WATERSHED RESTORATION
PLANNING AND PRIORITY SETTING

An Emphasis on Fish Habitat

March 2004

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Table of Contents

List of Tables

List of Figures

List of Appendices

<u>WATERSHED-LEVEL PLANNING</u>

IDENTIFYING PRIORITY WORK WITHIN TARGET WATERSHEDS AND PREPARING A WATERSHED RESTORATION PLAN

INTRODUCTION

These guidelines describe a structured process for: *selecting* subbasins *within target watersheds* that have a high likelihood of restoration success; *identifying* those watershed components that are most critical to restore; and *establishing* a priority list of works within those components. The end product is a *Restoration Plan* (RP) which:

- identifies the critical fresh-water limiting factors affecting fish and/or domestic water supply
- identifies the components targeted for restoration
- describes the subbasin, component and site-level restoration objectives
- identifies the high-priority restoration activities and sites to meet these objectives
- establishes a baseline for completion
- provides a schedule of works and budget estimate, and
- describes an evaluation plan.

Creating a RP is a two-staged approach:

- Stage **A** identifies the high priority subbasins and components for restoration – those that are a high priority in relation to specified restoration goals for the watershed.
- Stage **B** develops watershed action strategies based on habitat limiting factors, cost and risk assessment for the high priority subbasins.

By targeting subbasins and priority components, there are opportunities to reduce detailed assessment work. For example, it is unlikely that detailed field assessments will be required for every subbasin or for all components within subbasins targeted for restoration.

This approach differs from previous versions of Integrated Watershed Restoration Plans (IWRPs) outlined in program materials and standards agreements as it is based on a progressively more targeted identification of:

- priority subbasins in relation to probable critical limiting factors and potential for success of restoration, and
- specific works required to address only the critical limiting factors for fish.

KEY PRINCIPLES

Watershed-level planning is guided by a number of key principles:

- *Stakeholder and partnership involvement*
  Numerous groups within a community may have an interest in a particular watershed. Such groups may include forest tenure holders, forest worker groups, permitted water users, First Nations, resource stewardship groups, recreational groups, licensed outfitters or guides, and various government agencies.
- *Integrated Restoration Plan*
  A planning procedure that integrates the assessment of watershed geomorphology, risk (hazard and consequences) and critical limiting factors into the selection and prioritization of cost-effective restoration works.
- *Preventative work is most cost-effective*
  Restoration work that targets sites with potentially high hazard and high consequences are usually the most cost-effective.
- *Restoration work not to impact non-target aquatic organisms*
  Decisions on restoration sites and activities to benefit the target species should not negatively impact or reduce historic habitat area for non-target aquatic organisms.
- *Implementation of restoration works to adhere to government regulations*
  Implementation of the program adheres to the various regulatory acts where required; i.e. Fisheries Act, Water Act, municipal bylaws, Navigable Waters Protection Act, Forest Practices Code and any other approvals that may be pertinent.
- *Feedback monitoring results to incrementally improve program design.*
  Restoration works are monitored and evaluated in the short and long term including both routine monitoring, and detailed monitoring for a subset of projects and operational trials. Results are used to evaluate the overall program design. For example, results may indicate improvements to existing techniques and activities or may suggest how new activities may be added to meet the full range of program objectives.
- *Maximize resource benefits in priority watersheds*
  Where feasible, planners and implementers work cooperatively with other stakeholder initiatives so that the full range of land use impacts within a watershed are addressed.

ASSOCIATED TERMS

Watershed units: major watershed boundaries identified on a base map for each region of BC (usually 3rd to 5th order streams averaging 30,000 ha, but ranging from 10,000 to 50,000 ha for the coast to 500,000 ha in the dry interior).

Subbasins: the watersheds of tributary streams within a watershed.

Components: groupings of watershed processes—hillslope, riparian, and channel components.

Watershed process types: a classification of B.C. watersheds / streams according to process types, based on *hillslope connectivity* or *coupling* (the degree to which the stream channel is coupled to the hillslopes) and *stream connectivity* (the capacity of the stream channel to transport sediment).

Target Watersheds: those watersheds that contain high to very high values of targeted fish species/stocks.

A ~ Selecting Subbasins and Identifying Watershed Components for Restoration

The initial task in this phase is to identify subbasins of the target watershed that are the best candidates for restoration works. A target watershed will likely range from a 3rd- to 5th-order stream comprised of a number of subbasins. Problems are often restricted to one or two subbasins in the entire watershed.

Existing overview assessment information can be used to:
- identify the important subbasins,
- estimate the impact on fish habitat by *watershed component* for each subbasin, and
- determine the potential for restoration success for each subbasin.

A six-step approach is recommended to complete the task. The steps are summarized below. Detailed procedures for each step follow the summary list.

Step 1	Identify the subbasins.
Step 2	Compile an overview information sheet for each subbasin.
Step 3	State objectives for each target watershed.
Step 4	Assess the relative impact of components (i.e., landslides, gullies, roads, riparian, channel, and instream fish habitat) on critical limiting factors for fish habitat for each subbasin.
Step 5	Determine the potential for restoration success for each component in each subbasin.
Step 6	Identify the high priority subbasins for more detailed assessment, planning and restoration.

Step 1
Identify the subbasins

Subbasins are commonly one or two stream orders less than the key watershed stream order. Major subbasins of a watershed can be identified by reviewing an appropriate map. Residual areas should be grouped together. If an Interior Watershed Assessment Procedure (IWAP) or a Coastal Watershed Assessment Procedure (CWAP) has been carried out previously, then subbasin boundaries will have been identified already.

Step 2
Compile an overview information sheet for each subbasin

Overview information will need to be compiled for all subbasins. In some cases, this information may already be available from a previous Watershed Restoration Program (WRP) Overview Survey or a Watershed Assessment.

The information needed for each subbasin includes:
- land tenure

- approximate area logged (obtained from the MWLAP Watershed Condition Atlas)
- overview channel stability and channel type (using Re-Cap – the Reconnaissance-level Channel Assessment Procedure)
- riparian condition of the tributaries and mainstem (obtained from recent air photos, forest cover maps or aerial reconnaissance)
- overview fish habitat assessment (e.g., Overview Fish Habitat Assessment Procedures (FHAP) – Johnston and Slaney 1996) that identifies critical habitat reaches, estimates habitat condition, and designates areas of special concern
- overview hillslope condition that describes the extent of landslides and roads with potential of landslides (obtained from air photos, aerial reconnaissance, or terrain stability maps).

This overview information is best summarized in a one-page format. An example summary – for the Rainy Creek subbasin in the Maple River target watershed – appears in Table 1 on the next page. In the example, the channel and riparian conditions of the subbasin are rated as poor; the hillslope and road conditions are fair.

A contractor could quickly gather the information by contacting key individuals and organizations in the region and by reviewing existing reports.

Table 1. Example summary overview information for the Rainy Creek subbasin / Maple River target watershed

Watershed:	Maple River
Subbasin:	Rainy Creek
Drainage Area (ha):	491 ha
Tenure:	100% TFL
Area Logged (%)	Approximately 50%, mostly recent
Equivalent Clearcut Area (ECA) (%)	Approximately 40-50%
Channel:	
Type (CAP):	Step-Pool
Width (m):	6-9 m
Gradient %):	3-6%
Watershed type	The stream channel is highly coupled to the hillslopes. Limited floodplain development.
Channel Conditions	Poor. The mainstem channel of Rainy Creek appears to have been substantially aggraded as a result of forestry-related landslides. There is evidence on the 1995 air photos of channel aggradation on the alluvial fan, upstream of the Bend River, and of avulsions on the fan. In addition, there is evidence that the Rainy Creek channel experienced a "debris torrent," with deposition of the sediment and debris in the channel adjacent to the B Main bridge. The air photos indicate that the sediment and debris was excavated from Rainy Creek upstream of B Main, resulting in channel straightening. The high ECA for this basin results in a high risk of increased peak discharge and accelerated bed material transport.
Riparian Condition	Good. All riparian forests are intact.
Road Condition	Fair. Approximately 1 km of the 12 km road system is high risk. Failures from this mid-slope road will impact the mainstem of the river. The rest of the road system is isolated from fish habitat but has not been deactivated. Road materials in general have a low soil erosion hazard.
Hillslope Conditions	Fair. A number of natural and forestry-related landslides have deposited coarse sediment into Rainy Creek, including 3 moderate sized slides about 500 m upstream of the alluvial fan apex. Two of these slides are still actively transporting sediment to the creek channel. It is expected that elevated bed load transport from the mid- and upper-reaches of the Rainy Creek basin will continue for a few year, with ongoing aggradation of the channel from the Bend River to the fan apex, above the B Main bridge.
Fish Target	Steelhead/Rainbow Trout
Habitat Conditions	Fair-poor. A debris torrent and aggradation of landslide coarse sediments have infilled pools and boulder dominated sections in the middle and upper reaches of the creek. This has impacted rearing habitat for trout. Ongoing aggradation will continue to limit the carrying capacity of rearing habitat.

Step 3

State objectives for each target watershed

This step involves developing objectives for entire target watersheds. These will be high-level objectives addressing the major problems or degraded resources in relation to the fish values. This will allow you to place the work on subbasins within the context of the whole watershed.

Step 4

Assess the relative impact of watershed components on critical limiting factors for fish habitat for each subbasin

Watershed processes are administratively organized into "component" groups – hillslope components, riparian components and channel components. (The hillslope component is further divided into road, gullies, and landslide-risk aspects.) Estimating the impact on fish habitat of each component requires an assessment of the relative importance of the components affecting the stream reaches containing the fish habitat. The relative importance of the components in affecting channel integrity varies by watershed type. This is discussed in Figure 1 and in more detail in Appendices 2 and 3.

Figure 1 **Watershed Process Types**

Watersheds have unique combinations of physiography, climate and geology which drive the geomorphic processes that determine the sediment supply, the stream discharge, the channel type and ultimately the fish habitat. Upstream of an identified reach, the main difference between watershed types is the degree to which the hillslopes are connected to the streams (its hillslope connectivity or coupling) and the capacity of the stream to transport sediment (its stream connectivity). Typically, as you move downstream from reach to reach in a watershed, the dominant watershed processes above the identified reach progress from one dominant type to another. For example, in small coastal watersheds the channel is often strongly coupled to the hillslopes and landslides dominate the stream channel morphology, but there are few alluvial reaches. Further downstream channels become partially coupled to hillslopes and landslides can trigger dramatic changes in alluvial reaches of the channel. As watershed area increases and hillslope and stream channel gradients become less, fluvial processes dominate channel morphology and the relative affect of hillslope processes is much less. Further downstream, the channel may become locally coupled to valley sides, where it is incised through thick glacial sediments.

Watersheds in different parts of the province have "typical" sequences of process types affecting the stream reach as one moves downstream (Appendix 1). Each of the types has a characteristic sediment budget, stream channel type, dominant processes affecting the stream reach, and appropriate restoration techniques (Figure 2).

A more complete description of each type, the dominant processes affecting the stream reaches and recommended priority restoration activities for that type are described in Appendix 1: Watershed Process Types and Associated Restoration Opportunities. A thorough description of watershed processes appears in Appendix 2: Watershed Dynamics, prepared by Dr. Michael Church (available on request from Heather.Deal@gems1.gov.bc.ca).

Use the compiled overview information for each subbasin (from Table 1) together with an appreciation of the dominant watershed components affecting the identified stream (as outlined in Figure 1 and Appendices 2 and 3) to estimate the impact on fish habitat of each component. The grid shown in the Table 2 example can be used to record this information.

