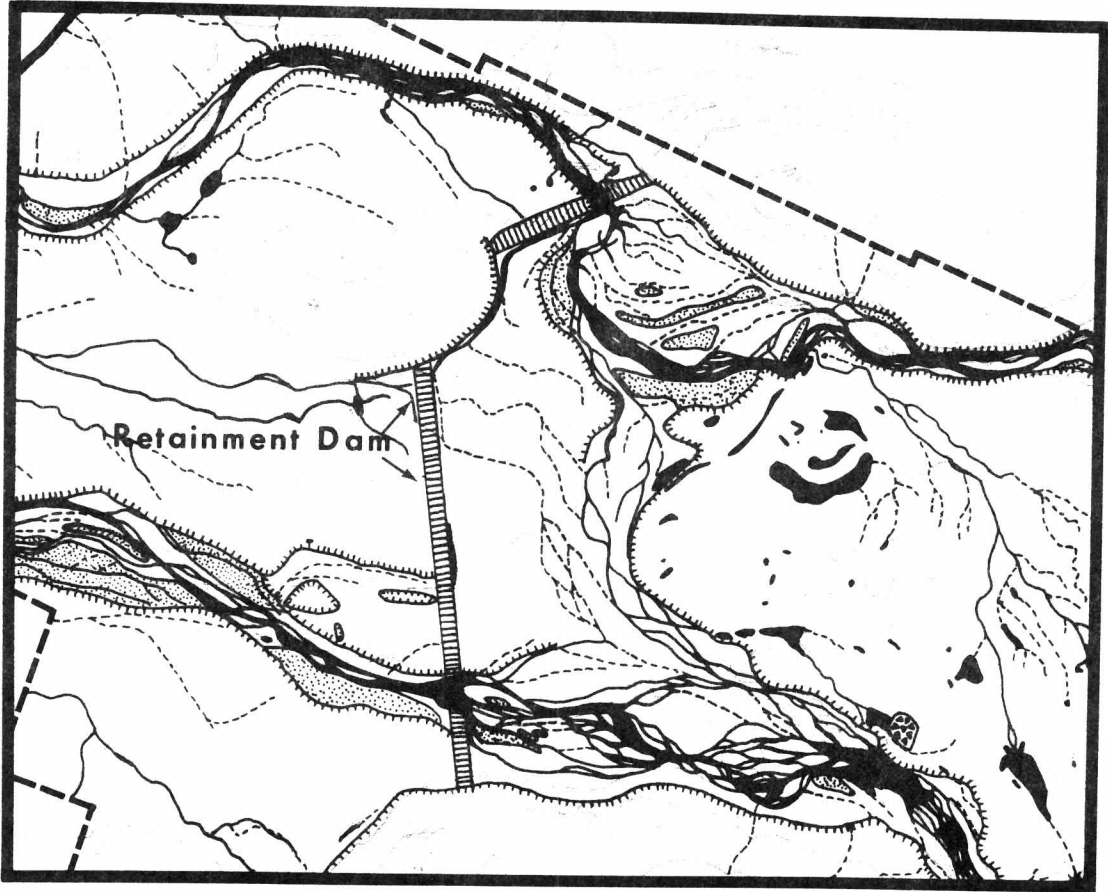


Figure 8. Physical appearance of the retention dam area on 05 March 1982.



Figure 9. Location of the river bifurcation point west of Elk Rock. (Top) On the 06 February 1982 map a small off-shoot stream from the main stem of the river is flowing towards Bear Creek. A similar relationship existed on the 11 and 16 December 1981 map. (Bottom) The 05 March 1982 map illustrates the physical features that were produced by the 20 February 1982 flood surge. Note the numerous terraces located in the new floodplain. The river has since returned to its former channel. There is no longer any direct discharge into the Bear Creek system from this point, probably because of a rise in the floodplain levee.

from the available imagery to be migrating headward through the former deposits of sediment and debris. Discharge from the main stem of the river continues to flow towards and then through the north spillway in response to the integration of the two sediment storage areas.

The last of the interpretative maps, dated 13 October 1982 (Fig. 10), indicates how the main river channels have changed during the spring and summer months. At the southern end of the south dam structure the river is in the process of cutting a new channel and creating a shallow gradient alluvial fan. During high runoff periods, part of the main stem of the North Fork Toutle River now flows into Deer Creek. This river course change can be expected to continue during the coming year. As a result of a steepened river slope gradient caused by rapid down cutting through dam structures, a confining floodplain with steep embankments has been developing in both the north and south sediment storage areas. The areal extent of terraces has also increased during the summer low flow discharge period. This would suggest that the river, during the summer of 1982, was experiencing a period of degradation. This stands in direct contrast to the aggradation processes that dominated the area previously. A comparison of the sediment storage area immediately behind the south dam reveals that from October 1981 to October 1982 the width of the floodplain has increased from approximately 275 m (900 ft) to 800 m (2,640 ft); a nearly three-fold change in the actual channel width.

An aerial view of the retention dam site on 13 October 1982 is provided in Figure 11. The bright gray area indicates the spatial distribution of the sediment that had been previously deposited behind the dam structures. The darker tones within the storage area indicates the presence of antecedent moisture below the surface of the active channels. If the current trends remain significantly unchanged, the river channel can be expected to continue its down-cutting progression through the stored sediments during the course of the next several years.

