Columbia Mountains Institute of Applied Ecology

Proceedings of the

Fourth Annual Roads, Rails and Environment Workshop:

“Impacts and Solutions for Aquatic Ecosystems”

November 2-3, 1999
Hillcrest Hotel
Revelstoke, B. C.

About the Columbia Mountains Institute of Applied Ecology

The Columbia Mountains Institute of Applied Ecology (CMI) is a not-for-profit society established in 1996 to promote, facilitate, and support co-operative interdisciplinary research centred in the Columbia River Basin. The Institute seeks to collaborate with individuals and organizations conducting ecological research in the Columbia Basin and to communicate knowledge in the basin to the public, educators, decision-makers, and other researchers.

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We would also like to thank our presenters for sharing their expertise with us, Karen Bray for chairing the workshop organizing committee and being our Master of Ceremonies, and Jackie Morris and Francis Maltby keeping the workshop running smoothly.

Preface

The first Roads, Rails and Environment (RRE) workshop was hosted in 1996 by Parks Canada, before the Columbia Mountains Institute was a society, incorporated and with a membership. The response was so positive that organizers decided to hold it again the following year, this time under the banner of the Institute although Parks Canada has remained an integral partner. And so it has become an annual affair.

At each of the RRE workshops our aim has been to bring together people and professions that are involved in roads, railways, and environmental issues, who either do not usually meet or may not always see eye to eye. Within our respective professions we often go to workshops and conferences to learn about and discuss advances within our particular fields of work and in our daily work life we are focused on our individual responsibilities. Sometimes even within our own agencies we learn very little about the perspectives of our colleagues. But we hear more often now that we need to start integrating disciplines to achieve a more holistic approach to environmental management and to be more effective.

The RRE workshops are for everyone: the engineers, the biologists, the maintenance crews, the drivers, the researchers, the planners, the managers, the supervisors, the administrators, and the just plain interested. We hope the 4th Annual RRE workshop was useful to you and introduced you to some people and perspectives you might otherwise miss.

So, spread the word.

Thanks for coming and we hope to see you at future RRE's.

Organizing Committee

Karen Bray
Columbia Basin Fish and Wildlife Compensation Program/
CMI Director

Pamela Ladyman
Canadian Pacific Railway

Charlie Pacas
Banff National Park

Agenda

Tuesday, November 2, 1999

08:30	Welcome and Introductions
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11:10 - 11:50	***Impacts of railroad and highway on hydrology, water chemistry and productivity of montane floodplain wetlands in Jasper National Park.*** Suzanne Bayley, Sheena Majewski, and Julie Guimond, Dept.of Biological Sciences, University of Alberta
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Wednesday, November 3, 1999

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Ric Olmsted, BC Hydro

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Paul Schaap, Dillon Consulting Limited

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Dave Polster, Polster Environmental Services

11:40 - 12:00 Wrap Up/Discussion/Future Workshop/Info Needs

12:00 Adjourn

Sediment in Streams: Muddy Waters Got Us Singing the Blues

Charles Newcombe
Ministry of Environment, Lands and Parks

Abstract

Review of the available literature yields a variety of models suited for assessment of impacts caused by excess channel sediment in fisheries streams. Of these, five are summarized here: two apply to suspended sediment and three apply to deposited sediment. These models are applicable (a) to various species of fishes, particularly salmon and trout, (b) to various life-history phases, particularly incubation and rearing, and (c) in the context of a stream before, during or after a sediment pollution episode. Collectively, these models constitute a useful tool-kit for resource managers.

Synopsis

This review of the available water quality literature yields five useful models for assessing the fisheries impacts of excess channel sediment in streams. Two of these models are based on water quality and three are based on sediment quality. Since the quality of water and sediment are related phenomena - suspended sediment carried by a stream is eventually deposited elsewhere in the channel - the models serve different but related functions. Each has potential utility for impact assessment and restoration monitoring as follows:

Excess Channel Sediment

- (1) Water Quality Models:
  - (a) Semi-quantitative, for sediment "climate" - Model 1;
  - (b) Dose Response, for sediment pollution episodes - Model 2;

  and,

- (2) Sediment Quality Models:
  - (a) "Sediment Score", for coho rearing - Model 3;
  - (b) "Substrate Size Composition", for incubation of chinook and steelhead - Model 4;
  - (c) Pebble Count Techniques for stream impacts and fish habitat changes caused by excess channel sediment - Model 5.

(1) Water Quality Models: Of the two promising water quality "models" for assessing the impact of excess sediment in aquatic ecosystems, one (Model 1) is relatively new (1996, 1997), and the other (Model 2) is several decades old (published as a manuscript in 1962 and as a paper in 1965). Both are of potential use for monitoring and impact assessment, or in the design and implementation of a stream restoration program.

(a) Model 1 - Suspended Sediment: This “older” model is a classic. It offers two parts of interest here - the *first* describes half a dozen modes of action of suspended sediment on fishes, whilst the *second* draws general conclusions about the effect of ambient suspended sediment and the size of fish populations. This “model” is an excellent primer because it offers a concise summary of knowledge available up to 1965. Its “modes of action” and “general conclusions” are still current today. Such longevity reflects the thoroughness of the review on which the model is based, and the relatively slow pace at which new sediment impact knowledge is generated.

(b) Model 2 - Suspended Sediment: This new module is based on a compendium of data that links dose and response (ill effect) in fishes and aquatic invertebrates. “Dose” is expressed as mg.h.L-1 (milligram-hours per litre of suspended sediment), and ill effect is expressed on a 15-step *semi*-quantitative scale. This “dose-response” model (the first of its kind in this branch of fisheries science) offers predictive capability much needed in environmental protection and restoration. It has potential utility (a) in the design of mitigation measures when environmental impacts are unavoidable, and (b) in the field of pollution credit trading when there is a need to establish functional equivalence among disparate sediment pollution events thereby to balance credits and debits.

(2) Sediment Quality Models: Several models - semi-quantitative, and objective - have potential use for impact assessment in salmon and trout streams where deposition of excess sediment has occurred. They may be used to corroborate impact assessment where suspended sediment data are available; and they can be used independently when suspended sediment are not available. In most instances of sediment pollution, deposited sediment is the persistent legacy of an ephemeral event - elevated suspended sediment concentrations. It is often easier to study the former than the latter.

Deposited Sediment: Short-term and chronic changes in the sediment deposition patterns of a stream can alter the particle size composition of the streambed. These changes affect water quality of “spawning” gravel where salmon eggs incubate, and the quality of the substrate in “rearing” habitat used by juvenile salmon and trout. Several models describe changes; two examples are:

(a) Model 3 - Deposition; Rearing of Coho: The growth rate of juvenile salmonids is a function of the quality of rearing habitat. In reaches where excess deposition of sediment has altered the streambed texture, salmon grow more slowly: this effect can be measured experimentally in winter and summer rearing phases. These experimentally derived results should be directly applicable to stream channel harmed by deposition of excess sediment.
(b) Model 4 - Deposition; Egg Incubation; chinook and steelhead: Measurements of the amount of coarse and fine sediment in gravel can now be linked to the incubation success (% survival) of chum and coho embryos.
(c) Model 5 - Pebble Count Technique: A comparative field procedure for assessing changes in particle size distributions in streams. This model detects changes in the amount of fine gravel, in the field, without the necessity of bulk samples.

These methodologies for impact assessment of excess channel sediment - suspended and deposited phases - are described in functional detail below (section 1 and 2). Notes on long-term effects of excess deposited sediment (Section 3), and notes on stream restoration (Section 4) provide a general context for these impact assessment models, and conclude the discussion.

NOTE: A 30 page handout was also distributed to participants at the workshop, by the author.

Transportation Corridors in Banff National Park: Achieving a Balance Between Environmental Benefits, Public Safety and Costs

Fes de Scally,
Department of Geography,
Okanagan University College

Transportation corridors through mountains frequently cross alluvial fans built up at the mouths of small tributary basins. The transportation routes therefore are affected by water and sediment transport processes – streamflow and flash floods, debris flows, and sometimes snow avalanches – on these fans. Traditionally in western Canada the active channels containing streamflow and debris flow processes have been crossed using short-span bridges or culverts, employing measures such as diversion, ditching and channelisation, riprap placement and regular excavation to ensure the integrity of these crossings. However, it is now being recognised that the ecological consequences of alterations to alluvial fan processes which result from these measures may be unacceptable particularly in a national park setting.

These ecological consequences are:

•Adverse impacts on stream fish habitat including obstacles to fish movement such as culverts, high suspended sediment concentrations during excavation or cleaning, and degradation of habitat.

•Reduction in the sediment load carried to trunk streams by the alluvial fan processes, in particular in situations where the active channel of the fan is diverted away from the trunk stream; the cumulative reduction in sediment load from several fans may have a significant effect on the downstream morphology of the trunk stream.

•Increased sedimentation rates in wetlands as a result of streams being diverted into them, resulting in infilling and ecological changes in these wetlands.

•Loss of riparian vegetation and trembling aspen and balsam poplar communities as a result of the cessation of disturbance by flooding and debris flows. These processes would under natural conditions overflow periodically onto the fan surface, resulting in deposition of coarse sediment which encourages the regeneration of these species. The loss of these vegetation communities by competition from species less tolerant of such disturbance is significant because these are normally communities with a high degree of biodiversity.

This paper reports on a recently completed project in the lower Bow Valley, Banff National Park which investigated alterations to alluvial fan processes by the Trans Canada Highway, Canadian Pacific Railway, and secondary roads. The study includes an inventory of water and sediment transport processes (streamflow and flooding, debris flows) and alteration of these processes on 80 alluvial fans or cones adjacent to these transportation corridors. Fifty-five of these fans are crossed by a highway, road or railway (and in many instances by both highway and railway), and of the 36 of these which possess modern water and sediment transport processes all have been impacted to some degree by the transportation route. The study also includes a detailed investigation of water and sediment transport processes and their alteration on two alluvial fans – one a small steep fan affected by debris flow, flash flood and snow avalanche processes, and the other a large low-angled fan possessing perennial streamflow with a significant potential for flash flooding. Specific options including their approximate cost for restoring more natural water and sediment transport processes on these two fans are explored.

The results of this study have a number of implications for alluvial fan restoration in other Mountain Parks and areas where the alteration of water and sediment transport processes is deemed undesirable from an ecological perspective. First, on small steep fans supplied by basins smaller than about 10 km2 the potential for debris flows in addition to flash flooding needs to be assessed. While debris flows are generally less frequent than flash floods, having a recurrence interval of 10 to 100 years at a given location compared to floods with a recurrence interval of less than one year to 10 years, their peak discharge and total volume of sediment transport is usually one to two orders of magnitude greater than what a flood from the same basin is capable of. This means that: no size of culvert will be adequate for debris flow passage; bridges must have sufficient clearance to allow a debris flow to pass unobstructed beneath them; fords must be extremely strong to withstand the impact forces associated with the moving debris and have sufficient freeboard so that the debris does not flow down the road (see below); vehicles or trains struck by a debris flow have a much greater chance of damage and injury to their occupants than in the case of floods; and debris flows have a better chance of overflowing from an active channel and taking a different route down the fan than do floods.

Second, the degree of activity or inactivity of the fans must be assessed. While many of the fans in the lower Bow Valley were constructed several thousand years ago and are today relatively inactive away from the modern active channel, fans in other mountain areas may be much more active. Not only may the active channel of such fans experience more frequent and larger flash flood and debris flow events, but since that channel is probably not as deeply incised into the fan surface the possibility of events overflowing onto the fan surface is greater. Therefore, floods and debris flows may cross transportation routes at more than one location on more active fans. Even on relatively inactive fans, large debris flows or floods may infrequently overflow into abandoned channels.

Third, assuring the integrity of water and sediment transport processes on alluvial fans and their associated ecological functions by closing roads, or allowing floods and debris flows to impact them with little or no human intervention, is only practicable for secondary roads in the Mountain Parks. These are clearly not appropriate solutions for major transportation corridors. In these situations the best means of achieving a balance between the frequently competing objectives of maintaining the integrity of environmental and ecological processes and the integrity of the transportation route, is to design crossings of active channels with the following multiple objectives in mind:

•Natural water and sediment transport processes are allowed to occur as naturally as possible, with minimal disruption by the crossing structures or the maintenance carried out on them.

•Disruptions of road and rail traffic by flood and debris flow events are minimised.

•The safety of people using the transportation route is not compromised.

•The future cost of maintenance of the active channel crossings, in the past associated with work such as cleaning out culverts, excavating channels and replacing riprap, is minimised or eliminated.

•Improved wildlife underpasses are incorporated into the design of crossing structures. In particular, multiple-span bridges or elevated roadways, where the entire natural width of a channel is available for wildlife movement, may provide a superior alternative to existing confined underpasses.

•Public awareness and education of alluvial fan processes form a part of the fan restoration efforts whenever appropriate and possible in the Mountain Parks.

Most if not all of these objectives can be met by design of crossing structures which satisfy the first objective, and therefore the additional cost of realizing the first objective may be justified. Good examples of such structures are found in New Zealand where many of the road and rail crossings of active channels on alluvial fans are designed to allow relatively undisturbed movement of water and sediment. These structures include concrete fords on secondary roads and in some cases even major highways which provide little impediment to the passage of debris flows or flash floods. Sediment deposited on the ford by an event is easily and quickly cleaned up. In Canada the use of fords would probably have to be limited to secondary roads with low traffic volumes, and the safety issue associated with the public's use of fords during hazardous conditions would need to be addressed by signposting (as in New Zealand) or road closures. Common on major highways and railways in New Zealand are multiple-span bridges which permit as much as possible of the natural width of an active channel to be maintained under them. The foundations of the bridge piers are designed to withstand bed degradation and aggradation during even large flash floods, but they would not be able to withstand the erosion and impact forces generated by debris flows. If a ford is not employed for crossing an active debris flow channel, then a single-span bridge with a deck clearance sufficient to allow passage of the design event is the only option. Such a crossing would not only ensure the integrity of the transportation route; the ecological objective of unaltered water and sediment transport would also be satisfied.

Impacts of Railroad and Highway on Hydrology, Water Chemistry and Productivity of Montane Floodplain Wetlands in Jasper National Park

Suzanne Bayley, Sheena Majewski, and Julie Guimond.
Dept.of Biological Sciences, University of Alberta

In the mountains of western Canada, most of the major river valleys are occupied by roads, railroads and pipelines that bisect the riverine ecosystems. In the eastern portion of Jasper National Park, the Athabasca River floodplain is bounded on the north by the Canadian National Railroad and on the south by the Yellowhead Highway (Rt 16). These systems were constructed in 1912-1914 and the floodplain has had over 85 years to adapt to the new hydrologic patterns. To assess the impacts of the roadway embankments, we measured hydrology, chemistry and vegetation in wetlands on both sides of the roadways for three summers. We found that the wetland communities on either side of the roadways differ, as do the processes that control them.