Table 2. Impact by watershed component on fish habitat (Example: Rainy Creek)

Rainy Creek	Landslides	Gullies	Roads	Riparian	Channel
Habitat	M	M (old)	M	L	H

Step 5

Determine the potential for restoration success for each component in each subbasin

This step involves determining the potential for success in restoring each watershed component in each subbasin. The potential for success should be guided by the following principles:

- The main goal is to restore channel function so that the watershed will naturally recover critical habitat *at an accelerated rate*. Restoration work that addresses the component most strongly affecting the identified reach has the greatest potential for success.
- The most cost-effective works are those that address the *critical limiting* factors for the targeted fish species.
- Watersheds with a *single* impacted component generally have the *highest* potential for restoration success.
- Watersheds where *many* components are impacted (e.g., stream disturbance, landslide activity and hillslope erosion, and riparian disturbance have all contributed to habitat loss) have the *lowest* potential for restoration success.

Table 3 shows a decision-making matrix for the Maple River Watershed example. This is not intended as a "yes or no" matrix, but rather as a guide – using low, moderate and high ratings – to assist regional groups in understanding the complexities and interactions of watershed processes, and to help identify the target subbasins for more detailed assessment as outlined in Step 6.

The table helps to guide (and record) a procedure that evaluates the likelihood of restoration activities benefiting the probable limiting habitat for the fish species of concern. It does this in a stepwise fashion:

- in the first line for each creek under consideration, the *level of existing or potential disturbance* for each watershed component is noted
- in the second line, the *impact or risk that is posed to the critical fish habitat* by the disturbance is recorded.
- in the third line, the *likelihood of benefit to critical limiting fish habitat* from works on that component is given a rating.

In the example shown, under Howler Creek, there is a *high* riparian disturbance, and because the critical fish habitat is rearing habitat for Steelhead and Rainbow, the risk to that habitat is also given a *high* rating. Again, using the Howler Creek case, there is a *high* expected benefit from restoring the riparian component of the watershed that would be realized in the long term (>75 yrs).

Table 3. Example of a procedure to evaluate the likelihood of restoration activities benefiting fish habitat in the Maple River Watershed

				Watershed Components					
Subbasin Example	**Target Species**	**Limiting Fish Habitat**	**Watershed Condition and Restoration Benefits**	**Landslides**	**Gullies**	**Roads**	**Riparian**	**Channel**	**Instream Fish Habitat**
Rainy Creek	Steelhead/ Rainbow	Summer rearing	Level of Existing or Potential Disturbance	Moderate	Moderate	Moderate	Low	High	High
			Impact or Risk to Fish Habitat	Moderate	Moderate	Moderate	Low	High	N/A
			Likelihood of Benefits to Fish Habitat from Restoration of Component	Low	Low	Low	Low	Low	Low
Howler Creek	Steelhead/ Rainbow	Summer rearing	Level of Existing or Potential Disturbance	Low	Low	Low	High	Moderate	Moderate
			Impact or Risk to Fish Habitat	Low	Low	Low	High	Moderate	N/A
			Likelihood of Benefits to Fish Habitat from Restoration of Component	Low	Low	Low	High (Long Term)	Moderate	High
Punch Creek	Steelhead/ Rainbow	Summer rearing	Level of Existing or Potential Disturbance	High	Moderate	Low	High	Moderate	High
			Impact or Risk to Fish Habitat	Moderate	Moderate	Low	High	Moderate	N/A
			Likelihood of Benefits to Fish Habitat from Restoration of Component	Moderate	Moderate	Low	High (Long Term)	Low	Low

Step 6

Identify the target subbasins for more detailed assessment, planning and restoration.

The format shown in Table 4 can be used to tabulate the ratings for each subbasin, summarizing the information from Table 3. The subbasins receiving one or more *high* ratings go on the priority list for restoration works. These subbasins have the greatest potential for positive outcomes to help speed the natural recovery process.

Table 4. Likelihood of restoration success (Example: Maple River Target Watershed)

Watershed	Subbasin	Low	Moderate	High	Primary Component for Restoration	Secondary Component for Restoration
Maple	Rainy	*			None	
	Howler			*	Instream habitat	Riparian
	Punch			*	Riparian	

This concludes ***Stage A*** of the process. Building on the information gathered thus far, ***Stage B*** sets out a *plan of action* for restoration works for each high priority subbasin within a target watershed.

B ~ Developing a Plan for Implementing Restoration Works in High Priority Subbasins

Following the initial identification of subbasins that are the best candidates for restoration works (outlined in the previous section), the task now is to create a detailed plan for each high priority subbasin in the whole watershed.

The ***Restoration Plan*** (RP) will include a work plan for each priority subbasin identified. The plan should:

- define restoration objectives for the whole watershed based on fish goals
- identify priority subbasins and targeted components for restoration work
- establish subbasin, component, and site-level restoration objectives
- identify appropriate restoration activities by component and site
- create an implementation plan for activities, including access management, and
- develop an effectiveness evaluation plan, and identify benchmarks for determining completion of work within the watershed.

The RP should follow an integrated, holistic approach and be focused on speeding recovery of freshwater fish habitat but particularly the watershed processes that create and maintain fish habitats. For this reason, activities are integrated with watershed processes and targeted to critical limiting factors. Decisions on habitat restoration activities and sites are also guided by the principle that restoration for the target species should not negatively impact or reduce habitat of other endemic fish species.

It is recognized that other factors – such as exploitation pressure or ocean survival – may be limiting fish-stock productivity. However, the fish habitat goals of RPs are focused on speeding the recovery of freshwater habitats and increasing survival at each freshwater life stage through the restoration of watershed components and processes. Although restoration activities are sequenced to favor the recovery of targeted species, it is expected that the recovery of watershed processes will restore habitat for other endemic fish species over the long term.

An eight-step approach is recommended to complete the task. The steps are summarized below. Detailed procedures for each step follow the summary list.

Step 1 Complete required assessments and/or obtain existing ones.
Step 2 Identify critical limiting factors and confirm the watershed components affecting these factors.
Step 3 Determine priority components for restoration.
Step 4 Develop subbasin, component, and site-level restoration objectives.
Step 5 Identify priority restoration activities and field locations.
Step 6 Select restoration alternatives through analysis of cost-effectiveness and risk.
Step 7 Develop an implementation plan.
Step 8 Complete a RP document encompassing work plans for all high priority subbasins in the watershed.

The user will find many of the steps seemingly repetitive from the previous section. The difference is that overview information is required to select priority subbasins in Stage A; whereas, detailed assessment information is needed here in Stage B to guide the development of a *Restoration Plan*. When complete, the RP document will present a *recommended* plan for the watershed, including detailed restoration activities at a subbasin level.

Step 1

Complete required assessments and/or obtain existing ones

Detailed information about watershed condition and habitat limitations for the identified fish species are obtained from focused field-based assessments. To secure this information, first review any existing assessments. *In many watersheds, previously completed assessments will be adequate to determine priorities for restoration works*. If no information is available, the following assessment(s) can be done.

Assessments in Target Watersheds

Here are the action steps when fish habitat is the issue:

- Determine the important reaches in each subbasin for the identified species.
- Complete a detailed fish habitat assessment on the critical reaches. If the critical limiting factors are known, the habitat assessment should assess only those habitat characteristics that relate directly to the critical limiting factors *within* the specific reach. A Channel Conditions and Prescriptions Assessment (CCPA) for specific reaches may be conducted as part of the habitat assessment where it is evident that stream channel instability is a concern. Also, a Fish Passage Culvert Inspection may be warranted if fish access is known or suspected within the subbasin.
- Complete a Riparian Assessment of only the identified, impacted reaches.
- Conduct either a Sediment Source Survey (SSS) – see WAP – or Erosion and Mass-Wasting Risk Assessment (EMRA) or equivalent on roads and hillslopes that could affect the identified reaches.

For the assessments in the final point above, the focus is on the following high-risk sources of sediment:

- roads with severe, active erosion from unconsolidated soils linked to a stream that is well above background rates of erosion (fill slopes into streams, high-raveling cutbanks, etc.)
- roads at risk of landsliding with linkage into a stream (e.g., midslope roads on steep slopes where a landslide will affect a stream)
- road crossings, particularly those on sensitive soils
- channel sediment sources where active streambank erosion is evident
- landslides, particularly those that are actively mass wasting
- eroding gullies tributary to a stream
- gullies at risk and tributary to a stream and
- livestock crossings.

Step 2

Identify critical limiting factors and confirm the watershed components affecting these factors

From the detailed fish habitat assessment, identify which element(s) of fish habitat are limiting the target fish's production. The elements of fish habitat include the nursery, rearing, food supply, and migration areas as well as the spawning grounds. For each stream reach, identify the factor(s) that are seen to be affecting specific elements of fish habitat or survival of particular life stages, and thus limiting production.

An increased sediment load, for example, is often a factor limiting for spawning (incubation survival) and rearing habitats. Freshwater fish survival may also be limited by a combination of factors, such as low nutrient concentrations, high temperatures and poor rearing habitat. Using a SSS, EMRA, CAP, Riparian Assessment or other appropriate procedures, identify the watershed components and processes that are causing or affecting the critical limiting factors.

Step 3

Determine priority components for restoration

Information to accurately identify important components for restoration can be summarized in a table or decision-making matrix. A completed example of this is shown in Table 5. This table is similar to Table 3, except that the table is now based on detailed assessment information. A greater understanding of the watershed occurs as new information becomes available. For example, the critical limiting habitat for Howler Creek in Table 3 was summer rearing habitat. After the detailed habitat assessments, the critical limiting habitat was identified as summer and winter rearing habitat in Table 5. The potential impacts of components and benefits of restoration on the critical limiting factors needs to be re-considered as new information becomes available.

Table 5 provides a mechanism to document watershed characteristics and condition, and to qualitatively assess the likelihood of significantly improving critical fish habitat for the species of concern by restoring specific watershed components. It includes a column for the dominant watershed process type for the identified reaches and rows organized in a progressive fashion:

- in the first line for each creek under consideration, the *level of existing or potential disturbance* for each watershed component is recorded based on information from the detailed assessments.
- in the second line, the *impact or risk that is posed to the critical fish habitat* by the disturbance is recorded.
- in the third line, the *likelihood of benefit to critical limiting fish habitat* from works on that component is estimated.

Each estimate in the third point above is conditioned by the watershed process type.

Step 4

Develop subbasin, component, and site-level restoration objectives

Subbasin, component, and site-level objectives provide the basis for all restoration and evaluation work conducted within a watershed. The objectives will direct the development of prescriptions and become a benchmark for future effectiveness monitoring. (For more information on developing restoration objectives, see the document: *A Framework for Effectiveness Evaluation of Watershed Restoration Projects 1999;* http://srmwww.gov.bc.ca/frco/bookshop/tech.html)

Where possible, restoration objectives should be phrased to address a particular watershed process (physical or biological) and *structured to address the critical limiting factors identified through the restoration planning process.* Component-level objectives include the road, gully, landslide, riparian, and stream components within a subbasin. Where appropriate, component-level objectives should specify the extent of risk reduction. For example, the objective may state that road deactivation works will reduce risk of road related slope failures from a high to a low risk level. Site-level objectives include distinct site features within each component (e.g., cutslope, fillslope, running surface, and ditches are sites that make up the road component).

All objectives should be:

- specific, measurable and attainable
- indicate a change in direction (increase or decrease) toward a more stable state or a future condition of reduced environmental risk, based on current conditions
- focused on manipulation of hillslope and stream processes in relation to Watershed Level objectives.

