Footprint Impact of BC Hydro Dams
On Aquatic and Wetland
Primary Productivity in the Columbia Basin

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Executive Summary

As part of the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) inquiry into the impacts of hydroelectric development within the Columbia Basin, this report focuses on aquatic and wetland primary productivity. A "hydroriparian" approach has been adopted herein, to reflect the tight linkage of the aquatic and riparian environments, including river floodplains, fans, lakes, wetlands and headwater streams. This report has endeavored to integrate the wetland and aquatic ecosystem components to gain a multidisciplinary, ecosystem perspective of the long-term implications of reservoir alterations to the primary productivity of floodplain ecosystems. In particular, the emphasis has been on; the amount, location and significance of ecosystem impacts, to assist the CBFWCP to develop, prioritize and monitor compensation projects, particularly in relation to higher trophic levels (fish and wildlife). This synthesis of aquatic and wetland information was based on numeric data from historical mapping, supplemented with historical records of the pre-dam condition of the Columbia Basin (photos, personal observations of locals and researchers, published documents, unpublished government and consultants reports) and tempered with professional judgment.

A Canadian approach to compensation for losses of the productive capacity within aquatic ecosystems was applied, as the “no net loss” principle under federal habitat policy. A hierarchy of *preferences* with priority on ‘like for like compensation’ by replacing natural habitat at or near the site of loss, followed by off-site compensation either as habitat replacements or productivity improvements of existing habitats.

Lacustrine

The surface area of pre-impoundment natural lacustrine ecosystems was about a half the surface area of present hydroelectric reservoirs of 1,505 km^2 (including Kootenay Lake). The pre-dam lacustrine habitat was dominated by the 6 large lakes, Kootenay, Upper and Lower Arrow, Duncan, Kinbasket and Whatshan Lake. Kootenay and Arrow lakes, contributed slightly over 90 % of the pelagic C and just over 85% to the total littoral C production. The total estimated pre-dam pelagic C from all natural lakes was 14,773 tC yr^{-1}. Kootenay, Kinbasket, Bush, Arrow and Duncan lakes were strongly influenced by high spring and early summer turbidity, which diminished light penetration (euphotic depth) and greatly reduced areal production rates until late summer when production increased. Littoral C production was driven by the large size of Kootenay and Arrow lakes but the littoral periphyton and macrophyte communities were more stable and biodiverse. Aquatic macrophytes were minor contributors to total lacustrine C production in the historic lakes with a few notable exceptions.

The creation of reservoirs within the basin has increased surface and pelagic area and pelagic C production by 2-fold over historic pelagic production from the natural lakes. Kootenay Lake, together with the 3 large main stem Columbia River reservoirs (Kinbasket, Revelstoke, Arrow), contributes about 29,000 tC yr^{-1} and over 90 % of the total present pelagic C production. Without nutrient supplementation, the present Kootenay Lake and Arrow Lakes Reservoirs pelagic C increase over historic is only 15-20 % higher, owing largely to gains from a deeper euphotic zone (better transparency) and losses from nutrient retention in upstream impoundments, i.e. oligotrophication. Kootenay Lake and Arrow Lakes Reservoirs represent 58 % of present lacustrine pelagic habitat area and contribute over 22,500 tC yr^{-1} or about 70 % of yearly total C in the presently configured basin. Without fertilization, Kootenay Lake’s and Arrow Lake’s contribution falls by over 6,000 tC/yr or about 20 % of present total lacustrine C production. Due to the magnitude and frequency of drawdowns, most of the reservoirs within the footprint now have severely compromised biotic communities in their littoral zones; their communities are ephemeral and lack biotic diversity.

Fluvial

Impoundments within the reservoir units caused losses of river and stream areas; total habitat area lost was 12,000 ha, which equates to both a gross and net loss of lotic area. From Donald Station to Keenleyside Dam in the Columbia system, only a very small un-flooded river segment (~2 km) remains at Revelstoke. Among all reservoir units in total, 97.3 % of the flooded habitat areas were rivers and large streams and only 2.7 % were small streams. The extent of losses of wetted side-channel areas remains an uncertainty owing to their difficult detection from historical 1:50,000 scale floodline maps. Undetected losses of productive side-channel areas may be up to 20 % per reservoir unit, which would elevate primary production by a similar amount. Additional uncertainty is associated with pre-dam glacial effects on primary production, which is discussed. Gross primary production (GPP) losses were largely proportional to areas impounded with the largest losses occurring in the Donald-Mica reservoir unit, followed by the Mica-Revelstoke unit, then the Wardner-USA unit and Arrowhead-Keenleyside unit. Estimated lotic GPP losses totaled 5,500 t C y^{-1}.

As a scoping exercise, estimated lotic salmonid losses were approximated from a biomass-alkalinity relation, adjusted for estimated weighted useable area as well as highly glacial conditions. As a first approximation, standing crop or biomass losses were predicted to range from 56,250 to 112,500 kg.

Fluvial compensation to achieve like for like replacements will need to focus on existing, nearby unflooded tributaries within a reservoir unit, and to attain larger river compensation, focus on habitat replacement and productivity improvements of rivers situated off-site throughout Columbia Basin.

Wetland/floodplain

The total area of pre-dam wetland/floodplain habitats has been calculated as 39,338 ha, of which 21,705 were forested and 17,633 were non-forested. Only understory components of forested wetlands were included in biomass estimates. An additional 1,016 ha of shallow water bodies were identified; these have not been included in productivity estimates due to a lack of information regarding their nature and some overlap with aquatic components. Present day reservoir 'wetlands' amount to less than 14% of the historic wetland/floodplain habitats. The most significant losses occurred in the Donald-Mica unit where 89% of these habitats were lost due to impoundment. The Duncan reach lost 93% of its historic wetland and floodplain habitat. Although major historic vegetation losses occurred, following impoundment of the Revelstoke-Arrowhead Reach, recent revegetation of the drawdown zone has occurred in conjunction with the agronomic fall rye seeding and fertilization in the Revelstoke dust control program areas. These re-vegetated areas are now dominated by reed canarygrass and native sedges, and serve as an example of potential enhancement/restoration opportunities in the reservoir environments.

Historic net primary production (NPP) in wetland and floodplain environments in the Columbia Basin has been calculated at 66,752 metric tons C per annum. Productivity is generally only measured, as NPP in wetlands and the conversion to GPP is an area of uncertainty as GPP: NPP ratios are poorly understood for wetlands, but it is generally acknowledged that GPP rates far exceed NPP. Estimating a conversion rate of (NPP=50% of GPP), the annual total C fixed in wetland and floodplain environments was calculated as 133,504 metric tons. The carbon contribution from the wetland/floodplain areas to the aquatic environment was dominated by the Donald-Mica reservoir unit (54%), followed by Arrow Lakes (18%), Revelstoke (11%), Duncan (8%), and Koocanusa (8%). Kootenay numbers are excluded due to a lack of wetland information for the area, but considering the nature of the lake, wetland areas are expected to have changed very little in response to alterations to the inflows.

Present day carbon export from reservoir wetlands is estimated at 12,000 metric tons per year; less than 14% of historic. Kinbasket is estimated to produce 40% of present day export compared to the Revelstoke Reach production of 48%. Kinbasket reservoir shorelines at present contain a larger area, but relatively impoverished cover of vegetation compared to Revelstoke Reach.

Synthesis

Wetland/floodplain ubiquity in the basin pre-dam era resulted in a GPP carbon contribution of over 87% of total C compared with lakes (10%) and rivers/steams (4%). The present era river/lake autotrophic C template is slightly larger than the pre-dam total but the rivers/streams component has basically been replaced while reservoir pelagic habitats have risen to a dominant position (73%) and are now contributing more C than wetlands C production (27%). Rivers/streams presently contribute only negligible quantities of C. There has been a shift from a high-level of aquatic habitat diversity and accompanying biodiversity to a more simple and linear pelagic driven landscape; major losses of biodiversity have occurred within the present basin across all aquatic habitats. The loss of a productive, functional littoral and shoreline ecosystem where periphyton communities are abundant on soils and on macrophytes, and where wetlands are plentiful and prolific, in most all reservoirs has constrained total basin C production.

The total annual carbon production (GPP) from the hydroriparian environments (lakes, rivers, wetland/floodplains) of the historic Columbia Basin was calculated as 180,445 tC yr^{-1}. In contrast, the current carbon production from the reservoir environments has been assessed at 53,506 tC yr^{-1}, or 30% of historic.

Compensation options for each component (lakes, rivers, wetlands) are addressed in the report.

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We thank the many individuals who were willing to share their recollections of early times in the Columbia Basin which assisted us in developing a pre-impoundment vision for this report.

Cover – Kinbasket Reservoir drawdown zone near Beavermouth, July 2003 (A. Moody photo).

1.0 INTRODUCTION

The Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) has been conducting a multi-phase project to evaluate the footprint impacts[1] of BC Hydro developments (including the Koocanusa Reservoir, a Libby Dam impact) within the Columbia Basin (Figure 1). The project is intended to determine habitat, primary productivity, and fish and wildlife community changes resulting from the original dam construction impacts. The subsequent operational impacts of the dams are considered a separate issue, dealt with in the WUP (Water Use Planning) process.

Phases 1 and 2 of the footprint project (an assessment of existing data[2] and pre-impoundment habitat mapping using air photos and historic base maps[3]) were previously completed. This report continues with the interpretation and analysis phase by determining the impacts of reservoirs on aquatic and wetland primary productivity, from pre-impoundment conditions to the current scenario, the Columbia Basin dominated by reservoirs controlled by BC Hydro and other dams. The footprint impacts project is intended to provide a baseline understanding of the amount, location and significance of ecosystem impacts of dam footprints in the Columbia Basin, and to assist the CBFWCP to develop, prioritize and monitor compensation projects. Therefore, the primary production component of this project is a stepping-stone to addressing higher trophic level losses in the basin.

[1] see Appendix 1 for definition of footprint impacts

2 Ahrens and Korman. 2004. An evaluation of available data to assess BC Hydro dam footprint impacts in the Columbia River Basins, British Columbia and Phase II recommendations. Report prepared for Columbia Basin Fish and Wildlife Compensation Program, Nelson, BC. September 2004.

3 Ketcheson, M.V., K. Misurak, V. Lipinski, G. Kernaghan, K. Lessard, T. Dool, L. Bradley and E. White.2005. Columbia Basin BC Hydro Footprint Mapping: BC Hydro Reference Number DFIM040. Report prepared for CBFWCP, Nelson, BC.

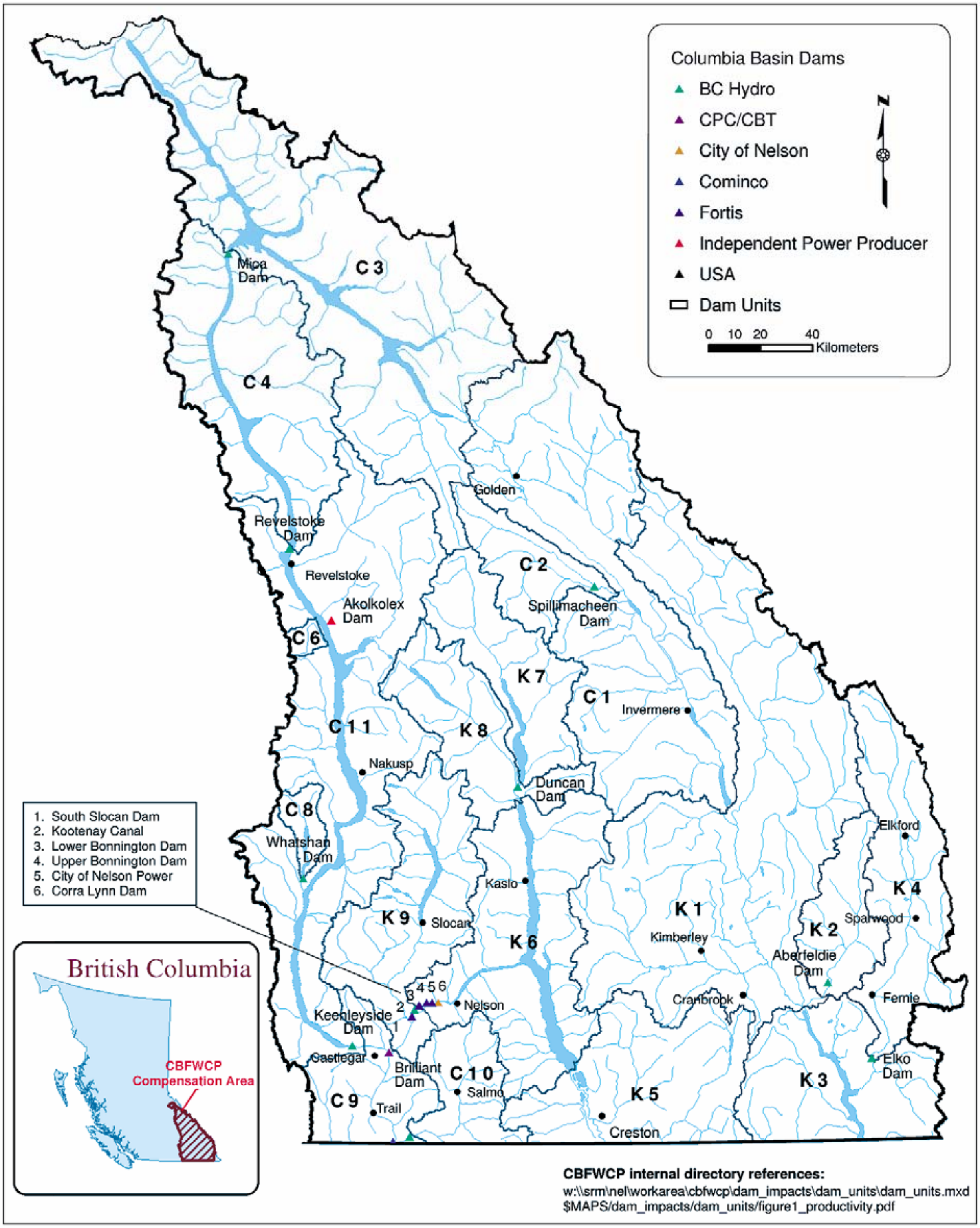


Figure 1: Columbia Basin Fish and Wildlife Compensation Program Area showing major dams and reservoirs.

1.1 Scope and Objectives

The objectives of the primary productivity assessment, as initially identified by the CBFWCP, were to:

- Establish and/or update the understanding of net (gains and losses) **aquatic and wetland footprint impacts on primary productivity** from BC Hydro dams in the Canadian portion of the Columbia River Basin;
- Identify a full range of **aquatic and wetland primary productivity compensation opportunities** and their predicted effectiveness;
- Provide a summary of **approximate costs to implement** the identified compensation opportunities; and,
- Identify **performance measures** and provide costs for program and project monitoring and evaluation.

During the course of the project, some of the objectives were modified to better reflect the overall goals of the project and to deal with data gaps. The foremost change in the scope was the inclusion of Kootenay Lake in the footprint assessments.

The study is intended to be a synthesis and analysis of information related to pre-impoundment conditions (prior to construction of the BC Hydro dams) within the CBFWCP program area, as related to subsequent changes in aquatic and wetland primary productivity. As such, it has been necessary to examine historical information to determine the physical factors affecting primary productivity and to clearly define those segments of the riparian and wetland environments supporting the aquatic food chains. Carbon (grams of carbon per hectare per year) has been chosen as a common currency to compare footprint impacts across a range of aquatic and wetland systems and to assess pre and post dam effects. Specific tasks include a quantification of the impacts of habitat changes on primary productivity and consideration of how these impacts could affect other trophic levels particularly the wildlife and fish resources of the basin. The latter includes salmonid fishes, for which losses are approximated as support for aquatic compensation options that include fish habitat measures as well as broader ecosystem treatments. Impacts of dams as fish migration barriers that cause fragmentation of fish communities and issues related to habitat biodiversity are dealt with in other components of this multi-phase project.

The suitability of the available metrics was to be evaluated with recommendations made for potential alternates. Compounding effects from upstream to downstream were to be included and quantified, where possible. Primary productivity impacts that could not be quantified were to be identified. Based on the results of the impact analysis, a review of potential compensation options was undertaken. Monitoring requirements, to determine the effectiveness of each compensation option, (including performance measures, measurement frequency, spatial and temporal measurement horizon, measurement units, and associated costs) were addressed. Performance measures were identified to evaluate the results of the recommended compensation options.

Twelve reservoir units (Table 1) were identified as the scope of this study. These ranged from the very small run-of-the-river reservoirs, on the Spillimacheen and Elk rivers, to the largest two reservoirs, Arrow and Kinbasket lakes, which together represent over 72% of the footprint area. The small reservoirs in the Kootenays are the oldest in the system, dating as far back as the 1920’s and 30’s. Revelstoke Reservoir is the most recent (completed in 1984). Although not directly affected by a BC Hydro reservoir, the cumulative effects of watershed changes on Kootenay Lake were considered too significant to leave out of the synthesis. However, five dam units were excluded from the study as:

- one is in the process of being restored (Cranberry Creek-Walter Hardman),
- others had no direct impacts from BC Hydro reservoirs (Columbia-Donald, Kootenay-Wardner, USA-Kootenay Lake), and
- the remaining unit (Keenlyside-USA,) was considered addressed by the coverage of the other dam units.

Table 1: Reservoir Units and Footprint Areas (based on CBFWCP-GIS data 2006).
Units not included in this study are shaded.

Dam Unit	Reservoir Unit	Reservoir Unit Area (ha)	Dam	Year Completed	Reservoir Age	BC Hydro Footprint Area (ha)	% of Total Footprint
C1	Columbia-Donald	865,932					
C2	Spillimacheen River	145,719	Spillimacheen Dam	1955	50	1	0.0%
C3	Donald - Mica	1,103,953	Mica Dam	1973	32	42,045	34.8%
C4	Mica - Revelstoke	525,489	Revelstoke Dam	1984	21	11,450	9.5%
C6	Cranberry Creek-Walter Hardman	14,898				-	
C8	Whatshan	39,344	Whatshan Dam	1952	53	1,764	1.5%
C9	Keenleyside-USA	180,542				-	
C10	Waneta - USA	141,307	Seven Mile Dam	1973	33	428	0.4%
C11	Arrow Lakes Combined C5 & C7	972,795	Hugh Keenleyside	1968	37	47,131	39.0%
K1	Kootenay-Wardner	1,201,720				-	
K2	Bull River	151,424	Aberfeldie Dam	1922	83	12	0.0%
K3	Wardner - USA	342,712	Libby Dam	1972	33	6,649	5.5%
K4	Elk River	351,893	Elko	1924	81	18	0.0%
K5	USA-Kootenay lake	387,033				39,400	
K6	Kootenay Lake tributaries	492,923					
K7	Duncan River tributaries	243,000	Duncan Dam	1967	38	7,299	6.0%
K8	Lower Duncan - Lardeau	233,223					
K9	Corra Linn - Brilliant	363,843	Kootenay Canal	1976	73	49	0.0%

1.2 Approach

The overall approach to documenting footprint impacts was to develop a comprehensive perception of wetland and aquatic habitats and physical factors influencing primary production, as they were prior to the development of hydroelectric projects in the Canadian portion of the Columbia Basin. Historical information was gathered from as many sources as possible. This included a review of BC Hydro archives, Provincial Government archives, local museum and historical society archives, published documents concerning the history of the Columbia Basin, and “grey literature” (i.e., unpublished government and consultants reports). Further information was gained from consultation with people who had personal knowledge of the area prior to dam construction. This included local residents, fishing guides and biologists who had worked on the various projects. Pre-impoundment photos collected from the various sources provided an invaluable resource for re-creating the ecological history of the Columbia Basin. The historical record was complemented by scientific literature sources and the professional experience and judgment of the authors. Finally, all the accumulated information was pooled with numerical data from the historical mapping, undertaken as an earlier phase of the footprint project, to form an overall perspective of the pre-dam nature of the lakes, streams and wetlands of the region.

Documenting historical change in ecosystems has been likened to viewing a movie from isolated clips. Our understanding of the past is based on snapshots in time, consisting of various narratives and sets of data accumulated by researchers in different fields, over widely spaced time and place. Standards of research were different in the past and levels of effort varied according to discipline. Wetland research was in its infancy when the damming of the Columbia was occurring and did not become “mainstream” until the mid to late 1970’s (Mitsch and Gosselink 1993), therefore it is not surprising that quantitative and qualitative data for the pre-impoundment wetlands of the Columbia Basin is lacking. Fisheries biology and limnology preceded the development of wetland science by at least 50 years; they were in a more advanced state as disciplines, at the onset of Columbia Basin hydroelectric developments, consequently there is a greater (but still limited) store of historical information available in these areas. In the past, scientific disciplines involved in river basin studies (fisheries biology, wildlife biology, forestry, limnology, plant ecology) tended to examine portions of habitats in isolation, without considering the connectivity and importance of the wetland/floodplain/aquatic complex. Therefore, the historical information bank is also lacking an ecosystem perspective.

Recently, watersheds (drainage basins) have been viewed from a more holistic perspective and ecological theory in lentic and lotic system ecology has been moving toward integration across existing disciplines.
Major theories for nutrient transfers in river systems have included the:

- River Continuum Concept (Vannote et al. 1980)
- Nutrient Spiraling Concept (Newbold et al. 1981)
- Serial Discontinuity Concept (Ward & Stanford 1983,1995b)
- Flood pulse concept (Junk et al. 1989)
- Hyporheic Corridor Concept (Stanford & Ward 1993)

These theories have generally been moving toward a more unified landscape level theory. The term "hydroriparian" has been adopted by the scientific community in western North America to reflect the tight linkage of the aquatic environment and the riparian area. Although it does not specifically refer to the above theories, it incorporates elements from them that emphasize the interconnection between land and water. The hydroriparian system, at a landscape level extends from headwaters through to the estuary, with floodplains comprising a subsystem. Hydroriparian ecosystems can be considered aquatic ecosystems and their adjacent terrestrial environments in a symbiotic relationship. They include river floodplains, fans, lakes, wetlands and headwater streams, and can be regarded as transportation corridors from mountain headwaters to the ocean, transferring water, sediment, nutrients, organisms, and wood through the watershed. They are multi-dimensional in nature, extending, longitudinally (along the river course), laterally (across the floodplain), vertically (below ground into saturated substrates) and temporally (seasonal changes). Hydroriparian ecosystems are characterized by regular disturbance, which their resident organisms are adapted to, by high biodiversity and by the presence of some of the most productive portions of the landscape. Most riparian research has occurred in coastal environments, Carnation Creek on Vancouver Island, the Queen Charlotte Islands, southeast Alaska and the US Pacific Northwest (Price & McLennan 2001). The prevalence of riparian research in coastal environments has been due, in large part, to wet environments where distinguishing between aquatic, riparian and terrestrial can be a challenge. In British Columbia, the term was first used in various studies related to Clayoquot Sound area (Scientific Panel, 1995) and most recently for the northern British Columbia coastal region in the hydroriparian planning guide (Price and McLennan 2001). Although the concept of hydroriparian has, to date, been applied primarily to coastal watersheds, we consider it a valuable model for this study. The Columbia Basin has many features in common with coastal environments (high precipitation in its upper portion, natural disturbance regimes) and is a large, complex river system with its ultimate destination as the Pacific Ocean.

Determining losses of carbon from alienated habitats was much more than a bookkeeping exercise, despite the advantage of having numeric results from lake, stream and wetland mapping. We recognized that the Columbia River basin was much more than a sum of its parts, and that we had to consider it as an interactive ecosystem. This report has endeavored to integrate the wetland and aquatic ecosystem components to gain a multidisciplinary, ecosystem perspective of the long-term implications of reservoir alterations to the primary productivity of floodplain ecosystems.

2.0 LANDSCAPE OF THE EARLY COLUMBIA BASIN

The following section provides a synthesis of the historic nature of the Columbia Basin, assembled from documented sources and historical photos. The description follows the course of the rivers, from headwaters to the U.S. border. Reservoir units are described in sequence, first on the Columbia, then the Kootenay River. The treatments follow the sequence presented in Table 1, but are somewhat uneven, depending on the availability of information and on the size and significance of the reservoir units. The historical photos have been included despite sometimes-poor image quality as they are of significant value in assessing pre-reservoir conditions. Although the dates of some of the photographs were unavailable, they were clearly taken long before the reservoirs were established.

First and foremost, the Columbia Basin region is defined by four mountain ranges: the Monashee, Selkirk, Purcell, the Rocky Mountains, and their unique geology, soils and climate. The growing season, light availability and ambient temperature, which in turn control primary production, are governed by elevation and other effects of the mountains such as glacial inflow and debris torrents from avalanches. Most of the Columbia Basin lies within the Nelson Forest Region and, characterized based on broad climatic patterns, lies within three climatic regions (wet, moist, and dry) (Braumandl & Curran 1992). The dry climate region occupies rain shadows of the Coast and Columbia mountains, and covers the Rocky Mountain Trench and much of the Rocky Mountains in the East Kootenay. All other areas are included within the moist and wet climate regions (Figure 2). The moisture regime is of utmost importance for aquatic and wetland habitats and dictates the changing nature of the Columbia Basin from its headwaters to the limit for this study, the US border.

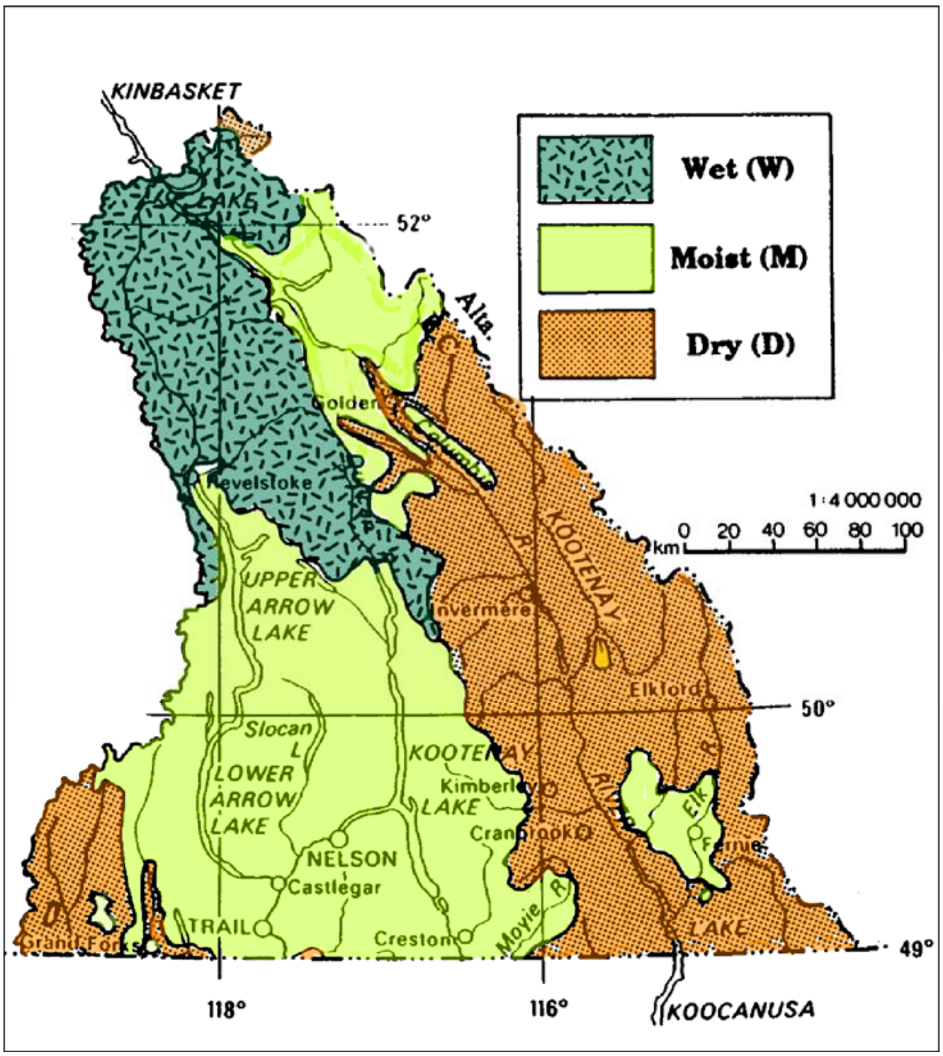
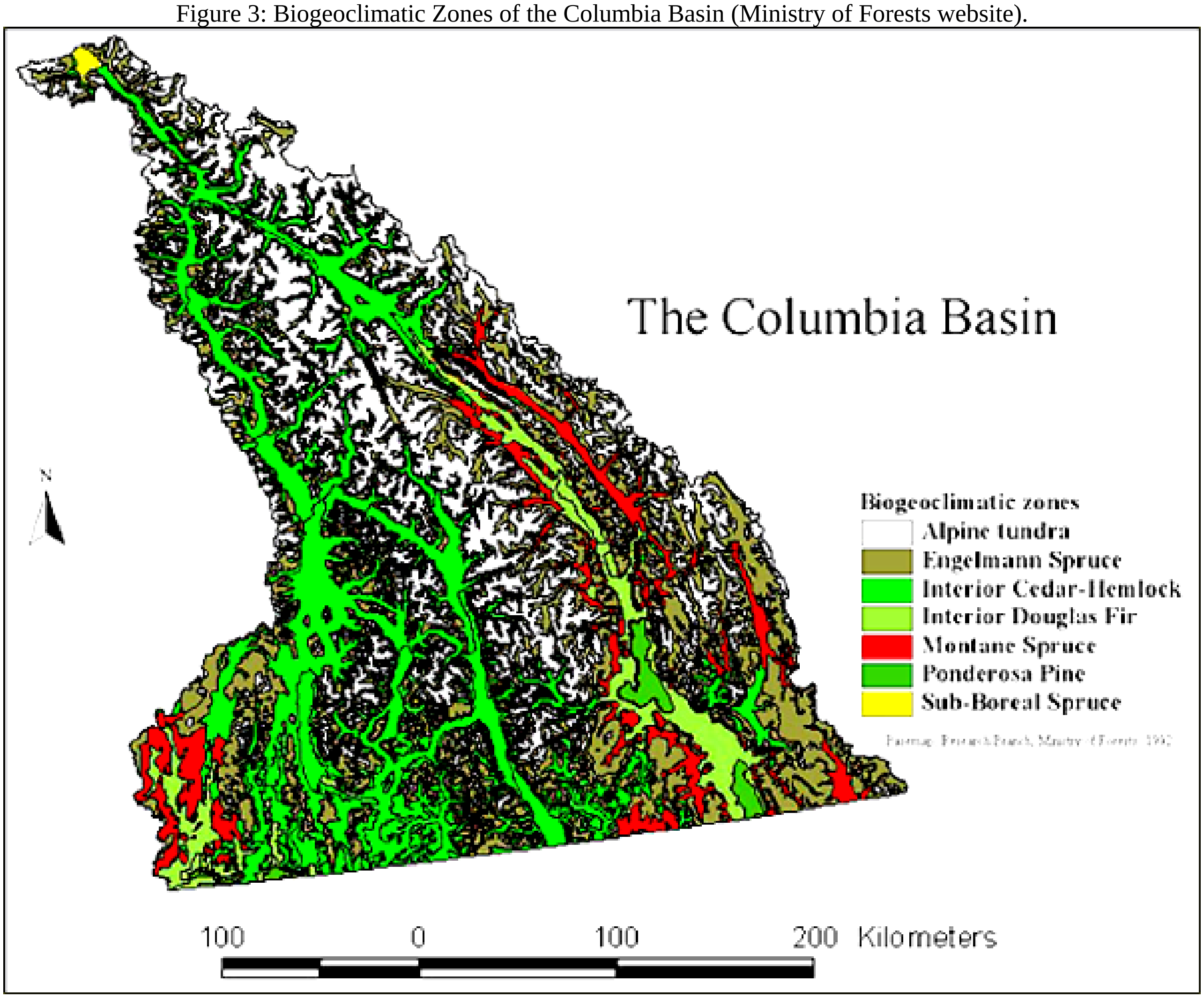


Figure 2: Climatic regions of the Columbia Basin (after Braumandl and Curran 1992).

Within these climatic ranges, four biogeoclimatic zones encompass the valley bottoms affected by reservoirs (Figure 3): the Ponderosa Pine (PP); Interior Douglas-fir (IDF); Interior Cedar-Hemlock (ICH) and Sub-boreal Spruce (SBS). The **Ponderosa Pine Zone (PP)** is found only in the driest sections of the southern Rocky Mountain Trench, north of Cranbrook and on the southeast side of Lake Koocanusa (Braumandl & Curran 1992). In the East Kootenay, the **Interior Douglas-fir Zone (IDF)** surrounds the PP, covering much of the Rocky Mountain Trench as far north as Golden. The **Interior Cedar-Hemlock Zone (ICH),** one of the largest zones in the Nelson Forest Region occupies the lower slopes of the Rocky Mountains, north of Golden and around Fernie and the Columbia Mountains. The ICHdw occurs in a band below the ICHmw2 in the valley bottoms and lower slopes of the southern Columbia Mountains. The ICHmw2 is the largest ICH subzone/variant in the Nelson Forest Region and occurs above the ICHdw on lower slopes of the southern Columbia Mountains. It can be found in valley bottoms north of the ICHdw. The ICHmw1 is found on lower to mid-slopes in the Rocky Mountains from Golden to the Sullivan River. The ICHwk1 and ICHvk1 variants are located in the more northern parts of the Nelson Forest Region in the wet climatic region. The ICHwk1 is located in the valley bottoms and lower slopes of the upper Duncan River and the Columbia River drainages from Revelstoke to Goldstream River and along the west shore of Kinbasket Lake from Gold River north to the regional boundary. The ICHvk1 is located in the valley bottoms and lower slopes in the Selkirk and Monashee Mountains from the Goldstream River to Mica Creek. The Sub-boreal spruce zone only occurs in the portion of the Columbia Basin outside the Nelson Forest Region, in the northern portion of Canoe Reach, near Valemount.

Figure 3: Biogeoclimatic Zones of the Columbia Basin (Ministry of Forests website).



Climatic conditions vary considerably within the Columbia basin (Table 2). Frost-free days range from 96 to 149 days; snowfall from 122 to 734 mm, and summer precipitation from 197 to 385 mm (Braumandl and Curran 1992). Mean daily temperatures in July are generally 16-20°C (Environment Canada).

Table 2: Climatic characteristics of the Nelson Forest Region Biogeoclimatic Zones and subzones/variants (Braumandl & Curran 1992).

Subzone/ variant[a]	Number of climate stations[b]	Mean annual precip-itation[c] (mm)	Mean summer precip-itation (mm)	Mean annual snowfall (mm)	Growing degree days (>5°C)	Frost-free period (days)
PPdh2	4	484 403-605	227 165-270	129 109-170	1777 1712-1861	117 107-128
IDFun	1[d]	498 --	203 --	122 --	1918 --	160 --
IDFdm2	14	455 369-577	197 158-291	187 121-379	1437 1197-1668	96 42-122
ICHdw	18	740 566-941	243 189-300	239 122-495	1870 1475-2140	143 90-184
ICHmw1	1	1064 --	325 --	422 --	1808 --	149 --
ICHmw2	5**	840 661-1113	294 229-393	304 204-556	1792 1673-1988	149 127-169
ICHmw3	3**	1004 895-1171	307 275-336	461 460-462	1435 --	135 89-165
ICHwk1	5**	1214 868-1725	385 325-461	588 375-1090	1364 991-1808	121 104-149
ICHvk1	1	1419 --	331 --	734 --	1387 --	138 --

[c] Climate data (mean and ranges given) compiled from the 1951-1980 climate normals for British Columbia. Long-term records from the AES were used to normalize short-term records from AES and Ministry of Environment stations (G. Reynolds, 1991, Climate Data Summaries for the Biogeoclimatic Zones of British Columbia, Version 3, BC Ministry of Forests. Unpublished report).

[d] Deer Park station.

2.1 COLUMBIA RIVER/DAM UNIT DESCRIPTIONS

The Columbia River begins its 2,000 km journey to the Pacific Ocean at Columbia Lake in the Rocky Mountain trench. Although its tributary streams flow down steep mountain slopes, the Columbia River for the most part, flowed in a broad valley, periodically constricted by bedrock into hazardous rapids. The broad valleys became today's reservoirs and the rapids are either, hidden by reservoir waters, or buried beneath dams. The constrictions in the valley served to impede flow during spring run off, resulting in a backlog of water, which overtopped the floodplains, resupplied the wetlands with moisture and nutrients, removed the previous year's detritus and transported it downstream.

A relatively gentle gradient in the Columbia River headwaters supports an expansive wetland system for the first 160 km of the river between Invermere and Golden (Figure 4). This section of the river serves as a reminder of pre-impoundment conditions for some downstream reaches. These relatively undisturbed habitats presently consist of sedge fens, bulrush and cattail marshes and intertwined swamps covering over 26,000 ha (Pedology Consultants et al. 1983).

Figure 4: Columbia River wetlands upstream of Golden (photo A. Moody).

2.1.1 **Spillimacheen Reservoir (Dam Unit C2)**

Figure 5: Spillimacheen River and headpond (top) entering Columbia River (bottom) (air photo –CBF&WCP files).

The 90-km long Spillimacheen River, a tributary of the upper Columbia, enters the Columbia River approximately 40 kilometres north of Radium Hot Springs near Windermere Lake. The river was dammed in 1955 to create a small run-of-the-river reservoir with a headpond approximately 1 ha in size. Little descriptive information is available concerning the pre-dam characteristics of this dam unit. The steepness of the terrain has produced a confined stream with little wetland development until it reaches the floodplain of the Columbia. At the confluence of the Spillimacheen and Columbia rivers, the Columbia valley is occupied by extensive areas of wetland (Figure 5), apparently unaffected by this facility.

2.1.2 Kinbasket Reservoir (Dam Unit C3)

The Columbia valley was first explored in 1807 and 1811 by David Thompson; he was followed by many others including artist Paul Kane some 30 years later. Paul Kane described the Columbia as follows:

> "*This river exceeds in grandeur any other perhaps in the world, not so much from its volume of water, although that is immense, as from the romantic wildness of its stupendous and ever-varying surrounding scenery, now towering into snow-capped mountains thousands of feet high, and now sinking in undulating terraces to the level of its pellucid waters*." (Clark 1995).

At an elevation of approximately 785m, near Golden, the Columbia begins a more rapid descent into its first hydroelectric impoundment, the area now referred to as Kinbasket Reservoir.

Of modern accounts, a pre-impoundment survey of the Columbia and Canoe river valleys undertaken in 1962-63 is one of the few pre-dam descriptions of fisheries, wildlife and habitat characteristics of the area (Peterson and Withler 1965a), They observed:

> *"The mainstem Columbia valley is steep walled throughout most of its length and rises on both sides to alpine elevations. There is little flat bench land along the valley sides above the maximum flood line elevation. Extensive areas of flat bottom lands exist in the wider portions of the mainstem valley below maximum reservoir level. Most of the bottom lands are seasonal and permanent marshes, much modified by beaver activity."*

> *"Permanent open water suitable for waterfowl and aquatic mammal habitat comprises 1010 acres of the Columbia valley portion of the reservoir. There are about 32 'open water' areas (excluding Kinbasket Lake) adjacent to the river. Populations of Canada geese and ducks use the sloughs as nesting habitat and large numbers of migratory waterfowl, including whistling swans, use this habitat during spring and fall migration."*

> *"About 2,800 acres of semi-permanent and seasonal sedge meadows will be inundated by Mica reservoir in the mainstem section. Moose, deer, black bear and elk occupy the sedge meadow areas at various seasons, including the winter months. Beaver and muskrat are present in large numbers in this habitat. Canada geese and ducks utilize wet sedge areas containing water."*

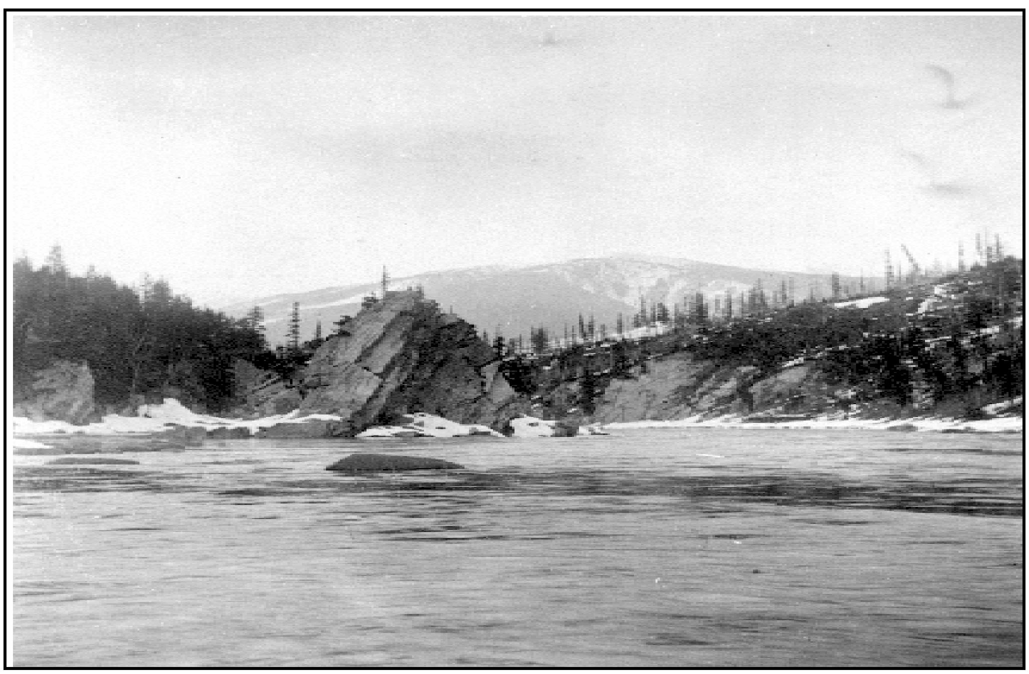
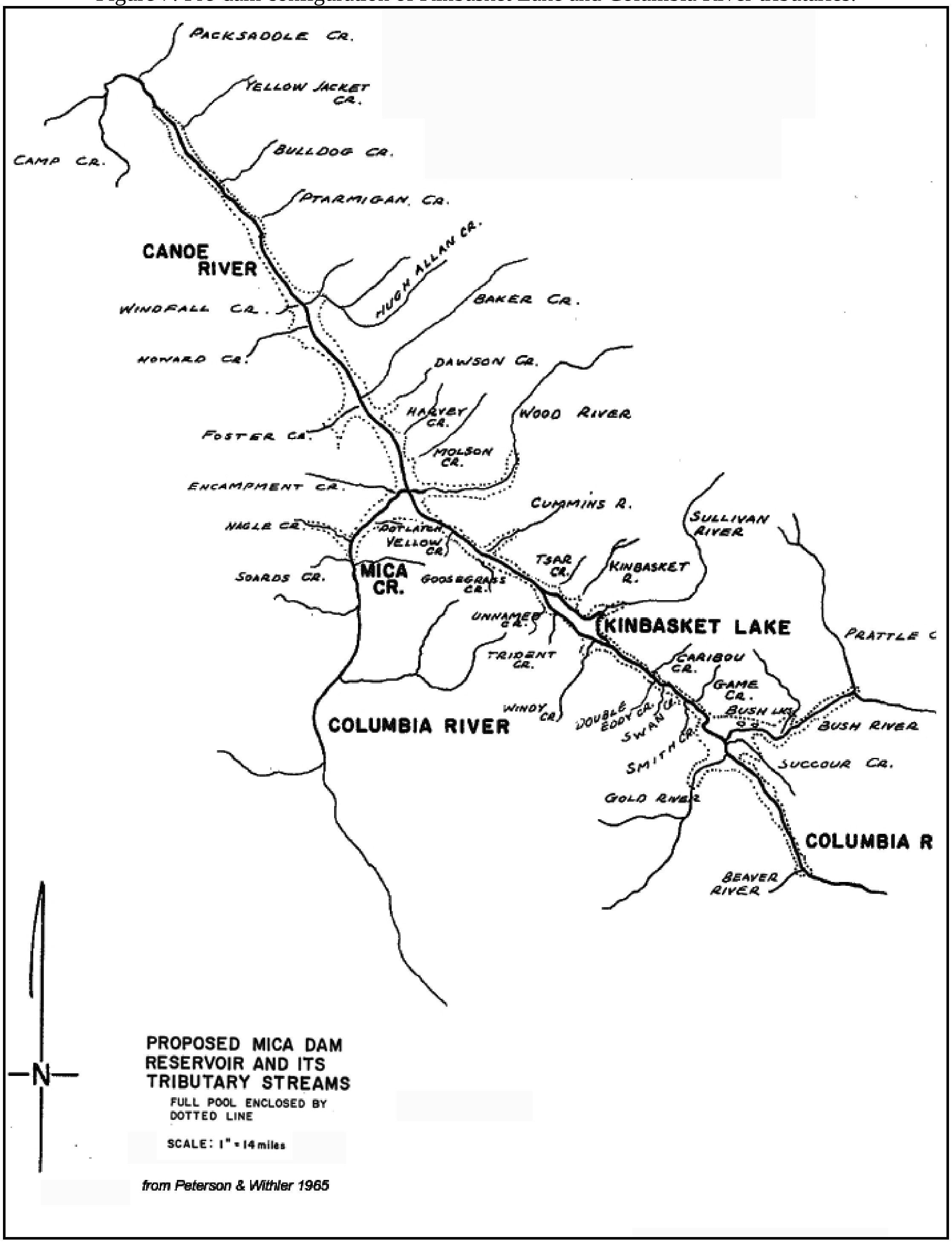


Figure 6: The Columbia River, at a small canyon south of Kinbasket Lake 1894 (BC archives A-09302).

During early spring, the upper Columbia River, upstream of Kinbasket Lake (Figure 6), was much less turbid than later in the spring to summer. By September freezing of higher elevations resulted in low turbidity until the following early spring months. All the tributaries flowing into the Columbia basin in this area (Figure 7) were described as being of glacial origin, carrying heavy sediment loads and having minimal amounts of spawning gravels. The best fish and wildlife habitat in the area was identified as occurring in and around Bush lakes, where extensive wetlands and spawning gravels were noted (Farquharson 1973, Peterson and Withler 1965a).

Figure 7: Pre-dam configuration of Kinbasket Lake and Columbia River tributaries.



Bush River and Lakes

Bush River was the first major tributary flowing into the Columbia River in the area now occupied by Kinbasket Reservoir (Figure 7). Bush Lakes were unique within the upper Kinbasket area of the Columbia River because they were observed to be highly productive (Figure 8, Figure 9) compared to most of the nearby rivers and streams, including the nearby Bush River, which were dominated by glacial flows.

Figure 8: Bush Lake (note dense macrophytic vegetation in foreground) (from Farquharson 1973).

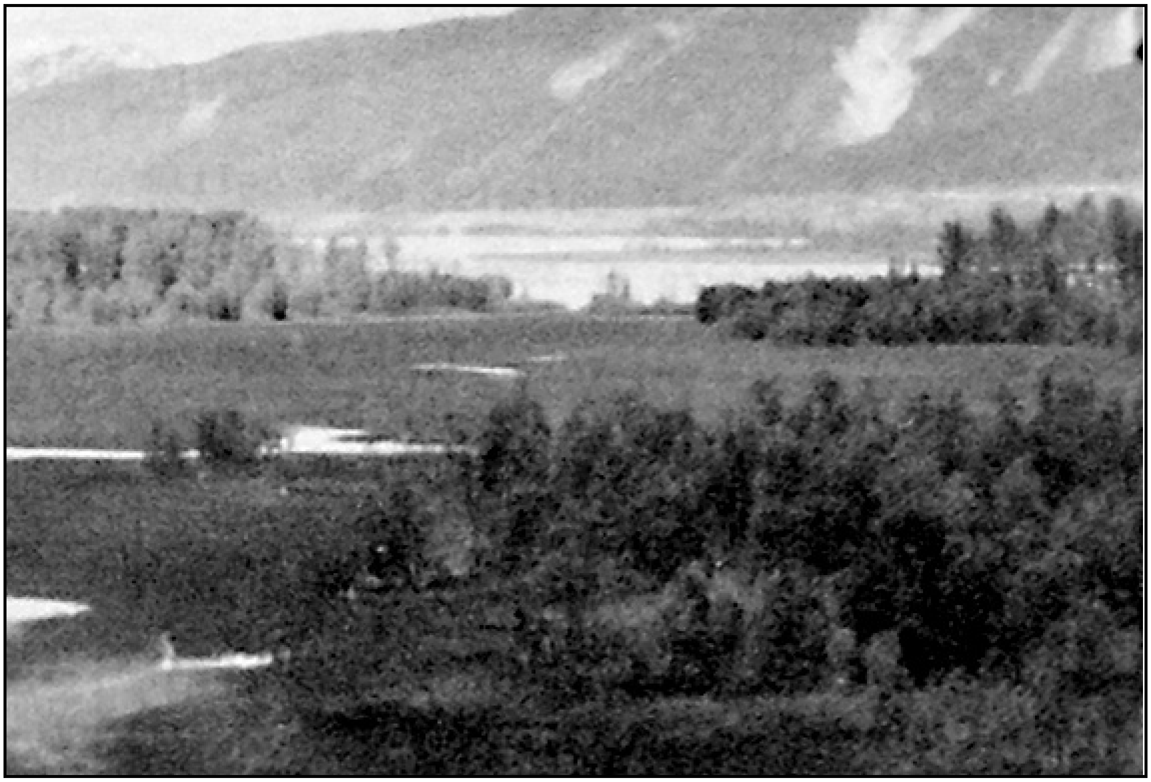


Figure 9: Bush Lakes looking northwest to Surprise Rapids (from Farquharson 1973).

The two Bush lakes were approximately equal in size; 3.2 km in length and 0.3 km in width, or about 100 ha, and had low mean depth, suggesting they were historically ice-melt lakes. Small gravels existed along their shorelines as well as throughout the 0.4 km stream connecting the two lakes and within two low-gradient tributaries. *Chara* (sp) was the primary macrophyte among a large macrophyte community that was associated with the expansive littoral zone of each lake (Peterson and Withler 1965a). Bush Lakes, as well as Kinbasket Lake and the Kinbasket "sloughs" were highly important for waterfowl (Fish and Wildlife Branch 1963 in Pedology Consultants et al. 1983).

The water in these lakes was humic, but not to the degree, that it limited lake productivity. Aquatic insect hatches were evident to a pre-reservoir survey crew in 1964, as were the numerous leeches along the shoreline and within the outlet streams. These were lakes to fish but not to wade and swim (P. Slaney pers. obs.). These readily accessible and productive lakes attracted attention from anglers with reports of 3.3 and 5 kg rainbow trout and char being caught, respectively (Peterson and Withler 1965a). Owing to their reputation and recreational use by anglers, especially from the town of Golden, the lakes became a remote stocking site for 30,000 fingerling rainbow trout from 1955 to 1960 by the BC Fish and Wildlife Branch (Peterson and Withler 1965a). There were several other productive small lakes approximately 50-80 ha in area, which were associated with the 760 m elevation adjacent to the Bush and Columbia rivers. These productive shallow lakes, only 3-5 m in depth, were noted by anglers for catches of 15 rainbow trout per angler day, with trout 1-2 kg in size (Peterson and Withler 1965a).

Kinbasket River

Kinbasket River was typical of the many tributaries flowing into what is now Kinbasket Reservoir. The steep valley slopes and stream gradient resulted in a high-energy, braided stream that discharged considerable amounts of sediment into Kinbasket Lake (Figure 10).

> *The valley floor was composed largely of dry gravel flats with relatively small areas of dry meadows along the valley edge. The few small areas of wetland are contained in the lower end of the valley* (Peterson and Withler 1965a).

Kinbasket Lake

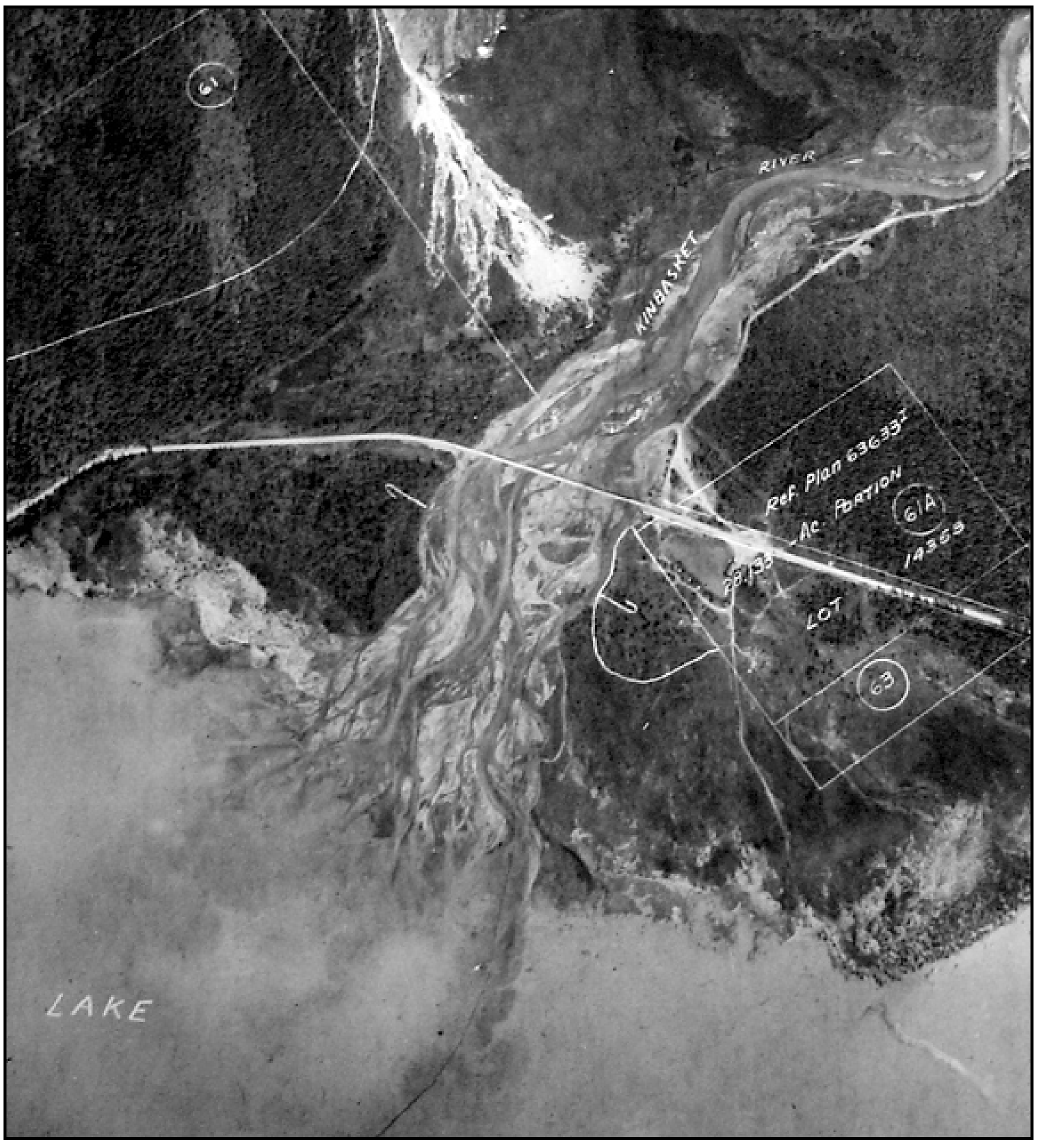


Figure 10: Kinbasket River entering Kinbasket Lake (BC Hydro Land Mosaic - Columbia River Developments-Mica Project; Air Photos June 6, 1966, courtesy of Arrow Lakes Historical Society).

