A Sediment Transfer Hazard Classification System: Linking Erosion to Fish Habitat

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Abstract. A problem in watershed management is linking upslope erosion associated with forestry practices to downstream sedimentation of fish habitats. To overcome this problem, a sediment transfer hazard classification system was developed and applied to a northwestern British Columbia watershed. The system is based on geomorphic factors that influence sediment production, transport, and deposition. Data to describe these factors are obtained from air photographs, topographic maps, fish habitat inventories and interpretive terrain maps. The final product of the system is a sediment transfer hazard map that indicates where in a watershed sediment production and movement is a potential problem. This is an important tool for watershed and integrated resource managers because not all unstable or erodable sites pose a sedimentation hazard to fish. Knowing the hazards, managers can decide in an informed way where to restrict forest harvesting or focus limited dollars on special road construction and harvesting techniques. This paper describes the Sediment Transfer Hazard Classification System.

Many watersheds along the Pacific Northwest coast have high forestry and fisheries values. For this reason, integrated resource management is a common goal of resource managers in both Canada and the United States. This goal has been supported by several major research programs (e.g., Salo and Cundy, 1987; Scrivener, 1987; Poulin, 1984). These programs have expanded our understanding of physical and biological processes and have led to improved watershed management. However, one persistent shortcoming has been the failure to provide an *operational* planning tool that links individual processes so that downstream impacts, due to sediment introduced at some point upstream, can be predicted. Conceptual models have been presented in the literature (e.g., Swanson *et al.*, 1982; Church, 1983; Megahan, 1985), but these fall short of operational needs.

As a result, inputs to operational forest land use planning include discrete components, with little or no integration. For example, routine interpretive terrain maps identify the potential for upland erosion, but there is no operational methodology presently available that links these areas to potential sedimentation hazards in downstream fish habitats. While resource managers rely on their own individual approaches, until a consistant hazard assessment is established, true integrated resource management will remain a concept rather than a reality.

To address this situation, a method that links upslope erosion to fish habitat was developed and applied to a northwestern British Columbia watershed. The objective of this paper is to describe the method, the "Sediment Transfer Hazard Classification System".

The system is based on key geomorphic factors that influence sediment production, transport and deposition. The assessment of downstream hazards is accomplished by viewing the overall watershed as a network of linked tributaries and mainstem channel segments that transfer both water and sediment to the watershed outlet. The system evaluates the sediment transfer characteristics *within* each tributary and mainstem channel segment and then estimates potential for transfer *between* different areas of the watershed. Therefore, the sequential arrangement of tributary and mainstem stream channels determines whether an upstream sediment source is *connected* to sensitive environments downstream.

The final product of the system is a sediment transfer hazard map that indicates where sediment production and movement is a potential problem. This is a useful tool because it indicates where special operational measures to control sediment production are most critical.

The system is designed to be used as an operational planning tool. The terrain and stream channel data requirements are obtained from air photographs, topographic maps and terrain maps. Field work requirements are minimal.

Description of the System

The movement of sediment from a source to a downstream fish habitat involves many hillslope and stream processes. A useful way to illustrate the movement is through a sediment transfer model (Figure 1). Hillslope materials are moved downslope by various processes; for example, rockfalls, debris slides and soil