Table 5: Example of a decision-making matrix for identifying investment opportunities to address critical habitat limitations in a watershed based on targeting components with a high likelihood for success

Example for Maple River Watershed

Subbasin Example	Target Species	Watershed Process Type	Limiting Fish Habitat (from detailed habitat assessment)	Watershed Condition and Restoration Benefits	Landslides (from SSS)	Gullies (from SSS)	Roads (from SSS)	Riparian (from detailed habitat assessment)	Channel (from Re-CAP)	Instream Fish Habitat (from detailed habitat assessment)
Howler Creek	Steelhead /Rainbow	High hillslope coupling	Summer and winter rearing	Level of Existing or Potential Disturbance	Low	Low	Low	High	Moderate	Moderate
				Impact or Risk to Fish Habitat	Low	Low	Low	High	Moderate	N/A
				Likelihood of Benefits to Fish Habitat from Restoration of Component	Low	Low	Low	High (Long Term)	Moderate	High
Punch Creek	Steelhead /Rainbow	Partially coupled	Summer rearing	Level of Existing or Potential Disturbance	High	Moderate	Low	High	Moderate	High
				Impact or Risk to Fish Habitat	Moderate	Moderate	Low	High	Moderate	N/A
				Likelihood of Benefits to Fish Habitat from Restoration of Component	Moderate	Moderate	Low	High (Long Term)	Low	Low

Step 5

Identify priority restoration activities and field locations

This step identifies the general type of restoration activity proposed and the field locations where restoration prescriptions should be prepared. Watershed assessments completed in Step 1 will have identified reaches, segments, and sites that have experienced negative impacts of earlier forestry practices and would benefit from restoration. Step 3 identified components with a high likelihood of improving habitat. From this information, it is possible to identify the sites, segments or reaches for each high priority component where restoration prescriptions will be prepared. Restoration work in a subbasin can occur on multiple high priority components and at multiple sites for each high priority component. These locations should be illustrated on a map.

The Table 5 matrix is used to identify which component(s) have the greatest potential to affect the critical limiting habitat of the identified fish species through restoration works. Within each component, a variety of activities are possible but each may be judged by the restoration professional to have a certain level of effectiveness. The following is provided as a set of restoration alternatives for each component that have been grouped into 'levels of effectiveness' based on the effectiveness of treatments observed in restoration projects to date. Treatment effectiveness was based on a general assessment of cost-effectiveness, risk, primary or persistent sediment sources, and whether benefits were expected in a long or short time period. Preventative work is seen as the most cost-effective. It is recognized that exceptions to these levels of effectiveness may exist or will occur with further experience in watershed restoration. The choice of treatment will depend ultimately on the assessment by and experience of the restoration professionals.

Hillslope Component

Highly Effective
- Drainage control and road deactivation on roads at high risk of landsliding into the stream.
- Drainage control and revegetation on roads on unconsolidated sediments (glaciolacustrine or glaciofluvial) with recurrent point soil erosion sources and high delivery to a stream.
- Recovering, unstable fills and old bridge abutments at stream crossings (all watersheds).
- Hand- and heli-seeding of exposed mineral soil sites.

Moderately Effective
- Gully restoration of high-risk gullies.
- Drainage control and road deactivation on moderate-risk sites.
- Road ripping and revegetation of roads (except as specified above).

Least to Moderately Effective
- Landslide stabilization using bio-engineering techniques. The appropriateness of landslide stabilization techniques is best determined at the site level on an individual cost- effectiveness analysis. In general, however, landslide scars are not significant parts of the watershed sediment budget and the cost of mechanical or bio-mechanical stabilization is high. Where sediment yield is high, with a high consequence, the priority will be greater.

Riparian Component

Highly Effective

- Riparian works immediately adjacent to instream or off-channel habitat rehabilitation to obtain both short- and long-term benefits.
- Riparian work that will provide shade in a few years.

Moderately Effective

- Riparian work upstream of but in the same reach as prescribed instream works. While downstream movement of large woody debris (LWD) occurs, the majority of the benefit of riparian re-growth for LWD recruitment is realized in the same reach.

Least Effective

- Restoration of riparian forest not associated with instream work.

Stream Channel Component

Highly Effective

- Bank stabilization structures, such as “debris groins” that also provide instream habitat.

Moderately Effective

- Streambank stabilization using vegetative revetments at key sites.
- Bar stabilization using planted willow and cottonwood.
- Bank stabilization using integrated structures at key sites.

Least Effective

- Bank stabilization using rock at key sites. This treatment is less beneficial as fish habitat then when rock is integrated with LWD. However, for certain high energy sites it may be the most appropriate technique.

Fish Habitat Component

Highly Effective

- Removal of fish migration barriers where roads cross streams.
- Restoration of floodplain habitat through removal of barriers to back channels and side-channels and other off-stream habitat.

Moderately to Highly Effective

- Restoration and construction of off-channel habitat. This includes restoration of access by fish to historic off-channel habitats.
- Instream structures. The feasibility, type and number of channel structures that are appropriate are determined through the use of diagnostics for the channel type.

Least to Moderately Effective

- Stream fertilization using slow release fertilizer on nutrient-poor streams. Fertilization is most effective when coupled with physical habitat restoration and conservative risk fisheries management.

Step 6

Select restoration alternatives through analysis of cost-effectiveness and risk

For each subbasin, start by tabulating the existing restoration work and the future priority opportunities associated with each component. For each opportunity, list the anticipated cost and the habitat benefit expected. Anticipated costs should encompass all costs needed to fully implement a treatment. For example, riparian treatments may require follow-up manual brushing treatments over several years or stream fertilization may occur annually over multiple years.

This summary of investment opportunities (by watershed) can be used to identify potential trade-offs between activities and allow resource managers to make informed choices. It may still be necessary to choose between worthwhile priorities, given a restricted budget. In such cases, watershed-specific information on resource benefits and priorities, anticipated costs, and residual risks can be used to compare benefit and costs, and make choices on allocating funds between areas and activities. Refer to 'Revisions to the Forest Road Engineering Guidebook' (FPC) for a detailed method of risk assessment.

To compare investment opportunities within a watershed, the following premises apply:

- Complete, balanced mixes of activities are usually needed to effectively rehabilitate areas affected by past forest practices. The optimum mix depends on site conditions and restoration objectives. Therefore, in allocating funds choices should be made regarding which watersheds to address, without compromising any of the recommended activities for a chosen watershed.
- Total funding needed to implement restoration activities at the specified risk-level should be calculated for each watershed. Also, restoration costs associated with a reduction in risk to a specified risk level (e.g., high to low) should be factored into the calculations. Estimated costs correspond to a defined scope of activities. These are fixed amounts for that watershed – *not* flexible to fit available budgets. It costs what it costs.
- The use of cost-effectiveness comparisons is encouraged to systematically rank a large array of restoration options. For example, the priority, costs and resource benefits of various culvert replacements to improve fish access could be compared to additional hillslope, riparian or instream treatments. This will allow the selection of activities offering greater returns earlier in the restoration sequence.
- Watershed restoration techniques must be done on the principle of adaptive management. Follow-up monitoring of effectiveness in achieving results is a necessary funding item.

In some cases, activities may simply cost too much for the benefit that accrues. The recommended approach is to set maximum amounts – specified on a \$/km of road, \$/landslide, or \$/km of treated-stream basis. Activity costs that *exceed* these amounts should have an individual cost-effectiveness analysis completed. This approach has the administrative advantage of simplicity and repeatability.

Step 7

Develop an implementation plan

The *Implementation Plan* should provide details for all subbasins that will receive attention. Samples of a suitable format are included in the accompanying document, *Restoration Plan: An Example*. The following background may be helpful in preparing the plan.

Worksite Priorities and Prescriptions

A map will be prepared that shows the proposed sites, segments or reaches where prescriptions for each priority component are recommended. Prescriptions are prepared for all high-priority components and on those sites identified in Step 6. This activity can be undertaken concurrently for all components.

Access Management

An *Access Management Plan* should be prepared for the entire subbasin. The goal of the access management plan is to integrate the watershed restoration plan with the needs of the various users of the watershed. Access management planning identifies current and future access needs in the watershed so that roads which may be needed for access are not deactivated without due consideration. This will involve addressing known access management strategies and/or developing strategies to the satisfaction of the District Manager (where access strategies are not known or not available). The following references will be useful for preparing access management plans: Watershed Restoration Program Technical Circular No.3, page 14; Integrated Watershed Restoration Plan, Schedule A, Section 5; and Forest Road Regulation, part 5.

Time Frame of Works

Works are generally completed from the top down. That is, work progresses from the hillslopes, to the gullies, to the riparian, and finally to the stream channel (Johnston and Moore 1995 in WRP Tech Circ. 1). However, depending on the watershed type, some of these steps can be omitted or works can be completed in parallel (as shown in Figure 2 on the next page). Some flexibility or discretion is needed for these decisions owing to site-specific conditions. For example, restoring fish access at culvert crossings may take precedence over all restoration works and be implemented first. Alternatively, hillslope works may occur concurrently with construction of an off-channel habitat that is isolated from potential sediment impacts.

Figure 2. Typical Restoration Activities and Sequencing by Watershed Process Type

Activities in the same column can be undertaken concurrently. See Appendix 2 for further clarification of watershed process types.

Time →

Implemented First	Implemented After or Concurrently With Activities in Left Column[1]

Hillslopes Coupled and High Channel Connectivity (Step-Pool Morphology)

Implemented First	Implemented After or Concurrently With Activities in Left Column[1]
Stabilize Roads	
Stabilize Gullies	
Restore Fish Access	

Partially Coupled and High Channel Connectivity (Cascade-Pool/Riffle-Pool Morphology)

Implemented First	Implemented After or Concurrently With Activities in Left Column[1]
Stabilize Roads	Restore/Construct Off-Channel Habitat
Stabilize Gullies	Floodplain Restoration
Erosion / Drainage Control	Riparian Restoration
Restore Fish Access	Bank Stabilization
	Construct Instream Structures

Uncoupled Hillslopes and Low to Moderate Channel Connectivity (Riffle-Pool Morphology)

Implemented First	Implemented After or Concurrently With Activities in Left Column[1]
Fine Sediment Source Control	Restore/Construct Off-Channel Habitat
Bank Stabilization	Floodplain Restoration
Restore Fish Access	Riparian Restoration
	Construct Instream Structures

[1] Implemented after activities in left column have stabilized conditions, or can be done concurrently with left column activities if existing watershed component conditions and processes (eg., sediment delivery, flow regime) do not negatively impact restoration works.

All high-priority work should be completed in each of the priority subbasins of the target watershed before moving on to another watershed. This is important because:

- a significant amount of work must be done in a watershed before *any* measurable benefit can be obtained
- access may be cut off by road deactivation, and
- the interactive nature of the projects means the benefits of the restoration activity accrue synergistically.

There may be economies of scale that make a combination of projects less expensive to complete together rather than in isolation. Non-completion of an integrated, or multi-project, watershed restoration program may simply postpone the resource benefits to be derived from the whole program.

Milestone/Restoration Completion Benchmarks & Evaluation

For accountability and reporting purposes, the RP must address the issue of *completion* for each target watershed. To this end, the RP should describe benchmark(s) for determining when project expenditures can be concluded.

Expenditures in aquatic restoration projects will fall into three distinct phases: planning/assessment, major works, and evaluation/maintenance. The *planning and assessment* phase includes overview and detailed assessments as well as the preparation of restoration designs. In the *major works* phase, restoration treatments on all high-priority works are implemented. The third phase – *evaluation and maintenance* – continues beyond the major works phase. It encompasses the implementation of routine effectiveness evaluations as well as maintenance and additional treatments, if appropriate.

