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**Watershed Restoration Management Report No. 1
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**Watershed Restoration Program
Ministry of Environment, Lands and Parks
and Ministry of Forests**

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ABSTRACT

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The British Columbia Watershed Restoration Program is a proposed provincial government initiative to accelerate the restoration of logging impacted watersheds. The Program is designed to rehabilitate local impact sites within logged watersheds, and therefore requires a multi-disciplinary approach. This report summarizes the major recommendations of a one-day workshop that was held to gather experts and allow a synthesis of recommendations for experimental design, monitoring, restoration techniques and innovations.

The program should monitor an experimental comparison of similar treated and untreated watersheds, forming a triplet block (or at a minimum, paired comparisons), comprising a complete restoration treatment, where hillslopes to stream channels are restored, a also low-level treatment, where only hillslope restoration work would be conducted, and an unrestored control. It is hoped this will provide further information on partitioning the success of each major component of restoration when compared to each other and the untreated control watershed. A decision analysis model indicated that the optimal benefit to cost return to evaluate a restoration program would be over a 4-8 year period, using 8-16 experimental stream triplets.

Appropriate response variables to monitor treatment effects were considered, and groups of geophysical and biological variables that could be used to assess treatment effects were identified, as were potential methods for quantifying the response variables. The workshop also compiled a preferred menu of bioengineering techniques that are likely to be the most appropriate for re-establishing vegetation, controlling erosion, and restoring fish habitat. Site-specific flexibility in designing fish habitat structures for watershed restoration was emphasized by the workshop, given the large number of restoration scenarios that are likely available. Public involvement in restoration projects, through stewardship or stakeholder groups, should also form an important component of the Program. The success of these groups can be enhanced by training group leaders, providing administrative support, project funding, and technical guidance.

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INTRODUCTION

The impact of forest harvesting in the Pacific Northwest has had dramatic effects on the natural landscape and thereby stream channels for over 100 years (Koski 1992). In British Columbia, the areas impacted by road building, logging and silviculture have grown steadily, particularly in the past few decades. As a result, forest harvesting activities have been at least partially responsible for changes in ecosystem diversity and the population size of many organisms normally found in wild forest habitat (Allan and Flecker 1993). For instance certain native fish stocks face extinction due to losses in suitable habitat (e.g. summer steelhead trout in Washington State, J. Doyle pers. comm.; or rainbow and steelhead trout in Carnation Creek, B.C., B. Holtby pers. comm.; see also Miller et al. 1989). On a larger scale, 33 to 75 % of aquatic organisms are believed to have become rare or extinct, largely due to the destruction of natural stream ecosystems in the Pacific Northwest (Doppelt et al. 1993). Given that streams are often one of the most severely affected ecological systems within disturbed forests, perhaps these numbers are not surprising.

While the forest industry forms an important component of the economy in the Pacific Northwest, the damage to other natural resources (e.g. commercial and recreational fisheries) due to certain forest practices, is considered to be substantial (Koski 1992). Programs designed to change and improve timber harvesting standards, such as the B.C. Forest Practices Code (Anon. 1993) are a major advance in integrated resource management. However, the function of new standards is primarily to prevent future problems. On Vancouver Island alone, most of the productive low-land old growth forest have been logged, leaving only high elevation old-growth forests (Ministry of Forests, Forest Inventory 1991). The vast areas harvested in British Columbia may require decades for watersheds to recover naturally. Special programs are required to accelerate and enhance the recovery process. In stream channels specifically, historical logging of riparian old-growth has left a critical deficit of large woody debris (LWD) and hence, a loss of vital summer and overwinter habitat for rearing salmonids as well as gravel storage areas for spawning salmonids (Koski 1992). These sites may require a century or more to recover naturally (Koski 1992).

The US Forest Service (USFS) has been conducting stream restoration on federal lands for almost a decade. The USFS has been expanding its activities in the West since its reviews in 1982 (Hall and Baker 1982; Reeves and Roelefs 1982). The focus has primarily been on replacing diminished large woody debris (LWD) within smaller stream channels. The USFS budget for restoration work in 1993/94 for all US National Forests was proposed at \$18 million (\$US) for anadromous fish habitat, \$18 million for inland fish habitat and \$5 million for restoration of habitat of threatened and endangered species (later modified by implementation of a broader watershed restoration program in 1994 within the Pacific Northwest).

Although logging-impacted hillslopes and stream channels are evident in B.C., restoration has sharply contrasted with the intensity of restoration in US National Forests.

British Columbia has logged approximately 40% more timber volume per annum on its public lands than on all US National Forests (Forest Planning Canada 1990), but progress towards restoration has been much slower. The province's Ministry of Forests (MoF) has a small annual engineering program for restoration work on MoF roads (\leq \$1 million/yr Cdn) and most of these funds are expended at "crises sites", particularly within community watersheds. However, there has been considerable applied research on rehabilitation techniques via the Fish-Forestry Interaction Program (FFIP). Industrial hillslope restoration activities in recently harvested areas are now becoming more common because of the development of Coastal Fisheries/Forestry Guidelines (1988) which will be incorporated into the Forest Practices Code (1994). However, there is no MoF or other institutional program for stream channel restoration, aside from an earlier MoF research project on the Queen Charlotte Islands and small scale cooperative projects with industry that involved the donation of heavy equipment use.

The British Columbia Ministry of Environment, Lands and Parks, in partnership with the B. C. Ministry of Forests and with the participation of the Department of Fisheries and Oceans (Canada), has proposed a province-wide program of watershed restoration for hillslopes and stream channels directly impacted by logging. Building on recent experiences over the past decade in B.C. and in the U.S., the Program will commence planning activities and pilot projects early in 1994. The main purpose of the Watershed Restoration Program (WRP; Anon. 1994) is to:

- 1. Restore, protect and maintain fisheries, aquatic and forest resources adversely impacted by logging-related activities that would otherwise require several decades to recover naturally.**
- 2. Provide community-based training, employment, and watershed stewardship opportunities throughout the province.**
- 3. Provide a mechanism to bridge historical forest harvesting practices and the new standards established by the Forest Practices Code, thus diversifying jobs in the forest sector.**

Watershed restoration will attempt to improve locally impacted areas within a water drainage system by altering the rates of processes that control the physical and biological structure of watersheds. Restoration to the original, unperturbed state is probably unattainable, in part because the natural conditions of most watersheds have not been documented. However, the work undertaken in this program will hasten the recovery of logging-degraded watersheds by such means as reducing the generation and routing of sediments from hillslopes to stream channels, re-establishing natural drainage patterns, replacing lost channel-structuring elements within streams, increasing the quality and amounts of fish habitat, and altering patterns of energy flow towards pre-logging conditions. The intent of the Program is to re-establish conditions more similar to those in unlogged watersheds; measures of the Program's success will therefore be positive changes in the rates of physical and biological processes which are known to be altered by past logging

practices. Watershed restoration will rehabilitate or accelerate the recovery of logging-degraded stream channels and hillslopes, the latter including roads, hillslopes, gullies, and riparian areas.

The province-wide implementation of the Program will require the cooperation and assistance of many local communities through stakeholder or stewardship groups. The program will also attempt to bridge previously unsustainable forest harvesting practices and new forest standards (Anon. 1993). This may involve employing forestry workers, for example, to de-activate unstable roads, remove logging debris from gullies, stabilize torrential gullies or improve erosion prone areas by re-vegetation. Combined with re-fresher or upgrade training, these experienced people will make a valuable workforce for the program.

In late 1993 and early 1994, the Watershed Restoration Program began organizing the key components of the program. Thus far, the program has been organized into a number of technical and administrative units that are described in Fig. 1.

Two key planning workshops were held to ensure that the training and evaluation components were addressed early in the Program. On 22 February 1994, the Training Education Working Group organised a skills identification workshop to outline the training and skills needed for the Program workforce as well as identify and initiate a process for establishing courses (Downie 1994). On 5 March 1994, a second workshop was held to plan the evaluation component of the Program; including experimental design, monitoring and restoration techniques. This second workshop was designed to gather the advice of experts from a variety of disciplines to design the main features of the program. The purpose of this document is to summarize and synthesize the advice and recommendations of the evaluation workshop experts.