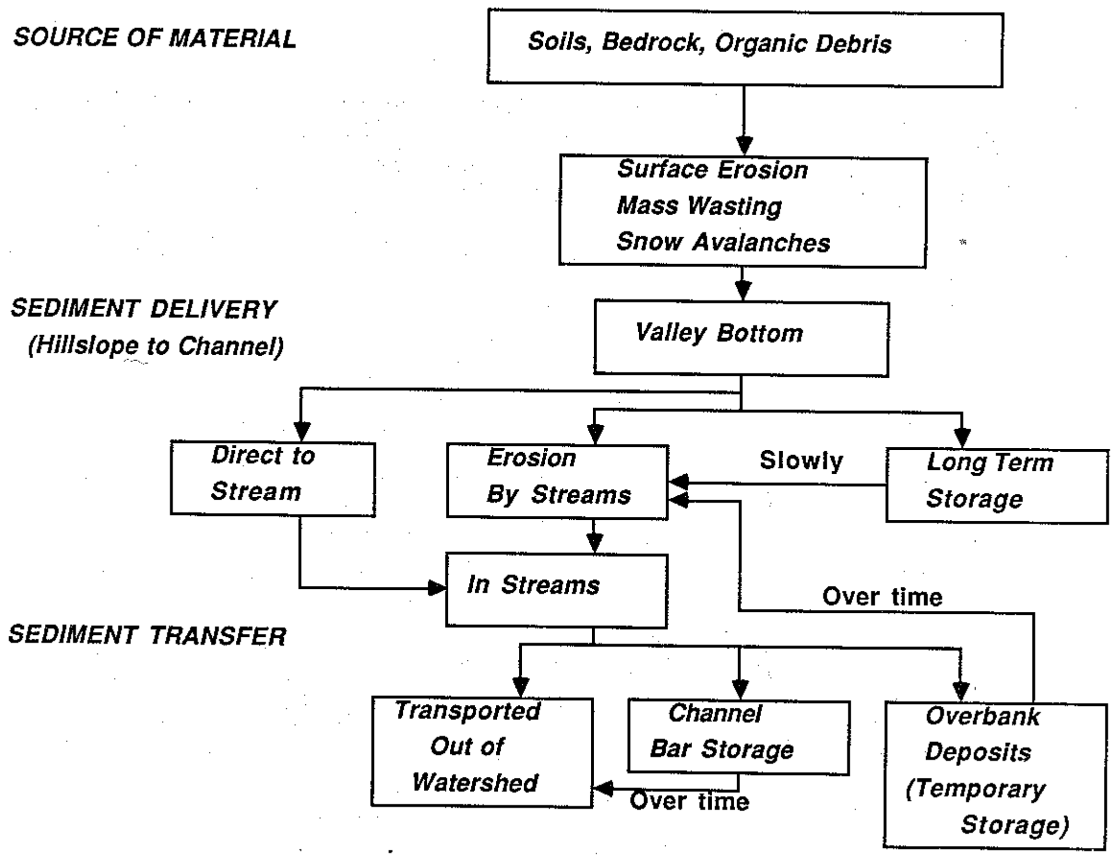

Figure 1. A conceptual model of sediment transfer.

creep transfer sediment from the hillslope to the valley bottom. Eventually this material enters a stream channel, often as a result of streambank erosion, and is moved downstream by fluvial sediment transport mechanisms. The transfer of sediment is rarely continuous over time or space, so the downslope/downstream movement through the watershed is sporadic and sediment is stored in specific zones for various time periods. The efficiency of sediment transfer from a source can be anticipated based on the surrounding terrain and fluvial characteristics. The Sediment Transfer Hazard Classification System links these features to provide an operational planning tool for resource managers. The approach has been generalized in Figure 2 to show the importance of channel and sub-basin arrangement, with respect to the downstream sensitive environments. Figure 2 also illustrates the kinds of questions and issues considered and the steps followed. A simplified schematic showing the general features considered to evaluate sediment delivery to the stream channel and sediment throughput to the sensitive environment downstream is given in Figure 3.

The system involves five main steps (Figure 4): defining the fish habitat; describing the geomorphic features of the watershed; determining sediment delivery potentials; evaluating channel sediment throughput by reach and tributary; and integrating this information to define sediment transfer hazards. This information is presented on a large scale map.

Delineation of Fish Habitat

The initial step is to determine the location of important fish habitat such as spawning or rearing areas (Figure 4). This defines the stream reaches that are critical from a sediment deposition and channel morphology standpoint. These areas are identified on the largest scale base map available. This information is generally available from fisheries agencies, but if not, field work may be necessary.