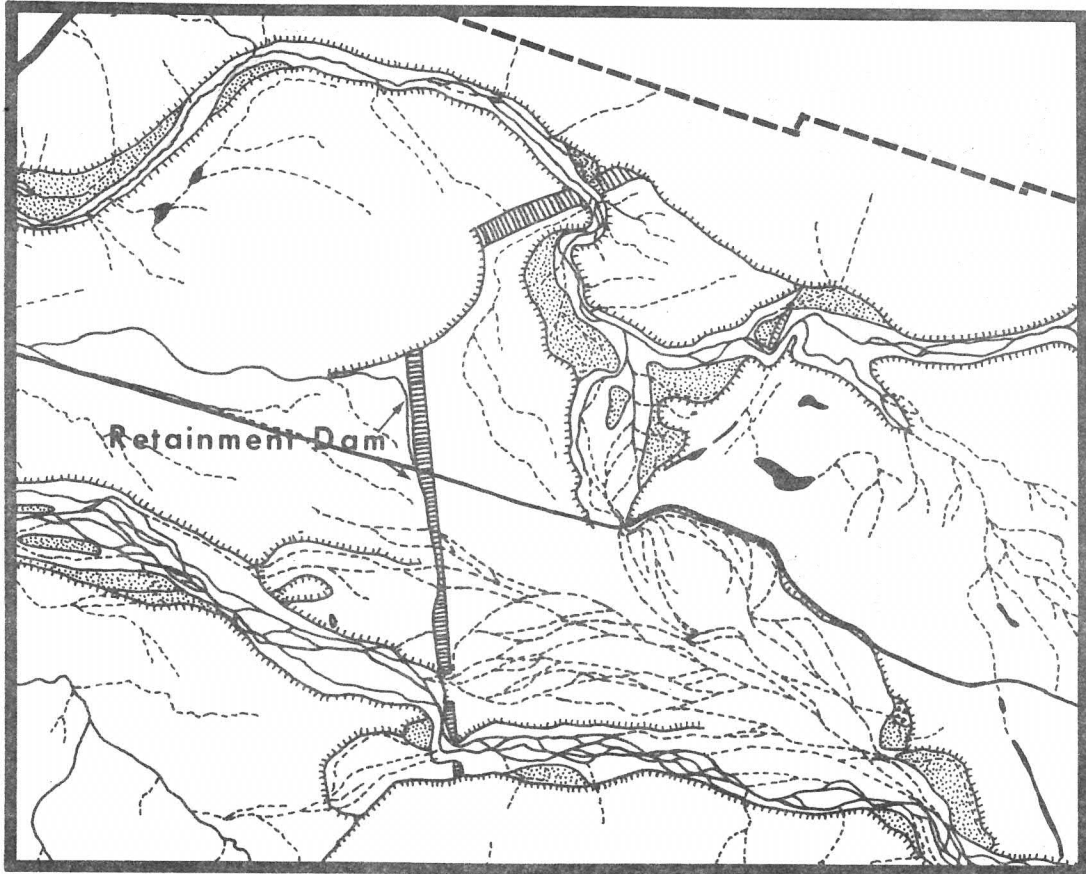


Figure 10. Physical appearance of the retention dam area on 13 October 1982.



Figure 11. Aerial view of the sediment retention dam area on 13 October 1982. Compare this photograph with the interpreted map presented in Figure 10 (Oregon Army National Guard).



## Evolution of a Braided River Pattern

Of the numerous hydrologically formed or modified landform features that exist in the study area, one of the most interesting in terms of its temporal and spatial evolution, is a particularly large region characterized by an extensive braided river pattern. The identified reach of the North Fork Toutle River is located 4 km (2.5 mi) west-southwest of Coldwater Lake and 1.6 km (1 mi) northeast of Jackson Lake. This section of the valley floor has been predominated by a complex network of divergent and convergent river links since the late fall of 1981. The braiding process begins at approximately the upper limit of the thin, discontinuous mudflow deposits that lie on the surface of debris avalanche material emplaced following the 18 May 1980 eruption of Mount St. Helens (Lipman and Mullineaux, 1981). The following series of map descriptions, chronicle through a one year period, the spatial changes to the hydrologic regime that occurred in response to rainfall and snowmelt runoff from the 1981-1982 storm events.

The 13 October 1981 map (Fig. 12) shows the main river channel is located on the north side of the valley. Only limited braiding of the river is taking place. The interpreted features indicates periods of alternating aggradation and degradation channel processes modifying the terrain surface prior to the map date.

Degradation of the channel is limited to isolated occurrences of streambank erosion within the confines of the identified floodplain. There are only a few terraces present along the margins of the floodplain. An intermittent stream network has evolved on the generally smooth terrain surface immediately south of the main river channel. A break in the floodplain embankment is evident towards the headward source of these streams. At this hydrologically identified critical point, overflow and sediment deposition by the river have occasionally coincided with periods of peak discharge conditions. A