The evaluation workshop addressed four main issues, central to the planning and development of the program:

1. What are the most powerful and efficient experimental designs to permit the evaluation of the Program and various restoration techniques?
2. What are the most appropriate response variables to monitor within the program?
3. Based on Canadian and American experiences, what are the most appropriate restoration techniques, given the need and opportunities for watershed rehabilitation activities that exist?
4. How can technical innovation and community stewardship be captured and incorporated into the program?

This document outlines the overall approach and methodology used by the workshop, and summarizes the discussions and consensus-building deliberations of the workshop.

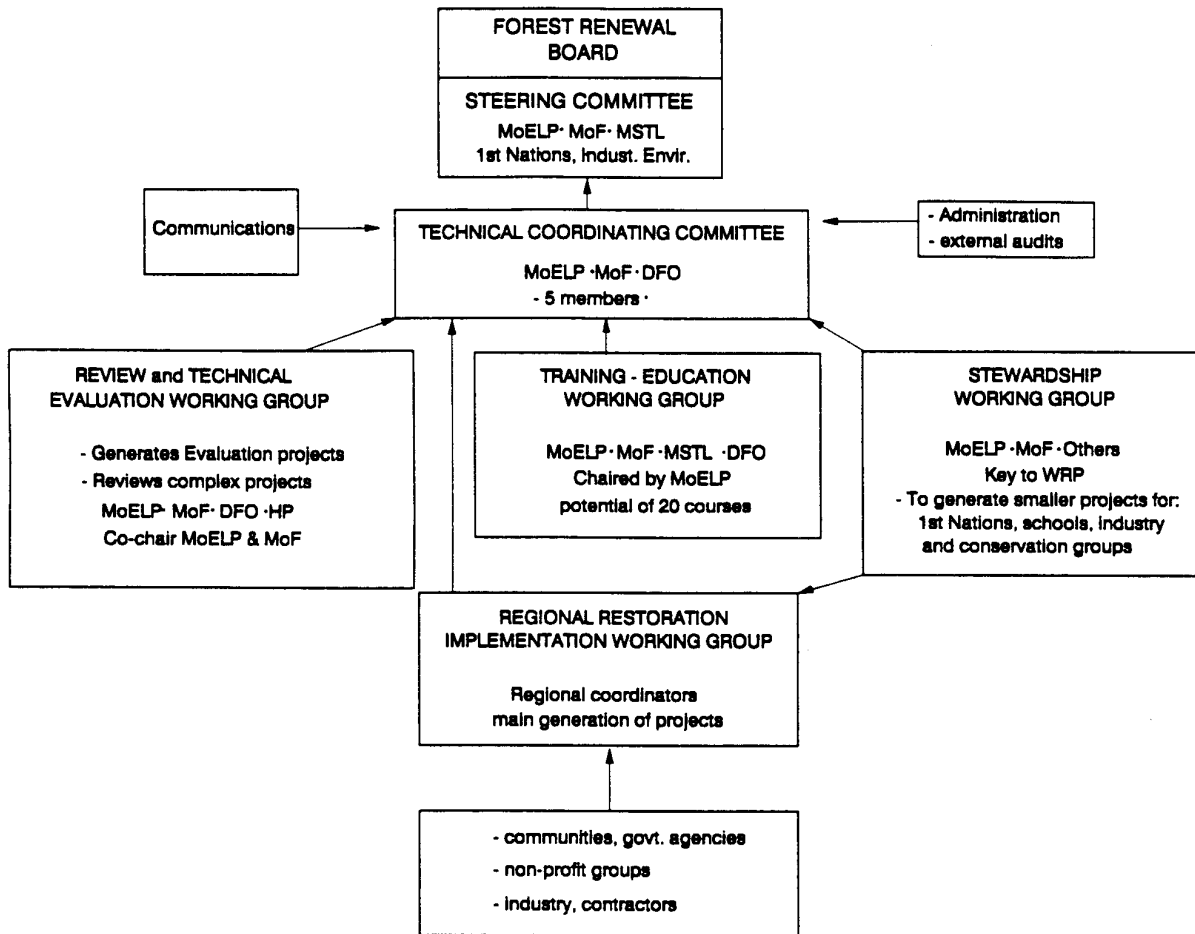


Fig. 1. Suggested interim organizational structure of the Watershed Restoration Program. Acronyms are defined as follows: DFO, Department of Fisheries and Oceans; MAA, Ministry of Aboriginal Affairs; MoELP, Ministry of Environment, Lands and Parks; MoF, Ministry of Forests; MSTL, Ministry of Skills, Training, and Labour.

METHODS AND ORGANIZATION

Given the multi-disciplinary nature of the WRP experimental design, monitoring and techniques workshop, organization was focused at two levels. Plenary sessions included all participants and were designed to allow a general explanation of the structure of the WRP as a whole and for the workshop. Participants were then divided into subgroups, based on expertise. The three subgroup categories were: 1) experimental design; 2) monitoring; and 3) treatment and innovations (or techniques). A list of participants divided by subgroup is reported in Appendix 1.

The goal for all subgroups was to produce the most effective recommendations for a province-wide restoration program, by identifying the major requirements and areas of application in each of the subgroup headings.

The purpose of the experimental design subgroup was to develop a powerful and efficient experimental approach to evaluate the effectiveness of the Program and its restoration techniques. The treatment and innovation subgroup was allocated the responsibility of selecting the most effective technical solutions to watershed impacts, given previous experience in American and Canadian research management programs. In order to evaluate the success of the program, several response variables were proposed by the monitoring subgroup for conducting statistical comparisons.

Subgroups met twice to discuss and resolve each of their respective mission statements. A morning subgroup session identified and made initial recommendations that were reported in a mid-day plenary session. The plenary session not only facilitated a presentation of initial ideas, but also allowed a question and answer period, enabling subgroup members to consider the opinion of a wider audience. Final recommendations were formulated in an afternoon subgroup session and were reported to the workshop at a final plenary session.

RESULTS, DISCUSSION and RECOMMENDATIONS

The discussions, results and recommendations from the workshop are reported below, by subgroup.

EXPERIMENTAL DESIGN SUBGROUP

Five key and fundamental considerations were identified by the experimental design subgroup and presented to the workshop.

1. Retrogressive Experimental Design. When treatment comparisons are made *within a stream* by reach, results become questionable. Because the watersheds under consideration have all been impacted by human activities, experimental sites within a stream will inevitably affect each other regardless of whether treatment sections are up or downstream of controls.

2. Temporal Scale. The time scale of observing measurable effects by hillslope and in-channel restoration work may be substantial. Therefore, in determining the time period in which to monitor results, the most powerful method based on variability of measures, should be used.

3. Spatial Scale. The spatial scale of watershed analysis is important in detecting meaningful treatment differences, particularly because localized random events may obscure findings by creating extreme variation in results. Hence, units of comparison need to be of sufficient size to reduce such local problems.

4. Identifying Control-Treatment Pairing. The matching of treated and untreated areas should be based on appropriate monitoring variables as well as taking the above problems into consideration.

5. Biological Indicators. Although there are many potential indicators for such a program, fishes are a prime candidate. Fishes are of high economic and aesthetic value and a large body of information is available for monitoring and evaluating their responses. However, other biological indicators such as invertebrate stream drift and benthos may also be suitable secondary sources that are simple to sample and measure.

Experimental Approaches

The experimental design subgroup identified and considered three potential experimental approaches for the Watershed Restoration Program:

- 1) Control-Treatment pairing (within stream)
- 2) Before-After Control Impact (BACI), or Control Impact (CI).
- 3) Watershed comparisons (whole vs partial)

Because BACI comparisons often require long periods of time before results are obtained and CI comparisons create difficulty in pairing observations, both of these approaches were excluded from further consideration. Instead, a control-treatment pairing of whole watersheds was thought to be the most appropriate (see also Whitehead and Robinson 1993).

Assessment of Optimum Size and Duration of Paired Comparisons:

Because differences are likely to occur when comparing any two individual watersheds, a replicated analysis of similar paired watersheds, based on physical habitat variables, was proposed as an initial experimental design for the program. A simple statistical decision model was designed to gain insight into the optimal number of paired watersheds to include in the estimation of treatment effects and the duration to monitor responses in these paired comparisons. This decision model provides a better basis for

estimating the statistical "power" of alternative designs than a simple statistical power analysis. In general, the decision analysis model found that the most powerful comparison with the greatest cost to benefit return would be from 8 to 16 watershed pairs, observed over a period of 4 to 8 years. A detailed description of the decision analysis model is provided in Appendix 2.