Specifically we found that the roadway embankments and culverts obstruct the lateral spread of turbid glacial riverine floodwaters into secondary channels, shallow lakes and wetlands. Runoff waters from local mountains are impounded behind roadway embankments resulting in higher water levels in early spring and in more uniform water levels year round than in wetlands with free access to Athabasca River. Typically, the impounded wetlands are extremely clear and low in all nutrients, while the wetlands with access to the main river are sometimes turbid and receive sediments and some nutrients during the summer. The hydrologic changes and resulting chemical changes have altered the productivity, species composition and diversity of the emergent and submersed aquatic vegetation and the associated algal communities.

Furthermore, beaver dams have aggravated hydrologic changes caused by the roadways by incorporating the embankments into their impoundments. In contrast, beaver dams in the floodplain without roads or railroads are overtopped during high flood years (1999) resulting in a sediment "fertilization" of the marshes. Thus, beavers alone do not cause fragmentation of the floodplain habitat, while the roadways (either alone or in association with beaver) have caused significant fragmentation in the habitat. Numerous culverts are blocked or hanging and access for fish and amphibians prevented.

Regional Hydrology Studies in the Columbia Mountains

Hugh Hamilton and Brian Guy
Summit Environmental Consultants

Correctly determining the size of the opening of culverts and bridges, which is a function of the design discharge or flow, is fundamental to the environmental management of roads and railways. If the opening is too small to pass the design flow, the road or railway could be washed out, resulting in damage to downstream habitat, property, or infrastructure. Less catastrophic but nevertheless serious effects include increased erosion and sedimentation, creation of velocity barriers to fish passage, and alteration of aquatic habitat. The consequences of building culverts and bridges larger than what is necessary to pass the design flow are primarily financial, but may result in resources being diverted that could be directed to other aspects of environmental mitigation. This summary outlines several common methods for estimating design discharges in B.C., discusses the challenges of design flow estimation in mountainous regions, and presents a brief case study from the West Kootenay region of the Columbia Mountains.

The West Kootenay region contains hundreds of kilometres of roads (including forest roads) and railways, and thousands of culverts and bridges. On Crown forest land, the Forest Practices Code of British Columbia Act and Regulations provide design criteria for culverts and bridges. Culvert and bridge sizing is based on calculating the minimum opening required to pass the 100-year return period[†] instantaneous peak flow (Q100) for all stream culverts and permanent and semi-permanent bridges, and the 50-year return period instantaneous peak flow (Q50) for temporary bridges and all other culverts. Most permanent non-forest road and rail bridges require designs for higher return-period flows, typically 200 to 500-year return period. Flow estimation in the region is complex, due to the highly variable nature of flows resulting from strong climatic and topographic gradients.

Because they are responsible for numerous culverts and bridges, forest companies need effective tools for estimating design flows within their operating areas. The Forest Practices Code provides several options for making these estimates. The simplest method is also the most conservative. This involves measuring the cross-sectional area of the channel at the crossing location, and multiplying by three to obtain the recommended culvert opening size. This method assumes that the bankfull flow of any stream represents the mean annual peak flow for that stream (Q2), that the ratio applied to obtain Q100 is 3.0, and that the discharge is not sensitive to pipe slope or other hydraulic factors (Ministry of Forests and B.C. Environment, 1995). Other methods are more complex, requiring more data and the services of an engineer or hydrologist. Despite its simplicity, experience with the "Q2(3" method since the Code was implemented indicates that it results in oversized culverts and bridges. Although the resulting incremental cost at a single crossing is small, the cumulative cost increase for a new road, which may require many culverts and bridges, is much larger. This has led forest companies to reconsider the design process.

In 1993, a West Kootenay-based forest company commissioned the development of a consistent methodology for estimating the 50- and 100-year design flows, and for sizing the culverts and bridges necessary to safely pass these design flows. For estimating the design flows, a hybrid approach was followed, using a regional model (the Index Flood method) for watersheds >10 km2 and a modification of the Rationale Formula for watersheds (10 km2. The regional hydrology study used existing Water Survey of Canada streamflow data and was aimed at developing empirical design equations applicable throughout the company's operating area (essentially the Arrow and Kootenay Lake Forest Districts). Data from 46 WSC stations formed the data set, nine stations from within the operating area and the remainder from adjacent areas. Although there are spatial and temporal data gaps, the West Kootenays are actually reasonably well monitored, with more higher-elevation stations than other mountainous areas of B.C. This is partly due to a long history of mining and water resource development.

Data analyses found significant ($p<0.05$) differences in discharge per unit area with changes in average watershed elevation. Four elevation bands were identified (<1,300 m, 1,300-1,500 m, 1,500-1,800 m, >1,800 m), for each of which different governing equations were developed. Uncertainty in the design discharge estimates is addressed by calculating the standard error of the estimate. New culverts and bridges are recommended to be sized to pass the mean design discharge plus one standard error. Since culverts generally come in standard sizes, an additional factor of safety is provided by "bumping up" that size to the next largest standard opening size. Despite this, the design openings generated by the regional model are less than what would be implemented by the simple "Q2(3" guideline. In the West Kootenay area the average ratio of the 100-year instantaneous flow (Q100) to the mean annual instantaneous peak flow (Q2) is 2.12. Results from other regions in B.C. are in the range of about 1.8 to 2.4.

Reference

Ministry of Forests and B.C. Environment, 1995. Forest Road Engineering Guidebook. Forest Practices Code of B.C. Act. Victoria. 153 pp.

[†] Return period is a way of expressing the exceedance probability. The probability of the 100-year peak flow being exceeded in any given year is 1/100 or 0.01. In other words, in any year the odds that this flow will be exceeded are 1 in 100. The probability that the flow will be exceeded over the life of a road obviously increases with the length of time that the road is needed. For example, there is a 22% chance that the 100-year flow will be exceeded within 25 years, and a 40% chance that it will be exceeded in 50 years. In contrast, the probabilities of the 500-year flow being exceeded are about 4% for a 25-year lifespan and 9% for a 50-year lifespan.

Harlequin Ducks and Highways in Banff National Park

Cyndi Smith
Simon Fraser University and Parks Canada, Banff National Park

A study of Harlequin Ducks (*Histrionicus histrionicus*) in Banff National Park, Alberta, was conducted from 1995 to 1999 in response to concerns about the potential impacts of human activities and habitat modifications due to the twinning of the Trans Canada Highway (Smith and Clarkson 1995). The Bow River has the highest reported density of Harlequin Ducks on a breeding stream in North America (Robertson and Goudie, in press). The median population estimate based on four years of Capture-Mark-Recapture/Resighting is 151 adults (± 2.0 S.E.; Smith 1999).

The potential impacts of road, railway or pipeline construction on Harlequin Ducks and their breeding habitat include: destruction of riparian areas (Genter 1993); disruption of watershed stability and stream flow regime, which can alter the invertebrate community structure (Latta 1993); immediate and/or extended decrease in the food base due to increased sedimentation (Cassirer 1995); isolation of brood-rearing areas by roads (Kuchel 1977), and; disturbance from human activities related to construction or increased access post-construction (Ashley 1994; Cassirer 1995; McEneany in Smith and Clarkson 1995). In northern Idaho at least one order (Ephemeroptera) of macroinvertebrates known to be used by Harlequin Ducks declined in both absolute and relative abundance as a result of high levels of sediment and turbidity during pipeline construction (Cassirer 1995).

In this paper I will describe: (1) site fidelity during the breeding season, (2) nesting streams, (3) pre-hatch movements of females, (4) post-hatch movements of females with broods, and (5) management implications.

Study area and methods

Study area. — This study centred on the Bow River in Banff National Park, between the Town of Banff and the village of Lake Louise, including some tributaries. The river is paralleled by the Trans Canada Highway (TCH) on the south, and the Canadian Pacific Railway (CPR) and Bow Valley Parkway (BVP) on the north.

Roadside surveys. — Surveys were conducted in all five years by travelling west from Banff on the TCH to Lake Louise and east again on the BVP, stopping at 27 sites along the river. The location, time, number of birds by sex, pair status, banded or unbanded status and band code were recorded, as well as any interactions or disturbance (Smith 1996). Some bias in time of day may have occurred due to the consistent counter-clockwise route, but this was necessary for reasons of safety in stopping along the highway. The Kruskal-Wallis One-Way ANOVA on Ranks test was used to compare surveys and sites between years. Comparisons were split into May/June (adults) and July/August/September (females with and without broods).

Radio telemetry. — In 1997 some adult females and males received intra-abdominal radio transmitters (Korschgen *et al*. 1996), and in 1998 and 1999 back-mounted anchor-and-suture transmitters were attached to some adult birds (Pietz *et al*. 1995). Locations were determined by triangulation using a hand-held three-element Yagi antennae or two-element "H" antennae.

Results and discussion

An average of 13.6 roadside surveys per year (range 12-16) were conducted for adults in May and June, 1995-1999. The number of Harlequin Ducks observed during surveys was significantly different in 1995 ($P < 0.01$), 1997 ($P < 0.05$) and 1998 ($P < 0.01$). There were highly significant differences ($P < 0.001$) between sites in each year except 1998 ($P < 0.05$). Comparing all five years three sites had significantly higher numbers on average ($P < 0.05$).

An average of 8.3 surveys per year were conducted in July, August and September, 1995-1997, which were predominantly females with broods. The number of ducks observed was not significantly different between years ($P > 0.05$), but was significantly different between sites in each year ($P < 0.05$).

In 1997 six females and four males received radio implants in May. In 1998 extreme high water just as birds were arriving allowed the capture of only one female, but three females returned from 1997. In 1999 six females were captured and two females from 1997 returned.

Of the 18 radio-marked females (including successive years) there were 15 breeding opportunities (1 was censored because she disappeared from the study area and 2 because they were depredated before attempting to nest), which resulted in 13 nesting attempts. Two active nests of non-radio-marked females were also located. Only two of the 15 nests were located on the Bow River, the rest were on tributaries. Four of the tributary nests were within 600 m of the Bow River, and the ducklings were led there within 24-48 hours of hatching.

Female GV hatched five young (two eggs did not hatch) during a cold wet period between 8 and 9 July, 1997. On the evening of 9 July one duckling was observed trying to cross the TCH to go back upstream (towards the nest site). The water was support-to-support under the bridge, covering the shoreline and too swift for the duckling to swim upstream against, forcing it onto land. The bird was caught and placed on an island upstream of the bridge. GV was subsequently observed with only one duckling; the rest were presumed to have died. Female JS led her six young down to the Bow River on the day after hatching by swimming through one of two side-by-side culverts under the TCH. Each culvert was 26 m long and 0.8 m in diameter, and ended 1.8 m from the river and 1.3 m above water level, where the creek cascades over riprap to the river.

There were no significant differences in the adaptive kernel home ranges (Hooge and Eichenlaub 1998) of female GV and JS, either pre-hatching or post-hatching.
On 3 June 1997, male JN (mate of female JS) was observed feeding in the nesting creek just upstream of the TCH and then flew across the highway to the river at less than 2 m height. His flight path was below the normal height of most vehicles. On 17 May 1998, one adult

male Harlequin Duck was struck and injured by a motor vehicle along the TCH at the Minnewanka Junction east of the Town of Banff. It is possible that he was following the original, usually dry, streambed of the Cascade River, which is diverted by the Lake Minnewanka Dam. Massemin and Zorn (1998) found that mortalities of owls killed along a highway in northeastern France increased along embanked highway stretches.

Management implications

1. Amount of use by Harlequin Ducks of specific sites varies between years and between months, but three sites received significantly higher use overall. Surveys should be conducted for both pairs and broods, and for a minimum of two breeding seasons to determine timing and amount of use. Avoid construction during the local breeding season.
2. Females' home range utilization varies before hatching and after hatching, and also by age of the brood.
3. Nesting streams vary considerably in size and gradient.
4. Culverts may be suitable structures provided there is air space at all water levels, an opening is visible at the end, and if brood movement is expected to be downstream only (i.e., a short stream that may be ephemeral). Culverts will likely prevent upstream movement.
5. Bridges should have accessible shoreline on both banks at all water levels to facilitate movement up- and down-stream by broods.
6. Avoid construction at junctions of watercourses as Harlequin Ducks concentrate at these sites, and they provide connectivity to nesting streams.
7. Harlequin Ducks typically fly 1-2 m above the water surface. On streams where they may be forced to fly over a road because of a culvert, or a bridge they cannot fly under, hedges or some other barrier should be established to force them to fly higher to cross the road, above the height of vehicles.
8. When reconstructing roads eliminate parking areas and pullouts that increase access to streams (Cassirer *et al.* 1996).

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Positive Benefits of Wetlands for Pollution Control from Highway Construction and Operation

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Wetlands are natural filters of suspended and dissolved solids. Their role as flow attenuators in stream systems is well documented. They act much the same as beaver ponds to settle out sediment but are much more permanent features of watershed landscapes. Wetland forms, using the BC wetland classification system, vary from open-water shallow ponds, to cattail marshes, to sedge fens, to shrub carr and ultimately cycle into a land-based landscape unit. This natural process of succession is relatively fast, on a geologic time scale, and results in wetlands becoming energy sinks. This means that energy is trapped in the form of carbon within the sediments and soils that constitute the succeeded wetland.

Although wetland's ecological systems are diverse with fauna and flora they are self-maintaining. That is, wetlands cycle through a complex system dominance structure of aerobic to anaerobic decomposition. This implies seasonal shifts in bacterial and algal communities. These communities are able to break down and alter chemical compounds with varying levels of efficiency. For example, tetrachloroethylene (a chemical used for dry cleaning and commonly referred to as perc) is broken down to trichloroethylene under anaerobic conditions, leaving an equally toxic by-product. The trichloroethylene then breaks down to less harmful by-products under increasingly aerobic conditions, until the ultimate end-product is ethylene (EBA 1999). Consequently, the seasonal cycles experienced in temperate wetlands promote break down of environmental contaminants to less harmful or even benign by-products.

Organic matter, in the form of living and decomposing vegetation, has substantial capacity to bind contaminants. Binding is accomplished by both absorption and adsorption. This means that with greater amounts of plant biomass and accumulated debris there will be greater binding capacity, concomitant with increased biomass and increased surface area.

Constructed wetlands have been used extensively as part of effluent treatment systems for mines and municipalities and as settlement basins for urban development projects. Linear developments (e.g., highways and railways) are another application for wetlands as water quality improvement areas. Shallow wetlands promote greater plant biomass, which makes them more adept at filtering contaminated water in the form of surface runoff from highway construction and operation.