Three to five years after completion of all high-priority works, a brief status report on watershed recovery will be provided by qualified professionals doing the routine evaluations. The report will provide an interdisciplinary evaluation on the state of recovery of the subbasin and on the effectiveness of restoration treatments at meeting the stated restoration objectives. Specifically, this report will:

- summarize routine evaluation findings
- describe the present status and extent of recovery of the watershed components (e.g., sediment sources; levels of risk on roads, landslides and gullies; hillslope, riparian, channel and habitat condition)
- describe the state of recovery of watershed processes
- provide the rationale if further restoration work on recently identified high-priority sites or moderate-priority sites is required, and
- identify the specific sites requiring maintenance or treatment.

Helpful background information is included in the document: *A Framework for Effectiveness Evaluation of Watershed Restoration Projects*. Samples of the practical application of this appear in *Restoration Plan: An Example.*

Budget

Estimate costs for the restoration prescriptions, implementation of restoration works and the routine effectiveness evaluations. Ensure that the costs reflect the implementation of all evaluations and restoration work for each treatment, even if the work occurs over multiple years (e.g. follow-up manual brushing in a riparian treatment or multiple stream fertilization treatments).

Step 8

Complete a RP document encompassing work plans for all high priority subbasins in the watershed

The RP document should be prepared for the target watershed and include the following:

- A summary on the rationale for investment and a brief introduction.
- The rationale for selection as a target watershed.
- Description of the watershed – location, boundaries, category, and dominant processes affecting the watershed.
- A map of the targeted watershed with all subbasins identified and their priority shown (~1:50,000).
- Specification of priority subbasins.
- Subbasin maps, showing detailed assessment highlights, and targeted restoration sites.
- Restoration priorities for subbasins, with information on basin condition, limiting fish habitat, and access management.
- Statement of specific restoration objectives (at the subbasin, component, and site levels) with activities for each components ranked in priority order.
- An implementation plan, including information on work-site priorities, time frame of works, and milestone and restoration completion benchmarks, an effectiveness evaluation plan, an access management plan and a budget.

Assessments do not need to be included in the plan, but should be referenced and available.

The accompanying documents, *Restoration Plan: A Coastal Example* and *Restoration Plan: An Interior Example,* can serve as guides in preparing similar documents in the regions. Following the format and style of these documents will ensure consistency and allow for easy reference to new plans as they become available.

Applying the Guidelines Where a Restoration Plan Exists and/or Where Considerable Work Has Been Completed

Previously completed *Restoration Plans* for target watersheds should be revised to reflect the new emphasis on targeted resource values. The key is to tie ongoing and planned works to the new goals. In some cases, decisions will have to be made using best judgment where dated assessments are less than perfect for the new goals. The revised RP should outline the watershed processes, critical limiting factors, restoration objectives, results of the assessments, high-priority components, and the schedule of works required to complete restoration in each subbasin. A checklist is provided to help determine possible shortfalls in an existing RP. Steps in the RP planning process that have been missed or that need to be revisited will be identified by the checklist.

The checklist can also be used if restoration in a watershed has progressed to the implementation phase and prescriptions or restoration works have been undertaken. Again, it is important that the restoration objectives be described relative to the revised goals of the RP, and that future restoration work relate to the revised site-level objectives.

Figure 3: Checklist for Determining Possible Shortfalls in a Completed RP

If the answer is 'No' to a specific question, refer to the specified sections (Stage A or B) of this planning guide (Stage: Step).

Yes	No	Product
	A:1-6	Are there maps and a general description of the target watershed that include its location, boundaries, and geomorphological type?
	A:1-6	Are there maps of the targeted watershed with all subbasins identified and their priority shown?
	A:4-6	Is there a rationale for the selection and prioritization of the watershed and subbasin(s) for restoration?
	B:1	Are there subbasin maps, showing Level 1 and Stage 1 Assessment highlights, and targeted restoration sites?
	B:2-3	Has the interpretation of watershed conditions and habitat limitations been done in relation to the revised RP goals?
	B:2	Have the critical limiting factors been identified for the subbasin?
	B:3	Have the components been ranked in priority order of restoration at the subbasin level?
	B:4	Have subbasin-, component- and site-level restoration objectives been stated?
	B:5-6	Do proposed prescriptions or restoration works meet the revised objectives of the RP?
	B:5-6	Have anticipated restoration works been identified that address the priority components (i.e., site, anticipated type of work)?
	B:5-7	Is there a description of the critical work?
	B:6	Have the proposed restoration works been assessed for the acceptable level of risk?
	B:7	Have milestone/completion benchmarks been described and scheduled?
	B:7	Is there a project Implementation Plan?
	B:7	Is there a schedule of works?
	B:7	Is there an Access Management Plan?
	B:7	Is there a projected budget with estimated costs for each component?
	B:7	Is there an evaluation plan for assessing performance of restoration works, achievement of goals and objectives, a measure of the state of recovery of the watershed, cost-effectiveness of restoration work, etc.?

Assessments Commonly Applied in Watershed Restoration Projects

Overview and Stage 1 Levels

Hillslopes: Erosion and Mass-Wasting Risk Assessment (EMRA)
Sediment Source Survey (SSS) now used primarily for Forest Practices Code
Access Management
Gully Assessment Procedure

Riparian: Overview Assessment

Channel: Channel Assessment Procedure (CAP)

Stream Habitat: Overview Fish Habitat Assessment Procedure (FHAP)

Detailed Assessments (Level 1)

Riparian: Level 1 Riparian Assessment

Channel: Channel Conditions and Prescriptions Assessment (CCPA)

Stream Habitat: FHAP Level 1 Field Assessment

Restoration Designs or Prescriptions (Level 2)

Hillslopes: Prescriptions for Road Deactivation, Road Modifications, Landslide and Gully Rehabilitation

Riparian: Level 2 Riparian Assessment

Stream Habitat: FHAP Level 2 Field Assessment

List of Abbreviations

CAP	Channel Assessment Procedure
CCPA	Channel Conditions and Prescriptions Assessment
CWAP	Coastal Watershed Assessment Procedure
ECA	Equivalent Clearcut Area
EMRA	Erosion and Mass-Wasting Risk Assessment
FHAP	Fish Habitat Assessment Procedure
IWAP	Interior Watershed Assessment Procedure
IWRP	Integrated Watershed Restoration Plan
LRMP	Land and Resource Management Plan
LWD	Large Woody Debris
MWLAP	Ministry of Water, Land and Air Protection
MoF	Ministry of Forests
Re-CAP	Reconnaissance-level Channel Assessment Procedure
RP	Restoration Plan
SSS	Sediment Source Survey

CONCEPTUAL MODELS OF WATERSHED DYNAMICS

Appendix 1. Watershed Process Types and Associated Restoration Opportunities
Appendix 2. Watershed Dynamics

APPENDIX 1

WATERSHED PROCESS TYPES AND ASSOCIATED RESTORATION OPPORTUNITIES

S. Chatwin, S.Chatwin Geoscience Ltd.

M. Gaboury, LGL Limited

A. Chapman, Chapman Geoscience Ltd.

WATERSHED PROCESS TYPES AND ASSOCIATED RESTORATION OPPORTUNITIES

The following discussion outlines a simple classification system for B.C. watershed process types based on the degree to which the stream channel is coupled to the hillslopes and the connectivity of the stream channel reaches. Watersheds have unique combinations of physiography, climate and geology which drive the geomorphic processes that determine the sediment supply, the stream discharge, the channel type and ultimately the fish habitat. From an aquatic perspective, that is if you are located in a specific reach, the main difference between watershed types is the degree to which the hillslopes are connected to the streams (its hillslope connectivity) and the capacity of the stream to transport sediment (its stream connectivity). Typically as you move from reach to reach, downstream through a watershed, the dominant watershed processes above the identified reach progress from one dominant type to another (Types A, B, C, and D). Certain watershed restoration techniques will be more effective than others depending on the watershed process type.

Type A: Small streams (<10 km^2) in mountainous areas

Small streams in the Coast mountains and wet Interior mountains are directly "coupled" to the hillslopes; that is landslides from the hillslopes directly enter the stream channels. Small streams also experience floods infrequently but with much greater extremes than larger watersheds, resulting in the main sediment transport mechanism being debris flows. Post logging acceleration of these sediment input rates can be 2-10X natural rates. Sediment moves through the reach mainly through debris flow events on a time scale of 20 - 100 years. Small steep gradient streams typically have a robust boulder step pool structure which is not easily destabilized and recovers quickly once destabilized.

Preventative works
Maintain hillslope, road and gully stability.

Remedial works
Re-establish natural drainage of roads and pullback of sidecast material at potentially unstable sites and remove unstable slash from gullies.

Type AB: Coupled channels of order 10 km^2 – 30 km^2- Coast and Wet Interior mountains

On the Coast and wetter Interior mountains, stream channels in watersheds of 10 km^2 – 30 km^2 area are typically coupled to the hillslope, but in the zone immediately below headwater slopes the channel can become partially decoupled across floodplains. The greatest source of sediment is landslides and debris flows. These sources are 10-100 times as significant as any other sediment source.

Channels in this type of watershed exhibit the greatest structural complexity of any. They are subject to large sediment inputs from landslides and banks and strongly influenced by woody debris in diverting flow and storing sediment. Storage of bed material can increase rapidly. Dramatic channel aggradation is possible, because fluvial transport out of the reach can be much less than sediment input rates.

Preventative works
Maintain hillslope stability.
Maintain riparian forests.

Remedial works
The emphasis should be on maintaining slope stability of roads and gullies as even at this scale mass wasting is the primary sediment source. Riparian and channel stabilization work in wet mountainous areas may be futile unless it can first be established that sediment from the hillslopes has declined. The time for the sediment to work its way from the gullies into and through the critical reaches can be on the order of 50 - 100 years. A single large flood can destroy the effect of channel or riparian work. In watersheds with unstable slopes, the most effective management procedure is light engineering work on the floodplain to assure the maintenance of secondary and back channels.

Structures in stream channels in this type of watershed with a high hillslope sediment load are very risky. Structures should be placed only in channels that are stable, or only modestly unstable, and replicating natural circumstances as far as possible. Once the hillslopes have stabilized, riparian re-vegetation of bartops and riparian re-generation of stream banks is warranted.

Type B-1: Coastal and Interior mountain watersheds of order 100 km^2

Larger streams on the Coast and Interior mountains exhibit valley flats, floodplains and uncoupled stream channels in their downstream portions. They experience significant floods relatively more frequently, but they become relatively less extreme. Flows are less variable than further upstream.

The greatest source of sediment to coastal mid sized streams is progressive channel bank erosion, with the initial disturbance often triggered by landslide inputs. The fluvial sediments are highly mobile and floods move the bed materials annually. Significant volumes of material are stored in the floodplain. Mid sized streams are typically pool riffle streams in which most of the channel bed is wetted at moderate flow indicating a channel that is capable of transporting the sediment supplied to the channel. Large woody debris forms an important element of the channel and log jams can dominate the storage and transport of gravel as well as channel avulsion onto the floodplain. If increased bed material is delivered, then much of it is stored in the channel, diverting flow to the banks and further increasing sediment load in the channel. The channels are sensitive to a change of sediment regime because gravel mobilized upstream move into bars and progress further downstream only slowly, on average a few meters a year. Hence a sharp increase in gravel supply creates aggradation in the reach. The stream is diverted around the deposits growing in the channel, attacks the banks, and recruits more gravel sediment and woody debris. Because the total volume of sediment stored in the reach may be greatly increased in relatively short period of time, it is possible for these channels to become dramatically unstable. A disturbance created by natural or induced slope instability in the headwaters may take decades to a century or more to work its way through the reach. Such channels are very sensitive to loss of riparian forest. Historical studies have shown dramatic channel widening following riparian forest harvesting. This process is eventually attenuated downstream when the bed material is incorporated into the reconstructed floodplain.