Further experimental design considerations

All members of the subgroup agreed that a paired watershed analysis would make the most powerful comparison to evaluate the effectiveness of the program. However, the information gained from a treatment effect would be increased by comparing a "triplet" rather than simply two similar watersheds. The idea behind this approach is to use two of the watersheds for restoration treatment effects and a third as a control. By treating one watershed with all major watershed restoration techniques (hillslope and in-channel work) and a second with partial restoration (hillslope only), it may be possible to assess where most of effective restoration occurs when compared to the control watershed. A triplet level of comparison also allows for more tolerance in errors in matching watersheds as well as providing direct measures of success in implementing certain techniques.

The application of a triplet design, however, may suffer from certain disadvantages that program managers should keep in mind. First, if the temporal scale of hillslope and in-channel work is very different, then it may require a longer time period to detect an effect. Secondly, three different watersheds within a triplet will increase the level of monitoring effort required by the project. However, if the intermediate treatment effect does become problematic either logistically or otherwise, it could always be excluded from the analysis. There is no shortage of impacted watersheds in British Columbia.

MONITORING SUBGROUP

As other restoration programs have noted, evaluating the success of restoration techniques will require a well planned monitoring program (Gore and Bryant 1988; Brooks 1989). Responses to watershed restoration treatments are likely to occur at several different time scales, and hence may require both a short and long-term monitoring strategy. In the short term, because fish species often integrate relatively rapid responses from several different mechanisms, monitoring fish production was thought to be a likely response variable. On the longer term, watershed restoration should lead to increased forest production and eventually a normally functioning forest ecosystem.

The monitoring subgroup considered five issues to be important considerations in a comprehensive monitoring program:

1. Identify packages of monitoring components and set priorities
2. Select the most appropriate spatial and temporal scales for monitoring
3. Ability to discriminate between alternate treatments and allow for flexibility of monitoring methods

4. Cost assessment of monitoring program (including administration costs)
5. Description and adherence to monitoring standards

Four key processes were identified, for a monitoring program:

1. sediment production
2. water dynamics
3. woody debris budgets
4. biological indicators

Each of these main categories were subdivided to include specific monitoring variables.

Sediment Production

1. Surface Erosion. Surface erosion is a primary source of sediment production. To evaluate changes under different treatments, surface erosion must be monitored in gullies as well as larger open areas where sheet erosion is likely. Surface erosion from roads, ditches and landings is a high priority before, during and after restoration.
2. Mass Wasting. Because mass wasting can periodically produce large sediment input, the frequency and volume of mass wasting events should be monitored during the Program. Managers should also attempt to assess the risk of future events, as well as putative causes.
3. Channel Erosion. An obvious problem for fish habitat degradation is the destruction of channel habitat. The program should monitor channel responses by measuring the stability of channel morphology as well as the composition and variance of substrate available in the stream bed.

Water Dynamics

1. Water discharge. Given that extreme stream-flow discharges can cause serious erosion and sedimentation problems in a watershed, the program must include several baseline measures of water flow. The measures should include mean water flows, high and low extremes, and also variability in these measures, spatially and temporally.
2. Water Quality. The alteration of natural ranges of water temperature, nutrients, and sediment production is often an important underlying mechanism in biological problems. If the restoration program is successful, then major improvements in each of these factors should be detected and hence, monitored.

Woody Debris Budgets

The input of woody debris into a system, and the role it plays in various destructive forces such as debris torrents and reduction of habitat complexity for fish species, will depend on its net loss and movement rates. If the program is to assess changes in a wood

budget, then large woody debris (LWD) and small woody debris (SWD) must be monitored in terms of its structure, quantity and delivery rates.

Biological Indicators

Although restoring physical habitat features is a quantitative measure of watershed rehabilitation, the ultimate measure of a program is the restoration of animal and plant populations as well as biodiversity.

1. Fish Populations. As emphasized earlier, fishes are often viewed as a key measure of success in restoration programs. Documenting the return of viable, naturally reproducing populations of fish species requires monitoring changes in fish numbers over time, as well as changes in average sizes and growth rates of fish that reflect changes in productivity. For anadromous fish populations, smolt output is a key measure of a fish species' response.

2. Invertebrates. Primary and secondary consumers, such as stream invertebrates, often form the basic food components for important vertebrates such as fish. The short-term scale of response and ease of measuring these organisms makes considering this group desirable.

3. Other Wildlife. The census of several other animal populations to assess recovery strategies may also be feasible as indicators of environmental restoration. This may include aerial surveys of large mammal populations and mark-recapture studies of various bird species.

Measuring Environmental Responses: Variables, Methods, Temporal and Spatial Scales, and Priorities

Tables 2 and 3 summarize response variables that could be considered by the Program, the techniques involved in monitoring, the scale of consideration (temporal and spatial) and its priority. Although Table 2 provides a comprehensive list of monitoring variables to consider, the number of variables monitored may not include all of these factors, given the benefit to cost return.

Because the primary goal of the program is to restore watersheds, monitoring should be directed towards those response variables that have a high statistical power to detect treatment effects. Response variables should also be good integrative measures of overall treatment effects and be closely tied to direct measures of potential economic and social benefits of the Program.

As noted in the experimental design section of this report, fish abundance is a particularly important response measure given the relatively short (4-8 year) time frame suggested by the experimental design subgroup for the initial assessment phase of the program. Other biological measures (insects, fish growth) may be important predictors of responses in fish production that take longer to emerge clearly.

The choice of response variables is largely dependent on the restoration techniques and experimental design that are adopted by the Program because these will influence the expected magnitude and time dynamics of potential responses. In the absence of a clear design and set of treatments, the monitoring group did not attempt to establish a definite set of response variables. The subgroup did note that some of the biophysical measures may be important in assessing the reality of any apparent non-response by the biota. The rationale for the Program has been phrased in terms of restoring biological productivity in logging-impacted systems, which implies that biological response variables such as fish production need to be considered in assessing treatment effects.

Table 2. Potential response variables to be monitored as measures of watershed restoration treatment effects and their relative priority.

PROCESS	MONITORING TECHNIQUE	PARAMETERS	TIME SCALE	SPATIAL SCALE	PRIORITY
Surface Erosion	air photos field examination	areas changes	< 5yrs.	slope polygon	high
	sediment fences	vol/area/time	< 5 yrs.	slope polygon	medium
	checkdams	depth/time	< 5 yrs.	slope polygon	low
Mass Wasting	air photos field examination	area changes vol/area/time	< 5 yrs. < 5 yrs.	slope polygon slope polygon	high medium
	checkdams	vol/time	< 5 yrs.	gully	medium
	Sediment Transport	air photos	planform bars	1-30 yrs.	basin
cross-sections long profiles		gradient pool dimensions		↓	medium
				to	
GPS/video (may require field sampling)		textural properties		↓ reach	high
	total retention in-stream monitoring	vol/time, texture vol/time, texture	< 5 yrs. < 5 yrs.		medium very low
Wood Debris Budget	channel surveys (storage characteristics) source inventories	vol/area channel veget. patterns wood volume on near bank no.vol/area/time	< 5 yrs.	reach ↓ to floodplain	very high

Table 2. concluded

PROCESS	MONITORING TECHNIQUE	PARAMETERS	TIME SCALE	SPATIAL SCALE	PRIORITY
Water Volume	crest gauge/sensors	peak flows	variable	basin	low
	continuous	hydrograph	< 5 yrs.	basin	medium
	channel evidence (from aerial photography)	channel morph. textural changes	< 5 yrs. < 5 yrs.	reach	high
Water Quality	continuous monitoring grab samples	temperature turbidity, DO nutrs., TDS	< 5 yrs.	basin or reach	high in heavily used watersheds
Biological Process					
Fish Abundance & Smolt Yield	electrofishing	summer/winter density	long term	reach	variable according to species & region
	counting fence	smolt yield	short term	watershed	
	visual estimates	spawner density	long term	watershed	
Fish Growth	seining	adult density	long term	reach	low
	trapping smolts				
	as above	size at age growth rate	as above	stream	

TREATMENT SET AND INNOVATION SUBGROUP

In restoring logging impacted areas, many techniques with a variety of purposes are available. However, in considering the value of any one restoration technique, several factors must be considered *a priori*. The treatment set and innovation subgroup identified several basic criteria that the program should consider to provide environmental restoration and the best benefit to cost return. The subgroup recommended that this decision would be best made under a pre-treatment assessment phase which would allow for an estimate of the benefit to cost return (Ryder and Kerr 1989). The assessment would follow under two categories:

1. **Habitat Assessment.** Large-scale habitat changes are often associated with logging-impacted areas. Changes in overall landscape can often be assessed by both the use of aerial photography and video image analysis. Similarly, habitat features including LWD in channels can be quantified by these techniques and treatments prescribed (photometric analysis and prescriptions as a standardization innovation) These techniques can also be complemented by on site field reconnaissance.
2. **Stock Assessment.** To determine the level of fish recruitment required to respond to rehabilitation, an initial assessment of fish stock abundance must first be determined. By comparing impacted areas to either historical data or unharvested areas, an estimate of the replacement required can be obtained. Whenever possible the treatment assessment should be coordinated with monitoring assessment.