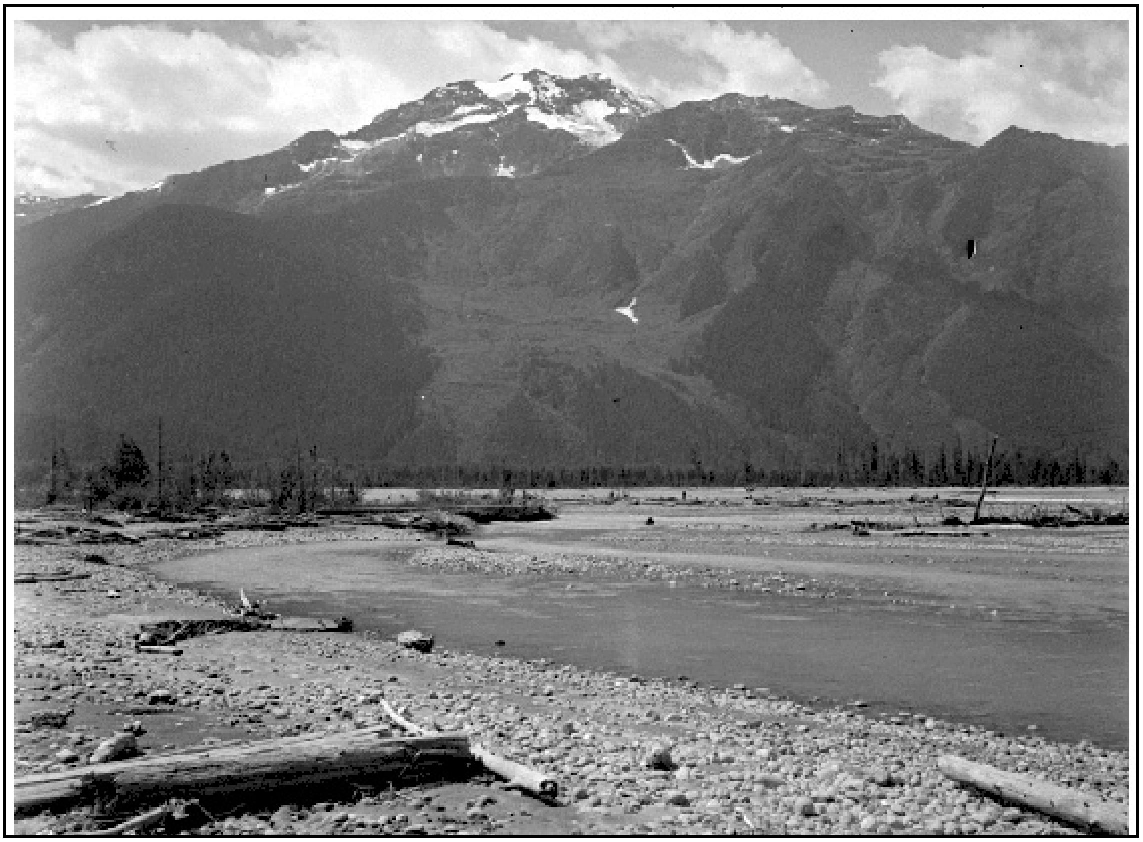


Figure 11: South end of Kinbasket Lake (pre-dam) viewed toward Windy Mountain (BC Archives NA- 07123).

Kinbasket Lake, located near the Big Bend of the Columbia River, was of profound natural significance to the productivity of the upper Columbia system (Figure 11). Prior to the development of Mica Dam, Kinbasket Lake was a widening of the Columbia River, occupying an area of approximately 2250 ha. Over its 11 km length, the large cool Columbia River dove deep into it, depositing great amounts of fine sediments on to its bottom, as well as unloading organic materials from 100's of kilometers of wetland and river production, which circulated through the lake driving heterotrophic productivity. It was a deep expansive settling basin which left a much less turbid-flowing Columbia River at its outlet where it dropped through steep "haystack" rapids towards its confluence with the Wood and Canoe rivers several kilometers downstream. The lake was steep-sided with only a narrow shoal bench on the east shoreline.

Combined primary and heterotrophic productivity was unusually high, as gill net catches of fishes indicated. Catches of fishes from Kinbasket Lake during late summer of 1964 were abundant to the degree they could not be processed in one day from standard gill net sets. Few were salmonids and most were peamouth chub, indicating a highly pelagic trophic structure, although kokanee were probably too deep to be caught in conventional gill net sets. Stream mouths were popular among anglers, attracted to large catches of sizeable char and whitefish (Peterson and Withler 1965a). The upper end of the lake, as well as the south east margins, were heavily dominated by wetlands that were drained via groundwater channels as well as side-channels from the Columbia River itself. The groundwater and slough channels, entering the lake below the Sullivan River and at the south end of the lake, were found by angling to be prolific feeding areas for 1-2 kg rainbow trout in late summer. These trout were likely taking advantage of aquatic insects and small forage fish from the productive wetlands, which were enriched by large abundances of waterfowl (P. Slaney pers obs., Peterson and Withler 1965a). The Columbia River below Kinbasket Lake was moderately turbid during early summer until flows subsided by late July to early August (Figure 12).

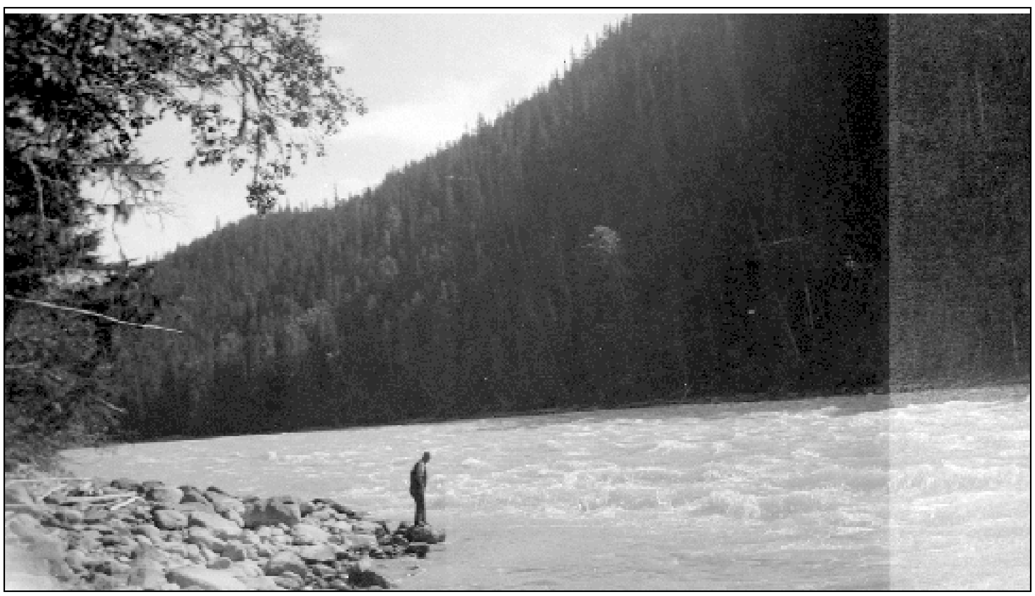


Figure 12: Rapids below Kinbasket Lake (photo taken 1936, BC Archives I-33432).

Wood River Valley

The Wood River valley is typical of many of the tributaries feeding the Columbia in this segment of the river. Steep sided valleys show many avalanche scars and the effects of heavy winter snowfalls (Figure 13, Figure 14).

> *Along the trail, stumps stood fifteen feet high, beheaded at snow level during winter crossings by David Thompson and his successors thirty years before. The snow was already twelve feet deep as Kane snowshoed down the western slope. He reeled from bank to bank of the Wood River and staggered into Boat Encampment. "He sketched in pencil the great turn of the Columbia-broad, flat, and as gray as the blade of a scythe, the peaks and ridges leaning into one another like a tumbled stack of slates.*" (Clark 1995).
>
> *Numerous areas of wetlands and open water sloughs extend along the valley edge where beaver have impounded tributary streams and rivulets…. The Fortress lake area of the system contains extensive sedge marsh areas…. Open water habitat used by waterfowl and aquatic fur species is about 45 acres in nine separate sites* (Peterson and Withler 1965a).

Figure 13: Wood River valley (from Farquharson 1973).

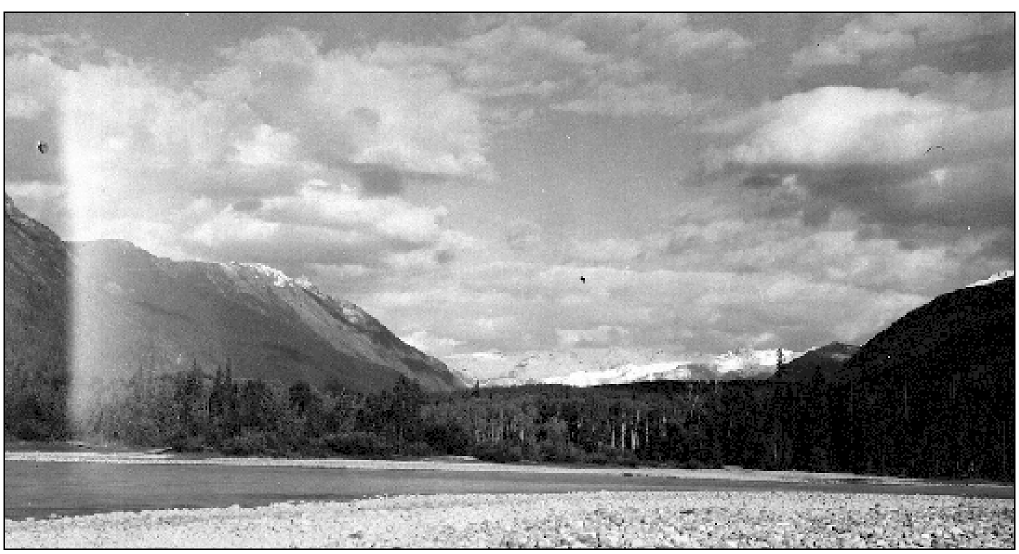


Figure 14: The upper Columbia River above Mica Greek at the mouth of the Wood River **(**BC archives I-57842).

Canoe River

The 100 km Canoe River was first explored by David Thompson. His journals document traveling up the river by canoe, but it soon became impassable and his party had to proceed by foot. Geomorphically, this river is similar to the Lardeau River, with a U-shaped valley, a moderate gradient, and large volumes of woody debris (Figure 15).

> *Many wetland areas occur on the valley floor, and are most extensive in the northern area. Sedges are the dominant wetland species mixed with rushes and grasses….Riparian plant growth is rich along the valley and on the edge of the wetlands*. (Peterson & Withler 1965a).

The habitats to be inundated by the Kinbasket reservoir were identified by Peterson and Withler (1965a) as including 1634 acres (661 ha) of open water, ponds and lakes (exclusive of Kinbasket Lake); 6645 acres (2689 ha) of "wet meadows" and 3720 acres (1505 ha) of "dry meadows" (Figure 16).

Figure 15: The Canoe River had a diverse mixture of riffles and pools, reflecting moderate gradients over most of its length (BC archives I-33436).

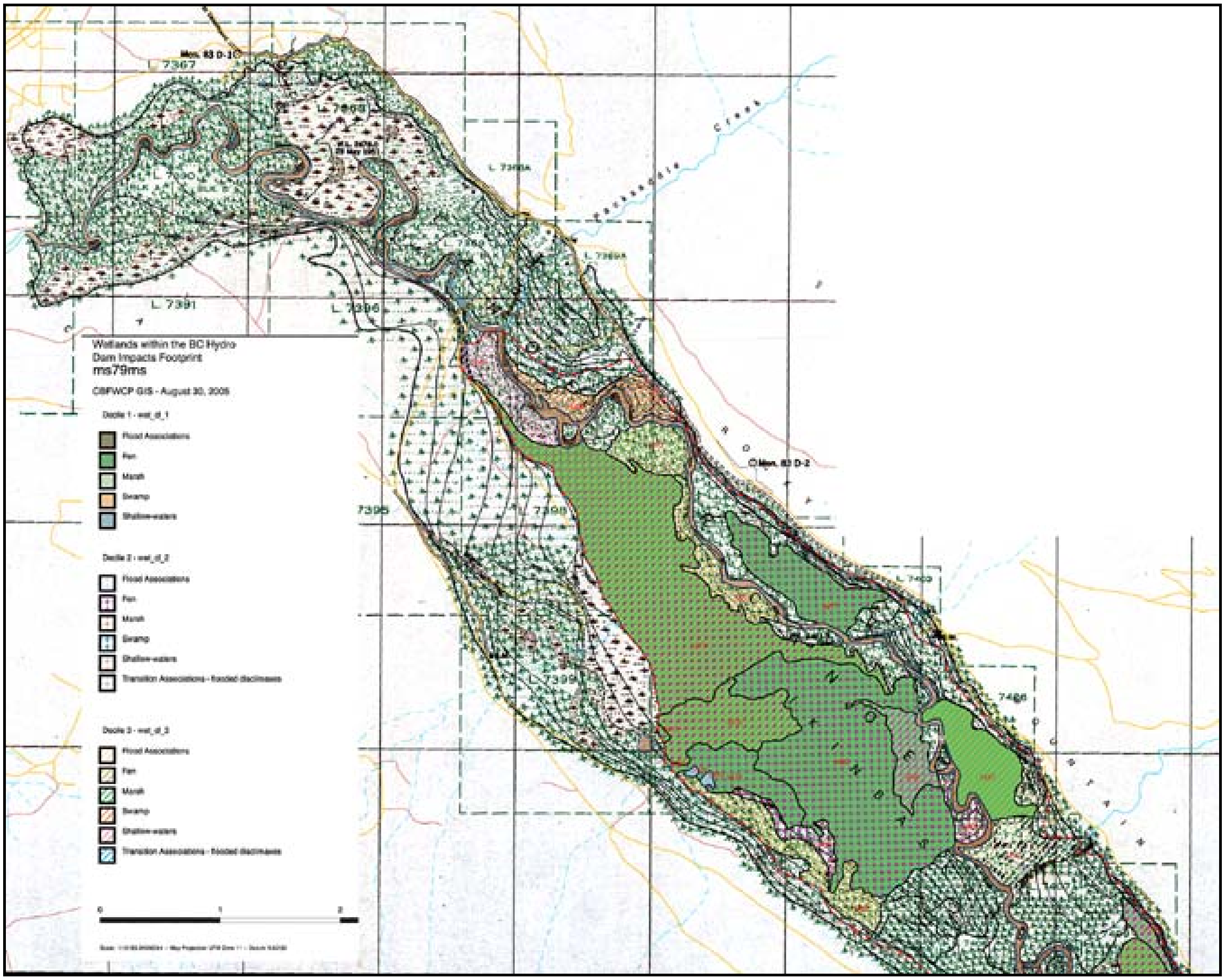


Figure 16: Historical mapping of upper Canoe River floodplain (MS79, Ketcheson et al. 2005).

Between the Big Bend and Mica Dam the Columbia River floodplain and river channel narrowed gradually. Extensive areas of valley bottom wetlands occurred between Mica Dam and the Big Bend area. Mica Dam was constructed in 1973 at the mouth of Mica Creek, where the Columbia River was constricted in width by bedrock outcrops. The characteristics of this area can be seen an image at the BC Provincial Archives website (BC archives call number I-50650 at http://www.bcarchives.gov.bc.ca/visual/visual.htm).

2.1.3 Revelstoke Reservoir (Dam Unit C4)

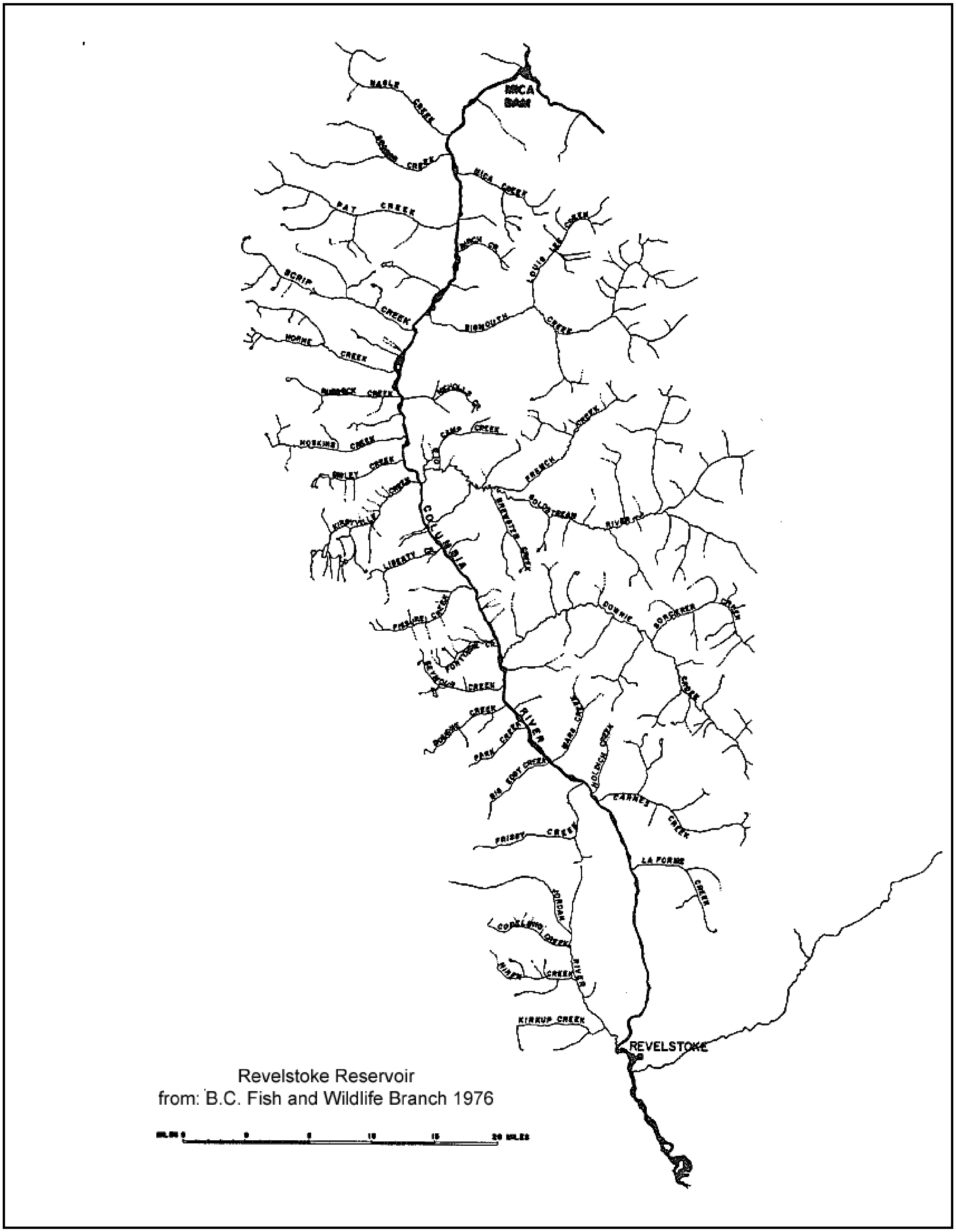


Figure 17: The Columbia River and tributaries between Mica and Revelstoke dams.

Construction of Revelstoke Canyon Dam (height 175 m) in 1977 through 1984, at the mouth of Little Dalles Canyon, inundated 140 km of the Columbia River downstream of Mica Dam (Ahrens and Korman 2004). The Columbia River within the Mica-Revelstoke Reach was, on average, much narrower than other Columbia Reaches (Martin 1978). Gradient was slightly less than the Mica-Donald reaches above Mica (0.18%), but the Mica-Revelstoke Reach had substantial pool-riffle development (Martin 1978). This was in sharp contrast to the lower gradient geomorphology of the Revelstoke-Arrowhead Reach. Thus, the entire Mica-Revelstoke Reach was rated as "moderate" in biological productivity throughout the mainstem Columbia (Martin 1978, Lindsay 1977). Accordingly, this lengthy reach of the Columbia supported significant resident and adfluvial fish populations. Abundant rainbow trout and bull trout populations were supported throughout the main stem river and its side-channels and tributaries (Martin 1978). Their annual production was supported by a high abundance of nursery streams, particularly from tributary alluvial fans and associated nursery side-channels. Kokanee salmon from Arrow Lakes (estimated at 0.5 million escapement; Martin 1978) operated as a "keystone species", because spawning occurred within the broad range of tributaries and their associated side-channels (Figure 17), as at the Lardeau River in the Kootenay Lake system (Slaney and Andrusak 2004). Keystone species are important in driving trophic production, through the supply of carbon as eggs and fish flesh, as well as nutrients, including the dominant limiting nutrient, phosphorus (Stockner and Ashley 2003). The middle Columbia River was glacially turbid early in the spring freshet, as Revelstoke-Mica tributaries warmed and their glacial sediments flowed into the mainstem Columbia (Figure 18). Some of the tributaries, particularly cooler or more glacial ones were more important for juvenile whitefish and bull trout, such as Sheep Creek. The large Downie Creek is another example, which supported rainbow, bull trout and kokanee, regardless of its seasonal glacial water quality and low productivity. The complex pool-riffle sequence of the mainstem, its side-channels and wetlands, and tributary alluvial fans were replaced with an ultra-oligotrophic "run-of-the-river" reservoir with a high turn-over or flushing rate of only about five days (Ahrens and Korman 2004).

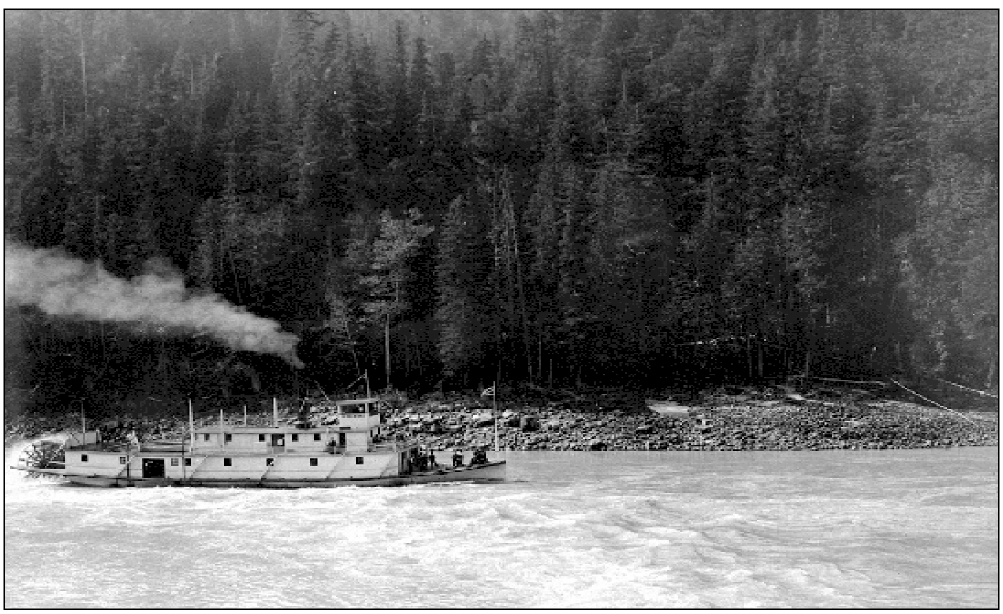


Figure 18: The S.S. Revelstoke on the glacially turbid, middle Columbia River at Priest’s Rapids during spring freshet 1904 (courtesy of Arrow Lakes Historical Society).

2.1.4 **Arrow Lakes (Dam Units C5 & C7 - combined into C11)**

The Arrow Lakes region of the Columbia was identified early on as prime territory for settlement and agriculture. The lower elevations, wider valley and warmer, drier climate than the upper Columbia reaches, made it an attractive option for early settlers. The river and lakes were highly navigable in these areas and consequently became major transportation corridors. However, seasonal water level fluctuations in Upper Arrow Lake extending up to 7 - 8 m (Fulton and Pullen 1969) necessitated the construction of buildings on piers and extended ramps to docks, to accommodate such water level changes (Figure 19, Figure 20).

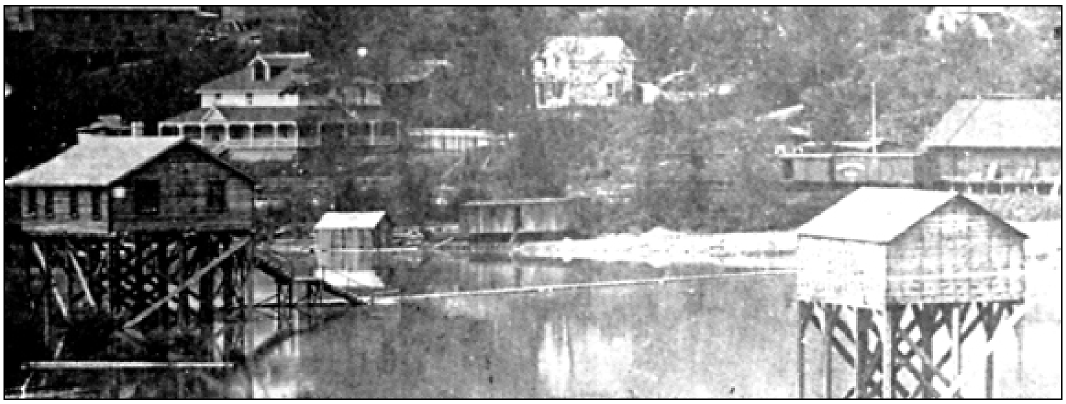


Figure 19: Shoreline buildings on piers with floating walkways at Arrowhead (courtesy of Arrow Lakes Historical Society).

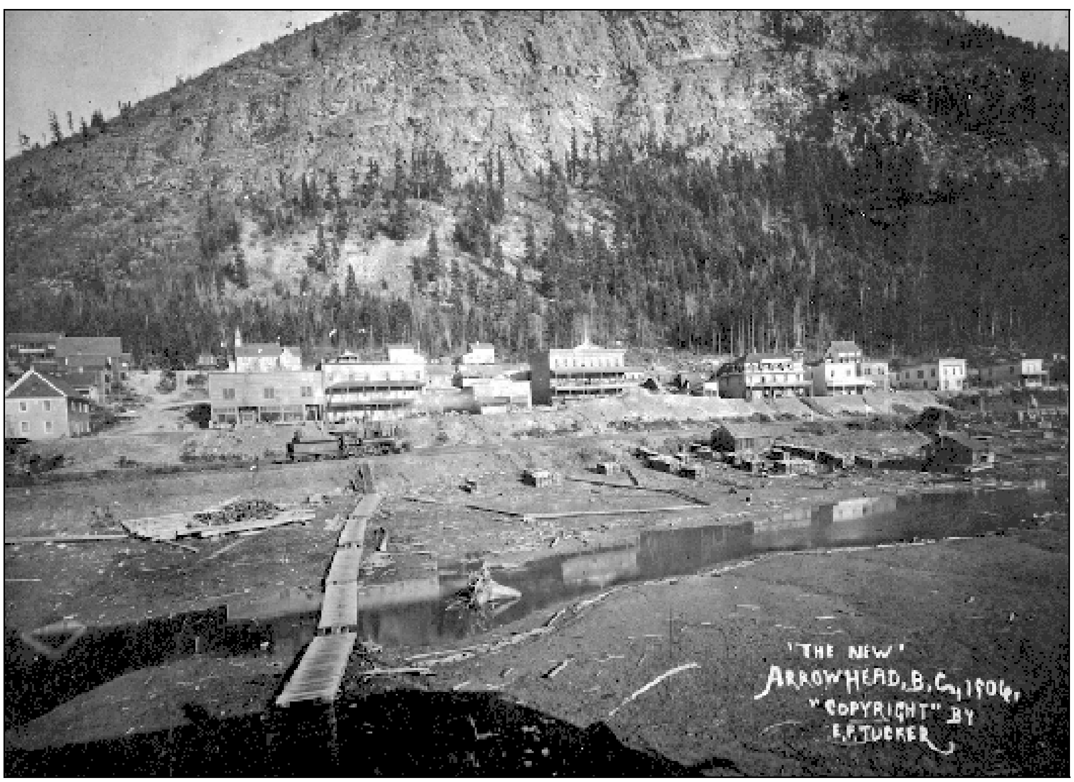


Figure 20: Arrowhead during low water in 1904 (courtesy of Arrow Lakes Historical Society).

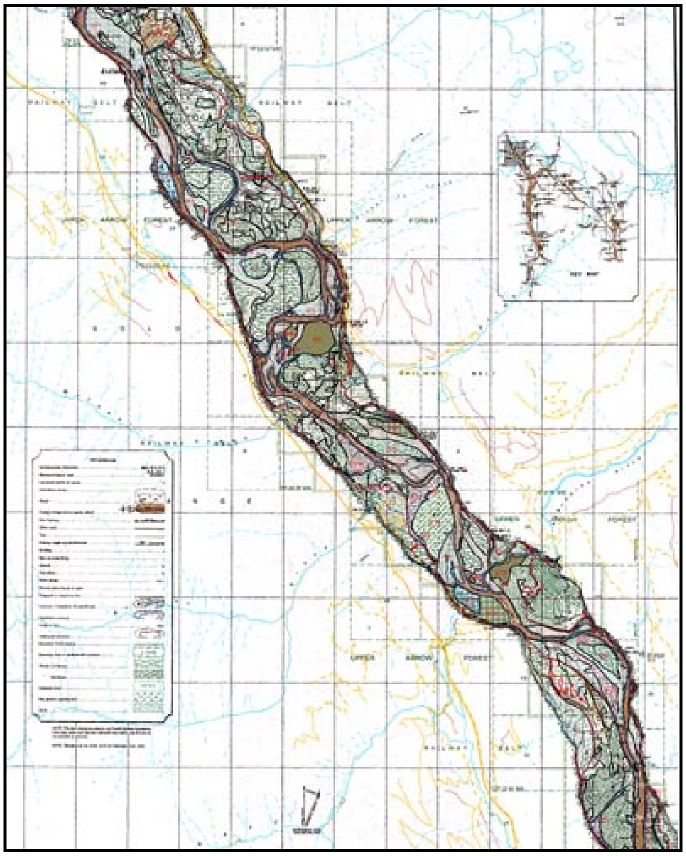


Figure 21: Historical mapping of the Columbia River floodplain, south of Revelstoke (Ketcheson et al. 2005).

The floodplain area between Revelstoke and Arrowhead was comprised of large, flat, floodplain deposits (

Figure 21), which became of great interest for agricultural development. Periodic spring flooding of these lands did not seem to deter settlement in the area (Figure 22), but newspaper accounts from 1903 document the ongoing concern with flooding. "…*Sixteen sections have been taken up at the mouth of the Columbia River near Arrowhead but owing to the land being flooded every season at high water, the settlement has retrograded rather than advanced. If some means could be found of lowering the river at high water, there are hundreds of acres of first-class land that can be converted into highly productive farms*…" Kootenay Mail Oct. 19, 1903 in Parent 1997). The extent of the flooding can be seen in pre-impoundment aerial photos of the Columbia River (Figure 23). Floodplain islands consisted of a combination of non-forested wetlands and stands of cottonwood with some spruce and cedar, all able to tolerate periodic flooding (Figure 24).

Flood protection (both in the US and Canada) was one of the identified reasons for construction of the 58 m high, Hugh Keenleyside dam at the lower end of Lower Arrow Lake near Castlegar. This was a Columbia River Treaty project, designed to provide hydroelectric storage and flood control for the benefit of downstream projects. It was completed in 1967 and the new maximum water level in the Arrow Lakes was reached by mid-1969.

Figure 22: Wetland and side-channel areas converted to agriculture (courtesy of Arrow Lakes Historical Society).

Figure 23: Pre-impoundment inundation of forested islands near Arrowhead (BC Hydro Land Mosaic Columbia River Developments Arrow, June 1960, courtesy of Arrow Lakes Historical Society).

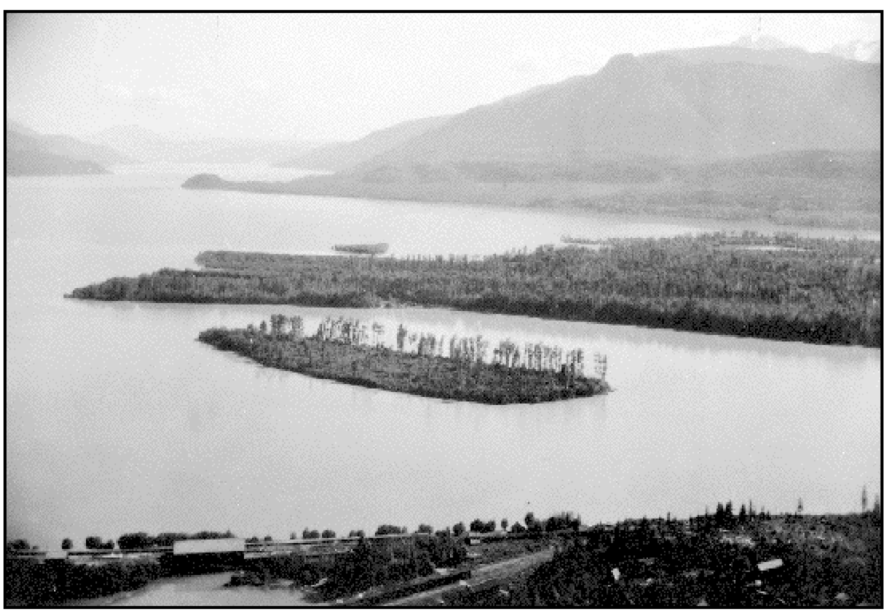


Figure 24: The Columbia River at Arrowhead, entering Upper Arrow Lake (courtesy of Arrow Lakes Historical Society).

The above images represent the same area; Figure 26 is an oblique image taken from above Arrowhead, (top left corner of Figure 25) toward Upper Arrow Lake. Figure 25, (aerial photo) was taken at a higher water level than Figure 26.

Figure 25: Columbia River flowing into Upper Arrow Lake (BC Hydro air Photo BC 1463-32 courtesy of Arrow Lakes Historical Society).

The annual Columbia River 'freshet' was the hydrographic/geographic feature that set limits to annual lacustrine productivity in these large main stem Columbia River lakes. Approaching Arrowhead from the south, aboard the SS Minto, Milton Parent describes the changes in water condition "*….the blue-green water was now showing patches of brown and the driftwood was increasing in density. The debris glancing off the bow was quite audible. Soon the lake was totally brown and the port of Arrowhead was in full view*." (Parent 1997). At 'ice-out' in early May the water was clear but by June increasingly turbid glacial flows arrived, often increasing lake levels dramatically, depending on the rate of snow-melt (Figure 25). The high energy of this system resulted in coarse material (sands and gravels) carried along the shores and deposited as islands in the vicinity of the "narrows" (Figure 26, Figure 27). The flow rates and volume of water during peak flows tended to scour the mainly gravel and cobble beaches (Figure 26) reducing periphytic communities and preventing any macrophyte growth, except in sheltered protected side-bays, where some macrophytes (e.g., *Potamogeton* spp.) were found along with sedges and aquatic grasses (T.G. Northcote, personal observations).

Figure 26: Columbia River, exposed beaches during low water (courtesy of Arrow Lakes Historical Society).

Figure 27: Sand Island (courtesy of Arrow Lakes Historical Society).

Owing to their large size, the productivity of the Arrow lakes was the main 'driver' of pelagic C production in the pre-dam basin. The high turbidity of Arrow pelagic, imparted both from mainstem flows (Figure 28) and from several large and very turbid tributaries e.g. Illecillewaet, Incomappleux, from June to mid-August, resulted in low light attenuation and associated low levels of net primary production (NPP). Even in the present setting with 2 dams upstream of Arrow lakes to trap much of the turbidity, glacially turbid tributaries continue to reduce light and create a shallow euphotic zone. We surmise that during the clear-water periods of spring and autumn, periods that were likely to be associated with moderate nutrient levels from deep mixing, that pelagic production in the Arrow lakes was the highest, perhaps in part compensating for the very low levels of mid-summer. The productivity of Arrow has been compared to the South Basin of Kootenay Lake south arm, a sector of the lake affected by glacial turbidity, but anecdotal reports based on abundance of animals in Ekman dredge samples suggest that Kootenay south was considerably more productive than Arrow Lake (T.G. Northcote, MSc. thesis, UBC, and personal observation).

Figure 28: Whatshan River inflow into turbid Lower Arrow Lake at Needles (BC Hydro Land Mosaic Columbia River Developments Arrow, June 1960, courtesy of Arrow Lakes Historical Society).

2.1.5 Whatshan Lake (Dam Unit C8)

Figure 29: Satellite image of Whatshan Lake, July 2001(source - GeoGratis http://geogratis.gc.ca).

Whatshan Lake is situated at 639m in elevation, perched above Arrow Lake near Needles. It is approximately 22 km long and 2.5 km wide and consists of two basins with a narrow connecting channel (Figure 29). The mean depth is approximately 50 m and the pre-dam surface area was about 1540 ha. The post-dam surface area is 1763.8 ha (CBFWCP-GIS-2006).

Historical accounts of this lake are very limited. Oblique aerial photos from 1936 show the shoreline of the lake as heavily treed to the waterline (Figure 30) and other pre-dam air photos show the original lake as having clear water with several shoals evident. Ministry of Environment, lake survey data from 1959 recorded a total dissolved solids content of 58 ppm, indicative of oligotrophic conditions. Low oxygen levels recorded at depth were attributed to macrophyte concentrations and possibly decomposition. The impounded lake is reported to have extensive mats of aquatic vegetation in the shallow lower basin (Hirst 1991) and beds of cattails in the narrows (Robertson Environmental Services Ltd. 2002). Natural rock barriers at the lake outlet are reported to have prevented fish access to and from the Whatshan River both before and after impoundment (B.C. Game Branch 1948, Fleming and Smith 1988b in Hirst 1991).

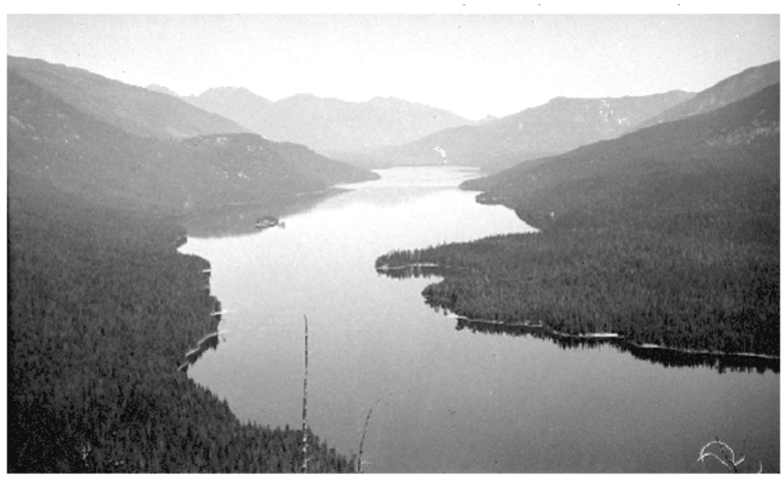


Figure 30: Aerial View of Whatshan Lake 1936 (BC archives NA-10933).

2.1.6 Seven Mile Dam (Pend d'Oreille) (Dam Unit C10)

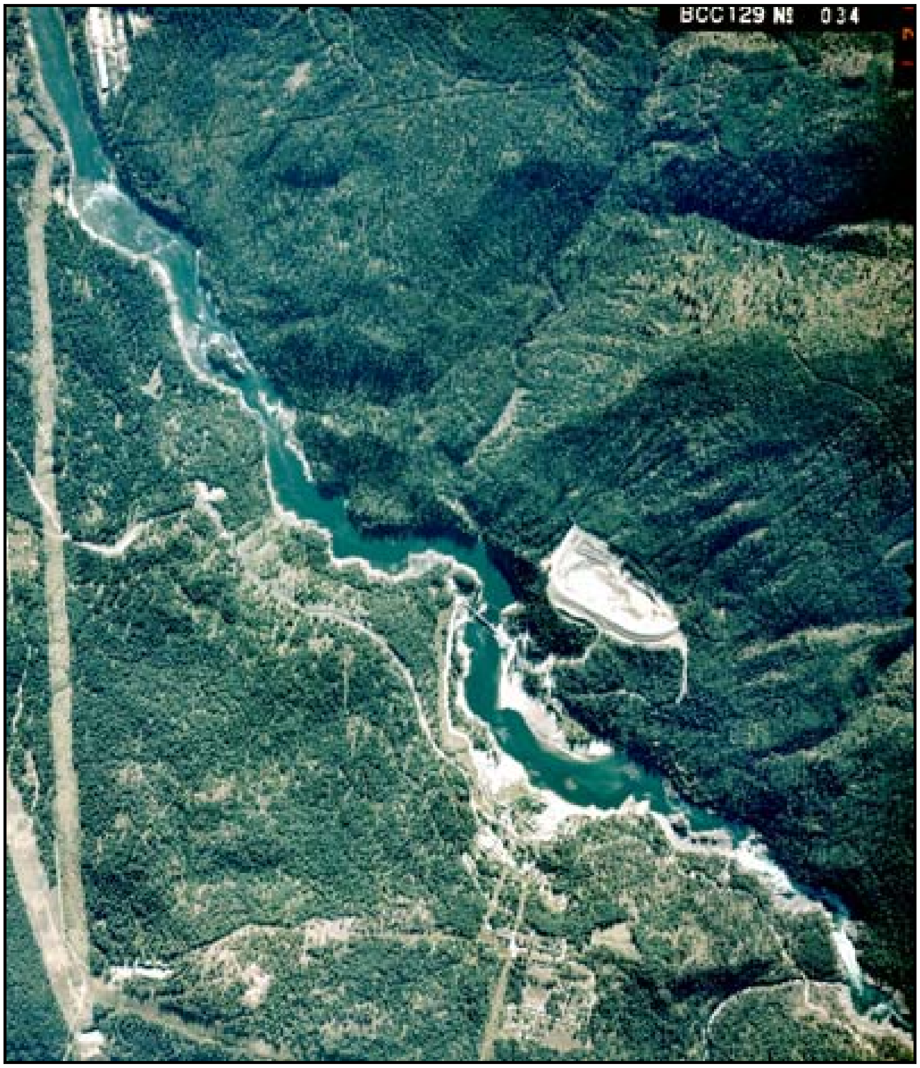


Figure 31: Section of the Pend d'Oreille valley (air photo number BC 129-34).

The Seven Mile project consists of a 79 m high concrete gravity dam on the Pend d'Oreille River. This project lies between two other run-of-river projects, Boundary Dam in the U.S. (upstream) and Waneta (2 km downstream). The reservoir has a mean depth of 28 m and a mean water residence time of 1-2 days (Hirst 1991). Historical accounts of river characteristics prior to dam construction are very limited. The steep, rocky shorelines appear to have had few low-gradient areas (Figure 31) and no wetlands. The Salmo River is the largest tributary to the Seven Mile Reservoir; smaller tributaries include Tillicum, Charbonneau, Nine Mile and smaller creeks. Eurasian milfoil (*Myriophyllum spicatum*) was identified as a potential problem in reservoirs upstream of Seven Mile, but had not yet become established in the reservoir by the mid-1980's, possibly because of the quickly fluctuating water levels (B.C. Hydro 1987 in Hirst 1991). Waneta Dam, completed in 1954, is a 76 m high earth fill dam is located on the Pend d'Oreille River immediately above the confluence with the Columbia. The project was built and is owned by Cominco and is presently operated as part of the FortisBC system. Waneta operates as a run -of-river project and is the final reservoir of a series on the Pend d'Oreille. Both Waneta and the Seven Mile reservoirs reflect the original shape of the valley, long and narrow with a relatively small surface area, and a high flushing rate (Hirst 1991). The main difference in the pre-dam valley and the present reservoirs appears to be the trade-off between rapids and whirlpools being replaced by lake-like conditions. This dam unit has a footprint area of 427.6 ha (CBFWCP-GIS-2006).

2.1.7 Aberfeldie Dam (Bull River) (Dam Unit K2)

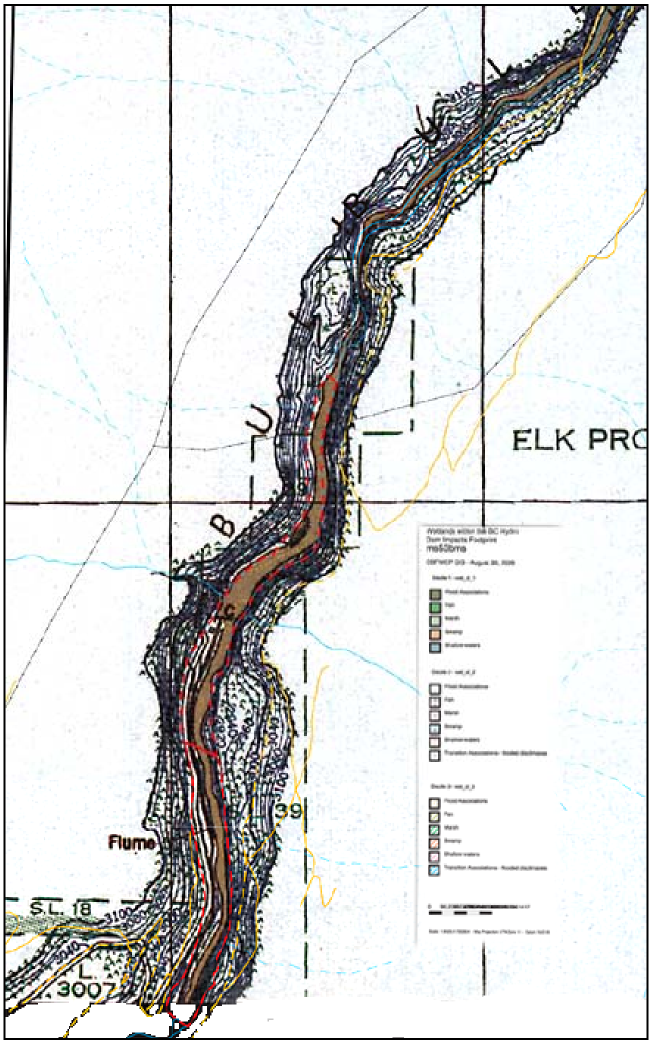


Figure 32: Historical mapping of the Aberfeldie Dam footprint area (Ketcheson et al. 2005).

Aberfeldie is a small hydro project located on the Bull River in the East Kootenays (Figure 32). The 27 m high concrete gravity dam was constructed from 1920 through 1922 creating a reservoir with a footprint area of 11.7 ha (CBFWCP-GIS-2006). Water temperatures in the reservoir are normally cold and it is ice covered through the winter. No physical or chemical characteristics of this unit have been found in the literature. The only tributary habitats are those in the upstream Bull River, but no information was located for these habitats. WSC gauging data for the Bull River near its confluence with the Kootenay indicates that impoundment has resulted in only very small changes in river discharges (Hirst 1991). Due to the steep-sided, narrow valley, there appear to have been no floodplain or wetland habitats affected by the creation of this reservoir.

2.1.8 **Libby Dam (Lake Koocanusa) (Dam Unit K3)**

Libby Dam, built in 1973, was not constructed as part of the Columbia River Treaty. It is located 130 km south of Eureka, in northwestern Montana (U.S.) on the Kootenay River. Libby Dam formed the 200 km long Lake Koocanusa that reaches north into British Columbia. The reservoir has a Canadian footprint area of 6649.4 ha (CBFWCP-GIS-2006). A large part of this area consisted of floodplain habitats (Figures 36 and 37) that were considered of high value to wildlife (Langin and Carswell, no date). Earlier wildlife reports by Smith (1970) and Smith & Demarchi (1969) could not be accessed for this study.

Photograph 3. East side of reservoir near the American border prior to the filling of the reservoir in 1974.

Photograph 4. Typical side channel of the Kootenay River, four miles south of Fort Steele.

Figure 33: Libby reservoir habitats (from Langin and Carswell no date).

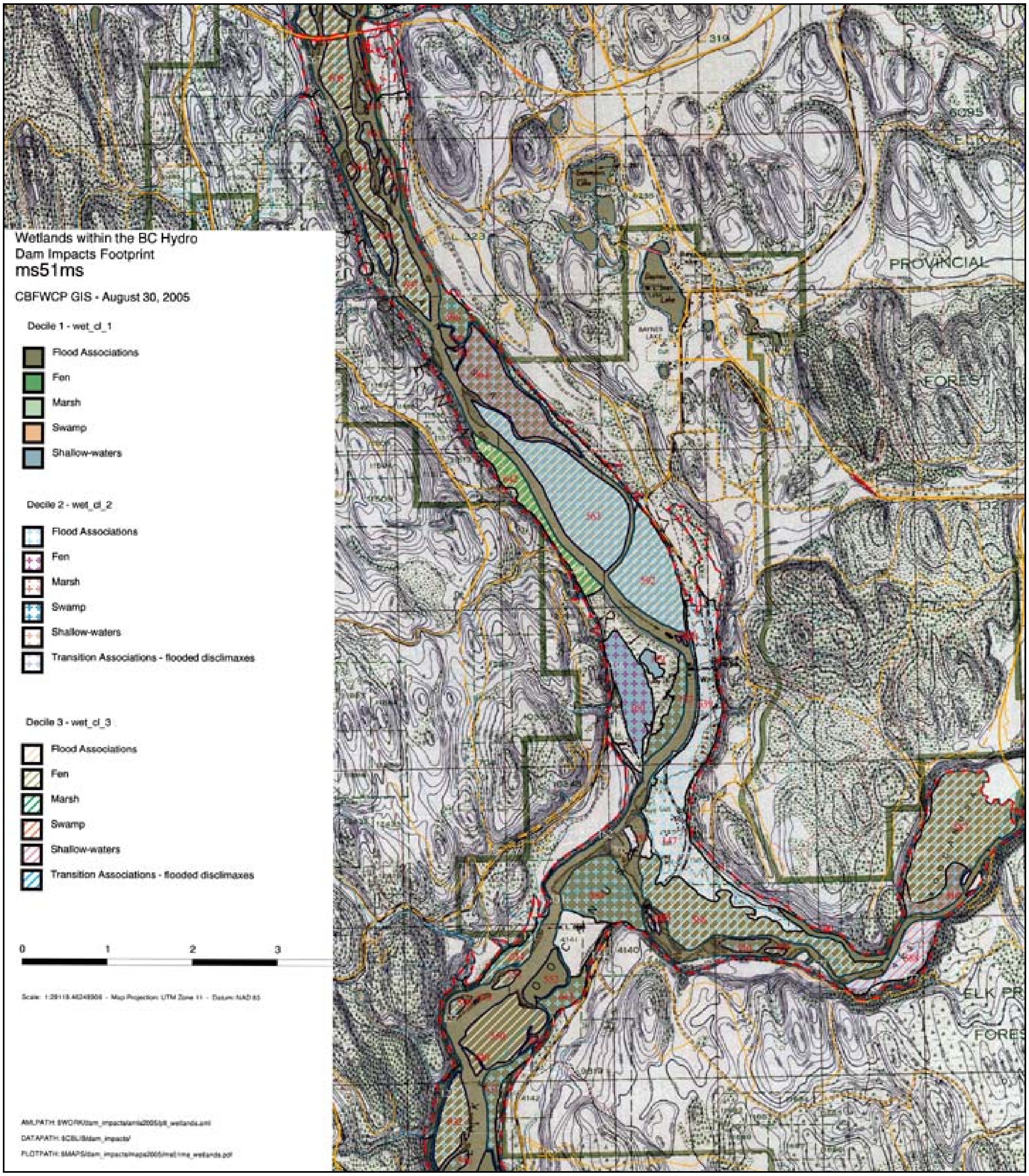


Figure 34: Portion of Koocanusa Reservoir (MS51) showing historical mapping of floodplain habitats (Ketcheson et al. 2005).

2.1.9 Elko (Dam Unit K4)

The Elko dam is a 10 m high, concrete gravity structure constructed in 1924 by the East Kootenay Power Company. The project is now owned and operated by B.C. Hydro. The project is located on the Elk River near its confluence with the Kootenay River (Lake Koocanusa) in the East Kootenays (
Figure 35). The Elko reservoir footprint area is 17.8 ha (CBFWCP GIS). The Elk River below the Elko Dam flows through a small steep-walled, high-gradient canyon with numerous rapids, chutes and small pools, and boulders, rubble and gravel substrates of limited value as spawning habitat (Hirst 1981). Due to the steep-sided, narrow valley, there appear to have been no floodplain or wetland habitats affected by the creation of this reservoir.

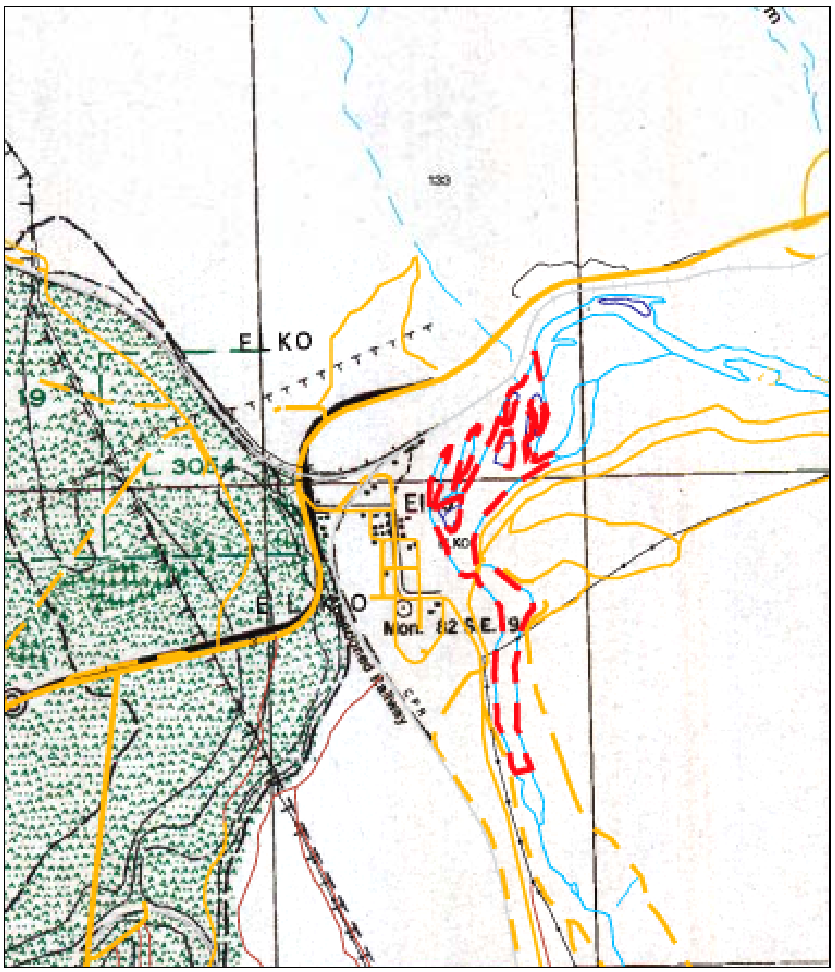


Figure 35: Historical mapping of the Elko Dam footprint area (Ketcheson et al. 2005).

2.1.10 **Kootenay Lake (Dam Unit K6)**

Kootenay Lake, lies within the central portion of the Purcell Trench, a valley between Selkirk Mountains to the West and the Purcell range to the East. The Kootenay Lake system forms one of the major branches of the upper Columbia River drainage in British Columbia, with inflows from three main tributaries: the Lardeau and Duncan rivers combined flows from the north-end of the lake and the larger Kootenay River from the south (Figure 36). The outflow of Kootenay Lake, through the West Arm, is located at the lake's mid-point between North and South Arms. The West Arm is a shallow, narrow basin near Nelson, BC that flows into the lower Kootenay River, which joins the Columbia River at Castlegar, some 40 km downstream of the outlet of the West Arm.