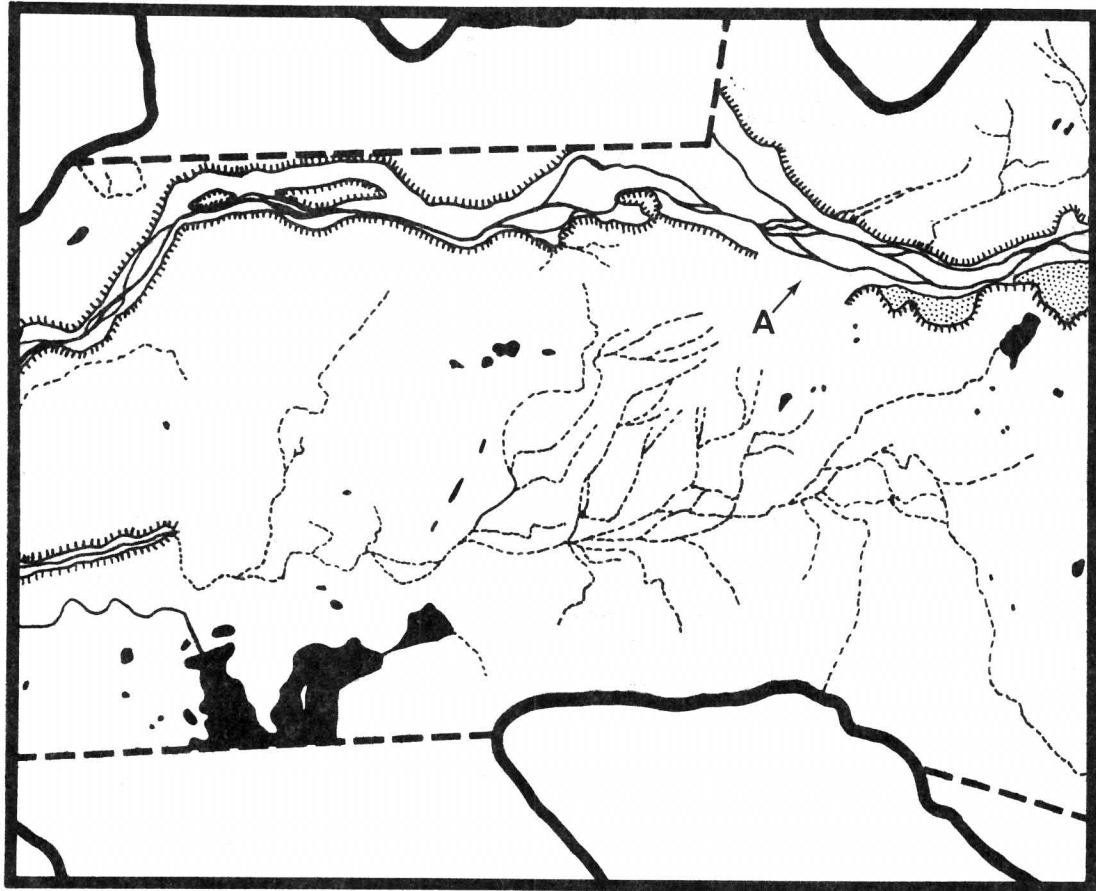


Figure 12. Physical appearance of the "braided reach" of the North Fork Toutle River on 13 October 1981. Jackson Lake is located in the lower left hand corner of the map. The natural break in the floodplain embankment is labeled "A".

major change in the course of the river occurred at this overflow point sometime between the map dates of 13 October and 24 November 1981. The large body of standing water situated at the bottom of the map is Jackson Lake. The impounded lake was formed as a result of debris avalanche material blocking the previous outlet point for the Jackson Creek drainage system.

The map dated 11 and 16 December 1891 (Fig. 13) illustrates the first full view of the hydrologic responses that took place within this selected river reach following the initial series of fall storm events. Several distinctive characteristics associated with a braided river network are clearly evident. The aggradation of sediment, transported into the area from upriver erosional sources, is the predominant hydrologic process. As a result of sediment and bedload deposition, numerous anastomosing channels are diverging and converging throughout this significantly modified reach of the river valley. The maximum width of braiding extends 480 m (1,575 ft) across a new floodplain zone that is conspicuous in its lack of confining lateral embankments and terrace developments. At the upper end of the mudflow deposit, the river network has generally bifurcated such that the greatest volume of total river discharge is flowing first towards and then along the southern half of the river valley. At this time, the river has continued to maintain a sustained flow through the northern channel as well.

The general character of the river flow suggests that the gently sloping, and for the most part, non-hummocky terrain surface consists of loosely consolidated sediment that is heterogeneous and predominantly coarse-grained in size. The presence of a braided river pattern of this size would also indicate that the channel is experiencing a high gradient/discharge ratio and massive amounts of sediment influxes derived from upper watershed erosional activities.

