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GEOMORPHOLOGICAL WATERSHED ANALYSIS:
A CONCEPTUAL FRAMEWORK
AND
REVIEW OF TECHNIQUES

By

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ACKNOWLEDGEMENTS

The concept of a Watershed Analysis originated from numerous individuals in CMER and other committees of TFW. In this document we develop some conceptual and technical guidelines which are consistent with those original ideas and directives. During this rather brief process, many individuals gave freely of their ideas that greatly facilitated the development of this report, and they included Tim Beechie, Brian Collins, Bill Dietrich, Tom Dunne, Jim Hatten, Paul Kennard, Kate Sullivan and Dave Summers. Thorough reviews by Dan Miller, Elizabeth Safron, Paul Kennard and Paul Bierman greatly improved this report.

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1.0 INTRODUCTION

1.1 AIMS AND OBJECTIVES

This report presents a conceptual framework and technical guidelines for evaluating present watershed conditions, and for predicting the response of hillslopes and channels to landuse. The goal is to provide a rational scientific approach for anticipating and solving problems related to forest management in mountain drainage basins. The framework and guidelines we present respond to and are consistent with the directives of the CMER taskforce on cumulative effects.

The conceptual framework is based on a single important concept: each level of analysis builds upon information acquired from the preceding step. Collectively, the analyses are referred to as a geomorphological watershed analysis (GWA).

The GWA consists of methods for measuring and interpreting erosion and channel processes in managed watersheds, and therefore for examining the relationship between watershed conditions and landuse activities. Its structure provides a variety of analyses to accommodate numerous watershed management concerns. For example, the GWA can determine whether erosion and sedimentation is produced by natural causes or by landuse (diagnosing present watershed conditions), screen for environmental thresholds, evaluate and predict influences of forestry activities on erosion and sedimentation (predicting future watershed conditions), and address habitat recovery and restoration. The protocol for applying these analyses to watersheds remains a policy decision for the participants of TFW. The analyses employed will depend on the specific environmental conditions found in a watershed, on the management questions asked, and on the education and experience of the user.

In this report we review technical methodologies for conducting a GWA. The guidelines are brief and consist of short narratives describing published techniques. We discuss relative merits and shortcomings of each. The GWA pertains primarily to hillslope and fluvial geomorphology, fisheries, and implicitly accounts for certain aspects of subsurface and surface hydrology.

This report is not a procedural handbook on how to conduct a GWA. Individuals trained in geomorphology and fishery science should, however, be able to conduct various levels of GWA using this document as a guide.

1.2 CONCEPTUAL FRAMEWORK

Geomorphological watershed analysis has three components: diagnosis, prediction, and habitat recovery (Figure 1); discussions of the three major components are located in sections 3.0, 4.0 and 5.0 of this report. The "Diagnosis" component provides a set of procedures for assessing present hillslope and channel conditions in a watershed. At this level of analysis, one can assess habitat quality or existing hillslope erosion (including natural erosion), check whether channel thresholds have been exceeded, and therefore determine the nature and cause(s) of an erosion or sedimentation problem. With "Prediction", the sensitivity of the land to future

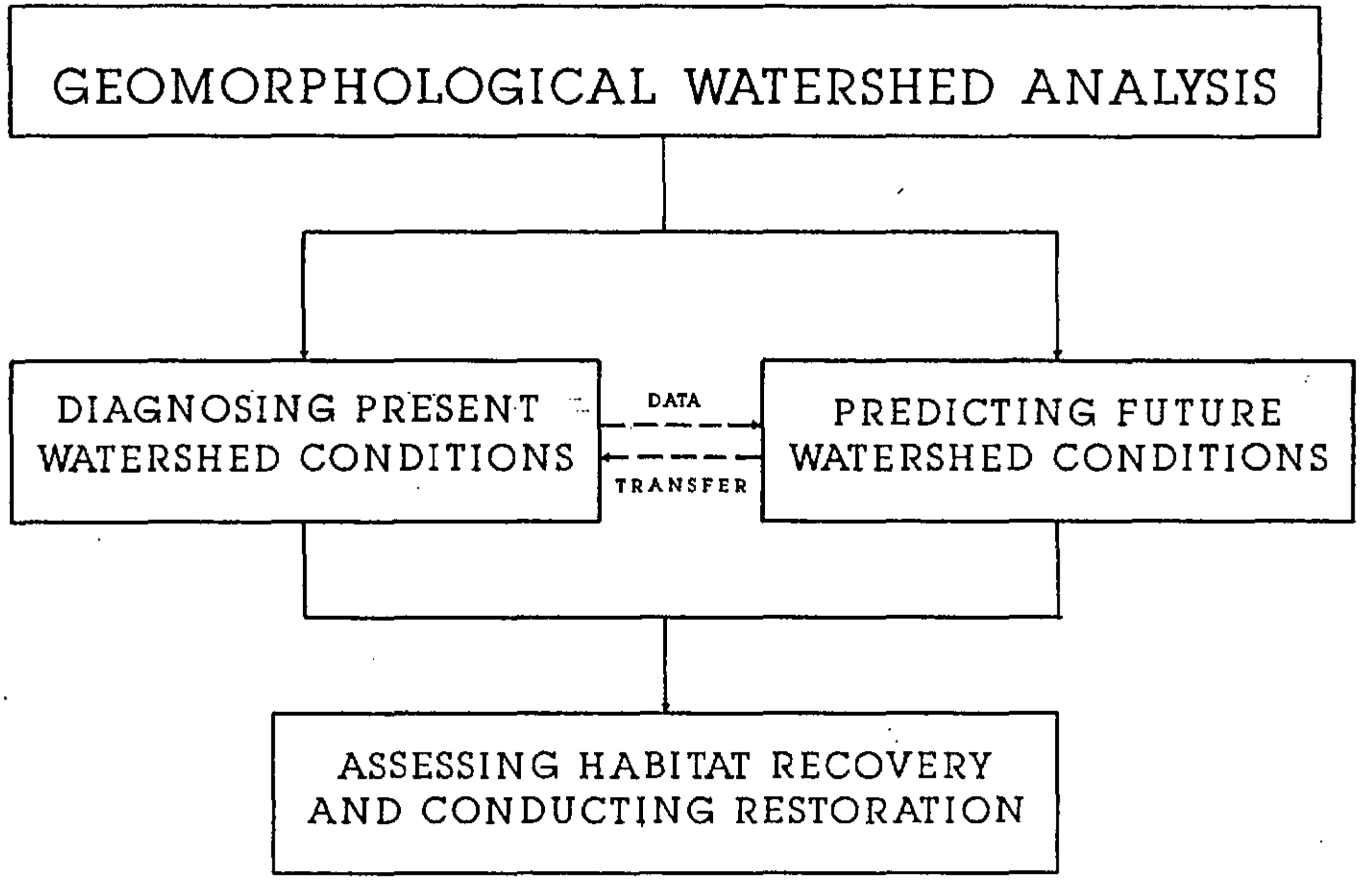


Figure 1. Flowchart showing the general structure of the geomorphological watershed analysis (GWA).

erosion and sedimentation is determined. Potential problems are anticipated at this level of analysis and adverse environmental impacts to watersheds can purposely be minimized. "Habitat recovery" uses the understanding of hillslope and channel processes gained with "diagnosis" and "prediction" to assess channel recovery and to develop programs for habitat restoration. Management applications and the general planning environment of the geomorphological watershed analysis are illustrated in figure 2.

1.3 DEFINITIONS AND TERMINOLOGY

SHALLOW-RAPID LANDSLIDE

A landslide characterized by thin soils or colluvium (generally less than two meters thick) typically overlying steep bedrock or compacted glacial deposits. Soil thickness is small compared to slope length or length of the landslide. In these landslides, debris moves quickly downslope, often breaking apart and developing into a debris flow. Shallow-rapid landslides often occur in converging bedrock topography (known as bedrock hollows, swales, or zero-order basins) where subsurface drainage is concentrated. This causes saturation of the soil and decreases stability. Shallow-rapid landslides can occur under natural forests and in clearcuts and adjacent to logging roads.

Other names given to shallow-rapid landslides: landslides, debris avalanches, planar failures. In this report, shallow-rapid landslides will be referred to simply as landslides.