The need for multi-disciplinary advice to identify problems within an area will be of particular importance in this type of assessment (Gore and Bryant 1988). Concurrent assessment with the monitoring program should also be used whenever possible.

Pre-treatment Observations

In assessing restoration requirements, several important observations should be made in the assessment process.

Key observations:

1. Document watershed road use plan to indicate present and future use of roads.
2. Define each restoration project's objectives according to the program criteria.
3. Prioritize impacted areas to be restored within watersheds. Hillslopes and gullies are normally rehabilitated first, to secure the route riparian area and stream channel work.
4. Prescribe treatments, design plans and applications (requires environmental protection plan for in-stream restoration).

5. Assess and prevent future failures which could have a major impact on a treated watershed.
6. Complete an inventory of equipment, materials required and estimate costs and time scheduling for project implementation (including training requirement).

Primary goals and considerations for restoration

1. Restoring Diversity. Many impacted areas will have lost much of the diversity in animals and vegetation, as well as habitat diversity. In restoring habitat and biodiversity, the program would be best served by following three "rules of restoration".

(a) Restore hillslopes and stream channels to improve conditions whenever possible, using "like materials", emulating natural conditions.

(b) If large-scale improvements are extreme, consider employing an alternate technique having the best increase in site stability and habitat productivity per unit cost.

(c) Consider naturally unproductive adjoining areas for stabilization or improvement if local logging impacts cannot be resolved and rehabilitated.

2. Guidelines for Repair. Targeted areas should follow basic manuals (e.g. Anon. 1980; Anon. 1989) for installing structure (see below) and repairing habitat problems. However, unless complex, the use and development of strict "blueprint" documentation (engineering designs) is generally not advised because each site will have slightly different requirements that will require flexibility in design.

3. "Storm Proofing". The success of any restored area will depend on whether it can withstand extreme storm conditions. Therefore, when repairing impacted areas, workers must be sensitive to high water events in drainages and stream channels when installing structures or improving habitat.

Restoration Techniques

The subgroup identified a variety of techniques and objectives to be employed in the restoration program. Because areas surrounding and leading into stream channels would generally be restored first, forest roads, landings, skid trails, and gullies were the first areas addressed by the subgroup.

Stabilizing and Adapting Local Geomorphology and Availability of Local/Riparian Material

Forest Roads

1. Prioritize road areas to be restored or de-activated, leaving roads with little impact to be considered last.
2. Target sensitive unstable areas with:
 - slopes > 20%
 - tension cracks
 - side castings
3. Manage the surface drainage system to increase slope stability and re-establish natural drainage patterns.
4. Re-vegetate actively eroding or high risk areas with trees, grasses, shrubs; hydroseeding from tank trucks and helicopter seeding with fertilizer and grass seed mix (avoid introducing exotic species and attempt to develop seed sources of local species)
5. The goal is to reduce road density over time (develop a long term use plan)

Landings and Skid Trails

1. Prioritize trails to be restored. Areas with steep gradient, fine soils and proximity to streams should be considered first.
2. Cover large areas with hydro or helicopter-seeding Target lacustrine silty terraces having eroded skid trails in interior areas. In smaller areas (skid trails), use hand-operated, cyclone-backpack seeders to revegetate erosion sites.
3. Control water run-off and add mechanically stabilizing structures.
4. In areas with large landslides, consider the risk of further failure as well as the probability of success and the costs. Abandon if too costly (e.g. Deer Creek, Washington).

Gullies

1. Prioritize areas, risk of failure and remove unstable debris (handwinch, grapple); always consider danger to persons while working on site.
2. Add gully fences, check dams, and cross logs where gully failures are at risk of further degradation.

3. Anchor structures in areas of high water flow with rebar, cable, or gabions.
4. Revegetate deforested gullies with native grasses, shrubs and trees.

Stream and Riparian Areas

Restoration of stream and riparian areas will involve attempts to achieve a suitable ratio of pools to riffles. Restoration will also improve in-stream structure and complexity, bank protection, bank side cover, and substrate quality (reduced infilling of cobble-boulder interstices and reduced "fines" in spawning gravels). Each of the stream and riparian area techniques were prioritized within 3 basic habitat types to be rehabilitated: small streams, large streams, and riparian zones. Once the hillslope areas (roads, slopes and gullies) are considered secure, the restoration of stream and riparian zones is to be undertaken with the techniques recommended in Table 3.

Tables 2 and 3 represent a subset of possible techniques. Durability was considered to be particularly important in selecting structures (target 20 years; Ward and Slaney 1979; Frissell and Nawa 1992). Many other techniques were also discussed in the workshop, however the above tables list the methods most commonly used and preferred by the workshop participants. The program should emphasise flexibility and innovation in solving site specific problems and should consider many of the available guides and manuals (e.g. Anon. 1980; Anon. 1989; Seehorn 1985) as well as published evaluations (Frissell and Nawa 1992; Wesche 1985; Ward and Slaney 1993) for restoration and habitat improvement.

Table 3. A list of techniques for stream and riparian area restoration and comments for application.

Small Streams			
Technique	Purpose	Priority	Comments
Re-open cut off and restricted areas for fish use	-re-establish fish habitat	very high	-target off channel over wintering areas, culvert problems
Side & Off Channels/ Ponds	-improve over-winter survival (refugia)	high	-creates salmonid spawning, rearing & over-winter habitat
Large Woody Debris Placements	-summer rearing habitat -improve over-winter survival -spawning gravel storage -improve channel stability	high	-fish structures, -anchor when needed -set standards based on natural LWD (see also Seehorn 1985)
Step Dams	-provide summer rearing and over-winter habitat -trap spawning gravel	med	-site specific, -must have sufficient gradient (locking well into banks) -mainly interior streams
Stream Bank "Retards" (trees) & Boulder Revetments	-erosion control -provide rearing and over-winter habitat	high	-use large boulders for habitat replacement (well into channel at moderate to high velocities)

Table 3. continued

Technique	Purpose	Priority	Comments
Boulder Clusters (boulder & log ramps)	-provide summer rearing and over-winter habitat	high	-boulder size increases with stream size (av. 0.5m), clusters (3-5) -used optimally 4-5m apart vs. singles 1 m apart
Low Level Stream Fertilization	-to compensate for nutrient input from salmon carcasses -increased insect & fish production	high	-site specific -seasonal (May-July) -slow release pellets (once/yr.)