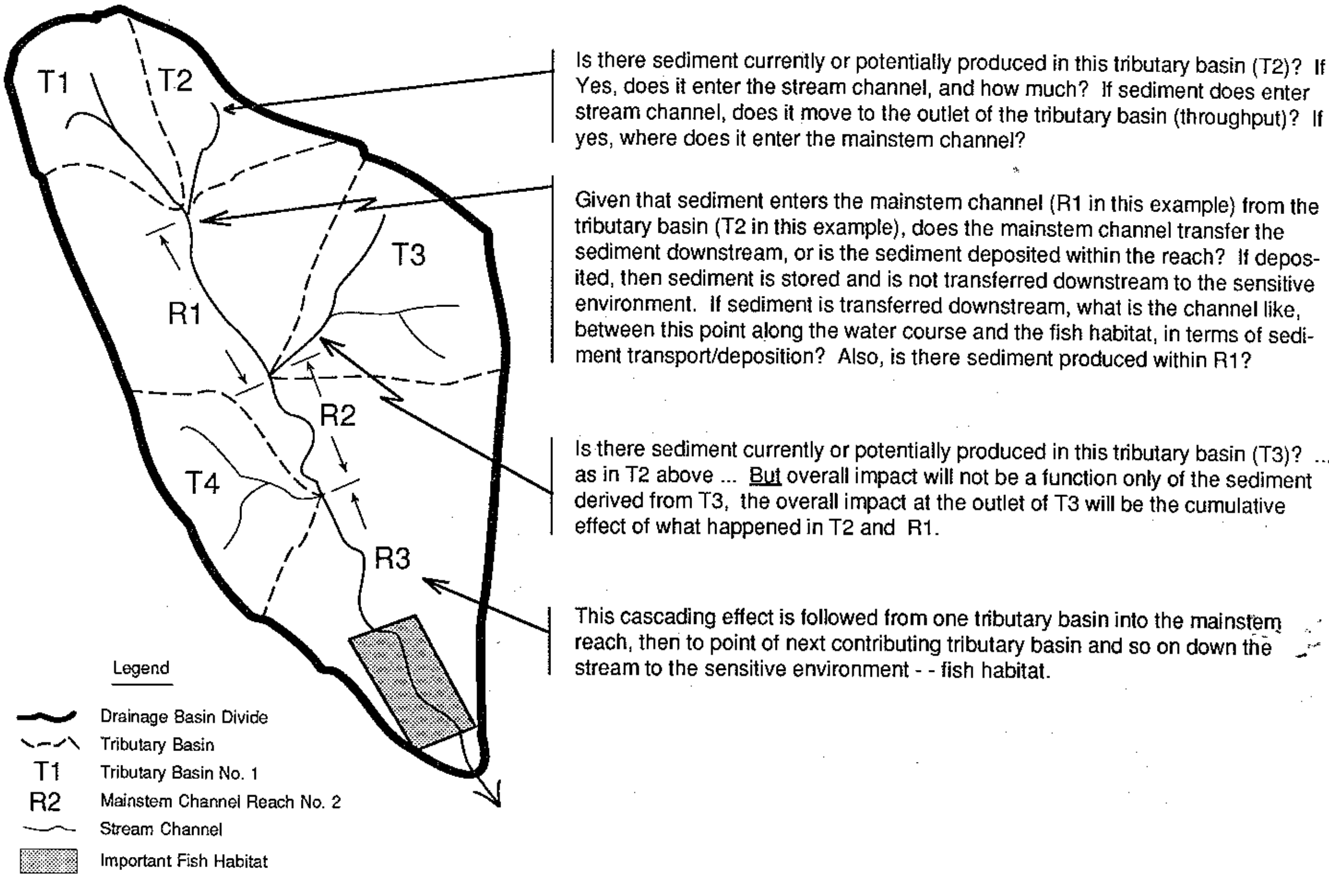

Figure 2. A schematic diagram showing the general approach to the sediment transfer hazard classification system.

Geomorphic Description

Details from the geomorphic description are used in determining sediment production, delivery and throughput potential. The channel network is divided into tributary and mainstem channels (Figure 4) each with their associated contributing watersheds (sub-basins). Homogeneous reaches of the mainstem stream channel are delineated on a base map and key morphological features are identified from airphotos and topographic maps (Table 1). The tributary watersheds are delineated and specific features are measured from the largest scale topographic maps and air photographs available (Table 2). Due to canopy closure and the smaller size of these channels, it is generally not possible to identify the same types of channel features on the tributaries as on the mainstem reaches.

Hillslope Sediment Delivery Potential

There are two components to the assessment of sediment delivery potential: identifying the nature of sediment sources; and evaluating these sources relative to potential sediment delivery to stream channels.

Sediment Sources. There are two basic types of sediment source: existing and potential. In most forest planning applications, existing sources are natural or background sources, but in some cases there may be previous logging or other human disturbance that is producing sediment. Potential sources are those that can produce sediment given certain land use practices (e.g. road construction).