Engineered wet and dry detention ponds have been the most common systems for the treatment of surface runoff from highways projects. A large-scale example of their use was the Island Highway on Vancouver Highway, BC. That project adopted practices from the BC Land Development Guidelines for the Protection of Aquatic Life, which was jointly authored by BC Ministry of Environment, Lands and Parks and the Department of Fisheries and Oceans (Chilibeck et al. 1992). Procedures developed in King County, Washington and California have also been adopted for projects in western Canada.

We present an example of a design/build highway project near Kelowna, BC. The project consists of a highway / urban interchange that is located within 500 m upslope of Powers Creek. This creek has been designated as one of the six most important spawning streams for rainbow trout (*Oncorhynchus mykiss*) and Kokanee salmon (*Oncorhynchus nerka nerka*) in Okanagan Lake. The BC Ministry of Environment, Lands and Parks (MoELP) mandated, in their approval of this project, the protection of Powers Creek from highway construction and operation. The BC Minstry of Transportation and Highways (MoTH), with the aid of EBA Engineering Consultants Ltd., Emil Anderson Construction and Alliance Professionals, initiated the development of wet detention ponds, with the ultimate vision of becoming shallow wetlands.

The wet detention ponds were placed as a last line of defense before surface runoff enters a system of culverts, which discharge directly into Powers Creek. Other protective measures included silt fences, gravel berms, check dams, and dewatering operations. The wet detention ponds have operated to settle out sediment during construction of the interchange. Their main function was to decrease the amount of Total Suspended Solids (TSS) in surface runoff. The goal is to see the detention ponds as permanent, water quality improvement facilities for storm runoff and potential spills on the highway.

For reasons of safety, water quality improvement, and esthetics, the final design will be for shallow, fully vegetated wetlands. We will maximize the available area to ensure that the ponds will attenuate the flow of storm runoff so that suspended sediments will be removed before they could enter Powers Creek.

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A Methodology to Salvage and Incubate Fertilized Salmonid Ova from De-watered Redds

Ric Olmsted and Dean den Biesen
BC Hydro, Kootenay Generation Area

Rainbow trout *(Oncorhynchus mykiss)* are a highly valued sport fish in the Canadian Columbia River downstream of Hugh L. Keenleyside Dam in southwestern British Columbia. Trout spawn in Columbia River tributaries and in two principal areas of the mainstem from March through mid-May, although the majority of reproduction occurs in April and May. The operating regime of Keenleyside Dam, as negotiated with provincial and federal fisheries regulatory agencies, maintains high flows during the month of March to protect incubating mountain whitefish eggs. Flows are then reduced in April to promote rainbow trout spawning at lower elevations to ensure that their fertilized eggs remain wetted throughout the incubation period.

In the past, when trout redds have dewatered, BC Hydro has used other methods, such as water sprinklers and wetted burlap sacks, to keep eggs moist, often with biologically and socially unacceptable results. As opposed to letting eggs die, BC Hydro proposed that relocation, a strategy never previously considered, be attempted. While the federal Department of Fisheries and Oceans biologists were skeptical that fertilized eggs could be handled without experiencing high rates of mortality, BC Hydro's review of relevant literature suggested eggs could be handled with high rates of survival. The literature indicated that there was evidence to suggest that salmonid eggs, when in early stages of embryonic development, could be successfully removed from redds and relocated to watered areas of the Columbia River where they would remain in incubators until they hatched.

In situ studies conducted in 1997 suggested that the survival of early developmental eggs excavated from and incubated outside the redd could be equal to or higher than those incubated in natural redds. Studies conducted in 1998 used stringent hatchery protocols for incubation. Survival of excavated ova that ranged in development from 5 to 180 Accumulated Thermal Units averaged 52.0%; ten percent is the accepted average survival rate of rainbow trout eggs in the natural environment.

In 1999, BC Hydro retained a consultant to jointly coordinate ova salvage, with the support of Hydro staff, Selkirk College students and First Nations to salvage over 23,000 fertilized eggs from primary mainstem Columbia River spawning locations over a three-day period in late March and early April. Preliminary results indicate about 40% egg-to-fry survival.

There are several benefits for BC Hydro from salvage operation, apart from the survival of trout fry. Regulatory compliance to preserve fish is addressed under the legislation of the Canada Fisheries Act. The public expects BC Hydro to adhere to contemporary environmental standards and this protocol enables Hydro to meet such standards. BC Hydro also gains increased operational flexibility in water management at Hugh Keenleyside Dam.

Fish-Friendly Solutions to Stream Bank Erosion: The Confluence of Two Narrow Streams

Paul R.H. Schaap
Dillon Consulting Limited

Abstract

Over the past few years our knowledge and experience in stream restoration in British Columbia have advanced considerably. Over the same period, regulatory agencies responsible for the management of the province's fish and wildlife habitat have become more demanding that alternatives to traditional stream bank erosion protection be investigated. Projects requiring authorization for the harmful alteration, disruption or destruction of fish habitat under the federal Fisheries Act have been pushed hard to include designs which consider the integration of these sometimes-opposing principles. This presentation describes recent experiences with the design and construction of various techniques to reduce stream bank erosion. The techniques described represent compromises between the "hard" and long-lasting preferences of the engineering discipline with the more "fish friendly" objectives of fisheries biologists.

Several case studies are presented which provide a range of design conditions and solutions to stream bank erosion. Techniques described will include root wad revetments, lateral brush layers, "bio-gabions", and the integration of wood debris and live material into rip rap designs.

Many of the examples presented have only been constructed over the past few years, and therefore their effectiveness in reducing stream bank erosion may not yet have been thoroughly "challenged" by Mother Nature. Similarly, monitoring programs intended to document benefits to fish production have only been initiated on one of these projects. Despite these limitations, I believe that when proper designs are selected to address the specific characteristics of a site, integrated "fish friendly" solutions which combine traditional engineering designs with biological principles will provide long-term stream bank erosion protection solutions which benefit fish communities across the province. The most effective solutions will truly represent "the confluence of two narrow streams".

Introduction

Over the past few years our knowledge and experience in stream restoration in British Columbia have advanced considerably. This is largely due to a province-wide push to implement restoration activities under the Watershed Restoration Program of Forest Renewal BC, but also due to a longer period of "in ground" experience and monitoring, heightened insistence from regulatory approval agencies that alternatives to traditional techniques are investigated, and the enhanced commitment by some project proponents.

Generally speaking, two narrow "streams" of thinking have been used in the past to address streambank erosion. The engineering "stream" considered solutions that were "traditional" and focused on stability and limiting liability. These solutions were often referred to as "hard" techniques as non-erodible materials (e.g., rip rap, boulders) often dominated these designs. Sometimes natural environmental values were overlooked by the traditional solutions. Conversely, the biology "stream" generally promoted solutions that were considered "experimental" and tended to overlook long-term stability needs. These "soft" solutions commonly relied on live or previously living materials, and sometimes failed to incorporate hydraulic/ hydrologic parameters into designs.

Current restoration techniques and initiatives that are emerging represent the "confluence" of the two "streams" of thinking. Using a more integrated approach to design, the needs of both "streams" are addressed, critical site-specific elements are respected. When protecting an investment, however, certain design elements are not always in balance with other design parameters. This presentation describes recent experiences with the design and construction of various techniques to reduce stream bank erosion. The techniques described represent compromises between the "hard" and long-lasting preferences of the engineering discipline with the more "fish friendly" objectives of fisheries biologists and address a range of investments to be protected. Each of the case studies presented were designed and constructed by Dillon engineers and biologists in 1999.

Case Studies

1. Use of an Integrated Root Wad/Boulder Revetment to Address Arterial Road Embankment Failure (Investment Level: High)

Problem Definition: peak flows in a highly productive salmon stream were promoting extensive erosion of an outside meander bend of the watercourse and undermining of the road fill; failure of the road embankment had the potential to result in significant risks and consequences to public health and safety.

Design Considerations: high winter flows and velocities; narrow and steep working area; requirement to ensure long-term stability to protect users of the road, as well as the road as an investment; requirement to maintain and enhance fish habitat values.

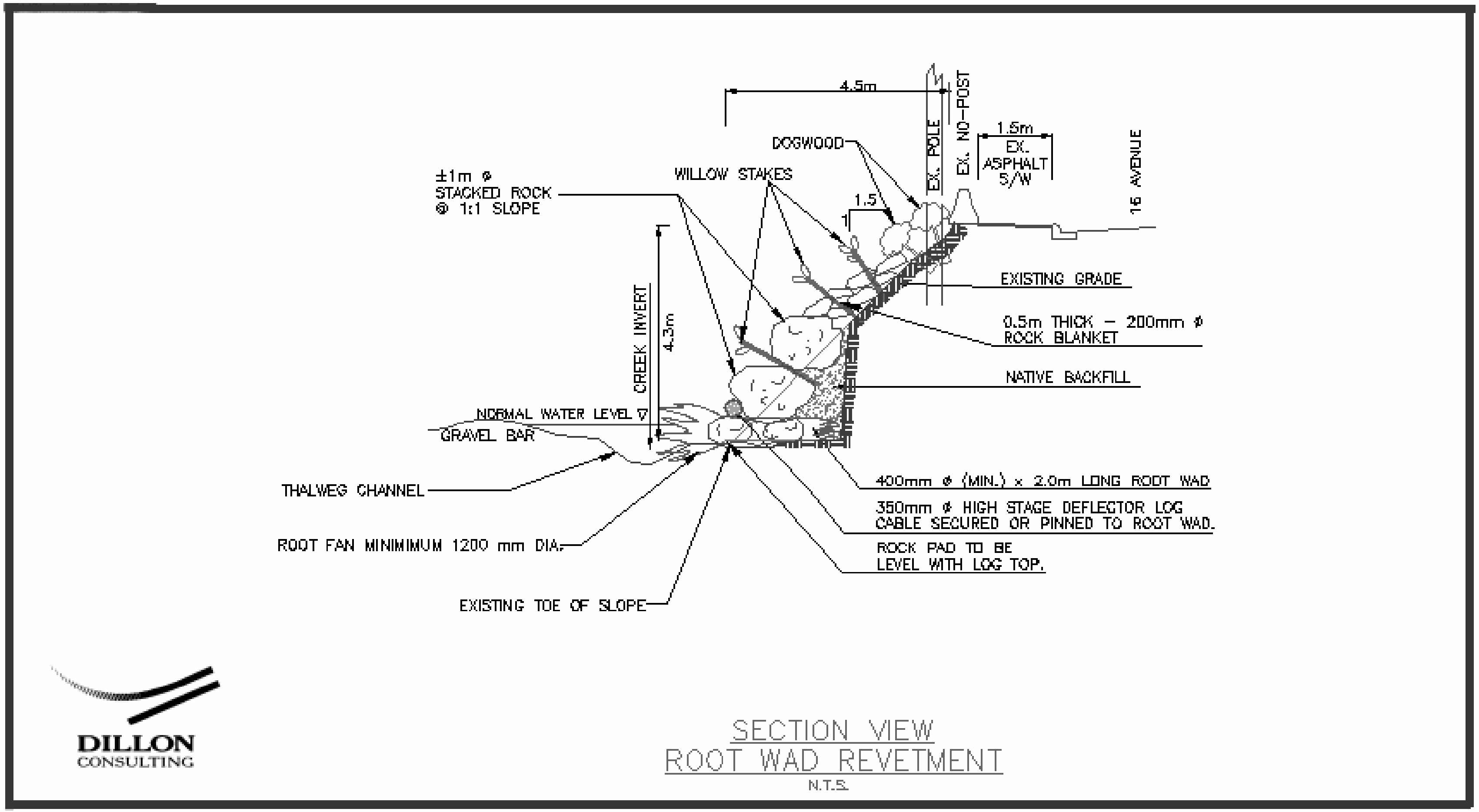
Restoration Prescription: integrated root wad-boulder revetment utilizing four large cedar root wads (root fans >3m diameter) and large boulders (>800mm); root wads and large boulders allow steep bank face required due to narrow working area; riparian habitat restoration (Figure 1).

2. Toe Erosion Threatening Private Property – Bio-Gabions (Investment Level: High)

Problem Definition: accelerated toe erosion of embankment induced by increasing peak flows; residence and gazebo located at top of eroding slope; high risk, significant consequence and potential liability issue; high fisheries values.

Design Considerations: Potential instability of entire slope and proximity to structures; requirement to ensure bank stability under existing and future hydrologic/hydraulic conditions; salmon-bearing watercourse situated within a well-vegetated and incised ravine.

Restoration Prescription: bio-gabion wall having the following specifications: pvc-coated wiremesh; “coir” cloth wrapping holding 50/50 mix of 75-200 mm riprap and planting soil; gabion face treated



4.5m
EX. POLE
EX. NO-POST
1.5m
EX. ASPHALT S/W
16 AVENUE
DOGWOOD
WILLOW STAKES
±1m ϕ
STACKED ROCK
@ 1:1 SLOPE
1.5
1
EXISTING GRADE
0.5m THICK – 200mm ϕ
ROCK BLANKET
NATIVE BACKFILL
CREEK INVERT
4.3m
NORMAL WATER LEVEL
GRAVEL BAR
THALWEG CHANNEL
ROOT FAN MINIMIMUM 1200 mm DIA.
EXISTING TOE OF SLOPE
400mm ϕ (MIN.) x 2.0m LONG ROOT WAD
350mm ϕ HIGH STAGE DEFLECTOR LOG
CABLE SECURED OR PINNED TO ROOT WAD.
ROCK PAD TO BE
LEVEL WITH LOG TOP.
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SECTION VIEW
ROOT WAD REVETMENT
N.T.S.

Figure 1.

with willow stakes at a density of 30/m2; footer row of concrete lock-blocks; back-fill and planting above top basket (Figure 2).

3. **Bank Erosion in Low Risk Areas – Lateral Brush Layering (Investment Level: Low)**

Problem Definition: stream bank erosion in areas of lower risk and consequence; low to moderate peak flows; high fisheries values

Design Considerations: site-specific hydrologic/hydraulic conditions; bank height; composition of native soils

Restoration Prescription: lateral weaving of willow branches between wood or steel posts to create a live "wall" or fence; ensure butt and tip of each branch is firmly embedded into soil; ensure that weave is tightly stacked and compact seeded soil as backfill in a series of lifts; insert live stakes into face of do not exceed 0.75m in height; armour toe, tip and tail of structure with rip rap of appropriate dimensions

4. **Stream Bank Erosion in High Energy Systems – Large Woody Debris Treatments**

Problem Definition: Stream bank erosion occurring in high flow/high velocity systems; significant fisheries values to maintain or enhance

Design Considerations: Non-erodible materials required to ensure stability under existing and future hydrologic/hydraulic conditions; requirement to maintain fish habitat function

Restoration Prescription: anchor large pieces of woody debris in various configurations into riprap area to increase fish habitat complexity; orientation should consider site-specific hydraulics and watercourse geomorphology; assess site-specific ballast requirements; where possible, use large diameter conifer logs; use Hilti method or other suitable technique to anchor wood

5. **Integration of Riparian Vegetation into Extensive Rip Rap Areas**

Problem Definition: Extensive areas of rip rap required to minimize stream bank erosion; requirement to provide riparian habitat function to maintain fisheries values

Design Considerations: Thickness of rip rap blanket; native soil characteristics beneath rip rap blanket; aspect and exposure of study area to determine appropriate riparian species to be planted (Figure 3).