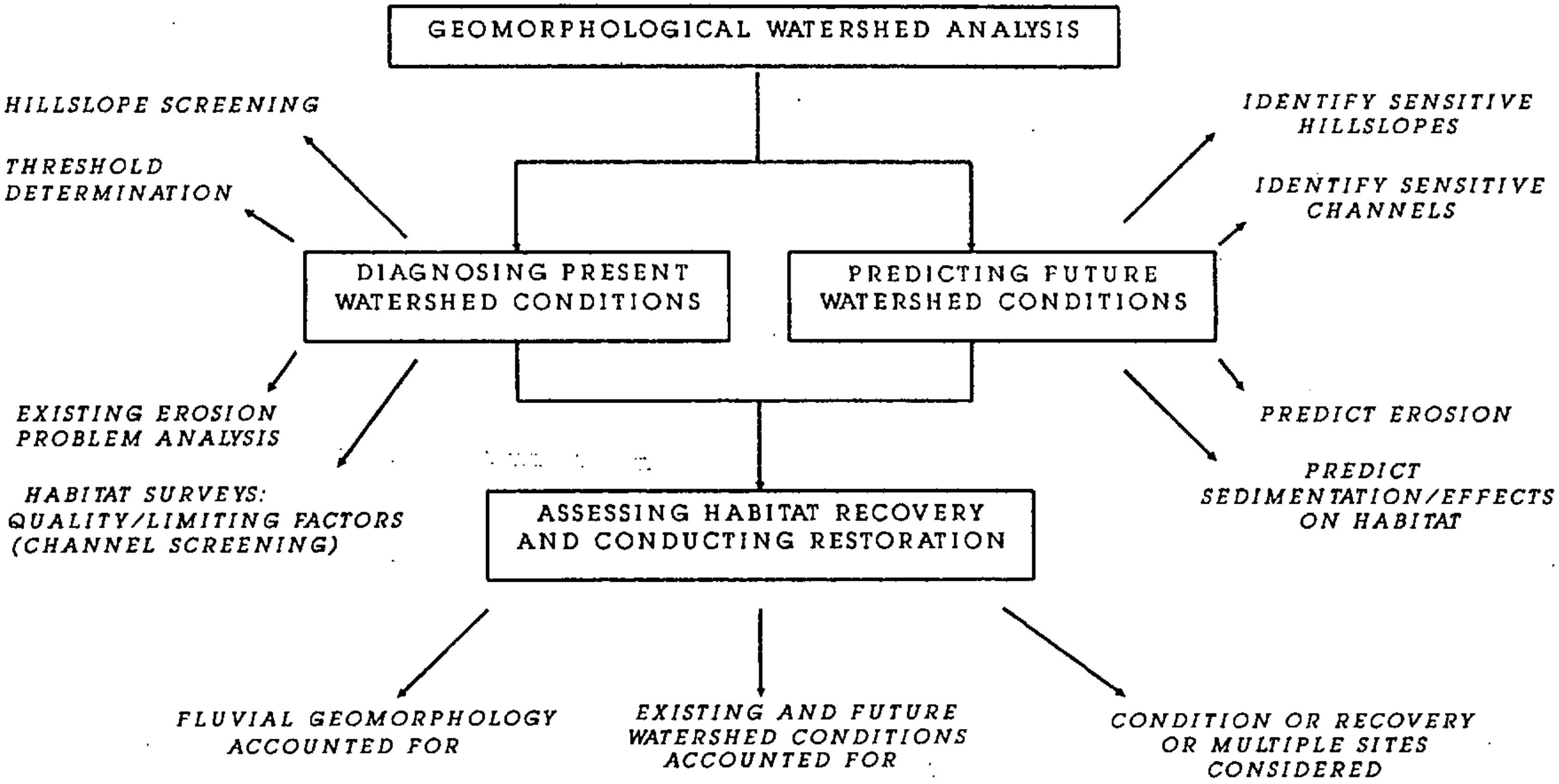


Figure 2. Management applications and the general planning environment of the geomorphological watershed analysis.

DEBRIS FLOW

A highly mobile slurry of soil, rock, vegetation and water that can travel kilometers from its point of initiation, usually in steep (> 5 degrees) confined mountain channels. Debris flows form by liquefaction of landslide material concurrently or immediately after the initial failure. Debris flows contain 70 - 80% solids and 20 - 30% water. Entrainment of additional material as the debris flow moves through first- and second-order channels (Type 4 and 5 Waters) can increase the volume of the original landslide by 1000% or more, enabling debris flows to become more destructive with travel distance.

Debris flows may impact structures and fish habitat considerable distances from their point of initiation and are one of the most destructive forms of soil mass movement in forested watersheds. Debris flows occur naturally in response to large storms and fires, and to land management activities, such as logging roads and clearcuts.

Other names given to debris flows: debris torrents, sluice outs, mud flows.

DAM-BREAK FLOODS

Deposits of landslides and debris flows can form a temporary dam within a narrow valley floor or canyon. Rapid failure of the dam releases the impounded water and an extreme flood is produced which destroys riparian vegetation and causes significant erosion and sedimentation along entire lengths of stream-order segments.

This process is referred to as a dam-break flood. In addition, dam-break floods can form from a collapse of logjams during a large flood event.

Dam-break floods entrain enormous volumes of live and dead organic material, including entire trees and large logs, and create an enlarging wedge of woody debris in the frontal portion of the floods. This wedge of organic material slows the flood and allows the capture of streamflow thereby greatly increasing the magnitude of the event.

In the Pacific Northwest, debris flows and dam-break floods have often been referred to as debris torrents, but for the purposes of hazard recognition and prediction they must be considered separately.

Other names given to dam-break floods: debris torrents and sluice outs.

SLUMP\EARTHFLOW

Slumps are deep rotational failures, typically triggered by the build up of pore water pressure in mechanically weak, and often clay-rich, rocks and sediments (Swanston, 1974). The failure surface is generally several meters or more below the ground surface. Slumping involves the downward and backward rotation of a soil block or group of blocks. The main head scarp is often steep and generally bare of vegetation. The toe is hummocky or broken by individual slump blocks.

Earthflows involve a combination of slumping and slow flow.

Earthflows can remain active for thousands of years, with periods of activity and dormancy (Swanson et al., 1987). Earthflows typically occupy a much larger portion of the landscape and move larger amounts of soil than do slumps. The toe of an earthflow is typically lobate and hummocky.

Slumps and earthflows can form on slopes as gentle as 4-20 degrees (Sidle, 1980). In Washington, they occur in altered sedimentary and volcaniclastic rocks and glacial sediments of both the east and west Cascades, the Olympics, and the coastal ranges. Deep-seated failures move most rapidly during the wet season and, unlike shallow failures which respond to individual storms, are controlled by the seasonal buildup of ground water at the base of the failure (Sidle, et al. 1985). Movement can accelerate as the wet season progresses (Swanston and Swanson, 1977).

The literature on earthflows indicates that although movement occurs naturally, it can be accelerated by landuse activities.

SURFACE EROSION

Surface erosion includes rainsplash and sheet wash erosion from all exposed soil surfaces and roads, and rilling and gullying erosion. Those areas most susceptible are fill slopes and cutbanks of roads, road surfaces, and recent landslide and debris flow scars.

CHANNEL BANK EROSION

Channel bank erosion can occur naturally as a result of large floods or because of forestry activities. The literature discussing the impact of forestry on channel bank erosion can be grouped into five topics. Forestry practices can increase bank erosion by (1) logging in and adjacent to streams, thereby decreasing stream-bank stability; (2) increasing sediment supply to streams causing aggradation of the stream bed with consequent channel and bank instability; (3) increasing the incidence of debris flows; (4) causing dam-break floods; and (5) increasing flood runoff thereby causing channel scour.

In this report, our discussion is confined to bank erosion caused by debris flows and dam-break floods, and mechanical erosion caused by machine impacts and logging or yarding operations.

SEDIMENTATION

In the context of the GWA, sedimentation refers to deposition of coarse and fine sediment in an active channel caused by an increase in sediment supply from accelerated upslope or channel bank erosion. Sedimentation may result in an increase in bed elevation, filling of pools, and an increase of fine sediment within the channel bed.

WATERSHED ANALYSIS

Watershed analysis is a term adopted by the CMER taskforce on cumulative effects and several other TFW committees to describe a process for collection of data in watersheds to analyze existing conditions and predict watershed response to landuse. Watershed analysis encompasses numerous disciplines, including botany, hydrology, geomorphology, and fish and wildlife biology.