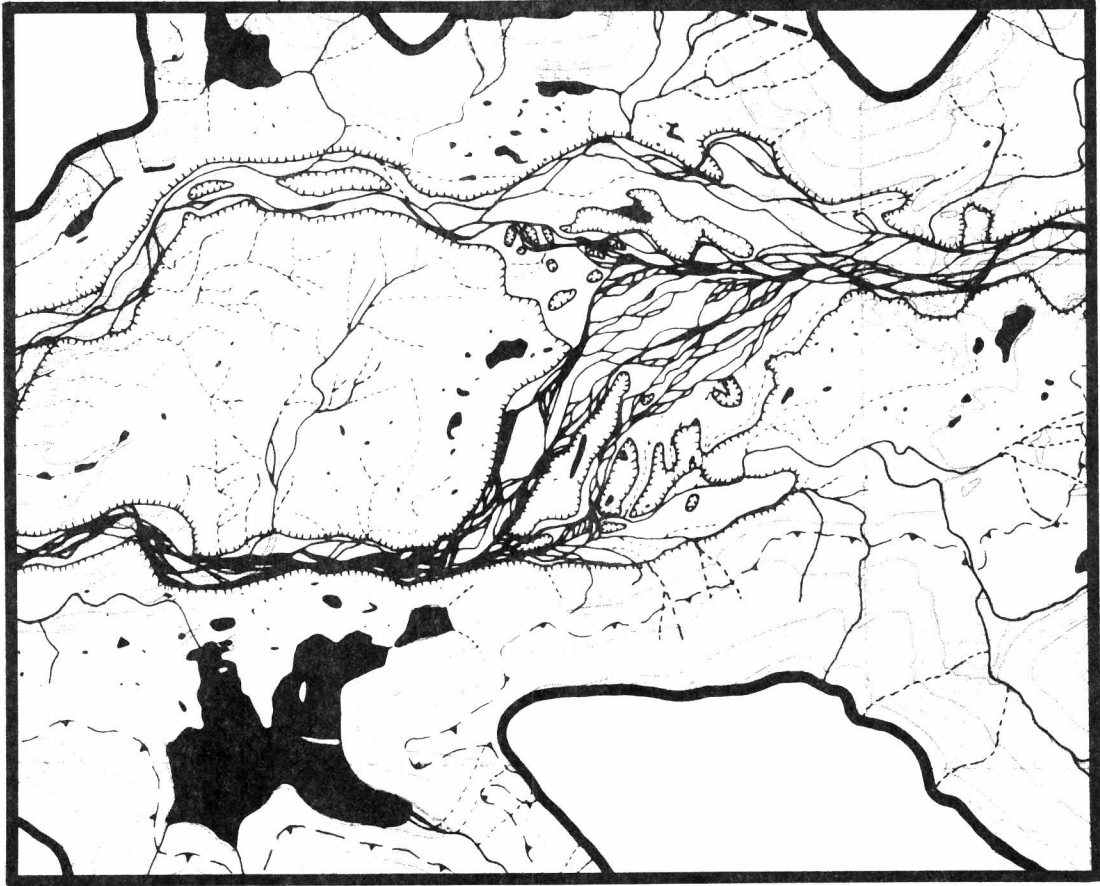


Figure 13. Physical appearance of the "braided reach" of the North Fork Toutle River on 11 and 16 December 1981.

The 05 March 1982 map (Fig. 14) further amplifies the dramatic hydro-morphological changes that have been taking place within this particular reach of the river. At the time of imagery acquisition, the river was experiencing a period of high discharge. Comparison with the two previous maps reveals a significant number of modifications to the land surface configuration in direct response to a variety of fluvial and associated mass wasting processes; especially from upriver erosional sources. Although the main channel continues to be dominated by braiding, and associated aggradational processes, the river channel is also beginning to degrade through the depositional material in the upper reaches of the braided area. Several large terraces are emerging along the floodplain margins as a result of this shift in process emphasis.

The river has moved laterally westward since December, reworking new areas of previous mudflow deposits and creating new, interconnected channels. The entire river system is becoming more integrated as the contributing streams and gullies develop their channels headward. Downcutting by the river in the northeast quadrant of the braided area is resulting in the truncation of the previously westward flowing branch of the river. Direct contribution to the northern channel is now restricted to a single flow route from the main stem of the braided river.

Most of the various channel modifications mentioned above are effectively exemplified in Figure 15. This photo is from the series used in producing the 05 March 1982 interpretative map. The bright gray linear strands indicate the location of the flowing braided river. The gray tonal reflectance quality of the river is indicative of high concentrations of suspended sediment. Subtle textural differences in the upper right hand corner of the photo indicate the location of a large, emerging terrace and resulting truncated flow support to the north channel floodplain.

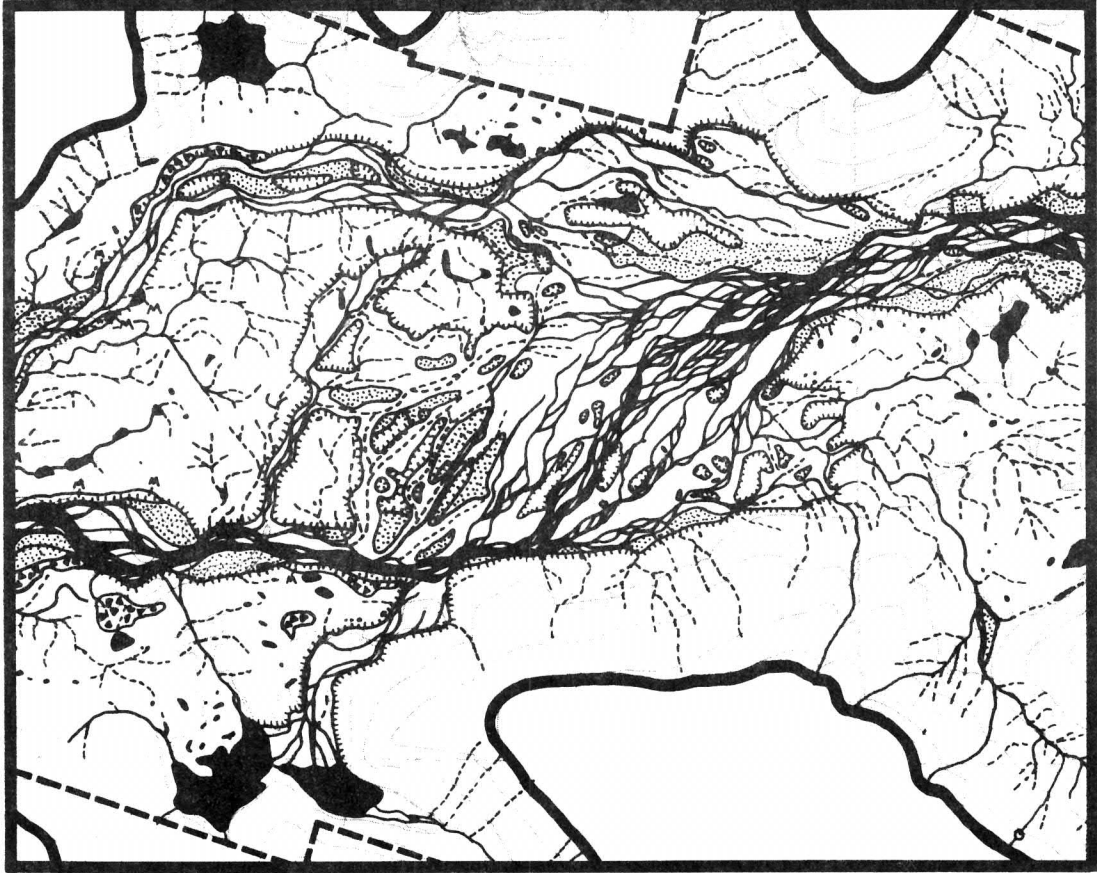


Figure 14. Physical appearance of the "braided reach" of the North Fork Toutle River on 05 March 1982.