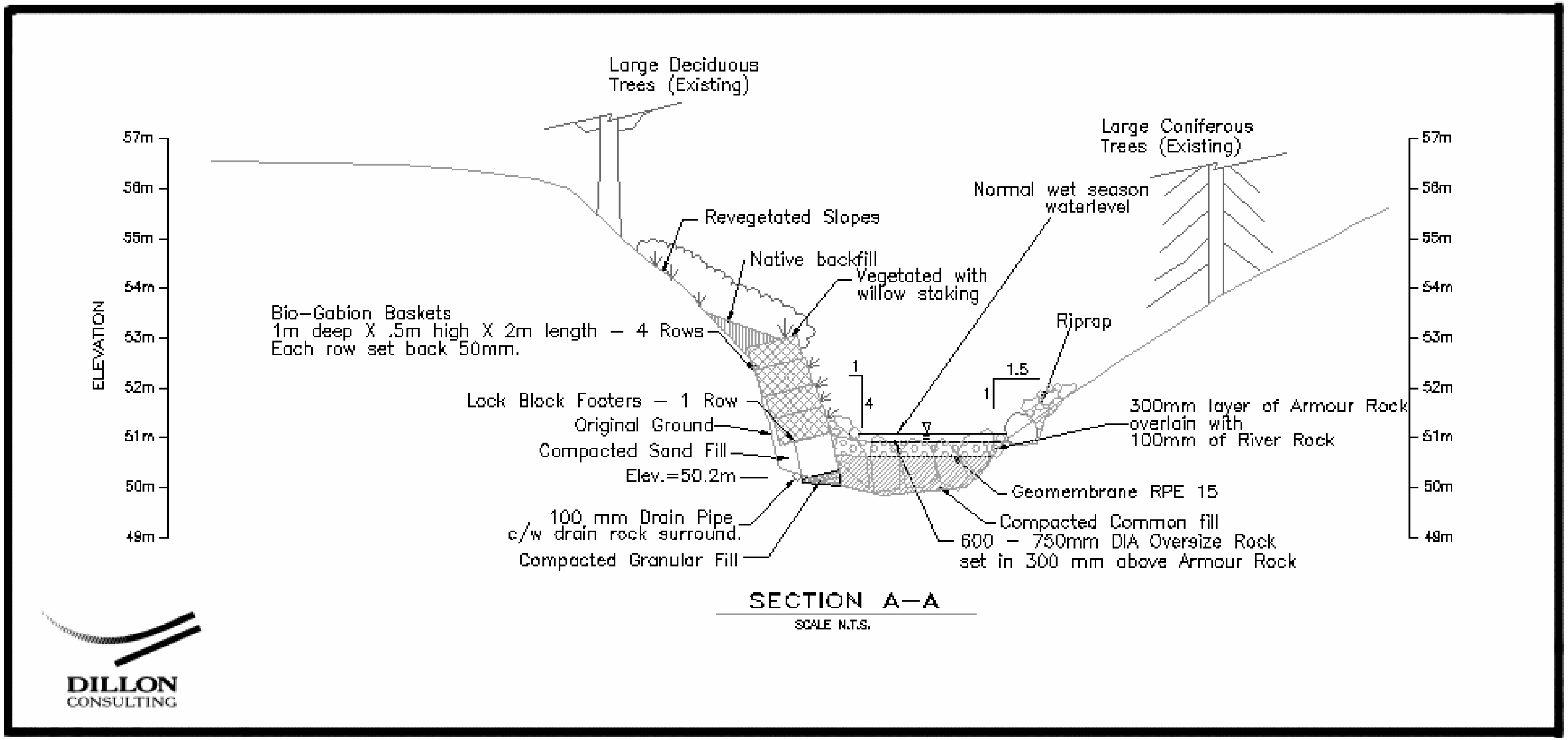
Large Deciduous Trees (Existing)
Large Coniferous Trees (Existing)
57m
56m
55m
54m
53m
52m
51m
50m
49m
ELEVATION
Normal wet season waterlevel
Revegetated Slopes
Native backfill
Vegetated with willow staking
Bio-Gabion Baskets
1m deep X .5m high X 2m length – 4 Rows
Each row set back 50mm.
Riprap
1.5
1
1
4
Lock Block Footers – 1 Row
Original Ground
Compacted Sand Fill
Elev.=50.2m
300mm layer of Armour Rock
overlain with
100mm of River Rock
Geomembrane RPE 15
100 mm Drain Pipe
c/w drain rock surround.
Compacted Common fill
600 – 750mm DIA Oversize Rock
set in 300 mm above Armour Rock
Compacted Granular Fill
SECTION A–A
SCALE N.T.S.
DILLON
CONSULTING

Figure 2.

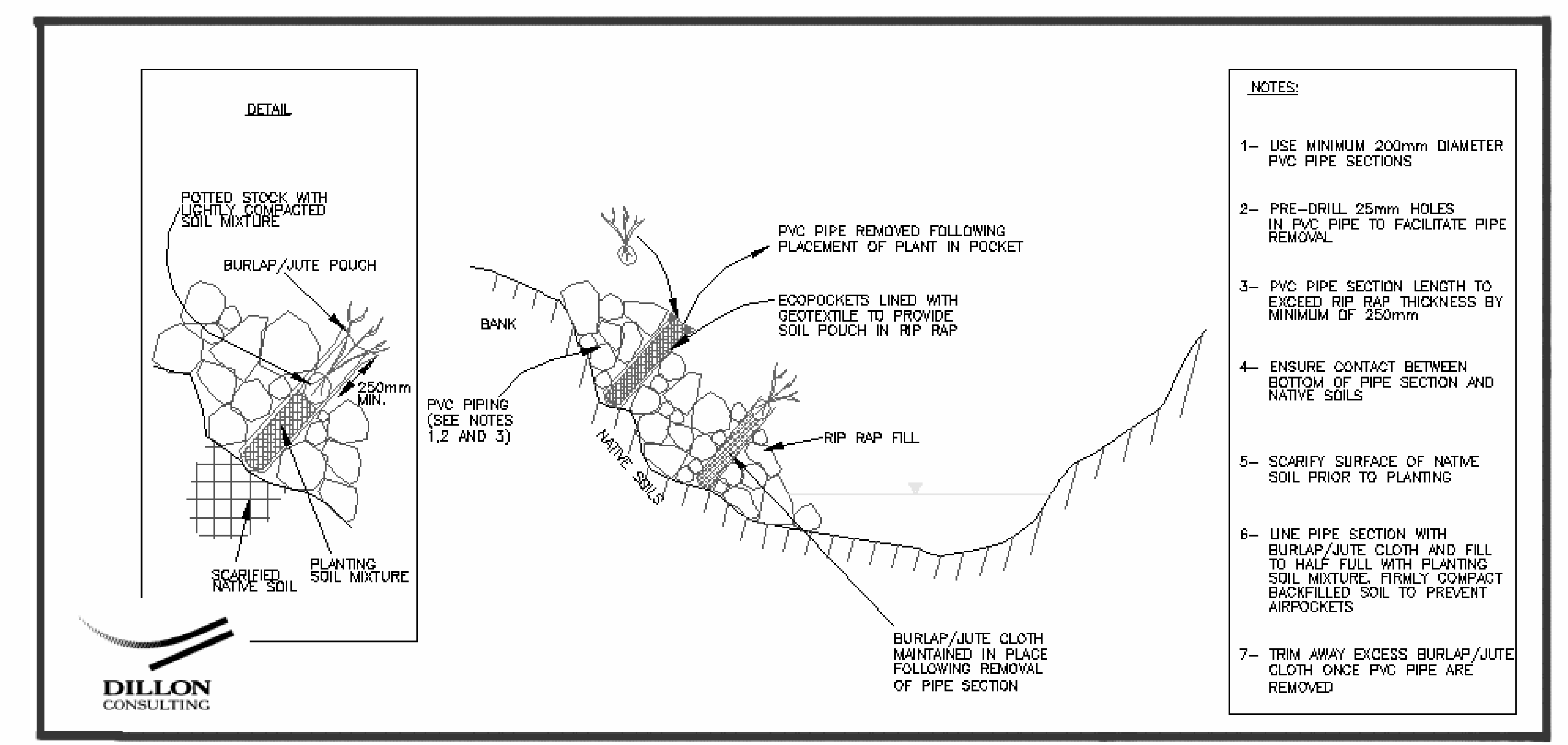
DETAIL
POTTED STOCK WITH LIGHTLY COMPACTED SOIL MIXTURE
BURLAP/JUTE POUCH
250mm MIN.
SCARIFIED NATIVE SOIL
PLANTING SOIL MIXTURE
PVC PIPING (SEE NOTES 1,2 AND 3)
BANK
NATIVE SOILS
PVC PIPE REMOVED FOLLOWING PLACEMENT OF PLANT IN POCKET
ECOPOCKETS LINED WITH GEOTEXTILE TO PROVIDE SOIL POUCH IN RIP RAP
RIP RAP FILL
BURLAP/JUTE CLOTH MAINTAINED IN PLACE FOLLOWING REMOVAL OF PIPE SECTION
NOTES:
1– USE MINIMUM 200mm DIAMETER PVC PIPE SECTIONS
2– PRE–DRILL 25mm HOLES IN PVC PIPE TO FACILITATE PIPE REMOVAL
3– PVC PIPE SECTION LENGTH TO EXCEED RIP RAP THICKNESS BY MINIMUM OF 250mm
4– ENSURE CONTACT BETWEEN BOTTOM OF PIPE SECTION AND NATIVE SOILS
5– SCARIFY SURFACE OF NATIVE SOIL PRIOR TO PLANTING
6– LINE PIPE SECTION WITH BURLAP/JUTE CLOTH AND FILL TO HALF FULL WITH PLANTING SOIL MIXTURE. FIRMLY COMPACT BACKFILLED SOIL TO PREVENT AIRPOCKETS
7– TRIM AWAY EXCESS BURLAP/JUTE CLOTH ONCE PVC PIPE ARE REMOVED
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Figure 3.

Restoration Prescription: Creation of "ecopockets" using lengths of PVC pipe to provide contact with native soils; line pipe section with burlap pouch and fill with soil mixture; place plant in pocket and remove pipe section.

Conclusions

Fish-friendly solutions to stream bank erosion are possible and represent the "confluence" of the engineering and biology "streams" of thinking. These integrated solutions require innovative and non-traditional thinking by representatives of both disciplines. First and foremost, these solutions must respect critical design requirements (e.g., hydrologic, hydraulic, geotechnical) to ensure the protection of the investment in question.

Mitigation of Man-made Barriers to Fish Movement on Blueberry Creek

Harald Manson and Steve Arndt
Columbia Basin Fish and Wildlife Compensation Program

The Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) is a partnership between Hydro, Ministry of Fisheries and Ministry of Environment, Lands and Parks. CBFWCP's mandate is to conserve and enhance fish and wildlife populations affected by BCHydro dam related activities in the Columbia Basin.

This presentation outlines the process and progress of the CBFWCP's attempts to mitigate the impacts of 3 man-made obstructions on Blueberry Creek, a small tributary to the Columbia River located between Castlegar and Trail. CBFWCP's objectives in entering into this project were to facilitate improvement to the passage of adfluvial rainbow trout.

Man-made barriers to fish movement such as dams and improperly designed culverts impact on fish populations in a variety of ways. Impacts may be both positive and negative. An important negative impact of man-made barriers on the tributaries to the main stem of the Columbia River is the exclusion of adfluvial rainbow from potential spawning and nursery habitat. An potential positive impact is that man-made barriers may delay the invasion of non-native species and stocked fish and the possible potential loss of genetic diversity and spread of disease.

Any decision to mitigate a barrier to fish movement must be based upon a thorough analysis of potential impacts (both positive and negative) and cost/benefits. Any decision to proceed with modification to a barrier to fish movement must be approved by MoELP (in the Kootenay Region) and/or DFO in other Regions of BC.

Not all culverts were created equal; factors which affect fish passage include, shape, length, gradient, velocity, bottom material, presence or absence of baffles. Generally, newer culvert designs tend to be more "fish friendly". Each culvert must be looked at in context with the fish community that is, or was originally, present. In assessing the impact of a culvert, it is important to consider: (a) it's location relative to other barriers in the system, (b) the fisheries potential of the upstream habitat which will become accessible and, (c) the potential impact on adjoining waters.

As a, "Small Works Project", CBFWCP was able to offer fisheries technical support, data from past fish and habitat surveys, liaison with MoELP, communications expertise, co-ordination and administrative support plus funding up to $5,000.00. Community input was obtained from area Fish and Game clubs and area residents. We met with the Blueberry Community Water Supply Board and noted their concerns. We encouraged the formation of a "Blueberry Streamkeepers Association", but the attempt was unsuccessful.

Options considered included: status quo, removal of man-made barriers and modification to man-made barriers, e.g. fish ways, baffles, improvement of plunge pools etc. There was broad support to proceed to mitigate all man-made barriers to fish movement by using a sequential approach starting with the lower most barrier. In the short term we decided to use low cost, technique as outlined below. We hope that this low-cost approach will not inadvertently deter more expensive, permanent mitigation efforts, i.e. removal of barriers.

The implementation process had multiple steps; we sought partners, secured funding, obtained engineering designs, surveys, landowner approvals and a permit to work in-stream. A contractor was hired and construction was monitored.. Adequate planning and physical presence during construction, (to ensure conditions of the permit are complied with and to deal with any problems that may emerge), are the most critical steps.

Work completed to date includes;

- raised water level in the plunge pool below the Hwy. 22/CPR culvert to improve fish access into the culvert - fall of 1998
- monitored rainbow trout jumping activity at all three barriers - spring of 1999, see below for results,
- assessed post-freshet condition of rock weirs - summer of 1999
- added rock to reinforce the weirs - fall of 1999
- the Ministry of Transportation and Highways raised the water level in the plunge pool below the abandoned CPR culvert by constructing a series of rock weirs - fall of 1999

Results of the monitoring of rainbow trout jumping activity confirmed that raising the water level in the plunge pool in the fall of 1998 immediately below the Highway 22 Culvert was effective in allowing rainbow trout access into the Highway 22 Culvert. Observations of rainbow trout jumping activity at the next upstream “barrier”, the Railway Culvert showed that a large number of rainbow trout passed through the culvert (Figure 1). It is also evident that a few fish were able to pass through the Railway Culvert since rainbow trout jumping activity was also observed at the next, and final man-made barrier, the Blueberry Creek Community Water Supply Weir.