WATERSHED SCREENING

Watershed screening is a set of methods to quickly assess certain environmental conditions which reflect the quality of certain resources, such as fish and wildlife, within the watershed. Watershed screening is a prelude to watershed analysis. Screening will identify and possibly rank the watersheds in need of more detailed watershed analysis. Watershed screening can also be used to determine whether hillslope or channel thresholds have been exceeded. At the time of this report, quantitative thresholds for channels and hillslopes are being developed.

The protocol for conducting watershed screening and analysis has not yet been developed, and remains a policy issue for members of CMER and DNR.

THRESHOLDS

A threshold uses a quantitative description of a watershed feature. A change in that feature (which results in some reduction in biological capacity) beyond a specified value indicates that a threshold is exceeded. Thresholds can be defined for measurable aspects of the channel (e.g. percent of fine sediment composing the bed, quantity of large organic debris). These quantities must be determined from field surveys. Channel thresholds can be linked to hillslope erosion (e.g. the spatial density of landslides and debris flows, and occurrence of dam-break floods). Hence, channel thresholds can be represented by hillslope conditions which can further be considered as hillslope thresholds.

SEDIMENT BUDGET

A sediment budget uses measurements from within the watershed to identify the sources of erosion and to quantify the rate of sediment production and delivery to stream channels, the flux of sediment through those channels, the volume and residence time of sediment stored in the channel and floodplain, and the distribution of grain sizes for all the sediment. A sediment budget can clarify the relationship between erosion and channel sedimentation, and the influence of forestry activities.

2.0 DIAGNOSING PRESENT WATERSHED CONDITIONS

Following is an overview of techniques for detecting and measuring hillslope erosion and sedimentation in channels for the purpose of diagnosing present watershed conditions. These processes may be identified by aerial photo analysis and are, therefore, useful for a watershed screening or threshold determination.

A more detailed analysis, such as determining the cause(s) of an erosion or sedimentation problem - either a natural or landuse related one, may require the rapid evaluation of a sediment budget.

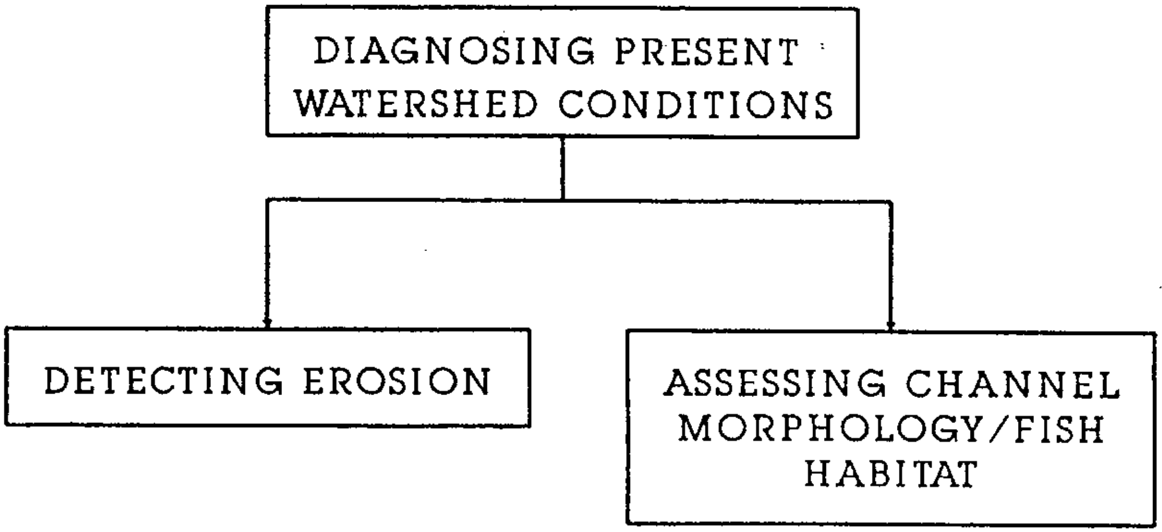
Diagnosing present watershed conditions is divided into two elements: (1) detecting erosion; and (2) assessing channel morphology and fish habitat. A flow chart summarizing the purposes and procedures of this component of GWA is shown in Figure 3. This component is incorporated into an expanded flowchart which shows all the major elements of the GWA in figure 4.

2.1 Detecting Erosion

This component of GWA can be used for several purposes. First, it can evaluate the relative severity among various erosion processes in a watershed. It can also be used as a preliminary analysis of the relationship between erosion and forestry activities. The hillslope information collected can be used as a surrogate for assessing channel conditions or channel thresholds, and therefore it be used to assess hillslope thresholds within GWA.

Erosional processes are grouped into five categories: (1) landslides and debris flows; (2) dam-break floods; (3) deep-seated slumps and earthflows; (4) channel-bank erosion; and (5) surface erosion by water and dry ravel. Subdivisions may be made and other processes added as needed.

Techniques for detecting and measuring erosion from landsliding and debris flows are often based on aerial photo interpretation and field measurements. Landslide and debris flow inventories have been conducted in the State of Washington in the Olympic Peninsula (Fiksdal, 1974; Reid, 1981), in the North Cascades (Peak Northwest, Inc., 1986), in the Lake Whatcom area (Syverson, 1984; Benda, 1990a), in the North Central Cascades (Parks, in prep.; Johnson, in



PURPOSES:	1) SCREENING FOR FURTHER WATERSHED ANALYSIS 2) ASSESS HILLSLOPE THRESHOLDS 3) EXISTING EROSION PROBLEM ANALYSIS	1) INVENTORY OF DISTRIBUTION, QUALITY AND LIMITING FACTORS OF FISH HABITAT 2) ASSESS CHANNEL THRESHOLDS
PROCEDURES:	1) EROSION INVENTORY/ RAPID SEDIMENTATION ANALYSIS 2) INVENTORY DAM-BREAK FLOODS 3) PARTIAL SEDIMENT BUDGET	1) CHANNEL AND HABITAT SURVEYS

Figure 3. Diagnosis of present watershed conditions.