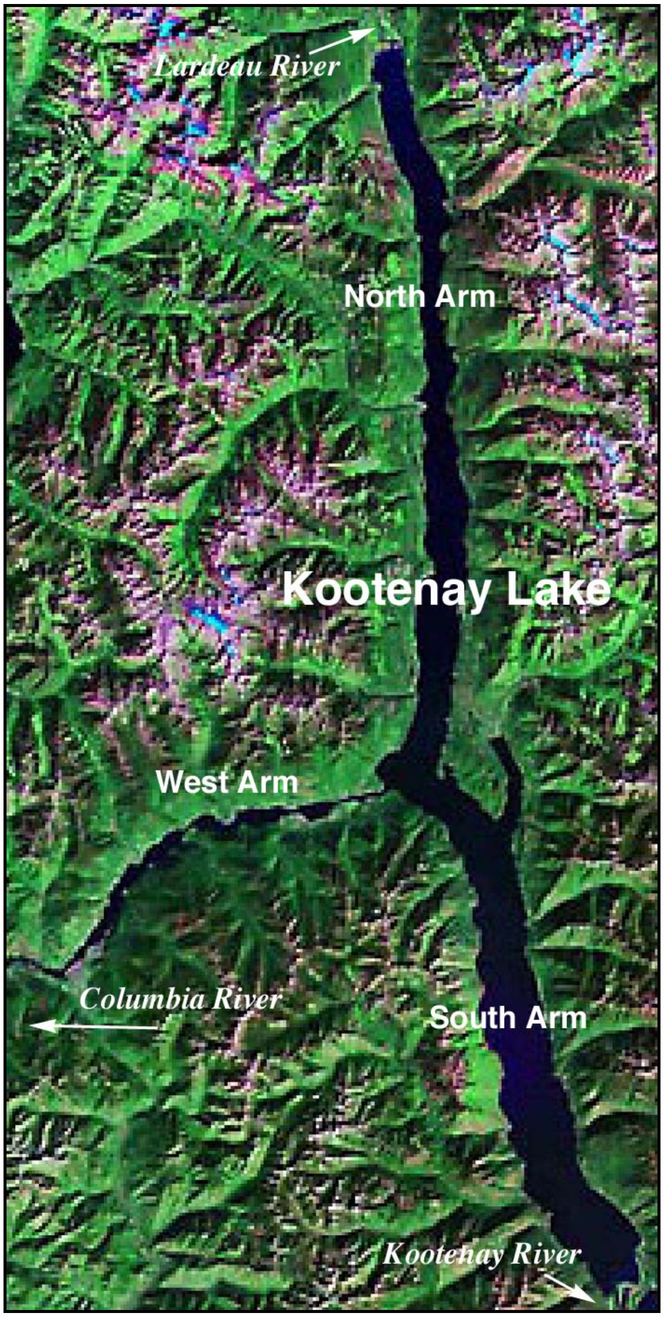


Figure 36: Landsat 7 image of Kootenay Lake (source - GeoGratis http://geogratis.gc.ca).

The mountains surrounding Kootenay Lake strongly influence the region's continental climate with warm summers and moderately cold winters, but despite cold winter temperatures, the lake seldom freezes over with complete ice-cover (Daley et al. 1981, Wiegand and Carmack 1986). July temperatures average about 18 -19°C near the lake, except in the northern mountain sectors where July temperatures are lower, averaging 15°C. Mean mid-winter (January) temperatures average -4°C along Kootenay Lake and its West Arm shorelines (Daley et al. 1981.)

Kootenay Lake was likely created by river erosion during the late Cretaceous period (Daley et al. 1981). As glacial erosive forces contoured the lake's basin, mountain ranges surrounding the lake grew in elevation, and in the Pleistocene period glacial ice filled the Kootenay valley, eventually withdrawing (melting) scouring the present drainage patterns observed in the basin (Northcote (1973a, Daley et al. 1981). Before the arrival of European settlers, the Kootenai peoples inhabited the region, subsisting by hunting and fishing, and using the lake and associated river systems as migration, trade and transportation routes (MacDonald et al. 1994; Crozier 1994). Initial development after the arrival of white Europeans was largely associated with mining. Important minerals were discovered along the shores of Kootenay Lake as early as 1825, but it was not until the late 1800s, with the establishment of small mineral claims around the lake, that the mining industry became established (Northcote 1972, 1973; Daley et al. 1981). The Kootenay Lake drainage basin is well recognized for its natural resources that include mineral deposits, timber, agriculture, and hydroelectric power generation facilities. The lake is situated in the Kootenay arc, a belt of complex and deformed sedimentary, volcanic and metamorphic rocks of Precambrian age, precursors to minerals such as silver, tungsten, lead, zinc, gold and copper (Irvine 1978). The west Kootenay Lake region is known as one of British Columbia's finest and most economically valuable recreational areas, known particularly for its sports fisheries in its numerous lakes and streams (Daley et al. 1981).

Kootenay Lake is considered a large lake (approximately 394 km^2), but actually is small relative to the immensity of its drainage basin (45,500 km^2). The Kootenay River basin (upstream of the Corra Linn Dam, near the outlet of the West Arm) has five distinct sub-basins:

- Upper Kootenay above Libby Dam (56% of the total),
- Middle Kootenay between Libby Dam and the south end of Kootenay Lake (24%),
- Duncan-Lardeau Basin north of lake (9%),
- Kootenay Lake basin (9%) and
- West Arm Basin extending to Corra Linn Dam (2%).

The Duncan-Lardeau Basin contributes 22% of the total outflow from Kootenay Lake, the upper Kootenay Basin 43.7%, and the middle Kootenay Basin 17.8% (Daley et al. 1981). Kootenay Lake has become increasingly regulated due to hydroelectric generation and flood control, beginning with Corra Linn dam in 1932, Duncan Dam in 1967 and Libby Dam in Montana in 1973. Corra Linn dam, in the west arm of Kootenay lake, is a 21 m high, 518 m long concrete gravity structure that provides additional storage and hydraulic control for its own generation and that of a sequence of four downstream run-of-river reservoirs (Upper Bonnington, Lower Bonnington, South Slocan and Brilliant). Grohmann Narrows, situated 8 km upstream of Corra Linn dam, is a natural constriction located at the junction of Kootenay Lake and the river that has historically been the primary control on flows and water levels in Kootenay Lake. It is estimated that 57 percent of the inflow into Kootenay Lake is regulated (Environment Canada 1988 in Hirst 1991). Kootenay Lake levels, which fluctuate over a 2.5 m range and reach minimum levels in April or May, are governed by water releases from Duncan reservoir, releases from Libby reservoir, and run-off from numerous unregulated tributaries in spring and summer (Daley et al. 1981).

2.1.11 **Duncan Lake (Dam Unit K7)**

The 40 m high Duncan Dam was completed in 1967 for water storage and flood control as part of the 1961 Columbia River Treaty. The project is located immediately upstream of the confluence of the Duncan and Lardeau rivers, approximately 11 km upstream of Kootenay Lake and 42 km north of the Village of Kaslo. The Duncan Reservoir, impounded by the dam, is approximately 45 km long when the reservoir is at full pool and has a footprint area of 7298.5 ha (CBFWCP-GIS-2006). At its northern end, it encompasses a large, shallow drawdown zone, which was previously occupied by wetlands adjacent to the Duncan River (Figure 37). Based on the historical air photos, these wetlands greatly resembled the current Columbia River marshes upstream of Kinbasket Reservoir. Peterson and Withler (1965c) described the wetlands as follows:

> *Above Duncan Lake, the valley floor is flat and contains extensive wetlands, about 6,400 acres (2590 ha). Along both east and west shores of Lower Duncan River, slough areas are connected to the river. These sloughs are excellent rearing ponds for juvenile game fish and they probably contribute much fish food to the river. The sloughs extend from the east bank of the river to the foot of the mountain which will form the east bank of the proposed reservoir...Some 4000 acres (1619 ha) of wet meadows occur in the reservoir area, much of which are of recent origin caused by beaver impoundments of stream fans...Eighteen permanent open sloughs, 450 acres (182 ha) in extent exist in the reservoir area.*

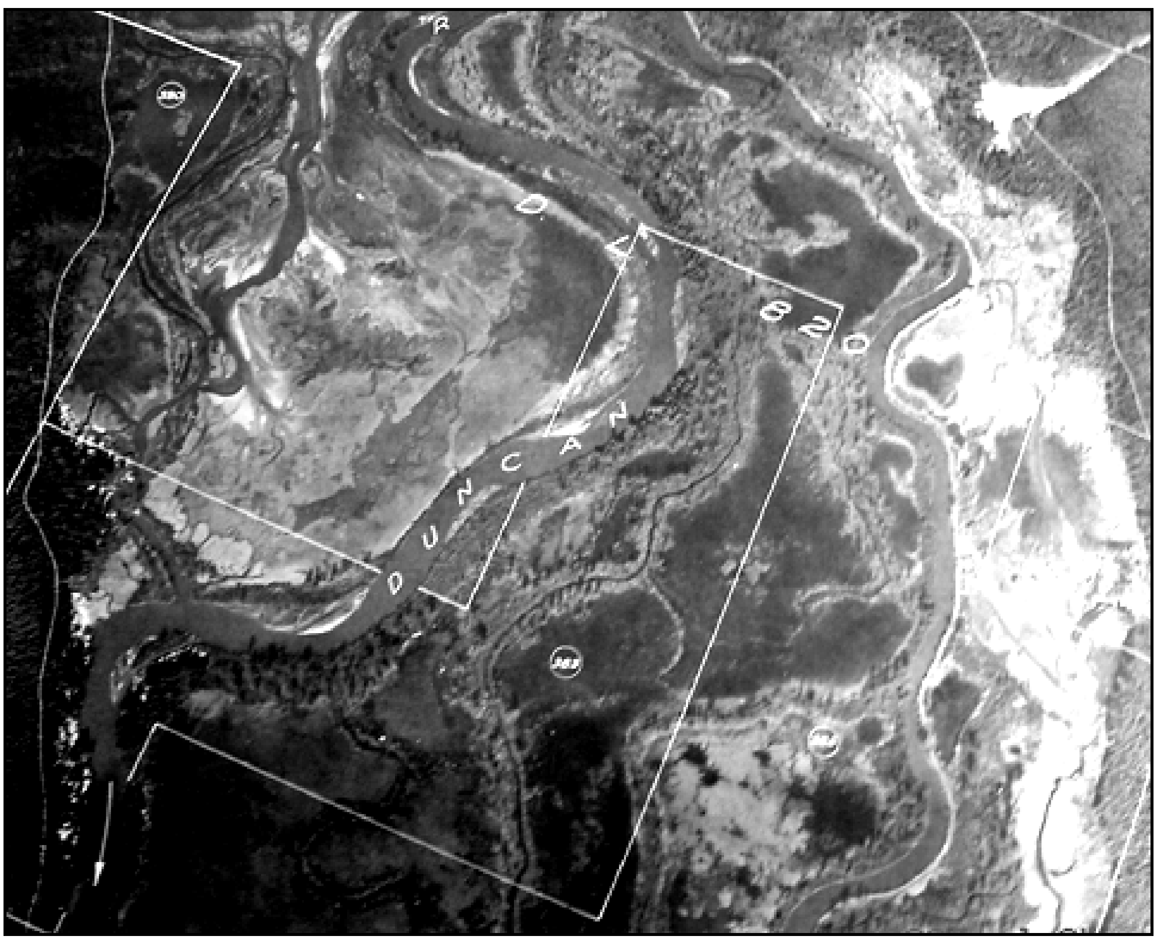


Figure 37: Aerial view of wetlands surrounding Duncan River, pre-impoundment (BC Hydro Land Mosaic Columbia River Developments Duncan, April 1965, courtesy of Arrow Lakes Historical Society).

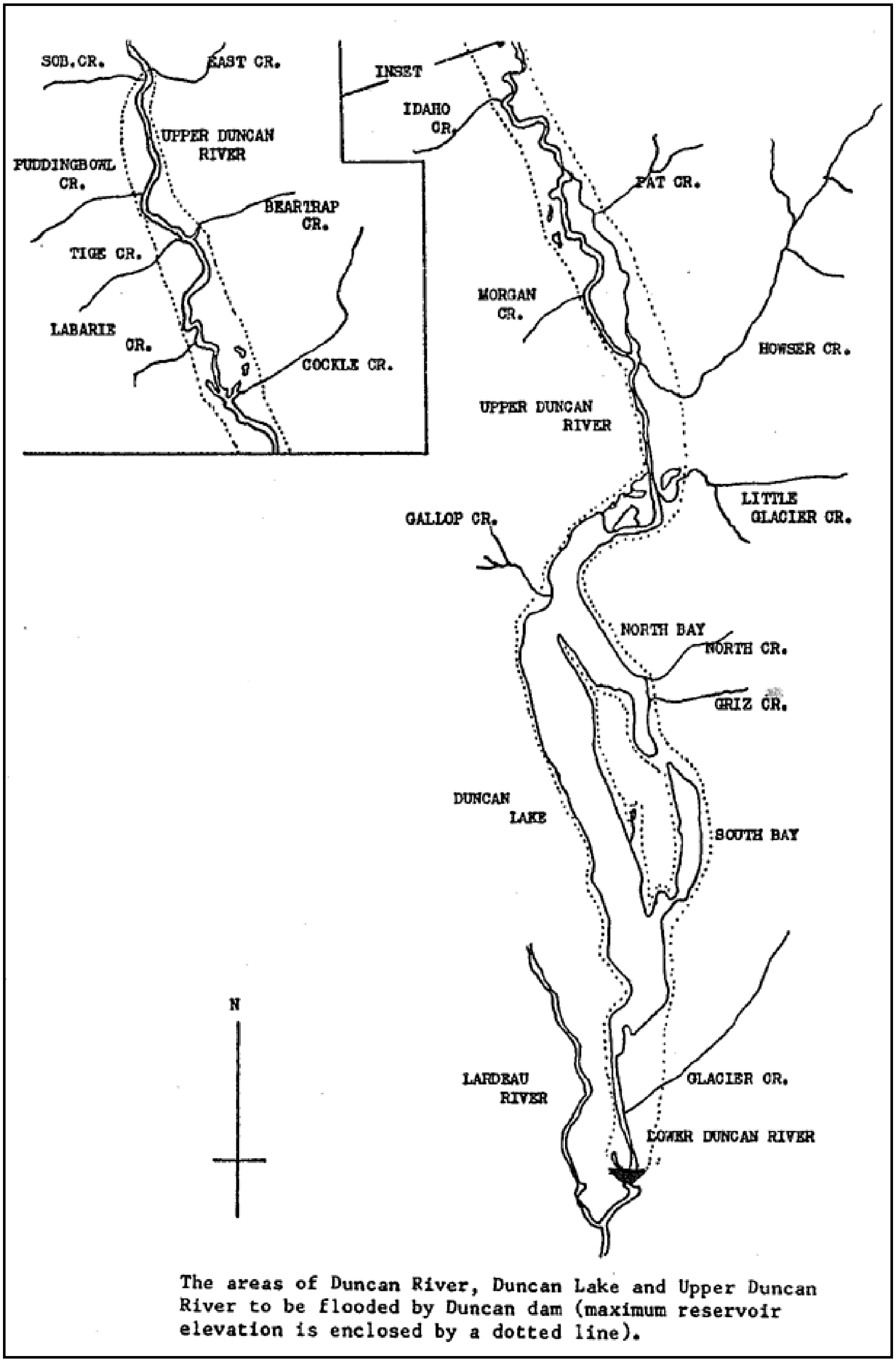


Figure 38: Areas of Duncan River, Duncan Lake and Upper Duncan River falling within the Duncan reservoir footprint (from Peterson and Withler 1965c).

In the1960s, prior to construction of Duncan Dam, Duncan Lake was a large oligotrophic lake that had steep sides, resulting in little littoral area in the main lake. There were three basins, a main-lake basin throughout the length of the lake, a north basin on the east side of the lake, and a south-east basin, known locally as “South Bay” (Figure 38). The basins were separated by a narrow peninsula of land that prevented glacial waters of the north basin from entering the south basin. In the spring to summer months, the main basin of lake at the north end and to a lesser degree in the north basin were glacially turbid from the glacial inflows of upper Duncan River, However by mid-lake, water clarity improved and the outlet of the lake was of moderate clarity during mid- to late-summer. Owing to glacial conditions at the north end as well as steep lake sides along the lake, littoral macrophytes were uncommon in the main lake. The only exception was at the outlet end of the lake adjacent to the small hamlet of Howser, located at the south-west corner of Duncan Lake. Macrophytes were also prevalent at the outlet reach of the river until its confluence with glacial Glacier Creek. The south basin was unique in that it was significantly warmer and more productive. It also had twice the light penetration of the main lake, 3.1 m in summer versus 1.5 m at the south end of the main basin, and only 1.1 m at the north end of the main basin (Peterson and Withler 1965c). The north basin had slightly greater clarity (1.5m) than the north end of the main basin, but half of that of the south basin. Macrophytes were ubiquitous in the south basin, which had a high proportion of littoral area, and *Potamogeton* spp. appeared to be the dominant macrophyte. Benthic invertebrate sampling with Ekman dredging in 1964 indicated that there was moderately abundant taxa in the south basin, which was dominated by chironomids. The benthos was 4-fold higher in the south basin than stations in the main lake and north basin (Peterson and Withler 1965c). One notable exception was off the inlet of the main lake where the detrital inflows from upper Duncan River (Figure 39) increased the benthos abundance to twice that of South Bay and 7-times that of other zones of the main lake. “South Bay” was where local residents recreated from spring to autumn, which including boating, swimming and fishing. Anglers targeted rainbow trout, bull trout, kokanee, whitefish, ling and white sturgeon, and two 70 kg sturgeon were taken on set lines in the summer of 1964 (data on file, BC Fish and Wildlife Br).

Thus, South Bay’s warmer waters and higher productivity were key features of Duncan Lake that were well established.

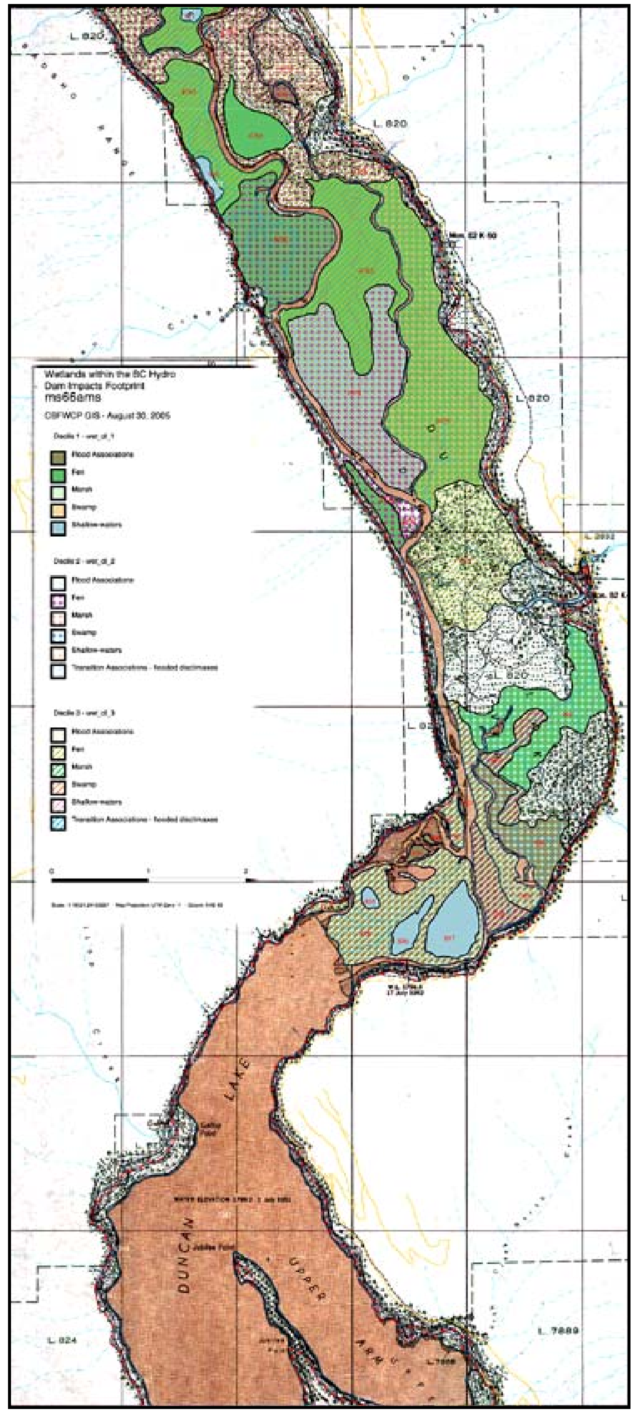


Figure 39: Historical mapping of Duncan River floodplain (Ketcheson et al. 2005).

2.1.12 Corra Linn – Brilliant (Kootenay Canal) (Dam Unit K9)

Figure 40: River segment in Dam Unit 9 (BC air photo CBF&WCP file).

The Corra Linn dam, constructed in 1932 (operated by B.C. Hydro), is a 21 m high facility in a sequence of four run -of-river reservoirs (Upper Bonnington, Lower Bonnington, South Slocan and Brilliant (all non-B.C. Hydro dams). The Corra Linn forebay is used by B.C. Hydro as the take-off point for the Kootenay Canal project. In general, the setting for these facilities is the narrow trough of the lower Kootenay River, which was characterized by relatively steep banks and an absence of littoral or wetland habitat (Figure 40). All flows released through Corra Linn are passed directly through the Bonnington and South Slocan plants. Lower Bonnington Dam is located less than 1 km below Upper Bonnington; South Slocan project is located 1.5 km below Lower Bonnington Dam. Kootenay Canal was constructed by B.C. Hydro in 1971-72 and consists of a concrete-lined canal that draws water from the Corra Linn forebay which then bypasses the Upper and Lower Bonnington reservoirs to drive a generating plant located below the South Slocan Dam. The Brilliant Dam, operated by FortisBC, is the final dam in the series of 5 located on the lower Kootenay River. The reservoir has a footprint area of 48.7 ha (CBFWCP-GIS-2006).

2.2 Ecological Effects of Reservoir Formation and Aging on Primary Production

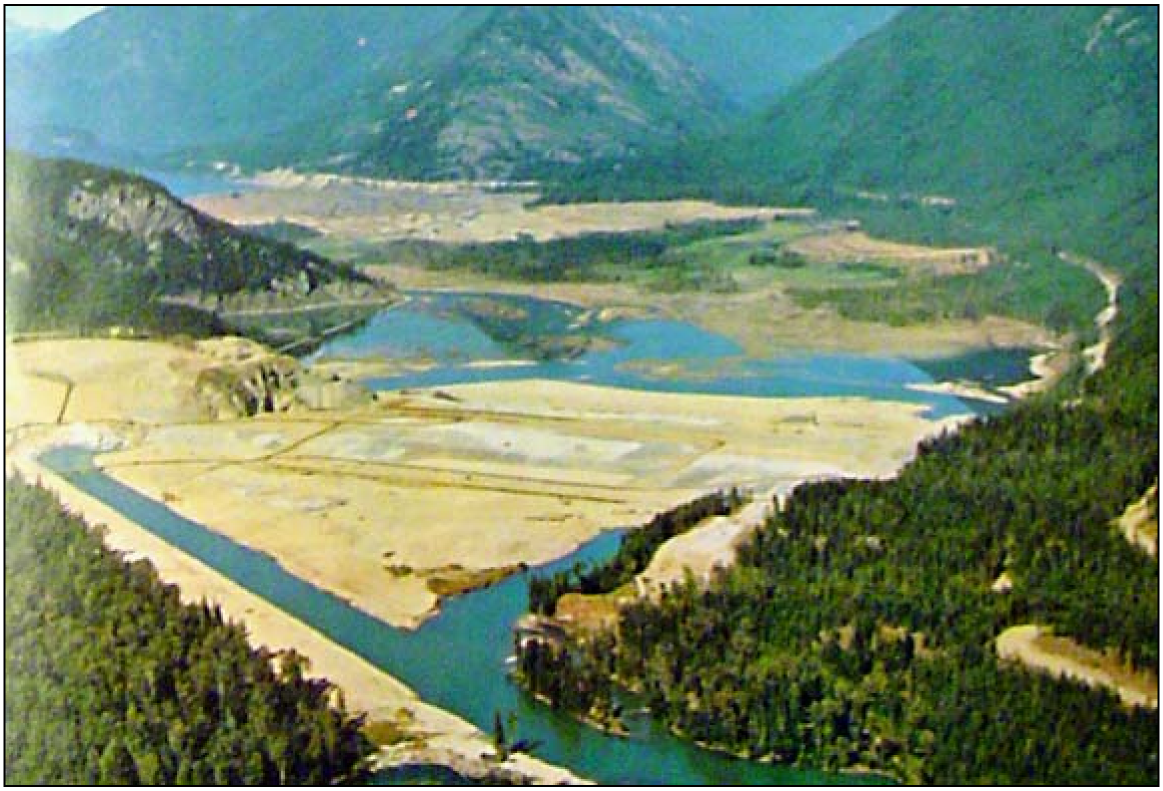


Figure 41: Construction of the Duncan Dam (photo BC Hydro library).

2.2.1 Vegetation Effects

With the completion of the various dams (Figure 41), came dramatic alterations to the hydroriparian systems of the Columbia River Basin. The lower reaches of tributary streams were flooded. The presence of the new, large water bodies resulted in the slowing of inflowing fluvial water and deposition of fine sediments in new locations. In some areas, this resulted in improved water clarity within the reservoirs. Ultimately, in many cases, deltas began to form or enlarge, where streams entered the reservoir. The establishment of such deltas, to a greater or lesser extent, is a feature common to many reservoirs in B.C. (Kinbasket-Bush Arm, Arrow-Revelstoke Reach, Duncan, Williston, Carpenter, Stave, Campbell and Falls River). As the reservoir levels rose, the former terrestrial vegetation succumbed to the inundation. Riparian and wetland vegetation survived for various lengths of time, depending on the speed of water level rise, but eventually the plants exhausted their reserves and expired. In Revelstoke Reach, vegetation mapping from historical photos showed that by 1977 (8 years after reaching operating levels) vegetation cover was reduced by 89% in the reservoir area (Moody 2002). Historic riparian habitats were eliminated and new ones were unable to establish due to fluctuating water levels. Physically, biologically and chemically the former valleys were changing.

However, after a period of some years, the shorelines, particularly in the deltas, began to stabilize and as propagules of wetland plant species arrived from upstream, some new growth was able to develop. This was not identical to the historic wetland vegetation since the new hydrologic regimes were very unlike those experienced in the historic hydroriparian environment. The new hydrology imposed strong selective pressure on the newly developing vegetation; only those individuals with tolerance of the extremes of drought and inundation were able to survive. This resulted in the development of a very simple vegetation community, but one that extended over a broad elevation range (up to 10 m), much greater than normally encountered in lakes. In Arrow Lakes Reservoir, this process was hastened and enhanced by the actions taken to control dust storms in Revelstoke Reach. Dust storms are another feature of reservoir drawdown zones where unvegetated shorelines are subject to wind erosion (Figure 42). Drill seeding of agronomic rye and fertilizer resulted in the incorporation of wetland plant seeds from upstream, into the substrates. The annual ryegrass served as a nurse crop and the fertilizer supplied additional strength for the developing seedlings. This developing vegetation has shown strong elevational zonation and strong responses to substrate. Similar species, the most common of which are lenticulate sedge (*Carex lenticularis*), swamp horsetail (*Equisetum fluviatile),* scouring rush (*Equisetum hyemale*) and reed canarygrass (*Phalaris arundinacea*) occur in reservoirs throughout B.C. (Figure 43).

Figure 42: Revelstoke Reach, experimental transplant program at low elevation unvegetated site (historical cottonwood habitat) (photo A. Moody).

Figure 43: Lenticulate sedge and reed canary grass, naturally established on former floodplain habitat at Revelstoke Reach (photo A. Moody).

2.2.2 Lake Effects

There are basically 3 types of reservoirs:

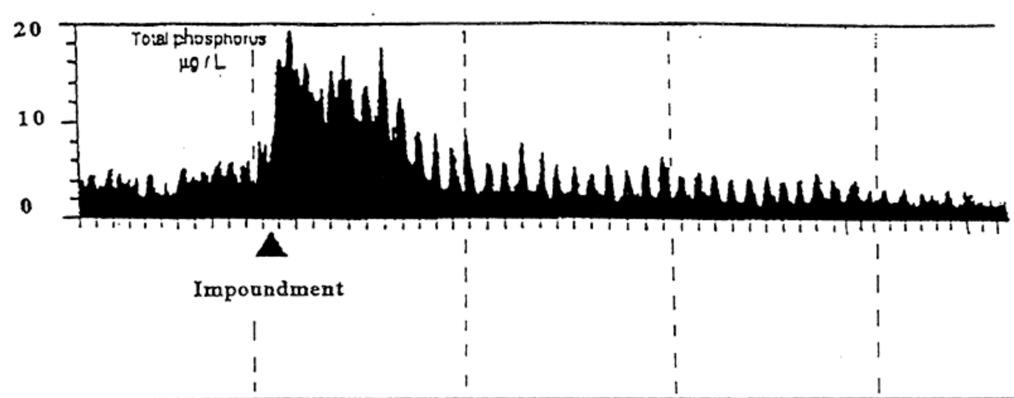
- those that are created by damming rivers (river reservoirs), e.g. Revelstoke,
- those that increase the level of existing lakes by damming the lake’s outflow (lake reservoirs), e.g. Kootenay, Whatshan or
- those that flood both river and lake e.g. Kinbasket, and Arrow.

Kootenay Lake has been far less influenced by hydroelectric or flood control operations than have the other historic lakes and remains as one of the only remaining large, natural lakes in the Upper Columbia Basin. It has not experienced the dramatic effects of impoundment, with associated large rises and fluctuations in lake level such as in the Kinbasket or Arrow systems. The Duncan and Libby dams have greatly reduced the amplitude of spring freshet, lake level rise, but the most significant effects of these dams has been the withdrawal of lots of particulate turbidity and nutrients which together have impacted downstream C production.

2.2.2.1 Trophic upsurge and collapse - How new reservoirs age

The building of dams on rivers or on lake outflows increases water retention and concurrently rates of bio-degradation and sedimentation of particulate organic (biologic) and inorganic (geologic) matter within the newly created impoundment. With increased sedimentation and longer water retention times, a new reservoir becomes an effective nitrogen (N), phosphorus (P), and carbon (C) sink. New reservoirs typically undergo a ‘boom’ and ‘bust’ production cycle following impoundment (Figure 44). The ‘boom’ or *upsurge* in production phase is caused by the release of soluble reactive nutrients (C, N, P) from eroding soils and from decomposing flooded vegetation, and the ‘bust’ or *collapse* in production is caused by sedimentation and sequesterization of C, N and P (Ney 1996, Stockner et al. 2000).

Figure 44: Typical "Boom and bust" production cycle following impoundment (after Stockner et al. 2000).



Phase	Pre-	‘Boom’	Transition	‘Bust’	Post-
Year		1-5	5-8	8-15	perpetuity
Production (gC/m^2/y)	50-70	100-120	80-100	40-60	30-50
Total P	2-4	10-14	6-8	2-4	1-3
Trophic state	oligotrophic	mesotrophic	oligotrophic	ultra-oligotrophic	ultra-oligotrophic
Fish prod.	low	moderate	low	very low	very low
Transparency	high	low	moderate	high	very high

This boom period is short and temporary, usually sustained by mineralization of organics for only 4-5 years following inundation. Within 10 years, ambient nutrient levels have declined too much lower levels than heretofore seen. This loss of nutrients hastens the decline in total C production or the ‘***oligotrophication’*** of the ecosystem. The condition is exacerbated by a loss of littoral C production caused by the drawdown/flooding cycles that destroy littoral and wetland vascular plant communities.

The river reservoir becomes a 'new' lake; the extent of flooded land and the associated environmental impact is usually large. The new higher elevation lake reservoir starts recording change the day the water level stabilizes behind the dam, but there is little or no background data with which to assess rate of change of 'new' river reservoir, i.e. it is a now a *new* lacustrine ecosystem. But, in old lake basin reservoirs (e.g. Arrow, Duncan, Whatshan), the land area flooded is smaller and impacts are less severe than in river impoundments. It is also easier to assess changes by using paleo-limnological techniques or by examining pre-regulation lake data on water chemistry, fish or aquatic biota. Despite differences in formation and environmental impact, both types of reservoirs seem to age in a similar manner after intervention, with typical 'boom' and 'bust' cycles (Ney 1996, Stockner et al. 2000). After about 10-15 years, there follows a post-intervention period when the biota of reservoirs reach a new equilibrium that is sustained by more predictable nutrient supplies and balanced production levels. From a fisheries perspective it is unfortunate that this post-impoundment stable condition, which occurs about 20 years *after* impoundment, is irreversible (except by fertilization) and usually stabilizes at a *lower* C production level than occurred in the pre-intervention ecosystem. But in highly turbid river systems, like the Columbia, or Duncan, impoundment can actually improve light condition that had heretofore limited C production; stabilization/equilibrium can occur at slightly higher levels than seen pre-intervention, e.g. Arrow. In new 'river' reservoirs there are no previous large lake systems with which to compare post-production levels, e.g. Revelstoke, and Koocanusa.

To summarize: reservoir aging or 'oligotrophication' is linked to substantial nutrient losses once the 'boom' cycle subsides, losses occur by:

- Reduced nutrient inputs (loads) from upstream impoundments (e.g. Revelstoke (Mica), Kootenay (Duncan and Libby), and Arrow (Revelstoke).
- Increased sedimentation rates of particulate organic and inorganic C, N, and P with concomitant sediment adsorption, sequesterization and retention.
- Deep-water (hypolimnetic) penstock discharge (nutrient export) that can increase downstream lotic C production.
- Chronic littoral zone impairment and dysfunction.

2.2.3 **Key Variables Driving Pelagic and Littoral Autotrophic Carbon Production.**

The term "carbon production" has been used frequently in this report, as it is in general use in the scientific literature. However, for the sake of clarity, it should be noted that carbon is actually not being produced; it is being fixed into biomass in the various watershed habitats (pelagic, littoral, rivers and streams, wetlands) as a result of biological production.

The following discussions refer at times to Arrow Lake, which has been used, because of the relative abundance of data available, as an example of the processes occurring throughout the basin.

2.2.3.1 Nutrients.

Dissolved inorganic nitrogen (nitrate/nitrite + ammonia) or DIN is moderately abundant in most Columbia basin lakes/reservoirs and Arrow is no exception with DIN ranging from 100-160 ug L^{-1} in early spring then declining to lower values as the season progresses but seldom dropping to values < 4 ug L^{-1}. On the other hand, total dissolved phosphorus (TDP) is quite low in the Columbia basin and is often close to the limit of detection by late-summer (1-3 ug L^{-1}), and hence is considered the nutrient most likely to limit C production by autotrophs. In recent years, N has been depleted by August in the epilimnion of certain sectors of Arrow Lakes Reservoir and in Kootenay Lake, and both systems are undergoing 'nutrient' supplementation that increases C production that can create co-limitation by both N and P. When the reservoirs are P limited, the DIN/TDP ratio is generally >25, which is favorable for the production of edible pico- and nano-plankters, and the ratio is sufficiently high to preclude the establishment of *inedible* N-fixing blue-green algae (Bloomqvist 1999). In summary, when light conditions are not limiting photosynthetic C production, then P limitation or both N and P co-limitation are key factors that set limits on C production in the upper Columbia Basin lakes/reservoirs, rivers and streams and likely wetlands as well. Current loads of 'available' P seem capable only of sustaining the 'oligotrophic' condition.

2.2.3.2 Light.

We consider light availability for photosynthesis to be an important 'governor' of autotrophic C production in the upper Columbia River footprint basins. Throughout several months of the growing season, glacial and erosional turbidity was a common feature of many Upper Basin lakes/reservoirs, rivers and streams. The large input of high turbidity freshets in early May, June and July, and their gradual decline from late July to early September, created low light conditions that flooded wetlands, reduced the depth of the euphotic zone in historic lakes, and reduced light to wetted substrate of rivers and streams. These factors collectively reduced C production during the peak of the growing season. It is not only inflow turbidity that affected light conditions but also the prevalence of strong winds and wave erosion that eroded clay and silt and other fine particulate detritus from unstable, bare shorelines and river deltas (littoral regions) that created and sustained conditions of moderate to high turbidity throughout much of the open-water season. However, this effect is not consistent across all reservoirs and shorelines; many shorelines away from the inflow deltas are well armored (e.g. Duncan and Revelstoke) and do not produce turbidity. Light penetration was often limited by turbidity to the upper 5-10 m of the reservoir in May/June/July while mixing depths in the epilimnion often ranged from 15-25 m by September/October (Pieters et al. 2000). Thus phytoplankters were exposed to a lower *average* light intensity and likely light limited in such a strongly mixed epilimnion (see Equation 1), and C production of wetland plants, lake littoral and stream periphyton and mosses was also impacted. The growing season used in this study and in previous production models compensated for lower light periods at freshet during peak solar radiation months. It included two heightened growth and production periods, one in spring and the other in fall, i.e. on the 2 tails of the annual Columbia River pre-dam hydrograph, incorporating the months of April – May and September and October to early November (Stockner and Korman 2002) (Figure 45).

Equation 1.

(from Stockner and Shortreed 1975)

Average light available at any depth

$$(I\ avg.) = I_o/D \int^{D} \exp^{(-kz)}\, dx$$

Where: $\mathbf{I_o}$ = Light intensity at z=0
D = mixed layer depth
k = extinction coefficient
z =depth with respect to surface

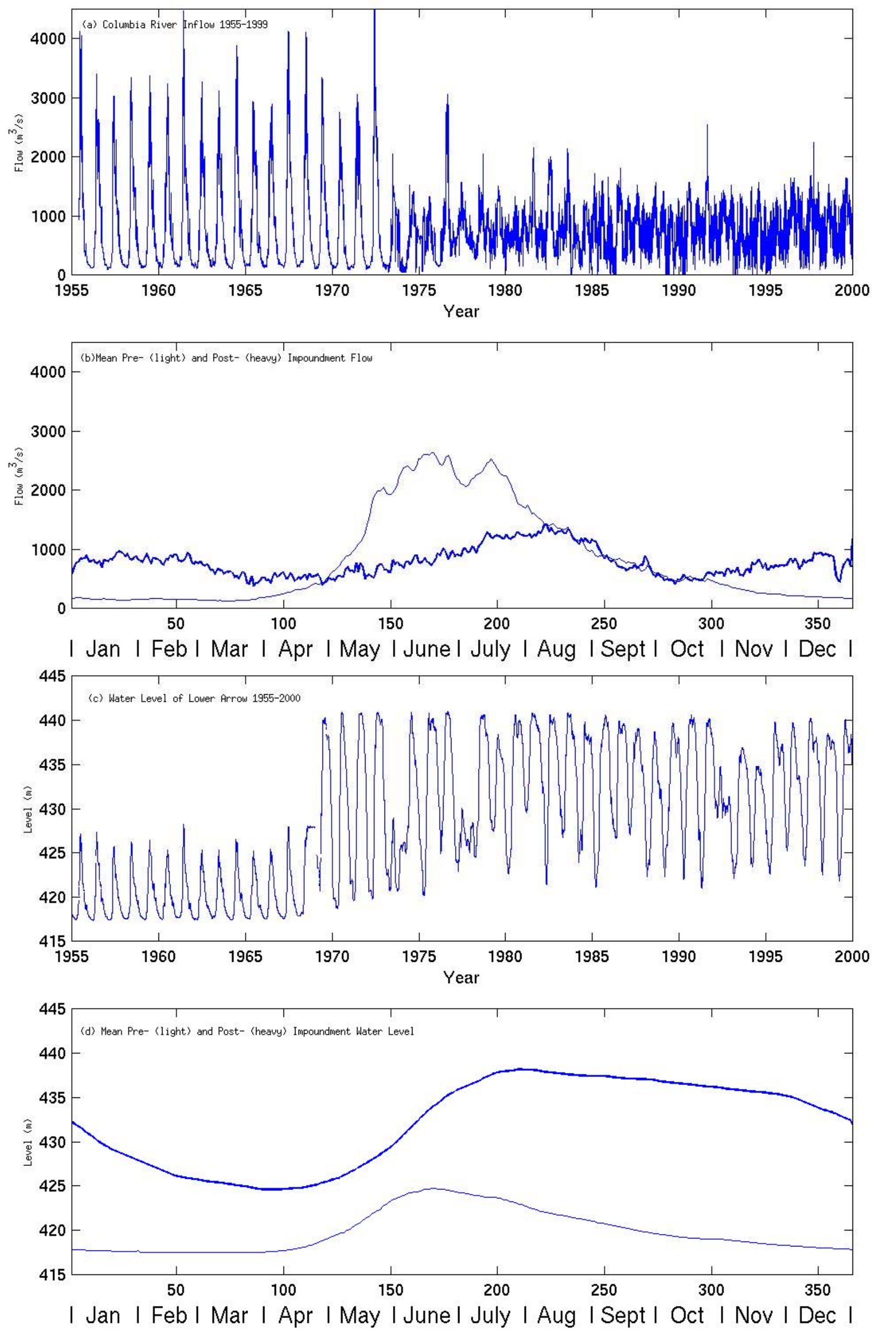


Figure 45: Hydrology of Arrow system 1955-2000 (after Pieters et al. MS 2001).

2.2.3.3 Hydrology

The fast-flushing, short residence time of water in reservoirs like Arrow Lake further exacerbates C production potentials by advecting and exporting both regenerated nutrients and over-wintering biomass from the system at crucial times, e.g. early fall/winter period. In natural lakes with longer hydraulic residence times, particulate biomass, nutrients and senescent biota normally precipitate out of the epilimnion and accumulate in the hypolimnion, to be mineralized and (in a well-oxygenated hypolimnion) sequestered on the sediment surface. A small fraction of particulate matter that is reduced and mineralized within the hypolimnion will support a modest spring production peak. The pre-dam historic Columbia lakes often had several meter changes in lake-level elevation during annual spring freshet that seasonally flooded *a moderately productive littoral zone and riparian habitat* with only modest amounts of erosional turbidity and no long-term littoral or wetland C production impairment. The productivity of the littoral zone varied from lake to lake. Arrow Lakes were somewhat unique among the Columbia Basin lakes in that they were, more or less, wider portions of the river and therefore experienced considerable wind and wave erosion in the littoral zone. This effect has only been magnified by the increased amplitude of the drawdown and slumping of reservoir shorelines. In the present post-dam reservoirs, the amplitude of water level fluctuation has increased to 5-20 m, and the timing of the peak flows and low water periods has been altered. Therefore, littoral communities are largely dysfunctional. Now the freshet periods impart shorter epilimnetic residence times and floods largely denude easily eroded littoral and riparian substrates. This imparts further turbidity to surface waters that diminishes light penetration and reduces pelagic and littoral C production (Stockner & Korman 2002).

3.0 METHODS

3.1 Spatial Analysis

This study is the continuation of a multi-phase project to determine the ecological footprint of BC Hydro dams in the Columbia Basin. Phase 2 of the project consisted of pre-impoundment habitat mapping using air photos and historic base maps, which was seen as a foundation for the analysis of the effects of the BC Hydro dams. The mapping of ecosystems included, geo-rectification of historic MS map series for the flooded areas, digitization of water features from the historic mapping, mapping and calculation of stream reaches and gradients using MS map water features and mapping of ecosystems following MOF site series classifications (Ketcheson et al. 2005).

The historical mapping was the only available quantification of pre-dam ecosystems and water features in the Columbia Basin. The GIS summary of the polygon areas and stream lengths was provided to us, to calculate the historic carbon contribution from wetland and aquatic ecosystem components. The reliability of these calculations is dependent on the accuracy of the historic mapping. In addition, other spatial information, such as historic and present day areas of waterbodies, was supplied by the Columbia Basin Fish & Wildlife Compensation Program, GIS department (Amy Waterhouse) based on TRIM analysis. The areas were calculated based on provincial TRIM mapping because this standard was available for all reservoirs in the study area.

3.2 Caveats and Assumptions.

In addition to the limitations of historical photographs, upon which the habitat mapping was based, there were other restrictions in using historical resources for the foundation of calculations in this analysis. Detailed limnological studies of pre-dam lakes and streams within the footprint basin are sparse and reported results are restricted mostly to ‘grey’ literature, e.g. BC Hydro, Provincial/Federal government, and consultant reports and some graduate student theses. The majority of these reports are focused on water quality issues and inventories of biotic resources. However, frequent inconsistencies have been identified in such factors as:

- locations of stations,
- frequency and types of physico-chemical variables sampled,
- means of collection and preservation, and
- methods of analyses.

Pre-impoundment wetland information was almost non-existent. To derive estimates of vegetation production in the pre-impoundment basin, we had to rely on biomass measurements from a range of habitats in B.C., western Canada and the US. Collectively all these factors have created a database with considerable variance in reported results that strains the validity of comparisons both among and between years and sometime between decades with pre- and post dam data (e.g. Thomas 1950, Peterson et al.1965, Peterson and Withler 1965a, b, c, Pieters et al 1998, 1999, etc.). Another source of variance came from the use of several different analytical chemistry laboratories, each reporting analytical procedures with different levels of detection.

We have focused on carbon as our currency and on gross primary production (GPP) as a measure of its annual production. Where necessary we have had to convert net primary production (NPP) values to GPP, (e.g. in lakes we used 25% as a conversion value because in oligotrophic lakes 10% can be applied for respiration (CO_2) losses and 15 % for extra -cellular organic carbon (EOC) releases). These metabolic costs (C losses) are common with all aquatic autotrophs, and are not effectively measured by conventional ^{14}C estimates of lacustrine production (Rieman and Sondergaard 1986). Conversion of NPP to GPP for river and littoral periphyton, mosses and for wetlands were higher 45% and 50%, respectively, mainly owing to much greater EOC releases, from these larger aquatic vascular plants and algal assemblages (Allan 1996, Wetzel et al. 1972). In this report, we deemed it important to provide an estimate of heterotrophic C production that was added to autotrophic C production to enable some understanding of the entire aquatic biotic C template in the present basin to contrast with the pre-dam C template. We have computed heterotrophic C production (bacteria, flagellates, protozoans, fungi) by adding estimates ranging from 25 – 65 % higher, to base autotrophic NPP production values. The amount of heterotrophic C addition was assessed based on the nature of the habitat and type of autotrophic community colonizing it, (e.g. phytoplankton, sedge, stream/littoral periphyton (Rieman and Sondergaard 1988, Cole et al. 1988, Cole and Caraco 1993, Weisse and MacIsaac 2000)).

3.3 <u>Primary Productivity Analyses</u>

Primary production is the conversion of solar energy into organic carbon by plant photosynthesis over time (Bott 1996), and gross primary production is the amount of carbon fixed per time interval, of which annual values (g C m^{-2} y^{-1}) are the most instructive metric for making comparisons of lakes and flowing waters (Morin et al. 1999). Gross primary production (GPP) is comprised of net primary production plus autotrophic respiration, whereby some of the fixed energy is lost as CO_2. <u>Gross</u> photosynthesis refers to the gross true synthesis of organic matter resulting from exposure to light. <u>Net</u> photosynthesis refers to the net formation of organic matter after losses from respiration, extracellular release of soluble organic matter, and other losses, e.g. mortality, that occur from the metabolic activities of algae & plants simultaneously with the photosynthetic processes.

Traditionally, there has been little overlap between the disciplines of limnology, fisheries biology and wetland ecology; therefore techniques for assessing primary productivity have evolved separately. Some methods and computations are well established in the research community, others are newly evolving. The nature of the organisms being studied also dictates methodology and manner of reporting.

From a vascular plant perspective, biomass refers to the amount of aboveground and/or belowground standing plant material at the time of measurement. Net primary production (NPP) can be considered the rate of supply of vascular plant matter potentially available to consumer organisms. Production is defined as the change in biomass of the entire plant over time. NPP of vascular plants is usually derived from a series of standing crop harvests and calculated from the incremental growth over time. This is usually considered to be a considerable underestimate of actual production since it does not account for losses to grazers and shoot turnover. Shoot mortality has been reported to be as high as 80-90% during the growing season (Bernard 1975, Bernard and Gorham 1978) and high turnover rates have been noted in temperate wetlands (Wetzel and Howe 1999). GPP is much simpler to assess in light/dark bottle experiments with phytoplankton than it is with inundated wetland vascular plants that have belowground organs, which are almost impossible to retrieve intact. To further confound matters; while aboveground growth is turned over annually (for the most part), the belowground organs are viable for years, perhaps even decades. Vascular plant production tends to be reported as NPP (primarily aboveground) and requires interpolation to be converted to GPP to be comparable with the aquatic components. However, GPP studies in wetlands are extremely rare and none could be found that were relevant to temperate floodplain wetlands. Details regarding wetland production values from literature sources and conversion calculations are presented in section 3.4.3.3.

3.3.1 **Lakes**

3.3.1.1 **Pelagic.**

Historic

There were only 6 lakes of the pre-dam footprint area and the extant limnological information about them was sparse. Most of the information focused on descriptive observations of available fish habitats of some of the larger lakes (Larkin 1951, Peterson and Withler 1965 a, b, c). After a review of these historic reports, and discussions with P. Slaney from personal observations of pre-dam conditions in Kootenay, Duncan, Bush and Kinbasket lakes, we used professional judgment, based on a large database of primary production measurements from over 50 BC lakes (K. Shortreed and J. Stockner, DFO, unpublished BC Lake's database, Cultus Lake Lab. Cultus Lake, BC) to estimate the likely seasonal daily rates of C production for Duncan, Bush and Kinbasket lakes. To better forecast the productive state of pre-dam Kootenay and Arrow Lakes, personal observations and photos of T.G. Northcote, together with anecdotal written accounts and photographs from the BC Archives, were used to estimate the likely levels of daily and annual areal C production for these three large lakes. We received an impression of the probable effect of high Columbia River turbidity on light penetration and on pelagic production rates through the growing season by reviewing comments of residents and biologists living in proximity of the old Arrow Lakes and Kootenay Lake. Further, we reviewed some of the paleolimnological data from Arrow Lake's reservoir cores obtained from Upper and Lower Arrow lake basins by Ashley (Pieters et al. 1998) and north and south arms of Kootenay by Ennis et al. (1983). We also examined total C values in surface sediment samples from a much more extensive analysis of short sediment cores taken from Kinbasket, Revelstoke, Arrow Lakes, and Whatshan reservoirs (Powertech report, BC Hydro Carbon Project, 1992). Pre-impoundment sizes of historic lakes were derived from historic mapping coupled with GIS analysis and present day areas of reservoirs were obtained from GIS analysis based on TRIM (Table 3). We used the average reservoir areas during the growing season (May 1 to October 31) for estimating post-dam pelagic habitat.

Table 3: Surface areas of historical (pre-dam) lakes and present day reservoirs in the Columbia Basin.

Name	Reach	Dam Unit	Polygon #	Historical[4] Surface Area (Ha)	Present Day[5] Surface Area (Ha)
Kinbasket	Donald - Mica	C3	5225	2,041.9	Kinbasket Reservoir 42,045.1
Unnamed	Donald - Mica	C3	3904	1.1	
Bush lakes	Donald - Mica	C3	4283	143.7	
Bush lakes	Donald - Mica	C3	4282	156.4	
Upper Arrow	Arrowhead - Keenleyside	C11	5215	21,316.2	Arrow Lakes Reservoir 51,195.5
Lower Arrow	Arrowhead - Keenleyside	C11	5212	13,676.1	
Whatshan Lake	Whatshan	C8	5048	1,528.9	Whatshan Reservoir 1,763.8
Duncan	Duncan River tributaries	K7	5043	2,583.9	Duncan Reservoir 7,298.5
Kootenay*		K6		39,000[6]	Kootenay Lake 39,400

* Kootenay Lake surface area includes the main lake but not the West Arm.

[4] CBF&WCP GIS analysis based on historical mapping (Ketcheson et al. 2005)

[5] CBF&WCP GIS analysis based on TRIM

[6] Kootenay Lake was not included in the CBF&WCP historic mapping, therefore precise surface areas are not available. The numbers used were selected based on information presented in several papers, (Daley et al. 1981,Northcote et al. 2005,Binsted and Ashley 2006, Carmack and Gray. 1982, Carmack et al. 1986). These were summarized using the professional judgment of J.G. Stockner as 390 km^2 for 'historic' and 394 km^2 for 'present'.

Present

To compute the magnitude of annual C production in present Arrow Lakes reservoir system we used average values of daily areal C production from unfertilized (1998) and fertilized (1999, 2000, 2001) years (M. Roshorne, MSc. thesis, UBC, S. Harris, unpublished data, Pieters et al. 2000, 2001). For Kinbasket, values reported by Stockner 2002, Stockner and Korman 2002, and Stockner 2004 were used. Values of epilimnetic chlorophyll from Revelstoke obtained in 2003 were used as a surrogate to rates of autotrophic production (P/B ratio) to estimate most likely values of daily areal and annual C production for Revelstoke Reservoir. After perusal of the Lekstrum et al. (1994) and Perrin and Korman (1997) reports, professional judgment was used to estimate present levels of areal C production in Duncan Lake Reservoir, and for the remaining smaller reservoirs, including the Canadian portion of Koocanusa. For Kootenay Lake we used an assortment of ^{14}C estimates (Table 4), For pre-dam Cominco estimates (Northcote et al. (1999, 2005) for post Duncan and Libby dam and post-Cominco 1980's we used Daley et al. (1981) and Jasper et al. (1983), and for present estimates we used Harris (2003).

Table 4: A. Kootenay Lake average daily production estimates from different time periods since 1800, and B. average daily production estimates from other interior large lakes and coastal BC sockeye nursery lakes.