Preventative works
Maintenance of hillslope stability.
Maintenance of riparian forest.

Remedial works
Restoration of hillslope stability to cut off "triggering" bedload.
Restoration of riparian forest is essential.

If these stream channels are already unstable, it will be a long time before the benefits of hillslope restoration will become apparent. Unstable watersheds at this scale are candidates for "do nothing."

Type B-2: Interior plateau streams of order 100 km^2

Interior plateau streams at this scale can be coupled or uncoupled from the hillslopes. Regardless, the natural landslide sediment supply is generally quite low. The greatest source of sediment to these streams is where they are incised through stored glacial sediments and through mass wasting the sand and silts from these deposits are entering the stream. Floodplains and streambanks are easily destabilized by loss of vegetation; cattle can be a major factor in destabilizing streambanks and channels. Where stream channels are steeper gradient boulder controlled cascades have the capacity to transport the sediment out of the watershed and into the larger river system below, where it can accumulate in fans or floodplain deposits. Channels are typically less affected by LWD input.

Preventative works
Maintenance of streambank vegetation.
Avoidance of direct damage to streambanks.
Reduce fine sediment sources, particularly where roads are designed across glaciofluvial or glaciolacustrine deposits.

Remedial works
Reduction of fine sediment sources at road crossings and on roads crossing glaciofluvial or glaciolacustrine soils.
Restoration of streambank vegetation.
Off and in channel restoration works.

Type C: Small streams on lowlands or in the Interior plateau scale 1 - 10 km^2

Small streams flowing though low relief areas are much less flashy and channels are incised or meandering. Without hillslope sediment sources, sediment loads are minimal. These streams are decoupled from the hillslopes and have low stream connectivity.

Preventative works
Prevent destruction by traffic entering the riparian zone, avoiding slash accumulations in the channel and prevent the introduction of fine sediment from roads.

Remedial works
Restoration opportunities are to reduce fine sediment input from road related sources, particularly at stream crossings and to re-open fish migration barriers.

Type C: Coastal watersheds of order 1000 km^2 – and Southern Interior watershed of order 1000 km^2

The downstream reaches in coastal watersheds at this scale are typically decoupled from the hillslopes. The greatest source of sediment to large streams is river bank erosion of stored alluvium. Channels are typically de-coupled from the hillslopes. Channel gradients are low and bed materials are medium to fine gravel or sand. Gravel movement is on an annual basis. LWD does not play a major channel structural role, but may block sidechannel entrances. Purely fluvial processes dominate the channel morphology.

Channel instability is caused by fluvial erosion of stream banks and progressive lateral shifting, punctuated by avulsions where secondary channels are re-occupied. The effects of headwater disturbance reach these channels only after some years and are considerably attenuated. Induced sediment mobilization affects these channels only moderately. If a major disturbance were to occur it would take centuries to pass the sediment pulse through the system. Because of the long time scale, it becomes difficult to impossible to separate the effects of land use or restoration from changes created by natural changes in the environment. Monitoring programs at this scale of watershed would not be able to detect any impact that watershed restoration was having. The exception to this is situations where there is a chronic supply of fine sediment from upstream sources. In the larger channels, deposited wash material can become a persistent problem with veneers of sediment or interstitial fills.

Remedial works
Restoration should focus on opening fish migration barriers on floodplains and on attempting to reduce the stream entry of fine sediment from the largest point sources. Rates of channel migration may be controlled by riparian vegetation reestablishment, however the efficacy of this unanswered.

Type D: Northern Interior watersheds of order 1000 km^2

Large northern Interior rivers are often incised through very thick glaciolacustrine sediments and the channel is strongly coupled to the near hillslopes. Undermining of toe slopes and slow creep in the glaciolacustrine sediments ensure a continual supply of fine sediment to the channel. Mobilization of fines from widespread glaciolacustrine silts is a major problem in some areas. Land use activity on valley terraces and lower slopes frequently rearranges drainage, resulting in gullying or slope failure along the terrace edge. Large woody debris generally plays only a minor role in channel stability.

Preventative works
Hillslope soil erosion control and drainage control is the main preventative measures.

Remedial works
Fixing point sources of fine sediment is probably inconsequential. The sediment budget is dominated by natural slumping of streamside glacial sediments.

APPENDIX 2

WATERSHED DYNAMICS

Michael Church
University of British Columbia

WATERSHED DYNAMICS

Introduction

Streams exist because of the need to evacuate water from the surface of the land. In wet landscapes, streams form along most declivities in the landscape. Where sufficient runoff water concentrates to erode the land surface, a stream channel forms and is maintained. Any actions that influence the concentration of water in the landscape, or affect the erodibility of the land surface, may affect the condition of stream channels.

The morphology of a stream channel is the outcome of specific governing conditions. The principal governing conditions are the amount and timing of water delivered to the stream channel, the amount and calibre (size) of sediment delivered to the channel, and the gradient over which the water flows. The latter is very important, for it determines the power of the water as it moves downslope, hence the ability of the stream to move sediment and modify its channel. In forests, the supply of wood to the channel may be another condition governing channel form.

Because of the dendritic (tree-like) structure of drainage networks (Figures 1 and 4), these governing conditions change systematically through a drainage system. Tributary confluences mean that the area drained and the water flows become systematically larger downstream. On the other hand, the gradient of the channel declines downstream as water moves off hillslopes into and along valley bottoms (Figure 2). The consequence for sediment transport by the stream is complex. The calibre of the individual grains that can be moved declines sharply, even though the total amount of sediment that can be transported increases. The latter is the consequence of the increasing volume and persistence of the streamflow downstream. The declining ability of the stream to move large material on lesser gradients (declining "competence") means that sediment transport is size-selective downstream, and that fluvial (stream transported) sediment deposits are strongly sorted. Hence, the channel boundary materials change their character. This has important consequences for the channel morphology, for channel stability, and for aquatic habitat.

Sediment in streams is classified according to the mode of its transport, either in suspension in the water column ("suspended sediment") or by sliding, rolling and hopping over the bed ("bedload sediment"). Of greater significance to understand stream morphology, however, is a division of transported sediment into "wash material" and "bed material." Wash material is fine material that, once mobilized, travels a long way; whereas bed material is the coarser and heavier sediment that is redeposited locally in the channel and makes up the bed and lower banks. Wash material is significant in water quality considerations, whereas bed material determines the character of the channel. The correspondence of these two classifications is not perfect (Figure 3). Wash material always travels in suspension. Usually, it consists of material finer than about 0.2 mm in diameter (that is, fine sand, silt and clay), but bed material may travel in either mode. In particular, sand may travel in suspension or along the bed, according to the strength of the flow.

In forests, individual wood pieces and collections of pieces constitute significant elements of the channel morphology. They direct the flow and trap sediment on its passage downstream, thereby significantly modifying channel morphology, sediment yield and sediment storage along the channel. Wood also plays a significant ecological role in stream channels.

What happens in a stream channel is determined by the flow of water down it.

Hydrology

The timing and magnitude of runoff are controlled by weather. Prolonged rainstorms produce high runoff, by strong snowmelt, and by rain-on-snow. Stream channels develop until they are adapted to convey the normally experienced range of flows, so major erosion and sediment transport occur in most channels relatively rarely, when exceptionally heavy runoff occurs. However, following soil disturbance along a channel or in the contributing drainage basin, a much wider range of flows may carry significant amounts of sediment. Fine sediment, eroded from the stream banks or delivered directly from the land surface, can be transported by a much wider range of flows than can the heavier bed material of the channel.

In coastal British Columbia, significant flooding is produced by heavy rain and rain-on-snow, primarily between mid-autumn and mid-winter, but significant rain may occur at almost any time of year. Within the Coast Mountains, spring snowmelt creates dependably high flows but it only exceptionally contributes major floods. In the south and central Interior, snowmelt is a relatively more important generator of floods but, even here, early summer or autumn rains may create the most serious sediment transporting floods in smaller streams. In the boreal Interior, snowmelt and early summer rain are most significant. Significant summer rains in the Interior are contributed by convectional disturbances (thunderstorms) embedded in weather fronts.

The heaviest rain is often strongly localized, even within large storms, so that significant flooding of headwater drainage is often quite local as well. The result is that, although headwater flooding occurs relatively frequently somewhere in a regional landscape, an extreme flood at a specific location is a rare event. However, the structure of drainage networks changes the incidence of high floods downstream (Figure 4). Drainage received from a larger and larger area is the sum of contributions from a steadily increasing number of headwaters. The probability for extreme flows to occur in some part of the area increases as the drainage area increases. Hence, larger streams experience significant floods relatively more frequently, but they become relatively less extreme in comparison with other floods that may have occurred recently because the entire upstream watershed almost never is all contributing water at an equally extreme rate. The downstream attenuation of high flows is less marked during snowmelt because melt may occur simultaneously from widespread areas of upland. However, peak rates of runoff production from snowmelt are less extreme than those that can be produced by heavy rain.

Slope drainage and slope stability

Streams in much of British Columbia originate on steep slopes. Slope stability is strongly influenced by slope drainage. Mountain slopes in British Columbia are rock dominated, with shallow surface materials consisting of glacial till or colluvial veneers. Pockets of deeper soil occupy slope declivities. Where forest cover is well developed, a surface layer of highly permeable, humic forest soil and litter mantles the slope (Figure 5). Along the valleys, deep deposits of glacial, glaciolacustrine, or glaciofluvial sediments may have been dissected by streams, creating steep slopes immediately adjacent to the channel. Water is absorbed into the forest soil and moves downslope under the surface, usually on the bedrock or on the surface of unweathered till. The water exploits root channels, animal burrows, and soil discontinuities at the base of the plant rooting zone to move relatively quickly downslope. The rapid subsurface drainage discourages surface erosion and slope instability.

Water moves directly downslope. Hence it drains away from spurs and into declivities and depressions (Figure 5). The concentration of subsurface drainage in depressions creates seepage lines where the soil becomes completely saturated with water, and springs where larger subsurface channels break through to the surface. These features are the origin of the surface drainage network. Depressions are also places where soil accumulates as the result of downslope creep, treethrow, and minor slippage. In depressions, water still in the subsurface may create sufficiently high water pressures that the overlying accumulation of soil and debris is induced to fail. Therefore, shallow slope failures often occur at the head of drainage systems. This both extends the drainage system and delivers sediment into downstream channels.

Most hillslopes have on them a system of shallow declivities or gullies which becomes obvious only after the slope is cleared of trees. In most cases, these declivities are probably relict surface erosion lines left over from early postglacial time when forest cover was absent or incomplete. They nevertheless still direct drainage, and can be aggressively reactivated if sufficient water moves down them to cause erosion. They are the primary conduits of hillslope-derived water and sediment into the drainage network.

Activities which alter slope drainage may substantially influence the erosional activity of water on slopes. Most commonly, construction of midslope roads intercepts subsurface drainage on the upslope cut-bank, redirecting the flow prematurely into the surface drainage system. The water flows via road ditches to the nearest downslope drainage line. The increased flow here promotes erosion and gullying, often followed by significant soil failures in the newly developed gully sideslopes.