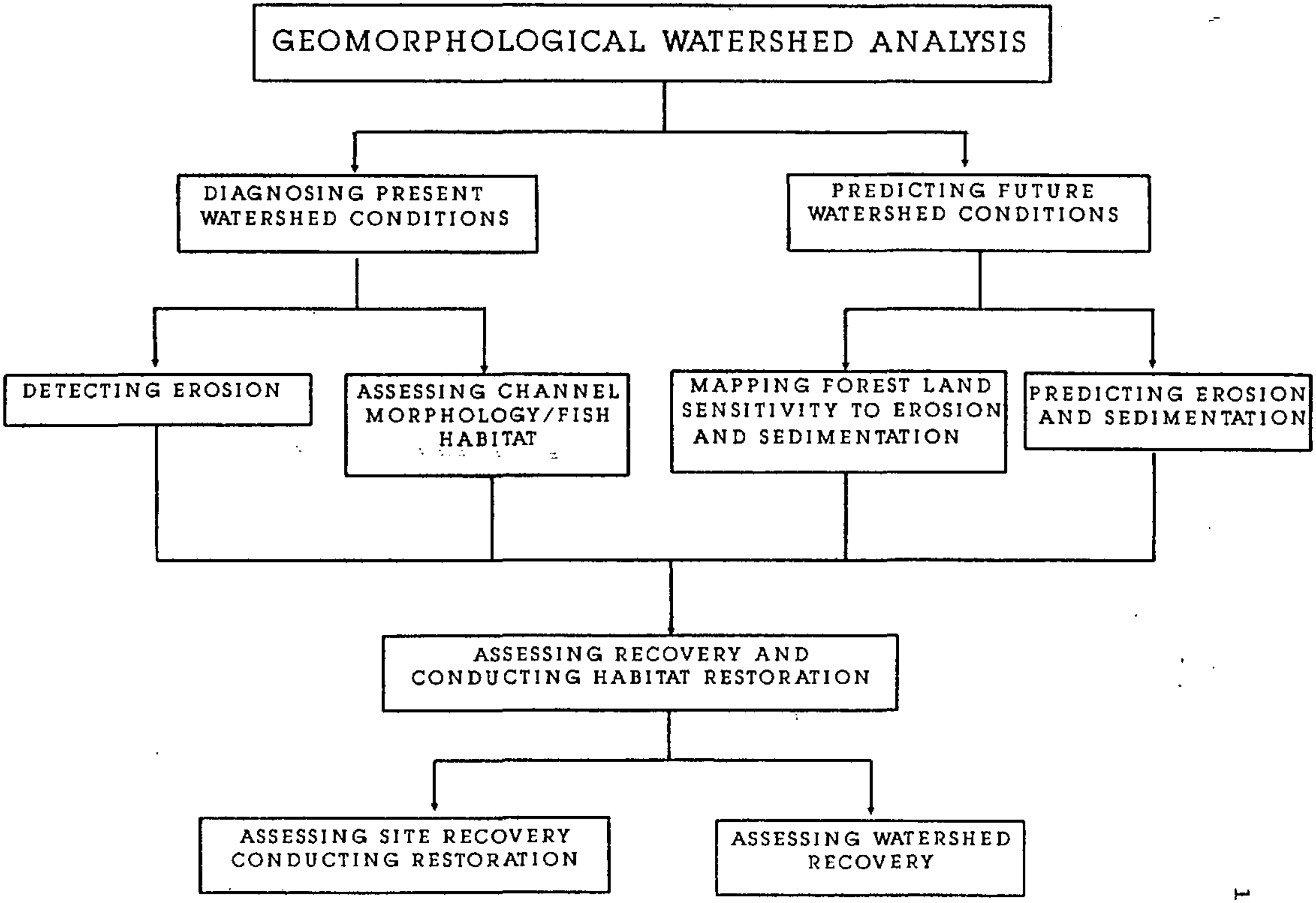


Figure 4. The major elements of geomorphological watershed analysis.

prep.) and in the Tolt River basin (Paul Kennard, Tulalip Fisheries Agency, unpublished data). For summaries of studies in Washington and Oregon, see Pentec Environmental (1991); NCASI, (1985); and McDonald and Ritland, (1989).

Typically, landslide and debris flow inventories compute an occurrence rate expressed as the number of events per square kilometer per year. A method for detecting landslides and debris flows, and for computing occurrence rates, is discussed by Pentec Environmental, Inc. (1991). Occurrence rates can be compared between managed and unmanaged forest lands over time; field surveys may be necessary to detect landslides in areas with dense forest cover. In general, landslide or debris flow rates provide an indication of the severity of mass wasting erosional processes in a watershed. Because debris flows transfer sediment into stream channels, an inventory of debris flows is preferable to an inventory of landslides alone as an indicator of sediment entry to streams. In addition, debris flows are easier to detect under dense forest cover, making the comparison between managed and unmanaged more accurate.

If the volume of sediment involved in landslides and debris flows is measured, the total amount of sediment moved and the "soil transfer rate" can be estimated (Hicks, 1981; Bush, 1982; Swanson et al., 1977; Ketcheson and Froelich, 1978). The soil transfer rate ($m^3/km^2/yr$) does not necessarily involve sediment transfer to a stream. A soil delivery rate (amount entering streams divided by the total eroded volume) can also be estimated and this information is used in the following section on assessing channel morphology and fish habitat.

The number of landslides and debris flows can be used to calculate the volume of sediment entering streams and this can be used as a surrogate for channel or fish habitat condition. This rapid sedimentation analysis requires the ability to assess landslide and debris flow volumes, and knowledge of the soil delivery rate. The time period selected for the analysis is critical. For example, Perkins (1989) found that sediment from landslides persisted approximately a decade in two small streams in western Washington. Residence time is also controlled by the location of the deposit within the watershed (Benda, 1990b). To assess the impact on streams, the volume of sediment entering the channels from mass wasting over the selected time interval (e.g. approximately 10 years) is spread evenly across the area of low-gradient channel within the watershed. The selected channel gradient is based upon theoretical models of sediment transport and the grain size distribution of the incoming sediment, or on historical patterns of sedimentation in the watershed. A threshold channel sediment depth is selected. That threshold is exceeded when the computation indicates a depth of sediment greater than the selected value; this can be thought of as a hillslope threshold. A field survey and/or further GWA might be prompted as a result of this analysis, particularly to verify the estimated sediment depth. This type of rapid sedimentation analysis is suggested within the GWA, and will require further development and testing.

Landslide/dam-break floods (Benda and Zhang, 1989), often referred to as debris torrents in the Pacific Northwest, cause significant changes to channels, floodplains, and valley floors. They occur in different areas of a watershed and have different effects on the channels than debris flows do. Dam-break floods move large organic debris, accelerate erosion of valley walls, and cause aggradation and scour. The occurrence of dam-break floods along low-gradient, fish bearing streams can cause a channel threshold to be exceeded. When dam-break floods (debris torrents) are detected, further channel surveys, more detailed GWA, or habitat restoration may be required. In this way, the occurrence of dam-break floods can be used as a hillslope threshold that can be detected using aerial photographs.

Road surfaces (including cut and fill slopes on active and abandoned roads) can be another major source of erosion in managed watersheds. The impact of logging roads can be evaluated with a synthetic budget which provides an estimate of the influx of road-generated sediment to streams (Reid, 1981; Reid et al., 1981). The technique applies erosion rates appropriate for roads in each management category to the length of road in each category to obtain an overall rate for the entire watershed. Further information on measuring road-related fine sediment is contained in Section 3.0.

Surface erosion from roads can also be used as a surrogate for habitat condition, and therefore as a hillslope threshold indicator. Cederholm (1982) developed a statistical regression that related logging road density to percentage of fines in spawning gravels. This approach can be used to screen basins with a high road density, indicating a need for channel measurements of habitat and possibly fine sediments in gravels.

Methods for measuring other erosional processes, such as slumps and earthflows, channel bank erosion, or surface erosion, are discussed in Section 3.0; for further information see Reid (1981), Dietrich et al. (1982), Lehre (1982), and Reid and Dunne (in prep.).

When more detailed information is required regarding erosion and sedimentation, a partial sediment budget may suffice. A partial sediment budget involves estimation of the sources and rates of sediment production and of the delivery of various grain sizes of sediment to channels over short time intervals.

The development of partial sediment budgets requires information that is obtained from aerial photographs, such as a landslide inventory or density of logging roads. Hence, data collected during a watershed screening analysis is used in later, more detailed problem analysis involving a sediment budget.

Partial sediment budgets are useful for identifying the source of the most troublesome erosion, for comparing erosional processes, for estimating the magnitude of erosion, and for comparing erosion between managed and unmanaged areas in a watershed (see Section 3.0 for further discussion on sediment budgets).

Sediment budgets for managed basins have been constructed in the Clearwater River, Olympic Peninsula, Washington (Reid et al., 1981); the Cascade Range of Oregon (Swanson et al., 1982); the Idaho Batholith, central Idaho (Megahan, 1982; Megahan et al., 1986) the north central Cascades of Washington (Eide, 1990), and the Queen Charlotte Islands, British Columbia (Roberts and Church, 1986).

2.2 Assessing Channel Morphology and Fish Habitat

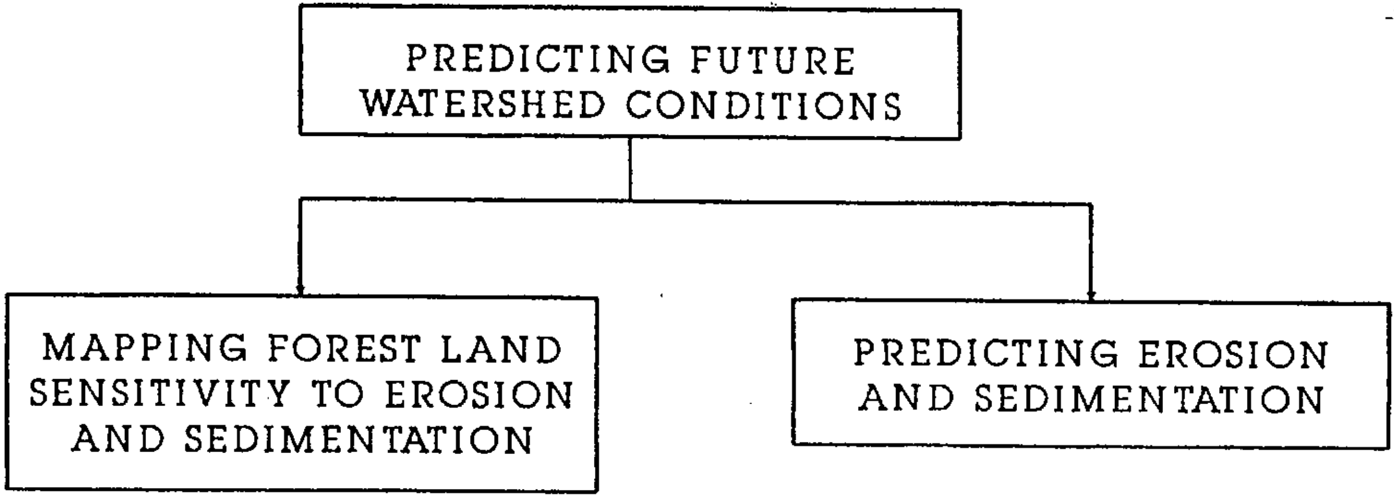
Hillslope erosion affects conditions in a stream channel; however, the detection of dam-break floods by aerial photographs, landslide and debris flow inventories, road density-fine sediment relationships, and sediment budgets often do not provide a clear indication of channel conditions or of the condition of fish habitat. Erosion-based methods of assessing present watershed conditions should be considered as preliminary to field-based habitat surveys.