Partners in this project include, Trail Wildlife Association, Columbia Basin Trust, Columbia Power Corporation, Ministry of Transportation and Highways, Ministry of Environment, Lands and Parks, BCHydro, riparian landowners and volunteers.

Future plans include looking in late summer for signs of bull trout movement or spawning, annual post-freshet assessment and maintenance as required, monitoring of rainbow trout spawning migrations and possibly monitoring productivity and fish community responses and testing of baffles.

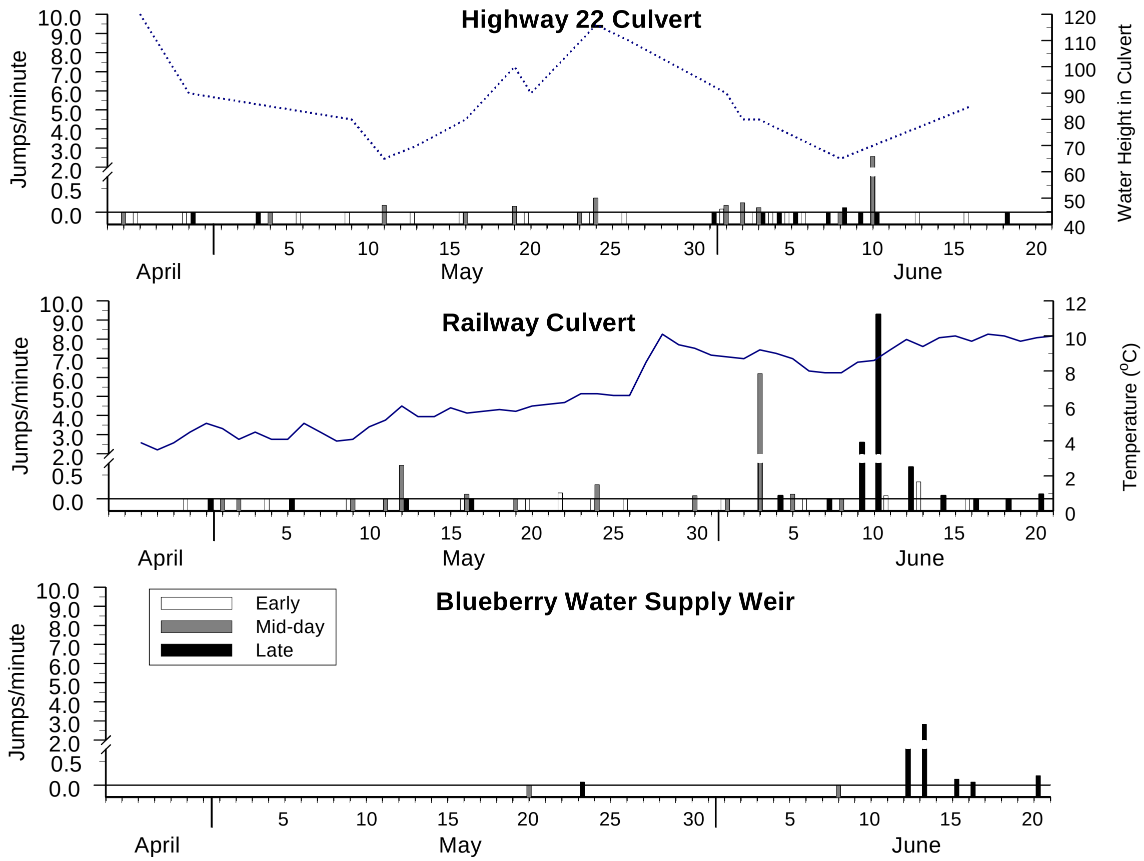

Figure 1. Number of trout jumps/minute (bars) at three man-made obstructions on Blueberry Creek in 1999. If no bar is present for a date, no observations were made. Bar shading indicates time of observation early (before 1130), mid-day (1130 - 1530) and late (after 1530).

Restoration of the Vermilion Wetlands

Charlie Pacas
Parks Canada, Banff National Park

Wetlands occupy a very small portion of Banff National Park and still a smaller proportion of the mountain park block. Despite their scattered distribution and small total area, wetlands contain a disproportionately diverse assemblage of flora and fauna. Human activity has encroached on the Vermilion Wetlands almost since the beginning of the Park. Few areas of the wetlands are free from human development. The cumulative impacts of trails and facilities, railway ballast, roads and highways, berms, weirs, artificial channels, beaver dam management and the close proximity of the Banff townsite, have resulted in habitat alteration and destruction and have compromised natural hydrological patterns. The aquatic emergent zone the highest quality habitat in the wetlands was determined to be the most at risk due to regulation of surface water fluctuations.

The restoration of water levels and flows and natural biodiversity, age and distribution of vegetation in a way that reflects the influence of natural processes while still allowing public use and enjoyment were outlined as strategic goals in the Banff National Park Management Plan.

A recent workshop outlined a framework for restoration, an approach acceptable to a number of stakeholders critical to earlier initiatives. This paper will provide a historical perspective to changes in the Vermilion wetlands, outline the framework developed by stakeholders as well as discuss some of the concerns that restoration (learning by doing or doing by learning) presents.

Soil Bioengineering for Steep / Unstable Slopes and Riparian Restoration

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Abstract

Soil bioengineering is the use of living plant materials to construct some engineered structure or to perform some engineering function. Bioengineering is used to treat steep and / or unstable slopes. Wattle fences, short retaining walls built of living cuttings, have been widely used to treat steep slopes while modified brush layers have been on ravelling slopes to control the movement of surface materials. Wet seepage areas have been treated with live pole drains while live smiles are used where flowing mud is causing slope instability. In all of these cases, the soil bioengineering structures are used to address some form of instability that is preventing natural plant establishment and growth. Riparian areas can be treated with a variety of bioengineering techniques. Live gravel bar staking provides pioneering vegetation on riparian gravel bars, encouraging sediment trapping and bar stabilization. Live bank protection provides hardened banks while enhancing riparian vegetation cover. Live shade provides immediate cover for newly constructed fish channels.

This paper presents a variety of soil bioengineering techniques that can be used for the treatment of problem sites. The benefits of bioengineering, including reduced cost and maintenance are discussed. Examples are drawn from the author's experience.

Introduction

Bioengineering can provide an effective means of treating problem sites. Bioengineering is the use of living plant materials to perform some engineering function, whether it be simple erosion control with grass and legume seeding or more complex slope stabilization with willows and other plants (Schiechtl, 1980). Bioengineering can be used to stabilize steep slopes to treat seepage zones and to control erosion (Gray and Leiser, 1982). Bioengineering can also be used in construction and in riparian restoration.

Bioengineering fits well within the successional reclamation model developed by Polster (1989). Successional reclamation seeks to reintegrate the disturbed site into the natural successional processes that would serve to vegetate the site eventually. By investigating how natural revegetation systems stabilize natural disturbances (Polster and Bell, 1980; Straker, 1996), systems designed to stabilize anthropogenic disturbances can be developed. Bioengineering uses the same pioneering species that are found on naturally disturbed sites. Characteristics of these species such as the ability to root from cuttings, continued growth following burial and the ability to grow under harsh conditions all serve to make these species useful for bioengineering.

The first step in the development of an effective bioengineering program is the identification of those site features, which are limiting growth of vegetation. Five key vegetation limiting features were identified by Polster (1991) steep slopes, adverse texture/compaction, poor nutrient status, adverse chemical properties and soil temperature extremes. Of these, steep slopes, adverse texture/compaction and poor nutrient status are often associated with forest landslides.

By far the most common feature limiting vegetation growth on road and rail corridors is steep slopes. Slopes in excess of the natural angle of repose for the material in question will typically be too steep for effective vegetation growth. For most materials, slopes in the 35 to 40 degree range represent the natural angle of repose. Some materials, such as saturated silts, fail at slopes of less than 10 degrees. Slopes above the natural angle of repose will continually fail and will therefore limit the growth of vegetation while slopes which are at or below the angle of repose will be reasonably stable and will support vegetation growth.

Adverse texture/compaction can significantly hinder vegetation establishment and growth. Soils that are too coarse will not hold moisture or nutrients essential for plant growth. In general, the seedling stage of plant growth is the most sensitive to adverse texture/compaction. A young seedling growing in a pile of boulders at the base of a talus slope will not do well during the hot, dry days of July. However, a mature tree growing in the same boulders may do quite well with its roots well down in the soil below the rubble (Polster and Bell, 1980). Fine textured soils such as compacted silty clay tills can prevent the growth of vegetation by limiting the extent of root penetration. Adverse texture can slow or preclude vegetation growth.

Poor nutrient status associated with many sites can severely limit plant growth. Most sub-soils have very limited nutrients and will not support much in the way of plant growth except species such as alder which are associated with nitrogen fixing bacteria and can thus bring their own nutrients to the site. Salvage and subsequent use of "topsoils" will serve to retain nutrients on the sites. However, even where attempts are made to retain topsoils for use in reclamation, soil mixing and loss of structure can result in nutrient deficient sites.

Plant growth may be limited by a combination of these factors. A 40^{o} loose shale slope with no fine textured soils may limit plant growth by continually ravelling and sliding as well as by becoming very dry in the summer. Similarly, a calcareous silty clay slope which is continually "flowing" in the spring may limit vegetation growth both by the movement and by the lack of nutrients associated with the high pH. In these cases it is essential that all of the growth limiting factors be addressed.

Bioengineering systems can be used to "treat" many of the growth limiting factors. Treatments can be designed to effectively reduce slope angles relative to the growth of vegetation without actually changing the overall slope. Similarly, bioengineering techniques can be used to drain excess moisture that may be creating slope instability. Bioengineering techniques can also be used to control erosion along watercourses and to prevent ravelling of angle of repose fill slopes. Some bioengineering techniques can be used to reinforce earth fills and thus provide a cohesive mass that resists movement. This paper explores the use of bioengineering systems for site restoration.

Plant materials for Bioengineering

Pioneering woody species are of particular importance in the development of bioengineering systems. This group of plants represents the successional bridge between the herbaceous initial colonizers (seeded grasses and legumes) of a disturbed site and later seral types and thus plays a key role in successional advancement of the site. Pioneering woody species perform important functions in the natural restoration of damaged sites such as stabilization, erosion protection and as wildlife browse. Pioneering woody species are often associated with rhyzobia, which fix nitrogen, and thus they serve to improve the nutritional status of a site (Binkley et al. 1982).

Stem cuttings of many species (Table 1) can be used for bioengineering although willows, red-osier dogwood and cottonwood are most effective. Cuttings should be collected while the plant is dormant. Cutting woody vegetation in the fall and winter results in the maximum amount of growth. At this time of year, carbohydrate (stored photosynthates) are at their highest level in the plants. This allows the cutting to provide fresh growth in the spring without the benefit of further photosynthesis. Cutting woody plant stems in the fall and winter allows all of this stored energy to be expended in the growth of new roots and shoots during the spring and early summer.

TABLE 1
Some Useful Characteristics of Pioneering Woody Species

Species	*Seed Numbers/Kg. (X 1,000)*	*Site Preferences (N Fixing)*	*Establishment*
Sitka Alder	2,514	mesic - moist N fixing	from seed, not cuttings
Red Alder	1,468	mesic - moist N fixing	from seed, not cuttings
Red-osier Dogwood	30 - 58	moist, riparian	from seed, cuttings & rooted stock
Wolf Willow	7.5	dry, well drained N fixing	from seed & stem cuttings
Cottonwood	6,684 *	moist to wet	from seed & cuttings
Aspen	7,936	mesic to dry	from seed & root cuttings
Willow .	4,400 - 6,600	mesic - moist - wet	from cuttings

* Seed number for the related *P. grandidentata.*

New roots and shoots on the cuttings develop either from buds, which developed in the axils of the leaves (axillary buds), or from other tissues in a process termed dedifferentiation. Buds arising from these are termed "adventitious" buds (Hartmann and Kester, 1975). Axillary buds result in the growth of new shoots and roots from sites where there were leaves on the plant in the past. Adventitious buds result in the growth of new shoots and roots from either axillary locations or from other areas on the plant such as the cut end of the cutting. The growth of shoots, that develop, from axillary buds can be maximized by maximizing the number of such buds on the cutting. The encouragement of adventitious bud formation can be enhanced in some cases by wounding the stem. Callus typically forms when plants have been wounded (cut), and may develop from the vascular cambium (just under the bark) or even the epidermal tissues. Although adventitious roots often appear to arise from under this callus tissue, the formation of callus and the formation of roots are generally independent (Hartmann and Kester, 1975). Adventitious buds may therefore form at any location where these tissues are present. In some species, such as willows, which are very easy to root and widely used for bioengineering, preformed (latent) bud initials are formed as the stem develops initially. These species have a variety of adaptations, which allow them to function well in bioengineering systems. The presence of preformed bud initials is one such adaptation, and allows these plants to regrow effectively from cuttings and after being buried.

Scheduling of bioengineering projects where cuttings are to be used to coincide with optimal collection periods allows the cuttings to be planted directly after collection, thus avoiding problems associated with storage of the cuttings. If cuttings are to be stored, they should be kept moist and at temperatures which minimize respiration (-1^{o} to -4^{o}C). Willow cuttings collected in February were successfully stored in a commercial cold storage unit and used at the end of June, well after the local flora had flushed (Polster, 1992). Cuttings, which are to be stored or transported for any significant distance, should be left in as long pieces as possible. This will minimize moisture loss through cut surfaces. Similarly, small branches and twigs should be trimmed so that the stems can be easily handled. Where a significant number of cuttings are to be collected, it is suggested that the highest quality clippers available be obtained for use as the cost of these will be offset by improved productivity and reduced fatigue.

Cuttings, which are collected from healthy, moderately rapidly growing parent plants, will perform better than those collected from decadent, senescent stems although the tips of stems should be avoided. Marchant and Sherlock (1984) report that cutting material with a low nitrogen / high carbohydrate reserve will root better than "exceptionally vigorous, "sappy" wood. Where significant amounts of bioengineering work is to be conducted in an area over several years, hedging of parent plants can provide cutting stock. In many cases, local power lines and logging sites will provide an abundance of healthy pioneering woody plants, which can be used, for cuttings. Willows, for instance, may be found growing on the side cast side of roadways and on skid trails where mineral soils have been exposed. Powerline, pipeline, railroad and road rights-of-way often provide ideal sites for the collection cuttings as the vegetation in these areas is often maintained in an early seral state. Permission from the landowner must be obtained prior to collecting cuttings from any site. In the case of Crown Land, local Ministry of Forests officers can provide advice on appropriate locations for the collection of cuttings. Care must be taken in the collection of cuttings to avoid environmentally sensitive sites such as stream banks or areas of heavy ungulate use.