A. **Kootenay Lake Date & period**	Range (mgC m^{-2} day^{-1})	Average (mgC m^{-2} day^{-1})	**Reference**
Historic Kootenay Lake 1800-1850's	85 -140	125	J. Stockner, professional judgment, 2006 & DFO lake PP database[1]
Kootenay Lake, pre-dam major Cominco period, 1966-1970	200 -1300	900	Northcote et al. 1999, 2005
Kootenay Lake, post-Dams, post-Cominco, pre-equilibrium period, 1977-1982	200 -1000	600	Daley et al. 1981, Jasper et al. 1983
2 Dams Kootenay Lake Fertilization, 2000-2004	50 - 600	170	Harris 2003, 2004
B. **Other BC Lakes Date & Period**	**Range**	**Average**	**Reference**
Slocan Lake, 2000 -2001	35 - 85	60	Harris 2003
Shuswap Lake	95-320	178	DFO lake PP database, 2006
Quesnel Lake	70-165	113	DFO lake PP database, 2006
Babine Lake	90 - 350	150	Stockner 1975
Glacial, turbid lakes (Kitlope, Morice, Chilko)	10 - 110	60	Stockner 1987, Stockner et al. 1993
Coastal lakes, untreated	50 -70	66	Stockner 1987, 1996
Coastal lakes, fertilized	145 -180	160	Stockner 1987, 1996

3.3.1.2 Littoral.

Historic vs. Present

With the exception of M.Sc. thesis work on periphyton communities in Kootenay Lake during its most productive 'eutrophic' phase (pre-Libby) (Ennis 1977), we have found no literature estimates of historic periphyton carbon accrual rates for any of the early historic lakes or present reservoirs of the Upper Columbia basin. Further, owing to moderate levels of turbidity in most all of the upper Columbia basin reservoirs in summer months, it was impossible to estimate, from historical air photos, the sizes of the historic littoral zones of most systems relative to present reservoir surface areas. However, from personal observation and aerial photographs we are confident that most reservoirs lack substantive littoral regions. Among those viewed (Arrow, Revelstoke, Kinbasket, Whatshan), the littoral regions (except for isolated areas with river and tributary "deltas", that experience some deposition and a steady moisture supply) are mostly denuded and lack significant perennial vegetative growth (Limnotek,1999; J. Stockner, A. Moody, personal observations). Without areal littoral area estimates, and no direct *in situ* measures of production we opted to use the range of percentages of annual pelagic C to littoral C production from the Stave Reservoir studies (Beer MS 2004), and from the periphyton studies of Shortreed et al. (1984). The comprehensive 3-yr study of the littoral C and 2-yr pelagic C production of oligotrophic Stave Reservoir (Beer 2004, Stockner and Beer 2004), confirmed the initial findings of Shortreed et al. (1984) of a <1% littoral C contribution to total C production in 21 coastal lakes, with Stave littoral contributing from 1-3 % to Stave total tC production. Thus, we opine that the estimated Kootenay, Arrow, Kinbasket, and Duncan littoral/pelagic production ratios that range from 1-3 % fit well within the pattern seen in the majority of periphyton studies of BC lakes. Revelstoke, as a run-or-the-river reservoir, has more elevational stability, and was given a higher littoral contribution (4 %), as was Kootenay (3 %) with more extensive fluvial deltas, particularly in the south arm and more gradually sloping littoral (Ennis 1975). The smaller Whatshan, Koocanusa and Kootenay River reservoirs contributions were higher (3-4 %) due largely to greater stability and less turbidity. The estimated value of the littoral/pelagic ratio for each system was used to compute the average annual littoral C production (tC/yr). We used professional judgment to apply an average annual littoral C production percentage deemed reasonable to each lake pre-dam within the footprint and to each present-day reservoir.

Based on historical accounts and photographs, supplemented by published macrophyte productivity data for appropriate environments (Wetzel 1975, Howarth et al. 1996, Truelson and Warrington 1994), we used professional judgment to estimate macrophyte contributions to littoral tC yr^{-1} in each lake and reservoir. Overall, the macrophyte C contributions were judged to be a very small percentage of the total littoral C contribution.

3.3.2 Rivers and Streams

3.3.2.1 Characteristics of River and Stream Primary Production

In stream ecosystems, production is mainly by algae, cyanobacteria, vascular macrophytes and bryophytes (mosses), and algae are usually the major component within a mixed assemblage comprised of algae, bacteria, protozoans and detritus (Hynes 1970). In large rivers, phytoplankton (or potamoplankton) also contributes to primary production, although in rivers as large as the Lower Fraser River, it was insignificant compared to attached periphytic algae (Northcote et al. 1975). Potamoplankton is more significant in the American reaches of the Columbia River (Williams and Scott 1962).

In stream metabolism studies, it is almost impossible to separate the metabolic rates of the primary producers or autotrophs from that of heterotrophs (Lamberti and Steinman 1997). Thus, gross primary production is the best measure of production in streams and rivers, rather than net primary production, and therefore gross primary production (GPP) is the unit used for primary production of streams and rivers in the BC Hydro (BCH) Reservoir units of Columbia Basin.

There is an exceptionally wide range of reported annual estimates of primary production in streams and rivers, which affects the methodology used to make GPP estimates in the BCH reservoir units. Arid desert or sagebrush streams, including Deep Creek, Idaho, and Rattlesnake Springs, Washington, have been documented to support 3540 to 5400 g C m^{-2} y^{-1} of primary production (Minshall 1978, Cushing and Wolf 1984). At the other extreme are small “deciduous streams” with dense canopies, such as 2nd order Bear Brook in the H.B Hubbard Forest of the eastern USA, which supported autotrophic production of only 4 g C m^{-2} y^{-1} (Findlay et al. 1993). There, an extremely dense deciduous canopy limited light to the extent that overall production of benthic organic matter (BOM) was highly heterotrophic from the extensive deciduous forest leaf litter, contributing 600 g C m^{-2} y^{-1} to Bear Brook.

Coniferous and boreal forest streams are at the low end of the range of primary production, but generally generate higher GPP than the low-order deciduous-canopy streams, although primary production may be asymptotic at higher stream orders (Figure 46). Rates of GPP of north temperate coniferous (fir-hemlock alder) and boreal (spruce-balsam-birch-aspen) forest streams and rivers range from 35 to 330 g C m^{-2} y^{-1}, generally increasing with stream order or watershed area. It is these lotic ecosystems that should have functional similarity to the streams and rivers of the various Columbia Basin BCH reservoir units prior to their impoundments and conversion to reservoirs.

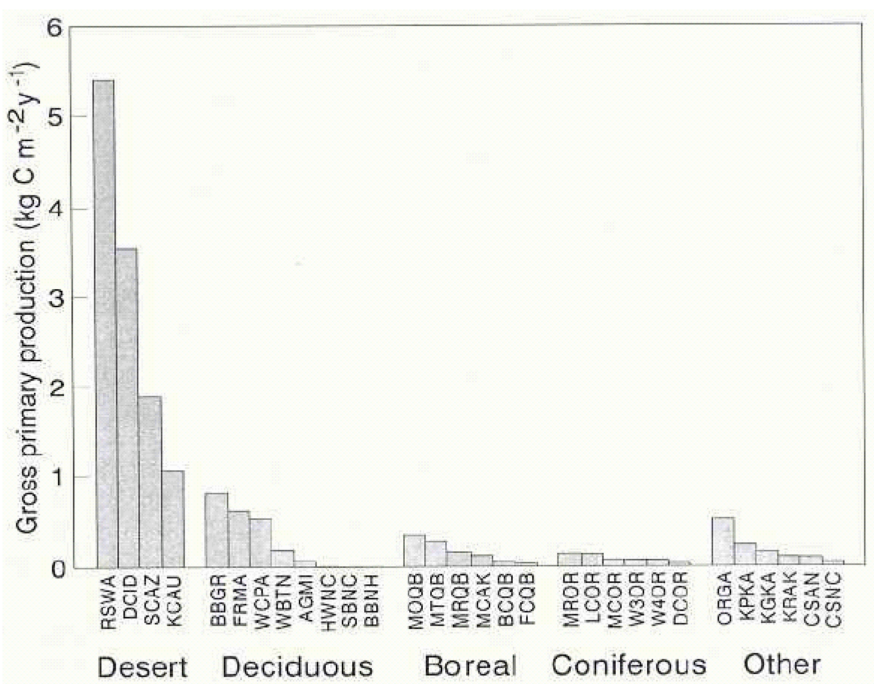


Figure 46: Range of gross primary production (kg C m^{-2} y^{-1}) among temperate rivers and streams of North America (Lamberti and Steinman 1997).

"Deciduous" forest streams are located in the eastern USA; "boreal" forest streams are within the north temperate zone of Quebec and Alaska; montane "coniferous" forest streams are in coastal Oregon; and "other" includes deciduous eastern blackwater, prairie, tundra, Antarctica and blackwater swamp streams.

Complete ecosystem studies of annual organic matter budgets of lotic waters are not abundant in the stream ecology literature, and there are only about 30 streams and rivers where there has been sufficient research to construct benthic organic matter budgets that include primary production (Webster and Meyer 1997). However, those that have been conducted have advanced the knowledge of stream processes as postulated by the Stream Continuum Concept (SCC) (Vannote et al. 1980) and they are instructive and applicable for GPP estimates elsewhere. Primary production-related tenants of the SCC, which are important for estimation of GPP in Columbia Basin BCH pre-dam streams and rivers, can be summarized as examined and/or reviewed by Minshall et al. (1983), Naiman et al. (1987), and Lamberti and Steinman (1997):

- GPP is low in low order or headwater streams because of light limitations by the riparian canopy, and thus GPP is negatively related to percent canopy closure;
- GPP increases as stream size increases, but may asymptote in large deep rivers;
- GPP can be predicted to decline with increasing latitude, largely because of lower temperatures and annual light inputs;
- GPP is negatively related to precipitation because of increased vegetation shading and greater scour and sedimentation;
- GPP is positively related to nutrient concentrations.

Although these have generally been supported by intensive SCC ecosystem or "biome" investigations and research, including a meta-data analysis by Lamberti and Steinman (1997), some of the relationships were weaker than expected, including latitude, precipitation, stream order, and most nutrient parameters. However, GPP and watershed area were more strongly related, and those of a larger size appear to reach an asymptote in GPP (Lamberti and Steinman 1997, Minshall et al 1983). Soluble reactive phosphorus (SRP) was the only nutrient significantly correlated with GPP, whereas others (total phosphorus, nitrate and ammonium), were uncorrelated (Lamberti and Steinman 1997).

3.3.2.2 Models of Stream and River GPP with Potential Application to Columbia Basin

There are potential applications of two regression models to predict river-stream GPP losses resulting from the Columbia Basin BCH reservoir developments:

1. Daily GPP-chlorophyll a-temperature model (Morin et al. 1999)

Morin et al. (1999) searched the stream ecological literature for simultaneous measurements of daily GPP (mg C m^{-2} d^{-1}), as measured by C^{14}-tracer techniques, and corresponding Chlorophyll a concentrations (mg chl a m^{-2}):

(a) GPP = 1.23 + 0.79 log chlorophyll a

Where: r^2 = 0.63 and n = 337 (entire data set)
GPP is mg C m^{-2} d^{-1}
Chlorophyll a is mg m^{-2}

or

(b) GPP = 1.6 + 0.63 log chlorophyll a

Where: r^2 = 0.65 and n = 130 (subset of data with temperature available)

and

Temperature effects were significant. For example, primary production (per mg of chlorophyll a) was 2.5-3 fold higher at 15°C than at 5°C:

(c) GPP = 0.80 + 0.70 log_{10}Chlorophyll a + 0.04temperature

Where: r^2 = 0.69 and n = 130
GPP is mg C m^{-2} d^{-1}
Chlorophyll a is mg m^{-2}
Temperature is C°

However, there are constraints to application of these regression models to Columbia Basin rivers and streams. Firstly, chlorophyll a data is lacking from the pre-dam rivers and streams. Secondly, a more serious limitation is that the models do not account for the primary production components generated by macrophytes and bryophytes, but rather only from periphytic algae. Lower order streams generally produce few macrophytes and mosses unless stable/lake headed (Webster and Meyer 1997). In contrast, higher order rivers and their off-channel areas (side-channels, groundwater-channels, back-channels and sloughs, and ponds) produce macrophytes and mosses, particularly at lake outlets and in stable off-channels areas. For example, macrophytes were prevalent pre-dam in Duncan River at its outlet and throughout a large side-channel located a few km downstream of Duncan Lake. Mosses are also common within large boulder-bedrock segments (e.g., Fraser River Canyon). Regardless of these limitations, the regression equations and Figure 47 were used for estimating GPP from reported assessments of chlorophyll a accrual of several BC Interior rivers and streams, adjusted for estimated growths of mosses and/or macrophytes.

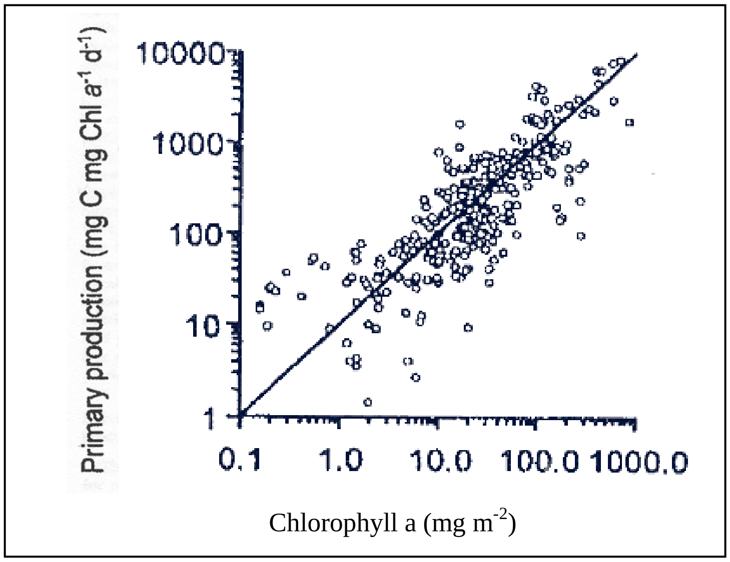


Figure 47: Scatterplot of data collected from the literature on algal chlorophyll a (chl a) and daily gross primary production (as mg C mg chl a-1d-1) for stream periphyton (from Morin et al. 1999).

2. Annual GPP-watershed area-mean annual discharge-SRP model (Lamberti and Steinman 1997):

$\log_{10}GPP = 0.717 + 0.689\log_{10}Area - 0.494\log_{10}Discharge + 0.387\log_{10}SRP$

where: $r^2 = 0.7$ and n = 30

GPP is g C m^{-2} y^{-1}

Area is watershed area in hectares

Discharge is mean annual discharge in L s^{-1}

SRP is soluble reactive phosphorus in µg L^{-1}

There are also some constraints to application of this model to BCH streams-rivers, although less so than the daily GPP model of Morin et al. (1999). The model incorporates extremely productive arid-land or desert streams that differ from the much less productive coniferous forest-dominated temperate streams of the Columbia Basin (Figure 46). Also, annual GPP data from 30 streams that is used in the multiple regression model are from latitudes ranging from 30-50^{o}, and therefore are probably not representative of north temperate coniferous rivers and streams of the Columbia Basin BCH reservoir units. Furthermore, mean annual discharge is not available for most streams and some rivers in the pre-dam reservoir units. In addition, SRP measurements are unavailable for most pre-dam rivers and streams, and few are available for above-floodline rivers and streams. Accordingly, this model was not applied to Columbia Basin rivers and streams, yet was utilized to indicate the relative significance of SRP to gross primary production in the Columbia Basin.

3.3.2.3 Application of Stream Order to Calculate GPP

GPP was highly related to stream order in a set of five boreal forest streams and rivers in Quebec where annual carbon budgets were calculated over several years; r^2 values for moss, macrophyte, and periphyton production as a function of stream order were 0.93, 0.93 and 0.96, respectively, or 0.97 as total GPP (Naiman et al. 1987). Similarly, among a set of four temperate streams located in Oregon, Idaho, Michigan and Pennsylvania, annual rates of GPP increased downstream with stream order in the four stream-river biomes (Minshall et al. 1983). However, the downstream or largest order river reach did not invariably have the greatest productivity; the third reach in Idaho and Oregon was slightly greater or equal to the higher order fourth reach in two of four seasons. Oregon streams, with their higher precipitation and conifer dominated forests, were lower than Quebec streams in GPP, yet both generally increased with stream order.

In contrast to this apparent GPP-stream order relationship in the biome studies, the Lamberti and Steinman (1997) analysis found there was only a weak correlation between GPP and stream order if all research streams and rivers are included. Rather, GPP was more positively correlated to watershed area (r^2 = 0.42). Yet in natural drainages, stream order and watershed area should be highly related. However, this anomaly resulted from inclusion of four small desert-sagebrush streams. These largely obscured the relationship because they were mainly low order, yet had a very sparse riparian canopy. Upon re-analysis with inclusion of only the coniferous and boreal forest streams and rivers, the r^2 was 0.77 (y = 29.2 + 28.2 x, where y is GPP and x is stream order (Figure 48). This equation was applied to rivers streams of Columbia Basin because desert streams are lacking.

Average GPP values for temperate high-precipitation watersheds may be more typified by the set of Douglas-fir/western hemlock/ red alder watersheds that were studied in the River Continuum Project in coastal Oregon. They ranged from 1st order Devils Club Creek to 3rd order Mack Creek to 5th order Lookout Creek to 7th order large McKenzie River. Respective annual GPP values were 36.5, 77.6, 141.4 and 148.3 g C m^{-2} y^{-1} (Webster and Meyer 1997). In the three smaller streams, dissolved nitrate nitrogen concentrations were near limits of detection and SRP was relatively high or up to 15 µg L^{-1}. In the large McKenzie River NO_3N averaged 0-4.2 µg L^{-1} but SRP ranged from 28 to 50 µg L^{-1}. Thus, these coniferous forest streams were N-limited and not P-limited. Accordingly, they are of higher trophic productivity than Columbia Basin streams which are very low in the primary limiting nutrient, phosphorus.

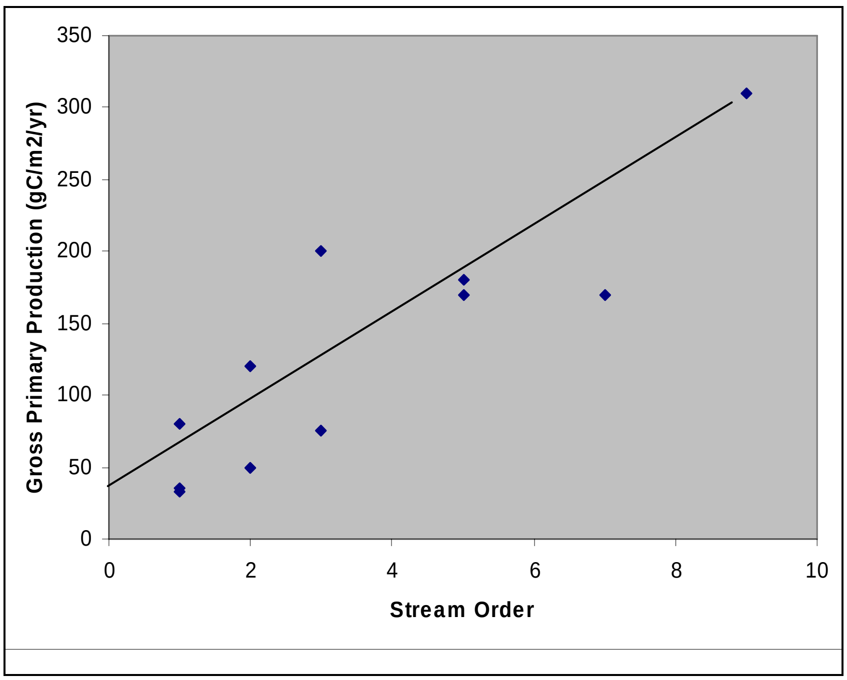


Figure 48: Relationship between gross primary production and stream order among coniferous and boreal forest streams and rivers in north temperate North America. (y = 29.2 + 28.2 x, where y is GPP in g C m^{-2} y^{-1} and x is stream order; r2 =0.77) (adapted from values used by Lamberti and Steinman 1997).

3.3.2.4 Application of BC Interior River and Stream Benchmarks

The average of the GPP values in Figure 48 is 129 g C m^{-2} y^{-1}, but this value is too high for rivers and streams of the Columbia Basin BCH reservoir units. This is because total alkalinity (as an indicator of productivity) and SRP decrease with increasing latitude from southern Idaho towards the BC border (Thomas et al. 2003). This reflects greater precipitation with increasing latitude associated with the BC Interior wet-belt, which increases in a northward direction in Columbia Basin. Unfortunately, no pre-impoundment measurements of chlorophyll a or GPP are available for rivers and streams of BCH reservoir units. Two measurements of chlorophyll a are available from the Columbia River, as sampled directly below both Revelstoke Dam and Keenleyside Dam (Perrin et al. 2004), although these are weak for estimating primary production of periphytic algae in the pre-dam case because of reservoir stripping of inorganic nutrients (Stockner and Ashley 2003). Also, estimates of GPP from these sites do not account for lotic bryophytes and macrophytes and were affected by hydro-operations (Perrin et al. 2004). Therefore, chlorophyll a data from other BC Interior sites, including a tributary of the Salmo River (Sheep Creek) in the Kootenays plus 8 other lotic waters in the Northern Interior, were used as *benchmark* estimates of GPP for application to Columbia Basin (Table 5). Although the two Columbia River measurements of peak chlorophyll a are values that are post-dam, they were used to ensure higher-order waters were incorporated in the benchmark. Increased water clarity in the post-dam case was assumed to offset other limitations. *Benchmark* waters range from ultra-oligotrophic and moderately glacial (Mesilinka River) to oligotrophic (Sheep Creek) because dissolved nutrients are near detection limits as either inorganic dissolved phosphorus (DIP) or inorganic dissolved nitrogen (DIN), or both. For the set of BC Interior *benchmark* streams, equation a and b from Morin et al (1999) were applied and averaged to calculate mean GPP using the estimated number of days available for algal growth (Table 5). Expansion to estimated total GPP accounted for significant macrophyte or bryophyte growths in one of the benchmark streams, based on the published coniferous/boreal forest biome studies by Minshall et al. (1983) and Naiman et al. (1987), where 50 % of primary production was generated by macrophytes and bryophytes in medium to higher order streams. As a case example, bryophytes accounted for 50-60 % of production in a tundra river study by Peterson et al. (1997). Accordingly, in 1 of 11 Interior of BC streams, periphyton GPP was expanded 50 % (medium ranking) to account for known significant growths of bryophytes (Table 5).

Table 5: Gross primary production (g C m^{-2} y^{-1}) estimates for BC Interior rivers and streams as generated from Chlorophyll a data using Morin et al. (1999) regression equations. Mean GPP values were used to proportionally reduce those of the coniferous/boreal forests biome data set of Figure 48.

Rivers/Streams	**Growth Days**	**Peak Chlor a**	**Macrophytes**	**Bryophytes**	**Periphyton GPP**	**Total Est.GPP**[7]
	per year	**mg m^{-2}**	**Ranking**	**Ranking**	**g C m^{-2} y^{-1}**	**g C m^{-2} y^{-1}**
Mesilinka River[1] 6th order	90	12	Low	Medium	14	21
Mesilinka Tributaries[1]:	90					
Carina Creek		80	low	low	53	53
Fatfish Creek		85	low	low?	55	55
Control Cr		38	low	low	31	31
Culvert Cr		44	low	low	35	35
Gopherhole Creek 3rd Order		27	low	low	25	25
Takla River 3 tributaries[2]						
- carcass area	100		low	low	14	14
- non-carcass 4th order	100		low	low	5	5
Sheep Creek[3] (Salmo R.) control, km1 2001-03 4th order	138	25	low	low	36	36
Middle[4] Columbia R. Revelstoke 8th order	100	11	low	low?	15	15
Lower[4] Columbia R. Keenleyside 8th order	150	26	low	low?	40	40
Arithmetic Mean						**30.0**

[1]Koning et al. 1995; [2]Johnston et al. 2004-table 2; [3]Slaney 2005 (1 of 2 control sites deleted as sampling anomaly); [4]Perrin et al. 2004 (means of shallow and deep river sites)

The arithmetic mean of total estimated annual GPP for the BC Interior river and stream set was 30.0 g C m^{-2} y^{-1} (Table 5, n = 11) or 30.0/129 = 23.26 % of the mean value of the GPP-stream order regression of (Figure 48). Accordingly, this was used as a BC Interior *benchmark* to proportionally adjust the GGP values downwards from the GPP-stream order regression derived from the more productive biomes summarized by Webster and Meyer (1997) and Lamberti and Steinman (1997). All GPP values derived from the GPP-stream order regression equation were multiplied by 0.2326 to estimate GPP of pre-dam rivers and streams of the Columbia Basin reservoir units.

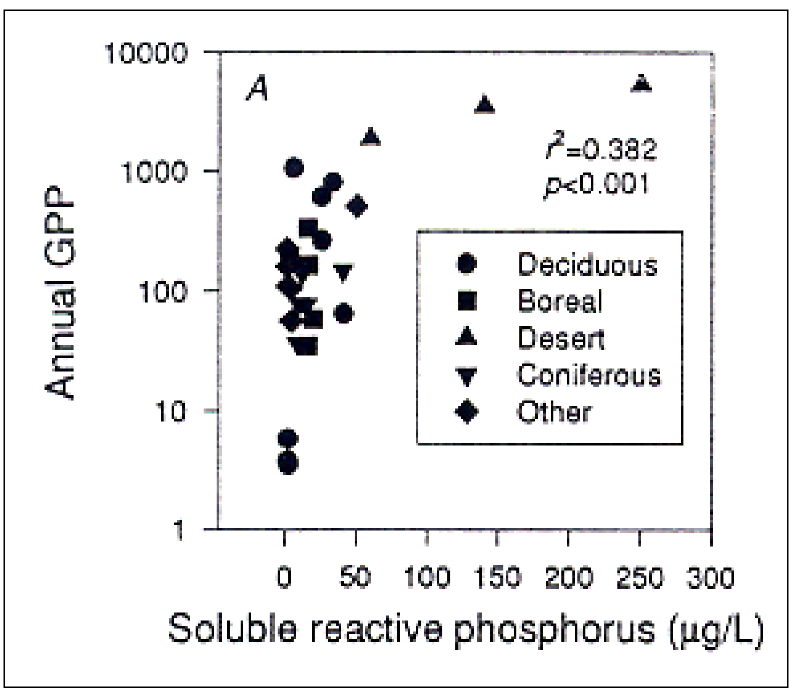
3.3.2.5 GPP-Stream Order Adjustments for Variable Trophic Status

In the multiple regression equation developed by Lamberti and Steinman (1997), SRP concentration significantly affected annual GPP (Figure 49). Although linear regression analysis of the data set resulted in a moderate significant relation (r^2= 0.4), it was evident that the relation was curvilinear (Figure 49), which resulted in its inclusion in Lamberti and Steinman's (1997) logarithmic multiple regression equation, which had a multiple r^2 of 0.7. As an example using their model, it was assumed that a medium-sized 4th order watershed had an area of 13,000 ha and a mean annual flow of 8,000 L s^{-1}. In this watershed, SRP at 1 µg L^{-1} versus 0 µg L^{-1} has no affect on a predicted GPP of 44 g C m^{-2} y^{-1}. However, small increments of SRP significantly increase predicted GPP; in the same example, 2 µg P L^{-1} = 58 g C m^{-2} y^{-1}, 4 µg P L^{-1} = 76 g Cm^{-2} y^{-1}, 8 µg P L^{-1} = 99 g C m^{-2} y^{-1}, and 16 µg P L^{-1} = 130 g C m^{-2} y^{-1} because of an exceptionally steep curvilinear relationship between GPP and SRP (Figure 49).

Regardless of SRP model sensitivity, nutrient data from the BCH reservoir unit rivers and streams are typically exceptionally low in dissolved phosphorus, or only <1 to 2 µg SRP L^{-1}, as well as in total dissolved P, and they are relatively higher in dissolved nitrogen (Hirst 1991). A complication with oligotrophic low-P streams is that available SRP is taken up by stream biota and thereby is not detectable. Furthermore, at these extremely low concentrations, SRP determinations can be subject to field and lab errors. Thus, in the pre-dam rivers and streams of the Columbia Basin reservoir units, SRP is relatively insensitive for making nutrient-related adjustments in predicted GPP because of an overriding dominance of oligotrophic waters with very low SRP.

An alternative to SRP for adjusting making nutrient-related adjustments in GPP data is the use of published relationships between chlorophyll a and total nutrient parameters (TP or TN) or nutrient surrogates, including conductivity, total dissolved solids (TDS) or alkalinity. For example, Chetelat et al. (1999) found significant correlations between algal chlorophyll a and total phosphorus (TP) (r^2 = 0.56) or conductivity (r^2 = 0.71) at 18 streams in Quebec (Figure 49). In addition, chlorophyll a was also correlated with total nitrogen (r^2 = 0.50). However, these relationships fail to account for primary production generated by macrophytes and mosses. Moreover, SRP was at or near detection limits in rivers and streams within the Columbia Basin reservoir units, and both conductivity and TP were very frequently at the low end of the ranges examined by Chetelat et al. (1999) (Figure 49). Accordingly, for Columbia Basin rivers and streams, it was assumed that GPP predicted by stream order and adjusted by an oligotrophic Interior BC data set was sufficient to account nutrient-related variations in GPP in the various reservoir units.

Figure 49: Relationship between gross primary production (g C m-2 y-1) and soluble reactive phosphorus from a meta-analysis by Lamberti and Steinman (1997).



A search was made for nutrient and nutrient surrogate concentrations, but pre-dam data were not available for most waters. Rather, the available data were utilized to characterize/scope trophic productivity as support for the Interior benchmark adjustment. Water chemistry data was also used for estimating pre-dam salmonid biomasses, the latter summarized within the Discussion.

Ratings of "stream/river productivity" were also used to adjust gross primary production in rivers/streams that were highly glacial during the primary summer-autumn growth season in some of the watersheds. Ratings[7] made were: (1) highly glacial with low biological productivity, (2) low-moderate productivity, (3) moderate-high productivity. These were relative ratings within Columbia Basin rivers and streams under pre-impoundment conditions. Water turbidity, water colour, temperature, flow stability (lake headed), observed incidence of aquatic vegetation (periphytic algae, macrophytes and mosses), incidence of large woody debris, kokanee carcass inputs, and known fish species use/abundance influenced ratings. Most rivers, and a few streams, were ranked.

Highly glacial or high sedimentation ratings were ascribed to the upper Duncan River system, the Wood River (Figure 13), and the main stem Columbia River combined with its glacial river tributaries, located upstream of Kinbasket Lake, including Kinbasket River. Regardless of sediment loads, most of the larger streams (e.g., Wood River) were associated with higher quality side-channel habitats (Peterson and Withler 1965a,b). Among these lotic off-channel habitats, primary production would have been significant under pre-dam conditions, as is evident today among the prolific side-channels of the Lardeau River (Slaney and Andrusak 2003). Regardless of their wide-spread glacial conditions, Columbia tributary mainstems were ubiquitously inhabited by mountain whitefish (Peterson and Withler 1965b).

Accordingly, in these highly glacial systems of lower productivity, stream-order-adjusted GPP values of higher order streams were reduced by 50 %. A 50 % reduction in GPP accounted for depressed macrophytes and bryophytes associated with high sediment scour and deposition. Algal GPP is also depressed under conditions of high suspended sediments because of light attenuation and scour (Allan 1996). However, a reduction >50 % was considered excessive because substantial near-surface algal accrual (40-80 mg m^{-1} as ash free dry weight) has been recorded at multiple sampling stations along the length of the glacial Lower Fraser River from spring to summer (Northcote et al. 1975). Thus, it is the deeper river zones where photosynthesis would be depressed by glacial waters, rather than the shallower zones.

3.3.2.6 Generation of Columbia Basin River-Stream Areas and GPP

Areas of reservoir-flooded rivers and stream were derived using a polygon-based GIS-analyses, conducted jointly by GIS-staff of Columbia Basin Fish and Wildlife Compensation Program and BC Ministry of Environment. Historical "reservoir flood-line" 1:50,000 scale maps as well as 1:20,000 TRIM maps were utilized by the GIS team.

Detailed methods and protocols are documented by the Columbia Basin Fish and Wildlife Program (GIS-methods on file, Columbia Basin Fish and Wildlife Compensation Program, Nelson). Briefly, for river and large-stream double-line water features, polygons were constructed from digitized MS map lines, and thus double-line stream areas were GIS generated. Channel widths of these double-line streams were not discriminated from wetted widths because these are similar during the high seasonal flows that occur during spring and summer as a result of extended run-off from high-elevation snow-packs in the Columbia Basin. For single-line or smaller streams, channel widths were predicted using regression analysis, based on total accumulated upstream length above the stream mouth. Predicted channel widths were applied to historical (pre-dam) stream segments that were flooded. Average stream wetted widths were predicted from channel widths. Where historical streams were not mapped, "construction lines" were used to estimate the "missing streams" that resulted from differences in map scales. Construction-line generated stream widths and areas were calculated using the same regression analysis as the historical MS streams. The construction lines had a sinuosity factor applied by watershed to adjust them to more realistically reflect historical stream lengths and areas. As expected, total GIS-generated areas of rivers and larger streams by far dominated total areas of the single-line plus construction-line streams.

[7] ratings were jointly made by biologists P. Slaney and H. Andrusak, using historical personal knowledge applied to rivers and streams denoted on historical flood-line (pre-dam) maps

Stream orders determined from 1:50,000 scale maps may differ from those determined from 1:20,000 maps because stream order is sensitive to map scale. Streams order within the published literature on GPP, as depicted in Figure 48, are mainly derived from 1:50,000 scale maps because most of the studies were undertaken in the early 1980s when 1:20,000 scale maps were not widely available. An exception was the set of five Quebec boreal streams and rivers because exceptional detailed analyses of geomorphology (including stream order versus stream length and watershed area) were conducted by Naiman et al. (1987) and adjustments were made to correct for under-representation of 1st and 2nd order streams. As the large Columbia River dominated lotic areas, an increase by one stream order from 7 to 8 would account for a 12-15 % over-estimate of GPP where 1:20,000 scale maps were used for stream order determinations and 1:50,000 scale maps were used for stream order from the published GPP research studies. However, because 50% of stream orders within Figure 48 were corrected for map scale, any error from this source would be small, or in the order of 6-7%.

Overall, the models and protocols, as applied to the river and stream area data for the Columbia Basin BCH Reservoir (pre-dam) units, can be summarized as calculation steps, whereby a single example is provided for the Mica-Revelstoke reservoir unit (Table 6).

Step 1: The GPP-stream order regression ($r^2 = 0.77$) was applied to Columbia Basin pre-dam rivers and stream areas: GPP = 29.2 + 28.2 x, where x is stream order.

Step 2: Predicted GPP by stream order was adjusted by the average BC Interior benchmark by multiplying the GPP values by an arithmetic mean value of 0.2326 to adjust predicted GPP downwards to reflect widespread oligotrophic conditions, as indicated from historical sampling of water chemistry at rivers and streams within Columbia Basin BCH reservoir units.

Step 3: The BC Interior-adjusted GPP was multiplied by the number of m^2, which for the rivers m^2 is obtained as ha x 10,000, to provide g C y^{-1}, which was converted to kg C y^{-1} and then to t C y^{-1}. For the streams the same calculation was employed, except the areas provided from the GIS analysis were in m^2, and conversion from ha was not required (Table 6).

Step 4: Biologist ratings were applied to account for highly glacial conditions, whereby GPP was reduced 50 % among 2-lines rivers and streams located (1) upstream of Kinbasket Lake, (2) Wood River and (3) upper Duncan River, to account for a lack of mosses and macrophytes, as well as depressed algal production from sedimentation.

Step 5: All GPP estimates for rivers and steams were summarized by pre-dam Columbia Basin BCH reservoir unit, and then totaled for all reservoir units.

Table 6: Calculation example of gross primary production (GPP) for rivers and large streams of the Mica-Revelstoke BCH Reservoir Unit.
The mean BC Interior value of Table 5 was used to proportionally reduce stream order-predicted GPP (i.e., based on the coniferous/boreal forests GPP-stream order regression of Figure 48).

River or Large stream Name	Stream Order	River or Stream Area ha	GPP as Predicted by Stream Order g C m^{-2} y^{-1}	GPPxBC adjustment (0.2326) g C m^{-2} y^{-1}	BC-adjusted GPP x Area (m^2) g C y^{-1}	BC-adjusted GPP kg C y^{-1}	BC-adjusted GPP t C y^{-1}
Bigmouth Cr	6	2.069	198	46.15	954799	955	1.0
Carnes Cr	6	1.537	198	46.15	709292	709	0.7
Columbia Reach 10	8	821.337	255	59.27	486777529	486778	486.8
Columbia Reach 11	8	21.505	255	59.27	12745257	12745	12.7
Columbia Reach 12	8	256.051	255	59.27	151752415	151752	151.8
Columbia Reach 13	8	271.620	255	59.27	160979613	160980	161.0
Columbia Reach 14	8	123.852	255	59.27	73402721	73403	73.4
Columbia Reach 15	8	174.874	255	59.27	103641664	103642	103.6
Columbia Reach 16	8	10.399	255	59.27	6163121	6163	6.2
Columbia Reach 17	8	314.409	255	59.27	186339147	186339	186.3
Columbia Reach 18	8	276.193	255	59.27	163689869	163690	163.7
Columbia Reach 19	8	344.021	255	59.27	193864805	193865	193.9
Downie Cr	6	50.172	198	46.15	23153294	23153	23.2
Goldstream R	6	2.366	198	46.15	1091858	1092	1.1
Horne Cr	4	0.935	142	33.03	308823	309	0.3
Totals		**2654.4**					**1565.6**

3.3.3 Wetlands

3.3.3.1 Wetland Definitions

A wetland is simply any area of land that is covered with water for a part of the day or year.... The limits of freshwater wetlands are usually established in the spring, when water levels are highest because of melting snow and flooding. Summer droughts, evaporation, and infiltration will gradually cause the areas to dry up, sometimes completely. But even if wet for only a short time each year, the area is a wetland (Canadian Wildlife Service – HWW).

Simply put, wetlands are transitional zones between land and water. They may be permanent, seasonal or temporary; they may be forested or open. *A wetland can be defined as any area of land that is under water for all or part of the year, and supports biological activity adapted to a wet environment* [8]. Wetlands are usually defined by a combination of hydrology, soils and vegetation. *A wetland is land where the water table is at, near or above the surface or which is saturated for a long enough period to promote such features as wet-altered soils and water tolerant vegetation. Wetlands include organic wetlands or "peatlands," and mineral wetlands or mineral soil areas that are influenced by excess water but produce little or no peat*[9] .

Wetland classification schemes are designed to compartmentalize wetlands primarily on structure. The Canadian wetland classification system segregates wetlands into five classes (bogs, fens, marshes, swamps and shallow water) according to their origins. An important distinction between these classes is the presence of mineral or organic substrates (National Wetlands working Group 1988). A structural classification provides an efficient method for categorizing wetlands, particularly as a mapping tool. However, difficulties may be encountered where boundaries merge and when field verification is not possible. Physical environments, particularly hydrological conditions, can change resulting in changes in vegetation composition. Defining wetlands and delineating their boundaries can be difficult especially when field-work is necessary to discriminate between superficially similar wetlands especially where the substrate characteristics come into play.

The British Columbia Wetland and Riparian Ecosystem Classification system (WREC), developed by the Research Branch of British Columbia's Ministry of Forests (MacKenzie and Moran 2004), was based on the Canadian Wetland Classification system but follows a stricter definition of wetlands than most others.

Excluded from the definition are deep water and flowing aquatic ecosystems and transitional ecosystems such as shrub-carrs, riparian low benches, and graminoid "wet"meadows, which have at various times been considered wetland ecosystems. Transitional sites are not saturated for long enough to be considered true wetland ecosystems and generally lack an abundance of hydrophytes. However, these types of ecosystems are frequently associated with wetlands. From an ecological perspective, it often makes sense to include them (and the surrounding riparian forest) with wetland sites and treat them as a larger ecological unit or wetland mosaic in the landscape....At a broad spatial scale, this complex of sites acts as a single ecological unit in terms of wildlife habitat (Banner & MacKenzie 2000).

The historical habitat mapping, of the Columbia Basin reservoir footprint areas, conducted for the CBFWCP, followed the BC wetland classification system (Ketcheson et al. 2005) (Table 7).[10] The GIS analyses and numeric results from the habitat mapping, were supplied by the CBFWCP in spreadsheet format, along with copies of the habitat maps. The historical aerial photographs used for the mapping were also available for further reference.

[8] Wetland Evaluation Guide 1992, North American Wetlands Conservation Council – Canada

[9] Federal Policy on Wetland Conservation – Implementation Guide for Federal Land Managers, Wildlife Conservation Branch, Canadian Wildlife Service, Environment Canada. 1996

[10] Refer to Ketcheson et al. (2005) for detailed descriptions of Ecosystem Units, mapping codes and site classes used in the historical mapping component of the footprint assessment.

Table 7: Summary of characteristics for wetland and related ecosystem Site Classes (Ketcheson et al. 2005).

Site/Realm Group	Site Class	Environmental features	Cover types	Species groups
Wetland Group	Fens (Fn)	***Wet or Very Wet SMR*** Groundwater-fed pH > 5.0 > 40cm fibric/mesic peat	Graminoid or low shrub	Deciduous shrubs, Sedges, and brown mosses
	Marshes (Ms)	Mineral soils or well-humified peat Protracted shallow flooding (0.1-0.2 m)	Graminoid or forb	Large emergent sedge, grass, forb, or horsetail species
	Swamps (Sw)	Mineral soils or well-humified peat Temporary shallow flooding (0.1-1.0m) Significant water flow	Tall shrub or forested	Conifers, willows, alders, forbs, grasses leafy mosses
	Shallow waters (Ws)	Permanent deep flooding (0.5-2 m)	Aquatic	Aquatic species Emergent vegetation < 10% cover
Flood Group of Terrestrial Realm	High bench (Df)	***Riparian flood zone*** Benches above normal waterflow Brief flood period	Coniferous Forested	Upland species of seepage sites
	Mid bench (Df)	Elevated benches flooded most years for < 21 days Areas of sedimentation	Deciduous treed or forested	Flood-tolerant deciduous trees and shrubs
	Low bench (Df)	Site directly adjacent to watercourse Annual flood > 21 days Significant annual erosion and deposition	Tall deciduous shrub	Flood-tolerant shrubs
Transition Classes from Terrestrial Realm	Shrub-carr (Tn)	***"Special" factor*** Frost prone depression with fine to medium-textured moist soils	Low shrub	Deciduous low shrubs, grasses, and forbs

Since there are no established protocols for determining wetland productivity from basic (historic) wetland classes, we explored a number of options for maximizing the information that could be extracted from the information at hand. The numeric data generated from the mapping included, Reservoir (Dam) Unit, BEC zone, polygon number, area (m^{-2} and ha), BEC variant, site series, US habitat class, structural stage, modifiers, stand type wetland class and cottonwood presence. Polygons were represented by up to three deciles, each representing proportions of the mapped polygon. In order to determine the sum of all of wetland areas, the total area of each polygon was divided by the decile proportions. For example, a 10 ha polygon might have been comprised of 50% open water, 30% sedge fen and 20% scrub birch. To account for the proportions of the polygons by different habitat components, the proportional area was calculated for each decile. For the above example, this would have resulted in 5 ha of open water, 3 ha of fen and 2 ha of scrub birch. The data was sorted, filtered and summarized according to reservoir unit and wetland class. Final analyses were undertaken using pivot table reports to summarize the data based on site series, structural stages and BEC zones.

Wetlands are transition zones between the aquatic and terrestrial realms. As such, they have boundaries that may not be well defined and may change with climatic and hydrologic changes. Some of the greatest insights into the Columbia River floodplain habitats came from a review of pre-impoundment aerial mosaics prepared for BC Hydro Lands Department, prior to creation of the reservoirs. Plans for the Duncan and Arrow reservoirs have fortunately been preserved by the Arrow Lakes Historical society. The plans show proposed reservoir boundaries and topographic lines superimposed on the aerial photo mosaics (Figure 50). Of particular significance was the timing of the aerial photography, which occurred during the spring run-off period in 1961 for Arrow and in 1964 for Duncan. Very limited coverage was also available for Kinbasket. These mosaics provided a clear impression of how much of the valley was inundated at what appeared to be moderate flood levels. As an example, a portion of one plan shows an island in the Columbia River that supports fens and floodplain forest (Figure 50). Note that much of the island is inundated but also, numerous channels run through the surrounding valley floodplain (lower lobe) and floodwater is obvious between the trees. At the top of the image, intrusion of floodwater is apparent in the fields.

Figure 50: Floodplain habitats, near Greenslide Creek (south of Revelstoke) inundated during spring runoff, June 1961 (BC Hydro Land Plan, courtesy of Arrow Lakes Historical Society).

Based on the examination of additional historical photos taken during flood stages, we felt that the active floodplain habitats had been under-represented in the historical mapping. By the inclusion of all site series, characteristic of the valley bottom floodplains, we felt that a more accurate assessment could be made of the floodplain production and contribution to the aquatic system. Based on the compelling evidence from the pre-impoundment photos, we chose to extend the habitat groupings beyond the habitats that had been mapped as part of the flood group (Df) and based on site series classifications (Table 8), considered the appropriate portions of the valley bottoms as functional floodplain. The forested wetlands could also be classified as floodplain benchlands but without further topographic analysis, the bench levels (low, medium or high) cannot be determined.

To ensure that duplicate tallying was not undertaken between the terrestrial and aquatic realms, **only wetland <u>area</u> (hectares) was tabulated for those areas classified as wetland in the historical mapping.** However, to obtain an accurate assessment of wetland functional contributions from an ecosystem perspective (discussed in the following section), the mapping was further segregated by site series and by structural stage, into non-forested wetlands (Structural stage less than 4) and forested wetlands (Structural stage 4 and greater)[11]. The area results for non-forested and forested wetland floodplains were then used to calculate net primary production using literature values for similar habitats (section 3.3.3.2). It was recognized that some of the lower structural stages represented seral stages that could evolve into mature forests later, but further analysis to refine this categorization would have required re-examining the aerial photos on a polygon-by-polygon basis. A similar issue occurred with the issue of potentially segregating floodplain associations into high, medium

[11] Structural stage 3 includes low shrub (3a) and tall shrub (3b) and both possibly include young trees less than 20 years in age. Structural stage 4 is identified as Pole/sapling with trees in the 20-40 year range.

high, medium and low benches. This could not confidently be done using the site series number alone and would have required re-examination of the photos. These refinements were beyond the scope of this study.

Cultivated fields, for the most part, were also considered to have been part of the floodplain complex and to have contributed nutrients and organics to the aquatic systems during spring floods. The rationale for including the agricultural fields was based on considering the “potential natural vegetation” of the valley bottom. A similar approach was adopted for assessing the pre-colonization nature of the Fraser River valley (North and Teversham 1984). Considering the identified issues of flooding of cultivated land, it is likely that some of the attempted agricultural practices would have been abandoned after successive years of inundation. Most of the lower elevation parcels would have reverted to their natural state and would have continued to function as part of the floodplain. Even as cultivated land, there would have been nutrient exchange occurring during flood periods.

Table 8: Wetland cross-reference for Wetland Codes and BEC classifications.

BEC zone[12]	Variant	Site series code	Site series number	Export Component[13]	Descriptive Name	Canadian wetland code
PP	dh2	AR	3	F	PyAt Rose Solomon's Seal	Df
SBS	dh1	BB	8	A	Sb - Scrub birch - Sedge	Fn
IDF	dm2	BH	6	A	Scrub birch - Horsetail	Fn,Df
ICH	mm	BS	7	A	SbPl - Bog-laurel - Sphagnum	Fn
ICH	mw2	BS	9	A	Bluejoint - Sedge	Fn,Sw
PP	dh2	CD	4	F	Act-Dogwood - Nootka Rose	Df
ICH	wk1	CD	7	F	Act - Dogwood - Twinberry	Df,Sw,Tn,Fn
ICH	mm	DH	6	F	CwSxw - Devil's club - Horsetail	Tn,Df,Sw
ICH	dw1	HD	3	F	CwHw - White pine - Devil's club	Df
ICH	mm, vk1	RC	6	F	CwSxw - Skunk cabbage	Df,Fn,Sw
ICH	mw3	RC	8	F	CwSxw - Skunk cabbage	Df
ICH	mm, vk1	RD	5	F	CwHw - Devil's club - Oak fern	
ICH	mw2	RD	6	F	HwCw - Devil's club - Lady fern	
ICH	mw3	RD	7	F		
ICH	vk1	RH	5	F	CwSxw - Devil's club - Horsetail	Df,Fn,Tn
ICH	wk1	RH	6	F	CwSxw - Devil's club - Horsetail	Tn
IDF	un	RH	6	F	Cw - Hooker's Fairy Bells	Df
ICH	mw1	RH	7	F	CwHw - Horsetail	Tn,Sw,Df
ICH	mw2	RH	7	F	CwHw - Horsetail	Df
ICH	mw2	RS	8	A	CwSxw - Skunk cabbage	Fn,Df,Sw
ICH	mw3	SE	9	A	Sedge - Sphagnum	Fn,Ms
IDF	dm2	SH	7	F	Sxw - Horsetail	Df
SBS	dh1	SH	7	F	Sxw - Horsetail	Tn
IDF	dm2	SS	5	F	SxwAt - Sarsaparilla	Df
ICH	wk1	SS	9	A	Sedge - Sphagnum	Fn,Ms
ICH	mw2	XX	0	F	complex of wet valley bottom site series along lake or	Df
ICH	mw2	XY	0	F	complex of wet valley bottom site series (80% 07, 20%	Df
All	all	-		A	Fen	Fn
All	all	-		A	Marsh	Ms
All	all	-		A	Swamp	Sw
All	all	-		A	Shallow-waters	Ws
All	all	-		F	Flood Associations	Df
All	all	-			Transition associations- flooded disclimaxes	Tn
All	all	OW	0	A	shallow open water - lacking extensive emergent plant	Ws
All	all	WE	0	A	generic wetland, lacks tree cover	Ms,Fn,Sw
All	all	GB	0	A	wave and current generated - composed of unconsolidated	Df
All	all	CF	0	F	Cultivated Fields	

[12] See Figure 3 for Biogeoclimatic zones, refer to Ketcheson et al. 2005 for detailed descriptions of site series

[13] F – floodplain (more terrestrial in nature) , A - aquatic

3.3.3.2 Wetland Function

Any wetland can have many ecological functions that are determined by its physical and biological characteristics. Wetland functions have been defined as:

- Hydrologic - (long and short-term surface water storage) maintenance of high water tables
- Biogeochemical - transformation and cycling of elements, retention and removal of dissolved substances from surface waters, accumulation of peats and inorganic sediments (sediment sinks)
- Habitat - maintenance of wetland plant communities, provision of food & habitat for waterfowl and other animals, maintenance of diversity (Nixon 1980).

Existing wetland classification schemes based on dominant plant types have been criticized for not accurately reflecting differences in the functions of wetlands (Sahagian & Melack 1996). The need for a functional characterization of wetlands has been emphasized. The major parameters identified for characterizing the role of wetlands are: hydrology, temperature, primary production, vegetation, soil type, chemical information, transport of organics/sediment, and topography/geomorphology. Vegetation characteristics can be inferred to some extent from the wetland class but in many cases, the species overlap between wetland classes (as discussed in the following section) and productivity can be highly variable within similar classes and between years.

Based on the limitations of the historic wetland mapping, (photo resolution and quality, freshet, lack of field verification) it was concluded that the wetland classes on their own would not provide sufficient information for assessing the historic carbon contribution to the aquatic systems. Therefore, supporting evidence was obtained from a variety of sources. Ecosystem unit descriptors and site series descriptions (Ketcheson et al. 2005-Appendix 1 and Braumandl and Curran 1992) were reviewed to gain an appreciation for characteristic species composition, slope position, parent materials, and water table. Specific prescription considerations often gave an indicator if the site series was likely to occur in a riparian location. This provided supporting evidence for aquatic connectivity. The historical mapping was reviewed in detail to determine floodplain position of wetlands, and proximity to streams and lakes. In many cases, the original aerial photos used for the mapping were viewed (in stereo) to obtain additional clues regarding landscape position and aquatic connectivity. Random polygons were chosen to examine valley bottom areas that had been identified as floodplain habitats (Df) and those which had not received such a rating. Based on the historical research and examination of a range of photos conducted for this study, it was concluded that much of the active floodplain area was not adequately represented by the classification used for the mapping. Floodplain benches export a portion of their production to the aquatic environment depending on their elevation and the hydrologic characteristics of the site. Wetland plant detritus is considered a high quality food source, for both wetland and aquatic consumers (Brinson et al. 1981).

Historical accounts, particularly Peterson and Withler (1965a,c), document the valley bottom floodplain habitats in the Donald-Mica and Duncan river tributary reservoir units as being overwhelmingly dominated by wetlands. Pre-dam photo mosaics of Arrow Lakes and the Duncan River tributaries show the rivers in freshet with the floodplains heavily inundated (Figure 37, 50). The Columbia valley was widely known for its spring floods that raised water levels by several meters. Based on this compelling background, the analysis was expanded to include all site series representative of the floodplain environments.

The U.S. Fish and Wildlife Service (Cowardin 1979), uses a broader classification of wetland than the one developed for B.C. Their “palustrine” system reflects the range of habitats and hydrologic conditions encountered in a floodplain environment (Figure 51). This approach fits the hydroriparian concept that was considered when examining the B.C. Ministry of Forests typical landscape profiles for site series that would be characteristic of floodplain environments (Braumandl and Curran 1992.)

Figure 51: Distinguishing features of palustrine wetlands (from Cowardin 1979).