Large Streams

Technique	Purpose	Priority	Comments
Boulder Revetments and Boulder Berns	-stabilize & secure natural channel	med	-site specific to restore or preserve fish production
Tree "Retards" Boulder Revetments & Boulder Groins	-erosion control -provide summer & over-winter habitat	med	-site specific, for bank -large boulders at toe
Boulder Clusters	as in small streams	med	-site specific -large boulders needed -increased risk of loss (bury)
Boulder V-Weirs & Opposing-Wing Deflectors	-create summer rearing, over-wintering & angling habitat	med-high	-site specific -channelized sections -mitigation sites (Anon. 1989)

Table 3. concluded

Technique	Purpose	Priority	Comments
LWD Catchers	-as above	high	-interior streams, untested on coastal streams -location is critical (Ward and Slaney 1993)
LWD Placements	-as above	med-high	-avoid cross-channel LWD (Frissel and Nawa 1992) -spring and summer application -site specific
Low Level Stream Fertilization	-increases insect & fish production in nutrient deficient waters (Slaney and Ward 1993)	med	-main application: mitigation for destabilized channels; particularly when no other options are -
increased size-related survival	(Scrivener and Brown 1993)	available	
Riparian Zones			
Technique	Purpose	Priority	Comments
Vegetation & Tree Planting	-bank stabilization -future LWD sources -terrestrial insect & N sources	high	-mixed complex for future LWD and leaf litter -erosion control (grasses & trees)
Channel Re-diversions by boulder & log berms	-maintain & restore natural channel -prevent erosion and forest site loss	med	-site specific

Stewardship or Stakeholder Groups

Given the province-wide scale of the Watershed Restoration Program, a large component of its success will depend on the assistance of stewardship or stakeholder groups. Stewardship groups will often consist of highly motivated local people with keen interests in restoration and watershed management. The effectiveness of such groups will depend on proper organization and management of people. To facilitate this process a number of key considerations should be met by the Watershed Restoration Program:

1. Organize well informed group leaders, with specific tasks.
2. Set up a training program for key people, and provide an administration budget for the group.
3. Provide technical support from professionals in government or consulting agencies. This may include a range of activities, from advice on planning decisions, to providing equipment, to on-site prescriptions and application of restoration techniques.

CLOSING COMMENTS

The Watershed Restoration Program is one of the most important environmental initiatives to be undertaken in British Columbia this century. The scope of the program is unprecedented in British Columbia, as no other program has addressed watershed management in such a direct, holistic and multi-disciplinary manner.

The need for a restoration program of this type has become increasingly obvious. For the past three years the Ministry of Forests has provided training sessions on watershed restoration techniques because of the urgent need for restoration work.

The Watershed Restoration Program should not be seen as duplication of other initiatives such as the Erosion Control Policy or the B.C. Forest Practises Code. Each of these programs is aimed at preventing future damage or improving forest harvest methods. The Watershed Restoration Program is designed to rehabilitate previously damaged areas.

In many respects, the WRP can be compared to FRDA program (Canada-British Columbia Forest Resource, Development Agreement). FRDA was initiated because of public concern about the lack of reforestation. FRDA's mandate was, and still is, to re-establish forests in logged areas that were not satisfactorily reforested. FRDA has been a success, and one way to gauge the success is to consider the way business is presently conducted on B.C. forest lands. There has been a fundamental shift in the way licensees deal with reforestation, since it is now the legal responsibility of the licensee to care for the forest land until seedlings are free-growing. As a result, there are fewer "Not Satisfactorily Restocked" forest lands in British Columbia.

The public is currently highly concerned about the environmental health of forest watersheds, and the B.C. Forest and Environment agencies are equally concerned. It is anticipated that the Watershed Restoration Program will lead to substantial improvements in habitat quality. However, the required level of watershed rehabilitation is staggering. To be successful, all parties will need to implement the program in a multi-disciplinary fashion. The ecosystems concerned are complex, they form important links to human ecology and therefore will require experts to work cooperatively from a variety of disciplines. Taking advantage of the advice of people with previous experience in watershed restoration, in particular the U.S. Pacific Northwest, will make the task at hand easier to execute.

The WRP will place a substantial responsibility on individuals within the public service as well as those placed locally within stewardship groups. In order to make the program a success, a great deal of organization, preparation and training will be required. The workshop, and this planning-evaluation document will provide a first step to help ensure that watershed restoration in B.C. will be executed in the most effective way.

REFERENCES

- Allan, J.D. and A.S. Flecker. 1993. Biodiversity conservation in running waters. *Bioscience* 43:32-43.
- Anon. 1980. Stream enhancement guide. Department of Fisheries and Oceans, Canada, and B.C. Provincial Ministry of Environment. Victoria. 82 p.
- Anon. 1989. Fish habitat enhancement designs: typical structures. Alberta Environmental Protection, Water Resources Management Services, Technical Services and Monitoring Division, River Engineering Branch. 32 p.
- Anon. 1993. British Columbia forest practises code: rules. Queen's Printer, Victoria, B.C. 128 p.
- Anon. 1994. An overview of the Watershed Restoration Program. B.C. Ministry of Environment, Lands and Parks and Ministry of Forests. 24 p.
- Brooks, A. 1989. Alternative channelization procedures. p .139-162. In: Alternatives in regulated river management. (J.A. Gore and G.E. Petts, eds.). CRC Press, Boca Raton, FL. 344 p.
- Chatwin, S.C., Howes, D.E., Schwab, J.W. and D.N. Swanston. 1991. A Guide for management of landscape-prone terrain in the Pacific Northwest. B.C. Ministry of Forests. Land Mangement Handbook no. 18.
- Downie, B. 1994. Watershed restoration program: skills identification workshop. Manuscript report, B.C. Ministry of Environment, Lands and Parks. Vancouver. 20 p.
- Doppelt, B., Scurlock, M., Frissell, C., and J. Karr. 1993. Entering the watershed: a new approach to save America's river ecosystems. Island Press, Washington, D.C. 462 p.
- Forest and Planning Canada. 1990. Volumes logged and revenue benefits, U.S. National forests versus B.C. public lands, 1988/1989. Table published in *Forest Planning Canada* 6:48.
- Frissell, C.A. and R.K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. *N. Amer. J. Fish. Manage.* 12:182-194.
- Gore, J.A. and F.L. Bryant. 1988. River and stream restoration. p . 23-38. In: *Rehabilitating damaged ecosystems*. Vol. I. (J. Cairns, Jr. ed.). CRC Press, Boca Raton, FL. 192 p.

- Hall, J.D. and C.O. Baker. 1982. Rehabilitating and enhancing stream habitat: 1. Review and evaluation. In: Influence of forest and rangeland management on anadromous fish habitat in western North America. (W.R. Meehan, ed.) U.S. Forest Service, Gen. Tech. Rept. PNW-138. 29 p.
- Koski, K.V. 1992. Restoring stream habitats affected by logging activities. p. 343-403. In: Restoring the nation's marine environment. (G.W. Thayer ed.). Maryland Sea Grant: College Park, MD.
- Miller, R.R., Williams, J.D. and J.E. Williams. 1989. Extinctions of North American fishes during the past century. *Fisheries* 14:22-38.
- Ministry of Forests, Forest Inventory 1991. Vancouver Island satellite image map Q.P. #93544/1. Prov. B.C.
- Reeves, G.H. and T.D. Roelefs. 1982. Rehabilitating and enhancing stream habitat: 2. Field applications. In: Influence of forest and rangeland management in western North America. (W.R. Meehan, ed) U.S. Forest Service. Gen. Tech. Rept. PNW-140. 38 p.
- Ryder, R.A. and S.R. Kerr. 1989. Environmental priorities: placing habitat in hierarchic perspective. pp.2-12. In: Proceedings of the national workshop on effects of habitat alteration on salmonid stocks. (C.D. Levings, L.B. Holtby, and M.A. Henderson, eds.) Can. Spec. Publ. Fish. Aquat. Sci. 105:2-12.
- Scrivener, J.C. and T.G. Brown. 1993. Impact and complexity from forest practises on streams and their salmonid fishes in British Columbia. p. 41-49. In: G. Shooner et S. Asselin (eds). Le développement du Saumon Atlantique au Québec: connaître les règles du jeu pour régles du jeu pour réussir. Colloque international de la Fédération Québécoise pour le saumon Atlantique. Quebec, Canada. December 1992. Collection Salmo salar no. 1.
- Seehorn, M.E. 1985. Fish habitat improvement handbook. USDA Forest Service, Southern Region. Tech. Publ. R8-TP 7. 21 p.
- Slaney, P.A. and B.R. Ward. 1993. Experimental fertilization of nutrient deficient streams in British Columbia. p. 128-141. In: G. Shooner et S. Asselin (eds). Ledéveloppement du Saumon Atlantique au Québec: connaître les règles du jeu pour régles du jeu pour réussir. Colloque international de la Fédération Québécoise pour le saumon Atlantique. Quebec, Canada. December 1992. Collection Salmo salar no. 1.
- Ward, B.R. and P.A. Slaney. 1993. Habitat manipulations for the rearing of fish in British Columbia. p. 142-148. In: G. Shooner et S. Asselin (eds). Le développement du Saumon Atlantique au Québec: connaître les règles du jeu pour régles du jeu pour réussir. Colloque international de la Fédération Québécoise pour le saumon Atlantique. Quebec, Canada. December 1992. Collection Salmo salar no. 1.