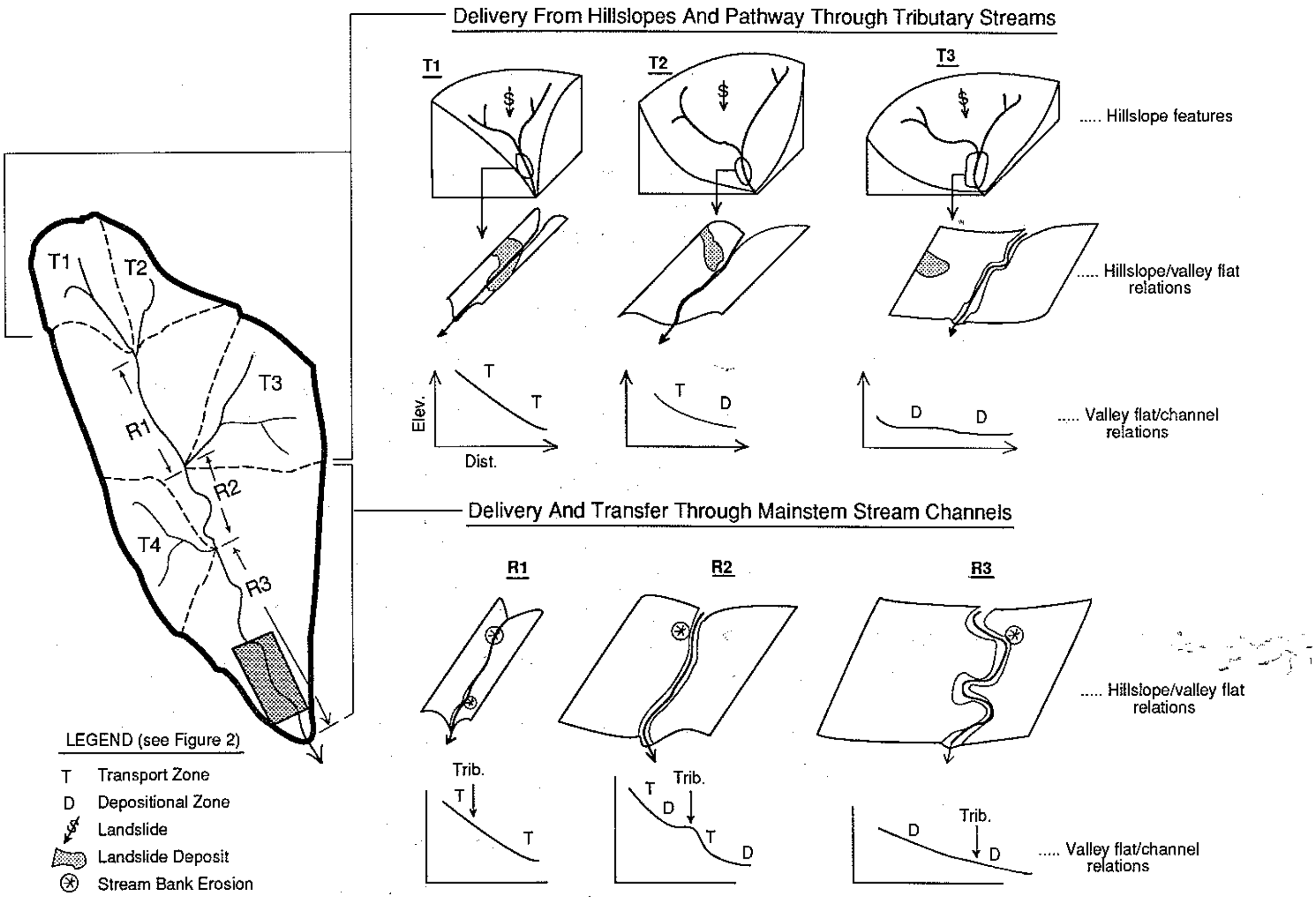

Figure 3. A schematic diagram illustrating the general feature considered to evaluate sediment delivery to the stream channel and sediment throughput to the fish habitat.

Table 1. Descriptive features of mainstem channel reaches.

Total Basin Area	Reach Gradient (profile)
Reach Length	Reach Sinuosity
Channel Pattern	Predominant Bar Type
Predominant Bed Material	Predominant Bank Material
Predominant Bank Vegetation	Lateral Stability
Hillslope-Valley Flat Relations	Reach Type
Valley Flat-Channel Relations	

Table 2. Tributary basin characteristics.

Total Sub-Basin Area	Channel Gradient (profile)
Channel Length	Length of Channel <1% Gradient
Valley Flat Extent	
Number of Lakes	Area of Lakes
Number of Swamps	Area of Swamps