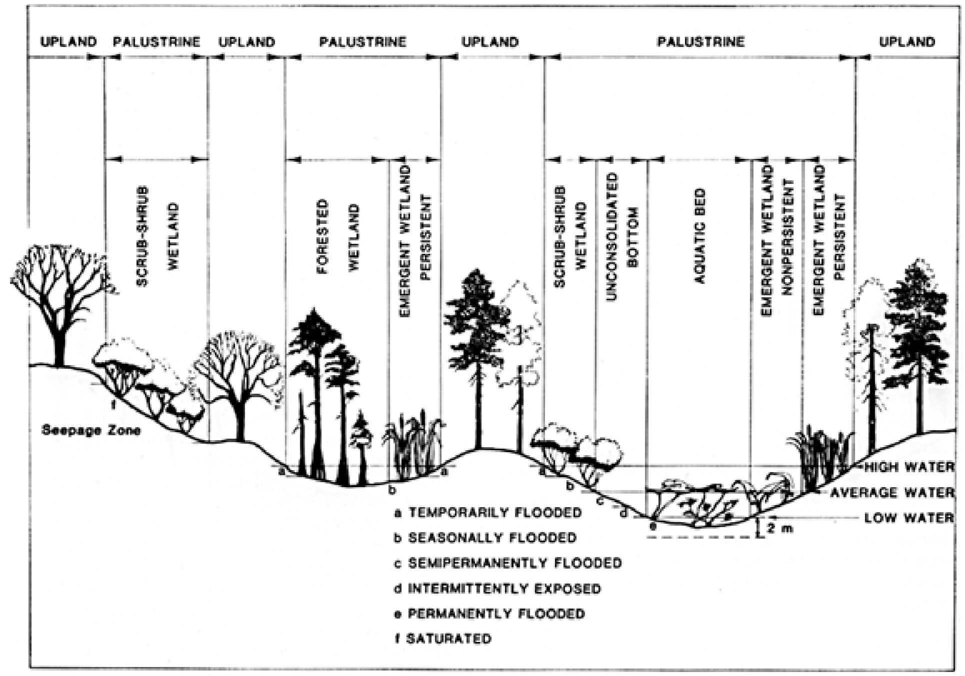
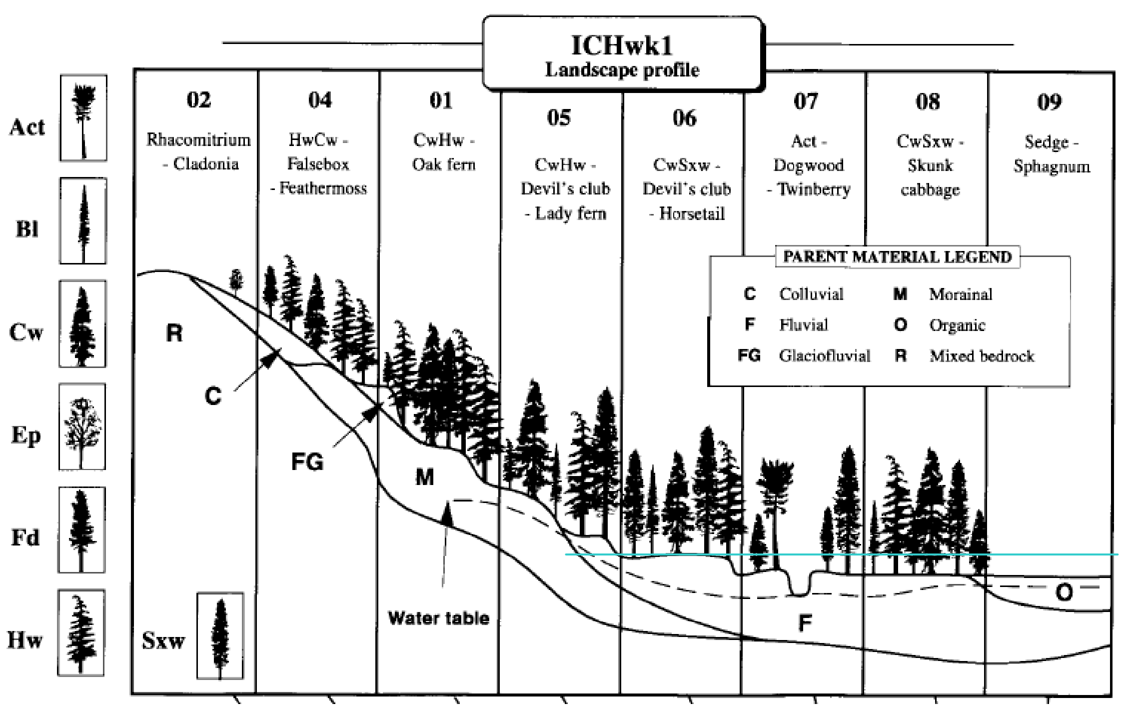
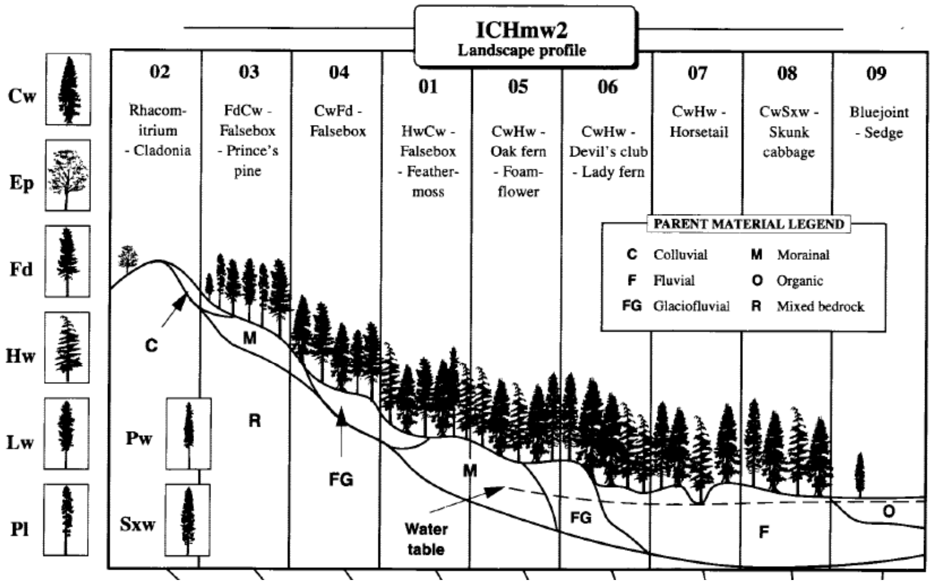


Figure 52: Landscape profile of ICHwk1 typical of Donald-Mica and Mica-Revelstoke reservoir units (from Braumandl and Curran 1992).



Floodplain habitats were considered to extend over site series 5 to 9 in the ICHwk1.

Figure 53: Landscape profile of ICHmw2 typical of Arrow Lakes reservoir unit (from Braumandl and Curran 1992).



Floodplain habitats were considered to extend over site series 6-9 in ICHmw2.

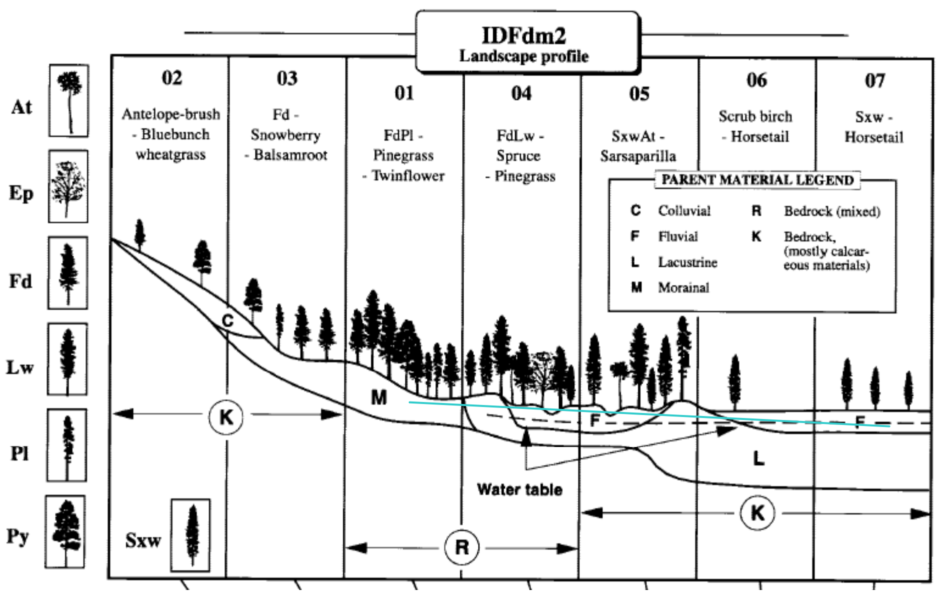


Figure 54: Landscape profile of IDFdm2 typical of the K3 reservoir unit (from Braumandl and Curran 1992).

Floodplain habitats were considered to extend over site series 4-7 in IDFdm2.

Depending on landscape position and hydrology, wetlands may contribute anywhere from none to almost all of their annual NPP into the aquatic system. Wetlands with no aquatic connectivity retain most of their biomass in situ, sequestering carbon in the substrates. This can only be determined by field verification of organic (peat) accumulation; an impossibility for the historic component of this study.

3.3.3.3 Wetland Productivity

Consistent data on net primary productivity of terrestrial vegetation is lacking, particularly in response to global assessments of carbon fluxes, carbon sequestration and in modeling ecosystem response to climate change. The use of the term net primary productivity has still not been standardized in the literature. Terrestrial NPP data are more widely available than other estimates of biosphere-atmosphere exchange of carbon such as gross primary productivity (GPP) and net ecosystem exchange (NEE) but there are significant problems with inconsistency in measurement techniques between NPP studies separated in space and time. Comprehensive summaries are rare and published data in individual studies are published in diverse formats (Scurlock and Olson 2002).

To place wetland productivity values in perspective, it is useful to consider the range of values from other biomes. Mean TNPP values for grasslands range from 182-3538 g $m^{-2}a^{-1}$ and boreal forests from 291-1190 g $m^{-2}a^{-1}$, dry matter. The mean above ground production (Mean ANPP) for C_4 grasslands was established as 668 and boreal forests 448 g $m^{-2}a^{-1}$, dry matter. (Scurlock & Olson 2002).

Wetlands are found in many environments and therefore it is difficult to compare the productivity of one site to another because of environmental differences. The productivity of wetland plants is know to vary according to:

- species (Bernard et al. 1988)
- season (Bernard, 1974; Bernard and MacDonald 1974),
- temperature (Gorham and Somers 1973, Gorham 1974, Keefe 1972),
- latitude and altitude (Bernard, 1973, Pearsall & Newbould 1957, Dennis et al.1978, Reynolds et al.1978, Solander 1983 a,b,c),
- hydraulic connectivity (Szumigalski and Bayley 1996, Thorman and Bayley 1997)
- nutrient availability (Pearsall and Gorham 1956, Gorham 1974, Gorham & Bernard 1975, Auclair et al. 1976)
- annual cycles, (Kvet 1983, Bernard et al. 1988 Solander 1983), and
- stresses to which the plants are subjected (Grime and Campbell 1991).

Wetland production values are generally reported as NPP, particularly of aboveground components. The measurement of gross primary production is rarely undertaken in wetland habitats due to the complexity of the analyses involved (Esser 1997). Of the range of production studies reported in Table 9, only one has reported GPP (Moore et al. 2002). Recently, a few studies have been undertaken using oxygen exchange rates to determine GPP (Liptak and Mitsch 2000, Reeder 1990). However, these studies have been undertaken in the eastern United States, one in an artificially created wetland. In another published review, gross primary productivity was reported for forested (mean 20.2 ± 6.8 g organic matter m^{-2} day^{-1}) and non forested wetlands (mean 21.6 ± 5.2 g organic matter m^{-2} day^{-1}) but these studies took place in Florida (Brinson et al. 1981). Nevertheless, those values were subsequently extrapolated to calculate riverine GPP in more northern climes, for the Hudson River in NY state (Howarth et al. 1996).

Based on widely varying results from different climatic zones there have been no compelling studies to warrant using any particular wetland GPP conversion values for extrapolation to the Columbia R. system.

Changes in water levels, climatic conditions have resulted in dramatic differences in biomass within sampled sites between years (Szumigalski & Bayley 1997, Thormann & Bayley 1997) and substantial year-to-year variability has also been noted for repeatedly sampled sites (Bernard et al. 1988). In response to climatic variability, Kvet (1983) noted a range of standing crops (10 year period), from 126 - 507 g m^{-2} per annum. More than 20% annual variability in production was reported for sedge marshes in northern Sweden (Solander 1983). Literature sources emphasize the lack of research relating NPP of wetlands to environmental factors (hydrology, soil, water chemistry and climate) (Richardson, 1978, Gorham 1982).

Wetland production changes seasonally, with active growth in the spring and summer; senescence and translocation of some elements to underground storage organs in the fall; decomposition of remaining aboveground material over the fall and winter; and mobilization of belowground storage to initiate growth in the spring. The aboveground growth is annual, whereas belowground growth is perennial and offers nutrient support for the aboveground components.

Total NPP of wetlands has been documented to increase with higher mean temperatures and a longer growing season (Reader 1978, Brinson et al. 1981). Gorham (1974) determined that there was a strong relationship between the highest mean monthly temperature and the above-ground standing crop of wetland species.

This relationship is reproduced in (Figure 55), with representative locations from the Columbia Basin shown. Although of interest, it is likely that the strong moisture gradient from north to south would more or less compensate for opposite temperature gradients.

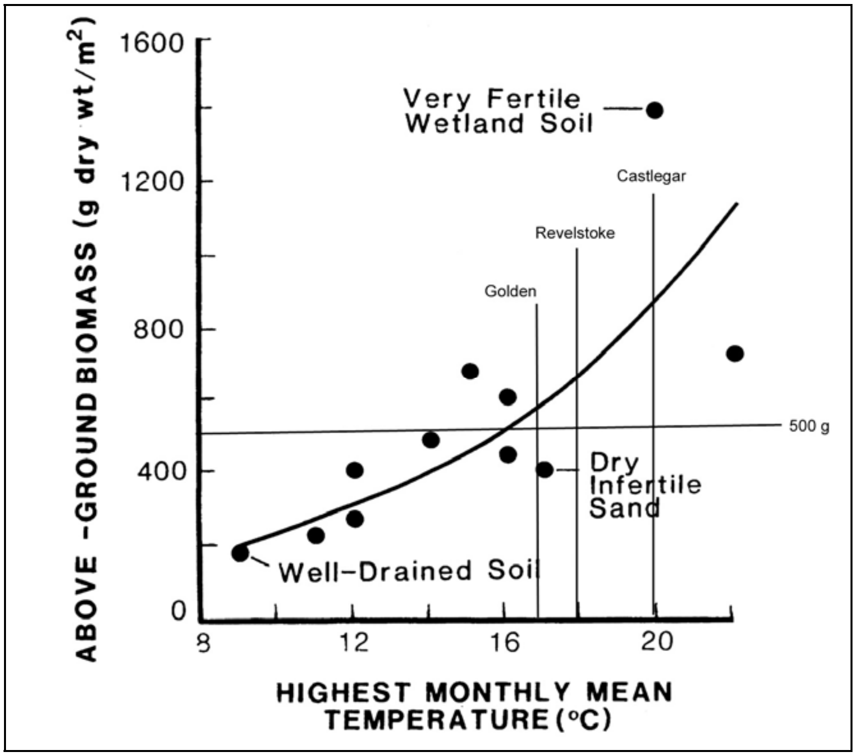


Figure 55: Relationship between highest mean monthly temperature and above-ground standing crop of various sedges in freshwater wetlands and uplands (after Gorham 1974).

Plant productivity is closely related to species, environmental conditions and geography. A number of biomass studies have been conducted in sedge (*Carex*) dominated wetlands with a few species having been studied extensively *(C. lacustris, C. gracilis, C. rostrata, C. lasiocarpa,* and *C. vesicaria*). Of these, only the last 3 species occur in B.C. and only *C. rostrata* has been utilized in shoreline revegetation programs (Moody 1998). A considerable amount of research has been conducted in Alberta, however this relates primarily to peat dominated wetlands (van der Valk and Bliss 1971, Gorham and Somers 1973, Szumigalski and Bayley 1996, Thormann and Bayley 1997, Thormann et al. 2001, 2004). The various studies from Alberta are the only geographically similar studies to address wetland classes, but even then, the terminology varies between studies and presents a level of refinement not distinguishable from air photos (e.g. floating sedge fen (moderate-rich fen), lacustrine sedge fen (extreme rich fen), riverine sedge fen, riverine marsh). These wetland types cannot be identified by vegetation composition alone because there is overlap of species from one type to another. For example, *C. aquatilis* dominates in the riverine sedge fen, riverine marsh and lacustrine marshes, whereas, *C. lasiocarpa* is a dominant in the lacustrine sedge fen, riverine sedge fen and floating sedge fen. Biomass production varied within sites from year to year (e.g. the lacustrine sedge fen production increased by 285% from one year to the next (80 to 300 g m^{-2} $year^{-1}$). However, this was not a consistent pattern in specific years as other sites underwent decreases at the same time. The lacustrine marsh (757 g m^{-2} $year^{-1}$) and riverine sedge fen (409 g m^{-2} $year^{-1}$) were reported as having the highest production. It was noted that "*The hydrologic regimes within North American bogs, fens and marshes may account for a large proportion of the variation in herb production observed*".

Biomass data for natural British Columbia wetlands is available for only a few locations, mostly from a mild maritime climate. Wetland biomass has been measured primarily in the Fraser River estuary (Yamanaka 1975, Moody 1978, Kistritz et al. 1983), the Squamish estuary (Levings and Moody 1976) and in the Pitt River marshes (Ogwang 1979, Barnard 1975). Little research has been conducted into wetland productivity in central B.C. The northern or interior B.C. marshes have been researched almost exclusively from the perspective of agricultural development (McLean et al. 1963, van Ryswyk et al. 1973, 1974, Cariboo Poorly Drained Soils Development Extension Committee, 1992). Relevant biomass and productivity results from literature sources are presented in Table 9.

The work most relevant to this study, albeit post–dam, comes from the regenerating wetlands at Revelstoke Reach, Arrow Lake. *Carex lenticularis*, with its dense, caespitose growth form, produced the highest biomass with a mean shoot AFDW of 2323 g m^{-2}. Aboveground plant standing crop in the vegetated drawdown zone averaged approximately 300 g m^{-2} immediately prior to inundation (June 23, 1999) with a low of 219 $g \cdot m^{-2}$ at 438m to a high of 390 $g \cdot m^{-2}$ at 437m. (full pool occurs at 440m) Dramatic differences were noted over the 10 m inundation range. The average belowground biomass was 840 $g \cdot m^{-2}$ with an overall root to shoot ratio of 2.8. (AIM & Carr 2000). It should be noted that due to reservoir rise, these plants are only able to photosynthesize for about half of their growing season. Survival of inundation is accomplished by reliance on root reserves.

Hydrologically unaltered floodplain wetlands, with a cycling of wet and dry periods, similar to the historic floodplain forests in the Columbia basin, have been reported to have an above-ground NPP of more that 1000 $g \cdot m^{-2}$ yr (Mitch & Gosselink 1993). The pulsed floods in riparian wetlands are believed to have resulted in greater productivity than that of standing water or rarely flooded conditions. To date, there is still a great dearth of information available for riparian forest and wetland productivity in northwestern North America. Most forested floodplain work has emerged from the eastern United States and from the deep south. Recent work in Wisconsin has estimated the NPP for nonforested wetlands to consist of 3.9 t dry mass ha^{-1} a^{-1} of understory components and 0.5 t dry mass ha^{-1} a^{-1} of foliar material. Forested wetlands as were estimated to produce 2.5 t dry mass ha^{-1} a^{-1} of foliar material and 0.4 t dry mass ha^{-1} a^{-1} of understory components. Wood contributions were listed separately (2.4 t dry mass ha^{-1} a^{-1} for forested and 0.1 t dry mass ha^{-1} a^{-1} for non forested).

Table 9: Wetland and Macrophyte Biomass and Productivity Values

Habitat	Species	Location	Above ground (g dry mass m^{-2} a')	Below ground (g dry mass m^{-2} a')	GPP (g dry mass m^{-2} a')	NPP (g dry mass m^{-2} a')	Max. above ground production rate (g dry mass m^{-2} a	Reference
Wetland	C. lenticularis	Arrow Reservoir	2323					AIM and Carr 2001
Wetland	Sedge/reed canarygrass	Arrow Reservoir	390	840			8	AIM and Carr 2000
Wetland	C. atherodes Sprengel	lowa	2858	548			23	Van der Valk and Davis (1978)
Wetland	C. atherodes Sprengel	NWT, Canada	432					Reynolds et al. (1978)
Wetland	C. gracilis Curt.	S. Poland .	580	250				Baradziej (1974)
Wetland	C. lyngbyei Hornem.	Fraser River, B.C.	687-1322					Kistritz and Yesaki (1979)
Wetland	C. lyngbyei Hornem.	Fraser River	909*					Moody (1978)
Wetland	C. lyngbyei Hornem.	Fraser River	930*					Yamanaka (1977)
Wetland	C. lyngbyei Hornem.	Squamish estuary,	1323				22.9	Levings and Moody (1976)
Wetland	C. rostrata Stokes	Alberta	515				6	Gorham and Somers (1973)
Wetland	C. rostrata Stokes	New York	540	260				Bernard and Hankinson (1979)
Wetland	C. rostrata Stokes	New York	1080	260				Bernard and Hankinson (1979)
Wetland	C. rostrata Stokes	Minnesota	740	180			11	Bernard (1974)
Wetland	C.aquatilis Wahlenb	Alberta	550				4	Gorham and Somers (1973)
Wetland	C.aquatilis Wahlenb.	Quebec	820	210			15.3	Auclair et al. (1976)
Wetland	C. lacustris Willd.	New York	970	210				Bernard and Solsky (1977)
Wetland	C. lacustris Willd.	Wisconsin	940	130				Klopatek (1978)
Wetland	C. lacustris Willd.	Czechoslovakia	1160					Husak and Hejny (1973)
Wetland	Carex sitchensis	Pitt Meadows, B.C.	852*	2110				Ogwang (1979)
Wet meadow		Interior BC	150-300 approx.					Cariboo PDSDEC '92
Bog			587		530	340		Moore et al. (2002)
Riverine sedge fen						409		Thormann and Bayley (1997)
lacustrine sedge fen						277		Thormann and Bayley (1997)
floating sedge fen						356		Thormann and Bayley (1997)
riverine marsh						323		Thormann and Bayley (1997)
lacustrine marsh						757		Thormann and Bayley (1997)
moderate-rich fen						359		Szumigalski and Bayley (1997)

Habitat	Species	Location	Above ground (g dry mass m^{-2} a')	Below ground (g dry mass m^{-2} a-')	GPP (g dry mass m^{-2} a-')	NPP (g dry mass m^{-2} a-')	Max. above ground production rate (g dry mass m^{-2} a-	Reference
Wetland	C. lenticularis	Arrow Reservoir	2323					AIM and Carr 2001
Wetland	Sedge/reed canarygrass	Arrow Reservoir	390	840			8	AIM and Carr 2000
Wetland	C. atherodes Sprengel	lowa	2858	548			23	Van der Valk and Davis (1978)
Wetland	C. atherodes Sprengel	NWT, Canada	432					Reynolds et al. (1978)
Wetland	C. gracilis Curt.	S. Poland .	580	250				Baradziej (1974)
Wetland	C. lyngbyei Hornem.	Fraser River, B.C.	687-1322					Kistritz and Yesaki (1979)
Wetland	C. lyngbyei Hornem.	Fraser River	909*					Moody (1978)
Wetland	C. lyngbyei Hornem.	Fraser River	930*					Yamanaka (1977)
sedge fen						213		Szumigalski and Bayley (1997)
extreme-rich fen						245		Szumigalski and Bayley (1997)
Poor fen						310		Szumigalski and Bayley (1997)
non-forested wetlands						500		Burrows et al. 2003
leaf litter								
Riparian	Populus deltoides wislizenii	Colorado	250					Andersen and Nelson 2003.
Forested fen		Minnesota	412			746		Reiners (1972)
Floodplain forest		Illinois	491			668		Brown and Peterson (1983)
		Illinois				1250		Johnson & Bell 1978).
forested wetlands						450		Burrows et al. 2003
Floodplain forest		various				>1000		Mitch and Gosselink 1993
macrophyte	Potamogeton pectinatus		250					Anderson (1978)
	macrophyte mix	Canada	4-363					Chambers and Kalff (1985)
	macrophyte mix	Mackenzie Delta	0-6000					Squires and Lesack (2003)
	macrophyte mix	various	200-1000					Westlake (1963)

The key findings from the analysis of production literature are:

- The measurement of Gross Primary Production (GPP) has been rarely undertaken in wetland habitats.
- Productivity is generally reported as Net Primary Production (NPP) and usually only for aboveground components
- Changes in water levels and climatic conditions can produce annual biomass differences within and between sites
- There is a lack of research in environments and wetlands similar to those encountered in the Columbia Basin,
- It is likely that there would have been substantial biomass variability within the classes of wetlands mapped in the Columbia Basin;
- Biomass values in the literature vary widely, but most temperate zone sedge production has been measured between 500-900 $g \cdot m^{-2}$ (5 to 9 t/ha) of aboveground dry matter production per annum (Bernard et al. 1988).

Due to the lack of productivity measurements for habitats comparable to those in the historic Columbia Basin, it has been necessary to use the best available information from the literature, combined with professional judgment, to make general assumptions regarding the likely productivity of the historic wetlands. As more research data becomes available in the future, refinements can be made to the values presented here.

The assumptions are as follows:

- wetland dry organic matter NPP (non-forested) pre-dam is estimated at a basin average of 4.4t/ha (Burrows et al. 2003).
- floodplain dry organic matter NPP (forested wetland-understory and litter values only, no wood included) production pre-dam is estimated at a basin average of 2.9 t/ha (Burrows et al. 2003).
- wetland production post-dam is estimated at an average of 3 t/ha for Revelstoke Reach (AIM and Carr 2000) values for others are lower (estimated at 2 t/ha -A. Moody, personal observations and field observations of plant density, vigour and height)
- carbon composition of wetland constituents is 47.5% (Esser 1997)
- the conversion factor for NPP to GPP has been estimated at 50%

Plant production estimates are generalized values at this point based on average standing crop values (for a range of wetland conditions) and an assumption of export (Wetland Group 90%, Flood Group 45%). These estimates are considered conservative and can be revised as additional information becomes available.

4.0 RESULTS

4.1 LAKES

4.1.1 Historic

4.1.1.1 Pelagic

The pre-dam lacustrine habitat was dominated by the 3 large lakes, the largest was Kootenay with a surface area of 394 km^2, then the Arrow lakes whose combined surface area was estimated to be 350 km^2. The next largest lakes were Duncan (25.8 km^2) and Kinbasket (20.4 km^2) whose combined surface areas (46.2 km^2) were some 7 to 8 fold lower than Kootenay and the 2 Arrow lakes. Whatshan Lake (15.4 km^2) was slightly smaller than Kinbasket, and Bush Lakes were the smallest of the lakes in the basin, with a surface area of only 3.1 km^2, or about 5-fold smaller than Whatshan Lake. Kootenay and Arrow lakes, because of their immense size relative to the other natural lakes in the basin, contributed slightly over 91 % of the pelagic C – 13,563 tC yr^{-1}. However, on an areal basis, Arrow Lakes were not as productive as the other basin lakes owing to lower ambient light conditions (turbidity) and shallow euphotic depth during peak growing season months, and also to a very short hydraulic residence time (rapid flushing). Both Kinbasket and Bush lakes, with their many backchannels, bays and interconnected ponds/wetlands were considered, on an areal basis, to be the most productive pre-dam lakes. Despite its high freshet turbidity, Kootenay Lake was likely moderately more productive than Duncan, Arrow or Whatshan lakes owing mainly to the large input of higher alkalinity, nutrient-rich waters of the Kootenay River drainage from the calcareous Rocky mountain trench sub-basins. Duncan Lake due to very high glacial turbidity and shallow euphotic depth, was considered only slightly more productive than the Arrow lakes. The total estimated pre-dam pelagic C production from all natural lakes was 14,773 tC yr^{-1} (Table 10). This estimate is likely conservative, as it does not include several productive, small oxbow/ice-melt lakes that were flooded within the Kinbasket and Arrow drainage basins, where limnological information was lacking.

The paleolimnological data from Arrow, albeit brief and preliminary, showed the effects of the impact of flooded soils and vegetation with the attendant nutrient releases had on key micro-fossils (biomarkers) like diatoms, e.g. *Cyclotella, Asterionella*, *Fragilaria*, and cladocerans (*Bosmina*, *Daphnia*) within the newly created reservoir (Vidmanic and Ashley in Pieters et al. 1999) . However, there were no readily discernable peaks or declines in C or N sediment analyses that could be correlated with biomarker increases in abundance in the surface 5 -7 cm. Dating of Arrow cores was confounded by the dense clay composition of the sediments that indicates a high rate of sedimentation and a high dilution of radioactive isotopes ^{210}Pb and ^{137}Cs used in dating. Thus, dates were difficult to ascribe to specific strata, which made interpretations of change difficult to correlate with known dates of system perturbations. The 1997 Arrow cores showed little variance in biomarker abundance from the deepest strata, 30-35 cm ‘old’ Arrow Lake sediment, to within 5-7 cm from the surface or commencement of ‘new’ reservoir sediment. The old lake sediment had extremely low biomarker abundance that strongly suggests a pre-dam low and invariant production level in the ‘old’ Arrow lakes. It is informative to compare these Arrow studies to, paleolimnological studies of Kootenay Lake sediment that showed a much greater abundance of diatom frustules than enumerated in Arrow, especially in cores from mid-lake and the north arm of Kootenay (Ennis et al. 1983).

Collectively then, early historic reports and anecdotal personal observations when coupled with paleolimnological data clearly indicate that, with the exception of Kootenay and Whatshan Lakes, all of the Columbia River main stem lakes were strongly influenced by extreme turbidity events associated with the Columbia River annual ‘freshet’ discharge that peaked June and extended well into early August (T.G. Northcote, personal communication). The high turbidity, which greatly diminished light penetration and reduced the depth of the euphotic zone greatly affected areal production rates in Kinbasket, Bush, and Arrow lakes. Even Duncan Lake was heavily influenced by turbidity but served as a partial settlement basin, thereby reducing turbidity of the Duncan River discharge to the north arm of Kootenay and lessened its impact on light and photosynthesis. It is clear from early photographs that in the south arm both higher flows and greater turbidity of the Kootenay River discharge advected a turbidity plume as far north as the mid-lake outlet to the west arm (Northcote et al. 2005). Hence, the Kootenay River freshet turbidity plume, like the Columbia River plume in Arrow and Kinbasket lakes, greatly compromised C production for more than half of the growing season in these lakes. Whatshan lake/reservoir is the only system that was not seriously affected by freshet turbidity. Rather, it was judged to be a low nutrient-status and very unproductive lake in the pre-dam condition, owing largely to its steep-sided forested basin, slow weathering granitic bedrock basin and fast-flushing hydrograph. Current information on Whatshan Reservoir substantiates the continuance of the ultra-oligotrophic condition to the present time (Sherbot, B, WGS-WUP-FTC 01, 2003).

4.1.1.2 Littoral (historic)

Like pelagic C contributions, total littoral C production (periphyton + macrophyte) was driven by the large size of Kootenay and Arrow lakes, contributing 441 tC yr^{-1}, about 79 % to the total littoral C production pre-dam. Kinbasket Lake contributed 42 tC yr^{-1} and Duncan 26 tC yr^{-1}, comprising most of the remaining littoral C production in the basin (Table 10). Littoral macrophyte C production alone (exclusive of littoral periphyton production) was a minor contributor to total C production in most of the lakes of the pre-dam Upper Columbia Basin, contributing in total 64 tC yr^{-1}, slightly more than 12 % of total littoral zone C production. There were shallow sectors of Kinbasket and Duncan lakes (South Bay) where early photos showed visible macrophyte beds within the littoral zone of moderate slope, so despite some freshet turbidity in both, these lakes contributed slightly more to littoral and macrophyte C production pre-dam.

Early reports by Peterson and Withler (1965a) describe Bush and Kinbasket lakes shorelines as ‘diverse and sinuous’ with many back channels (oxbows), small embayments and associated shallows with intermittent connections, habitats capable of supporting moderate levels of littoral C from periphyton and macrophytes. Duncan Lake, like Bush and Kinbasket, also experienced high glacial turbidity in its main steep-sided basins and littoral periphyton and macrophyte growth was likely negligible. However, in its shallow, South Bay there was less turbidity, warmer water and reports of moderate densities of both periphyton and macrophytes common in summer. This prime fish habitat likely increased the lake’s average contribution to littoral C and macrophyte C production (Peterson and Withler 1965b).

Macrophytes (mostly *Potamogeton* spp.) were present in the pre-dam era in discrete bays, side channels and contiguous ephemeral ponds associated with Bush and Kinbasket lakes, in Duncan Lake South Bay, and in small bays of Whatshan Lake. They were also observed in a few sheltered bays out of direct impact of major flows of the Columbia River at peak discharge in the historic Arrow lakes (T.G. Northcote, P. Slaney, personal observations), and were also likely present in Kootenay Lake in the shallows associated with the Kootenay River and Duncan River inflows, but pertinent comments on their ubiquity, distribution and abundance are lacking.

Table 10: Summary of Pre Dam Area and Production.

HISTORIC	Lakes	Surface Area Km²	Pelagic Daily PP (mgC ·m²)	Pelagic Total C (tC.yr-1)	Pelagic/littoral %	Littoral (tC.yr-1)	Macrophyte (tC.yr-1)
C2							
C3	Kinbasket Lake	20.4	130	477	6	29	13
C3	Bush lakes	3.1	135	75	6	5	3
C4	-						
C11	Arrow lakes	350.1	75	4788	3	143	15
C8	Whatshan Lake	15.4	95	263	7	39	5
C10							
K3							
K6	Kootenay Lake	390	125	8775	3	263	20
K7	Duncan Lake	25.8	85	395	3	18	8
K9							
Total system		**805**		**14,773**		**497**	**64**

Table 11: Summary of Post Dam Area and Production

PRESENT	Reservoirs	Surface Area Km²	Daily PP (mgC ·m²)	Total C (tC.yr-1)	Pelagic/Littoral %	Littoral (tC.yr-1)	Macrophyte (tC.yr-1)
C2	Spillimacheen	0.01	85	3	3	0.1	0
C3	Kinbasket	370	80	5,328	1	107	18
C4	Revelstoke	114.5	75	1,546	6	93	23
C11	Arrow Lakes [1] - *treated*	476.2	128	10,972	2	219	46
C11	Arrow Lakes -*untreated*	476.2	92	7,886	2	157	33
C8	Whatshan	17.6	90	285	4	11	2
C10	PDO	4.3	70	54	4	2.2	0.5
K2	Aberfeldie	1.2	75	16	5	0.6	0
K3	Koocanusa	60	95	1,026	3	31	1.0
K4	Elko	1.8	80	26	5	1.0	0
K6	Kootenay [1] - *treated*	394	172	11,958	4	478	25
K6	Kootenay -*untreated*	394	125	8,865	4	355	18.5
K7	Duncan	65	85	995	2	30	6
K9	Corra Linn - Brilliant	0.5	75	7	5	0.3	0
Total system -		**1505.1**		**32,216**	**littoral/pelagic 2.6 %**	**973.2**	**121.5**

[1] Treated values used in total computations   Littoral = periphyton & macrophyte

4.1.2 Present

4.1.2.1 Pelagic

The surface area of natural lacustrine ecosystems in the upper Columbia basin pre-dam era was about 805 km^2 or a little more than half the surface area of present hydroelectric reservoirs and Kootenay Lake of 1,505 km^2. Arrow Lakes, Kinbasket, Revelstoke Reservoirs, and Kootenay Lake represents 90 % of present lacustrine pelagic habitat area and contributes close to 30,000 tC yr^{-1} or nearly 90% of yearly total C in the presently configured basin (Table 11). A portion of this annual total C production (4-5,000 tC) can be attributed to nutrient supplementation (fertilization) in both Arrow Reservoir and Kootenay Lake. Kinbasket and Revelstoke Reservoirs are the second and third largest reservoirs in the basin and both are judged to be ultra-oligotrophic. Together they contribute about 7,000 tC yr^{-1} or 21 % of the annual total lacustrine C production. The remaining 8 smaller reservoirs contribute < 10 % to the total C production. The creation of reservoirs within the basin has increased both pelagic area and pelagic C slightly greater than 2 -fold above historic pelagic production from the natural lakes. Duncan and Koocanusa reservoirs each contribute about 1,000 tC y^{-1}, or together contribute 6 % to the present total pelagic C contribution. The remaining systems are all very small and make inconsequential contributions to the total.

If you normalize yearly reservoir tC production to surface area (km^{-2}), Kootenay (treated) annually produces about 30.4 tC km^{-2}, Arrow Lakes 23.0, Kinbasket 14.4 tC, Revelstoke 13.5 tC, Duncan 15.3 tC and 17.1 tC in Koocanusa. Arrow (untreated) produces only 16.6 tC km^{-2} or a 28 % reduction in C contribution without fertilization (Table 12). The primary production in the pelagic habitat of the historic lakes was higher on average than that in the present pelagic habitat. If littoral C production were factored in, the historic lakes tC km^{-2} would be even higher, largely because of poor littoral C production in present reservoirs, but also to the prevalence of low ambient nutrient concentrations in all lacustrine systems of the upper Columbia basin, i.e. oligotrophication.

Table 12: Pre-dam and present Columbia Basin 'footprint' normalized areal annual production.

Pre-Dam Lakes	GPP tC Km^2 yr^{-1}	GPP tC Km^2 yr^{-1}	Present Reservoirs
		3.6	Spillimacheen
Kinbasket Lake	23.4	14.4	Kinbasket
Bush lakes	24.1		
		13.5	Revelstoke
Arrow lakes	19.1	23.0	Arrow Lakes (treated)
		16.6	Arrow Lakes (untreated)
Whatshan Lake	17.1	15.1	Whatshan
Duncan Lake	15.3	15.3	Duncan
		17.1	Koocanusa
Kootenay Lake	22.5	30.4	Kootenay Lake (treated)
		22.4	Kootenay Lake (untreated)
		12.5	PDO
		14.0	Corra Linn - Brilliant
		14.4	Elko
		13.3	Aberfeldie
Average	**22.1**	**15.5**[1] **14.4**[2]	

[1] Treated values for Arrow and Kootenay used in average. [2] Untreated values used in average

4.1.2.2 Littoral

Kootenay Lake has not been severely impacted by reservoir drawdown, and most of its historic littoral zone (shoreline) currently remains intact (Ennis 1975), Most 'new' reservoirs within the 'footprint' now have severely compromised biotic communities of low production in their littoral zones. Causal factors include an atypical hydrograph, and large elevational fluctuations, i.e. drawdowns within the littoral zone., The only exceptions are reservoirs that are run-of–the-river such as Revelstoke Reservoir and some of the smaller reservoirs on the Kootenay River. Not surprisingly Kootenay Lake's annual littoral zone production, i.e. periphyton and macrophyte (503 tC) comprises nearly 50 % of total estimated present littoral production, while Arrow Lakes reservoir under current operations (treated) is estimated to contribute 265 tC yr^{-1} , that represents 24 % of total annual littoral C production (Table 11). Kinbasket with a more severe drawdown contributes only 125 tC yr^{-1} , <1 % of its estimated pelagic C production while run-of-the-river Revelstoke littoral contributes 116 tC yr^{-1} , 7.5 % of its pelagic C, a value that would doubtless be even higher were it not for moderate turbidity from inflow of several large tributaries that reduce euphotic zone depth. Koocanusa and Duncan reservoirs together contributed 68 tC yr^{-1}, or just over 3% respectively of their annual pelagic C contribution. Macrophyte contributions are greatly impacted by large drawdowns common to most of the present lacustrine ecosystems in the footprint area and their respective contributions to the littoral are now very low, with the largest reservoirs – Kootenay, Kinbasket, Revelstoke and Arrow Lakes, contributing the majority of the estimated macrophyte C or nearly 91 % of the total – 121.5 tC yr^{-1}.

4.2 Rivers and Streams

4.2.1 Water Chemistry: Nutrient Limitations of Trophic Productivity

Several characteristics of running waters influence the amount of carbon production in rivers and streams, and nutrients play a major role in both autotrophic and heterotrophic carbon production (Allan 1996). Some water chemistry was sampled during summer in the rivers and streams of the Columbia Basin BCH reservoir units before dams were constructed. Additional water chemistry was sampled post-dams at tributaries where they enter reservoirs, and these are applicable to the pre-dam case. Tables 13, 14, 15 and 16 combine to provide indicators of trophic status or biological productivity from either nutrient values directly (particularly dissolved inorganic N and P) or indirectly from nutrient surrogates including conductivity, total dissolved solids (TDS) and alkalinity. These oligotrophic nutrient and nutrient-surrogate values provide support for the BC Interior adjustment to GPP, and are required for model predictions of salmonid biomass that are tabled in the Discussion.

The distinction between N and P limitation is as outlined in Ashley and Slaney (1997), for which a more detailed description is available in section 6.2.1 on stream/river productivity augmentation as a compensation option.

In the Donald-Mica reservoir unit, moderate conductivity levels (mean 160 µmho cm^{-1}) were present under pre-dam conditions in the mainstem Columbia River (Table 13). Upper Columbia tributaries upstream of Kinbasket Lake also had moderate conductivities, yet tributaries directly below Kinbasket had lower conductivities (Table 13). However, most tributaries above Kinbasket Lake have glacial water quality, which tends to dampen biological productivity, although pre-dam fish collections show there was significant biological productivity supporting fish communities, particularly mountain whitefish, (Peterson and Withler 1965a). Trophic productivity there can be expected to be supported more by heterotrophy rather than autotrophy (Allan 1996).

Table 13: Summer nutrient and nutrient surrogate concentrations in and near the Donald-Mica Reservoir Unit, pre-dam and post-dam.

River / Stream	Location	Conduct µmhocm^{-1}	TDS mg L^{-1}	Alk mg L^{-1}	NO_3N µg L^{-1}	TP µg L^{-1}	SRP µg L^{-1}	Source
Columbia R.	Golden	175	98					Anon 1950
Blaeberry Creek		203						Anon 1950
Columbia R.	Donald	161	95	70	48	9	1	BCHydro 2003
Gold River	Mainstem	70						MoE fish data warehouse
Bush River	Big Bend	159						Anon 1950
Kinbasket River	Big Bend	134	83					Anon 1950
Wood River	Composite -tribs	102						MoE fish data warehouse
Canoe River	Valemount	38						MoE fish data warehouse
Camp Creek	Valemount	29						MoE fish data warehouse
Columbia R.	Encampment	152	91					Anon 1950

A few of the sampled tributaries are in a similar range of conductivity as coastal streams, including the upper Canoe River at Valemount (38 µmho cm^{-1}), Bigmouth Creek (52µmho cm^{-1}), Big Eddy Creek (30 µmho cm^{-1}) and Frisby Creek (18 µmho cm^{-1}) (Table 13, Table 14). However, most are higher than oligotrophic streams, with the Columbia in a moderate conductivity, TDS and alkalinity range (Table 13). As above and below Mica Dam, SRP is exceptionally low relative to moderately-high nitrate nitrogen, strongly suggesting ubiquitous P-limitation. Production is considered to be limited by P or N or both, when TDP values reach 1-1.5 ug/L and TDN < 5-10; when light is adequate and mixing is within a moderately shallow epilimnion.

Table 14: Mean summer nutrient and nutrient surrogate levels in upper Columbia River and tributaries in the Mica-Revelstoke to Revelstoke-Arrowhead Reservoir Units.

River / Stream	Location	Conduct µmhocm^{-1}	TDS mg L^{-1}	Alk mg L^{-1}	NO_3N µg L^{-1}	TP µg L^{-1}	SRP µg L^{-1}	Source
Columbia R.	Mica Dam	141	115	61				Envir. Rs. Con. 1976
Columbia R.	Carnes Cr	103	85	45	403			Envir. Rs. Con. 1976
Columbia R.	Downie Cr.	98	72	38	385			Envir. Rs. Con. 1976
Columbia R.	Revelstoke	141	130	56			1.3	Envir. Rs. Con. 1976
Copeland Cr.	Columbia			77	320			Envir. Rs. Con. 1976
Big Mouth Cr.	Columbia	52	40	18	151	9	2	Watson 1985, Anon 1950, BCHydro 2003
Scrip Creek	Columbia	54		20	530	5		Watson 1985
Ruddock Cr.	Columbia	75		30	510	4		Watson 1985
Hoskins Cr.	Columbia	52	23	19	158	4.5	1	Watson 1985 BCH 2003
Kirbyville Cr.	Columbia	52	35	21	47	2	<1	BC Hydro 2003
Goldstream R.	Columbia	100	80	43	126	5	2	Envir. Rs. Con. 1976, Watson 1985 BCH03
Downie Creek	Columbia	139	88	58	242	12		Envir. Rs. Con. 1976, Watson 1985 BCH 2003
Pitt Creek	Columbia	63	81	18	92	17		BC Hydro 1995
Birch Creek	Columbia	63	67	19	147	7		BC Hydro 1995
Moses Creek	Columbia	82	66	26	74	6		BC Hydro 1995
Mars Creek	Columbia	113	88	43	50			Envir. Rs. Con. 1976
Carnes Creek	Columbia	138	94	59	209	13	<1	Envir. Rs. Con. 1976, BC Hydro 2003
Big Eddy Cr.	Columbia	30		11	380	16		Watson 1985
Frisby Creek	Columbia	18		7	203	40		Watson 1985
Laforme Cr.	Columbia	80	61	34	218	2		Envir. Rs. Con. 1976 Watson 1985, BCH 2003
Jordon River	Columbia		84	40	340			Envir. Rs. Con. 1976
Greeley Creek	Revelstoke	94	55					Anon 1950
Illecillewaet R.	Revelstoke	107	72	55	107	20	2	Envir. Res. Consult. 1976. Anon 1950, Pieters et al. 2000 Schindler 2005
Akolkolex R.	Revelstoke	103	58		118	10	1.7	Pieters et al. 2000
Up. Arrow Lk	Airport	131	84	50	260			Envir. Rs. Con. 1976

Within the Arrowhead-Keenleyside Reservoir Unit, tributaries of Arrow Reservoir varied from a high in conductivity of 230 µmho cm^{-1} (Slewiskin Creek) to a low of 35 µmho cm^{-1} (Halfway River) (Table 15). Mosquito, Deer and Little Caycuse creeks were intermediate in level of conductivity, or 113 µmho cm^{-1}on average. The P-limited pattern of upstream waters was inconsistent, with TP typically higher than the Mica-Revelstoke reach. In contrast to the latter, nitrate nitrogen was low to moderate with several streams showing evidence of N-limitation or at least co-limitation (Inonoaklin, Cape Horn, Syringa, Little Caycuse and Halcyon Springs creeks). In addition, three others would become N-limited if any P is added (Mosquito, Burton, and Eagle). There is evidence that summer concentrations of nutrient surrogates decreased in the Arrow system post-dams. (Ahrens and Korman 2004)

Table 15: Mean summer nutrient and nutrient surrogate water chemistry in lower Columbia River at Lower Arrow Lake (1950) and within tributaries to Arrow Reservoir (2000 to 2005).

River/Stream	**Location**	**Conduct. µmhocm^{-1}**	**TDS mg L^{-1}**	**Alk. mg L^{-1}**	**NO_3N µg L^{-1}**	**TP µg L^{-1}**	**SRP µg L^{-1}**	**Source**
Incomappleux R.	Arrow	75	40		78	36	1.7	Pieters et al. 2000 Schindler 2005
Kuskanax River	Arrow	39	37		30	7	1	Pieters et al. 2000 Schindler 2005
Mosquito Creek	Arrow	104	70		20	12	2	Pieters et al. 2000
Burton Creek		70	47		22	5	1	Pieters et al. 2000 Schindler 2005
Cariboo Creek	Arrow	81	54		67	19	1.7	Pieters et al. 2000
Inonoaklin Creek	Arrow	93	75		3	19	1	Pieters et al. 2000
Halfway River	Arrow	35	30		97	7		Pieters et al. 2000
St Leon Creek	Arrow	36	30		84	9		Pieters et al. 2000
Slewiskin Creek	Arrow	230	160		58	10		Pieters et al. 2000
Whatshan River	Arrow	72	70		34	14		Pieters et al. 2000
Eagle Creek	Arrow	144	110		21	16	1	Pieters et al. 2000
Cape Horn Creek	Arrow	44	40		8	11	1	Pieters et al. 2000
Syringa Creek	Arrow	78	70		8	23	6	Pieters et al. 2000
Deer Creek	Arrow	103	70		2	13	3	Pieters et al. 2000
Little Caycuse	Arrow	131	100		11	26	11	Pieters et al. 2000
Halcyon Springs	Arrow				4	64	2	Pieters et al. 2000
Brouse Creek	Nakusp	185	121					Anon 1950
Columbia River	Nakusp	124						Anon 1950
Columbia River	Castlegar	130						Anon 1950

Other river and stream concentrations of nutrients and nutrient surrogates in other units including Duncan, Pend d'Oreille and Kootenay-Wardner (Koocanusa) varied from moderate (Duncan) to moderately-high levels (Kootenay R. Elk River and Gold Creek), with Pend d'Oreille-Salmo River intermediate (171µmho cm^{-1}) (Table 16). Highest conductivities (235-300 µmho cm^{-1}) were in the Koocanusa reservoir unit. Aside from Duncan River, these should be more biologically productive waters than elsewhere in the Columbia-Arrow system.

Table 16: Mean summer nutrient and nutrient surrogate water chemistry in Lower Duncan River (pre-dam, 1950) and within tributaries to Arrow Reservoir (2000 to 2005).

River/Stream	**Location**	**Conduct** $\mu mhocm^{-1}$	**TDS** mg L^{-1}	**Alk** mg L^{-1}	NO_3N µg L^{-1}	**TP** µg L^{-1}	**SRP** µg L^{-1}	**Source**
Duncan River			103				<1	Northcote et al. 1999
Pend d' Oreille	Mouth, Salmo	171	99		100	16		Anon 1950, TP-Fed/Prov data 90-95
Kootenay R.	Wardner	252	146					Anon 1950
Kootenay R.	Wardner		265					Northcote et al. 1999
Elk River	HWY 93	300	180	140	150	13	3	Anon 1950
								Fed/Prov data 90-95
Gold Creek	Cranbrook	235	123					Anon 1950

Conductivity was the parameter most widely available, particularly pre-dams. Regression analysis confirmed conductivity was highly correlated with TDS and alkalinity, as common indicators of trophic productivity (e.g., Northcote and Larkin 1956, Ptolemy 2005). For example, based on this Columbia Basin river-stream data set, TDS can be predicted from conductivity (TDS = 17.4 + 0.54conductivity; $r^2 = 0.9$); alkalinity can be predicted from conductivity (Alkalinity = 0.48conductivity – 6.5; $r^2 = 0.9$); and alkalinity can also be predicted from TDS (Alkalinity = 0.71TDS – 12.7; $r^2 = 0.8$). These regressions were used calculate missing values that were required for model calculations of salmonid biomass, summarized in the Discussion.

4.2.2 Kootenay BCH Reservoir Unit Rivers and Stream Areas and GPP Losses

Impoundments within the reservoir units caused major losses of river areas and relatively smaller losses of stream areas. This is because the mainstem widths of Columbia and to a lesser degree Kootenay River are exceptionally large within the various Reservoir units. Moreover, it is also because the tributary streams are higher gradients, and thereby many small lengths were flooded.

Total habitat area lost was 12,000 ha. Among all reservoir units in total, 97.3 % of the flooded habitat areas were rivers and large streams and only 2.7 % were streams (Table 17). The GIS map-based analysis was conducted on 2-line and 1-line flowing waters, resulting in the two categories, “rivers and large streams” and “streams”, respectively. The latter had higher gradients and smaller widths and thereby much smaller areas flooded. From Donald Station to Keenleyside Dam in the Columbia system, only a very small un-flooded river segment (~2 km) remains at Revelstoke, which is operationally affected by peaking-flow releases (Perrin et al. 2004).

Estimated GPP losses were largely proportional to areas impounded, and totaled 5,500 t C y^{-1} (Table 18). Thus, the largest losses were in the Donald-Mica reservoir unit, followed by the Mica-Revelstoke unit, then the Wardner-USA unit and Arrowhead-Keenleyside unit. Small but significant losses were incurred in the Pend d’Oreille and Duncan Reservoir units, whereas others were very small, comparatively. Similar to habitat areas, rivers plus larger streams comprised 97 % of the losses of GPP, whereas streams were only 3 %. Among the primary reservoir units, GPP losses per unit area in metric tones of carbon per ha were: Donald-Mica, 0.40; Mica-Revelstoke, 0.58; Revelstoke-Arrowhead, 0.58; Arrowhead-Keenleyside, 0.56; Wardner-USA, 0.58; and Duncan, 0.30 t C y^{-1} ha^{-1}.

Estimated GPP losses from rivers and streams included few of the pre-dam side-channels because the vast majority were difficult, if not impossible, to detect from historical map analyses alone. Thus, they are highly underestimated in areas and particularly GPP, using estimated areas of the Lardeau River and its side-channels as a template (Slaney and Andrusak 2003). Within the Lardeau River floodplain, side-channels accounted for 30 % of the total wetted main stem and side-channel area.

Table 17: Rivers and stream flooded habitat areas (hectares) by Columbia Basin BCH Reservoir Unit (Rivers and large streams were 2-line lotic waters and streams were 1-line lotic waters on maps used for the GIS area analyses).

Rivers/Reservoir Unit	Stream Area (ha)	Rivers+Large Stream Areas (ha)	Totals (ha)
Pend d'Oreille	1.5	179.0	180.5
Donald-Mica	192.1	4897.1	5089.2
Mica- Revelstoke	53.4	2654.4	2707.8
Revelstoke-Arrowhead	10.6	626.6	637.2
Arrowhead-Keenleyside	40.0	1393.0	1433.0
Wardner-USA	10.3	1496.0	1506.3
Duncan	17.7	420.0	437.7
Spillimacheen		0.3	0.3
Whatshan	0.5	15.0	15.5
Bull River	No pre-dam photos/mapping		0.03
Total Areas (ha)	**325.6**	**11,681.5**	**12,007.3**
Percent	**2.7**	**97.3**	

*** Stream Area includes construction lines & digitized streams

*** stream areas were summarized from astrm_footpx_du_bec_ver5_feb22_06.xls and tcon_strm_footpx_du_bec_ver3.xls

Table 18: Estimated gross primary production (tC yr^{-1}) of rivers and streams in the pre-dam Columbia Basin BCH Reservoir Units (Duncan at upper Duncan and Donald-Mica at Wood River and above Kinbasket Lake are adjusted for glacial depression of GPP).

Reservoir Unit	Gross Primary Production (t C y^{-1})
Donald-Mica	1675.8
Mica-Revelstoke	1565.6
Revelstoke- Arrowhead	369.4
Arrowhead Keenleyside	791.8
Wardner-USA	877.1
Duncan River & Tributaries	126.7
Pend d'Oreille	106.1
Whatshan River	5.9
Spillimacheen River	0.17
Bull River	0.01
Total	**5,518.6**

4.3 Wetlands

4.3.1 Area Assessment

The spatial analysis of the historical mapping results provided a clear accounting of pre-dam wetland habitats. According to the WREC classification scheme, the total wetland area lost to reservoirs was 15,989 ha. This was comprised of 10,621 ha in the wetland group, 5,322 ha in the Flood Group and 28 ha in the Transitional Group (Table 19). The overwhelming majority of these habitats, 61% occurred in the Donald-Mica Dam Unit. No wetlands or floodplain habitats were identified for Dam units C2, K2 or K3, and only minimal areas occurred in C8, C10 and K9.

Table 19: Wetland and flood associations according to WREC classification.

DAM UNIT	Df Flood Group (ha)	Tn Transition (ha)	Fn Fen (ha)	Ms Marsh (ha)	Sw Swamp (ha)	Ws Shallow Water (ha)	Total (ha)	% OF TOTAL
C2								
C3	1834.6	25.3	5983.6	75.1	1364.0	513.4	9796.0	**61**
C4	679.7	2.8	139.4	160.5	250.4	21.2	1253.8	**8**
C5&C7 (C11)	810.2	0.0	435.7	8.1	58.8	103.0	1415.7	**9**
C8			1.5				1.5	**0**
C10								**0**
K2								
K3	1662.2		116.2			210.6	1989.0	**12**
K4								
K6 not mapped[14]								
K7	335.7		1004.2		24.2	167.9	1532.0	**10**
K9			0.9				0.9	**0**
Total	**5322.3**	**28.1**	**7681.5**	**243.7**	**1697.3**	**1016.1**	**15988.9**	

** Based on Canadian Wetland Classification in Habitat Mapping – (t_jun19_06.xls) See table 1 for wetland classification codes and Table 6 for descriptions*

Of the Wetland Group, the largest proportion, (75%) occurred in the Donald-Mica dam unit followed by Duncan 11% and Arrow Lakes 6%. Flood Group associations were distributed more uniformly but were concentrated in two reservoir units; two-thirds of the Flood Group area was within the Donald-Mica and Wardner-USA dam units (Figure 56). The remaining Flood Group habitats were, in order of diminishing proportions, Arrow Lakes, Mica-Revelstoke and Duncan River tributaries (Figure 56).

Fens represented the greatest area of wetland mapped in the Columbia Basin (7,681 ha), with swamps a distant second (1,697 ha). and shallow waters third (1,016 ha). All of these classes were most prevalent in the Donald-Mica dam unit (Figure 57). Marshes were by comparison, minor components with a total of only 244 ha, the majority of which were in the Mica-Revelstoke dam unit.

[14] Kootenay Lake was not included in the historic mapping terms of reference, therefore no information is available.

Figure 56: Habitat proportions according to Dam Unit.