- Ward, B.R. and P.A. Slaney. 1979. Evaluation of in-stream enhancement structures for the production of juvenile steelhead trout and coho salmon in the Keogh River: progress 1977 and 1978. Prov. B.C. Fish. Tech. Circ. no.45:47 p.
- Wesche, T.A. 1985. Stream channel modifications and reclamation structures to enhance fish habitat. In: The restoration of rivers and streams. (J.A. Gore, ed.). Butterworth, Boston, MA.
- Whitehead, P.G. and M. Robinson. 1993. Experimental basin studies - an international and historical perspective of forest impacts. J. Hydrol. 145:217-230.

Appendix 1. A list of participants of the experimental design, monitoring and techniques workshop for the watershed Restoration Program.

Experimental Design Subgroup

Participant	Organization
Carl Walters	UBC - Fisheries Centre (Workshop Leader)
Wendy Bergerud	MoF - Research Branch
Michael Church	UBC - Geography
Roger Green	UWO - Zoology
Blair Holtby	DFO (Rapporteur)
Ernest Keeley	MoELP/UBC - Fisheries Centre
Marc Labelle	MoELP - Fisheries Branch
Tony Pitcher	UBC - Fisheries Centre
Vera Sit	MoF - Research Branch
Art Tautz	MoELP - Fisheries Branch
Ray White	Trout Habitat Specialists

Monitoring Subgroup

Participant	Organization
Tom Johnston	MoELP (Subgroup Leader)
Bob Bilby	Weyerhaeuser Co.
Michael Bovis	UBC - Geography
Jeff Cederholm	Washington DNR
Ted Down	MoELP - Region 7
Gordon Hartman	Consultant
Dave Heller	US Forest Service
Dan Hogan	MoF - Research Branch (WRP closing comments)
Jack Leggett	MoELP - Region 5
Gerry Oliver	MoELP - Region 4
Charles Scrivener	DFO
Peter Tschaplinski	MoF - Research Branch (Rapporteur)
Bruce Ward	MoELP - Fisheries Branch
Craig Wightman	MoELP - Region 1
Kate Sullivan	Weyerhaeuser Co.

Treatment Set and Innovation Subgroup

Participant	Organization
Pat Ahern	Steelhead Society of B.C.
Jim Allan	Pisces Environmental
Ken Ashley	MoELP - Fisheries Branch (Rapporteur)

Appendix 1. Concluded

Participant	Organization
Don Cadden	MoELP
Pat Slaney	MoELP (Subgroup Leader)
Brian Chan	MoELP - Region 3
Jim Doyle	US Forest Service
Rheal Finnigan	DFO
Matthew Foy	DFO
Sig Hatlevik	MoELP - Region 3
Ron Jordens	MoF
Al Martin	MoELP
Glen Moore	MoF - Timber Harvesting Branch
Marvin Rosenau	MoELP - Region 2
Jim Spear	US Soil Conservation Service
Jim Schwab	MoF - Prince Rupert
Bill Traub	Washington DNR

Appendix 2. Description of the Decision Analysis Model

The decision model views the Watershed Restoration Program as consisting of two phases or stages (similar to the approach used in planning the Salmonid Enhancement Program, SEP):

1. Phase 1, experimental comparison of n treatment-reference watershed pairs for t years, to produce an estimate R_{bar} of the average annual effect of treatment over the years; and
2. Phase 2, either discontinuing the program if R_{bar} is too low to justify further expenditure, or applying the treatment regime to an additional $N-n$ watersheds for $T-t$ years. The variable N represents the maximum number of watersheds to which the treatment might be applied and T represents a planning horizon or total number of years over which the program costs and benefits are considered worth evaluating.

A planning horizon approach was elected to assess benefits and costs, rather than a discounting (infinite time horizon) approach. This enables the model to (1) maintain a simple distinction between short term benefits and costs over t years versus long term benefits and costs over T years, and precludes debates over the appropriate discount rate for public investment decisions (it is easier to obtain consensus about an appropriate T than an appropriate discount rate).

Statistically speaking, there are two possible errors that could occur at the end of phase 1: (1) continuing and expanding the program when in fact it will not produce long term benefits as large as predicted from R_{bar} ; or (2) discontinuing the program when in fact it would produce higher benefits than indicated by R_{bar} . A cutoff or expansion decision will presumably be made at some time by comparing R_{bar} to some response standard R_o needed to justify expenditure from a cost/benefit perspective (R_o represents the response level for which the benefit/cost ratio just reaches a minimum standard such as 1.0). Given a decision rule based on R_o , the probabilities of the two types of errors are estimated simply by computing the probability P_q that $R_{\text{bar}} < R_o$ given long term mean response greater than R_o , and the probability P_c that $R_{\text{bar}} > R_o$ given that the long term mean is less than R_o . P_q is defined as the power of the experiment to detect a successful treatment regime, and P_c is the power of the experiment to detect a potential waste of long-term public investment.

Assessment of the Expected Value of a Design Option

The best measure of the performance of a given experimental design option (n,t) is taken to be the expected value of net benefits over all N systems for T years. If the actual mean response is R , and R is assumed to have only two possible values (0 or high), this expected value can easily be calculated. It is a prior probability P_o that the response will exceed R_o , times the expected net benefit if R exceeds R_o , plus $(1-P_o)$ times the expected net benefit if R is less than R_o . The expected net benefit if R does exceed R_o is in turn calculated as $(1-P_q)$ times the value if the treatment is extended to all N systems after t years, plus P_q times the value obtained just during the first t years (i.e. quit after treating just

the n experimental systems). The expected net benefit if R is less than R_o is calculated as P_c times the net benefit if the treatment is extended to all systems (but fails), plus $(1-P_c)$ times the net benefit if the treatment is stopped after year t . For proponents of statistical decision theory, the calculation is simply the expected value over a decision tree with four terminal branches. The first branch is defined by the probability P_o , and the second two branches are defined by P_q and P_c . For all assessments it was assumed that P_o was 0.5 (i.e. all outcome possibilities were assumed to be equally likely, considering it is potentially misleading to make any prior judgement as to the likelihood of success). The expected value calculation can be readily extended to a multi-branch decision tree where many possible response levels ("true" R values) are included. This generalization does not affect the basic conclusions derived below. The advantage of considering only two extreme possibilities for R is that P_q and P_c are easily interpreted in this case (with many R values, these failure probabilities are functions of R rather than single numbers).

For each of the four possible decision outcomes (success-detected, success-not detected, failure-detected, failure-not detected), the net economic benefit was assumed to be predictable from (1) an average annual economic benefit B (obtained only if R is truly large) per watershed, (2) an initial capital cost C per treated watershed, (3) an annual operating cost c per treated watershed, and (4) an annual monitoring cost $2m$ per treated watershed (must expend monitoring cost of m on both the treated watershed and a paired reference watershed). Accumulating these costs and benefits over time for each decision outcome results in the following assessments of total net benefit:

- success-detected: $TnB+(T-t)(N-n)B-NC-Tnc-(T-t)(N-n)c-2tnm$
- success-not detected: $tnB-nC-2tnm-tnc$
- failure-detected: $-nC-2tnm-tnc$
- failure-not detected: $-NC-2tnm-Tnc-(T-t)Nc$

The net benefits are obtained for each outcome by multiplying $B, C, c,$ and m components by the number of watersheds times years where each economic component is incurred. For example, $2tnm$ is the cost of monitoring $2n$ watersheds for an experimental period t at cost m per watershed-year. Note that while the net benefits are calculated as though every watershed and year were identical, the basic terms and relationships can be thought of as averages over time, and over watersheds, of variable costs and benefits. However, this assumes that the initial treatment and reference set of $2n$ watersheds is selected representatively from the overall set N of possible working systems.