Channel habitat surveys are necessary to confirm the analyses discussed in the preceding section, and to quantify the effects of erosion on habitat. Surveys should measure channel attributes that are both relevant to fish habitat and related to geomorphic processes (refer to Sullivan et al. (1987) and Bisson et al. (1987) for further information). Measurements, such as bed material size, percentage of fines, pool size, or quantity of large organic debris, should be considered in the context of other data collected in the process of conducting a GWA. For example, percentage of fines in spawning gravels and pool volumes should be considered with respect to erosion in the watershed. It is important to note that the quality and distribution of habitat varies along the longitudinal profile of a stream, and that surveys must focus in those areas that naturally provide high quality fish habitat.

There are several methods useful for surveying the physical attributes of channels important to fish habitat. Bisson (1982) developed a habitat classification system for small streams based on salmonid utilization. Hankin and Reeves (1988) quantify habitat based on measurements of channel units important to fish habitat. Reeves et al. (1989) outline a procedure for identifying habitat factors limiting production of coho salmon. The Timber Fish and Wildlife Stream Ambient Monitoring Field Manual (Ralph, 1990) provides details for measuring pool space, pool depth, frequency of large woody debris, and bed material size.

SECTION 3.0 PREDICTING FUTURE WATERSHED CONDITIONS

Prediction includes two levels of analyses: (1) mapping of forest land sensitive to erosion and sedimentation and (2) construction of a sediment budget to predict erosion and sedimentation (see flowchart in Figure 5). The first level anticipates (either quantitatively or qualitatively) the response of land to naturally occurring large storms and to forestry practices. For example, one may identify areas likely to experience landslides or debris flows, and the streams likely to be affected, either naturally or following timber harvest and road construction. The second level is more detailed and, although it employs many of the same methods as the first, it quantifies



PURPOSES:	1) IDENTIFY SENSITIVE HILLSLOPES 2) IDENTIFY SENSITIVE CHANNELS	1) PREDICT EROSION 2) PREDICT SEDIMENTATION AND SCOUR
PROCEDURES:	1) EROSION MAPPING 2) CHANNEL MAPPING 3) EFFECTS OF FORESTRY ON EROSION	1) PARTIAL SEDIMENT BUDGET 2) FULL SEDIMENT BUDGET

Figure 5. Prediction of future watershed conditions.

erosion magnitude (volume) and channel sedimentation (volume or depth). Quantitative measurements of individual erosion processes are the basis for constructing sediment budgets. Discussions and details of measuring erosion processes in the context of sediment budgets are given in Dietrich et al., (1982), Lehre, (1982), Swanson et al., (1982), Benda, (1988) and Reid and Dunne (in prep.).

Many of the procedures in this section require information obtained during "diagnosing present watershed conditions" discussed in the preceding section; therefore, each level of analysis can build on information acquired from the preceding step.

3.1 Mapping Forest Land Sensitivity to Erosion and Sedimentation

3.1.1 Hillslopes

The sensitivity of forest lands to erosion is governed by the geomorphology of the area and by the effects forestry activities have on hillslope processes. Quantitative and qualitative methods can both be used to estimate sensitivity.

The geomorphology of a watershed is defined in terms of the underlying bedrock and structure (the geology), the surficial materials (e.g. Quaternary sediments), the hydrology, and the active sediment transport processes. Based on the geomorphology, areas with equal potential for erosion can be delineated. This exercise has been referred to as landform mapping, terrain mapping, and erosion mapping. Descriptions and examples are available in Fiksdal and Brunengo (1980; 1981) for Washington State, and in

Ryder and Howes (1984) and in Rollerson et al. (1986) for British Columbia.

Erosion mapping, in conjunction with the potential effects forestry activities could have, is used to identify and map forest lands sensitive to erosion. The effects of forestry can be estimated using field measurements of past erosion patterns associated with forest practices or with theoretical models. Geographical information systems (GIS) or USGS topographic maps are used to display the information on land sensitivity.

In the following discussion, erosion is divided into the five categories previously mentioned: landslides and debris flows, dam-break floods, slumps and earthflows, bank erosion, and surface erosion.

3.1.1.1 Landslides: Occurrence Rates Used for Prediction

Measurements of landslides and debris flows are made using a combination of aerial photo interpretation and field surveys. An inventory of landslides (or debris flows) that produces occurrence rates (#/area/time) for clearcuts, logging roads, and unmanaged forests is the method of choice for many investigators in Washington (Fiksdal, 1974; Peak Northwest, 1986; Eide, 1991; Benda, 1990a; Gowan, 1989; Kennard, unpublished data; Johnson, in prep.; Parks, in prep.), and in Oregon (Swanson et al., 1972; Morrison, 1975; Swanson and Grant, 1982; McHugh, 1986; Chesney, 1982). Landslide and debris flow inventories have also been conducted in California, British Columbia, New Zealand, and Japan. A standardized method for computation of landslide (or debris flow) occurrence rates is presented and proposed as a test of the Washington state forest practice rules by Pentec Environmental, Inc. (1991).

Field measurements or estimates of sediment volumes for landslides and debris flows can be used to compute sediment flux to streams by these processes. This is an important method used in the rapid sedimentation analysis presented in Section 2.0 - Diagnosing Present Watershed Conditions, and in the construction of sediment budgets (discussed later).

Past erosion patterns related to forestry activities, as obtained from landslide or debris flow inventories, can be used to anticipate future patterns following proposed forest practices. A model of this form has been developed for Regions 1 and 4 of the U.S. Forest Service by Cline et al. (1984).

In Smith Creek basin in Northwest Washington state landslide rates for the period 1940-1980 were used to predict the probable number of landslides that would occur because of future logging (Benda, 1990a). When using this method, it is important to consider the influence of unusually large storms on the landslide record, to apply landslide rates over similar geomorphic areas (site stratification by erosion mapping), to remove previously failed sites from the total population of potential landslide sites, and only to apply the rates to similar forest practices. This method predicts the number of landslides over a general area and it is not accurate in time (because of climate variability).

Furthermore, the landslide rate is only accurate for time periods similar to that of the historical aerial photo analysis used to derive the rates. The differences between rates computed for clearcuts, logging roads, and unmanaged forests are, however, more accurate, and the relative rates may be more useful for prediction purposes.

3.1.1.2 Landslides: Empirical Predictive Models

The probability of landsliding can also be estimated with empirically-based models which determine the relative stability between hillslope sites. The methods applicable to the Pacific Northwest include those of Bush (1982) (clearcuts), Duncan et al., (1987) (logging roads) and Benda (in review) (clearcuts and logging roads). These models use easily measured hillslope variables, such as gradient, slope form, amount of vegetation, slope position, and type of forest practices (e.g. timber harvest, road construction). Some models also include other factors, such as springs, old slide scarps, and wetland vegetation. These models require less training than the more theoretical models discussed below and are appropriate for large scale mapping of erosion hazards.