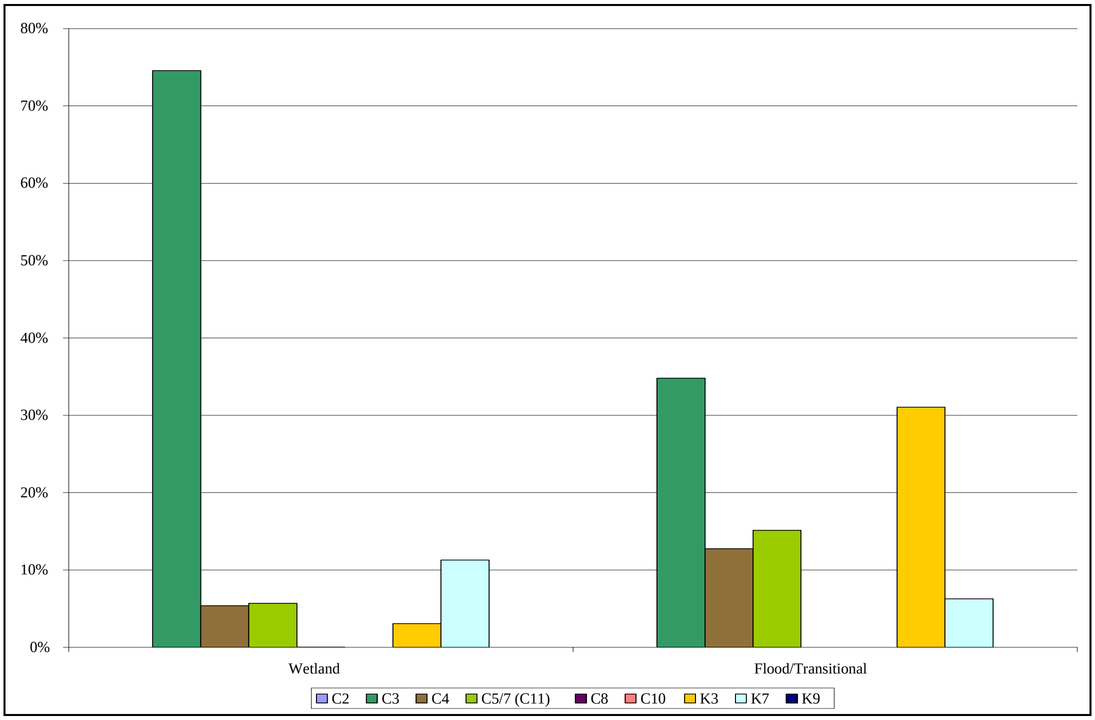
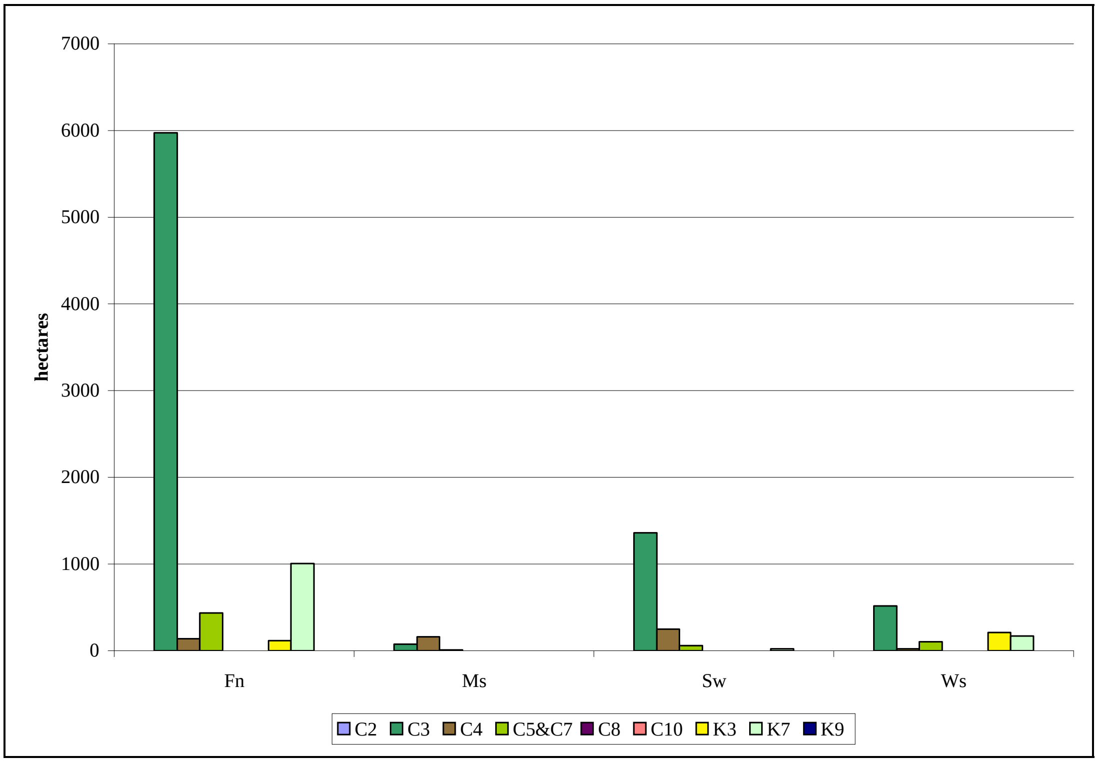


Figure 57: Wetland Type by Dam Unit



4.3.2 Functional Assessment

To carry the wetland analysis into a more functional approach, it was felt that all floodplain habitats (mapped wetlands and those additional to the WREC classification) needed to be included, (rationale outlined in the methods section). Inclusion of all floodplain habitats resulted in an additional 23,350.5 ha of hydroriparian elements being considered in the analysis. At the first level of analysis, all floodplain habitats were segregated into forested and non-forested wetlands (Figure 58, Table 21).

Since terrestrial forest habitats are considered in a separate report, it was essential that the woody component not be included in the production assessment. We maintained a clear distinction between timber production and the forb and shrub components. Only understory and leafy components were included in the tallying of forested wetland habitat production (Figure 58).

The non-forested (SS <4) components were segregated according to their position in the landscape as a “Wetland group” (Fn, Sw, Ms) and a “Flood group” (mostly Df, Tn, plus additional site series judged to be part of the active floodplain) (Figure 58, Table 21).

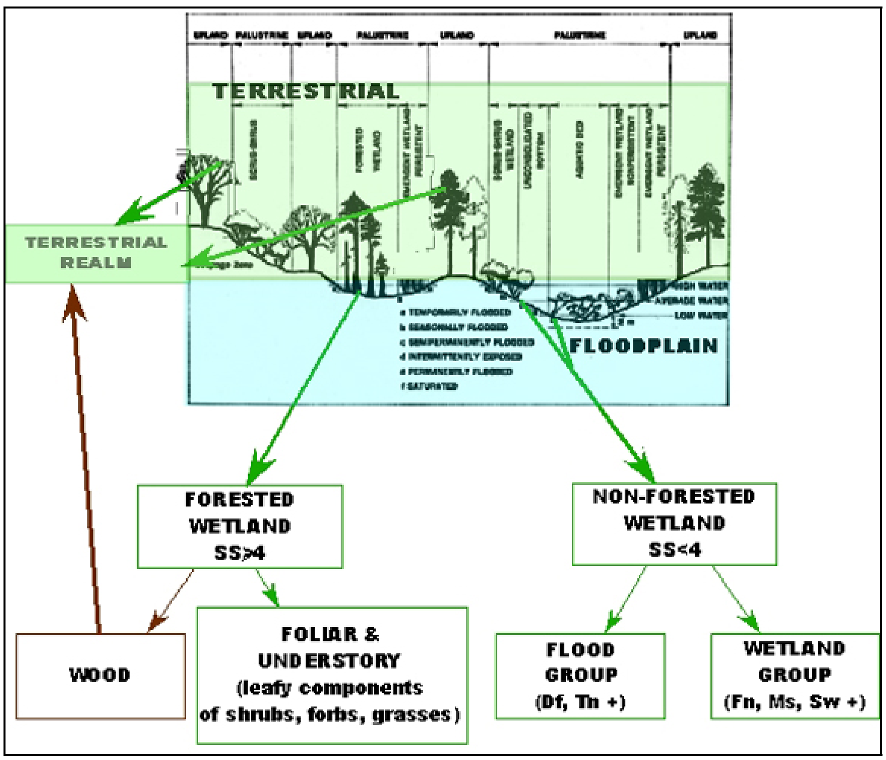


Figure 58: Illustration of Floodplain Components.

The shallow water (Ws) category is potentially the most diverse wetland category and its interpretation is highly dependent on the depth and clarity of water and dates of the aerial photography used in the mapping. Therefore, this class was tallied separately from other floodplain habitats. For the most part these were undoubtedly highly productive habitats, characterized by warm, shallow water, abundant macrophytes and high algal production. Some of these water bodies would have been the highly important "slough" habitats described by Peterson and Withler (1965a,b) as highly important for the rearing of fish in the Donald-Mica and Duncan River Tributary dam units. However, it is also possible that they were ephemeral water bodies that dried up in the summer period and would therefore have supported minimal primary production. Since these habitats can be so extremely variable, it is difficult to apply a general production value to them. If they were interpreted as water bodies similar to Bush lakes, a daily pelagic production 260 tC /yr might be applied to these areas. However, as stated earlier, these shallow waters might have been seasonal, and therefore much more limited in production. Further analysis of the historic air photos, to clarify the characteristics of these water bodies may provide greater confidence in ascribing production values to them. At present, they have not been included in the carbon calculations.

Table 20: Floodplain and shallow water area (ha) according to Dam Unit.

	C 03	C 04	C11 (5&7)	C 08	C 10	K 03	K 06	K 07	K 09	TOTAL
Vegetated Floodplain Areas (ha)	21,391.7	4,460.6	6,994.9	16.1	7.8	3,245.0	n/a	3,220.7	1.6	39,338.4
Shallow Water (Ws) (ha)	513.4	21.2	103.0			210.6	n/a	167.9		1,016.0

All of the vegetated floodplain habitats (those which had been assigned a wetland classification code as well as polygons which had not) were classified as forested or non-forested based on structural stage. The site series information, segregated according to structural stage (Table 21) reveals a relatively even distribution between forested (55%) and non-forested habitats (45%). The Donald-Mica reservoir unit had the greatest proportion of each type (55%). The Mica to Revelstoke unit and the Arrow Lakes unit had the next highest percentages of forested wetlands (17%and 15% respectively), whereas for non-forested it was Arrow Lakes and Wardner to USA (21% and 13% respectively),

Table 21: Forested and non-forested wetland areas (ha) and proportions according to Dam Unit.

	FORESTED[15] ha	FORESTED % of Total	NON-FORESTED ha	NON-FORESTED % of Total	TOTAL ha	% of Total
C 03	11,824.6	54%	9,567.1	54%	21,391.7	54%
C 04	3,780.0	17%	680.6	4%	4,460.6	11%
C 05/07	3339.3	15%	3655.6	21%	6994.9	18%
C 08	8.3	0%	7.8	0%	16.1	0%
C 10	6.0	0%	1.8	0%	7.8	0%
K 03	890.8	4%	2,354.2	13%	3,245.0	8%
K 06	Not mapped					n/a
K 07	1,855.6	9%	1,365.1	8%	3,220.7	8%
K 09	0.7	0%	0.9	0%	1.6	0%
TOTAL	**21,705.3**		**17,633.1**		**39,338.4**	

[15] Forested – included structural stages 4 and greater; Non-forested - included structural stages 0 to 3 (a & b) inclusive

4.3.3 Production Assessment

The estimated total NPP of wetlands was calculated from the area (hectares) of wetland and floodplain habitats derived from the historic mapping (Ketcheson et al. 2005) and the estimated dry mater production of forested and non-forested (Burrows et al. 2003) (Table 22). Only those site series considered part of the wetlands or floodplain (Table 7) were included in these calculations. Export levels were based on assumptions identified in the methods section.

Table 22: Net Primary Production according to source (Forested and non-forested wetland/floodplain areas) by Site Series and Dam Unit

DAM UNIT	Wetland (W) or Flood (F) Group	BEC Site Series[16]	TOTAL AREA (ha)[17]	NON-FOREST AREA (ha)	FOREST AREA (ha)	NON-FOREST NPP tons dry matter yr^{-1}	FOREST NPP (understory & foliar) tons dry matter yr^{-1}	ESTIMATED TOTAL NPP tons aboveground dry matter yr^{-1}
C 03	W	BB	239.8	239.8		1,055.1		1,055.1
C 03	W	BS	180.3	180.3		793.3		793.3
C 03	F	CD	983.4	373.6	609.8	1,643.8	1,768.4	3,412.3
C 03	F	CF	29.7	29.7		130.7		130.7
C 03	F	DH	1,200.6	271.7	928.9	1,195.5	2,693.8	3,889.3
C 03	F	RC	655.6	296.7	358.9	1,305.5	1,040.8	2,346.3
C 03	F	RD 05	7,314.2	1,377.7	5,936.5	6,061.9	17,215.9	23,277.7
C 03	F	RH	4,960.2	1,104.5	3,856.2	4,868.6	11,183.0	16,040.4
C 03	F	SH	172.8	38.5	134.3	169.4	389.5	558.9
C 03	W	SS09	501.2	501.2		2,205.3		2,205.3
C 03	W	WE	5,151.4	5,151.4		22,666.2		22,666.2
C 04	F	CD	492.7	23.5	469.2	103.4	1,360.7	1,464.1
C 04	F	RC	557.2	53.1	504.1	233.6	1,461.9	1,695.5
C 04	F	RD 05	67.7	67.7		297.9		297.9
C 04	F	RD 07	1,527.3	21.0	1,506.3	92.4	4,368.3	4,460.7
C 04	F	RH	1,359.8	59.4	1,300.4	261.4	3,771.2	4,032.5
C 04	W	SE	10.4	10.4		45.8		45.8
C 04	W	SS09	117.4	117.4		516.6		516.6
C 04	W	WE	328.1	328.1		1,443.6		1,443.6
C 05	F	CF	1,036.0	1,036.0		4,558.4		4,558.4
C 05	F	RC	1,588.3	424.7	1,163.6	1,868.7	3,374.4	5,243.1
C 05	F	RD 6+7	688.8	105.2	583.6	462.9	1,692.4	2,155.3
C 05	F	RH	151.4	18.7	132.7	82.3	384.8	467.1
C 05	W	SE	0.1	0.1		0.4		0.4
C 05	W	WE	115.4	115.4		507.8		507.8
C 05	F	XX	6.3		6.3		18.3	18.3
C 05	F	XY	8.7		8.7		25.2	25.2
C 07	W	BS	7.6	7.6		33.4		33.4
C 07	F	CF	1,116.7	1,116.7		4,913.5		4,913.5
C 07	F	HD	307.1	19.6	287.5	86.2	833.8	920.0
C 07	F	RC	274.0	40.2	233.8	176.9	678.0	854.9
C 07	F	RD	181.5	4.3	177.2	18.9	513.9	532.8

[16] see Ketcheson et al. 2005 for site series descriptions
[17] based on CBF&WCP GIS analysis of historical mapping (Ketcheson 2005).

Table 22 **continued.**

DAM UNIT	Wetland (W) or Flood (F) Group	BEC Site Series[18]	TOTAL AREA (ha)[19]	NON-FOREST AREA (ha)	FOREST AREA (ha)	NON-FOREST NPP tons dry matter yr^{-1}	FOREST NPP (understory & foliar) tons dry matter yr^{-1}	ESTIMATED TOTAL NPP tons aboveground dry matter yr^{-1}
C 07	F	RH	299.7	87.8	211.9	386.3	614.5	1,000.8
C 07	F	RS	88.6	49.7	38.9	218.7	112.8	331.5
C 07	W	SE	14.7	14.7		64.7		64.7
C 07	W	WE	340.9	340.9		1,500.0		1,500.0
C 07	F	XX	738.9	274.0	464.9	1,205.6	1,348.2	2,553.8
C 07	F	XY	30.2		30.2		87.6	87.6
C 08	W	BS	1.5	1.5		6.6		6.6
C 08	F	HD	0.3		0.3		0.9	0.9
C 08	F	RD	9.3	1.7	7.6	7.5	22.0	29.5
C 08	F	RH	5.0	4.6	0.4	20.2	1.2	21.4
C 08	F	XX						
C 10	F	CF	1.8	1.8		7.9		7.9
C 10	F	HD	6.0		6.0		17.4	17.4
K 03	F	AR	280.2	165.9	114.3	730.0	331.5	1,061.4
K 03	W	BH	120.6	116.2	4.4	511.3	12.8	524.0
K 03	F	CD	721.9	461.3	260.6	2,029.7	755.7	2,785.5
K 03	F	CF	964.0	964.0		4,241.6		4,241.6
K 03	F	SH	781.1	461.7	319.4	2,031.5	926.3	2,957.7
K 03	F	SS05	377.2	185.1	192.1	814.4	557.1	1,371.5
K 07	W	BS	605.2	605.2		2,662.9		2,662.9
K 07	F	CF	48.3	48.3		212.5		212.5
K 07	F	RD	148.6	1.5	147.1	6.6	426.6	433.2
K 07	F	RH	761.4	227.8	533.6	1,002.3	1,547.4	2,549.8
K 07	F	RS	486.5	29.3	457.2	128.9	1,325.9	1,454.8
K 07	W	WE	401.8	401.8		1,767.9		1,767.9
K 07	F	XX	38.8		38.8		112.5	112.5
K 07	F	XY	730.1	51.2	678.9	225.3	1,968.8	2,194.1
K 09	F	CF						
K 09	F	HD	0.7		0.7		2.0	2.0
K 09	W	WE	0.9	0.9		4.0		4.0
TOTAL			**39,338.4**	**17,633.1**	**21,705.3**	**77,585.6**	**62,945.4**	**140,521.2**

NON-FOREST NPP – based on area *estimated NPP of 4.4 t/ha (dry matter)

FOREST NPP only includes understory & foliar contribution – based on area* estimated NPP of 2.9 t/ha (dry matter)

[18] see Ketcheson et al. 2005 for site series descriptions

[19] based on CBF&WCP GIS analysis of historical mapping (Ketcheson 2005).

4.3.4 Post-dam Assessment

Vegetation mapping data from the Water Use Planning process was available for Kinbasket, Arrow Lakes and Duncan reservoirs for comparisons of pre-dam and present day wetland areas. Although Water Use Plans have been prepared for Whatshan Lake, and Revelstoke Reservoir (Columbia WUP) the vegetated areas were not significant enough to warrant mapping, hence the present day floodplain/wetland area is considered negligible.

Based on the above information, only 13.6% of the historic floodplain areas remain within the Columbia basin footprint (Table 23). The most significant losses occurred in the Donald-Mica reach where 18,944 ha (89%) of these habitats were lost due to impoundment. The Duncan reservoir area lost 93% (3,009 ha) of its historic wetland area and Lake Koocanusa lost 91% (22,964ha) of historic floodplain habitats. A dramatic anomaly in this table of losses is the Arrow Lakes reservoir, which lost most of its vegetated habitats after impoundment (Moody 2002) but has recently experienced native sedge and grass colonization of upper drawdown zones. This is, in part, due to the annual fall rye seeding of the dust control program, which facilitated the establishment and expansion of a native perennial vegetation cover during the past two decades. Although these recovering reservoir shorelines do not represent the full biodiversity or productive capacity of the presumed pre-impoundment wetlands, they do provide vegetated drawdown zone habitats, uncommon in the present day Columbia Basin.

Table 23: Comparison of pre-dam and present day wetland areas.

Reservoir Unit	Dam Unit	Historic Total (ha)	Present Day Total (ha)	Forested and Non-forested wetland loss (ha)	Present Day as % of Historic
Spillimacheen River	C2	0	negligible		**0**
Donald - Mica	C3	21,389	2,395	18,994	**11**
Mica - Revelstoke	C4	4,461	negligible	4,461	**0**
Revelstoke - Keenleyside	C11	6,985	2,455	4,530	**35**
Whatshan	C8	16	negligible	16	**0**
Waneta - USA	C10	8	negligible	8	**0**
Wardner	K3	3,245	280	2,965	**9**
Duncan River tributaries	K7	3,221	212	3,009	**7**
Corra Linn - Brilliant	K9	2	negligible	2	**0**
Total		**39,327**	**5,342**	**33,985**	**13.6**

Present day areas, except for Wardner, are based on WUP data. Wardner mapping results provided by CBF&WCP.

4.3.5 Carbon Contribution

The net primary production calculated in the functional assessment (section 4.3.2) was used to determine the amount of carbon being produced in the floodplain (Flood and Wetland groups). The production of forested and non-forested wetlands was calculated separately (Table 22) and then summarized for each dam unit and habitat type (Table 24). The summarized NPP values were converted to carbon, using a conversion factor of 47.5% C per unit of dry organic matter. This value, commonly found in the literature, was considered appropriate based on laboratory analyses of native sedges and grasses sampled in Revelstoke Reach (CARR and AIM 2002). A total net aboveground production of 66,752 tons of carbon was estimated for the Columbia Basin floodplain environments.

Table 24: NPP of Wetland and Flood Groups (non-woody aboveground dry matter tons yr^{-1}) and estimated total carbon content.

	NPP tons dry matter yr^{-1}			tons C yr^{-1}
Dam Unit	**Wetland Group**	**Flood Group**	**Total NPP**	**Total Carbon** [20]
C 03	26,720	49,667	76,387	*36,284*
C 04	2,006	11,951	13,957	*6,629*
C 11	2,106	23,662	25,769	*12,240*
C 08	7	52	58	*28*
C 10	0	25	25	*12*
K 03	524	12,418	12,942	*6,147*
K 07	4,431	6,957	11,388	*5,409*
K 09	4	2	6	*3*
TOTAL	35,798	104,734	140,531	*66,752*

Since the overall footprint project seeks to maintain a clear separation between terrestrial and aquatic environments, we tried to place into perspective, the floodplain export to the aquatic system. The position in the landscape and connectivity to the aquatic environment was used to segregate the habitats according to their presumed ecological contribution. The Wetland Group was considered highly connected to the lotic and lentic environments and was therefore considered likely to export most of its NPP to the aquatic realm. The Flood Group was considered connected to aquatic system only during spring flooding periods, therefore likely to retain much of its NPP in a semi-terrestrial setting (either by consumption of terrestrial organisms, or sequestered in the substrates). Since the floodplain environments have been considered ecotones or moving littoral zones (Junk et al. 2004) with a great deal of variability in connectivity, production and export, we made educated guesses at the amount of carbon which was likely to be exported from these two categories. The habitats identified as Wetland Group were considered to export 90% of their aboveground NPP at the end of their growing season or during spring floods. Obviously, this would change, from site to site, and season to season, depending on the connectivity of the habitat to the fluvial environment. The Flood Group was estimated to contribute about half as much as the aquatic connected habitats, or approximately 45% (Figure 59).

[20] Carbon content of NPP has been estimated at 47.5%

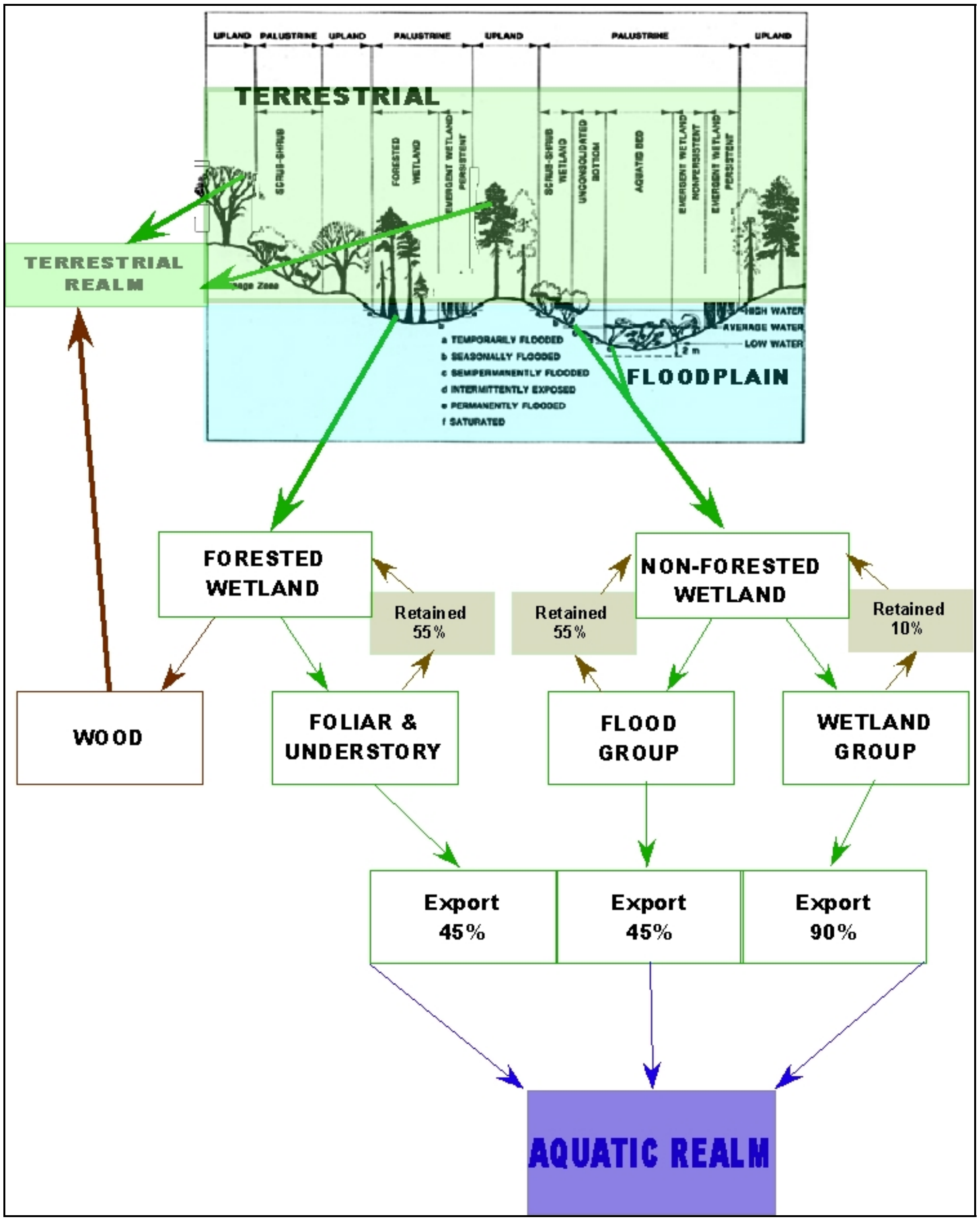


Figure 59: Floodplain Export Proportions.

Based on the presumed level of export from the floodplain habitats, in combination with the calculated estimates of carbon production (based on aboveground dry matter NPP), a total of 37,690 metric tons of carbon was estimated to have been exported annually from the pre-dam floodplain habitats into the aquatic food chain (Table 25). This was again dominated by the Donald-Mica reservoir unit with 58% of the total wetland carbon. The next closest was Arrow Lakes (combined dam units 5 and 7) at 16%, followed by Revelstoke (9%), Duncan (9%), and Koocanusa (8%), The relative carbon contribution from the various sources was estimated at 41% Wetland Group, and 59% Flood Group.

Table 25: Estimated Historic NPP export to aquatic realm (tC yr^{-1}).

	ESTIMATED EXPORT tons carbon yr^{-1}		
Dam Unit	**Wetland Group**	**Flood Group**	**Total export[21]**
C 03	11,423	10,616	22,039
C 04	858	2,554	3,412
C 11	900	5,058	5,958
C 08	3	11	14
C 10	0	5	5
K 03	224	2,654	2,878
K 07	1,894	1,487	3,381
K 09	2	0	2
TOTAL (tC yr^{-1})	15,304	22,387	37,690

Table 26: Post-Dam NPP and Carbon Export from floodplain habitats.

	Present Day Vegetated area (ha)	**Est. NPP t dry matter ha^{-1}**	**Total NPP t dry matter yr^{-1}**	**Total (NPP) Carbon t dry matter yr^{-1}**	**Estimated Carbon Export t C yr^{-1}**
C 03	2,395	2	4,790	2,275	2,048
C 04					
C 05	1,948	3	5,844	2,776	2,498
C 07	507	2	1,014	482	433
C 08					
C 10					
K 03	280	2	560	266	239
K 07	212	2	424	201	181
K 09					
Grand Total	5,342		12,632	6,000	5,400

In contrast, the present day NPP carbon export from reservoir wetlands is estimated at 14% of historic (5400 metric tons) (Table 26). Over 48% of the estimated present-day carbon export (2498 t yr^{-1}) comes from Revelstoke Reach in Arrow Lakes reservoir. Kinbasket reservoir shorelines contain a larger total area of vegetated habitats than Revelstoke Reach but these areas are relatively impoverished (Figure 60) compared to Revelstoke Reach (Figure 61); the export of these vegetated drawdown zones is estimated at (2048 t yr^{-1}) or 40% of the total present day export. This value has been calculated using a production estimate of 2 t ha^{-1} (2/3 that of the values measured for Revelstoke Reach) based on vegetation characteristics observed during field surveys (productivity estimate is based on observations of plant size and density-A. Moody).

[21] Values derived from NPP aboveground dry matter, converted to carbon (at 47.5%), with export rates of 90% applied to aquatic and 45% applied to floodplain

Figure 60: Kinbasket Reservoir, high elevation sedge/grass mix (photo A. Moody).

Figure 61: Revelstoke Reach, high elevation sedge/grass mix (photo A. Moody).

GPP Conversion

To maintain consistency with the other ecosystem components, the calculated NPP for floodplain environments required conversion to GPP. Conversion of NPP to GPP has rarely been addressed in wetland literature; when it has the rates have been highly variable. A seminal paper on primary productivity in freshwater wetlands (Brinson et al. 1981) identified problems with interpretation of primary productivity and in categorizing biomass across geographical ranges. Despite an extensive literature search, we were unable to locate any appropriate references for wetland GPP values in a geographical area comparable to the Columbia Basin.

Due to a lack of applicable GPP results in wetland or floodplain literature, a general rule of thumb for conversion of NPP to GPP (NPP = 50% of GPP) has been applied. This is likely an underestimate since much higher percentages have been reported, albeit for Florida wetlands (NPP = 28% of GPP -Brinson et al. 1981). However, we chose to maintain a conservative and simple approach that can be reconsidered once better information becomes available. Thus, the historic annual GPP of carbon in floodplain habitats (in situ) was estimated at 133,504 metric tons, contrasted with the present day estimate of 12,000 metric tons. The total carbon export historically, was estimated at 75,380 t C yr^{-1} as opposed to the present 10,800 t C yr^{-1}. Vegetation production in the post dam reservoir drawdown zones is estimated at less than 9% of the pre-dam production (Table 27). Due to reservoir inundation, the present day shoreline vegetation production is considered 90% exported to the aquatic realm. This accounts for the percentage difference in comparing in situ production to export production, historic versus present. The large historic floodplain component meant that a portion of the production was being accumulated and retained on site instead of being exported.

Table 27: Estimated Floodplain GPP - Historic and Present.

Total Estimated Floodplain GPP Carbon	**Historic t C yr^{-1}**	**Present t C yr^{-1}**	**Present % of Historic**
GPP – in situ	133,504	12,000	9
Estimated export (from in situ)	75,380	10,800	14

4.4 Ecosystem Contributions to total Carbon template

4.4.1 Autotrophic Carbon pre-dam vs. present

The changes in distribution and amounts of the total C production template resulting from dam construction and large reservoir creation within the Upper Columbia Basin 1970's and 1980's are summarized below (Figure 62, Table 28). The template has 2 components, autotrophic (phytoplankton, attached algae (periphyton), macrophytes, lotic mosses, and wetland vascular plants) and heterotrophic (lacustrine free-living bacteria, attached bacteria in streams, in littoral zones, upon the plants and soils of wetlands, and various protozoans, e.g. ciliates, flagellates, amoebas, and fungi). Allochthonous riparian leaf litter is one of the major energy sources. Wetlands are among the world's most productive habitats and it is not surprising that their ubiquity in the basin pre-dam era resulted in a large contribution (over 87%) to total C compared with lakes (10%) the next largest contributor with rivers/steams contributing slightly less C (4%) than lakes. The present era autotrophic C template reveals that one component has basically been replaced (rivers/streams) while reservoir pelagic habitats have risen to a dominant position (73%) within the present landscape and are now contributing more C than wetlands C production (23%). Rivers/streams presently contribute only negligible quantities of C. These shifts from pre-dam wetlands, streams and small lakes domination, to an overwhelming pelagic domination, carries with it a somewhat ominous signal. There has been a shift from a high-level of aquatic habitat diversity and accompanying biodiversity to a more simple and linear pelagic driven landscape. Major losses of biodiversity have occurred within the present basin across all aquatic and floodplain habitats The loss of a productive, functional littoral and shoreline ecosystem where periphyton communities are abundant on soils and on macrophytes, and where wetlands are plentiful and prolific, in most all reservoirs has constrained total basin C production. Most notably, these losses have diminished aquatic biodiversity.

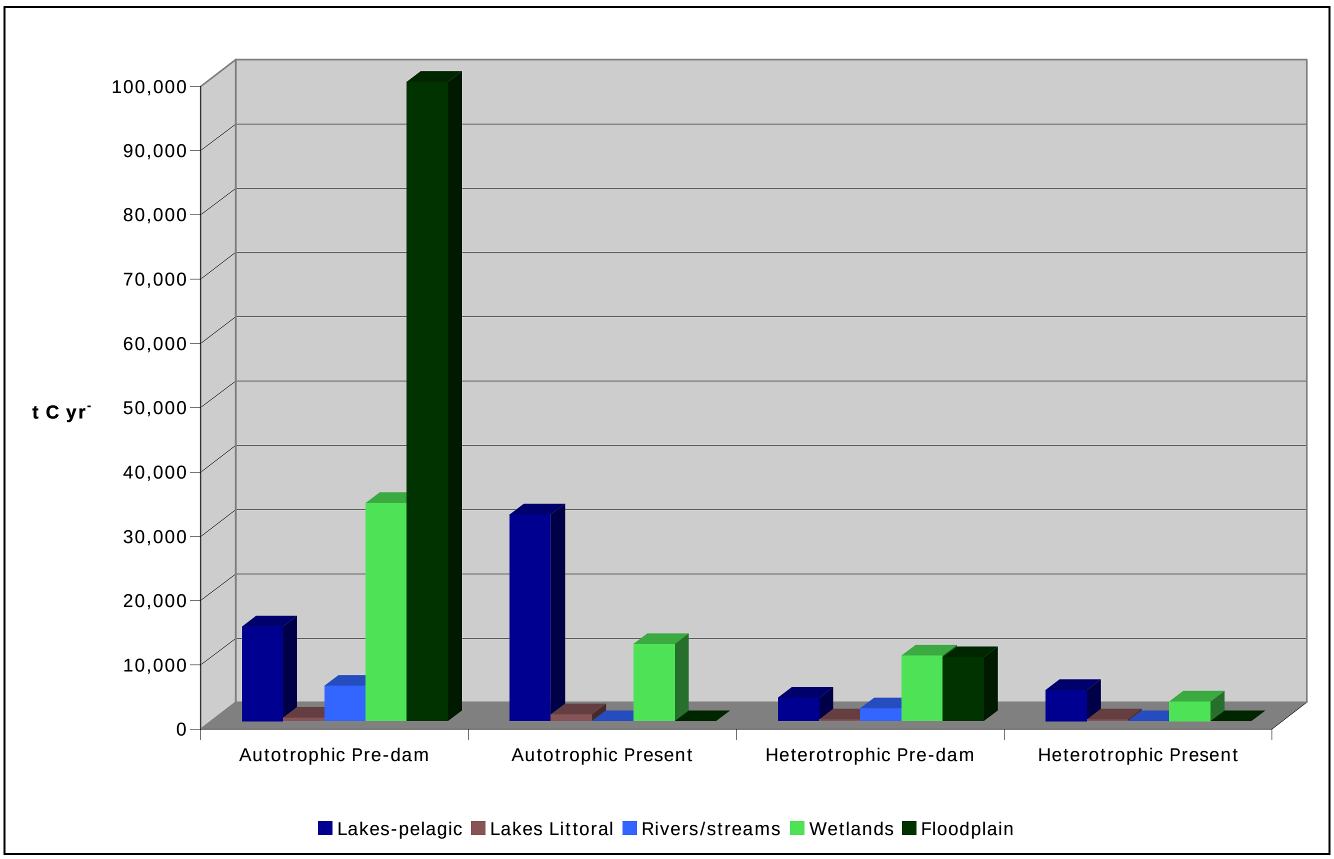


Figure 62: Distribution and amounts of the total C template by habitat in historic pre-dam period and present landscape after dam construction and large reservoir creation.

Although wetlands were, and continue to be, the greatest primary producers in the aquatic realm per unit area, it is important to recognize the dramatic amount of floodplain area lost as a result of impoundment and that current wetlands in the Columbia Basin are extremely restricted compared to their historic abundance.

Figure 63: Example of wetland autotrophic and heterotrophic components (inundated Revelstoke Reach drawdown zone vegetation, October 2003. photo A. Moody).

Heterotrophic C production has been estimated to contribute about 18% as much as autotrophic production to the yearly total C template with little change in the proportion despite a large change in the magnitude, owing to loss of productive wetlands and periphytic communities of rivers/streams and lakes. The current littoral zone of the major reservoirs owing to wide water level fluctuations is basically non-functional; desiccation and/or inundation keeps communities in a perpetual state of early succession. The biofilm, periphyton, or wetland plant communities that become established within the reservoir wetted littoral (Figure 63) are removed annually or sometimes semi-annually by the cycle of flooding and/or drawdown. It comes as no surprise that heterotrophic production is much lower in the present post-dam setting, since the drawdown zones (shorelines, littoral slopes, and flats) of most reservoirs in the basin are mostly bare and devoid of soil or vegetation, (i.e. no carbon).

Table 28:Values of total autotrophic and heterotrophic C production by habitat. Units $tCyr^{-1}$.

	Autotrophic C		***Heterotrophic C***	
Habitat	**Pre-dam $tCyr^{-1}$**	**Present $tCyr^{-1}$**	**Pre-dam $tCyr^{-1}$**	**Present $tCyr^{-1}$**
Lake Pelagic	14,773	32,216	3,693	4,832
Lake Littoral	561	1,095	262	298
Rivers/streams	5,519	4	2,000	1
Flood Group	99,479	0	9,948	0
Wetland Group	34,008	12,000	10,202	3,060
Total	154,340	45,315	26,105	8,191

4.4.2 Allochthonous vs. autochthonous contributions to tC of Columbia Basin reservoirs.

It is clear that there are very high fluxes of both dissolved and particulate carbon in newly created reservoirs and that the sediments accumulate an ever increasing pool of inorganic C (geological) and organic C (biological) that is mostly allochthonous in origin (Mulholland and Elwood 1988, Ritchie 1989). Most of the allochthonous organic C is derived from terrestrial vegetation and soil erosion that is delivered via tributary inflows from the drainage basins to the reservoirs. The upper Columbia River reservoirs are no exception to the rule with allochthonous C contributing > 90% and autochthonous <10 % to total organic carbon pools in 4 reservoirs studied (Table 29).

Table 29: Estimated yearly organic/inorganic C accumulation in sediment of 4 Columbia Basin reservoirs compared with yearly contribution for pelagic/littoral C.

([1]data from Powertech Labs, Surrey, BC 1990, [2] J. Stockner, present study).

	Kinbasket	**Revelstoke**	**Arrow Lakes[3]**	**Whatshan**
[1]Organic C $t.yr^{-1}$ (%)	98,800 (71)	45,100 (57)	204,600 (56)	16,300 (81)
Inorganic C $t.yr^{-1}$ (%)	40,200 (29)	33,600 (43)	162,400 (44)	3,700 (19)
Total C $t.yr^{-1}$ sediment	139,000	78,700	367,000	20,000
[2]Pelagic + Littoral $tC.yr^{-1}$	5,453	1,662	11,237	298
Autochthonous (%)	3.9	2.1	3.1	1.5
Allochthonous (%)	96.1	97.9	96.9	98.5

[3]Treated

During the spring freshet period large quantities of imported organic and inorganic C from terrestrial, riparian and wetland habitats within tributary basins are either deposited in the receiving reservoir or transported out via outflow depending on the specific gravity (weight) and sinking velocity of the load. What is surprising is the small, <10 %, contribution of autochthonous C from phytoplankton, littoral algae and macrophyte detritus to the total organic C pool estimated for upper Columbia basin reservoir sediments (Table 29). Clearly, allochthonous organic C coming from wetlands, river benthic algae, mosses and terrestrial vegetation (leaves, needles) from the riparian and beyond plays a huge role in the annual C cycle of reservoirs that now have become ‘catchment’ basins for settlement of most all particulates entering from river/stream inflows. Kinbasket and Arrow both receive large tributary inflows of suspended silt and have the highest rates of annual deposition of inorganic and organic C. Run-of–the-river Revelstoke has a substantially lower rate of annual C deposition. Differences in the rates of accumulation reflect differences in the origins of reservoirs (impounded lakes vs. rivers), the degree of preparation of the reservoirs (pre-clearing of forests, vegetation), the amount of terrestrial vegetation and soils flooded, and the magnitude of glacial silt and suspended sediments delivered by tributary inflows (Powertech 1990). Kootenay Lake, after completion of Duncan and Libby dams on its two major inflows, has doubtless lost a considerable portion of what must have been a large load of allochthonous C from the immense Kootenay River drainage and a lesser load from the Duncan River smaller Duncan River. The Duncan river allochthonous and inorganic C load was much lower than from Kootenay River, partially owing to particle settlement in Duncan Lake prior to discharge to Kootenay Lake (Northcote 2005). Duncan Reservoir presently must be the recipient of a considerably higher load of both allochthonous and inorganic C.

5.0 DISCUSSION

Figure 64: Upper Wood River canyon (From Farquharson 1973).

The early historic upper Columbia basin pre-dam was largely river dominated with a steep gradient and high velocity flows (Figure 64). As such it was primarily an ‘exporter’ of C, with large woody debris, and terrestrial vegetation (leaves, twigs, needles) accumulating on river delta flats, but with few opportunities for significant settlement of allochthonous inorganic C (lighter silt, clay particles) until reaching lakes or large back eddies. Some C deposition no doubt occurred in the first series of small lakes, Bush or Kinbasket but they were not large or of sufficient depth to retain significant amounts of the sediment and organic load. We surmise that it was in upper Arrow Lake and then lower Arrow that there was sufficient velocity reduction for the Columbia River to deposit substantial quantities of heavier silt/sediment and allochthonous C. Greater deposition was likely to have occurred in upper Arrow than in lower Arrow. The Columbia River upon leaving the Arrow Lakes during freshet periods retained turbidity, picked-up in transit through the lakes, from large, turbid tributary inflows. Thomas (1950) noted the gradual reduction of total dissolved and suspended solids in the Columbia River as it transited from its headwaters in the Rockies to the Canada/US border. We therefore construe that the historic Columbia transported significant quantities of particulate and dissolved C to the US border and beyond, without any further significant settlement after leaving Arrow lakes outflow to the border. The present upper Columbia is a ‘staircase’ of dams and reservoirs that have since their inception served as depositional basins, with the resultant reduction of sediment/silt loads and successive improvement in water clarity from dam to dam in outflow water. It comes as no surprise now to see the Columbia River so clear and low in allochthonous particulates as it exits Canada, a simple consequence of changing what was mainly a large, powerful and effective riverine transport system into a series of large lacustrine depositional basins.

5.1 Lakes

5.1.1 Historic Lakes - Pre-dam Pelagic

Kootenay Lake.

There is a paucity of limnological observations prior to the late 1940s or early 50's when the lake was first described as typically oligotrophic (Larkin 1951). Most all events of the 19th century were considered of minor consequence with regard to their effects on lake productivity (Northcote et al. 2005). The consent among chroniclers of Kootenay Lake basin history is that only after the mid-1950s, with large inputs of phosphorus (P) from Cominco mine in the late 60s and early 70s with completion of Duncan (1967) and Libby dams (1973), that major changes in the lake's trophic status occurred (Northcote 1972, 1973, Daley et al. 1981, Ashley et al. 1997).

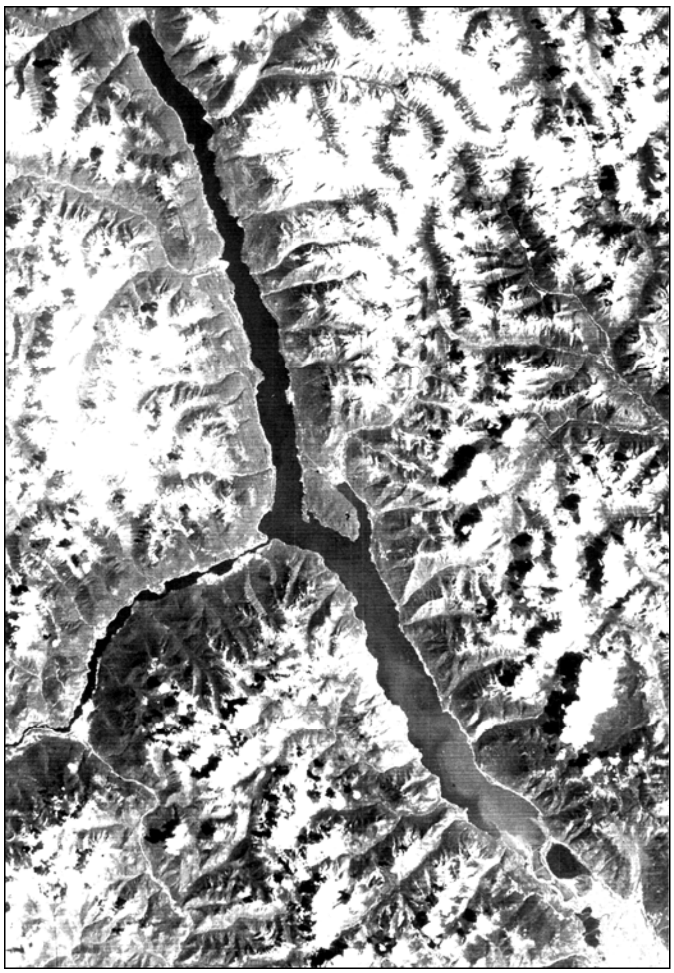


Figure 65: Landsat image of Kootenay Lake, August 3, 1974 (from Ennis 1977).

So what were some of the major features affecting annual C production in 'historic' Kootenay Lake in its 'natural' state without the impacts of white European man's intervention? Firstly, the presence of high turbidity surface waters during spring freshet (May, June, early July) was a dominant feature of the lake's seasonal cycle, most significantly so in the south arm where discharge from the larger Kootenay River spread a turbidity plume nearly to mid-lake (Figure 65). The discharge of the Duncan River also imparted turbidity to Kootenay Lake, but Duncan Lake acted as a reasonably effective settling basin, moderating the scale of freshet turbidity in the north arm. In conjunction with turbidity came the potential for 'washout' or export of plankton out of the system owing to the very short (<1 month) residence time of the <3 m euphotic layers within the lake that lasted for 3-6 weeks in June/July (Carmack and Gray 1982). The union of north/south turbidity plumes close to mid-lake in juxtaposition to the west arm outlet was the sector of the lake least affected by turbidity, exhibited the greatest euphotic depth and was the most productive sector of the lake during the freshet period (Northcote et al. 2005). Turbidity reduced the depth of the euphotic zone from mid-May to July, but it is likely that by August transparency was no longer a major factor affecting C production in the 'historic' lake from the north arm to mid-lake and into the west arm. Water transparency (Secchi depth) values reported in the 1960's ranged from 5 - 7 m in the north and west arms and 3 – 5 m in the south arm (Northcote et al. 2005). By September and October light would no longer have been a factor affecting rates of C production in the lake, but it is probable based on the high N/P ratio that low ambient P values were by this time limiting rates of C production within the epilimnion. It was likely to have been most severe in the north arm, where nutrient concentrations in the inflow from the Duncan River were much lower than the Kootenay River discharge that was 'rich' in contrast to Duncan and strongly influenced by drainage from largely sedimentary, calcareous rocks of the eastern Rocky Mountain trench. Thus, the early 'historic' Kootenay Lake during spring freshet period exhibited a clear south to north turbidity gradient with an associated gradient of major ions, pH and total phosphorus (TP) (Daley et al. 1981, Northcote et al. 2005). It is likely nitrate-N, about 2-fold higher in the Duncan River than in Kootenay River inflow, was abundant in the north arm triggering P-limitation from summer to fall. In the south arm where P values were much higher, that N-limitation coupled with a reduced euphotic zone limited C production during the late summer growth period (September-October). Paleolimnological studies of the quantitative abundance of diatoms from sediment cores taken in 1974, dated to well before 1900, clearly show that prior to any human intervention the mid-portion of the lake, adjacent to the outlet to the west arm, was the most productive sector of the lake, followed by the north arm and then the south arm, which consistently had the lowest densities and highest sedimentation rates (Ennis et al. 1983). Clearly, the 'historic' south arm sector of the lake, despite having moderate to high nutrient concentrations, has experienced the most severe photosynthetic C limitation and lowest C production, owing mainly to the persistence of high turbidity throughout much of the growing season (Northcote 1973). The gradient of C primary production rates measured in the 1960's mirrored the paleolimnological studies of Ennis et al. (1983), showing lowest values in the south arm, highest mid-lake adjacent to lake outlet and lowest in the north arm in both May and August datasets. This trend was far less observable in the October dataset, nonetheless, the south arm remained the lowest and least productive in the lake (Northcote et al. 2005).

In the 'historic' Kootenay Lake of the early 1800's, annual phosphorus loads were doubtless lower than when first measured in the 1960's, a period when Cominco mine phosphorus effluent was beginning to profoundly impact C production, lake-wide. Owing to the surface turbidity in the lake during freshet periods, light extinction and euphotic depths would have been very similar to, but likely lower than, those reported by Northcote et al. (2005) for the 60's. This would have primarily due to more extensive land clearance and logging, plus higher P loads from Cominco, likely producing more protracted turbidity events in the 60' than in pre-intervention times. A realistic estimate of <u>average</u> whole-lake, daily production of 'historic' Kootenay Lake would be close to 125 mgC m^{-2} day^{-1} (J. Stockner, professional judgment, DFO - lake production database, Cultus Lake Lab, BC). The lowest seasonal values would have corresponded with peak spring freshet and highest turbidity from late-May through July. Moderate values would have occurred in August, in the north and west arms, with highest daily rates in all arms of the lake in September extending into mid-October. The primary limiting factors affecting C production in spring and early summer in the historic lake were turbidity (light) and a very shallow euphotic depth. By August, with better transparency, light limitation shifted to P limitation in the north and west arms while in the south arm reduced transparency was still prevalent but not as severe as in spring, so likely co-limitation by light and N-limitation prevailed. Finally, by September/October with the absence of light limitation, C production values would have been moderate to high with P-limitation in the North and West arms and N-or co-limitation in the south arm.

The 'historic' Kootenay Lake average C production value (125 mgC m^{-2} day^{-1}) is considerably higher than estimated for historic Arrow lakes average (75 mgC m^{-2} day^{-1}) and this difference is corroborated by early studies in the 40's and 50's by T.G. Northcote on both lakes. He commented: "*historic Arrow production was like the south arm of Kootenay Lake and both were severely impacted by freshet turbidity*". But, based on his early studies of benthic insects from Ekman Dredge samples in both upper and lower Arrow lakes and north and south arms of Kootenay, he stated "i*t was clear that Kootenay Lake was a <u>far</u> more productive lake than Arrow*" (Northcote, personal communication). His observations of pre-dam conditions are further validated by paleolimnological studies of Kootenay by Ennis et al. (1983) and of Arrow by Vidmanic and Ashley (1996 unpublished data). They found quantitative counts of diatom frustules/mm^3 of sediment were considerably higher in Kootenay, especially mid-lake to north arm cores than in any of the cores from upper or lower basins of Arrow (Ennis et al. 1983).

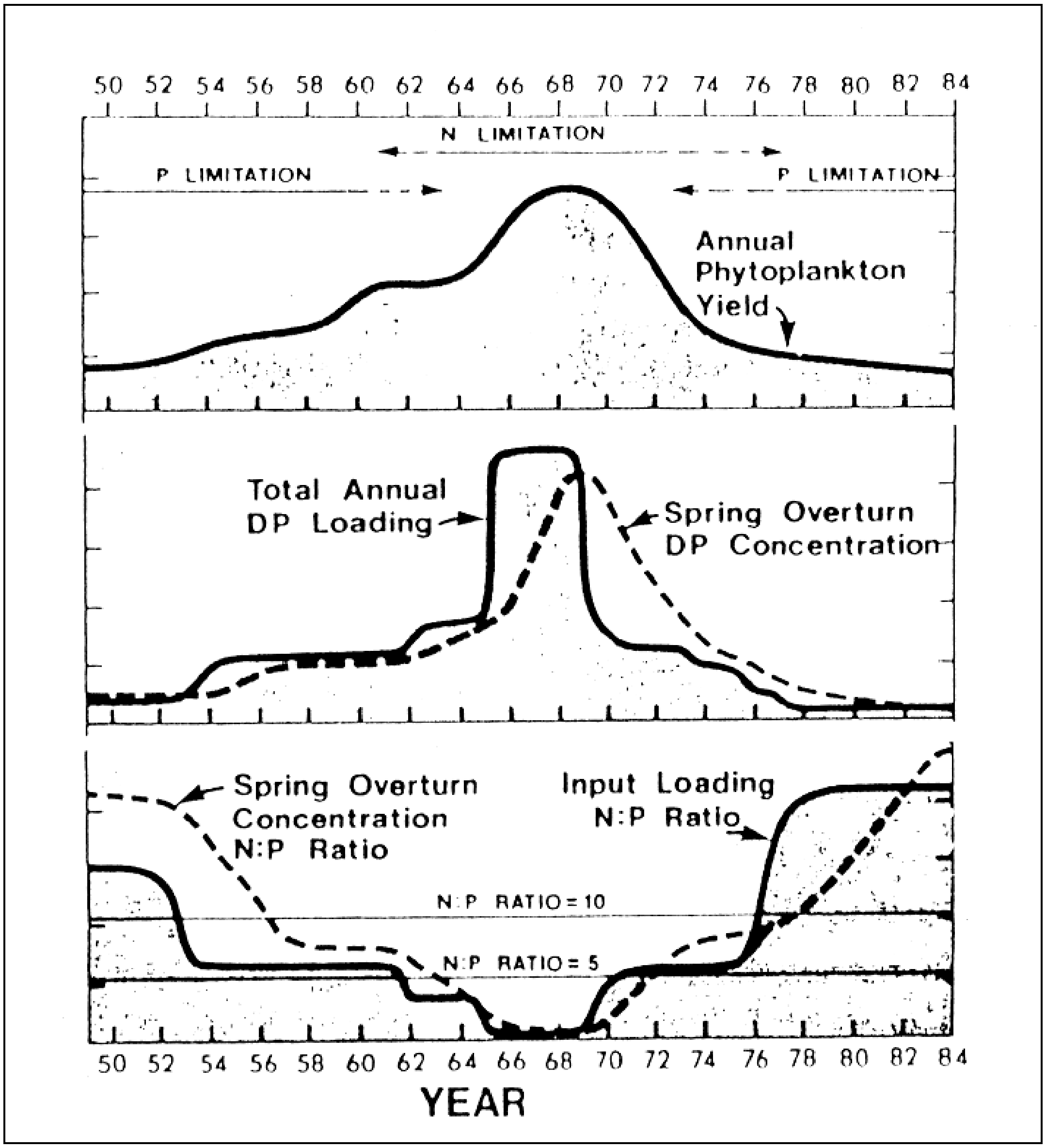
With the exception of Whatshan Lake, the lakes of the pre-dam main stem Columbia River, Bush, Kinbasket, and Arrow, together with Duncan Lake all experienced high turbidity during freshet periods (early June to September), with the attendant reduction of available light for photosynthesis that resulted in low average pelagic C production rates. At the 2 tails of the annual Columbia River hydrograph, when turbidity was moderately low, e.g. early spring at ice-out before freshet and again in September and October, we surmise that light conditions were no longer limiting C production and that rates of autotrophic C production doubtless were higher than in mid-summer (Stockner and Korman 2002). Early surveys as well as anecdotal reports described Bush and Kinbasket lakes as moderately productive, notably in sectors removed from the direct influence of the Columbia River main flow, and these small lakes were accordingly given higher average daily areal production rates (115-120 m mgC m^{-2}) than Arrow or Duncan lakes (75 -85 mgC m^{-2}). The higher average daily rates for Kinbasket and Bush lakes are very similar to present average from Quesnel Lake (ave.113 mgC m^{-2}) in the Fraser River drainage (see Table 4 – section 3.3.1.1) (Shortreed et al. 1999), and considerably higher than measured in glacially turbid Kitlope Lake (ave. 54 mgC m^{-2}), or Chilko a much larger lake on the Chilcotin Plateau with moderate mid-summer turbidity (ave. 82 mgC m^{-2}) (Stockner et al. 1993, Stockner and Shortreed 1994, Shortreed et al. 1999). Whatshan Lake with low turbidity and nutrient status was ascribed daily areal production values of 95 mgC m^{-2}, similar to Chilliwack, Curtis, and Swan lakes of similar size, trophic status and free of major turbidity inflow (Shortreed et al. 1999). Owing to the prevalence of high turbidity, both Arrow lakes and Duncan Lake were given the lowest average daily rates 75 and 85 m mgC m^{-2}, respectively. C fixation rates very similar to lakes of similar size and that are strongly impacted by glacially turbid inflows include Chilco, Morice, Owikeno and Kitlope lakes (see Table 4 – section 3.3.1.1**)** (Stockner and Shortreed 1985, Shortreed et al. 1999).