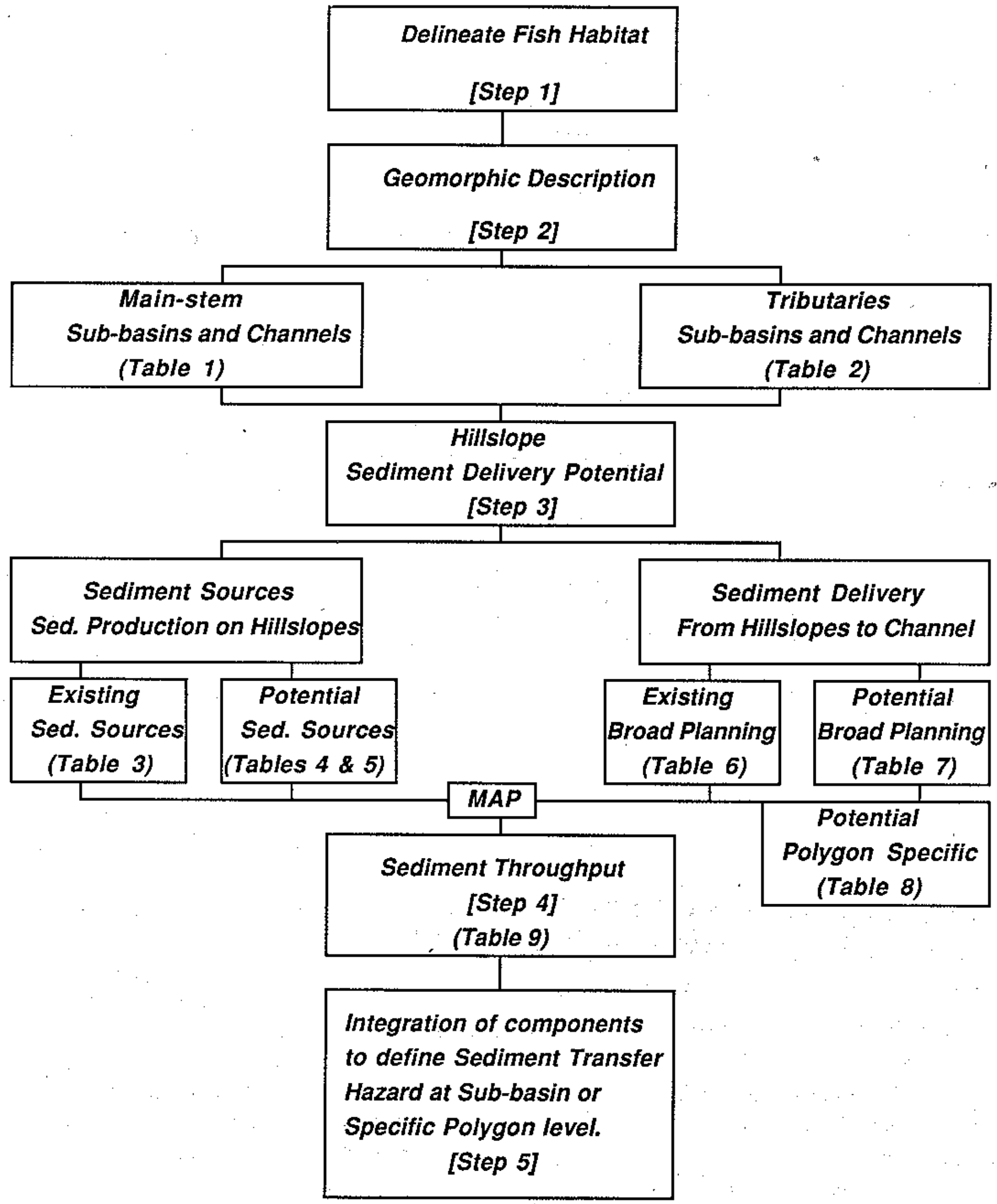

Figure 4. A flow diagram outlining the steps followed to classify the Sediment Transfer Hazard Zones for resource development planning. (Tables and Steps are discussed in the text).

Table 3. Existing Sediment Sources

General Type	Sediment Source	Map Symbol[1]
Areal	active colluvial slope	C-R, C-Rs, C-Rd
	active till slopes	M-R, M-Rs, M-Rd
	glaciers	I
	active bedrock cliffs	R-Rf
Linear	snow avalanches	A
	active gullying	V
	steep channels with high sediment loads	->
	multiple steep, low order stream channels	E
Point	stream bank erosion	●
	small slides and debris flows	x
	anthropogenic	a

[1]Howes and Ryder, 1984

Sediment and organic debris can be produced from numerous existing sources (e.g., streambank erosion, mass wasting, and snow avalanches). These sources are identified on terrain or landform maps (Ryder and Howes, 1984). The maps should cover an entire watershed so all existing sources of sediment production can be determined. Existing sediment sources are grouped into three general types: areal, point and linear (Table 3).

Potential erosion hazards for forestry are identified on interpretive maps of erosion potential; a common planning tool on the coast of British Columbia. The interpretive maps identify homogeneous polygons and generally have 5 classes for surface erosion potential and 5 classes for potential mass wasting or slope instability (Tables 4 and 5). Polygons are determined qualitatively based on soil texture, landform, slope angle and shape, soil moisture, natural erosion processes, and past incidence of logging related erosion in similar terrain (J. Schwab pers. com., 1988). These maps are usually produced at a scale of 1:20,000.

Sediment Delivery to Stream Channels. There are two levels at which sediment delivery from hillslopes to stream channels can be determined: broad planning; and specific to a landscape feature.

The broad planning level allows watersheds to be compared at an early planning stage, and highlights where the sediment delivery is a current or potential problem. This planning level infers delivery of sediment from hillslopes to stream channels based upon the spatial occurrence and type of natural and potential sediment sources. The basic unit for assessing sediment delivery is the tributary or main channel segment watershed, and a label is attached to the downstream end of each watershed (this information is presented on an overlay map). The criteria are presented in Tables 6 and 7. The class limits are scale dependent and must be modified to reflect the range of conditions in a specific area.

Table 4. Classes for surface erosion potential.[1]

Symbol	Class Definition
VL	very low potential for surface erosion: flat or very gently sloping terrain
L	Low potential: gentle slopes and short slopes
M	Moderate potential: moderately steep slopes and long slopes; some gentler but relatively moist slopes
H	High potential: steep slopes, and some moderately steep but relatively moist slopes
VH	Very high potential: very steep slopes with presently active slope proceses

[1]J.M. Ryder. 1987. Terrain analysis for the Hanna-Tintina area. 93p.