Direct planting of root cuttings may be used for the establishment some species. Although the collection and use of root cuttings is significantly more difficult than using stem cuttings, there are cases (e.g. Aspen) where root cuttings provide the best results and stem cuttings are not effective. As with stem cuttings, healthy, moderately rapidly growing roots that are one half to one centimetre in diameter will work best. These should be collected during the dormant period of the parent plant when the parent plant has stored food reserves contained in the roots. Collections should be made well before any flushing of the parent plant in the spring. Collection of root cuttings during clearing operations can provide an efficient means of collecting large quantities of suitable roots. Cuttings should be 5 to 15 cm long and at least 0.25 cm in diameter. Root cuttings must be planted with the proximal end (end towards the parent plant) up, or horizontally. Root cuttings should be planted 2.5 to 7.5 cm deep. As it may be difficult to determine the proximal and distal ends of a root cutting, having one end with a straight cut while the other end is cut on a slant, keeping in mind which is which will assist in determining the proximal and distal ends of the cutting. Root cuttings should be kept moist and planted at the restoration site as soon as weather conditions allow.

Bioengineering systems for water management

Live Pole Drains

Live pole drains (Figure 1) are constructed of bundles of living cuttings and are used to provide stability to sites where excess soil moisture results in soil instabilities. The bundles of cuttings are placed in shallow trenches in such a manner that they intersect and collect the moisture. The bundles are then lightly buried with local materials, leaving some of the cuttings unburied on the top. Careful trimming of the cuttings is not required, although the bundles should be as tight as possible. The bundles should be a minimum of 30 cm in diameter. The plants (typically willows) used to form the bundles sprout and grow, with the moisture continuing to drain from the lower end. Sites where excess soil moisture results in site instability can be treated with live pole drains. Traditional engineering solutions often entail the installation of "French drains" or loading the face of the slope with rock. However, live pole drains can be used to drain excess moisture from the site and provide a cover of woody vegetation. The growth from the live pole drains forms the initial cover on the seepage site, allowing other species to invade. As with other bioengineering systems, live pole drains must be designed to suit the specific conditions of the site.

A variety of different shapes can be used for the drains depending on the site conditions. A "Y" pattern of the drains can be used to collect moisture from a diffuse seepage zone while a linear pattern can be used where a discrete seepage site exists. The objective in design of the drains is to collect all of the moisture and to get it to drain away as quickly as possible. The drains grow into a dense stand of hydrophytic vegetation, which is exactly what nature would produce given enough time. Thus this technique fits into the successional reclamation scheme far better than conventional "French" drains would. In addition, live pole drains can be installed without machine access and at fraction of the cost of traditional hard engineering solutions. Soil slumps such as those which occur the first spring after road resloping operations can be stabilized using live pole drains.

Figure 1. Live pole drains can be used to stabilize slumping soils. This view shows the layout of live pole drains in a slump with the covering soils removed for clarity. The section shows a typical covering. Some twigs from the bundles should be left above ground.

Live Silt Fences

Live silt fences (Figure 2) are used to reduce sediment movement on low gradient streams. Where live gully breaks can be used on very steep gullies and streams, and live bank protection can be used on larger streams and rivers, live silt fences are used on smaller streams with lower gradients. The live silt fences are simply rows of cuttings stuck into the streambed to slow water velocities and cause sediments to be deposited. The rows of cuttings also serve to trap floating debris that further slows water velocities. Once the cuttings grow, the water flows between the stems of the growing cuttings, creating a brushy, swampy area characteristic of natural seepage areas and small streams.

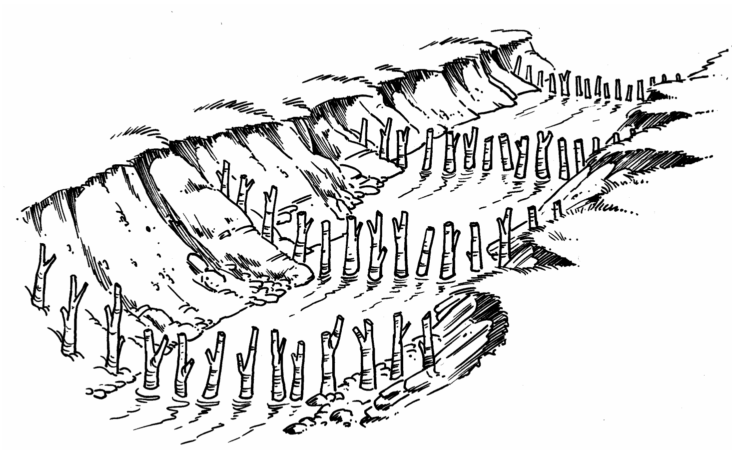

Figure 2. Live silt fences can be used to provide a willow coppice in small streams and ditches. They act by slowing the velocity of the water and allowing sediments to settle out. The cuttings can be either in single rows (as shown) or multiple rows in each band.

Willow and cottonwood cuttings are particularly useful for live silt fences, as these species will continue to grow when their stems are buried. Live silt fences can be established in swales and small drainage channels along roads and in gullies on deactivated roads. These will assist in restoring the sites so that rather than continuing to erode, these small channels can act as sediment traps and provide clean water to downstream sites. The natural filtering ability of deciduous brushland can be recreated using live silt fences on the small drainages and seepages on forest lands. Care must be taken to ensure the hydraulic integrity of the drainage system when live silt fences are used.

Live Bank Protection

Live bank protection (Figure 3) provides a means of stabilizing stream sides which may have become destabilized by debris torrents or through the growth of nick points related to harvesting. Live bank protection can be very useful in stabilizing roadside ditches and culvert inlets and outfalls. By providing living plant materials in these locations, damage which might result from high flows can be avoided and maintenance reduced. Live bank protection structures are wattle fences (see below) built to protect the bank from the scouring action of streams. The typical arrangement for live bank protection provides the structure on the bends of the stream where undercutting is occurring or may develop. The structures are arranged so that the upstream ends are located at the tangent point between opposing curves. The ends should be tucked well into the bank to avoid "catching" the flow and causing more erosion. The structures are backfilled with local materials, taking care to avoid large cobbles and boulders which will tend to be dry in the summer.

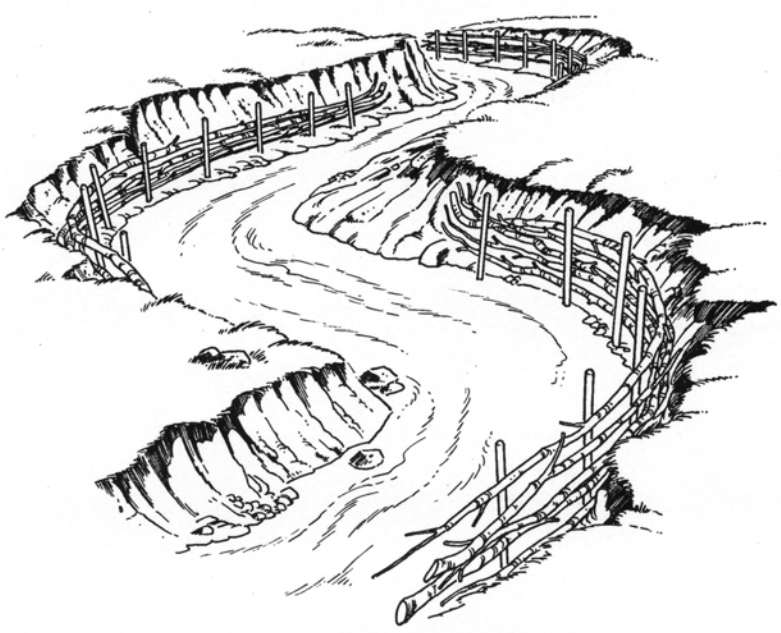

Figure 3. Live bank protection can be used to control erosion on the outside of curves. The backfill has been removed in these drawings for clarity. Typically, the undercut bank would be resloped to backfill be structures. Live bank protection can be used where the stream has eroded the materials down to bedrock (above) or where unconsolidated materials are still present (below). Backfill is shown in these sections and the undercut banks have been resloped.

Growth of the live bank protection structures provides a cover of riparian vegetation along the streams. The willows and cottonwoods used in the structures provide a strong network of roots which help to hold the stream bank in place. Stabilization of the stream bank reduces the amount of material moving with the water and therefore reduces the erosive power of the water. In addition, live bank protection systems can be used where streams are cutting the toe of steep banks which feed material to the creek. By doing so, the live bank protection systems can reduce the amount of sediment moved from the site and can stabilize the oversteepened bank. Live bank protection systems work best where fine textured soils are being eroded. These can be effectively protected using live bank protection systems.

Live Gully Breaks

Live gully breaks (Figure 4) are large wattle fences (see below) built in gullies to control the initiation of torrenting and the flow of water. Where gully torrents originate from minor collapses of gully sidewalls, live gully breaks can assist in reducing the potential for torrents to initiate. Live gully breaks act by controlling the initiation of torrents rather than attempting to control the torrent once it gets moving. As this is the case, the live gully breaks must be established high in the channel where torrents are initiated. Live gully breaks can be helpful in the revegetation and stabilization of gullies which have already torrented by providing sites where materials may be trapped and where vegetation can become established. As with any bioengineering system, live gully breaks will strengthen with age.

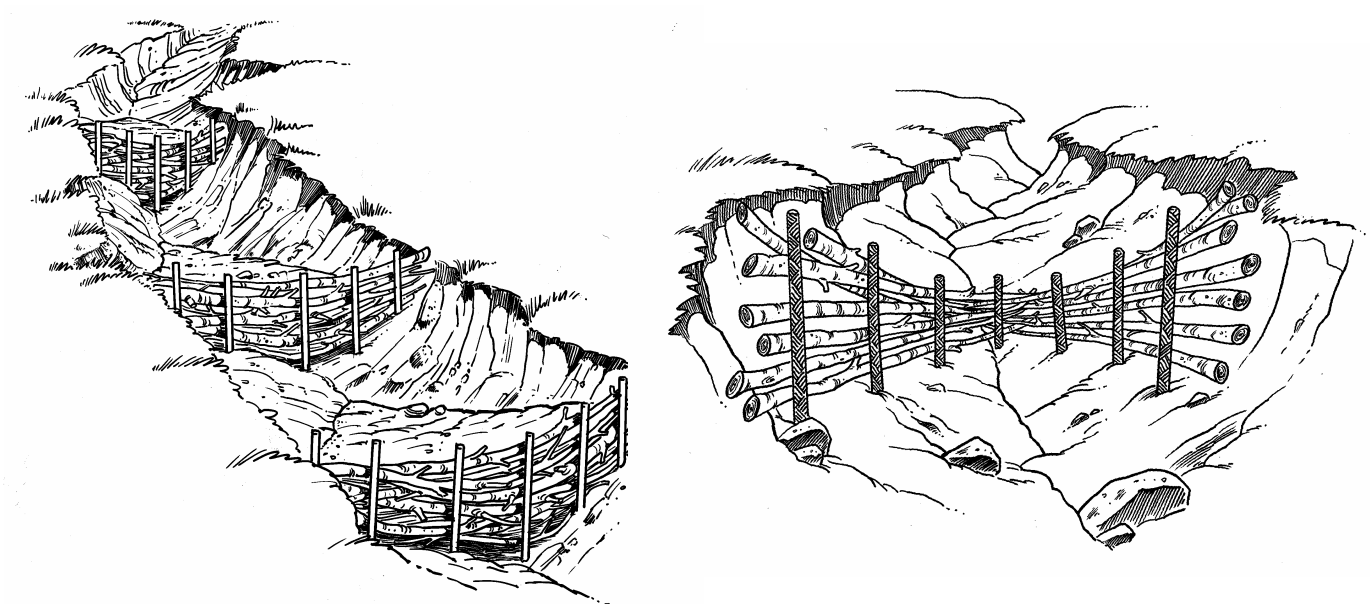

Figure 4. Live gully breaks act to slow the velocity of water movement down a gully and thus to trap sediments. In narrow gullies (right) the cuttings are crossed at the back of the gully (backfill removed for clarity) while in wider gullies (left) the structure is like a wattle fence.

Live gully breaks can be used in ditches and drainages to reduce flow velocities and to provide control of water movement. Working from the bottom, the breaks are established at intervals up the ditch or gully. Spacing of the live gully breaks depends on the steepness of the channel but ranges from 5 to 10 m between the structures. Rebar stakes are driven into the gully to form a crescent on the contour, with the outer ends slightly higher than the stakes near the centreline of the gully. Cuttings (willows should be used) are then established behind the stakes. For tight gullies, the cuttings may need to butt into the opposite side wall, forming an overlapping lattice while on wider gullies, the cuttings may be bent around the inside of the gully. The centre of the live gully break should be lower than the wings to prevent water from flowing out along the wings and creating a problem. The gully breaks may be backfilled with local materials. In some cases, it is useful to provide a rock drain in the centre of the gully break to allow water to flow through, although care must be taken to provide fine textured materials for most of the backfilling. Backfilling should create a small terrace in the gully that will trap additional materials.

Live gully breaks will act to trap materials, that would otherwise serve to initiate a debris torrent or contribute sediment to streams. The physical structure of the live gully breaks will serve this purpose initially while the growth of the cuttings and the establishment of rows of willows will provide long term control of materials. Willows will continue to grow even when deeply buried and will reinforce the soil through the growth of roots. Roots from the willows used in the live gully breaks will provide substantial reinforcement of the soils. Root tensile strengths of birch (expected to be similar to willow) have been measured to be 464 kg/cm^2 for root sizes less than 2 mm while spruce - hemlock roots were found to have a strength of 102 kg/cm^2 for root sizes less than 2 mm. Coastal Douglas fir roots were found to have a tensile strength of 578 kg/cm^2 for root sizes less than 2 mm ^{2}. The root strength of the rapidly growing pioneering species used in bioengineering can replace, in part, that lost due to harvesting activities. Live gully blocks act by creating numerous small structures in the ditches or high on the slopes rather than creating massive engineered structures to trap debris down below. Many bioengineering systems use this strength in numbers concept to create some very stable, strong stabilization systems. Live gully breaks can provide effective control of sediment at or near the source.

Live Staking

Live staking (Figure 5) is perhaps the simplest form of bioengineering. Live staking is simply the use of living cuttings to stabilize slumping materials or to "pin" sods to a slope. Live staking is particularly useful in silty materials which tend to flow down the slope in the spring. In these cases, the cuttings are inserted into the soft materials in the spring and as the cuttings grow over the summer, the roots serve to bind the unstable materials and to prevent further flows.

The cuttings used in live staking should be inserted into the soil so that at least three-quarters of the length of the cutting is underground. On drier sites, seven-eighths of the cutting should be inserted. Cuttings need not be planted vertically (as shown) but can be slipped into the soil diagonally, as long as the cutting will remain moist over most of its length. Cuttings should be planted with the distal (top) end up. It may be useful to leave short stubs of branches on the cutting (as shown) so that the top of the cutting will be known when the cutting is planted. The spacing between cuttings will vary depending on the materials, but can be as little as 10 cm. On flowing silts, spacing of about 20 cm work well.