3.1.1.3 Landslides: Theoretical Predictive Models

Several theoretical models predict the relative likelihood of landslide occurrence. Most are based on the infinite slope model which considers the balance of forces on a soil mass (e.g. Burroughs, 1984). The infinite slope model requires field data on soil thickness over bedrock, depth of soil saturation, and soil strength parameters (including root strength). Complete soil saturation is usually assumed. The ratio of forces holding the soil in place to forces tending to move the soil downslope is called a factor of safety. A factor of safety less than 1 indicates failure and a factor of safety greater than 1 indicates stability. When much of the input data for these models are estimated, they may provide a prediction no better than the empirically-based methods discussed above.

Landslide prediction models based on the infinite slope solution have also been applied to large areas (a basin or watershed) for time periods longer than a year. This requires an estimate of the spatial variability of site parameters across the area of interest, and a procedure that considers the year to year variability in rainfall. Several stochastic models of landslide prediction exist and include those developed by Ward et al. (1981), Burroughs (1984), Hammond et al. (1988), and Benda and Zhang (1990). These models predict probability of failure within a given area over a specified time. The validity of these models depends on the data used. Unfortunately, adequate field data on site and climate variability are typically not available. Some models also assume a probability distribution of soil saturation rather than using a more sophisticated rainfall driven groundwater saturation model. In those models, the probability of failure is strongly influenced by the saturation distribution selected.

In addition to predicting landslides, a probabilistic model can be used to drive a sediment budget, and thereby predict erosion volumes and sediment entry to streams (Benda and Zhang, 1990).

3.1.1.4 Debris Flows: Empirical Predictive Model

Although debris flows can be lumped under shallow-rapid landslides and included in the above methods, it is important to differentiate between them because not all landslides trigger debris flows. Occurrence rates can be computed from debris flow inventories and used for predictive purposes (Benda, 1990a). Inventories of debris flows have been conducted by Swanson and Lienkaemper, 1978; by Benda, 1988; and by Eide, 1991.

The only model for predicting initiation and runout of debris flows developed for the Pacific Northwest is by Benda and Cundy (1990). This model does not require the rheological properties of the debris, but rather employs topographic criteria such as channel gradient and tributary junction angle.

3.1.1.5 Dam-Break Floods: Empirical Predictive Model

Another significant form of mass wasting is the dam-break flood (see Definitions and Terminologies, Section 1.0). No methods exist to accurately predict the occurrence and travel distance of dam-break floods. Ongoing research of dam-break floods in the Washington Cascade and Oregon Coast Ranges (Benda and Zhang, 1989; Benda, Zhang and Dunne, research in progress; Coho and Burgess, research in progress) indicates that landslide and debris flow dams are most likely to form in confined canyons located along the paths of debris flows, or at sites of landslide or debris flow deposits in narrow valleys. A provisional model for predicting dam-break floods has been proposed by Benda (in review), and is based on width of the valley floor or canyon at the site of landslide or debris flow deposition.

3.1.1.7 Slump-Earthflows: Interpretation and Measurement

Unlike landslides, slump-earthflows are generally confined to specific geologic terrain. They are usually long-term features in the landscape and forestry activities may reactivate or accelerate their movement. For this reason, it is important to inventory existing features and to analyze the impact of forest management.

Analysis of slump-earthflow features can determine the frequency of movement and number of failures triggered by weather patterns or forestry activities. Although a few case studies of slump-earthflows have been made in the Pacific Northwest, there is no systematic, landscape-scale study on the role of forestry activities in activating or accelerating slump-earthflows. As there has been so little previous work at a regional scale, the identification and interpretation of deep-seated failures must be conducted on a case by case basis.

Movement on new or previously dormant slump-earthflows can be determined by examining the aerial photographic record for the area of interest. These features are often subtle, and their identification can requires a geologist skilled at photo interpretation. For further information on recognition of slump-earthflow features, refer to Sidle et al. (1985) and to Pentec Environmental, Inc. (1991). Each incidence of slumping, particularly events associated with a road or in temporal association with a clearcut, should be noted. To associate a road or clearcut with a failure requires a detailed criteria, including identification of a mechanism by which the road or clearcut may have influenced the failure. This type of analysis was conducted on a slump-earthflow feature adjacent to the North Fork Stillaguamish River. A time series analysis of slump movement, timber harvest and rainfall strongly suggested that timber removal accelerated landslide activity (Benda et al., 1988).

Ability to predict the response of slump-earthflows to forestry activities is limited and no present models predict slump-earthflow movement. Therefore, in the context of the GWA, it is recommended that these features be mapped as individual erosional features with a potential for accelerated movement. The degree of accelerated movement associated with landuse must be determined from analysis of historical aerial photographs of the slump-earthflow in question, or on similar slump-earthflow terrain in the vicinity.

We recommend that further research be conducted in the dynamics of slump-earthflow terrain, and the effects of forestry activities on this erosion process. This is necessary for developing a field-based prediction of slump-earthflow response to land management activities.

3.1.1.7 Bank Erosion: Interpretation and Measurement

No existing quantitative methods for predicting bank erosion are appropriate for the Pacific Northwest. There are several forms of bank erosion in mountain drainage basins. Bank erosion following debris flows in first- and second-order channels is often severe and sediment yield is accelerated for many years following the event. Presently, there is not a method to predict this type of accelerated bank erosion, though ongoing research is addressing this issue (O'Connor, research in progress).

Another process of particular significance, is the large scale and persistent erosion of valley walls, usually in unconsolidated glacial deposits, that occurs following a dam-break flood. This type of erosion can be a major source of sediment supply to channels, however, little is known about this type of erosion. Research on this topic is recommended. Presently, prediction of erosion volumes for these types of valley wall disturbances (e.g. debris flows and dam-break floods) can be roughly approximated using field measurements of past erosion, and applying these rates to other areas. Erosion of valley walls by debris flows and dam-break floods also needs to be considered in the context of diagnosing present watershed conditions (Section 2.0).

Smaller scale channel bank erosion is detected and measured primarily using field surveys. Surveys allow comparison of bank erosion in areas recently disturbed by logging to areas in unmanaged forests. Procedures for measuring bank erosion are found in Reid (1981) and in Reid and Dunne (in prep.). Although we know some banks are more susceptible to erosion than others, it is difficult to predict where, when, or how much banks will erode.

Effects of forestry practices on bank erosion include (1) decreased bank stability caused by logging in and adjacent to streams (Roberts and Church, 1986); (2) bed and bank erosion triggered by the removal of large organic debris from stream channels (Klein et al., 1987; McDonald and Keller, 1987; (3) increased bedload (Madej, 1982); (4) increased peak flows (not well documented); and (5) increased incidence of debris flow and dam-break floods (Eide, 1991; Gowan, 1989).

3.1.1.8 Surface Erosion: Interpretation and Prediction

Surface erosion processes include dry ravel, sheetwash, rilling and gullying, and shallow sloughing. Pentec Environmental, Inc. (1991) reviewed the literature on surface erosion in managed forests. Many studies have also examined the effects of roads on sedimentation at a basin scale (for example, Bestcha, 1978; Sullivan, 1985, 1987; Anderson and Potts, 1987). These studies and others are summarized in McDonald and Ritland (1989) and in Swanson et al. (1987).

Only road-related surface erosion is discussed here; other sources of surface erosion include landslide scars and gully erosion in timber harvest areas. Road related surface erosion can be predicted in a watershed using a synthetic budget. Such an approach was taken by Reid (1981; Reid et al., 1981). This approach applies erosion rates measured or extrapolated from elsewhere to the total length of road segments of different management categories to determine an overall road-erosion rate for the watershed. Another method to predict road surface erosion is the Univeral Soil Loss Equation; Dunne and Leopold (1978) summarize this method. Studies of surface erosion from roads are often not predictive, but rather forensic: measurements are made over a specified period of time to determine the contribution of fine sediment production made by erosion from roads. Such analyses have been conducted by Megahan and Kidd (1972); Fredriksen (1965); Bestcha (1978); Potts (1987); and Rice et al. (1979). This type of study has value in the diagnostic component of GWA.