Calculation of the Statistical Power of a Design Option

It is easy to set up a spreadsheet calculation of the average of the possible decision outcomes, weighting each by appropriate probabilities calculated from $P_o, P_q,$ and P_c . The difficult problem is how to predict P_q and P_c from $n, t,$ and m . For this prediction, we assumed that the observed response R_{bar} is best estimated by taking the average over all years and treatment/reference pairs of the pair/year differences in response (the standard maximum likelihood estimator in a paired experimental design). Monte Carlo simulation

studies indicate that this average difference is likely to be almost normally distributed for $n > 4$, $t > 4$ even if the annual stream measurements are log-normally distributed with high variance and strong auto-correlation (strong within-system trends and patterns). Given an estimate of the variance of this normal distribution, the required probabilities P_q and P_c are given by probabilities of R_{bar} falling in the appropriate tail of the cumulative normal distribution function (being either less than or greater than R_o). With the variance and mean either 0 or R^* , where R^* is the expected response if the treatment is fully successful, a maximum likelihood criterion for cutting off the experiment would be to take $R_o = R^*/2$. Therefore, the program would be stopped if the mean response is more likely to be 0 than R^* .

Examination of components of variation, in response measurements such as salmon smolt production, reveals that R_{bar} should have the following variance components:

$$\text{var}(R_{\text{bar}}) = \text{var}(\text{systems})/n + \text{var}(\text{response})/t + \text{var}(s\&t)/nt$$

where:

1. $\text{var}(\text{systems})$ is the variance of the difference between treatment and reference systems due to factors other than the treatment, averaged over time (i.e. intrinsic differences between the two members of each pair, representing inevitable bio-physical variation over space). For response variables such as coho salmon smolt production, a review of available data revealed that the coefficients of variation among streams is usually between 0.5 and 1.2. The high variance may be reduced substantially through judicious pairing, but one must assume values of no less than 0.5 exist for the baseline calculations presented below.
2. $\text{var}(\text{response})$ represents variation over time in the response itself, combined with among- stream variation in response. For baseline comparisons, this source of variation was assumed to be similar in magnitude to the intrinsic variation among streams represented by $\text{var}(\text{response})$ or to the variation within streams over time as represented by $\text{var}(s\&t)$.
3. $\text{var}(s\&t)$ is the biological and measurement "noise" expected in the time series of measurements within each stream, due to processes that are not correlated among streams. The treatment - reference differencing removes components of temporal variation that are shared among systems, such as effects of large scale climatic change and regulation of ocean fisheries that influence many stocks simultaneously. Based on a review of time-series data for smolt production from coho and steelhead populations along the Pacific coast, the coefficient of variation in such counts (square root of $\text{var}(s\&t)$) is expected to be about 0.3-0.6. In order to be conservative for the baseline calculation, none of this variation was assumed to be shared between treatment - reference stream pairs, and was assumed to have a c.v. of 0.4.

Evaluation of Basic Design Options n, t

The variance components were incorporated into an Excel spreadsheet calculation of $\text{var}(R_{\text{bar}})$ and associated predictions of P_q , P_c , and expected net benefit. The Excel "Table" function was then used to calculate expected net benefit for various combinations of n and t , and contour plots were developed to show systematically how expected net benefit varies with these design parameters (Fig. 2). The spreadsheet also allowed variance in the economic planning factors (B, C, c, T , and m) to determine their effect on the expected value contour pattern (and the location in this pattern of the design combination n^*, t^* that gives the highest expected value).

As indicated in Fig. 2, the spreadsheet analysis consistently predicted (for a wide range of the economic parameters and variance assumptions) that the best experimental design is to use a relatively large number of experimental system pairs ($n^*=6-12$ pairs) and a relatively short experimental period ($t^*=4-8$ yrs). This result was somewhat surprising, since it was expected to require a longer experimental duration. There are two reasons for this result. First, note that $\text{var}(R_{\text{bar}})$, as defined above, has three variance components, and sampling for longer and longer times can only drive the components due to $\text{var}(\text{response})$ and $\text{var}(s \& t)$ to approach zero. For small n , the $\text{var}(\text{systems})$ component remains dangerously large, in the sense that it leads to persistently large P_q and P_c . Large values of these error probabilities reduce the expected value of the experiment by placing high weights (odds) on the "success-not detected" and "failure-not detected" economic outcomes defined above (both these outcomes have high negative economic value for reasonable assumptions about C , c , and m). Secondly, if in structuring the economic response and variance calculations the response to treatment is assumed to be immediate, then large values of $\text{var}(\text{response})$ could be used to roughly model transient and/or slowly developing responses over time. However, because the possibility of time lag was not included, a time period may be required before responses begin to appear. A simple approach to response delays would be to adjust the economic benefit calculations (over both benefit phases, assume benefits occur only over $t-t_0$ and $T-t-t_0$ years) and then to consider t as being the number of years after t_0 required to achieve a given power of experiment. Obviously, such response lags could greatly reduce the expected value of any experimental program if t_0 is a substantial fraction of T .

Another unexpected result from the analysis is that the optimum "power" of experiment, as measured by P_q and/or P_c , is not generally as high as one might expect from scientific standards for hypothesis testing. Peaks in the expected value function are generally associated with n, t combinations that result in P_q and P_c values of around 0.2-0.3 (i.e. implies accepting a 20-30% chance of making the wrong investment decision for the second phase of the program; Fig. 3).

By varying the model parameters over a wide range (factor of 0.2-5.0) while adjusting B to maintain a constant overall benefit/cost ratio for the nominal (best case) outcome, a rough assessment of the effects of each on the optimum experimental combination n^*, t^* can be made. Beginning with a base case benefit/cost ratio of 1.8, $C=0.8$,

$c=0.1$, $m=0.05$, $T=30$, $N=50$ and variances described above. For this base case, $n^*=10$ streams and $t^*=4$ yrs. The effects of changing these parameters are summarized below:

1. Increasing nominal benefit/cost ratio (BT relative to $C+T_c$):

Higher ratios favour increasing the number of treated streams (n) but have little effect on the duration t . For ratios exceeding 2.0, n^* stabilizes at around 16 pairs.

2. Increasing the planning time horizon T :

Taking a longer term view favours increasing both the number of treated streams and the duration of the experiment. For T greater than about 100 yrs, n^* stabilizes at about 15 pairs and t^* at about 8 yrs.

3. Increasing the number of watersheds N :

Considering more watersheds as potential candidates for restoration causes the best number of pairs n^* to increase, to an asymptotic value for very large N of around 16-20 pairs.

4. Increasing capital cost per watershed, C :

Higher initial costs have no noticeable effect on the optimum duration of experiment, but reduce the optimum number of pairs n^* to a minimum of perhaps 6 pairs for $C > 3$.

5. Increasing annual operating cost per system, c :

Higher operating costs (relative to capital costs, but while holding overall benefit/cost ratio constant) favour experimenting on more systems (n^* increases to 20 or more), and for longer times (t^* increases to 6-8 yr).

6. Increasing annual monitoring cost per system, m :

Even small increases in this cost cause a rapid decrease in both the optimum number of streams and the optimum experiment duration, and an increase in the optimum probabilities of a wrong decision at time t^* . In contrast, decreases in monitoring cost do not substantially increase the optimum experiment size. The relative cost level $m=0.05$ (relative to $C=0.8$, $c=0.1$) thus appears to be a quite well defined upper bound on how much it is worth investing in monitoring, per stream.

7. Increasing within-watershed over time variance $\text{var}(s\&t)$:

Increasing local "noise" in responses favours slightly reducing both the number of treated streams and the duration of the experiment, thus accepting slightly higher probabilities of a wrong decision at time t . However, this effect is minor.

8. Increasing among-watershed variation var(systems):

Increasing variation in average index values among watersheds favours increasing the number of stream pairs (to 14 for c.v.= 1.2) and slightly decreasing the duration of the experiment. The favoured increase is about that needed to result in stable probabilities of a wrong decision.

9. Increasing temporal variation in response var(response):

Curiously, increasing the year-to-year unpredictability in the treatment response has no apparent effect on the optimum size of experiment, even when the c.v. is increased drastically (to 3.0 or larger). Increasing this variance does reduce the expected value of the experiment and the probability of making a wrong decision down the road, but it is apparently not optimum to reduce the risk by increasing the size/duration of the experiment.