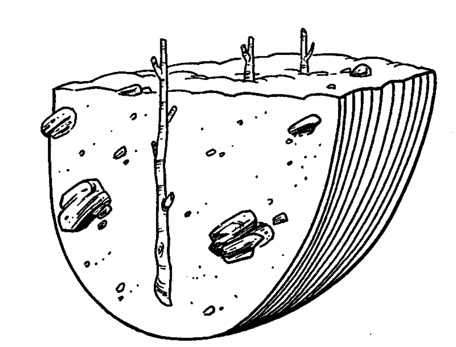

Figure 5. Live staking is a simple method of establishing pioneering woody vegetation. It can be effectively used on "flowing" silts and to establish riparian vegetation along streams.

BIOENGINEERING SYSTEMS FOR STEEP SLOPES

Wattle Fences

Wattle fences (Figure 6) are short retaining walls built of living cuttings. These walls take up the vertical component of the slope, reducing the effective slope angle and allowing vegetation to become established. In addition, the living cuttings used to make the walls sprout and grow, thus further strengthening the structure. Wattle fences are used where site moisture conditions will allow the living cuttings on the face of the fence to sprout and grow. Sites where fine textured soils can provide ample summer moisture or where seepage of groundwater provides moisture are suitable for wattle fence installations.

Wattle fences provide breaks in the slope and can therefore reduce the impact of rolling materials on vegetation growing lower on the slopes. In many cases, vegetation will have difficulty in becoming established where materials from above are constantly bombarding it. Wattle fences can protect vegetation growing lower on the slope and can assist in the revegetation of the sites through protection from rolling rocks and sliding debris. Wattle fences are used to reduce the effective slope of oversteepened areas. They are most effective where moisture is plentiful and where the cuttings used to construct the fences will not dry out. In this regard, backfilling the fences with fine texture materials will assist in providing moisture during dry summer periods. The first year of fence growth is the most critical as it is at this time that the cuttings may show significant amounts of shoot growth with little supporting root growth. This may cause summer desiccation. Pruning excessive shoot growth can help to balance root to shoot ratios. Willows can continue to grow when buried and therefore provide a good plant material for wattle fences where falling materials are expected to bury vegetation growing lower on the slopes.

Wattle fences can provide support for oversteepened cut and fill slopes and for small soil slumps where excess soil moisture results in small rotational failures of surface materials. In the case of slumping sites, the wattle fences allow moisture to drain through the face of the fence while the soils are retained behind the fence. Where slumps are particularly soupy, the branches and twigs may be retained on the cuttings to provide additional support of the wet soils. Wattle fences can be used in combination with live pole drains (see above) to support the slumps while the live pole drains provide drainage of the excess moisture.

Wattle fences are constructed by establishing the supporting rebar or cuttings in a row in the ground and placing the cuttings behind these supports. Soil materials are then backfilled behind the cuttings and additional cuttings are added with additional backfill to increase the height of the fence. Resloping behind the fence should be conducted to create a slope of about 2 : 1 or less between the top of the fence and the bottom of the fence above. Wattle fences are constructed from the bottom of the slope up the slope so workers may have a place to stand while additional fences are constructed.

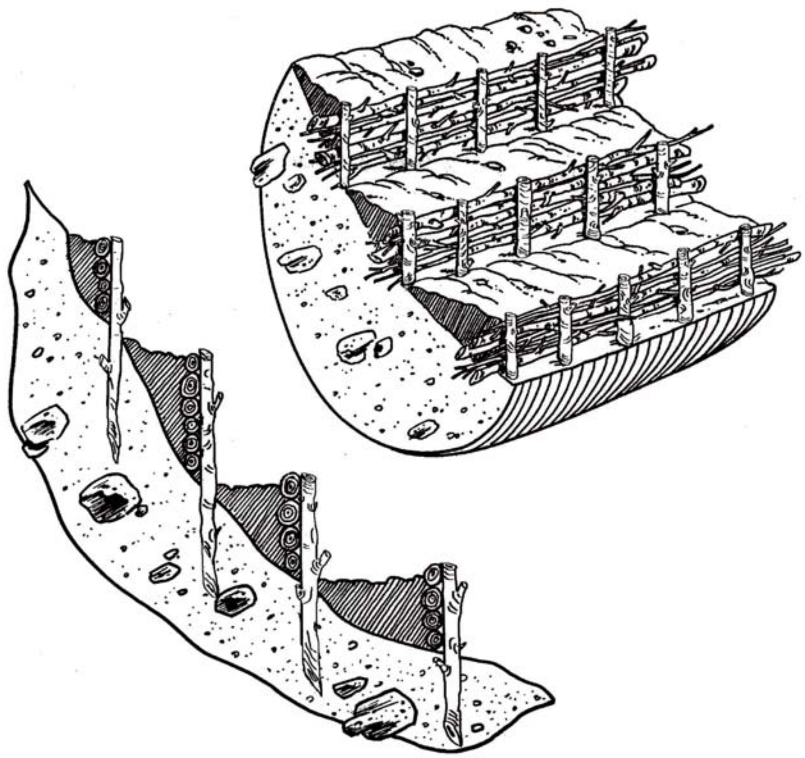

Figure 6. Wattle fences are short retaining walls constructed of living cuttings. They are used to provide slopes, which will support plant growth where oversteepened slopes are preventing plant establishment. The section shows the effects of steeper slopes on wattle fence spacing.

Modified Brush Layers

Modified brush layers (Figure 7) are essentially a brush layer (see below) supported on a short, small log or board. The use of a log or board for support of the brush layer provides the initial added advantage that the small terrace which is created can serve to "catch" rolling rocks rather than allowing them to roll down the slope, gathering speed and damaging vegetation. Although the log or board will eventually rot, the cuttings will, by that time, have grown to the point where they are stabilizing the slope. As the cuttings that are used in the brush layer grow, the wall of plants will also serve to trap rocks and soil and prevent movement of materials down the slope, thus further protecting vegetation on the slopes. Modified brush layers can be used on sites that would be too dry for effective wattle fence growth but where some form of additional support is needed for stabilization of the slopes.

Logs or boards approximately 2 m in length are used for the modified brush layers. This allows a large number of modified brush layers to be established on the slope rather than one or several long ones. This has the advantage of providing separate, independent structures so that if a very large rock comes down and destroys one of the modified brush layers, there are still others to do the work. Many bioengineering systems use this "strength in numbers" concept.

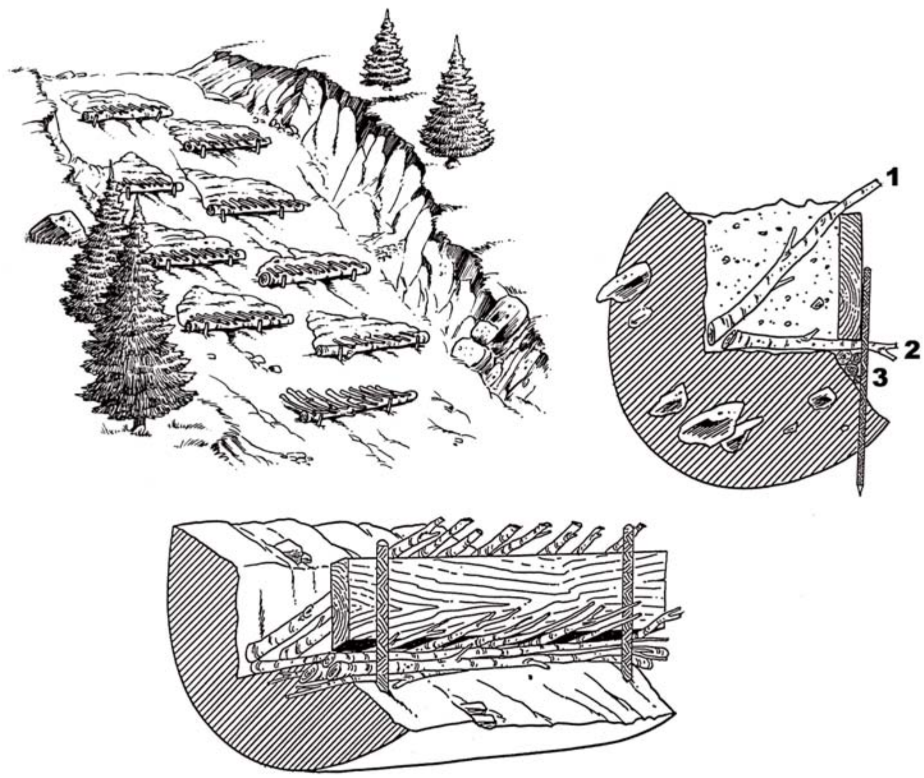

Figure 7. Modified brush layers can be built with either a log or a board for support. They should be staggered across a slope so that material rolling down the slope doesn't have a chance to get going before it is caught. The detail shows a modified brush layer prior to backfilling, while the section shows the normal backfill which creates a bit of a bench. Cutting position 1 is the normal position while position 2 shows how the cuttings should be placed when the site is very dry and position 3 shows the placement of cuttings where a drain is needed below the structure.

Reinforcing steel bar (rebar) or live stakes can be used to hold the modified brush layers in place. One metre long rebar has been found to be best for support of the modified brush layers. The modified brush layers are constructed by initially establishing the rebar in the ground. The log or board is then placed above the rebar on the slope, and partially back filled with fine textured material behind the log or board. This creates an initial bench. The cuttings are then placed on the bench and backfill is pulled down to cover the cuttings. The cuttings should stick out past the edge of the log or board about 5 cm. Like wattle fences, modified brush layers should be built from the bottom of the slopes to the tops thus providing places for the workers to stand as they construct additional structures. Modified brush layers can be very useful in the control of ravelling from a road cut slope. The bench created initially serves to trap rolling materials while the growth of the cuttings eventually forms a wall of living plant materials. Modified brush layers can also be effective in the stabilization of sliver fills and ravelling fill slopes.

Brush Layers in a Cut

Brush layers in a cut (Figure 8) are horizontal rows of cuttings (40 to 50 cm long) buried in the cut (in-situ materials) slope. In cuts or native ground, brush layers are constructed by digging a trench across the slope and laying in the cuttings. The cuttings should have at least three-quarters of their length in the ground and if the site is dry, seven-eighths of the cuttings should be in the slope. Brush layers in a cut are built from the bottom of the slope so that the second trench excavation can be used to backfill the first and so on up the slope. Brush layers in cuts add little to the stability of the cut as no significant bench is created by the brush layer as in a modified brush layer and the cuttings are not deep enough to provide substantial mechanical stability as in brush layer in fill. The wall of plant materials can act to control movement of materials from the slopes and can assist in maintenance of a rod where falling materials are a problem. Modified brush layers (see above) are easier to build and provide more immediate stabilization than brush layers in a cut.

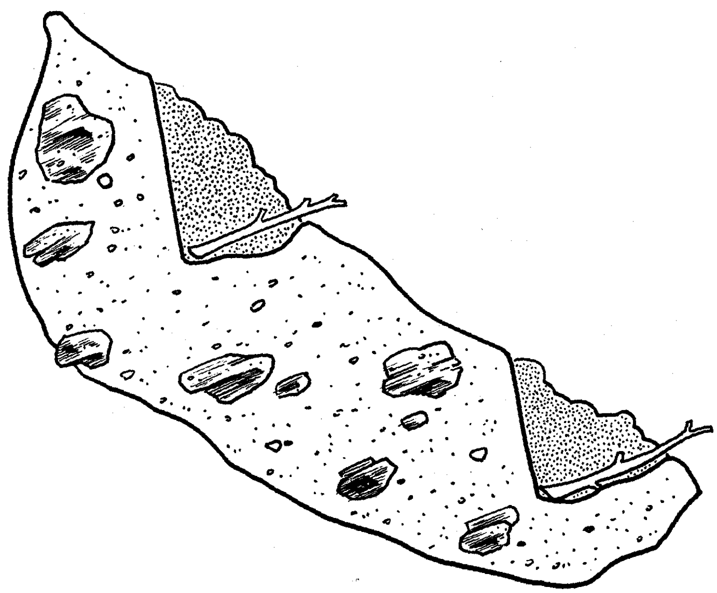

Figure 8. Brush layers in a cut can provide a row of living plant materials and assist in preventing movement of surface materials.

BIOENGINEERING SYSTEMS FOR SOIL REINFORCEMENT

Brush Layers in Fill

Brush layers in fill (Figure 9) are also horizontal rows of cuttings buried in a fill such as a pulled back road. Brush layers in fills are particularly useful where new roads are being built or where roads are being deactivated. In either case, brush layers can be used to strengthen the fill material. In some cases, fill materials must be placed on steep (1.5 : 1 or greater) angles due to the geometry of the site. In these cases, cuttings (1.5 to 3 m long) can be inserted into the fills as they are constructed and can assist in creating a cohesive mass from the fill material. The cuttings can act like the bands placed in a reinforced earth structure and can give significant mechanical strength to the fill even before they start to grow. As the living cuttings sprout and take root, this strength increases. The development of brush layers in fills may be particularly useful in situations where local oversteepening of the fill is required and incorporation of brush would be useful. Sites such as where gullies cross roads that are being deactivated are candidates for incorporation of brush layers in the pulled back fill. In these cases, the brush layers will provide stability to the fill and will eventually result in the development of shrubby vegetation along the gully. Scheduling requirements for the use of cuttings (see above) may dictate that machine work be organized for these sites at times when cuttings can be used.

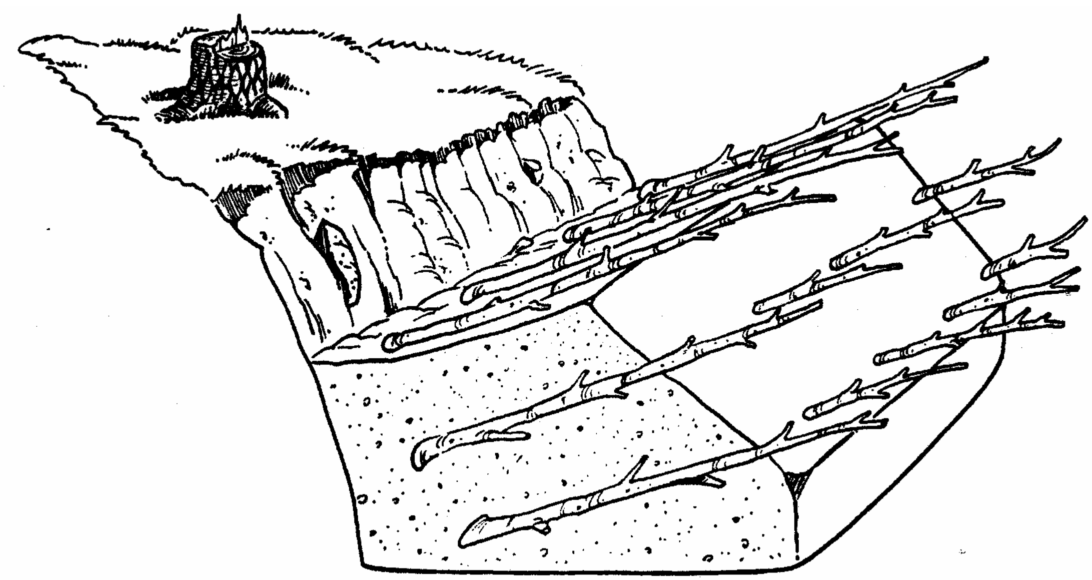

Figure 9. Brush layers in fill can act to reinforce the fill material. Full length cuttings can be used and can be expected to root along their entire length.