3.1.2 Channels

3.1.2.1 Catastrophic Processes: Debris Flows and Dam-Break Floods

Debris flows and dam-break floods cause severe impacts to channels and valley floors (riparian zones). These impacts can result in a threshold being exceeded in the channel. Channels where these events have occurred can be detected remotely during the diagnostic portion of GWA. Channels and valleys susceptible to debris flows and dam-break floods can be identified using methods previously described (e.g. Benda and Cundy, 1990; Benda, in review). Channels and alluvial fans at high risk from debris flows and dam-break floods can be included in the erosion map that identifies forest land sensitivity to erosion and sedimentation. This type of risk assessment allows identification of processes in the landscape that have the greatest potential for increasing risk to lives and property, and for damaging fish habitat. For example, Benda (1990a) assessed the increase of risk to residents from dam-break floods on an alluvial fan from timber harvest, and the reduction of that risk because of construction of dikes built to contain the floods. In addition, patterns of debris flow deposition have been mapped with respect to fish habitat in the Oregon Coast Range that allowed zoning of high hazard areas in the basin (Swanson et al., 1987). The effects of debris flows on channel and valley floor morphology is discussed in several studies (e.g., Swanson and Lienkaemper, 1978; Perkins, 1989; Benda, 1990b).

3.1.2.2 Sedimentation Processes: All Forms of Erosion

Erosion produces sediment that eventually enters channels. High-gradient, boulder and bedrock channels typically transport sediment efficiently, and therefore do not undergo extensive sedimentation or aggradation. Low-gradient channels, however, have less sediment transporting capacity. As a result, low-gradient, fish bearing channels are often susceptible to sedimentation caused by naturally accelerated or forestry related erosion. Although the fluvial geomorphology of mountain channels is less well understood than hillslope geomorphology, there are methods to estimate the sensitivity of channels to sedimentation. Channels sensitive to sedimentation can be included in the erosion map.

The history of sedimentation in a watershed can be used to identify channels at risk. Historical channel surveys indicate reaches which aggraded after previous erosional events. These same reaches may aggrade in the event of further erosion. In the absence of historical channel surveys, sequential aerial photographs might provide the necessary information. Methods such as the RAPID technique (Grant, 1988) produce a measurement of channel/riparian zone widening that can indicate channel sedimentation or aggradation. Channel widening detected by the RAPID method, however, might also include debris flow and dam-break flood effects, as well as bank erosion.

Another useful technique is to compare the geometry of channels suspected of widening from sedimentation with stable channels in the same region or adjacent watersheds. Madej (1982) employed such a technique in her evaluation of the effects of intensive forest management in the channel of Big Beef Creek, a Puget Lowland stream. In response to an increase in sediment yield from forestry operations, bedload transport increased from 500 to 4200 tons per year. Madej compared measured channel widths in Big Beef Creek with channel geometries of other streams in the region. This comparison, and a comparison with a survey of Big Beef Creek made eight years previously (Cederholm, 1972), led to the conclusion that widening occurred as a result of increased bedload input. Hence, information on regional channel geometry, such as that used by Madej (1982), can be used to identify those channels most likely to aggrade or undergo sedimentation in the event of accelerated erosion.

Patterns of sediment transport through a channel can also be used to estimate reaches likely to experience sedimentation.

Sediment transport formulae (such as Parker et al., 1982; or Meyer-Peter and Muller, 1948), in conjunction with the hydraulic geometry of the channel, can be used to predict the general depositional pattern on gravel-bedded streams and rivers. Such a procedure was conducted on the Pilchuck River to examine the effect of gravel mining operations (Collins, 1991). A similar approach requiring more effort is the HEC-6 sediment transport model (MacArthur, et al., 1991). Another approach compares the size distribution of sediment contained in the pavement layer at the surface of the bed to that in the subsurface of the bed (Dietrich et al., 1989); this model is in an early stages of development and requires testing.

All the methods described above for identifying channels sensitive to sedimentation or disturbance (e.g. debris flows and dam-break floods) should be linked to channel habitat surveys. This would make the potential for changing or reducing habitat more apparent. Survey methods such as those of Hankin and Reeves (1988), Reeves et al., (1989) and Ralph (1990) are useful for this purpose. There are few quantitative relationships between large sedimentation disturbances and changes to fish habitat and therefore, we recommend further research in this area.

3.2 Predicting Erosion and Sedimentation by Sediment Budgets

Sediment budgets represent the most sophisticated level of GWA's predictive capabilities. The sediment budget uses preceding analyses from both the diagnostic and predictive components to predict the sediment volumes produced by each process, the rate of entry of the sediment to stream channels, the grain size of the sediment, and the transport and storage of sediment throughout the channel network (the latter part is contained in a full sediment budget). Details on the construction of a partial or full sediment budget are discussed by Dietrich and Dunne (1982) and by Reid and Dunne (in prep.).

Sediment budgets are very useful in watersheds with an erosion and sedimentation problem. They provide information to identify specific actions for minimizing erosion and to evaluate restoration programs; a partial sediment budget is recommended as one of the tools in the diagnostic component of GWA.

3.2.1 Partial Sediment Budget: Time Averaged

A partial sediment budget identifies the major sources and estimates rates of all erosion processes in a watershed, it approximates the volume of sediment contributed by each source, and it may include the grain size distribution of that sediment. Future erosion rates can be extrapolated from past rates under certain conditions (see Reid and Dunne, in prep.). For example, erosion rates for some processes, (e.g. landslides) can be computed from past occurrence rates (#occurrences/area/time) obtained with methods previously described. These rates represent an average over a particular time for a particular area. Most sediment budgets constructed in mountainous areas treat the erosion component by mass wasting as an average value (e.g. Dietrich and Dunne, 1978; Swanson et al. 1982; Lehre, 1982 and Reid, 1981).

These sediment budgets estimate the relative importance of each erosion process, but the average rates do not capture the episodic nature of mass wasting and cannot, therefore, adequately account for the effects on channels of large, episodic events. Average rates can, however, be used to qualitatively estimate channel conditions in the future, thereby forming a link to fish habitat.

3.2.2 Partial Sediment Budget: Stochastic

Theoretical landslide prediction models, discussed earlier, have been used as part of a sediment budget to predict episodic delivery of sediment to channels (Benda and Zhang, 1989). A stochastic sediment budget may capture the general characteristics of frequency and magnitude of landslides and debris flows, but it only approximates the timing and location of events. Such a sediment budget, however, has utility for assessing long term changes in erosion patterns. For example, a stochastic simulation model can be used to compare the erosion and sedimentation regime under forestry activities with that of a natural forest that is disturbed infrequently by large storms and wildfires. Model results can indicate if and how erosion and sedimentation patterns are changing over long time periods and large areas because of landuse. Stochastic sediment budgets are still in early stages of development.

3.2.3 Full Sediment Budget

A full sediment budget is similar to a partial sediment budget, except that it also accounts for the transport and storage of sediment in channels and includes particle breakdown during transport. Quantitative methods to predict transport of bed material and suspended load are required. A review of these methods is found in Reid and Dunne (in prep.). A full sediment budget requires adequate spatial representation of the processes within a watershed, as well as some accounting of the episodic nature of mass wasting processes. This effort requires comprehensive topographic data bases, and is most appropriate for GIS technology; such sediment budget models are in their early stages of development.

Estimates for bedload transport, for sediment storage in the channel, and for sediment breakdown during storage and transport are important in deciphering the dynamics of channel morphology important to fish habitat. A quantitative understanding of sediment transport is a necessity for linking hillslope erosion to channel habitat. Methods for linking information obtained from sediment budgets to fish habitat must be more fully explored in subsequent development of a GWA.