Table 5. Classes for slope stability potential.[1]

Symbol	Class Definition
I	Flat or very gently sloping land; stable
II	Gentle slopes with little potential for instability
III	Moderately steep slopes with intermediate potential for instability, especially where ground is relatively moist and where bedrock is present at shallow depths.
IV	Steep slopes with high potential for instability
V	Slopes presently unstable at many sites and with very high potential for increased instability

[1]J.M. Ryder. 1987. Terrain analyses for the Hanna-Tintina area. 93p.

Table 6. Sediment delivery within sub-basins: existing erosion.

Symbol	Class Definition[1]
VL	Very low levels of sediment input from the hillslopes or terrain unit. Only stream bed and stream banks contributing minimal sediment to the stream.
L	Low levels of sediment input from one or more of the following contributions: •Areal sources; ≤10% •Linear sources; drainage density ≤0.1 km/km² •Point sources; ≤5 per km² (historic only)
M	Medium levels of sediment input from one or more of the following contributions: •Areal sources; 11-20% •Linear sources; density 0.11-0.2 km/km² •Point sources; 5-10 per km²
H	High levels of sediment input from one or more of the following contributions: •Areal sources; 21-30% •Linear sources; density).21-0.3 km/km² •Point sources; 11-15 per km²
VH	Very high levels of sediment input from one or more of the following contributions: •Areal sources; >30% of area •Linear sources; density 0.34 km/km² •Point sources; >15 per km²

[1]The class limits are scale dependent and must be modified to reflect the range of conditions in a specific area. Values given here were used in an operational application.

The specific level of sediment delivery addresses the question - if sediment is produced at a given point in a watershed, will it reach a stream channel? (See Figure 2.) Specific delivery potential is dependent upon the nature of both the source and the landscape between the source and the stream. The specific level focuses on the polygons of the erosion potential maps, and becomes a suffix to the polygon label (Table 8). The specific level is used in the development of detailed plans for roads and cutting units.

The map presentation of sediment delivery concludes step three of the Sediment Transfer Hazard Classification System. The last step is to assess the sediment throughput of channels.

Sediment Throughput. The ability of a stream channel to entrain and transport sediment is a function of several factors (e.g., stream velocity, local channel gradient, nature of the bed and bank materials, channel shape and morphology, etc.). However, it is rarely feasible to collect specific data regarding these factors and it is usually impossible to rely on direct measurements when making management decisions at the operational level. For this reason it is necessary to use indirect measures of sediment transport to assess the probability that sediment introduced at one point will be moved downstream. Sediment throughput is assessed here from air photographs and topographic maps. The morphology and sediment character of each tributary and mainstem reach is documented from air photos (Tables 1 and 2). This is evaluted along with reach gradient, channel-valley flat relations and channel shape to classify throughput (Table 9). The gradient intervals in Table 9 are scale dependent and must be modified to reflect the range of conditions in a specific area.

The sediment throughput classes for the main tributaries and main stem reach segments are colour coded onto the 1:20,000 overlay map.

Using The System. The Sediment Transfer Hazard Classification System can be applied at two levels: the broad planning level; and the specific, cutting permit level.

Table 7. Sediment delivery within sub-basins: potential erosion.

Symbol	Class Definition	
I	Very low levels of potential surface erosion or hillslope instability. Expansive low relief terrain effectively stores sediment so that delivery to the stream channel is disconnected. Sediment delivery from terrain units is not important.	
II	Low levels of potential erosion. Surface Erosion H and VH or Hillslope Instability IV & V Low relief terrain less extensive than in Class I, less than 10% of the high erosion polygons border or intercept a stream channel.	<10% of total area of sub-basin
III	Medium levels of potential erosion. Surface Erosion H and VH or Hillslope Instability IV & V All polygons are separated by a medium sized valley flat or low relief terrain (VF is 3-5wb), but other terrain features (e.g., gullies, low order streams) will transfer medium amounts (10-30% of total) to the stream.	10-20% of total area of sub-basin
IV	High levels of potential erosion. Surface Erosion H and VH or Hillslope Instability IV & V A narrow valley flat or low relief terrain (VF ≤3wb) separates the potential erosion sites from the channel but other terrain features (e.g., gullies, low order streams) will deliver much (30-70%) of all potentially eroded sediment to the channel.	21-30% of total area of sub-basin
V	Very high levels of potential erosion. Surface erosion H and VH or Hillslope Instability IV & V Steep relief and no valley flat will deliver most or all (70-100%) of all potentially eroded sediment to the stream channel.	>30% of total area of sub-basin

Table 8. Sediment delivery from individual potential erosion polygons.