5.1.2 Present Reservoir Pelagic Production

So much has been written about the impacts of white European settlement, (interventions) within the Kootenay basin, on the trophic status of the lake from the early 1960's to present, that to repeat this chronology is unnecessary and beyond the scope of this project (see Zyblut 1970, Northcote 1972a, 1972b, 1973, Daley et al. 1981, Ashley 1997, Northcote et al. 2005, Binsted and Ashley 2006.) It is quite clear that the large phosphorus inputs in the 60's and 70's, from Cominco mine effluent transported to the lake by the Kootenay River, resulted in a major trophic upsurge or '<u>boom</u>' period in Kootenay Lake. This resulted in eutrophic conditions in the 1970s, e.g. high chlorophyll *a*, large protracted diatom blooms and the initiation of colonial blue-green algal blooms, with associated increases in biogenic turbidity (Northcote 1973a, Ennis 1977, Ennis et al 1983). Despite high turbidities and shallow euphotic depths, the rates of primary C production measured during mid-60's within Kootenay Lake were comparable to those from eutrophic lakes, ranging from 800 - 900 mgC $m^{-2}day^{-1}$ in mid- and north basin locations and >400 mgC $m^{-2}day^{-1}$ in the more turbid south basin (Northcote et al. 2005).

The construction of 2 dams, Duncan and Libby, on the major inflows to the lake, together with the cessation of P effluent discharge from Cominco had an equally large impact on C production in Kootenay Lake, this time creating a trophic down-surge of C production or '<u>bust</u>' period, in C-decline equal to if not more rapid than, the upsurge or 'boom' phase. The nutrient loads reduced from a 1968 peak of 2,031 t P to a low in 1979 of 36 t P, the inevitable collapse of meso-eutrophic conditions and a rapid return to the 'historic,' oligotrophic condition by the early - 1980's, highlighted a near-collapse of the famous lake Kokanee fishery (Northcote 1972a, Ashley et al. 1997, Binsted and Ashley 2006). This dramatic cycling of Kootenay Lake's productive status is well illustrated in a schematic figure from Daley et al. (1981) (Figure 66), where it is apparent that present levels of turbidity, ambient N and P concentrations and values of the N:P ratio are now considerably changed from the pre-dam Cominco mine effluent 'boom' period (Northcote et al. 2005, Binsted and Ashley 2006).

Figure 66: Idealized lake-wide trends in important limnological characteristics of Kootenay Lake between 1949 and 1984. The upper graph depicts annual phytoplankton yield and likely growth limiting element. The middle shows total annual dissolved phosphorus (DP) and spring overturn concentrations. The lower graph depicts N:P ratio of annual loads and at spring overturn concentrations (after Daley et al. 1981).



5.1.3 Impact of Dams

As part of the Columbia River drainage basin, Kootenay Lake and its entire basin falls within the terms of the Columbia River Treaty, a joint agreement between U.S. and Canada to optimize hydro-electric generation and minimize flooding in the Columbia basin (Crozier 1994). The outflow of Kootenay Lake has been controlled by a hydro-electric dam (the Corra Linn Dam) since 1939, and inflows from the Duncan River have been controlled by the Duncan Dam since 1967. Inflows from the Kootenay River are now controlled by Libby Dam in Montana, used since 1973 for flood control and hydroelectric generation (Daley et al. 1981, Perrin and Korman 1997). There is a large disparity in amounts of water and nutrients supplied by discharge from these dams with initial estimates by Daley et al. (1981) of 45% from Libby and 12% for Duncan (Daley et al. 1981) recently increased to 56% for Libby and 21% for Duncan (Binsted and Ashley 2006). Daley et al. (1981) estimated the maximum total reduction in nutrient supplies to Kootenay Lake phytoplankton from the two dams at 45% P and 35% N. Using simulations based on 60 % TP retention in Koocanusa Reservoir and 90% retention in Duncan, the model predicts a small decrease of 14% TP from pre-dam Duncan River and 44 % decrease from pre-dam Kootenay River TP loads for a total dam impact of 56% (Perrin and Korman 1997).

Present Levels of C production.

After perusal of most the 'key' variables used in the assessment of present trophic state of Kootenay Lake, it is clear that its current status is well within the oligotrophic condition (Northcote et al. 2005, Binsted and Ashley 2006). But the on-going nutrient fertilization coupled to changing climatic conditions has resulted in a wide range of annual estimates of chlorophyll, phytoplankton densities, biovolume and C production, that are related to the biometrics - lake level elevation, river discharge and SRP loading, fertilizer application rates, etc. All of the above variables have a direct affect on rates of C production, resulting in high inter-annual variability in estimates of C production (Harris 2002, Binsted and Ashley 2006). It should be emphasized that the impact of dams has had both positive and negative impacts on C production in Kootenay and all 'new' reservoirs. The positive effect has been a lessening of freshet turbidity in the reservoirs/lakes with an attendant increase in 'euphotic' depth diminishing the significance of 'light' limitation. However, with turbidity reduction comes nutrient retention by sedimentation and biogenic uptake in the reservoir and a markedly reduced load of N and P in river outflow. As a result we have substituted historic 'light' limitation with nutrient limitation of C production. Though some low to moderate turbidity still occurs in spring (some from moderate tributary inputs, e.g. Arrow Lakes Reservoir) and early summer, peak flows are now greatly diminished and the impact on photosynthesis greatly reduced. Estimates of ^{14}C primary production used in this report were done in 2000 and 2001, a time when only the north arm was fertilized and P loads from fertilizer varied between years, 29.5 tons P in 2000, 47.1 in 2001. A whole-lake average daily C production rate estimate for Kootenay in 2000 was 195 m mgC m^{-2} day^{-1} and in 2001 149 mgC m^{-2} day^{-1} (despite a higher fertilizer load) with an average for both years of 172 mgC m^{-2} day^{-1}. By contrast, the whole lake average for 2000-01 in Arrow Reservoir (only Upper Arrow treated) was 140 mgC m^{-2} day^{-1}. The Arrow treated value used in this report, 128 mgC m^{-2} day^{-1} is the average of several years of production estimates done over several years, including 2000 (Pieters et al. 2000, Stockner and Korman 2002).

All of the historic pre-dam lakes with the exception of Kootenay have been subsumed within current reservoirs and all , including Kootenay have undergone moderate to severe 'oligotrophication' or nutrient reduction due to reservoir aging, e.g. high rates of sedimentation, P-retention, loss of littoral production. Kootenay Lake historic levels and present untreated are 'estimated' to be the same, owing to marked turbidity and light limitation of production pre-dam and post-dam current untreated with P and N limitation. The positive light conditions of present are negated by severe N and P limitation 'untreated'. In Kootenay Lake the historic pre-dam rate was 125 mgC m^{-2} contrasted to the current rate with fertilization 172 mgC m^{-2}, while the average daily rate for Arrow Lakes Reservoir 'treated' - 128 mgC m^{-2}, is higher than the 'untreated' Arrow rate of 75 mgC m^{-2} values that illustrate the efficacy of nutrient supplementation for such oligotrophic fast-flushing lakes and reservoirs (Stockner et al 1980, Stockner 1987, Stockner and MacIsaac 1996, Stockner and Milbrink 1999). The rationale for elevated average daily C production values for present Kootenay and Arrow Lakes Reservoir than in historic Kootenay and Arrow Lakes is largely based on our perception from photographs and anecdotal reports of very high turbidity during the peak growing season in the historic lakes, which would have markedly suppressed the daily C production rate. Present conditions and *in situ* measurements from untreated, and several years from 'treated' Kootenay Lake and Arrow Reservoir show, not unexpected, higher C production rates during 'treated' conditions due both to the additions of nutrients to the epilimnion but also to a much improved light climate (less turbidity) and greater euphotic zone depth throughout the major seasonal growth periods than occurred pre-dam (Northcote et al 2005). Areal daily production rates among most all of the present reservoirs were in a similar range - from 70-90 mgC m^{-2}, and most have experienced improved water clarity (deeper euphotic zone) that has in part compensated for nutrient sequesterization and littoral zone production losses in all systems (Stockner and Korman 2002). The Koocanusa Reservoir (Canadian sector) and Kootenay

Lake receive increased nutrients from the more calcareous rocky mountain trench drainage and nutrients that used to provide direct benefit to C production in Kootenay Lake now enhance C production in Koocanusa, now one of the more productive reservoirs within the Columbia Basin. Kootenay Lake has retained its 'natural' lake basin and has not been significantly affected by impoundment but its loss of nutrient load from dams on its major inflows has restored it to the oligotrophic status (Northcote et al. 2005, Binsted and Ashley 2006). Most all lacustrine systems within the Upper Columbia Basin retain a lower level of C production, values still well below those from interior 'natural' lakes, e.g. Babine, Shuswap, Francois, Quesnel, Fraser, etc. (Stockner 1987, Stockner and Shortreed 1985, Shortreed et al. 1999, Ashley et al. 2002). Kootenay has had a litany of human interventions in its drainage basin that have had serious impacts on the C production and trophic status of the lake over the past 50 yrs; first with the introduction of mysid shrimp (*Mysis relicta*) in 1949, followed by Cominco fertilizer plant effluent discharges to the Kootenay River - 1952-1975 (Northcote et al. 2005), then construction of Duncan and Libby dams and finally to slow oligotrophication in the 1980's to nutrient fertilization from 1992 to present. The dams now catch spring peak flows in reservoirs, where the processes of sedimentation and nutrient sequesterization are occurring, greatly reducing both turbidity and nutrient content of outflow water, hastening the onset of oligotrophication in the system (Daley et al. 1981, Stockner et al. 2000). Clearly the most significant for C production was Cominco discharges, but those who have chronicled the changing trophic state have amply demonstrated the resilience of Kootenay lake to restore equilibrium oligotrophic conditions, indicating the importance of moderate to fast-flushing hydrometrics and sediment sequesterization and retention of a significant portion of annual TP and TN loads. Said another way, owing mainly to hydrometric factors, Kootenay Lake has no 'memory' or carryover of year to year production and nutrient loading, and through sedimentation and outflow (flushing) losses, annually resets it's 'plankton' clock.

5.1.4 **Historic Lakes – Pre-dam Littoral Production**

Shortreed et al. (1984) studied periphyton growth and production in 21 BC lakes and concluded that in most 'natural' lakes the littoral zone, when compared to the pelagic, contributed < 1-2 % of algal biomass as chlorophyll and < 1 % to estimated total annual lake C production. The more detailed primary production studies of both pelagic and littoral regions of Stave and Hayward reservoirs found a similar low contribution of littoral C to total pelagic C production, ranging from 1-2 % (Beer (2004), Stockner and Beer (2004). Littoral C production in most of the pre-dam lakes (Arrow lakes were notable exceptions), we suspect, played a more significant role than in BC coastal lakes. Descriptive accounts and personal observations of several extensive, shallow wetlands within side channels, bays, oxbows and fluvial deltas with sizeable beds of aquatic macrophytes and attached periphyton to support the contention of a greater historic C contribution from the littoral zone than at present (Peterson and Withler 1965a,c; P. Slaney, T.G. Northcote - personal observations). Professional judgment was used to estimate the historic littoral contribution, which we believe, ranged from 2 - 6% of total pelagic C production. Though the marked annual freshet of the Columbia River often increased lake water levels by as much as several meters in Bush, Kinbasket and Arrow lakes, (Duncan Lake slightly less), and the Kootenay River created the same impact in Kootenay Lake, the flooded shorelines were composed of deep soils and mature vegetation that could retain good floodplain 'memory' and were not easily erodable. Air photos of flooded shorelines reveal well developed vegetation cover, essentially the wetland and floodplain components discussed in the wetland section, adapted to the annual flood events (Figure 23). These littoral zones were important sites of nutrient exchange and organic export.

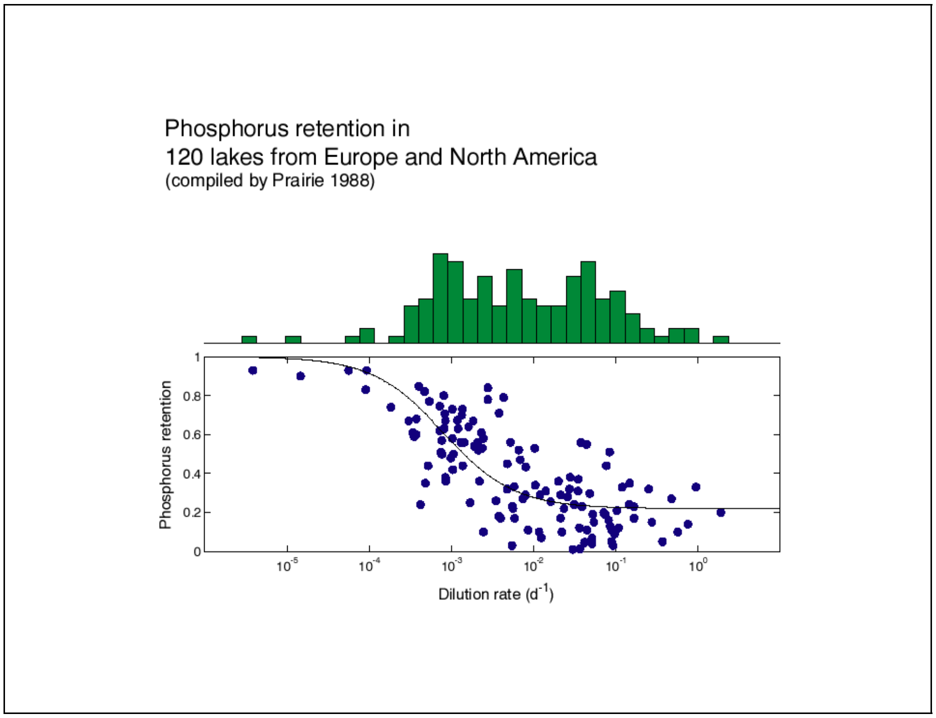
5.1.5 **Present Reservoirs - Littoral Production**

Present day littoral production should be higher than historic due largely to reduced turbidity, but the large drawdown and winter ice-scour of the littoral zone of some reservoirs has seriously affected colonization and subsequent growth of both periphyton and aquatic macrophytes in all systems, perhaps with the exception of Kootenay and Whatshan lakes. The present estimate of littoral production is 973.2 tC yr^{-1} for periphyton and 121.5 for aquatic macrophytes, slightly higher than historic, but considering the magnitude of 'new' colonizable effective littoral zone (ELZ) in the new reservoirs, it should be 2-3 fold higher than historic estimates. If greater water level stability could be achieved, particularly in winter and early spring to effectively eliminate the deep winter drawdown and destruction of established periphyton communities, there is a very large ELZ, presently non-productive, that would be available for colonization.

5.1.6 **The Sustenance of Reservoir Oligotrophication**

There are several, interrelated factors that collectively sustain the ultra-oligotrophic condition in the Columbia Basin 'footprint'. Among the more important are low productive oligotrophic 'equilibrium' status of the reservoirs that deliver a very low ambient N and P ground and surface water input to the system and through sedimentation, sequester nutrients. Another is the large hydrologic input volume that replaces the water of the reservoirs monthly during prime C production periods (Stockner and Korman 2002). This rapid flushing advects particulate C particulate matter, increases sedimentation within deep basins and markedly affects N and P retention within the system by reducing organic reduction and attendant nutrient recycling within the reservoir. It is well documented that in 'natural' lakes sedimentation and P-retention decline in concert with increased flushing, i.e. shorter water residence times (Figure 67). With the rapid flushing by interflows common in reservoirs, they tend to become 'C-export' systems both to sediments and, if residence time is extremely short (weeks), to outflow as well, further exacerbating pelagic production by 'draining' the euphotic zone of dissolved and particulate organic C, N and P. Increased sedimentation rates of reservoirs can favor the pelagic/benthic coupling pathway by increasing the rates of nutrient transfer and recycling in the sediment which increases benthic faunal production and sequesters N and P. The last piece in the puzzle that assures sustenance of reservoir oligotrophication is the perpetuation of a "dysfunctional", low-production littoral community owing to the atypical fluctuations of water level that accompany high flushing rates in hydroelectric storage reservoirs.

Figure 67: The role of flushing in phosphorus retention in lakes and reservoirs (after T. Anderson, Oslo, Norway).



5.2 Rivers and Streams Gross Primary Production

The autotrophic signature of GPP in lotic waters of Columbia Basin was generated by diverse taxonomic groups including periphytic algae, bryophytes (aquatic mosses) and macrophytes. Any focus on periphyton alone would be highly misleading because several biome studies show 50-60 % is attributable to bryophytes and macrophytes. Other than periphytic algae, the bryophytes or mosses are the only taxa that can withstand fast currents (Allan 1996). The periphytic algae are typically ubiquitous in all Columbia Basin rivers and streams. However, mosses and macrophytes are dependent on the physical nature of flowing conditions, and there is no pre-dam documentation available on the latter groups. Under pre-dam conditions, lotic periphytic algae are likely to be the dominant taxa in the Columbia Basin BCH reservoir units, as "epilithon" on a broad range of stony and woody substrates, "epipelon" on soft sandy-silty-clay-mud substrates, and "epiphyton" attached to bryophytes and macrophytes. Thus, it is this broad range of diverse plant groups within diverse lotic habitats that generated lotic primary production in the pre-dam BCH reservoir units. This is well supported in arctic, and boreal, coniferous aquatic lotic ecosystems (Minshall 1983, Naiman 1997, Webster and Meyer 1997) and it would occur in varying degrees in the Columbia Basin reservoir units under pre-dam conditions. Mosses, in particular, are exceptionally common in fast-flowing waters, especially on rocky substrates as well as on large woody debris that is a major component of north temperate forested rivers and streams (Allan 1996, Minshall et al. 1983), and the rocky substrates of glacial waters are known to support mosses (e.g., Fraser River).

Uncertainties regarding lotic GPP estimates within Columbia Basin are related to the high variability of lotic conditions. Uncertainties relate to what duration that the spring freshet dampened primary production under pre-dam conditions within the main stem rivers, and secondly, what proportion of the tributary streams had glacial conditions that extended beyond early- to mid-summer. Among periphytic algae in rivers and streams, diatoms are generally dominant over other algal classes, and their abundances are greatest in early-spring and late-summer to autumn. This is because of light limitations and scouring during the spring to early summer freshet, as well as a summer-time shading effect in smaller order streams (Allan 1996). In some cases where rivers remain open in winter, particularly if lake headed, algal accrual can be high in winter (Bothwell 1989) as well as in early spring, mid- to late-summer and autumn. Extreme discharges can have a negative impact on periphytic algae (Tett et al. 1978, Shortreed and Stockner 1983). However, algal communities recover as rapidly as 10 days from strong floods, and in rocky streams it was only epilithic populations of *Achnanthes* (spp.) that were depressed by severe floods (Douglas 1958).

Rivers highly dominated wetted lotic areas within the pre-dam Columbia Basin BCH reservoir units, and thereby light attenuation with river depth is likely to be a significant constraint that is not readily predictable, given present knowledge in both the grey and published literature on glacial conditions. In the mainstem Columbia River, there is evidence of periphytic accrual at depth as examined by Perrin et al. 2004. Downstream of Keenleyside Dam, calculated GPP from sampled peak Chlorophyll a in September to early October was 50 g C m^{-2} y^{-1} at depths of 2.5-3 m, compared to 30 g C m^{-2} y^{-1} at a shallow depth of 1-2 m, or 50 % higher at depth in the lower Columbia River. In the middle Columbia River at Revelstoke, calculated GPP from sampled peak chlorophyll a was 50 % lower than Keenleyside at a shallow (1 m) depth, or 15 g C m^{-2} y^{-1}. However, the middle river station was subject to peaking flow releases from Revelstoke Dam, which varied depths considerably, and likely dampened production (Perrin 2004). Thus, under post-dam conditions, there is evidence from a periphyton accrual study in the Columbia River of significant algal GPP at depth. Pre-dams, the 11-13 km-long Kinbasket Lake reduced glacial conditions considerably in the Columbia River (personal observation, P. Slaney 1964). Thus, primary production was only highly depressed by light attenuation during spring to mid-summer, and much less so in all other months. Furthermore, nutrient values would have been higher without reservoir sinks that currently exist. A possible exception is below Keenleyside Dam, but its current productivity is probably related more to reservoir fertilization coupled with local industrial and domestic effluents. Diatoms are less affected by light attenuation than green algae and there are numerous low-light adapted species (Allan 1996). Water temperatures may also have been affected post-dams, but it is not nearly as much of a limitation as light attenuation because strong algal GPP occurs at 5^{o}C (Bothwell 1998), even though algal GPP can be twice as high at 15^{o}C (Morin et al. 1999).

The Lower Fraser is a good example of a large glacial river, and year-round growths of mosses are evident in the canyon reach above the town of Hope, as are macrophytes prevalent throughout the mid- and especially the lower reaches of the river. Significant growths of periphytic algae are also well documented throughout the lower river, where they were sampled on abundant woody debris, floating logs, piles and submerged wharfs (Northcote et al. 1975). Average seasonal ash-free dry weights of periphytic algae ranged from 6-10 mg cm^{-2} in the lower mainstem to 1.7-6 mg cm^{-2} in the mid- to upper-mainstem. These are rather high biomasses for a significantly glacial river, indicating that glacial rivers can support high GPP, at least at shallow depths and at moderate nutrient levels. In the “muddy” Lower Fraser, algal growth depth may be only one meter during mid-spring to early summer months when near surface biomasses are depressed and range from 1.7-4 mg cm^{-2}. However, biomasses are 3-4-fold greater (5-18 mg cm^{-2}) in late summer to fall-winter months when water clarity increases substantially and light attenuation decreases markedly. Algal growths at depths >1 m in the Lower Fraser have not been measured, yet there is anecdotal evidence from anglers of algal growths at depth on submerged woody debris.

Unfortunately, there is a substantive data gap in the lotic benthological literature on river depths at which attenuated light restricts algal growth under variable glacial conditions. Regardless, nutrients are a key driver of GPP in these types of glacially influenced systems because chlorophyll a was documented to increase 5 fold by inorganic fertilization within the moderately glacial Mesilinka River at Williston Reservoir in the northern BC Interior (Slaney and Ashley 1999). This river is cooler than much of the middle Columbia River system (compared to that documented by Perrin 2004) and it is highly-P limited, although became N-limited once P was added. Certainly, substantive growths of diatoms and green algae were reported in the mainstem Columbia during summer in 1976 at varying distance below Mica Dam (Environmental Research Consultants 1976). Nutrients were elevated, as indicated by nitrate nitrogen sampling, which was during the early phase of trophic upsurge from Kinbasket Reservoir. Pre-Revelstoke Dam, chironomids heavily dominated the benthic insect fauna of the Columbia River below Mica Dam until mid-distance to Revelstoke, where a more diverse river benthic insect fauna was documented (Environmental Research Consultants 1976). Benthic insect abundance can be depressed by sediment-laden water quality by abrasion and infilling associated with high concentrations of silts and sands (Cordone and Kelly 1961). However, the moderately glacial Mesilinka River was documented to support significant benthic insect densities during summer, especially within fertilized reaches (Slaney and Ashley 1999). Thus, glacial conditions need to be severe to greatly depress stream productivity.

Most of the primary production in the Columbia River would have been generated during early spring, and mid-summer to autumn, or for four months when the river was relatively clear, compared to spring melt during May to mid-August. Some production would also be generated for four to five months from winter to spring within ice-free zones downstream of Kinbasket Lake, Upper Arrow Lake and Lower Arrow Lake, similar to that documented in the South Thompson River by Bothwell (1998). In addition, the larger streams or rivers in the literature data set, used to calculated GPP, also had lengthy periods of glacial spring run-off (Mesilinka River), snow melt (Quebec Rivers) and fall to spring storms as well as spring melt events (McKenzie River, Oregon). Finally, Columbia Basin side-channels are under-accounted in the estimates of habitat area by as much as 20 %, and they would have much greater GPP than the mainstem because of their greater stability, less glacial influence and higher nutrient concentrations. Furthermore, there is evidence from pre-dam fish sampling in the Kinbasket reaches that even the glacial streams had significant juvenile and adult populations of mountain whitefish (e.g., Sullivan River) as well as other species (Peterson and Withler 1965b). Thus, the 50 % reduction, as an adjustment for glacial depression of GPP within all rivers and streams above both Kinbasket Lake and Duncan Lake, is not considered unrealistic.

In the post-dam case, there also may be a modest amount of GPP compensation because there is greater water clarity in remaining lotic reaches of the Columbia River, including 2 km at Revelstoke and about 40 km of the free-flowing river downstream of Keenlyside Dam. However, maximum periphyton accruals, sampled by Perrin (2004), were relatively low, or on average 11 and 26 mg m^{-1} below of Revelstoke and Keenleyside dams, respectively. Some algal blooms have been observed at the latter near Castlegar, but this may be related more to reservoir fertilization and local effluent discharges than any changes in turbidity because water clarity was already high pre-dam in this reach of river (P.Slaney, personal observation). Furthermore, observed increases in fish abundance and size in this Canadian reach of the Columbia River are also affected by management activities in downstream American reservoirs.

Accordingly, there is some uncertainty associated with the estimates of pre-dam GPP, as well as heterotrophic carbon, for rivers and streams of the various BCH reservoir units of the Columbia Basin. These could be further refined or calibrated by field-estimating GPP of periphytic epilithon, epipelon and epiphyton as well as bryophytes and macrophytes within carefully selected sub-sets of remaining reaches of the Columbia and Kootenay, rivers, as well as several of the medium-sized rivers and larger streams.

As noted in the results, estimated GPP losses from rivers and streams included few of the pre-dam side-channels. Thus, they are considered significantly underestimated in habitat areas, which would vary by reservoir unit according to the incidence of side-channels. Furthermore, they likely comprise a significant proportion of the overall autotrophic and heterotrophic carbon production in some of the reservoir units because they are more productive waters than main stems (Lister and Finnigan 1997). If the estimated wetted areas of the large Lardeau River and its side-channels are used as a riverine template, this suggests a large component of GPP was not detectable using the available mapped data. In late summer of 2002, the wetted area of the mainstem Lardeau River was 32.24 ha and the wetted side-channel areas were 13.31 ha, which equates to 30 % of total wetted area (Slaney and Andrusak 2003).

Log jams play a major role in development and long-term persistence of side-channels (Kellerhals and Church 1989), and although some reaches of the pre-dam mainstem Columbia may have had a low incidence of side-channels, other reaches may have had a significant side-channel area (e.g., Donald to Kinbasket). As a key example in the Columbia system, the 100 km Canoe River was geomorphically similar to the Lardeau, with a U-shaped valley, a moderate gradient and large volumes of instream LWD. Thus, it is likely the Canoe had a high percentage of productive side-channel areas, nutrient-enriched by groundwater. Side-channels are typically highly productive as a result of their isolation from the mainstem during most of the growth season. Most are flooded temporarily in the spring freshet, and thus their forest canopy is frequently open to ambient light. Such lotic waters can support high biomasses of periphyton because they are frequently enriched by nutrients from groundwater sources and/or kokanee carcasses. The incidence of side-channels may be positively correlated at a watershed scale with the incidence of wetlands, which his worth investigating further to develop a correction factor. Accordingly, among the Columbia Basin BCH reservoir units, some further refinements of the incidence of side-channels could be achieved by detailed pre-dam air-photo interpretations.

Overall, the rivers and stream estimates of GPP, totaling 5500 t C y^{-1} are a first approximation, in need of further refinement, while diverse large-scale compensation measures are being further implemented.

5.2.1 **Predicted Columbia Basin Salmonid Standing Crop Losses**

Primary and heterotrophic production combine to support fish food chains, of which salmonids are at the third and fourth levels of the trophic pyramid. Fisheries management agencies have frequently estimated salmonid production capability of rivers and streams, which are used as a basis for setting harvest regulations, compiling supply analyses and estimating benefits of enhancement or restoration efforts. Several habitat models have been used to predict the abundance or biomass of river and stream salmonids. Application to the rivers and streams of the Columbia Basin BCH reservoir units may be useful as a scoping exercise as a first approximation of salmonid losses.

In western North America, the Habitat Quality Index (HQI) model has been widely applied to both rivers and streams (Binns and Eiserman 1979, Binns 1982) to predict habitat capability. The model is based on its rating protocols and applies 10 physical, chemical and biological attributes, to calculate salmonid standing crop as biomass per unit area. These include late summer stream flow, annual stream flow variation, maximum summer temperature, nitrate nitrogen, fish food, water velocity, substrate, cover, eroding bank and stream width. The data underlying the model is from arid Wyoming where N-limitation is commonplace among trout streams. However, because there are nine other parameters, it can be broadly applicable to the Interior of British Columbia, particularly in the more arid regions. For example, it was applied to upper-most canyon reach of the large N-limited Nechako River, where the model predicted a salmonid biomass of 14 kg ha^{-1} (Slaney 1987, Slaney et al. 1994). Mark recapture estimates after a three year fishery closure confirmed that biomass approached this value. However, the HQI model requires river/stream-specific field data as well as data on flows and temperature which are largely unavailable for pre-dam waters of the Kootenay reservoir units.

There are more simple nutrient-based models that can be applied to Columbia Basin, although accuracy is apt to be less because these models ignore flow, water temperature and disturbance variables, although variables including cover or useable width or area can often be estimated and incorporated.

One multiple regression model is the Habitat Capability Model (HCM) which requires data on nitrate nitrogen and cover ($n = 26$, $r^2 = 0.96$, $SE = 47$) (Rosenau and Slaney 1983):

$$\text{Standing Crop in kg ha}^{-1} = 13{,}900\ (NO_3N)^2 + 190\ (\text{Cover})$$

where NO_3N is dissolved nitrate nitrogen in mg L^{-1} during the summer growth season, and cover is the proportion of the summer wetted river or stream area that provides holding spaces for trout, as defined in Rosenau and Slaney (1983) as well as Binns (1982).

A primary limitation to the application of the HCM model within the Columbia Basin reservoir units is that summary of nutrient data indicates that P-limitation dominated waters, whereas dissolved NO_3N concentrations were moderately high, relative to P. An exception is at most tributaries of Arrow Reservoir where N is limited, or N and P are co-limited. Furthermore, at high NO_3N, the cover component of the model is insensitive (and some nitrate concentrations in the Columbia pre-Revelstoke Dam may have been elevated by extensive wetland and terrestrial flooding associated with Kinbasket Reservoir). Also, an additional adjustment for weighted useable area may be required for larger streams and rivers, similar to Binn's stream width attribute.

The model can be applied to tributaries of Arrow Reservoir because of low NO_3N concentrations, with the exception of the higher-N Columbia River. At an average NO_3N concentration of 34 µg L^{-1} ($n = 16$) and a cover rating of 10 to 20 % (from visual estimation of Mosquito Creek), predicted average standing crop or biomass of salmonids is 35 to 54 kg ha^{-1}. The model's authors caution against applications to high N-waters that are low in P because the model was formulated largely from waters with N limitations, or similar to that of Sheep Creek in the Salmo watershed (Slaney 2004).

Alternatively, a simple nutrient-surrogate model can be applied, an alkalinity-trout/char biomass model that was derived from coastal waters that support cutthroat trout and char populations (Ptolemy 2005). Model data ($n = 150$, $r^2 = 0.84$, $SE = 93$) were collected largely on smaller streams over multiple years at "meso" habitats, which excluded marginal shallow waters (or about 20 % of wetted area):

$$\text{Trout Biomass (g 100 m}^{-2}) = 45\ (\text{alkalinity})^{0.60} \qquad (\text{with alkalinity in mg L}^{-1})$$

Application to larger streams requires application of useable widths (R. Ptolemy per comm.2005):

$$\text{Trout Biomass (g 100 m}^{-2}) = 45\ (\text{alkalinity})^{0.60} \qquad (\text{ proportion useable area })$$

The model can be applied as a scoping exercise to rivers and streams of the Columbia Basin BCH reservoir units, for which estimates of weighted useable area are required. Useable habitat is that of suitable velocities, depths and cover as measured in streams. Useable salmonid habitats were similar to those visually estimated by two experienced habitat biologists at the Lardeau River in 2002 (Slaney and Andrusak 2003). Thus, the Lardeau River was used as a template because depth and velocity and cover criteria were applied there to estimate 1+ parr habitat, based on earlier testing. A GVRD study in 2002 at the Capilano River used velocity and depth measurements to compare to visual estimates and this test supported its application for 1+ parr but not for underyearlings (Ward and Associates 2004). At the Lardeau River, mean useable trout parr habitat was estimated at 8 % of wetted mainstem area in late summer and ranged from 4 to 15 % from a random sample of 20 % of the river's area in six reaches over its length.

Guidance was also provided by steelhead fry-related velocity and depth measurements of useable area by sub-sampling undertaken over several years throughout the Skeena River system. In the glacial upper, middle and lower Skeena River, weighted useable habitats, were 10.4, 7.0 and 5.4 %, respectively, or 8 % on average (range, 5.4-10.4; Anonymous 1992). Among 13 tributary systems of the Skeena River, mean useable area was 8 %, and ranged from 1.6 to 32 %.

For Columbia Basin streams, proportions of useable areas were estimated using the above templates combined with experience from work on the systems per-dam, plus use of pre-dam photos and ratings of salmonid productivity by experienced habitat biologists. Estimated useable areas of "rivers" were 10 % except for Donald-Mica above Kinbasket (5%) and Duncan (weighted upper and lower 6 %). Estimated useable areas for "streams" ranged from 5 % (above Kinbasket) to 15 %, although as for GPP, streams accounted for little of the biomass (average, <200 kg, range 10 to 700 kg). At a scoping level, it is assumed that all salmonid species are estimated, given habitat segregation by species and glacial conditions in many of the river systems. Rainbow trout production includes three life history forms. Also, glacial tributary streams upstream of Revelstoke and Kinbasket Lake are more highly utilized by bull trout than rainbow trout (Peterson and Withler 1965; K Bray and H. Andrusak pers comm.).

As a scoping exercise, it shows that river-stream salmonid losses of trout in the Koocanusa-Wardner reservoir unit are proportionately larger, which is attributable to much higher biological productivity as indicated by alkalinity (Table 30). Overall, in all reservoir units, the estimated magnitude of losses totaled 56,250 kg of river-stream dwelling salmonids, or 56 t. Of note, this does not include additional footprint impacts such as oligtrophication of Duncan River which is caused by hypolimnetic withdrawal of flow releases, as indicated from the results of a study by Perrin and Korman (1997) (PSlaney Aquatic Science Ltd 2003). Smaller reservoir units are not included because of insignificant small losses, compared to those of the major reservoir units of Table 30.

Table 30: Estimated salmonid biomass based on alkalinity and useable area estimates calculated from an alkalinity-trout biomass model developed by Ptolmey (2005).

Reservoir Unit	**Mean River Alkalinity mg L[1]**	**Mean Stream Alkalinity mg L[1]**	**Estimated Salmonid Biomass kg**
Donald-Mica: above Kinbasket below Kinbasket Lk	61 40	48 48	16,800
Mica-Revelstoke	46	29	12,020
Revelstoke-Arrowhead	47	37	2,870
Arrowhead-Keenleyside	32	45	7,720
Wardner-USA (Koocanusa)	143	106	13,310
Pend d' Oreille	76	76	2,170
Duncan-Lower & Upper	60	60	1,360
Total			**56,250**

The trout alkalinity-biomass predictions were based on meso-habitats, which resulted in a much higher r^2 value (0.84) than a plotted alkalinity relation used by an earlier steelhead team for adjusting modeled steelhead smolt yields by alkalinity in the large Skeena system (Anonymous 1992). Of note, alkalinities were also 2-3-fold higher within Columbia Basin than the Skeena system. A comparison to the steelhead biomass alkalinity equation applied to the Skeena system (Anonymous 1992) was not useful possibly owing to an equation error in the Skeena analysis, as well as the low proportion of the variance accounted among the data ($r^2 = 0.30$). Validation of the more recent meso-habitat model against data from outside BC indicated a 20-30 % over prediction, which probably resulted from the meso-habitat stratification (Ptolemy 2005). However, the proportion of weighted useable areas are likely underestimated for Age 1+ to adult trout and char, and may be 20 % rather than 10 %, because useable area for juvenile salmonids, and not adult salmonids, are incorporated in the Lardeau and Skeena templates. Furthermore, many side-channels were not detected from the map analyses. Thus, under-estimation by 50 % is much more probable than overestimation for the pre-dam Columbia Basin rivers and streams, which would result in loss of twice that of Table 17, or 112,500 kg. Further air photo interpretations of side-channels and sub-sampling of useable habitat would be necessary to refine these salmonid biomass estimates, and thus river and stream salmonid biomass losses, as a 1st approximation, are considered to range from 56,250 to 112,500 kg.

Rainbow trout production in the Columbia system includes three forms, a fluvial or resident river/stream stock, adfluvial-lacustrine stock which forages on littoral benthic insects, and a highly piscivorous stock that largely feeds on kokanee in the expansive pelagic zone of large lakes/reservoirs. Other than these habitat-related biomass losses, habitat fragmentation of migratory rainbow stocks, as well as bull trout stocks, by eliminating migration routes to nursery system has been an over-riding impact of the various dams in the Columbia system (Ahrens and Korman 2004). For example Lindsay (1977) estimated that a spawning stock of 4000 large adult bull trout were cut-off by Revelstoke and Kinbasket Dam, as likely were similar numbers of rainbow spawners which included yellow-fin piscivorous rainbow (Martin 1976). The latter are either extinct or genetically compromised through hybridization by stocking of Gerrard rainbow throughout the Columbia system over a 15 year period (Andrusak 2005). Reducing habitat fragmentation via compensation measures needs to be an overriding objective.

It uncertain how accurate the estimates of salmonid biomass losses are, which would require field testing, given the glacial conditions of many of the Columbia Basin rivers and streams. Glacial streams in the Bella Coola watershed were found to support high densities of trout, salmon and char (R. Ptolemy per comm. 2005), but this may not apply equally to Columbia Basin. No quantitative sampling of river/stream salmonid biomasses was conducted in the pre-dam Columbia Basin, although sporadic sampling has been conducted post-dams (Ahrens and Korman 2004). Application of the model standard error of 0.93 kg ha^{-1} would not account for variation related to glacial conditions and habitat useable area. Accordingly, at this scoping level, any application of standard errors to salmonid biomass and GPP estimates would be premature. Thus, these estimates should be applied with caution until refined further by sampling of glacial rivers and streams and by refining estimated useable area for salmonids.

Refinements could be accomplished by systematic field sampling within above-flood-line zones of a subset of rivers and streams within the Kootenay BCH reservoir units over several years. The ultimate objective should be to construct a reservoir ecosystem habitat model, similar to the Skeena steelhead model, but more focused on compensation. Such a complex model would need to define and incorporate juvenile migrant size-survival relationships for larger rivers, lakes and reservoirs, as examined theoretically by Burrows (1993). Such a modeling exercise needs to be directed at compensation measures, similar to a routinely applied Puget Sound model for chinook salmon habitat. However, it should not be directed at stock management per se, or little diverse compensation, other than Kootenay and Arrow reservoir fertilization, may be accomplished. BCH-related compensation projects completed to 2003 in the Columbia Basin are outlined in some detail by Ahrens and Korman (2004), but it is beyond the scope of this project to review their benefits. However, it is clear from the salmonid biomass losses estimated above, that lotic efforts to date have not significantly offset the river and stream salmonid losses resulting from hydro-development of the BCH reservoir units. Thus, the Program has not broadly achieved “like for like” lotic habitat compensation, which is possible provided “like for like” compensation is also conducted off-site within Columbia Basin.

5.3 Wetlands

The losses of wetlands due to the Columbia Basin hydroelectric developments are clear and undeniable. The differences between pre and post dam floodplains are illustrated by the two images below. What was once floodplain (Figure 68) is now, for most of the year, pelagic (Figure 69). Bush Lakes, numerous other small, warm water, pocket lakes and their surrounding wetlands were subsumed by the reservoir. The complex hydroriparian environments (as exemplified by the Bush valley), of the Columbia Basin valleys pre-dam, have been replaced by oligotrophic reservoirs. Shallow zones, as in the upper Bush River valley have become primarily unvegetated drawdown zones, with physical stresses too extreme to be tolerated by any primary producers.

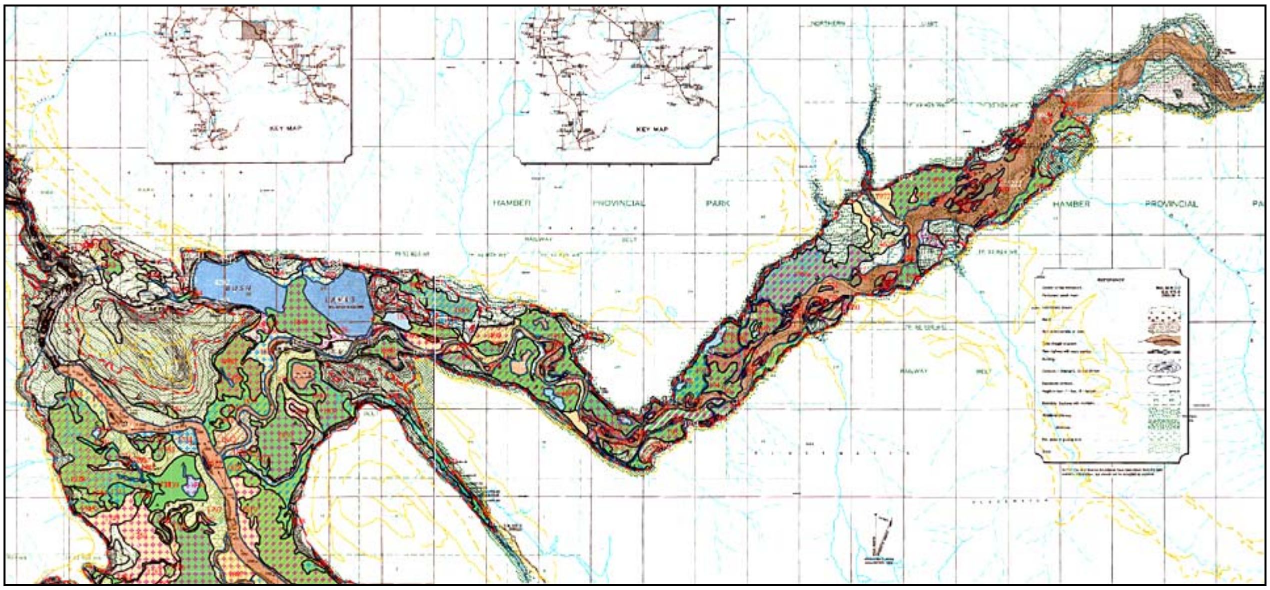


Figure 68: Historical mapping of Bush Arm (MS35 and 36) showing Bush Lakes and floodplain features.

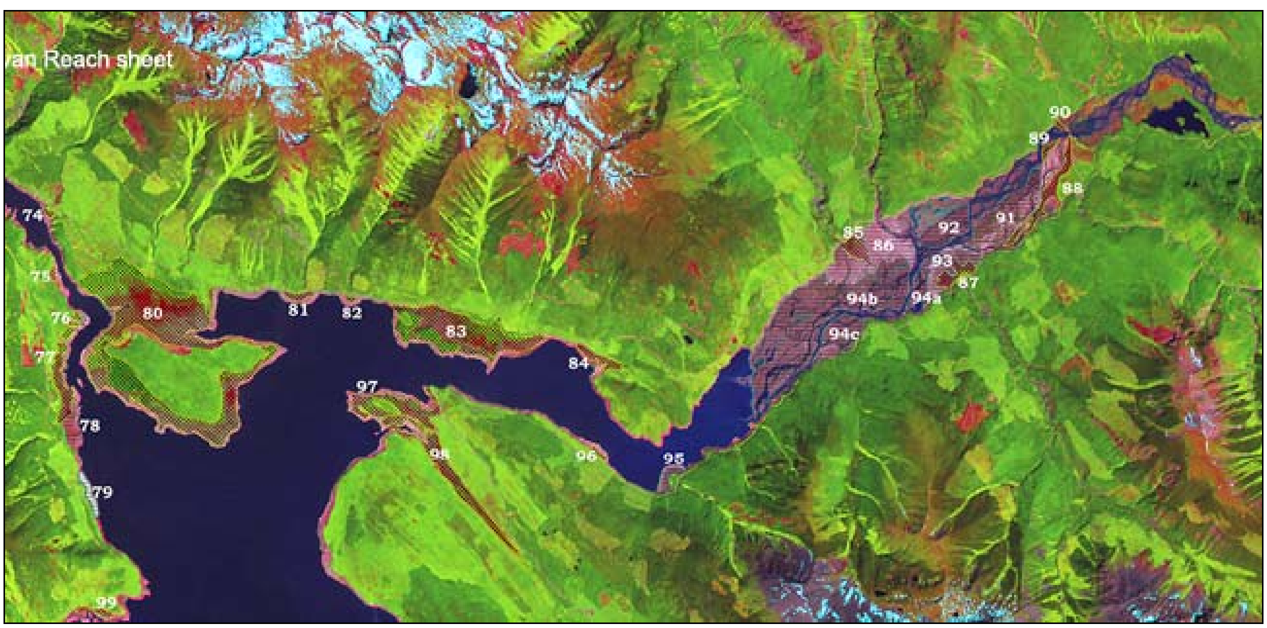


Figure 69: Satellite imagery (2001) of Bush Arm showing existing and potential wetland vegetation (prepared for Columbia WUP).

Very few wetlands remain, and those that do, exist as weak shadows of their former verdure (Figure 70, 75). The wetland below is an approximate 500 ha relict of a former Upper Canoe Reach fen. Reservoir stresses and erosion are gradually diminishing the diversity and productivity of this site.

New wetlands have evolved on former upper floodplain habitats (Figure 71) or in former terrestrial habitats (Figure 73) but overall these represent a very small fraction of historic wetlands and they do not support the same habitat complexity or diversity of the historic wetlands.

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Figure 70: Historic wetland that has survived reservoir creation - Upper Canoe Reach (2002) (photo A. Moody).

Figure 72: Lower elevation of historic wetland (Upper Canoe Reach) note drawdown zone visible on far shore (photo A. Moody).

Figure 71: Revelstoke Reach wetland comprised of reed canarygrass and lenticulate sedge (photo A. Moody).

Figure 73: Kinbasket reservoir wetland comprised of lenticulate sedge and horsetail, near Beavermouth (photo A. Moody).

If we adhere to the strictest definitions of wetlands, excluding floodplains and forested wetlands, only 10,639 ha of fen, marsh, swamp and shallow water was displaced by reservoirs. However, if we adopt a more holistic approach, one which is prevalent in current scientific thought, then we must consider the entire floodplain complex as an interrelated functioning ecosystem. The aquatic terrestrial boundary has been described as a moving littoral zone that passes across the floodplain as the flood pulse rises and falls (Junk et al. 1989). Early accounts of the Columbia basin have described flood levels rising by up to several meters during the spring freshet and historical photos show the floodplains filled with water. The Columbia River was characterized by a series of canyons, "bottlenecks", that caused a backup of spring meltwater, filling the floodplains. As the water forced its way through the narrows, the floodwaters in the valleys gradually receded, but only after the floodplains were recharged with upstream nutrients and cleansed of organic detritus from the previous year's growth.

The various floodplain habitats exemplified in the pre-dam Bush River valley can best be described as a continuum from open water to terrestrial. Upper floodplain habitats were situated at one extreme of the continuum where inundation only occurred during the flood period, but where regular alternation of flood and dry phases could be expected. Small lakes and shallow waters were at the other end of the continuum, where some water level changes occurred, but where water rarely disappeared.

Hydrology is the principal determinant of aquatic and transitional plant communities (Gosselink & Turner 1978) and the interplay between topography and hydrology governs the distribution of communities. The two extremes, the aquatic and terrestrial-like habitats support a range of plants which are adapted to these environments, but the zone of periodic inundation, typical of floodplains, is a particularly stressful environment which supports a community of stress-tolerant species (Grime 1979) and low species diversity (Menges & Waller 1983). Plants characterizing the wet end of the continuum develop from aquatic origins whereas in the upper floodplains, the terrestrial influences may dominate. Reservoirs impose extreme stresses on the vegetation existing in the drawdown zones. AIM & Carr (2000) reported that both species diversity and biomass decreased with increasing stress (inundation depth and duration) in the Arrow Lake drawdown zone. In floodplains, productivity may increase as the frequency and duration of inundation decreases, but may decrease when sites are infrequently flooded (Gosselink, Bayley & Turner 1981). Hydraulically active forested wetlands can be more productive that isolated wetlands (Brown & Lugo 1982). In wetlands, the majority of primary production occurs in the air, while consumption and decomposition occurs primarily during the flooded phase. This is in contrast to floodplain habitats, where decomposition and consumption can occur in both realms (Odum 1971). Floodplains are mosaics of different types of wetlands that have evolved in response to hydrology and have evolved in concert with specific floodplain features, oxbow lakes, point bars, sloughs, back swamps meander scrolls etc. These areas are dynamic features that may change in response to fluvial or mammalian (beaver, man) influences. Productivity can change as the hydraulics of the site change. The timing and extent of flooding has been identified as a key environmental factor controlling the functions of wetlands. Flooding delivers nutrients, takes away litter and creates a physical environment required by the plants and microbes. Modifications to wetland hydrology severely disrupt wetland functions. This was of particular importance in the historic river floodplains of the Columbia basin, which contained valley bottom wetlands, flood and riparian habitats that functioned in concert to support the aquatic productivity of rivers and lakes.

Recognizing that the vegetation shapes a floodplain as much as the floodplain shapes its vegetation, we considered the mosaic of interrelated floodplain habitats as vital elements of the Columbia Basin hydroriparian environment. Including the range of floodplain habitats in our analysis, led to the conclusion that **17,633 ha of non-forested floodplain and 21,705 ha of forested floodplain plus 1016 ha of shallo**w water were impacted by reservoir creation in the Columbia Basin study area.

The wetland mapping which was undertaken for the footprint analysis could be refined, using GIS analysis of present day reservoir DEM's (Digital Elevation Models), in conjunction with historical water level records, to establish the frequency of flooding at various elevations in these valleys. This would help discriminate between various floodplain benches and would clarify the magnitude of export from these habitats. Determining an appropriate productivity value for these different habitats is a more challenging exercise. Since no comparable data have been found in the literature, fieldwork would be required in comparable environments.

Large river floodplain functions have been poorly described in BC, perhaps in part because so many of the large river ecosystems have been altered by dams or by diking (Healey 1994). While separate components of these ecosystems have been addressed, primarily from a fisheries perspective, there has been little documentation of plant productivity from different habitats, export of nutrients or any of the other wetland functions now being recognized as being of critical value in these environments.

The spring freshet appears to have been a significant event every year with water level fluctuations as great as 7-8m near Arrowhead. The cottonwood and wetland islands situated in the Columbia River appeared to be flooded to considerable depth in the historical photos examined for this study (June/July 1961). It is evident that there would be a significant export of plant detritus from these habitats during the freshet period. Cool northern environments have been documented as experiencing slow breakdown of plant material over the winter period, therefore nutrient values of material exported during freshet would be substantial. Therefore, these areas need to be considered as functional contributors of carbon, in a way that terrestrial environments cannot.

Columbia Basin production - present day

Most of the reservoir drawdown zones are barren of vegetation except for some notable exceptions. Revelstoke Reach, part of Arrow Lakes reservoir has experienced a major expansion of native wetland vegetation since the early 1990's. This has in part been attributed to the BC Hydro dust control program, which involved drill-seeding of agronomic rye each spring to minimize wind erosion. Native vegetation, principally horsetail (*Equisetum fluviatile*), lenticulate sedge (*Carex lenticularis*), Columbia sedge (*C. aperta*) and reed canary grass (*Phalaris arundinacea*) has been expanding both clonally and by seed. Drill seeding of the agronomic rye has been discontinued in areas where native vegetation has become well established. Various studies, including biomass and soil analyses, have been undertaken to assess the developing vegetation (Carr and AIM 2000, AIM and Carr 2001, Moody 2002). The native vegetation mix observed in Revelstoke Reach is typical of other drawdown zones, but the density and biomass of the vegetation in Revelstoke Reach is greater than in other locations. Fertilizer included in the fall rye seeding program may be a factor in the enhanced growth of wetland vegetation in Revelstoke Reach (Figure 74). Fertilizer trials have shown a 20% increase in biomass over unfertilized sites in Revelstoke Reach and Williston Reservoir (AIM and Carr 2001).

Figure 74: Wetland development associated with drill-seeding of agronomic rye

Figure 75: Naturally regenerating sedge wetlands (at 437m- 3m below full pool), south of Revelstoke, Arrow Lake Reservoir- 1999.

The naturally establishing sedge, *(Carex lenticularis)*, with its dense, caespitose growth form (Figure 75), has established a very tenacious hold in the drawdown zone of Revelstoke Reach. Its elevational range is currently about 8 m. This sedge is only surpassed in areal extent by reed canarygrass, which although larger in size, is less productive than the sedge. While these areas are successful at producing large quantities of vegetation, their ability to support higher trophic levels is compromised by the operational effects of the reservoir. Waterfowl nests established in the vegetated zones are frequently inundated before the young are fledged and during the inundation phase, benthic invertebrates are hampered by timing and duration of inundation (Limnotek et al. 2000).