Live Reinforced Earth Walls (LaREWs)

Live reinforced earth walls have been developed to treat sites where piping or waterfalls have created a large cavity in the slope that must be re-filled to stabilize the slope. Traditionally, such sites would be backfilled with rock. However, the cost and in some cases, the lack of access requires that a different technique be developed. The large amount of fill required to treat these sites and the inability to effectively compact the fill would result in a slope that could easily fail again. In some cases, water flowing over a harder material (e.g. compacted till) may cut a large overhang when it hits a softer material (e.g. fine silts). Without effective stabilization, such a stream would continue to cut until the slope above collapsed and the process was repeated.

The use of traditional wattle fences for large undercut sites results in too much weight on the fences and the failure of the entire backfill. Most other options for such sites entail hard engineering and associated large costs. LaREWs, based on the traditional mechanically stabilized earth wall, provide a simple alternative to these hard engineering solutions. Figure 10 shows the current design for LaREWs.

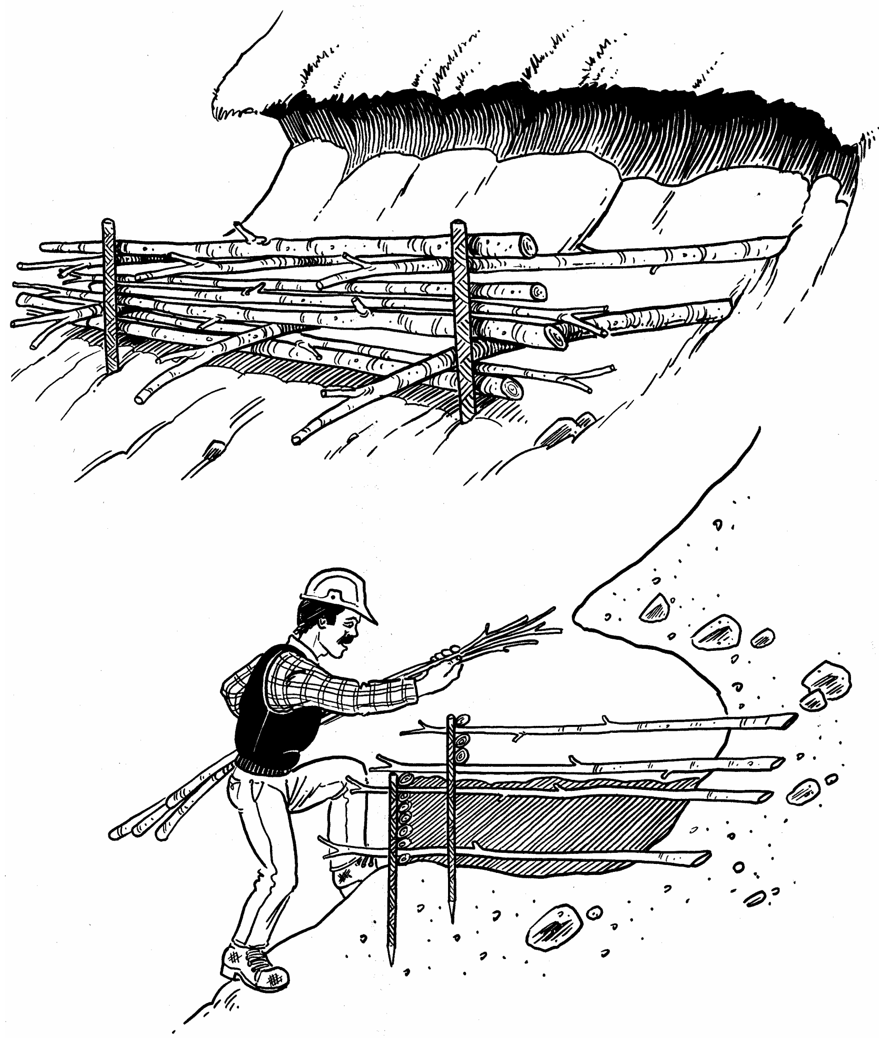

Figure 10. Live reinforced earth walls are constructed with a wattle fence on the face and long cuttings going back into the slope to hold the face in place. Re-sloping the overhang provides the backfill while the LaREW provides a vegetated cover on the undercut area.

Live Smiles

Live smiles have been developed to treat sites where flowing mud prevents growth of vegetation. Fine silty lacustrine or morainal deposits can experience surface flows during spring break-up with the underlying materials remaining firm. When covered by forest vegetation these sites will remain in place. However, if this material is exposed in a cut, for instance, weathering of the surface leads to surface flows, eventually expanding until a change of material is encountered. Typically, however, only the surface 10 cm or 15 cm actually flows, but when the surface covers several hectares, a large quantity of saturated material can end up at the bottom of the slope.

Wattle fence like structures have advantages in that they allow moisture to drain from the face of the fence while holding the solids back. A willow cuttings is very strong in tension, therefore a structure where the plant materials are placed in tension would use this attribute of the materials. The idea of "suspending" the mud with the willows would use the willows in tension. A catenary curve (Golden Gate Bridge) would put the willows in tension. Live smiles are designed to form a catenary curve. The ends of the curve must be firmly secured (Figure 11).

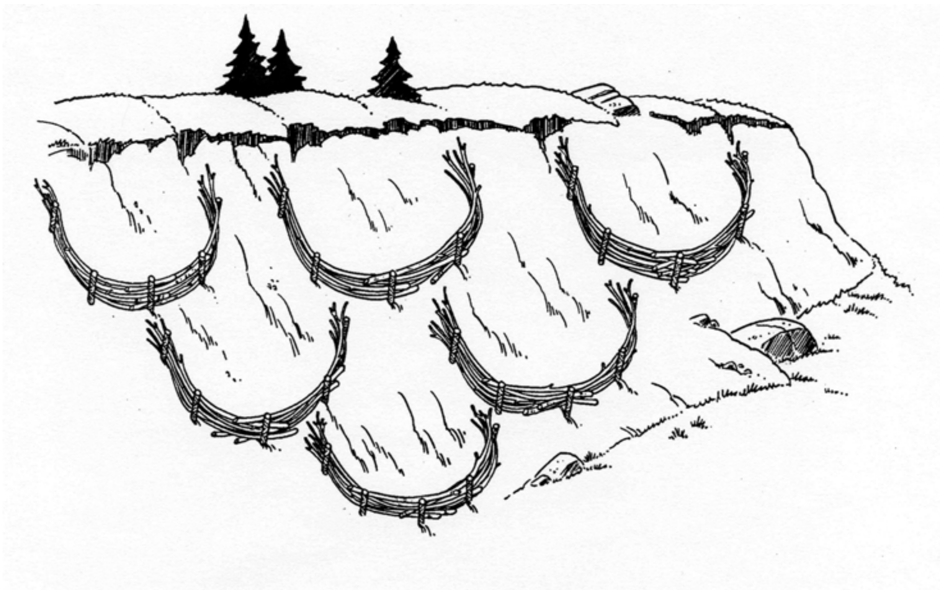

Figure 11. Live smiles have been designed to "suspend" flowing mud on the slope. They use a catenary curve much like a suspension bridge. With good anchors at the top ends, the cuttings are placed in tension. Live smiles are arranged in staggered rows of individual units. This uses the "strength in numbers" concept to create a strongly supported slope. The live smiles allow water to pass through the face, holding the mud back.

BIOENGINEERING SYSTEMS FOR RIPARIAN RESTORATION

Live Gravel Bar Staking

Live gravel bar staking was developed in response to a need to treat streams and rivers where upslope landslides and erosion had resulted in significant sand and gravel deposits in the channel. These deposits then result in streambed de-stabilization as the watercourse re-works alluvial deposits that had been inactive since glaciation. In some extreme cases, the de-stabilized stream channel goes from a stable single channel with significant fish habitat complexity to a braided channel with little or no habitat diversity.

Traditional treatments including physically digging out the channel and rip-rapping the banks are normally only carried out in situations where the excess sand and gravel threatens to cause a destruction of property (usually bridges or roads). Digging out the channel and rip-rapping the banks, however, often causes decreased stability as the stream fills in the void where the gravel was removed or "headwalls". Sometimes structures such as rock weirs or large woody debris are used in an attempt to capture some of the gravel. These structures tend to get overwhelmed by the massive amounts of gravel that may move in a system in a single year. In all of these traditional treatments, a significant investment must be made both initially and for many years after.

The primary problem with most sand and gravel bars is that the upper 30 cm or 40 cm gets very dry in the summer as the free draining substrate bakes in the summer sun. For little seedlings this is often the period of greatest stress. However, by using cuttings and getting them down to the water table or at least well into the gravel (Figure 12), growth is assured. The clumps of cuttings mimic natural clumps of woody vegetation, trapping driftwood and creating a flow disruption that causes sand and gravel deposition. Sediment capture rates of from 4,000 m^3 to 8,000 m^3 per hectare have been noted for a trial site in the San Juan River on the West Coast of Vancouver Island.

Figure 12. Live gravel bar staking gets the cuttings well down into the gravel bar to reach the water level. Where substrates are coarse, an excavator can be used to get the cuttings into the gravel. This work should be conducted under the supervision of a fisheries biologist. Clumps of live cuttings (right) are believed to be best in terms of maximizing the amount of sediment collected as these mimic natural patterns. The clumps of cuttings disrupt the flow patterns, causing sediment to be deposited.

Live Shade

Live shade was developed in response to the need for vegetative cover on newly constructed fish habitat. In many cases new habitat for fish is created in back channels and off channel areas as part of the mitigation for new highways and other facilities. This new habitat often involves excavations into the groundwater table to create permanent ponds and channels. In some cases, sufficient flow is available and new spawning habitat can be created as well. Construction of this new habitat clears large areas and generates a significant amount of spoil material that must be disposed of. The new habitat is then located in an area where significant riparian vegetation is lacking.

The normal solution to the lack of riparian vegetation is to plant new vegetation in the area that has been cleared and used for spoil disposal. Regulatory agencies, recognizing the need for shade and litter fall, request large planting stock. However, large stock is expensive and in many cases difficult to obtain and to plant. Even with large planting stock, shade over the channels and waterways depends on the orientation of the site relative to the path of the sun. Where hundreds of metres of new channel have been created, the cost of revegetation using large stock can easily exceed the cost of the initial channel construction. The ability of willows to root readily where moisture is available and to send up numerous new leafy shoots was recognized as a potential solution to the fish habitat revegetation problem. However, un-supported willow cuttings could easily be blown over in the wind or be knocked down under snow. A tripod design was developed to provide firm support for the above ground portions of the structure (Figure 13). The basal (butt) ends of the cuttings need to be placed well (30 cm to 40 cm) into the groundwater table adjacent to the newly constructed watercourse. The length of the cuttings depends on the channel to be spanned. However, where cuttings are greater than about 4 m long, the flexibility of the cutting becomes a problem. Overlapping the basal ends of the cuttings allows a dense lattice of willow to be constructed.

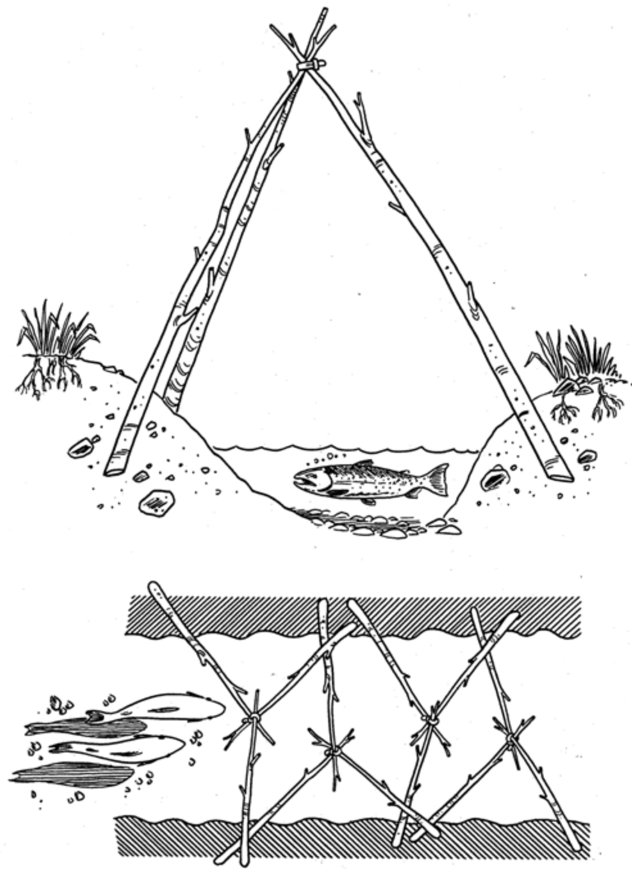

Figure 13. Live shade is designed to provide over-hanging riparian vegetation on newly constructed fish habitat. The structures will send up numerous new shoots while the butt ends of the cuttings will root in the moist soils on the banks. The basal ends of the cuttings used in live shade construction should be inserted well into the banks of the new channel. The key to avoiding a severe root to shoot imbalance is to ensure the basal ends are within the groundwater zone. The tips should be tied together with binder twine or straps. The legs of the tripod forming the live shade should be adjusted so that the slope of the cuttings is at least 45°. Overlapping the basal ends of the tripods used for live shade can be used as a means of controlling how much cover is afforded by the structures. A dense lattice work of living willows will provide more complete canopy closure than an open structure. This can be used to regulate water temperatures.

Conclusions

Bioengineering can be an effective tool for the treatment of unstable slopes and riparian areas. Treatments are relatively inexpensive and can provide significant benefits in terms of reduced maintenance, reduced erosion and enhanced stability. As living systems, bioengineering systems need little or no maintenance and continue to strengthen over the years. Bioengineering can provide a useful bridge between traditional engineering treatments and normal seeding work. Bioengineering can be a useful addition in the reclamation of difficult sites.

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