The stability of soil on steep slopes depends significantly on the continuation of forest cover, which spreads a tenacious root system over the slope. Studies of erosion on slopes in the Pacific Northwest, encompassing both coastal and interior drainage basins (but with little information as yet available from the boreal north), yield the results shown in Table 1 for various soil mobilizing mechanisms. (The figures have been generalized from many studies to order of magnitude comparisons.) When account is taken of the limited area occupied by landslide failures in forested terrain (typically less than 1% of the land surface), which reduces the impact of surface erosion from slide scars, it is apparent that the episodic landslides themselves—the shallow slope failures described above—are the most significant means of sediment delivery downslope. Lesser processes, including soil slumps, soil creep, tree throw and dry ravel, should not be ignored, however. They are important in recharging hillslope hollows over many decades or even centuries, which may lead eventually to a major failure, and in delivering material directly to stream banks.

Once mobilized, material either is delivered directly to a stream channel, or it moves onto colluvial footslopes more or less distant from a stream channel. Which happens depends mainly upon the width of valley floors. Headward, small streams tend to occupy narrow valleys, so they experience direct delivery of sediment from sideslopes. Whether or not sediment is delivered directly to the channel has a profound influence upon the organization and sedimentary character of the channel, hence discrimination of this condition is important. Channels which experience direct delivery of sediment from sideslopes can be said to be “coupled” to the hillslopes (Figure 1). Ones which do not are “buffered”. Buffered channels receive sediment inputs entirely by downstream sediment transport in the stream or by streambank erosion. They are flanked by floodplains. Between these two types is a class of “intermittently coupled” channels, ones which flow against the valleyside in some places and are buffered by valley bottom deposits in others. The occurrence of these types is correlated with position in the drainage network. Most small, headward streams are coupled.

A special class of slope failures in steep, headward channels is direct failure of the sedimentary fill in the channel or gully. Such failures commonly develop into debris flows (locally called “debris torrents”) which move rapidly down the channel. Despite their in-channel occurrence, they are more akin to landslides than to normal sediment transport by the stream (Figure 6). They are relatively rare in individual channels unless there is an unusually prolific source of sediment immediately adjacent to the upper channel, but they are by no means rare in upland and mountain landscapes. Considering the distance that a debris flow runs, they are the main means by which clastic sediment is transferred from mountain slopes to valley bottoms in the British Columbia mountains today. Debris flows are usually initiated in channel head declivities with gradients in excess of 35%, but they may also begin when a landslide enters a steep channel from an adjacent slope, temporarily damming it, so that a significant weight of water collects behind the “dam.” How far they run out depends upon how fluid the debris/water mixture is. That, in turn, depends upon the nature of the sediment. Fine sediments hold water tenaciously, and can flow out onto quite low gradients (or order 8% or lower), whereas coarser material, that drains readily, tends to stop on gradients of around 20%. The constitution of the materials depends, in turn, on the geology of the source rocks or glacial materials. Debris fans at the base of mountainside gullies show, by their surface gradient, the stopping angle of local materials.

Table 1. Sediment mobilization and yield from hillside slopes

Process	Mobilization rate		Yield rate to stream channels	
	Forested slopes	Cleared slopes	Forested slopes	Cleared slopes
Normal regime				
Soil creep (including animal effects)	1 m^{3}km^{-1}yr^{-1}*	2x	1 m^{3}km^{-1}yr^{-1}*	2x
deep-seated creep	10 m^{3}km^{-1}yr^{-1}*	1x	10 m^{3}km^{-1}yr^{-1}*	1x
Tree throw	1 m^{3}km^{-2}yr^{-1}	--	--	--
Surface erosion: forest floor	<10 m^{3}km^{-2}yr^{-1}		<1 m^{3}km^{-2}yr^{-1}	
Surface erosion: landslide scars, gully walls	>10^3 m^{3}km^{-2}yr^{-1} (slide area only)	1x	>10^3 m^{3}km^{-2}yr^{-1}	1x
Surface erosion: active road surface	--	10^4 m^{3}km^{-2}yr^{-1} (road area only)	--	10^4 m^{3}km^{-2}yr^{-1} (road area only)
Episodic events				
Debris slides	10^2 m^{3}km^{-2}yr^{-1}	2-10x	to 10^{4}m^{3}km^{-2}yr^{-1}	to10x
Rock failures (fall, slide)	No consistent data: not specifically associated with land use			

* These results reported as m^{3}km^{-1} channel bank. All other results reported as m^{3}km^{-2} drainage area.

Steep headwaters

Headwater channels drain the upland portion of the drainage basin. They are coupled to the adjacent slopes. They collect slope drainage water by seepage at the channel head and through the streambanks, and they directly receive sediments mobilized on the slope that move to the slope base. The channel head and stream banks are often only tenuously stable, unless they consist of competent rock, because the discharge of seepage water along these channels maintains high pore water pressures in the soil. Forest management along headwater streams must be conducted with soil stability conditions clearly in view.

The calibre of the sediment delivered to a stream channel is an important governing condition, for it—in combination with the channel gradient—determines the mobility of the sediment once in the channel. We have noted that exceptional volumes of water and sediment are delivered to individual headwater channels relatively rarely. In addition, the sedimentary material is often, at least in part, relatively large (up to boulder size). This suggests that, although fine sediments might be quickly washed downstream, the larger rocks may remain behind to form a stable channel framework for considerable periods of time. But mechanical considerations indicate that even boulders are unlikely to remain in place when submerged in a water flow on gradients of more than at most 6^0 (10%). Smaller material, which is apt to be deeply submerged, may be unstable on gradients as low as 2.5^0 (4.5%), yet many hillside stream channels substantially exceed these gradients. Many are bedrock-bound. But material may remain in place in such channels because individual stones are tightly interlocked with each other and with the channel margin. Most of the stability is afforded by the structure of the deposit, not by the weight of the individual pieces (Figure 7).

As a consequence of this structural requirement, the morphology of steep, sediment-lined channels takes a special form. A sequence of steps and pools, the steps being defined by dominant ‘keystones’ (or, sometimes, by wood), characterizes the channel. The individual pools are small. Collectively, the sequence is termed a “cascade”. Cascades are well-defined on gradients up to at least 12^0 (21%) in larger channels, including many channels on alluvial fans, and to about 24^0 (45%) in the smallest hillside channels. Pools become shorter as the gradient increases. At gradients above the limits given above, and in places where there are too few large stones to form an effective structure, one finds bedrock-bound torrents.

Cascade structures may be modified by large floods, but they are more usually destroyed by debris flows. This is not surprising: once the structural integrity of part of a cascade has been disturbed, the instability may easily propagate, so a large volume of material begins to move at once. After such an event, the cascade reforms surprisingly quickly, implying that it is more the consequence of the chance occurrence and mutual interference of large clasts (rocks) than the result of sediment transport processes. Where debris flows are rare (which means, in most channels), cascades may persist for a very long time, whilst a limited supply of material very much smaller than the framework stones of the cascade is transported by the stream. Such material is found temporarily stored in pool bottoms, whilst the longevity of the cascade is often advertised by moss growth on the framework boulders.

The structural requirement for stability has an important practical ramification: activity which destroys the structure of sedimentary deposits in steep channels, such as cleaning out the channel at road crossings, is apt to destabilize the bed upstream.

Farther downstream

Along valley bottoms, streams deposit and flow through materials that they have delivered from headward tributaries. The material is considerably smaller than the bouldery material that usually forms the framework of stream channels on steep slopes. The deposits are called "alluvium" or "alluvial deposits" (sometimes, fluvial deposits), and the channel is said to be an "alluvial channel". The significance of this designation is that, since the stream has transported the deposited material, it can reentrain it at sufficiently high flows. Hence, the stream forms its own channel morphology and may modify it relatively frequently by further bed and bank erosion. Bank erosion represents the main means by which further sediment is recruited into these channels.

The dominant morphological feature of alluvial stream channels is a sequence of pools and riffles (Figure 6). The pools span the channel and are relatively deep, often with a sedimentary accumulation—a bar—on one side. The riffle is shallow and possesses a sensible gradient. The pool-riffle-bar sequence is the consequence of the way in which the channel bed material is moved downstream. At relatively high flows, it is mobilized from the bar/pool, swept over the riffle, and much of the mobilized material is then deposited on the next bar downstream. The entire sequence modulates channel gradient, so that the channel may remain more or less stable for considerable periods of time on an overall gradient that nevertheless is sufficient to move the bed material downstream at a rate that approximates the long-term supply rate.

Riffles generally have gradients less than about 4% (2.3^0), but steeper riffles are common with structural organization of the surface constituent stones into "ribs" (transverse stone lines) or cells. These are termed "rapids" (although that term has a wider non-technical connotation, too).

The morphology of pools and riffles is closely tied to the volume of potentially mobile sediment that is stored in the channel. A well-developed pool-riffle sequence in which most of the channel bed is wetted at moderate flow levels indicates a channel that is able to transport the sediment supplied to the channel. If substantially increased volumes of bed material are delivered, then much of it is temporarily stored in the channel bed, diverting the water flow toward the banks and further increasing sediment supply by bank erosion. This process is called "aggradation." The result is a wider, less stable channel, possibly with multiple threads and shallower, smaller pools. In contrast, if the sediment supply becomes small, the stream eventually evacuates the moveable sediment from the reach without replacement so that it is "degraded" to a cobble paved, relatively featureless channel. This range of channel conditions is closely associated with channel stability: the degraded channel with negligible sediment supply is highly stable, whereas the aggraded channel with high sediment supply is characteristically unstable. It is also associated with habitat quality. Neither of the extreme states is desirable, the former because of the generally shallow conditions and limited pool space, the latter because of the hard bed. Another factor that has an important influence over sediment transfer and storage, hence channel morphology and stability, in forest streams is large woody debris in the channel. Sources of large woody debris include tree throw from the banks as the result of wind or of undermining by the stream, and delivery from upstream, particularly by debris flows. Woody debris enters stream channels of any size, but it interferes most significantly with channel processes and morphology when channel width is similar to the length of the introduced wood pieces (Figure 7). In small, headward channels, most wood pieces bridge the channel. In sufficiently large channels, most material can be floated into bank-parallel positions or downstream. Whilst it may pile up on bar surfaces and in side-channel entrances, and may influence bank stability, it does not interfere with flow in the main channel in a fundamental way. However, in intermediate sized channels, wood pieces may span the channel at water level. One or a few major pieces form the structural skeleton of a debris jam which becomes a trap for downstream moving sediment. A wedge of sediment is deposited upstream, and the downstream channel becomes degraded. Major debris jams may be effective for one or two decades, but then the cumulative effective of floods and wood decay weakens the structure to the point that sediment begins to move through it. The normal downstream transfer of bed material is reestablished during one to several more decades.

Significant valley-bottom accumulations of fluvially transported sediment form a floodplain—a surface that has formed by the accumulation of channel deposits as the river shifts laterally across the valley bottom over some time, and then by the deposit of finer sediment from suspension in the water when the river floods outside its normal banks. In British Columbia, floodplains commonly have sandy soils overlying a body of stream gravel (Figure 8). It is important to recognize that, although a part of the terrestrial surface, a floodplain is equally a part of the stream system. It occasionally is inundated by floodwater; the storage that this provides is the way in which the stream system handles excessive volumes of water delivered in a period too brief for all of it to be transferred immediately downstream. Furthermore, it represents the area through which the channel may in future migrate as the result of normal instability associated with the deposition and reentrainment of sediment being staged downstream.

An important practical question is how often does a stream flood over its banks. The answer is not straightforward since, the more often a floodplain surface has been inundated and received sediment deposits, the higher it becomes and the less likely it is to be flooded again in the near future. Hence, different parts of the floodplain, of different age, have a different likelihood to be flooded. In general, relatively low areas, often near main or side channels, are apt to be flooded more frequently than once in five years. Higher areas, with well-developed forest soils, are apt to be less frequently flooded.