Symbol	Class Definition
I	Very low levels of sediment delivery. The polygon does not border or intercept any stream channel. A very broad valley flat, or low relief terrain effectively disconnects the potential sediment source and the channel.
II	Low levels of sediment delivery. The polygon is separated from all streams by a wide valley flat or low relief terrain (VF ≥5 wb). Only minor amounts (≤10%) of the potential sediment eroded will reach the channel.
III	Medium levels of sediment delivery. The polygon is separated from streams by a medium sized valley flat or low relief terrain (VF 3-5 wb), but other terrain features (e.g., gullies, low order streams, etc.) may transfer low, but measureable amounts of sediment to the channel (10-30%) of potentially eroded sediment.
IV	High levels of sediment delivery. The polygon is separated from the stream channel by a narrow valley flat of low relief terrain (VF ≤3 wb) but other terrain features (e.g., gullies, low order stream channels) will deliver much (30-70%) of the potentially eroded sediment to the channel.
V	Very high levels of sediment delivery. The polygon directly borders a stream channel. the terrain is steep and all sediment produced will be delivered to the channel. There is no valley flat. Sediment is directly connected to the channel. All potential sediment (70-100%) will enter the channel.

At the broad planning level there are two key components. The first is the sediment delivery overlay map that characterizes existing and potential sediment movement to channels at the sub-basin level (Tables 6 and 7). The second component is the Sediment Throughput overlay map of the channel network according to Table 9. These two components are linked in a matrix (Figure 5) to determine the sediment transfer hazard from a specific sub-basin. For example, if a sub-basin has a high level of existing sediment input (H) and a very low level of sediment throughput (Class 1), the Sediment Transfer Hazard is low. Thus the hazard reflects not only the amount of sediment input but also the ability of the channnel to transport the sediment. The only exceptions are channel reaches with high fish values (Class 1a and 2a). Due to the depositional nature of these channels and their high fish values, they require special attention (e.g., sediment that is not transfered *is* a problem).

At the broad planning level the matrix identifies the sediment transfer hazard for a sub-basin. The next step is to use the Sediment Throughput map to determine how effective the channel network is with regards to sediment delivery between the sub-basin and the fisheries sensitive areas (Class 1a reaches). Any channel that has a low sediment throughput (i.e., class 1 or 2) will act as a sediment sink. Thus the probability of sediment transfer from any sub-basins above a Class 1 channel is low. As the sediment throughput class increases, the probability of delivery increases. Thus the sequencing of Sediment Throughput Classes is critical in the overall assessment of impacts to the fisheries sensitive area.

At the specific cutting permit level there are also two key components that are used to assess the potential for sediment leaving a specific site and impacting on a fisheries sensitive area. The first component is the sediment delivery suffix (Table 8) on the potential erosion map. This label indicates the level of sediment delivery risk associated with the polygon. The second component is the Sediment Throughput overlay map of the channel network according to Table 9. As with the broad planning level, the matrix (Figure 5) is used to

Table 9. Sediment throughput classes.

Class	Description	Interpretation	Color Code
1& 1a	Very low level of sediment throughput. Although headwaters may be steep, the basin has mainly low gradient channels (≤0.1%) with very wide valley flat and lakes/swamps. These channels store sediment.	There are two types of Class 1: **1.** A depositional stream channel with no fish values	Green
		1a. A depositional stream channel with high fish values. A high hazard channel.	Green with X's
2& 2a	Low level of sediment throughput. Lakes are present but are less effective sediment sinks due to location and size. Swamps are extensive, channels are low gradient (0.1-0.9%) and the valley flat is wide (>>5 wetted bank widths (Wb)).	There are two types of Class 2: **2.** No problem if cautious due to low sediment transfer capability.	Blue
		2a. A depositional stream channel with high fish values. A moderately high hazard channel.	Blue with X's
3	Moderate level of sediment throughput. Few large sediment sinks (lakes and swamps are small or ineffective). Steeper channel gradients (1.0-2.0%) with channel bars. Valley flat 3-5Wb.	Concern. Sediment transfer requires caution.	Yellow
4	High level of sediment throughput. Mainly steeper gradient channels (2.0-5.0%) with minor localized low gradient sections. Less extensive channel bars and valley flat is confined (1-3Wb).	High level of concern requiring detailed assessments and close supervision.	Red
5	Very high level of sediment throughput. Steep channels (≥5%) with no channel bars or valley flat.	Avoid - these channels transport all sediments.	Black