Figure 15. Aerial view of the "braided reach" of the North Fork Toutle River on 05 March 1982. Compare this photograph with the interpreted map presented in Figure 14 (Oregon Army National Guard).

An entrenched floodplain transecting the loosely-defined braided river area had emerged by 13 October 1982 (Fig. 16). Apparently, the period from March to October 1982 was characterized by a degradational dominance of the channel processes that was correlative with reduced discharge rates. Although river braiding continues in the restricted confines of a reduced floodplain, secondary intermittent channels are now present where previously the braided river had flowed over a wide expanse of the valley floor. There is no longer any evidence of direct contribution to the northern channel from the main river stem. Several tiers of terrace levels occupy areas both within and along the margins of the floodplain. Another notable change that has taken place is with regard to the isolated hummock islands consisting of irregular, blocky material. Most of these disjunct landform features from the 18 May 1980 eruption have either been totally or partially buried with sediment accumulations, or have experienced channel erosion processes that removed the upper most portion of the hummock mound. These changes probably occurred immediately after the completion of the previous map (i.e., during the period of March through May 1982). Entrenching of the floodplain, in contrast, probably occurred during the months of June to October 1982 which corresponds to the period of lowest discharge during the water year.

#### Major Outbursts of Depression Ponds and Impounded Lakes

The massive debris avalanche which accompanied the 18 May 1980 eruption transformed the upper North Fork Toutle River valley into a barren landscape. The conversion from virgin forest to a pristine, non-vegetated terrain surface was almost instantaneous. The new surface consisted largely of erratically distributed accumulations of





Figure 16. Physical appearance of the "braided reach" of the North Fork Toutle River on 13 October 1982.

rock, ash, ice, snow, and other debris. Atop this immoderate and hummocky terrain surface hundreds of depressions were created. Many of these closed depressions quickly filled with water during the succeeding months. Some water input was undoubtedly in direct response to the melting of snow and glacial ice blocks that had been entrained and rafted down from glaciers on the northern flank of the mountain. The two principal water producing sources for these depression ponds, however, were from surface runoff and sub-surface water flow as derived from rainfall and snowmelt events.

Surface runoff occurs whenever and wherever the surface infiltration capacity is exceeded. Numerous rills and gullies attest to occasional runoff flows into these closed depressional areas. Sub-surface throughflow of water has contributed to the formation and maintenance of these ponds in those situations where the groundwater level intersects the basal area of the depression. Many of these developed ponds are today classified as ephemeral; seasonally going dry during the low precipitation summer months. Those that are perennial tend to have a large areal extent and/or a slower groundwater seepage rate. Areas which have a preponderance of depression ponds are located within the Elk Rock narrows (N1/2, Sec. 7, T9N, R4E), and southwest of Coldwater Lake (Sec. 2 and 11, T9N, R4E).

Along the margins of the valley, numerous impounded lakes were formed when tons of debris material blocked the lower reaches of tributary stream watersheds. The most notable of these impounded lakes were Spirit, Coldwater, Castle, and Jackson Lakes. Because of their particular size (i.e., the total volume of potential water storage), and the possible catastrophic consequences to the lower Toutle River valley from flooding should any of the impounding debris dams collapse, the U.S. Army Corps of Engineers in the summer of 1980 embarked on a project designed to construct outlet channels through the Coldwater and Castle Lake blockages. In stark contrast to the alterations performed on these two impounded lakes, Spirit Lake remains a closed watershed sink with no natural outlet point. The

water level of Spirit Lake continues to rise despite the efforts by the U.S. Army Corps of Engineers to pump water from the lake. There remains a very real and serious flooding threat from any of a number of possible triggering mechanisms, such as: blockage area collapse; headward migrating gully channels; erosion due to underground piping; or if left unchecked, to the eventual over-topping and resulting down-cutting through the restraining debris material.

Within this study area scenerio, several major and minor outbursts from depression ponds and impounded lakes have occurred such that the fluvial dynamics of the evolving drainage networks have been impacted and the rate of development accelerated. Most of these ponds and lakes have been drained during periods of peak discharge, and have, therefore, gone unwitnessed and non-recorded. From these interpretative maps, approximate occurrence dates can be assigned, as well as the probable cause deduced.

One of the most noteworthy and ultimately consequential events was the demise of Jackson Lake. Probably during the peak discharge period that occurred on 20 February 1982, the debris flow material impounding the lake was eroded away. Emerging from the "braided reach" of the upper North Fork Toutle River valley, the coalescing channels of the river were directed southwesterly into the steep channel embankment that had separated the lake from the floodplain; a distance of approximately 73 m (240 ft). Rapid streambank erosion, coupled with the equally rapid removal of eroded material, allowed the main flow of the river to penetrate through the blockage barrier and continue its southwesterly trajectory into the lake storage area. In response to this hydrologic flood surge, the lake drained northwesterly to the main floodplain channel. This added volume of water was probably contributory to the downriver bifurcation into Bear and Hoffstadt Creeks which ultimately resulted in the collapse of the north retention dam spillway. Within the former lake bottom, sediment was deposited during the recessional phase of the flood event, forming an alluvial fan feature in the process. The sediment

accumulations had the effect of producing two smaller lakes within the former extent of Jackson Lake. Figure 17 contrasts the landform appearance changes that developed between the 06 February and 05 March 1982 mapping dates.