An important phenomenon of channel and floodplain development that is associated with woody debris jams is the possibility for streams blocked by debris jams in a valley flat to find a new route around the debris jam. This process of “avulsion” (the abrupt relocation of a river channel by diversion out of its former course) creates additional channels in the floodplain. The process creates a network of secondary channels that become superior habitat for fish and amphibians. Debris jams appear to degrade aquatic habitat in the short term by interrupting the downstream progress of bed material, so that an aggraded channel develops upstream and a degraded one downstream. But in the long run the hydraulic and morphological complexity that is introduced by flow around the jam may create an aquatic environment of very high quality.

Other aspects of the floodplain hydraulic environment are important, too. Tributary streams entering a main channel across a floodplain have a low gradient and provide additional superior habitat. Water seepage off adjacent slopes feeds small wetlands and channels at the “back” of the floodplain (Figure 8). These wetlands and wall-based channels, along with secondary channels in the floodplain, provide important “escape habitat” for fish during floods. Finally, the subsurface water in the gravels under the floodplain provides an interstitial habitat, connected with the channel, for many invertebrate organisms that spend part or most of their life cycle in the streambed or floodplain sediments. Roads constructed with inadequate cross-drainage on floodplains often isolate significant elements of this “hydroriparian” zone.

At the end of the drainage system, streams enter a standing water body, either a lake or the sea. Here, a delta develops as the remaining sediment load is deposited when stream currents slacken upon approaching the standing water. The delta may be a gravel or a sand body. Wash material usually is swept beyond the delta and settles into deep water. Because the delta is an aggrading feature, it is subject to episodic channel shifts. Hence, there are often a number of channels present with intervening wetlands. Delta surfaces, because of the intimate mingling of terrestrial and aquatic habitats, support uncommonly diverse ecosystems.

The effects of watershed scale

Figure 2 shows that water flows, topographic gradient, and sediment storage change systematically downstream. Changes occur too in the distribution of streamflows, sediment transport, and channel stability, and have important consequences. Some of these changes are evident in Figure 4. In this section, the changes are reviewed by focusing attention on watershed processes at several distinct scales. The scale is set by drainage area because that determines the water flows, the fundamental driving force in watershed processes.

Watersheds with area of order[1] 1 km^2 or less commonly drain individual hillslopes or groups of hillslopes. In mountainous country, they are steep, headward channels. Many of them are incised into hillside sediments or follow bedrock declivities and take the form of gullies. They are the steepest channels even in regions of moderate relief. High gradients promote rapid drainage of water, so the hydrological regime is “flashy.” Many such channels are ephemeral to seasonal in flow. Most of the time, very little sediment moves down these channels -- they sustain the image of pristine mountain waters. But near the tip of the drainage network, hillslope processes accumulate sediment in hollows and gullies over many decades or centuries. Eventually, the accumulated material may fail, creating a debris flow. Most of the sediment delivered by many channels in this class is delivered by this means. Shallow landslides from channel side slopes may also deliver significant volumes of sediment episodically. Subsequently, material that can be entrained by the flowing water is rapidly evacuated downstream. Sediment accumulation along the channel is restricted to large, structurally locked clasts, or accumulations behind woody debris jams. These channels drain the upland source zones of sediment; in the long term

[1] *“Order” here means order-of-magnitude. Broadly, it covers any size between about 1/3 the designated figure, and 3 times the figure. Hence, it covers about a 10-fold range in size.*

they are evacuators, not accumulators of sediment. But sediment yield is highly episodic. Individual channels may remain apparently stable for years or decades whilst sediment accumulates at the channel head.

These channels respond immediately when drainage is changed or sediment is delivered by hillside land use. But they also recover some stable state within a very few years afterward (unless a chronic sediment source has been activated) because sediment mobilized within these channels is rapidly moved out of them.

Headward channels in lowlands or, at least, in areas of low gradient, are quite different. Drainage arises in wetlands, places where the groundwater table intersects the ground surface. On low gradients, groundwater seepage is slow, so flow variations are highly damped. Stream channels are ditch-like, or strongly meandered. Without hillslope sources, mineral sediment loads are negligible. Channel margin sediments are fine and often highly organic. Such channels are sometimes found at the head of drainage in upland valleys as well, where moraines, bedrock sills, or glacial erosion have created low gradients. Beavers may create similar environments. The greatest threats to these channels are physical destruction by traffic entering the wetland or riparian zone, especially on organic sediments, and the introduction of fine sediment from roads.

Channels of order 10 km^2 may exhibit a limited valleybottom reach of low (<5%) or moderate (<15%) gradient channel. Flows are perennial, but remain highly variable. The valleybottom reach may store some volume of sediment, and may be only partially coupled to adjacent hillslopes. These are usually the steepest reaches occupied by fishes. The adjacent valley flat is usually very limited and discontinuous. The channels exhibit the greatest structural complexity of any. They are subject to arrival of sediments directly from adjacent hillslopes or high, steep banks along part of the reach, and they are also the most headward reaches in which woody debris is generally effective in diverting flow and intercepting fluvially transported sediments. The result is an irregular sequence of boulder cascades (Figure 7), pools, log steps, and log or boulder dammed accumulations of finer sediments. Bedrock steps may interrupt the channel gradient.

Debris flows may enter these channels from tributaries. Once stopped, the front is a steep boulder cascade or high log jam. Upstream, the channel rapidly forms a cascade over the flow, and the adjacent riparian zone is a bouldery or muddy levee. The clearance of sediments accumulated by episodic input into the reach may take years to decades, and boulder accumulations may persist for millennia. Pockets of habitat in these reaches may be of very good quality, but accessibility through log jams and boulder cascades is a significant problem. An important consequence of land management along such reaches is perturbation of the woody debris recruitment.

Alluvial fans exhibit the morphology described here, but these are depositional landforms accumulated where a steep tributary enters a larger valley with low gradient (Figure 10). Hence boulder or cobble gravel continuously accumulates as the channel gradient becomes too low for regular onward movement. But the channel is unconfined on the fan so, as it fills with deposited sediment, it is subject to avulsion to some other part of the fan. Always seeking the line of steepest descent, the extended channel zone encompasses the entire fan surface, even though mature forest may occupy much of it, where the channel happens not to have been located for a long time.

At order 100 km^2, watersheds exhibit valley flats and uncoupled stream channels in their downstream portions. Flows are strongly modulated seasonally, but are less variable than farther upstream. Fluvial sediments consist of cobble or pebble gravels, and floods capable of moving them occur every year. Significant volumes of sediment are stored in floodplains, and there are usually substantial glacial deposits along the valley bottom as well. The downstream channel exhibits moderate to low gradients, with the appearance of an approximately regular sequence of pools, bars and riffles (Figure 7). The riffles may take the form of rapids on the steeper gradients. Colluvial or alluvial fans formed by valleyside tributaries often form local gradient controls, so the channel often passes through a sequence of flatter (upstream of the fan) and steeper (past and downstream) reaches. Large wood debris forms an important element of the channel, creating an irregular secondary sequence of scoured pools and sediment accumulations. Log jams are common, and commonly dominate the pattern of storage and progress of gravel through the reach. They also cause channel avulsions into the floodplain.

These channels are sensitive to a change of sediment regime because gravels mobilized upstream move into bars here and then progress farther downstream only slowly -- as an average, a few metres per year. Hence, a sharp increase in gravel supply creates aggradation in the reach. The stream is diverted around the deposits growing in the channel, attacks the banks, and recruits still more gravelly sediment and woody debris. Because the total volume of sediment stored in the reach may be greatly increased in a relatively short time, it is possible for these channels to become dramatically unstable, braided reaches. A disturbance created by natural or induced slope instability in the headwaters may take decades to a century or more to work its way through the reach. At the end of this epicycle, much of the bed material that entered the reach will be incorporated into a reconstructed floodplain, so the disturbance attenuates downstream.

At order 1000 km^2, the downstream reach is apt to occupy a relatively broad valley. Channel gradients are low, and the bed material is medium to fine gravel, or sand, sorted every year by the spring freshet and occasionally moved more dramatically by major floods of snowmelt or rainstorm origin. Channel-spanning debris jams are uncommon,[2] although large accumulations of wood may occur on channel bars, and may block secondary channels, especially channel entrances. Consequently, purely fluvial processes dominate channel morphology. The pool and riffle sequence is well developed. Rivers with modest bed material supply dominated by fine gravel or sand develop a more or less regular meander pattern. Along mountain valleys in British Columbia, "wandering" channels are common. They exhibit irregular sinuosity, occasional low-order braiding, and significant secondary channels isolating individual channel islands or small groups of islands. The style of channel instability is progressive lateral shifting caused by bank erosion. Avulsions generally occur within the channel zone, as secondary channels become the main channel again, or islands are consumed.

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[2] *There is evidence that this is a modern consequence of the general occurrence of forest harvest along major valleybottoms. Much larger volumes of wood than are seen today formerly occurred along major river channels.*

The effects of headwater disturbance reach these channels only after some years, and are considerably attenuated. Consequently, natural and induced sediment mobilization affects these channels only moderately. Nonetheless, a single major disturbance may require centuries to millennia to pass through the system, and the serial occurrence of moderate disturbances upstream may create a secular change in the sedimentary regime of these channels. Because of the long time scale, it becomes difficult to impossible in most cases to separate the effects of major disturbances (for example, twentieth century forest land use) from changes created by natural changes in the environment (such as the 18th to 19th century period of relatively severe climate known as the Little Ice Age). We have reached the scale at which the diffusive nature of sedimentary disturbance masks the history of events in the drainage basin.

Before leaving the subject of scale, in which the scale effects of the passage of bed material downstream have been emphasized, it is important to contrast the behaviour of wash sediment in the river system. Once entrained, these fine sediments continue in motion until they leave the system with floodwaters, settle onto a floodplain surface in flood, or onto a bar top or other slack water location, or are trapped in the bed by filtration from water circulating through the gravels.

Substantial volumes of fine sediment may create significant deposited veneers or interstitial fills anywhere in the system. These are particularly problematic in streambed gravels, where they may interfere with water supply to fish eggs and larvae, and where they may create conditions inhospitable for benthic organisms. In the larger channels, farther from hillslope sources and where streambed gravels are more regularly turned over, deposited wash material becomes a persistent problem when delivery to the channel is chronic. This can occur as the result of land use activity in watersheds of intermediate size (say 100 km^2 scale), when the activity persists somewhere in the headwater over many consecutive years. The problem may also occur naturally in watersheds draining certain fine-grained sediments, such as glaciolacustrine silts.

Time

Rivers have histories. In British Columbia, history covers about 10 000 to 12 000 years since the last deglaciation. Within this period, there is a long range trend in fluvial sedimentation upon which the processes we have been discussing are superimposed. That trend has important consequences. In the early postglacial landscape, sediments were rapidly mobilized from newly exposed hillslopes and fluvial aggradation along the valleys was rapid. With the establishment of forest or grassland cover, most hillslopes stabilised. The rivers, starved of sediment supply from the slopes, began to remobilise sediments previously deposited along their channels. A generally degradational trend was established.

Degradation commenced first near the headwaters. Downstream, sediment supply continued as the result of the remobilization of sediments upstream. Degradation continued until sediment supply along the channel was exhausted, or until the channel became armoured by the coarser material present in the original late-glacial outwash deposits. The trend of degradation then shifted downstream. Today, it affects drainage areas up to more than 10 000 km^2. In smaller watersheds -- essentially all of those discussed here -- channels may be incised into old deposits as the result of the long-term degradational trend by amounts varying from about a metre to many tens of metres. How much degradation has occurred depends upon the nature of the older deposits, and whether the stream remained competent to move the material.