These results are encouraging in the sense that there appears to be a very robust "target" size for experimental design, in the order of 8-16 experimental stream pairs and 4-8 yrs of initial experiment duration. However, this conclusion must be carefully tempered by noting that very long term, slowly emerging treatment effects have not been considered at all in the analysis. A key need at this point is to review possible responses in terms of time-scales of appearance, and to determine which monitoring measures are likely to give the quickest "early warnings" about slower responses.

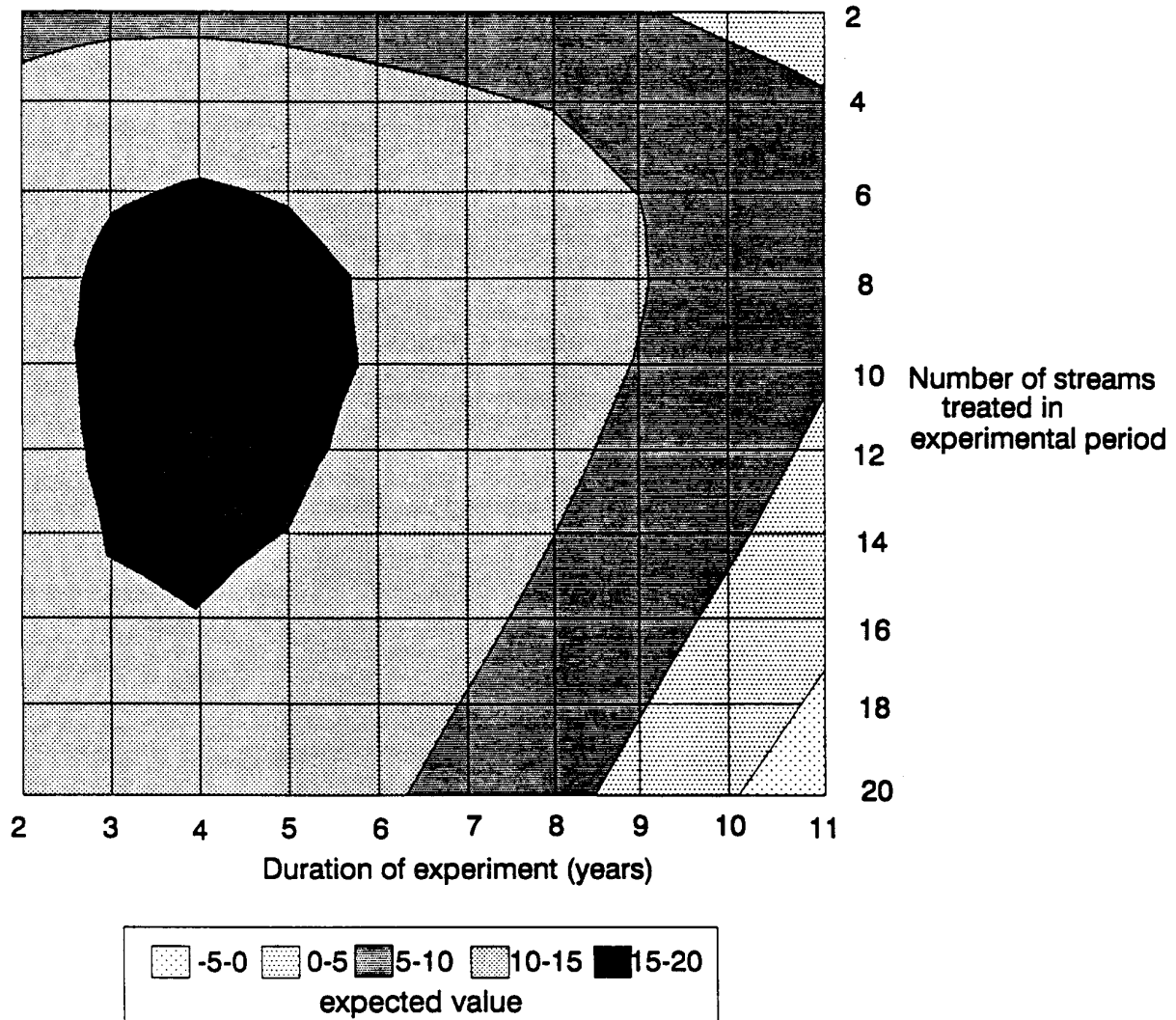


Fig. 2. The expected value of experimental policy in terms of the cost to benefit return of examining a number of watersheds over several time periods.

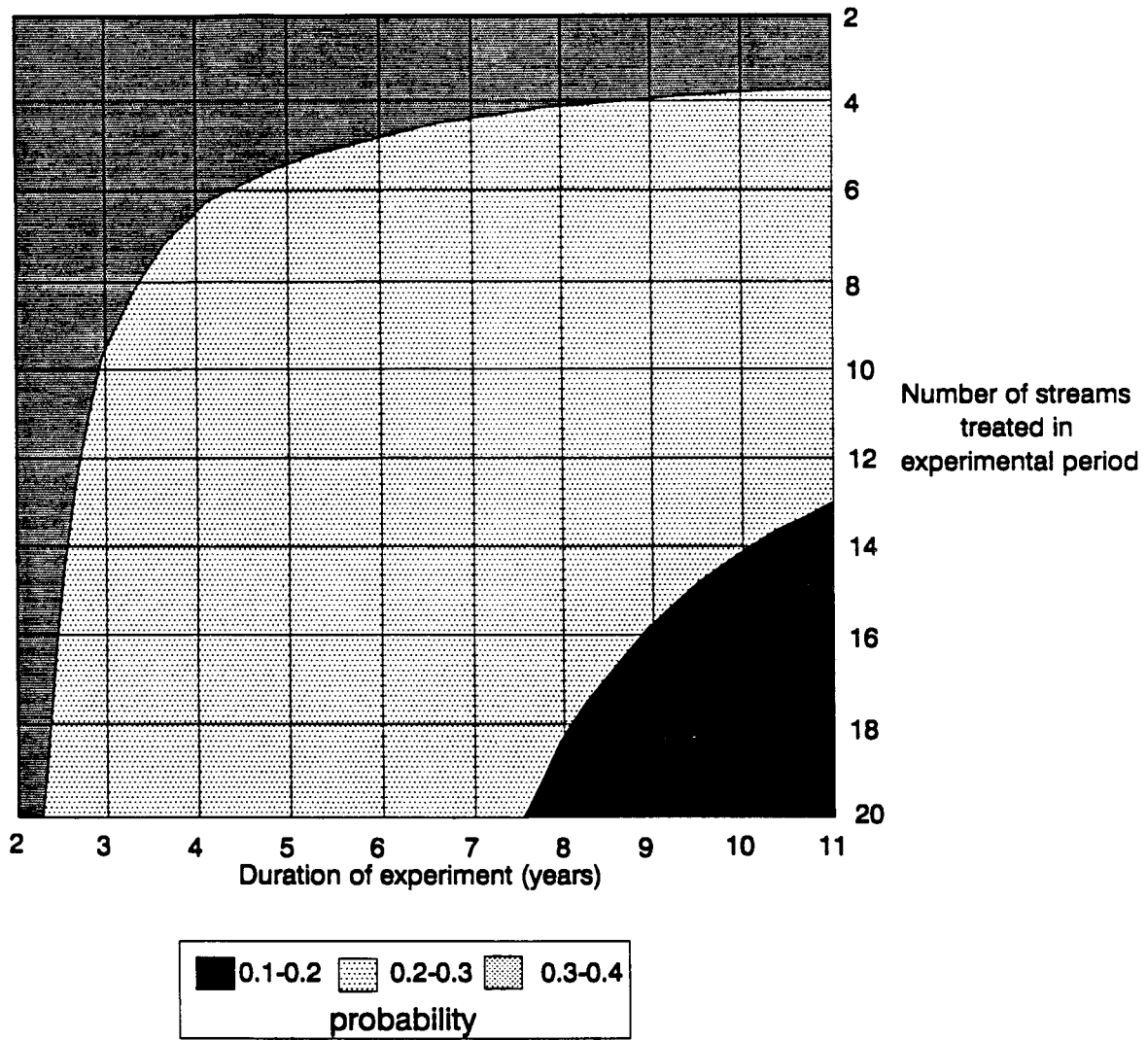


Fig. 3. The probability of making a false decision at the end of an experimental period based on the duration and the number of streams in the experiment.