In contrast to the hydrologic events that occurred with regard to Jackson Lake, in most cases the random draining of depression ponds and impounded lakes was in response to "capture" caused by the headward migrating network of gullies and streams. As the channels eroded in-situ material and transported it away from the source area, the distance separating the stored water and the evolving channels was reduced. During high intensity or long duration storm events, the threshold limit between stability and collapse of the retaining debris structures was occasionally exceeded, thus producing outburst drainage of the stored water. Nowhere in the study area has this progressional process been more evident than along the southwesterly flanks of Coldwater Ridge (S1/2, Sec. 12 and N1/2, Sec. 13, T9N, R4E). A comparative analysis of the 11 and 16 December 1981 and the 05 March 1982 map (Fig. 18) indicates that by March 1982 most of the ponds and lakes in this area had been captured by the headward migration of the rapidly evolving channel network. In the coming months and years, the total area occupied by ponds and lakes will continue to be reduced as these temporary landform features succumb to a renewal of relative landform stability and the dynamic equilibrium status between driving forces and resistance.

#### Shoreline Changes at Spirit Lake

Because of its proximity to Mount St. Helens, and the northerly direction taken by the lateral eruptive blast, Spirit Lake was the most severely impacted of the pre-eruptive lakes. A comparison of the lake prior to and immediately after the eruption indicates that

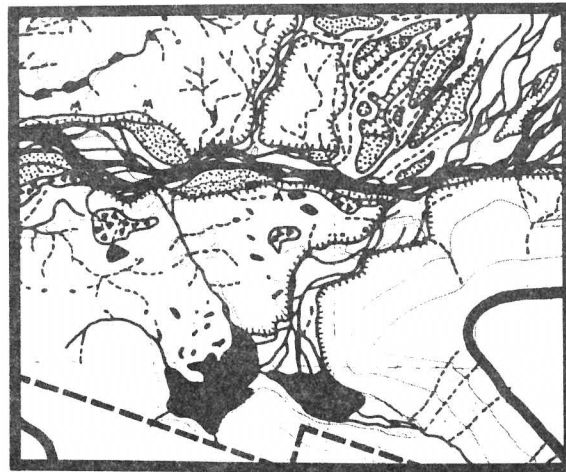
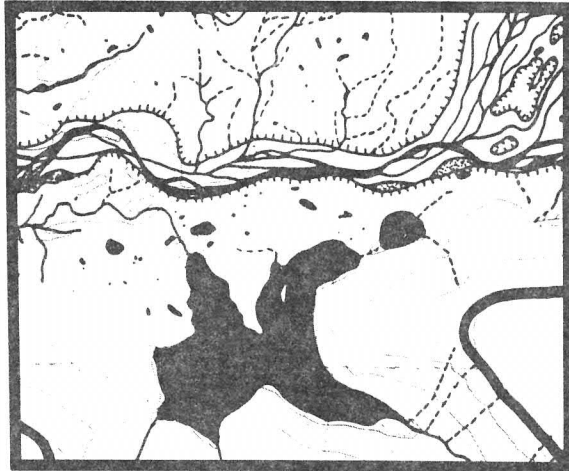


Figure 17. Jackson Lake before and after the outburst occurrence in February, 1982. (Top) The areal extent and physical appearance of the lake on 06 February 1982. (Bottom) The physical appearance of the former lake area on 05 March 1982 following inundation by the North Fork Toutle River.

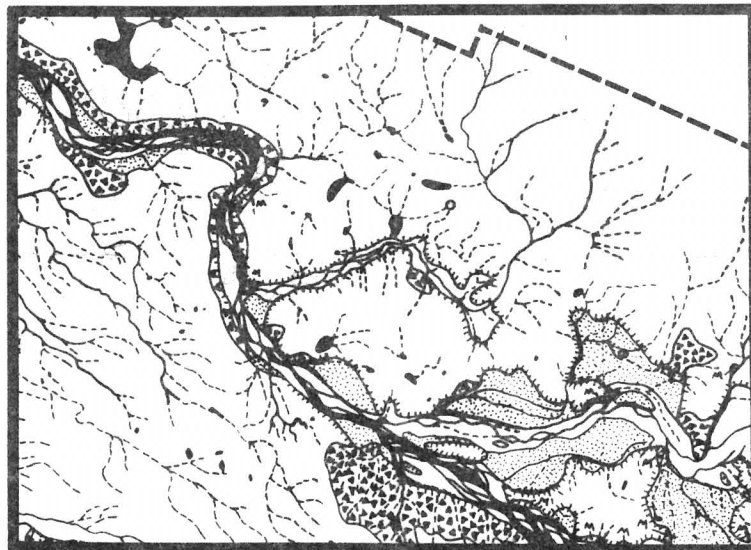


Figure 18. Evolution of an area on the flanks of Coldwater Ridge due to the occurrence of outburst ponds and lakes. (Top) Spatial distribution of depression ponds and impounded lakes on 11 and 16 December 1981. (Bottom) The same area on 05 March 1982. Note the change in the headward migration of the stream and gully network.

the lake rose in altitude, increased in areal extent, and decreased in depth. The initial 60 m (200 ft) rise in the lake level was due in large measure to the blockage of the North Fork Toutle River outlet, runoff from melting snow on the volcano, and the partial filling of the lake with debris material (Dion and Embrey, 1981). Since Spirit Lake is now the low point in a closed watershed (local base level), the lake level gradually but inexorably continues to rise in response to rainfall and snowmelt generated runoff.

The 11 and 16 December 1981 interpretative map (Fig. 19) indicates that the elevation of Spirit Lake is approximately 1,047 m (3,435 ft). There are a couple of small rocky debris islands present in the lake as well as several small peninsulas. Along the southwest shoreline (near the center of Sec. 15, T9N, R5E), the rising waters of the lake have inundated several phreatic explosion craters. Two small craters, partially filled with water, lie just beyond the shoreline of the lake. The drainage divide through the blockage area is located along the left hand margin of the map.

By 13 October 1982, the shape and character of Spirit Lake had been significantly altered (Fig. 20). In the 10 month period between map dates, the elevation of the lake had risen 75 m (25 ft) to approximately 1,055 m (3,460 ft).<sup>1</sup> The greatest increase in surface area caused by the rising waters occurred along the west to southwestern front. Here, the shallow slope of the pumice plain allows for the most rapid expansion of the lake surface.