Incised channels are commonly confined within their banks. Former flood surfaces are now terraces. The channel is imprisoned in its position. Two problems arise in this situation. When channels are only slightly incised, it may be difficult to decide whether they are incised at all; that is, it may be difficult to decide whether the adjacent valley flat is a terrace or an infrequently inundated flood plain. Second, the river sometimes has incised into glacial sediments. These sediments may be unstable, especially when road development on the terrace changes surface drainage patterns or groundwater seepage under the surface.

Regional effects

Governing conditions—hydrology, sediments, topography—vary regionally. In a large, mountainous province like British Columbia, the variations are dramatic. These affect the particular expression of watershed processes.

Coast

The British Columbia Coast is steep and wet. Landslides and debris flows are the principal means of downslope delivery of sediment to stream courses. A significant proportion of the material added to channels is of large calibre. This material moves onward through the channel system only relatively slowly. Once in the channel, it may deflect streamflow against the banks, promoting substantial further erosion. Landslides and streambank erosion are the principal sources of sediment recruitment.

Landslide material enters the drainage system via steep, headward gullies. In some parts of the world, special efforts are made (such as check-dam construction) to stabilize similar gullies. This is not a practical possibility in our landscape. Many gullies are initially destabilized by drainage rerouting from roads. The most practical remedial measure is to attempt to reestablish direct, downslope drainage, maintaining as much of it in the subsurface as possible. Once on the surface, however, there are no general techniques for inducing channeled flows to percolate back into the ground. The best preventive measure is to give careful attention to maintaining natural drainage patterns on all slopes.

At watershed scales between 10 and 100 km^2, the aggradation of coarse clastic material in reaches of moderate to low gradient may be dramatic. Many small rivers today exhibit reaches with wide gravel flats and braided channels. In many places this is the cumulative impact of development activities over many decades, including road and railway building as well as forest land use. In other areas, it is the legacy of old harvesting methods, including logging to streambank and through-channel yarding. But such accumulations may still develop today if headward slope instability is significantly accelerated by poor land management. The best defence is conservative zoning to avoid activity on potentially unstable slopes.

Once the bed material supply declines, such reaches slowly repair themselves by vegetation establishment on bar tops (usually cottonwoods, initially) and soil development. A new floodplain develops and the channel shrinks into a smaller channel zone. Remaining secondary channels may evolve into superior habitat. There is a striking asymmetry between the development and repair of such areas. They develop at rates dictated by sediment influx and bank erosion, so individual major floods may cause major changes in the channel zone. They are repaired at the rate of riparian vegetation establishment and growth. Planting, and bank reinforcement at key sites may accelerate repair processes, but they may be futile activities unless it can first be established by sediment budget studies that sediment recruitment from the upland has declined. A single large flood may destroy the effect of much effort. In the longer run, the most effective management procedure for such zones might be light engineering work to attempt to assure the maintenance of the secondary and back-channels that are the legacy of the braided period as aquatic habitat (often, they are deliberately cut off).

In stream channels of intermediate size, with channel widths of approximately 3 to 30 m, large woody debris is a significant structural element. Many such channels have lost the possibility for resupply as the result of riparian forest clearance. The consequences of this circumstance are not clear. Much old wood will remain in the channel for decades. Larger channels and channels in other regions function without controlling wood elements. The ecological function of large wood in channels is well established, but how critical this role is appears not to be. One clearly established function for large wood in watersheds in the 10 km^2 to 100 km^2 ranges (and sometimes even smaller) is to trap and store significant volumes of bed material. Log jams in effect form check dams which act to smooth downstream delivery of material episodically mobilized in headwaters by landslides and debris flows. Without this function, major aggradation is accelerated downstream. Nonetheless, it would not be advisable to attempt to replicate the function.

Large wood and wood structures are placed in stream channels to attempt to replicate habitat function. This practice deserves continued study in order to improve both knowledge of the ecological effectiveness of the placements, and understanding of how naturally placed wood achieves effect. In particular, the longevity of natural wood placements and their effects need to be better known. In the meantime, sound planning principles include selecting for placements streams that are stable or only modestly unstable, and replicating natural circumstances as far as possible. In particular, placements should not be engineered to be permanent. If they are successful in that respect, they may eventually force unexpected channel changes.

In channels draining larger areas, similar aggradation effects are observed. They usually are less severe because the proportional increase in sediment delivery is not so great but, in the vicinity of settlement, even modest channel instability attracts great attention because it threatens property and structures. In dealing with such issues -- usually not a forestry issue -- the long time scale for bed material transfer must be kept in view. That dominates both the ecological quality of the channel environment and the effectiveness of engineering measures for control.

Fine sediment—wash material in stream channels—is mobilized from road surfaces, gully sides, landslide scars and streambanks. Active roads are a major contributor. Significant volumes of fines are also mobilized by streambank collapse. The high runoff regime moves this material rapidly through main channel systems. However, it finds its way into the quieter waters of side channels where it may cover channel bottoms. Significant volumes of fine sediment may also be sequestered interstitially in aggrading gravel bars, later to be re-released into the stream. The most practical management procedure is to attempt to reduce stream entry of fine material from the largest accessible sources. This would include designing small sedimentation basins as part of good road drainage systems, and attempting to stabilize major streambank sources (typically, glaciolacustrine deposits) when they are accessible.

Interior Plateaus and Valleys

Differences in topography, hydrology and glacial history all make the Interior unlike the Coast (with the exception of some areas in the Columbia and Cariboo Mountains). Upland headwaters often have low gradients. The major flood event each year is spring snowmelt, and soils are apt to be thoroughly saturated far less frequently than on the Coast. In many areas, deglaciation left large accumulations of sediment on lower valleysides and in the valleys. Lesser precipitation and runoff mean that larger areas are required to support a specific level of stream flow: this leads to some systematic shift in certain scale effects described earlier in this discussion. Initial disturbance of many gravel-bed channels was by mining activity in the late 19th and early 20th centuries.

An important hydrological change that may accompany forest harvest is a change in timing, and possibly, magnitude of snowmelt runoff. The pattern of forest harvest may have a significant impact on the timing of melt by advancing melt at higher elevations. Downstream flood magnitudes may thereby be affected in small watersheds and this may have significant effects, particularly where riparian floodplains have been cleared.

Landslide incidence is relatively low on dry slopes in the Interior, but localities are found in groundwater discharge zones and on high slopes with thick surficial deposits where chronic slope failure may occur. These slopes often lead directly to river channels, and the river channel may influence their stability. In similar circumstances, gully systems may develop which feed directly into a substantial stream channel. On high, steep slopes snow avalanches may deliver significant volumes of debris downslope, the majority of which often is organic debris.

Regionally major glaciolacustrine deposits, silty tills, and extensive outwash deposits yield substantial volumes of wash material to many interior rivers. On average, fine sediment comprises a higher proportion of material delivered to stream channels in the Interior than on the Coast. The single dependable freshet, followed in many parts of the Interior by a long summer dry period leads to mobilized fines, especially sand, often being deposited along intermediate channel courses on a seasonal basis. The larger channels sustain sufficient flow to flush the material.

Principles for erosion and stream management are, in general, similar to those on the Coast. In dry forests in the Interior, woody debris appears to play a more limited role in stream channels. Pieces are smaller, more easily broken, and less persistent. In some channels, significant systems of old log jams appear to be associated with early floodplain harvest and may not be a natural feature at all.

Structural strengthening of stream beds by clast arrangements, indicating low ambient rates of bed material sediment transport, is a widespread feature in interior rivers. Therefore, problems created by excessive delivery of coarse material from headwaters may be expected to be less common. Proportionately more attention probably will be given to providing bank protection along channels where hydrological changes may threaten stream stability, or where moderately accelerated slope instability has delivered modest incremental volumes of bed material to the channel, so that bank attack is increased.

The Boreal Interior
Northern British Columbia presents a landscape topographically similar to much of the southern interior, but a cooler, damper climate, with a longer cold season. Major erosion problems are, again, often associated with substantial accumulations of glacial sediments in the valleys and on lower slopes. Mobilization of fines from widespread glaciolacustrine silts is a major problem in some areas.

Where valleys have considerable sediment fills, streams are often incised. Land use activity on the valley terraces and lower slopes frequently rearranges both surface and subsurface drainage, issuing in the development of gullying, or slope failure due to enhanced seepage along the terrace edge.

Headwater areas may have low gradients, and similarly low gradient reaches often occur along valley floors in relatively small systems since glacial sediments or alluvial fans often block valleys. Hence, wetlands are relatively widespread. There is often a strong alternation of aquatic habitat types downstream. Wetlands are effective sediment traps, even for wash sediments, but persistently high rates of sediment delivery eventually converts a wetland into a floodplain with through-flowing channel.

Wood debris is relatively abundant along northern rivers, but the smaller pieces are apt to combine into structures of only tenuous stability. Wood is often mobile in major floods, even in relatively small river channels. Hence, the interruption of downstream sediment transfer by debris jams is relatively less effective.

The distinctive emphasis of management efforts here should be on isolating significant and accessible sources of fine sediment from stream channels, and upon surface drainage management.

Summary Perspective
The foregoing discussion is a conceptual statement about watershed function in British Columbia. The emphasis has been on sediment mobilization and transfer, since that gives rise to channel morphology and to stream management problems. Major and systematic processes and effects have been emphasised. Locally, particular conditions of topography, geology, glacial history, hydrology, and fire and land use history will create particular conditions. These have to be analyzed on a case-by-case basis. Some general principles can be identified, however, at landscape scale.

In order to identify the major manageable problems associated with sediment transfer in watersheds, a reconnaissance sediment budget -- estimating sediment volumes mobilized from major sources, and sediment stored in stream channels -- is often a helpful tool. This exercise should identify the principal sediment sources, and it should provide the basis to decide whether direct manipulation of the stream channel (i.e., it is only modestly disturbed) is apt to provide significant habitat improvements in the short run.

An important focal point for fluvial sedimentation occurs in the uppermost valley bottom area of watersheds, in the zone immediately below headwater slopes where the channel first becomes partially decoupled, storage of bed material increases rapidly (Figure 2), and relatively dramatic aggradation is possible. This occurs in watersheds on the 10 km^2 to 100 km^2 scales. Here, a significant number of headward, source-zone tributaries deliver bed material to a valley bottom from where onward transport is much less rapid. Furthermore, the total contributing area is still sufficiently small that a significant proportion of the watershed may be disturbed in a relatively short time: ECA may be high. Where dramatic aggradation has occurred, relatively little can be achieved in the short run; nature must take its course. That probably will require more than 100 years to restore the stream channel to some semblance of its pre-disturbance state, and that is not long in nature’s time scale.

Upstream from this critical region, watershed restoration efforts should be focused upon slope stability, and the chief means to achieve that are conservative land use zoning and practice, and maintenance of natural drainage. Where instability has occurred, drainage should again be the focus of attention, except in the case of accessible chronic sediment sources which appear to be manageable.

Within and downstream from the critical zone, the focus of attention should be on the stream channel. Activities should include bank reinforcement at selected key sites (which should remain few); riparian planting where current channel stability indicates a good chance for success; and woody debris emplacement in channels of intermediate size. These are best when they are appropriately heavy pieces requiring no artificial constraint. Riparian planting includes both bank planting and flood surface planting. Within the critical zone, attention should be focused on long-term arrangements to assure the development of high quality habitat as the stream repairs itself.