4.0 ASSESSING HABITAT RECOVERY AND CONDUCTING RESTORATION

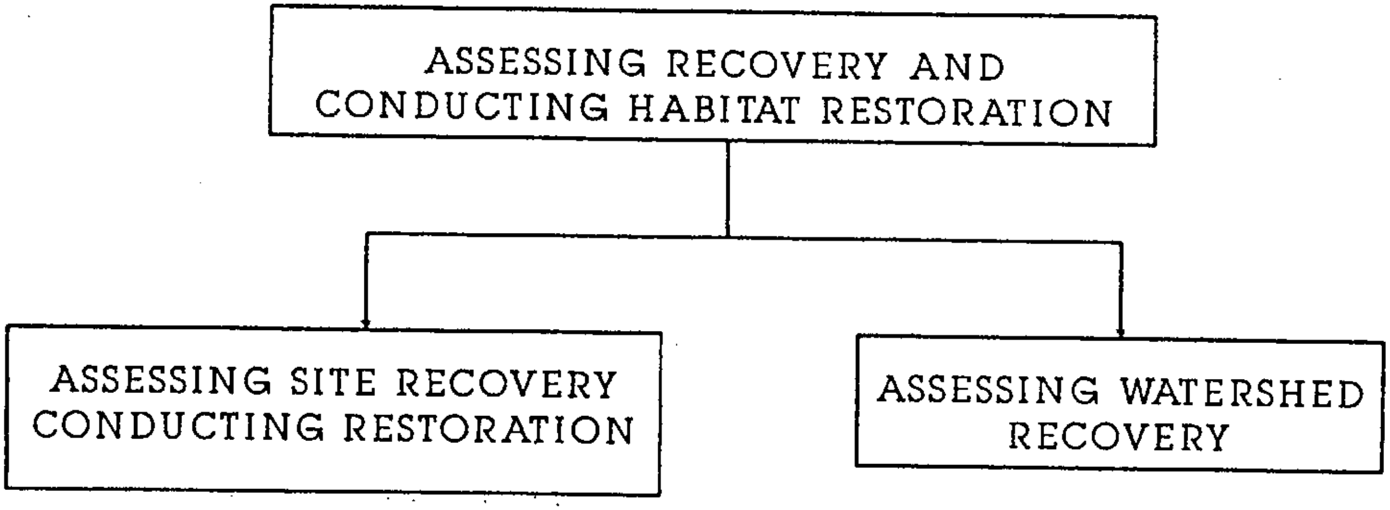
Many watersheds have ever-increasing landuse-related erosion problems so that habitat recovery and restoration become increasingly important. Proposed harvest plans often trigger a call for appraisal of fish habitat, even though the habitat is already effected by previous landuse activities. Therefore, habitat recovery often needs to be assessed, and occasionally restoration of fish habitat is suggested as a condition for further logging. GWA provides methods that are useful for assessment of habitat recovery and for conducting restoration projects.

The component of the GWA that pertains to assessing habitat recovery and restoration is shown in figure 6. This component has two levels of analyses: (1) assessing site recovery and conducting site restoration, and (2) assessing watershed recovery.

4.1 Assessing Site Recovery/Conducting Restoration

Habitat recovery is the attainment of channel features important to fish habitat after a disturbance; for a discussion of these features see Sullivan et al. (1987). These features might include low amounts of fine sediments in gravels, a non aggrading and stable channel bed, large and frequent pools, large riparian vegetation, and high densities of large woody debris in channels. Although assessment of habitat recovery is typically done by fisheries biologists, the physical habitat is immutably linked to both the fluvial and the hillslope geomorphology in the watershed. The geomorphic component of GWA should be considered during any habitat assessment or restoration program.

Habitat recovery can be assessed using an inventory of habitat conditions which can be compared to conditions prior to the disturbance (if known) or to some expected habitat condition. Unrealistic conditions should not be expected in areas where the habitat has historically been limited. Methods contained within



PURPOSES:	1) ACCOUNT FOR FLUVIAL GEOMORPHOLOGY 2) ACCOUNT FOR WATERSHED EROSION CONDITION	1) CONSIDERS RECOVERY OF ALL SITES IN A WATERSHED
PROCEDURES:	1) TECHNIQUES IN GWA	1) TECHNIQUES IN GWA

Figure 6. Assessing habitat recovery and conducting habitat restoration.

GWA, particularly those pertaining to fluvial geomorphology, are useful during recovery assessments. They can explicitly link limiting habitat factors to specific geomorphic conditions within the channel and to the erosional condition of the entire basin. For example, the limiting factor analysis of Reeves et al. (1989) can be coupled to the geomorphology of the watershed to identify the specific watershed condition or problem that is limiting habitat.

There is considerable information on habitat restoration (Anderson et al., 1984; Klingeman, 1984; Ward and Slaney, 1981 and Wesche, 1985). Restoration of habitat is often planned and implemented in the absence of information on the geomorphology of the watershed, including existing and future erosion conditions. Information on sediment supply, channel-bank stability and likelihood of future large disturbances is necessary to adequately plan restoration. Other important issues include flow regimes and channel hydraulics. Numerous restoration efforts are ill conceived and then poorly planned and constructed, particularly in mountain drainage basins. The GWA (both Diagnosis and Prediction) provides essential information to those risking substantial sums on restoration programs.

4.2 Assessing Watershed Recovery

A watershed may contain numerous individual stream reaches and tributaries which provide habitat for fish. Fish may move between tributaries if, for example, their home stream is severely impacted by a dam-break flood. Thus, a channel containing high quality habitat serves as a potential refuge for fish throughout the watershed. Such considerations, in the context of GWA, are referred to as "assessing watershed recovery". The GWA provides information (e.g. erosion status and channel conditions) at the scale of a watershed (multiple reaches or tributaries), and therefore can provide information from which to consider the importance of the condition (or recovery) of a single tributary based on the condition (or recovery) of other nearby tributaries in a watershed. Ultimately, this type of watershed assessment is a biological one. Methods contained within GWA, at both the diagnostic and predictive levels, provide information upon which to base those biological appraisals.

5.0 APPLICATIONS

5.1 Watershed Screening - Thresholds - Analysis

Watershed screening has been proposed as a means to quickly identify both watersheds with a reservoir of high quality habitat and watersheds with a significant problem. A screening process might contain hillslope or channel thresholds; exceeding a threshold may trigger a watershed analysis. The protocol of watershed screening - thresholds - analysis is not considered here. It remains to be decided at the policy level by CMER and DNR.

The geomorphological watershed analysis proposed in this report can efficiently and rigorously support watershed screening, threshold determinations, and watershed analysis (see Figure 2).

We have looked for rigorous and objective techniques based on published scientific methodologies. The analyses suggested are related, so that information gathered at one phase is applicable to another; e.g. data collected during screening is used again in subsequent, more detailed watershed analyses, such as mapping forest land sensitivity to erosion and sedimentation. Each level of analysis builds upon information acquired from the preceding steps. That is the element that unifies all methods under one planning environment: the GWA.

5.2 Uses of Geomorphological Watershed Analysis

The proposed GWA consists of methods to measure and interpret erosion and channel environments in managed watersheds. It therefore illuminates the relationship between those aspects of the watershed and landuse activities. At all levels of GWA, geomorphic conditions and changes in watersheds are linked to channel variables critical to fish habitat. In many cases, only weak or qualitative associations can be made. Further studies are needed to elucidate those linkages.

Geomorphological watershed analysis must be applicable for a variety of scientific concerns and land management questions. For example, the diagnostic component supports watershed screening to quickly identify relevant issues (e.g. none, hydrology or mass wasting) or to determine whether a threshold has been exceeded (hillslope or channel), efforts to define existing watershed conditions or problems (including natural erosion), and habitat surveys for identifying high quality fish habitat (Figure 2). The prediction component identifies (and maps) sensitive hillslopes, identifies (and maps) sensitive channels, and predicts erosion and sedimentation (Figure 2). The component on assessing habitat recovery considers the fluvial geomorphology and general erosion condition of watersheds in concert with evaluation of recovery and planning of habitat restoration (Figure 6). Biological considerations, such as the need or existence of refuge streams, can also be addressed.

Finally, the GWA framework and the technologies employed provide a platform from which to design interdisciplinary research studies linking geomorphology to fish habitat.

5.3 Users of Geomorphological Watershed Analysis

The methods contained in GWA are documented in the published literature and have been developed and used by trained professionals in both earth and water sciences (e.g. geomorphology, hydrology, and fisheries science). The majority of technologies and methods referred to in this report are of a technical nature and require a sound background in one of the earth or water sciences. In general, these analyses require training in geology, geomorphology, geotechnical engineering, and hydrology. Some methods (such as mapping of sensitive hillslope areas using empirically-based, qualitative slope features) can be accomplished by people with only limited training. Individuals trained in geomorphology and fishery science should be able to conduct various levels of GWA using this report as a guide.

5.4 The Next Step

This report is not a procedural handbook on how to conduct a geomorphological watershed analysis or screening. The GWA provides a set of conceptual and technical guidelines for analyzing the physical and biological environments of a watershed. At the heart of GWA is a flexibility to account for different skills of the users, for improvements of the methods over time, for the unique character of watersheds, and for the variety of questions that may be asked.

An expanded version of GWA can be built with these guidelines. The expanded version can include details not encompassed here. In an expanded form, however, GWA will likely require a relatively high degree of skill to conduct. Undoubtedly, improvements and modifications will arise from further development and application of GWA.

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