The islands that had been present in December 1981 were totally submerged by October 1982. The lone island appearing on the October map is actually the remnant of the former peninsula that had been jutting out into the lake. Several deltas built up by sediment

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<sup>1</sup> These elevation values are based on contour interpretations. The exact elevation levels on these particular dates were unavailable.



Figure 19. The location and spatial extent of the southwest portion of Spirit Lake on 11 and 16 December 1981.



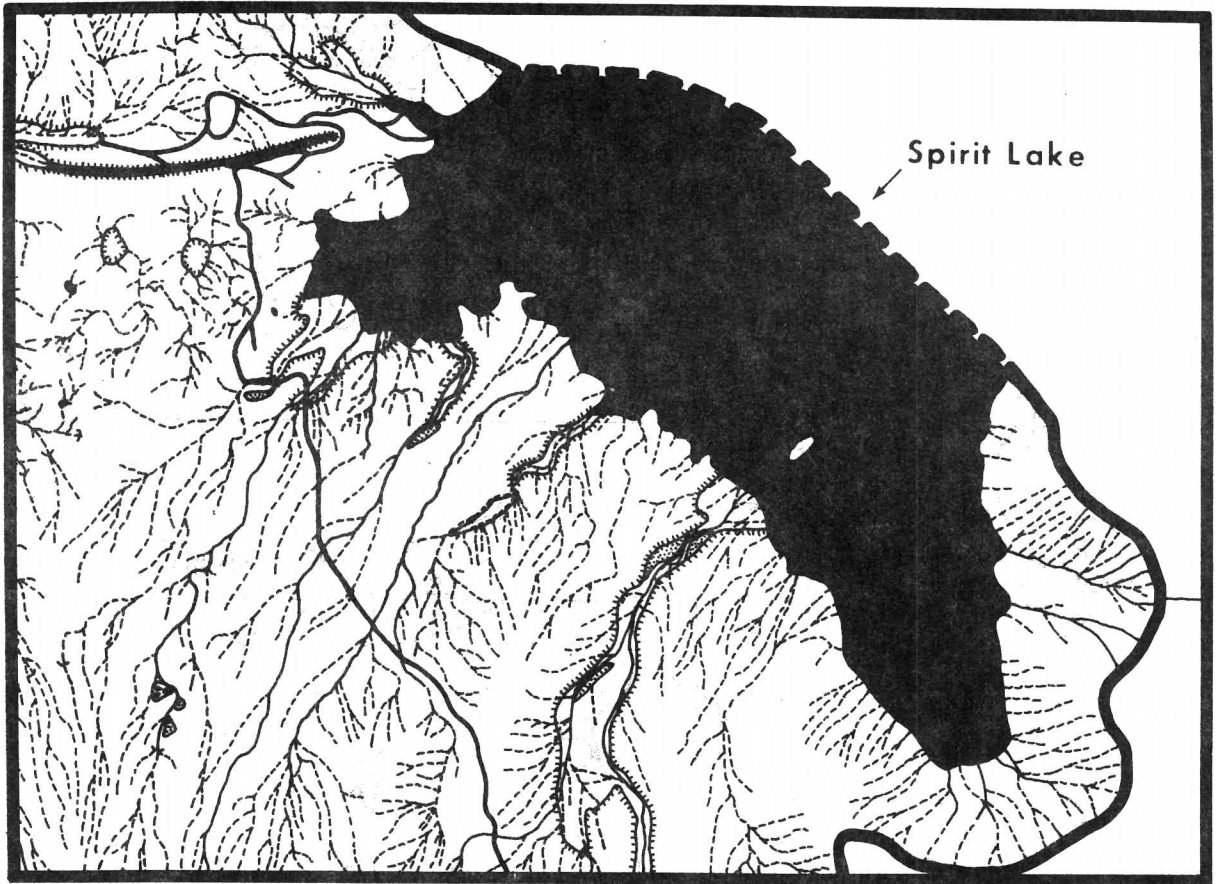


Figure 20. The location and spatial extent of the southwest portion of Spirit Lake on 13 October 1982.

deposition derived from the mountain are also present. The input of sediment, along with the occasional impacts from mudflows, contributed to the upward displacement of the lake surface and the corresponding increase in total shoreline. The major significance to this changing shoreline, of course, lies with possible consequences the encroaching waters may have on the continued stability of the debris blockage area. By the time this report was in the first draft stage, in early 1983, the shoreline of the lake had advanced to the point where the rising waters had inundated a portion of the access road delineated on the October 1982 map.

In addition to the rapidly changing appearance of Spirit Lake, the contributory terrain surface that surrounds the lake has also been evolving. For example, when the December 1981 and the October 1982 map and photo (Fig. 21) are compared and contrasted the increased density of perennial and, especially intermittent stream and gully channels, becomes quite evident. The photo and map products also serve to illustrate the general character of the hydro-morphologic features that comprise the relatively flat pumice plain area and the hummocky, irregular surface configuration of the blockage area. These various terrain features, along with the fluvial and geomorphic processes operating to modify their appearance, are intimately intertwined with the evolutionary development of Spirit Lake.