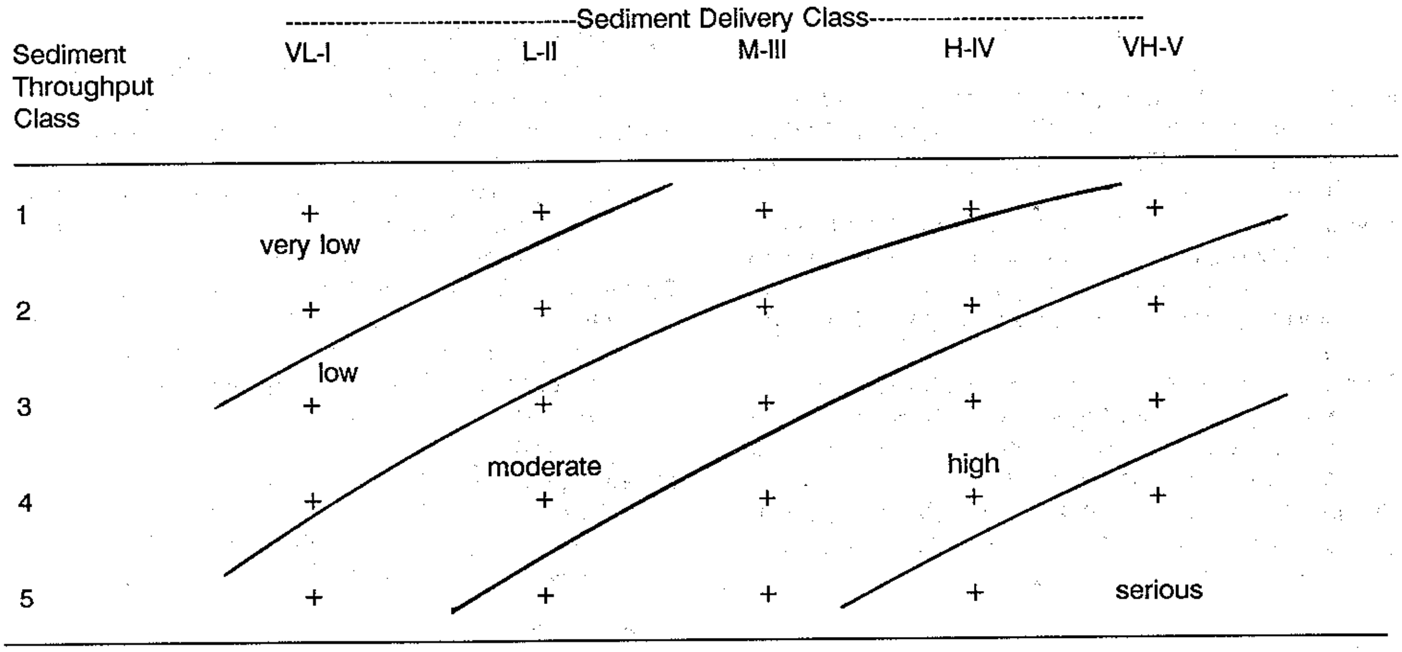

Figure 5. Sediment transfer hazard matrix.

determine the Sediment Transfer Hazard, and the sediment throughput map is used to determine the sequencing of throughput classes - a critical factor in determining impact to the fisheries sensitive area.

In summary, Class 1a and 2a are the fisheries sensitive zones. Sediment entering any channel may be transfered downstream to this area if there is not a sediment sink such as a Class 1 or 2 channel between the sediment source and the 1a or 2a zones. If there is not a "sink", a "red flag" situation is indicated because the fisheries sensitive area is directly connected to a more efficient channel transport segment. Based on the level of concern, the situation may require special road construction or harvesting methods to reduce sediment production, or in more extreme situations it may be necessary to call in a specialist to examine site specific features, or avoid forestry operations in the specific subbasin or polygon unit. If sediment produced on a site will not impact fisheries habitat, the decision to proceed with forestry activities is essentially a question of potential forest site loss.

Conclusions

The Sediment Transfer Hazard Classification System provides the link between erosion and downstream sedimentation impacts on fish habitat. The system does not provide absolute quantities of sediment delivered. The quantity of sediment delivered depends on precipitation, soil moisture and streamflow conditions at the time of sediment production. These conditions are factors that resource managers must consider when they undertake activities on areas that are linked to fish habitat.

The link between erosion and fish habitat is critical for true integrated resource management. The system uses information that is available, or can be generated quickly and cheaply at the operational level. The cost of applying the system is minor considering the costs of not harvesting "safe" timber, or costs associated with attempting to rehabilitate damaged fish habitat.

The system was applied to a watershed in northwestern British Columbia that has high forestry and fisheries values. The hazard map significantly increased the confidence of resource managers in the planning exercise. Areas of concern in the watershed were clearly identified. Special attention will be paid to stream crossings and harvesting activities in these areas. Special measures such as revegetation of disturbed areas were prescribed. A significant outcome of the application was a clear recognition that erosion can be linked to fish habitat. This is generally accepted in concept, but applying the Sediment Transfer Hazard Classification System made it a reality.

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