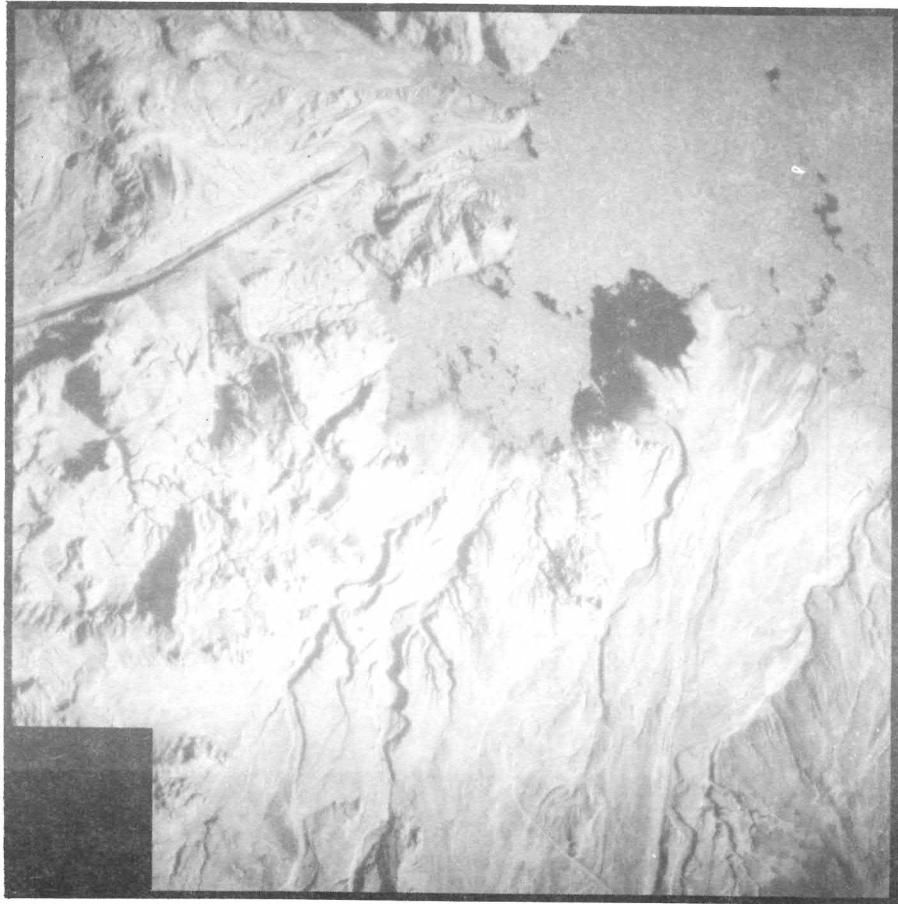


Figure 21. Aerial view of the southwest portion of Spirit Lake on 13 October 1982. Floating debris covers most of the lake surface indicating an easterly surface wind on this particular date. The access road can be seen crossing the pumice plain diagonally towards the linear-shaped drainage aqueduct constructed by the U.S. Army Corps of Engineers. Compare this photo with the interpreted map presented in Figure 20 (Oregon Army National Guard).



## 5. CONCLUSIONS

Channel changes along the main stem of the North Fork Toutle River defy generalization. Predicting the future appearance of this particular terrain surface and its associated hydro-morphologic characteristics has been extremely difficult. For example, up through March 1982, the general character of the river system above the retention dams had been one of aggradation and widening of the floodplains. Since March 1982, degradational processes appear to be predominating with terraces occupying a significantly increased proportion of the established floodplain area. In addition to these transformations, isolated parts of the study area have experienced rapid alterations ranging from periods that are dominated by incision and sediment removal, to the reoccurrence of depositional and channel-widening processes. River course changes within the floodplains occur frequently--almost daily--with occasional major shifts in the channel flow direction. Finally, the size of the actively eroding area that is contributory to downstream sediment discharge, has increased through recent drainage integration events.

In short, if one were to attempt an assessment of the evolutionary character of this unique river and its tributary stream network system, it would best be described as dominated by stochastic events. Prediction remains speculative because future weather patterns are unknown, the occurrence of mass movement and lake outburst events tend to be widely dispersed throughout the upper watershed, and our knowledge of the braiding process, and rates of bank erosion, channel development and drainage network extension is inadequate. A remote sensing based map series such as this one that chronicles drainage network changes over time, coupled with detailed ground measurements of erosional and depositional processes, can help provide the resource tools necessary to adequately predict future events and the short-term evolutionary character of the developing landscape.

The final impact of this project will not be fully realized for several years to come, as it is currently providing the observational basis for a number of other research projects. Among the on-going research projects using these interpretations are attempts to reconstruct a longitudinal profile of the North Toutle River from dispersed field transects and relate these observed changes to features depicted on these maps. Researchers calculating the annual sediment volumes for the debris avalanche area are attempting to determine the specific processes responsible for sediment loss and the sources of the sediment by correlating the particle-size distribution of sediment samples with mapped landform changes. Additionally, these maps are being used to evaluate the growth relationship with time of the drainage network and runoff contribution area in an effort to further our understanding of the taxonomy of rapid drainage network development.

As these projects, and a score of related ones, have direct bearing on the long-term erosion control and sediment management strategy decisions for the area, the Portland District of the U.S. Army Corps of Engineers has provided follow-on funding for the continuation of this mapping program through the summer of 1984.

The expected benefits range from specific observations of direct use to engineering works and applied projects of a short-term nature through long-term theoretical inferences gained by empirical measurement in the fields of hydrology and geomorphology. This project has provided an essential link between field measurement and existing theory, and has served to generate additional research approaches.

The intent of any systematic observation program is to record and represent change in a uniform manner which will be conducive to the determination of causal processes and the deviation of predicted behavior. This project has indeed met its goals and by its performance has enabled researchers to achieve some unexpected benefits.

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## APPENDICES



APPENDIX I:  
INTERPRETATIVE MAPS<sup>1</sup>

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Map #	Date
1	13 October 1981
2	24 November 1981
3	11 and 16 December 1981
4	06 February 1982
5	05 March 1982
6	13 October 1982

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<sup>1</sup> The following maps have been significantly reduced. The original mapping scale was 1:24,000. The maps were reduced to a 1:72,000 map scale for inclusion in this report.



APPENDIX II:  
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