5.4 Heterotrophic Inputs

Transfers to Higher Trophic Levels - PR model and Kokanee Abundance

The PR model computes annual tC/lake/reservoir that serves as the C template for 'zooplankton forage production' and calculates carrying (productive) capacity in terms both of density and biomass of juvenile planktivorous kokanee each lake/reservoirs are capable to support (Shortreed et al. 1999). The model uses euphotic depth and volume, surface area and the annual mean daily ***P***hotosynthetic ***R***ate (PR) as the primary input variables, and the model is sensitive to changes in lake/reservoir surface area and nutrient status i.e. PR rates. PR model predictions for the historic pre-dam lakes shows a potential kokanee carrying capacity of > 68,000,000 kokanee fry and total biomass of > 273,000 kg. Not surprisingly, the PR predicts that for post-dam reservoirs with vastly increased, newly created, lacustrine habitat, is capable of supporting a 4.3-fold increase in both abundance and biomass of kokanee (Table 31). The theoretical compensation benefits of nutrient supplementation can be seen by comparing the Arrow Lakes reservoir's potential carrying capacity with and without fertilization (Table 32). But these can be negated if C flow through food-webs is short circuited by 'C sinks' of large 'inedible' phytoplankton or by competition from other invertebrate zooplankton grazers, e.g. *Mysis relicta.*

Table 31: PR model calculations of total kokanee population abundance and biomass based on pelagic photosynthetic C production in pre-dam lakes and present reservoirs in the Upper Columbia Basin.

PAST

Lake/Reservoir	Area (km^2)	daily mgC m-^{2}	(tC·lake^{-1})	biomass (kg)	number
Kootenay	390	125	8,775	480,000	13,600,000
Kinbasket	20.4	130	477	22,200	740,000
Bush	3.1	135	75	3,500	116,000
Arrow	350.1	75	4,788	220,000	7,340,000
Whatshan	15.4	95	263	12,200	406,000
Duncan	25.8	85	395	18,400	613,000
				756,300	**22,815,000**

PRESENT

Lake/Reservoir	Area (km^2)	daily mgC m-^{2}	(tC·lake^{-1})	biomass (kg)	number
Kootenay 'treated'	394	172	11,958	567,000	18,900,000
Kinbasket	370	80	5,328	248,000	8,260,000
Revelstoke	114.5	75	1,546	71,900	2,396,000
Arrow 'treated'	476.2	128	10,972	510,000	17,000,000
Whatshan	17.6	90	285	13,300	443,000
PDO	4.3	70	54	2,520	84,000
Koocanusa	60	95	1,026	47,700	1,590,000
Duncan	65	85	995	46,200	1,540,000
Corra Linn-Brilliant	0.5	75	7	314	11,360
Elko	1.8	80	26	1,210	40,300
Aberfeldie	1.2	75	16	753	25,100
				1,508,897	**53,289,700**

Based on Arrow Lakes reservoir fertilization result ‘treated’ pelagic habitat can offset oligotrophication and potentially double C production and the carrying capacity of the pelagic habitat for planktivorous fishes, e.g. kokanee, whitefish, etc. These estimates, assume a small juvenile mortality by ‘entrainment’ at each reservoir’s outlet and efficient passage flow of phyto-C to zooplankton and to kokanee without major competitors, e.g. *Mysis relicta (*Martin and Northcote. 1991, Northcote, 1972b). Small, “run-of-river” reservoirs like Elko, PDO, Aberfeldie would likely not retain sufficient nutrients and forage to be effective, i.e. high export losses, and Whatshan would have to rely on annual juvenile ‘stocking’ as adult spawner access is blocked.

Table 32: PR model predictions of potential kokanee increases in Arrow Lakes Reservoir based on nutrient supplementation ‘treated’ and increased photosynthetic production of carbon, and without enrichment (untreated) - ambient production levels.

Lake/Reservoir	**Area (km^2)**	**mg C $m^{-2}d$**	**($tC \cdot lake^{-1}$)**	**biomass (kg)**	**number**	**Gain No.**
Arrow ‘ Upper Treated’	476.2	128[1]	10,972	510,000	17,000,000	+5,100,000
Arrow ‘ both basins Treated’	476.2	190[2]	16,286	757,000	25,200,000	+13,300,000
Arrow ‘Untreated’	476.2	92[2]	7,886	367,000	11,900,000	-
Kootenay ‘north arm treated’	394	172[2]	11,958	567,000	18,900,000	+5,170,000
Kootenay ‘both arms Treated’	394	220[3]	15,602	726,000	24,200,000	+10,470,000
Kootenay ‘untreated’	394	125[3]	8,865	412,000	13,730,000	--

[1] Reservoir average, both basin average, only upper basin Arrow and north arm Kootenay were treated in 2000, 2001 (Harris 2003)

[2] Treated and untreated average, Arrow Lakes, (Korman & Stockner 2002). ‘Treated’ values are used for present condition

[3] Professional judgment.

6.0 COMPENSATION OPTIONS

A Canadian approach to compensation for losses of the productive capacity within aquatic ecosystems is the “no net loss” principle as applied to fish habitats across Canada under the habitat policy of the federal Department of Fisheries and Oceans (Department of Fisheries and Oceans 1986). A hierarchy of *preferences* is applied to development projects that result in losses to fish habitat:

> 1st *preference* is to maintain, without disruption, the natural productive capacity of habitats by avoiding losses or harmful alterations to habitat sites;
>
> 2nd *preference,* after it proves impossible or impractical to maintain productive habitat capacity, is for compensatory approaches that are “like for like” compensation by replacing natural habitat at or near the site. However, if “like for like” compensation is not possible, then secondly it may be possible to consider either moving “off-site” with replacement habitat, or by increasing the productivity of existing habitat, assuming reliable techniques are available.
>
> Third or lowest *preference* is for those rare cases where it is not technically feasible to compensate for the habitat losses, and therefore compensation by artificial production is considered subject to three conditions including:
>
> - Such a solution is in accordance with a management plan (if available);
> - Genetic and other biological factors are satisfied; and,
> - Practical and proven techniques are available.

For the BC Hydro reservoir units, it is the 2nd preference which applies; either replacing “like with like’ habitat at or near the site of losses, or alternatively, by “offsite compensation” by replacement of habitats or by augmented productivity of existing habitats. For the Kootenay BC Hydro reservoir units, “like for like” compensation would apply mainly to a stream reach located upstream or nearby. “Off-site” compensation would apply to some streams where compensation is not feasible in the same watershed and particularly to river habitat losses where local options no longer exist, such as the lotic or riverine habitat losses incurred in the Columbia River mainstem. In some cases, off-site compensation may be most effectively applied at a considerable distance from the loss site because of remoteness, more hazardous conditions for users, and/or higher project costs. This may apply to large losses associated with Kinbasket Reservoir, some of which can be more cost-effectively compensated closer to the population centers of Golden, Revelstoke and Valemount. Furthermore, compensation projects that are ecosystem-based should receive preference because they generate benefits to all trophic levels as well as ecosystem biodiversity. Examples are river/stream fertilization and large woody debris projects, the latter because woody debris in streams and rivers functions as trapping and storage areas of nutrients, detritus, leaf litter, and kokanee carcasses. The latter is a *keystone species* in oligotrophic stream ecosystems of the Kootenay Interior wet-belt. Significant side-channel development projects are also ecosystem-based because they can generate high levels of multispecies productivity, particularly where kokanee are a key component, and they can be readily, trophically enhanced further in spring to summer using slow release nutrients.

Compensation measures are of two main classes: habitat compensation and stock compensation. The latter is typically associated with fragmentation of habitats caused by dams that create obstructions to fish migration between nursery areas and adult rearing areas, such as Mica and Revelstoke Dams. Measures may involve provision of fish access at dam or fish culture measure to achieve compensation. Specific needs and technical options for specific stock recovery strategies associated with fragmentations of habitats are dealt with elsewhere.

Habitat compensation options targeted on reservoirs/lakes and rivers/streams are of five types:

- Reservoir/lake Enrichment;
- Stream/river Productivity Augmentation;
- Fish Access Improvement;
- Off-channel Habitat Development;
- Instream Habitat Rehabilitation.
- Riparian/wetland Restoration

A sixth type is fish stock recovery actions where this is some evidence that reservoir development negatively affected a specific stock of fish by terminating access to historical spawning and/or rearing habitats or by the elimination of its lotic habitats. This type of compensation is summarized elsewhere.

6.1 Reservoir/lake

6.1.1 **Background - The Present Lacustrine Landscape**

The building of dams and creation of reservoirs has led to nearly a 3-fold increase in pelagic habitat over historic values, and in the process has eliminated most large river or historic lotic habitat and over 87 % of historic floodplain and wetland habitat. This expansive ‘new’ pelagic lacustrine habitat has already passed through a more productive, albeit brief (5-7 yr), ‘boom’ or high production phase, and because of progressive nutrient losses by sedimentation and export (oligotrophication), each of the upper Columbia reservoirs have aged and are now approaching a new equilibrium C production level that is close to or within the limits of the ultra-oligotrophic status **(**Table 33**)**. The input of highly turbid tributary inflows to many of the ‘new’ reservoirs has maintained some moderate turbidity but not as nearly as extensively as occurred in pre-dam era from Columbia River freshet turbid inflow and from the Kootenay and Duncan river inflows to Kootenay Lake (Northcote 1973a, Peterson and Withler 1965a,b; Stockner and Korman 2002). Increased sediment trapping, within each of the ‘new’ reservoirs, has gradually increased water transparency and slightly deepened the euphotic zone during peak growth periods, thereby improving photosynthetic C production. We opine these small gains have to some extent been negated by the effects of oligotrophication, i.e. sedimentary P-adsorption, and that P-limitation and co-limitation (N & P) in Kootenay now appears to set limits on pelagic C production (Pieters et al. 2003). Large drawdowns further exacerbate the tC production of the new reservoirs, nearly eliminating any effective littoral zone and associated littoral C or macrophyte C production. Thus, it seems that compensation options are quite limited within the new ‘footprint’, and nutrient supplementation has gained pre-eminence over other options that have been precluded, either by low nutrient inputs, or large drawdowns and the presence of a non-functional littoral zone.

Table 33: Comparison of trophic status of Kinbasket Reservoir with oligotrophic conditions in coastal lakes of British Columbia and lakes worldwide.

Variable (seasonal mean)	World wide oligotrophic lakes (Wetzel 1983)	Ultra-oligotrophic coastal lakes in BC (Stockner and MacIsaac 1996)	Kinbasket Reservoir data from 2005 study (K. Bray, unpublished data)
TP ($\mu g \cdot L^{-1}$)	8.0	1.6	3.0
TN ($\mu g \cdot L^{-1}$)	661	-	172
NO_3^--N ($\mu g \cdot L^{-1}$)	-	13	102
Chl-a ($\mu g \cdot L^{-1}$)	1.7	1.2	1.5
Secchi depth (m)	9.9	-	-

6.1.2 Reservoir/Lake Nutrient Supplementation

Perspective

The efficacy of lake fertilization to increase annual C production and zooplankton forage for planktivorous juvenile sockeye and kokanee has been repeatedly demonstrated in dozens of BC lakes and highlights have been given in several key publications (Stockner 1987, Stockner and MacIsaac 1996, Stockner and Ashley 2003, Ashley et al. 2000). The fertilization of Kootenay Lake and Arrow Lakes reservoir to restore kokanee and rainbow has been an on-going program for several years (Kootenay Lake since 1992, Arrow Lakes Reservoir since 1999). It has been viewed as one of the only feasible compensation options to restore lost nutrients, caused by 'upstream' dam creation on the Duncan River and later Libby Dam on the Kootenay River, and its associated nutrient trapping (Ashley et al 1994, 1996, 2000; Perrin and Korman 1997, Pieters et al. 2003). The building of Libby dam on the Kootenay River and Duncan Dam on the Duncan River, together with the closure of the phosphorus plant on the upper Kootenay several decades ago have collectively resulted in the rapid decline of TP in Kootenay Lake (Figure 76). This oligotrophication has led to the demise of what was heralded in the 1960's and 70's as one of the most productive kokanee and trophy rainbow trout fisheries in the world (Daley et al. 1981, Ashley et al. 1994, 1996; Lekstrum et al 1994). Between the two dams currently affecting Kootenay Lake, TP concentration and its tC production, Libby Dam has had by far the greatest impact on summer TP concentrations in the surface waters of the lake. Model simulations that remove the two dams and/or restore 'natural' hydrographs suggest that Kootenay Lake TP concentrations could be elevated by nearly 60 % (Perrin and Korman 1997).

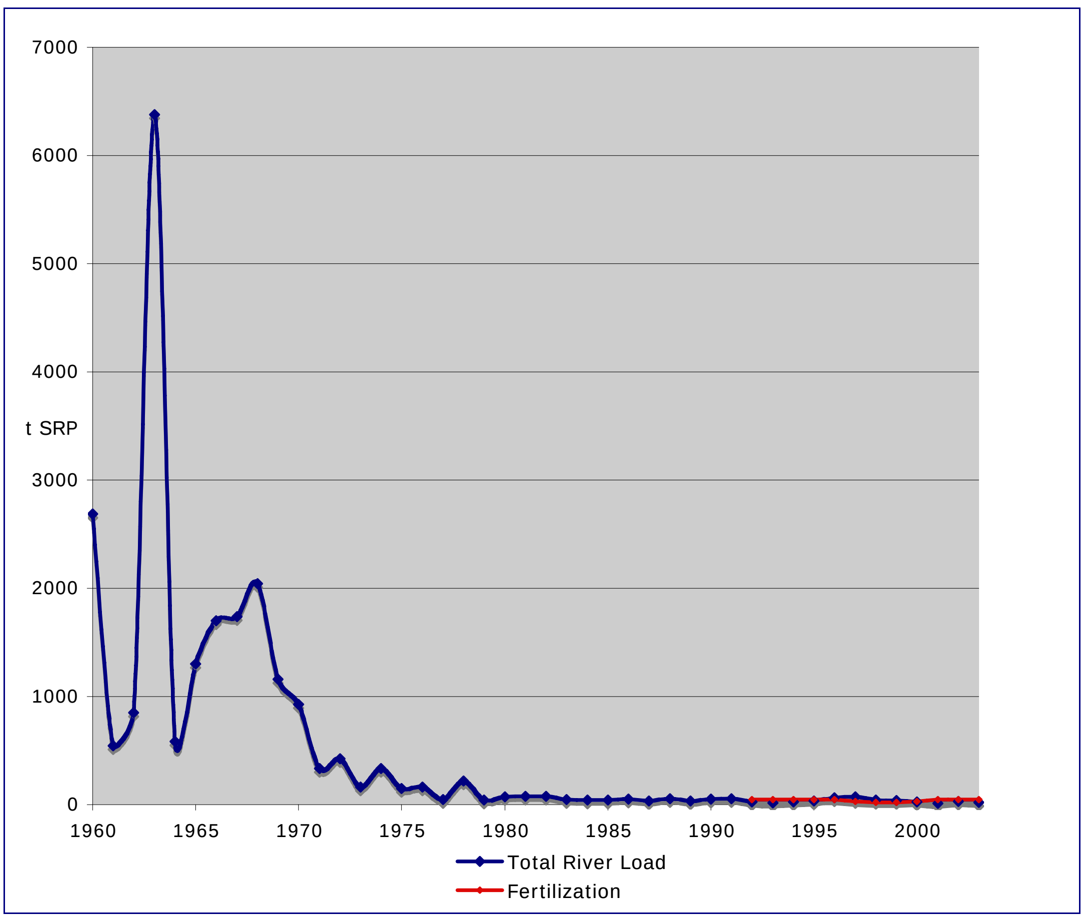

Figure 76: Time series of annual TP load from Duncan and Kootenai rivers to Kootenay Lake over 3 decades (after Binsted and Ashley 2006).

Sector or Reach Fertilization

The fertilization of Kinbasket Lake, whose current status is characterized as ultra-oligotrophic, would increase pelagic C production and the reservoir's capacity to support pelagic fishes, e.g. kokanee and other reliant piscivorous species, e.g. rainbow and bull trout. Owing to its large size and remote location, costs for whole-system treatment would be high, and options to treat specific sectors or reaches may be more feasible, e.g. Wood Arm, Canoe or Columbia Reaches. Fertilization has also been proposed to enhance shoreline vegetation (Columbia River Water Use Plan CC Report 2005).

Embayment Fertilization

Fertilization of select embayments of large reservoirs was first done successfully on a pilot-scale in a northern Swedish reservoir (see Stockner and Milbrink 1999), where bags of slow release fertilizer were place strategically in small inflow streams of one large embayment while a second, contiguous embayment was used as a control. Char and trout migrated from great distances to the greatly enhanced forage base (4-fold control) and the technique is currently an operational compensation mechanism on two reservoirs in mid-Sweden (G. Milbrink, Univ. of Uppsala, Zoology Dept., unpublished data and personal observation). Revelstoke Reservoir has several small embayments, well suited for trials of 'embayment' fertilization using slow-release fertilizer, and costs for application would be small, compared with application of liquid fertilizer with tug and barge to large sectors of the reservoir. The monitoring of such a program would doubtless increase costs, but the embayment fertilization option would be worth pursuing as a feasible compensation option for Revelstoke and other run-of-the-river reservoirs, including Duncan Reservoir's old South Bay sector. These small embayments in Revelstoke reservoir currently support some submergent macrophyte growth (K. Bray pers. comm.) that could also be enhanced by fertilization.

A potential constraint on embayment fertilization is turbidity/low light penetration that is caused by the spring melt, which can extend well into mid-summer. Thus, stream-embayment targets would need to be selected carefully, avoiding those with extended glacial conditions and higher embayment flushing rates. If combined with stream fertilization, increased primary production in both the stream and embayment should occur in less turbid waters. Certainly, there was strong evidence of a full trophic response to fertilization during summer to autumn within the Mesilinka River when enrichment was initiated in mid-July as glacial turbidity ceased annually (Slaney and Ashley 1999).

Embayments and stream mouths have been identified as locations along the reservoir littoral zone where riparian, emergent and submerged macrophytes have the greatest opportunity for success. In addition, fertilization has been identified as an opportunity for enhancement of vegetation survival and production. Slow release fertilizers have been applied experimentally in Williston Lake to test the efficacy for embayment enhancement (PWF&WCP – in prep.). A holistic approach to embayment fertilization could offer total ecosystem benefits including fish, wetland and wildlife components.

Littoral (shoal) Fertilization

Water temperature, nutrient levels, and duration of optimum conditions (drawdown frequency) in the littoral zone of reservoirs are key determinants of reservoir littoral productivity. Among Pacific Northwest reservoirs, drawdown can be substantial, e.g. 20 or 30 m as at Williston Reservoir located in north-central interior of BC. Arrow Reservoir has a more moderate but significant drawdown of 16 m (Pieters et al. 2000). Such reservoir "drafting" dewaters and destabilizes large expanses of littoral substrate, which severely limits suitable littoral habitats for aquatic biota and decreases benthic insect production (Fillion 1967, Benson and Hudson 1975, Kaster and Jacobi 1978, Knotek et al. 1997). The comparative study of periphyton production in Stave (7-9 m drawdown) and Hayward (1 m drawdown) reservoirs amply demonstrated the impact of drawdown on periphyton accrual rates, demonstrating that Hayward had C accrual rates 2-fold higher than measured in Stave (Beer 2004). Clearly reservoir drawdown has a profound impact on littoral C production by periphyton and macrophytes, as well as benthic invertebrates, as has recently been demonstrated at Kananaskis Lake, a montane reservoir in southern Alberta. There, the historical drawdown was 10 m, whereas the productive littoral zone has a depth of 6 m (Golder and Associates 1998). At Lake Kananaskis, prior to impoundment in 1936, benthic sampling demonstrated a diverse, benthic littoral fauna, including mayflies, stoneflies, caddis flies and amphipods; yet, post-impoundment sampling demonstrated a 100 % loss of all macro-invertebrates. This was associated with a <50 % pre-impoundment level of the littoral zone, which excluded aquatic plants and most woody driftwood debris; greater stranding, desiccation and erosion were prevalent (Golder and Associates 1998). A comparison of benthos in impounded upper Kananaskis Lake to natural lower Kananaskis Lake in 1948 revealed only 11 % versus 48 % macro benthos, respectively, in rainbow trout diets (Golder and Associates 1998). Thus, substantial reductions in macro-benthic insect production concomitant with a loss of littoral C littoral C production are major impacts of reservoirs with significant drawdown. Cumulatively, these drawdown effects on littoral C production limit littoral food (forage) production that supports fish, particularly trout and char, which rely on benthic invertebrates much more than zooplankton (Golder and associates 1998).

A compensatory measure for offsetting some of impacts of reservoir drawdown is shoal fertilization, which could be targeted at the lower drawdown interface that still lies within the euphotic zone for much of the year, where drawdown is moderate or 10 m or less. To be effective enrichment would need to be carefully targeted on benthic primary production by use of coated slow-release fertilizers, now readily available commercially for agricultural crop production such as rice. Because of their common use in food production, these fertilizers are low in any contaminants, and they are heavy enough that they are unlikely to be displaced by reservoir currents. These are currently utilized for river-stream fertilization in British Columbia in the Greater Georgia Basin Steelhead Recovery program, and have proven effective in generating periphyton responses in fast-flowing riffles from spring to autumn. The potential for the effectiveness of reservoir shoal treatments is suggested from a long-term fertilization experiment at a small montane coastal lake that was compared to an untreated control lake (Twin Lakes). Intensive sampling of aquatic insects demonstrated that the littoral zone (<6 m) produced 10-fold the macro benthos of the profundal zone (> 6 m), and overall, trout production was increased 2-3 times that of the control lake (Johnson et al. 1999).

Shoal fertilization has potential advantages over pelagic fertilization in that the slow release fertilizers can be carefully targeted where fish are likely to congregate in bays, embayments or over shoals, particularly after trout and char seasonally migrate from their nursery streams. Similarly, shoal fertilization can be targeted where there are benthic production bottlenecks and greater fishing pressure, which are frequently within reservoir bays and embayments. At this stage, there has been no research conducted that confirms the theoretical potential benefits of reservoir shoal fertilization to periphyton or macro-benthic insect production, as well as benefits to salmonid growth and abundance. Thus, an applied research phase is necessary before this potential compensation measure is widely applied. There are several reservoirs, within the 'footprint' area, where the effectiveness of shoal nutrient supplementation could be well tested. These include Arrow and Whatshan reservoirs, and selected embayments in Revelstoke and Pend d'Oreille reservoirs. In reservoirs like Koocanusa, Kinbasket and Duncan where either drawdowns are too large or low light conditions from suspended sediments prevail, it is less likely to be successful.

6.2 Rivers and Streams Compensation Options

Losses of lotic primary and heterotrophic production can be compensated for or offset by a number of technical measures. However, it is the strategy driving compensation that is key to effectiveness, and that strategy should emphasize compensation for lost ecosystem productivity, under the no-net-loss concept of "like for like" (Department of Fisheries and Oceans 1986).

The aquatic areas that were flooded to create BC Hydro reservoirs in the Kootenays vary by reservoir unit, and overall it would be an immense, if not impossible, task to compensate for such losses with similar lotic habitats that were lost. This is particularly evident for losses of river and stream GPP, which were estimated, as a first approximation, at 6000 metric tons of carbon per year. Overall, there has been a net loss of aquatic GPP across all habitats, rivers and streams, lakes and wetlands. Furthermore, heterotrophic aquatic production from riparian plant leaf litter and detrital sources accounted for another large source of carbon over and above primary production losses, and when it is also accounted for, as well as GPP, losses of total carbon from reservoir creation are increased further. Some of the un-flooded tributary-derived leaf litter, detritus and dissolved organic carbon are now processed in the reservoirs, but a substantial component accumulates in the deep reservoir sediments, in contrast to the pre-dam rivers where it was re-processed as confirmed via the stream continuum concept (Vannote et al. 1980, Minshall et al. 1983).

Like-for-like measures to replace productive lotic habitats are particularly challenging, given the large lotic areas that supported lotic production within the various reservoir footprints. The well documented decline of reservoirs in productivity over time through oligotrophication makes them a poor replacement for lotic habitat, and contravenes Canada's no-net-loss fish habitat policy of replacing "like with like" (Department of Fisheries and Oceans 1986). Moreover, run-of-the–river reservoirs are particularly sterile with few compensation options for increasing their productivity. Accordingly, an operational strategy that strives for a high diversity of compensation measures, applied equally to both lotic and lentic waters, are most likely to compensate for production losses from an ecological perspective, thus simultaneously compensating for losses of biodiversity.

6.2.1 Stream/River Productivity Augmentation

Increasing the productivity of remaining lotic habitats, as compensation is consistent with the no-net-loss principle for compensation. In both rivers and streams, this has been typically accomplished by inorganic fertilization using either liquid phosphate and or nitrate fertilizers, or alternatively slow-release fertilizers. Alternatively, stream enrichment can also be accomplished more “organically” by increasing kokanee escapements to a set of targeted streams because carcasses are comprised of 0.3 % phosphorus and 3 % nitrogen, as well as a large amount of carbon. One only has to travel to the Lardeau River in the fall months to gain an appreciation of how the entire ecosystem benefits from large inputs of carbon and nutrients from an exceptionally large spawner migration of kokanee from Kootenay Lake. Combining such “organic” and inorganic enrichment is apt to be most efficient because of ancillary benefits to the productivity of reservoir bays and embayments (Milbrink and Holmgren 1988). Fertilization as a technique is attractive for compensation because it can generate a complete ecosystem response at all trophic levels, and can be readily terminated and reversed at any time.

Liquid fertilizers are routinely utilized by the Compensation Program in Kootenay and Arrow lakes, and they are currently in use by BC Hydro for fish habitat compensation project at Sheep Creek in the Salmo River watershed. Generally, slow-release fertilizers are preferred in streams because of low maintenance costs, although slow-release products that have been adequately tested are currently expensive, or $3000 to $3500 per metric ton versus <$1000 for liquid fertilizers. Coated slow–release fertilizers are used in agricultural rice production and therefore the fertilizer are of higher quality than other dry fertilizers.

Given the historical importance of marine-derived nutrients from salmon carcasses, researchers in both British Columbia and Alaska experimented with adding inorganic nutrients to oligotrophic streams in an attempt to increase periphyton production at the base of the food chain (Stockner and Shortreed 1978, Perrin et al 1987), and thereby aquatic insect growth and abundance (Peterson et al 1985, Johnston et al. 1990), and ultimately the growth of salmonids (Slaney et al. 1986, Johnston et al 1990).

Stream fertilization as an applied stream restoration and enhancement technique evolved after two decades of research and development effort in British Columbia, initially at the Keogh River on northern Vancouver Island, followed rapidly in the late 1980s by operational applications at the nearby Salmon River, near Campbell River, which continues today. Both of these whole-river nutrient applications resulted in >2-fold increases in mean juvenile salmonid weights and substantial increases in smolt yield, especially of steelhead trout, which are heavily reliant on aquatic insects for their freshwater diet (Slaney et al. 2003). Benthic insect abundance was several-fold higher in the treated reaches than the control, and peak algal chlorophyll a was also increased markedly (Johnston et al. 1990, Slaney et al. 2003). The latter moderated rapidly with additional years of fertilization through increased benthic insect grazing, which was confirmed experimentally at the Kuparuk River by Peterson et al. (1993) in Alaska. Thus, after two to three years of low-level stream fertilization, only minor increases in algal biomasses are detectable because insect grazers expand sufficiently in abundance to suppress algal biomass accrual.

After the Keogh and Salmon River experiments, the large upper Nechako River was fertilized in 1990 as a potential compensatory measure for temperature impacts of a large proposed hydroelectric development (Slaney et al. 1994). Thereafter, two additional coastal streams were added to examine the effects of whole-stream fertilization on resident populations of brown trout and rainbow trout at the Adam River and Big Silver Creek, respectively (Wilson et al. 2003). Finally, the large Mesilinka River in the northern Interior was fertilized for five years to examine fish community responses that included Arctic grayling, rainbow trout, mountain whitefish and bull trout (Ashley and Slaney 1997). There, adult populations of these species responded markedly in both average sizes and numbers.

The Keogh and Salmon Rivers have been routinely fertilized for a decade (Ward et al 2003, Slaney et al. 2003), and more recently, in response to a sharp decline in steelhead returns, several other coastal rivers are fertilized. These include the Seymour River, Statlu River, Nimpkish River, Coquihalla River, tributaries of the Chilliwack River, and several other streams. Either liquid or slow-release nutrients are used to offset a deficiency in marine-derived nutrients, and in some streams, fish carcasses or carcass analogs are utilized. By 2006, between 100 and 200 km of streams were treated as one component of a Georgia Basin steelhead recovery program.

An early stream fertilization experiment associated with a reservoir was conducted in Sweden by Milbrink and Holmgren (1988) who demonstrated that migrations of lacustrine fish could be induced into reservoir embayments and stream mouths to forage on the increased production of aquatic organisms resulting from stream fertilization. Both stream fertilization and stream-embayment fertilization are of broad potential application as a compensation option, given that Columbia Basin reservoirs and associated streams are typically oligotrophic, and that past whole river experiments confirmed significant salmonid growth and numerical fish responses to fertilization treatments (Ashley and Slaney 1997). Whereas salmon function as a keystone species in providing sources of both carbon and nutrients for oligotrophic coastal streams and lakes in the Pacific Northwest, land-locked sockeye, or kokanee, in Columbia Basin provide a similar source of carbon and nutrients. Hydro-developments can affect kokanee by interfering with their migration, stream spawning areas, or lake productivity (Ashley et al. 1996). Accordingly, additions of slow-release fertilizers into streams to spiral nutrients into reservoirs is a sound means to offset losses of such an important keystone species.

The productivity of Kootenay rivers and streams is primarily a function of the underlying bedrock geology, which is further modified by topography and the precipitation regime (Northcote and Larkin 1966). Higher precipitation watersheds are generally lower in nutrients. Most of the Columbia Basin reservoir units lie within the interior wet-belt, and the underlying geology does not generate large amounts of nutrients. Phosphorus limitation is generally dominant in the Kootenays because concentrations during the growing season are less than the limit of detection or <1 µg L^{-1} SRP (or < 2-3 µg L^{-1} TDP). Dissolved inorganic nitrogen (DIN as ammonium and nitrate nitrogen) may also be limiting if concentrations are <20 µg L^{-1} (Bothwell 1988, 1989). P-additions can also drive DIN concentrations lower and thus a concentration of 30-40 µgL^{-1} can become limiting under these circumstances. The N: P ratio is also a guide to nutrient limitation, coinciding with the atomic ratio of N: P at 16:1 in aquatic organisms (Redfield 1958). Thus, aquatic systems that are <16:1 are considered N limited and those >16:1 are considered P limited. A 10:1 atomic ratio is equivalent to a 5:1 N: P weight-to-weight ratio, and therefore minimum target N: P weight ratios should range from 5-10:1 (Ashley and Slaney 1997). The lotic nutrient water chemistry of the Columbia Basin BCH reservoir units indicates nitrate nitrogen is generally high and phosphorus is very low. Thus, most rivers and streams, with few exceptions, are highly P-limited. From a fertilization perspective, this makes fertilization a more broadly viable option because it is much less expensive to increase P concentrations than N concentrations. Phosphorus only has to be increased to 3-5 µgL^{-1} to achieve a strong periphyton response, yet to achieve the same response in a N-limited stream, an increase of 50 µ L^{-1} is typically required. An example of this was evident at N-limited Sheep Creek where an increase to 60 µ L^{-1} DIN was required to obtain a strong periphyton response in 2005 compared to a weak response at a targeted rate of 30 µ L^{-1} in 2004 (Slaney 2005).

Accordingly, river and stream fertilization could be applied to achieve several objectives as compensation for loss of carbon production from rivers and streams:

Stream fertilization to augment production and quality of resident salmonids. Some rivers produce resident trout and char and support a significant sport fishery. For example, in summer the Akokolex River near Revelstoke is P-limited and may respond well to slow release fertilizer additions, increasing growth rates of a unique premium stock of cutthroat trout that currently supports a locally-significant trout fishery. Another example is the Salmo River, which flows into the Pend d'Oreille reservoir unit, which would respond to low-level fertilization. This would most effectively be accomplished by upper tributary enrichment to increase the production of juvenile rainbow and bull trout, with excess nutrients increasing the productivity of the Salmo River. With extensive losses of mainstem rivers in most reservoir units, there were substantial losses in trout/char riverine habitats that could, in part, be compensated by off-site enrichment of existing river systems in the Kootenays, including some of the less productive east Kootenay rivers (e.g., Moyie River).

Stream fertilization to attract foraging fish into embayments and stream reaches associated with Revelstoke reservoir. Primary targets would be streams with significant gradients for salmonid spawning and rearing as well as invertebrate production, which are associated with protected embayments. Some candidate stream embayment pairs were selected earlier in the Mica-Revelstoke reservoir unit, with input from Swedish scientists (K. Bray pers. comm.). Another suitable target would be in the vicinity of Valemount (e.g., Camp Creek), which was associated with production of endangered or extirpated "yellow-fin" rainbow trout (Peterson and Withler 1965). Some of the streams in this area are ultra-oligotrophic, and annual slow-release enrichment would ensure much greater juvenile production into the Canoe Arm of the reservoir. However, apriori, additional LWD habitat restoration may be required because a 1970s survey of Camp Creek indicated sparse salmonid rearing habitat. Both stream and embayment fisheries would be generated as a benefit to local communities and tourists.

Stream fertilization to increase recruitment of adfluvial lacustrine juvenile trout and char from spawning-rearing streams of Arrow Reservoir. Primary targets should be lake-headed streams/rivers, such as large Mosquito Creek, which are more stable and would generate greater trophic benefits than cool non-lake headed systems. Glacial streams would generate even less benefits and should generally be avoided unless they clear by mid-summer. Mesilinka River waters were of glacial quality from May until mid-July. Such enriched streams are also likely to attract foraging fish to their lake mouths and lower reaches (Milbrink and Holmgren 1988), and nutrient additions are also an additional means to deliver nutrients into reservoirs through downstream transport as well as nutrient spiraling.

Typical responses of juvenile salmonids to stream fertilization have been a two-three fold increase in average size of juvenile trout (Ashley and Slaney 1997). Underwater evaluations of whole river fertilization of the ultra-oligotrophic Mesilinka River at Williston Reservoir in northern BC indicated that adult rainbow trout increased in mean size at age 4+, and especially in population abundance, the latter by about 2-fold. Mountain whitefish increased by at least five-fold. There were also increases in Arctic grayling and piscivorous bull trout, with the latter after a lag time of about four years of whole-river treatment (Slaney and Ashley 1999, BC Environment data on file).

Costs of stream fertilization are dependent on flow during the primary growth season, or generally July to September in the mountainous Interior of BC. Targeted distance of treatment is also a factor that varies with average stream flow. Accumulated nutrients in the hyporehic zone support further enrichment beyond September and well into the fall, as documented at the Salmon River on the Coast. Cost also varies with the type of fertilizer utilized, the target concentration, and whether the stream is N limited as well as P limited. Most Kootenay streams appear to be P-limited and not N-limited. Assuming P limitation alone and a target concentration of five µg P L^{-1}, the amount of slow-release liquid fertilizer required is 200 L per one m^3 s^{-1} of flow (for 92 days of input), at a cost of $1.50 per L, or $300. The equivalent cost of slow release fertilizer is about $700 per m^3 s^{-1}. Thus, the annual cost of fertilizing a small river with an average flow of 10-m^3 s^{-1} would be approximately $3000 with liquid fertilizer and $7000 with slow-release fertilizer. However, the cost of application of the liquid fertilization is likely to be similar to slow-release fertilizer after accounting for operational costs, except in large systems. These costs include a fertilizer tank/drip system and periodic maintenance to adjust drip rates according to ambient flow to maintain the targeted concentration. Effective distance varies with stream flow and ranges from 5 km in a small stream to 15 km in a larger stream or river. Thus, to achieve greater distances of treatment, additional inputs of fertilizer are required along the length of the enriched stream or river.

6.2.2 Fish Access Improvement

There are numerous streams entering reservoirs where stream length was lost, as a result of flooding. Losses of tributaries were largest above Mica Dam (e.g., Canoe River, Wood River), but were smaller in km in the Revelstoke reach and along Arrow Reservoir, as they also were at Koocanusa, aside from the Elk River. For example, at Arrow reservoir, the average loss was 1.5 km and ranged from 0.5 km (St Leon Creek) to 6 km (Fish River). As compensation, some of the barriers or partial barriers could be made passable by improving fish access routes or by installation of a fishway. An example is at km 2 at Cranberry Creek where two partial barriers can be made fully passable to rainbow and bull trout by blasting a fish passage route at each obstruction (Andrusak and Slaney 2004). Until very recently, this stream was seasonally dewatered by a hydro-electric diversion located 13 km from the mouth of Cranberry Creek, and thus devoid of fish for several km. With a recently set minimum stream flow, there is a good opportunity to provide migratory fish access above these barriers. Similar opportunities to recover accessible stream length may be available at other streams, which require an assessment similar to that at Cranberry Creek. Resident fluvial fish, if any, inhabiting the stream segment above a barrier, requires assessment, and a management decision on sharing of habitat with migratory fish. Costs vary widely with the severity of the barrier, but blasting techniques are less costly than fishways, with rock-work blasting costing $25-50 per m^3 of rock modified by hand-removed fragments (Whyte et al. 1997).

Other fish access projects are likely to involve re-opening areas cut-off by past logging and road building practices, particularly road culverts that have substantial drops or obstacles, or steep extended gradients within the culverts. Unless road culverts are over-sized, the extremely high energy at the outlet typically results in degrading of the channel creating a large drop that prevents or interferes with fish passage. Maximum jump heights for adult rainbow and cutthroat trout are 1.5 m, and for juvenile rainbow, 0.6 m (12 cm fish) to 0.3 m (5 cm fish) (Whyte et al 1997). Where there are complete barriers to fish migration, restoration of fish access can be more cost effective than other habitat restoration techniques. This is because several km of habitat can be re-established, and often without replacement of the culvert, but rather by riffle re-construction to backwater the culvert, which is relatively inexpensive compared to other restoration techniques. Culvert replacements that assure fish access range in cost from $450-700 per lineal meter, and for tail-water modifications, costs range from $30-100 per lineal meter (Whyte et al. 1997).

6.2.3 Off-channel Habitat Development (semi-natural side-channels)

Off-channel habitats are created by the long-term processes of alluvial deposition, channel migration and changes in streambed elevation (Kellerhals and Church 1989). They are of three types including groundwater channels, wall-base channels, and surface flow channels, the latter often seasonally ephemeral. Combined, they can comprise a high natural proportion of the lotic wetted area in a watershed and are generally more productive than mainstem habitats because of greater stability and high nutrient inputs from groundwater and kokanee carcasses. Accordingly, they provide ideal opportunities for lotic habitat compensation because of their higher biological productivity.

Restoration and development of off-channel habitats have received considerable attention in British Columbia as result of past fisheries enhancement and watershed restoration programs of the 1980s and 1990s, respectively. This approach has been attractive because these projects are more manageable than within higher energy mainstems where there can be greater risks. In the Interior, side-channels may minimize severe winter and spring-runoff condition that reduce productivity and survival rates of stream biota. On the other hand, off-channel projects, without adequate design considerations and local stewardship have been criticized because they may interfere with the natural functioning of the floodplain by use of set-back dykes, and may also be colonized and rendered ineffective by beaver activity. Furthermore, they can require significant maintenance to maintain intakes and manage sedimentation, without adequate design features. As a technique, the benefits are dependent on minimizing these maintenance aspects, selecting sites of a suitable physical environment, as well as both the fish species and life stages adapted to that environment (Lister and Finnigan 1997).

For example, a fish habitat assessment of the large and important Lardeau River and its floodplain demonstrated that side-channel habitats accounted for an estimated 141,000 m^2 or 30 % of a total of 474,000 m^2 mainstem and off-channel habitat (Slaney and Andrusak 2003). Most of this off-channel area was well utilized by kokanee and juvenile stages of Gerrard rainbow trout. Historical road development has disconnected some of the side-channel habitat, which offers opportunities to restore connectivity as nearby compensation for loss of habitat and habitat productivity in the Duncan system (Slaney and Andrusak 2003). Similarly, there are numerous large extended side-channel tracks that could be re-supplied with secured log jams and then excavated and re-armored at the entrance to re-establishing a year-round flow, thus creating significant salmonid rearing habitat, as well as kokanee spawning habitat, the latter the ecological keystone species in the Lardeau system.

Although groundwater and wall-base channels provide opportunities for compensation at or near the BCH reservoir units, as habitat compensation projects they are considered at high risk of beaver encroachment. This makes these projects high risk without either extensive fencing or frequent maintenance to either remove beaver dams or control beaver activity. Similarly, low-flow surface side-channels are at similar risk. Although these projects will initially perform well, they will be inundated with beavers that take advantage of deciduous trees that are frequently enhanced by side-channel development. Accordingly, such side-channel projects should be avoided unless a stewardship group has made a volunteer commitment to routinely maintain them.

However, it is likely that most side-channel projects would be remotely located. Thus, no remote side-channel projects should be developed as compensation without incorporation of a substantive spring flushing flow to manage beaver activity. This rule would ensure continuous access for salmonids and other fish species, and thereby higher cost effectiveness over a decade of operation. A surface intake with the capacity to release spring beaver-dam flushing flows should be the hydraulic basis of the both the channel setting and the intake design. The biological basis should be an optimal water temperature regime and suitable water quality.

As outlined in Lister and Finnigan (1997), relic side-channel tracks should be the target for such intake side-channels, based on several check points, which are outlined in Appendix 2. Application of side-channel development and restoration in the Kootenay reservoir units are widespread and include:

- Lardeau River as compensation for Duncan system footprint area losses and oligotrophication of Duncan River;
- Salmo River and tributaries for Pend d’ Oreille losses;

- Kootenay River tributaries for lotic area losses from Koocanusa unit;
- Arrow tributary compensation, particularly at lake headed streams;
- Selected Revelstoke tributaries where there is embayment fishery potential especially in combination with stream-embayment fertilization;
- Selected projects near Valemount to increase recruitment and fish returns to the Canoe River, where a major late winter to early spring fishery for whitefish is historically documented in agency communications.
- Off-site compensation at east Kootenay rivers for lotic GPP and heterotrophic carbon losses at Columbia Basin BCH reservoir units.

Cost of surface-fed intake side-channel projects are typically $60,000 to $100,000 per km, but can be expected to cost more with more complex manifold-type intakes and greater excavation and flood protection. A more recent DFO cost estimate at the isolated San Juan River, an extreme rainfall area, for a one km side-channel ranged from $2000 to $3000 per 100 m^2 of side-channel. Thus, assuming a 5 m average width and a length of 1 km, a 5000 m^2 channel would be expected to cost $100,000-$150,000 in a more challenging remote environment.

An estimate of salmonid production benefits is provided in Koning and Keeley 1997, and kokanee benefits can be estimated from similar smaller channels that have been routinely evaluated in the Kootenays. Sockeye side-channel projects are documented to produce 1000 fry m^{-2} (Koning and Keeley 1997). Annual parr production benefits are likely twice that of less fertile coastal waters, or 20 per 100 m^2 per year in Kootenay waters. Slow-release fertilization (or extensive kokanee use) could be expected to increase benefits by 50-100 % (Ashley and Slaney 1997). As a recent example, a no-net-loss compensation project involving a side-channel was recently evaluated in Newfoundland. The 1.2 km side-channel supported 175 to 310 g 100 m^{-2} of Atlantic salmon and brook trout. The project was deemed successful because it achieved, on average, 100 % of the no-net-loss compensation of nearby lost stream habitat that was of lower productivity (Scruton et al. 2005).

6.2.4 Instream Habitat Rehabilitation

6.2.4.1 Impacts and Scale of Large Wood Losses from Rivers and Streams

Stream habitat rehabilitation has a long history in North America that began in the US Mid-west several decades after the very early conclusions of VanCleef (1885) based on an investigation of the Catskill trout streams in the State of New York:

> *"The destruction of trees bordering on streams and the changed conditions of the banks produced thereby, has resulted in the destruction of the natural harbours or hiding places of the trout; this is the main cause of depletion, and unless these harbours are restored, it will be useless to hope for any practical benefit of restocking them".*

Up until the introduction of riparian protection guidelines in 1988 on the Coast and until 1995 in the Interior, little had changed since time of VanCleef, in that logging or clearing was practiced to the banks of streams and rivers in British Columbia. Post-riparian logging, large woody debris (LWD) has been lost at about 10 % a decade in rivers and streams (Figure 1-4 in Slaney and Zaldokas 1997). Thus, at this latitude about 50 % of instream LWD has been lost through decomposition and transport, given that on average streamside logging occurred 50 years ago. There is a long-term large wood cycle after riparian logging, and a minimum of 100 years is required to regain significant large wood recruitment from riparian areas, with the lowest supply 50-60 years after riparian logging or clearing (Figure 77). Unfortunately, further losses of LWD and associated fish habitats can be anticipated for another 50 years. Survivals of juvenile salmonids in log-jams are documented through Pitt-tagging to be twice that of open areas (Quinn and Peterson 1996). Furthermore there are losses of spawning areas that are maintained at log-jam pool tail-outs, and log-jams act as retention devices for organic mater (including fish carcasses) which profoundly affect both stream and river productivity (Minshall et al.1983). After past riparian logging, tributary slope failures may become the primary sources of a reduced supply of mainstem large wood, as is becoming evident at the upper Lardeau River below Mobbs Creek (Slaney and Andrusak 2003).

There are examples of rivers/streams where LWD prescriptions have been completed in the Columbia Basin reservoir units, with Erie Creek a prime example of historical LWD losses. Examples include the Salmo River, Erie Creek, and Cranberry

Creek. A large alluvial cobble reach of Cranberry Creek was dewatered by an upstream hydroelectric diversion, but a recent minimum flow allotment makes instream habitat restoration viable. This would have significant benefits provided trout and char access from Arrow Reservoir was facilitated as additional compensation, beyond that of Hill Creek spawning channel at Arrow Reservoir (Andrusak and Slaney 2004).

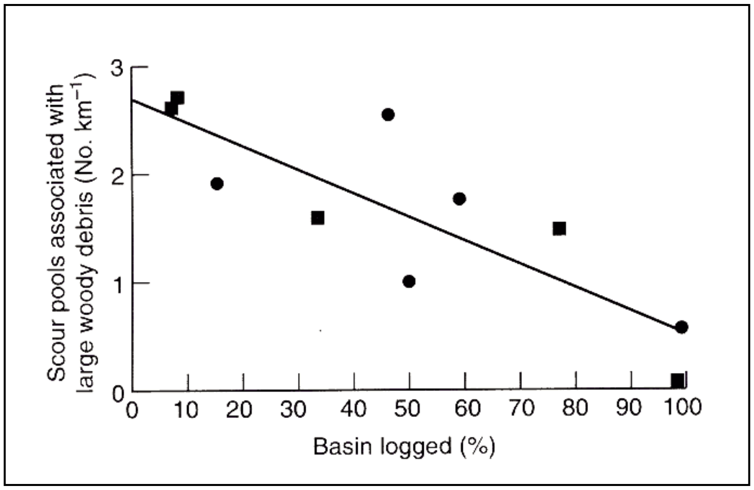

Figure 77: Frequency of pools associated with large woody debris in ten Oregon coastal streams with different logging histories and differing geology (square, basalt; circle, sandstone) (from Bisson et al., 1992)

6.2.4.2 Benefits of Large Wood Restoration

Because of past extensive logging of riparian areas in the Kootenays, there are numerous opportunities to restore LWD in streams and rivers and thereby compensate for reservoir losses of river and stream habitats. Considerable experience with rehabilitation of LWD has occurred in BC during BC's Watershed Restoration Program over the past decade. Even greater experience was gained by the US Forest Service in forested watersheds of Oregon and Washington over the past two decades. Thus, durability success rates can be high, ranging from 80 to 95 %, with any losses of LWD structures typically adding to complexity of LWD sites further downstream.

Benefits of large wood restoration can be significant, or at least 2 to 3 times that of untreated controls. Before and after controlled impact (BACI) evaluations of large wood additions in coastal Oregon and Washington provided strong support for restoration effectiveness. Smolt tracking of two streams in the Alsea and Nestucca watersheds (Oregon) confirmed substantive (3-4-fold) improvements in yields of coho, steelhead and cutthroat smolts (Solazzi et al. 2000). Rehabilitation measures were extensive replacements of instream large wood debris (LWD), integrated or paired with woody off-channel alcoves. An extensive post-restoration evaluation of 30 salmonid streams in coastal Washington and Oregon demonstrated much greater juvenile salmonid abundances in LWD-rehabilitated reaches, especially juvenile coho salmon. Of note, there were significant increases in steelhead and cutthroat trout parr (1.7-fold) compared to spatial control reaches, but it occurred over-winter. Thus, improved over-winter survival was the primary response of trout, rather than summer benefits (Roni and Quinn 2001).

Furthermore, Long-term reach-level monitoring at an alluvial-type rainbow trout river in the southern Interior of BC confirmed a 4-5-fold increase in juvenile and adult trout in response to lateral log jams of the West Kettle River (Slaney et al 2002; Figure 78). Of note, the initial 3-year response was subsequently depressed by about 50 % during a 2003 drought, but much less than the untreated control reach which declined to near zero in 2004 (A. Wilson, BC Ministry of Environment, Penticton; data on file). Thus, LWD structures can provide refuges from drought conditions that are associated with global warming.

In sharp contrast to these examples, a long-term evaluation of steelhead and coho smolt yields from 14 km of large wood restoration at Fish Creek, Oregon, in the 1980s was largely inconclusive. Results were associated with high natural variability, and reliance on a single sub-sampling rotary screw trap at Fish Creek and the larger untreated Clackamus River expanded the variance in annual smolt yield results (Reeves et al. 1997). Steep gradients with a high frequency of natural boulder habitats made LWD benefits difficult to detect at a time of declining adult runs.

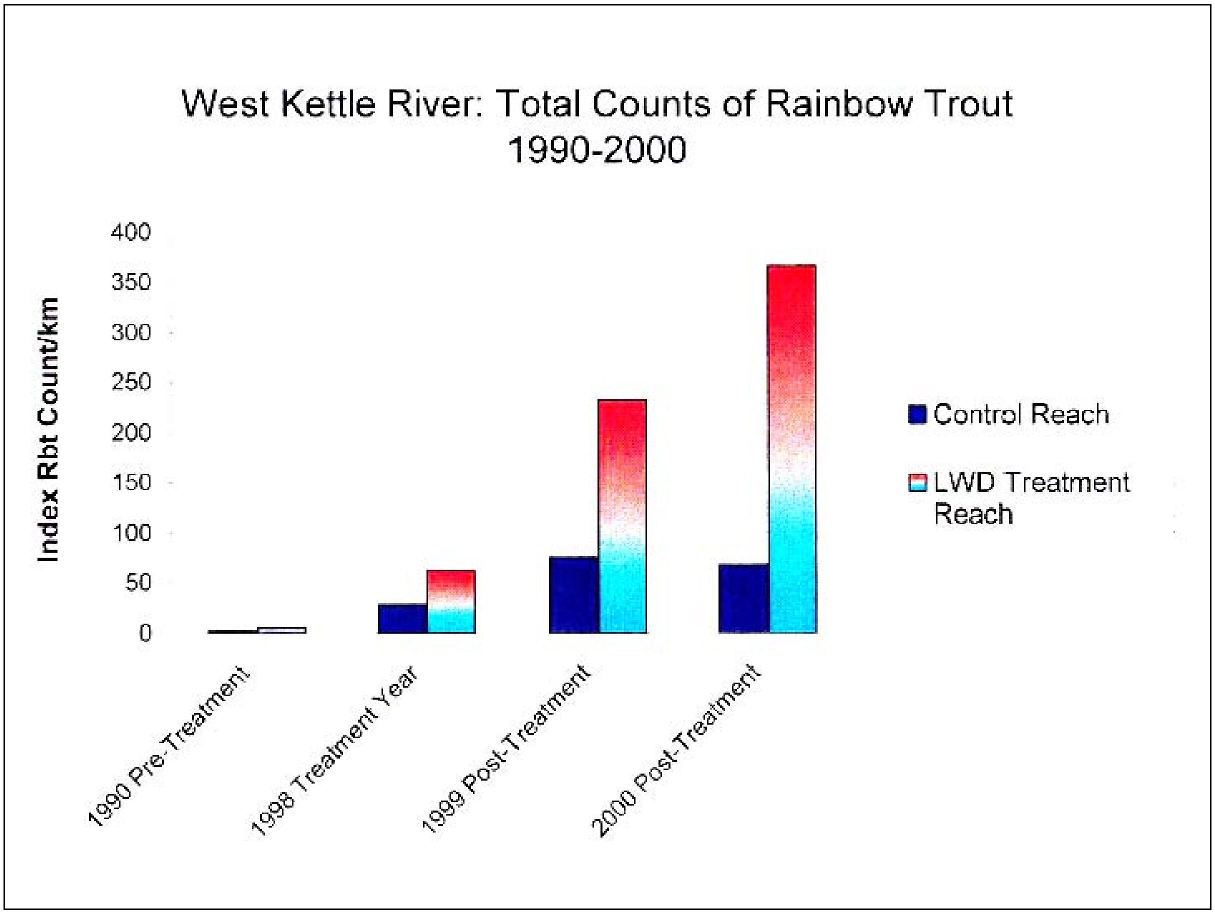

Figure 78: Response of resident rainbow trout in the West Kettle River to creation of lateral log-jam habitats in a 2 km test reach.

There is an instructive lesson provided by the Fish Creek study, which is that salmonid benefits from steeper, more bouldery streams can be expected to much less than alluvial gravel-cobble streams. This is not surprising because high boulder frequencies tend to provide abundant trout and salmon habitats and wood introductions are not as important in these hydraulic settings. Further, steeper gradient streams (> 3%) have less LWD in nature compare to lower gradients dominated by gravel to small boulder substrates (D. Hogan per comm.). Thus, LWD restoration should not be attempted in steeper (>2-3 % gradients) because fish benefits are less, regardless of other benefits.

6.2.4.3 Instream Restoration Methods and Costs

Methods for the restoration of large woody debris are outlined in detail in Slaney et al. (1997), Cederholm et al. (1997), and Ward (1997). In British Columbia, large wood has been restored successfully in many rivers and streams, including the Keogh River, West Kettle River, Seymour River, Englishman River, upper Silverhope Creek and the upper Nechako River. However, fewer attempts have been made in large higher gradient rivers such as the Chilliwack and the Coquihalla because of their high energy. Rather, side- channels and/or eroding mainstem banks have received restoration treatments. Yet, lower gradient rivers including the Lardeau or Salmo Rivers are not considered to be of high risk, and there are many suitable natural templates for securing LWD at featureless streambanks and at eroding bank sites.

Natural templates are LWD-formed primary tools that restoration specialists can use to guide LWD restoration. Triangular rootwad or lateral rootwad structures that are secured to stream banks are preferred as they are documented to generate prime scour pools in gravel to cobble substrates. In some locations where paddler recreation is prevalent, boulder ballasted log J-hook vanes set at 25 degrees facing upstream and at 5-7 % slope down into the channel provide an option that generates small scour pools (Rosgens 2001). These structures are also lower risk to paddlers because an ineptly paddled canoe or inflatable can readily pass over J-hook vane habitat structures. LWD structures are focused on glide or glide-riffle habitat units, with riffles entering the structure area providing suitable velocities and a source of aquatic invertebrates. In contrast, boulder clusters are widely utilized in riffles, provided there is sufficient stability and limited bed load; otherwise they are at risk of in-filling. Boulder ballasting (LWD) and boulder sizing (clusters) guidelines are provided in Slaney et al. (1997) and Newbury and Gaboury (1997).

Costs vary with ease of material access and by how much large wood and boulders are available locally or nearby. A cost of $50,000 per km is an average cost for all types of instream restoration from experience in the Watershed Restoration Program, where road access was readily available and materials did not require heli-transport. Where existing road access is unavailable and heli-transport is required, costs typically increase by $10,000-30,000 per km. However, heli-transport is extremely efficient and greatly reduces excavator time and disturbance of riparian areas, which can offset a portion of the increased cost.

A more accurate cost estimate can be made from past experience with triangulated large wood structures, ranging from $1200 to $3000 per large wood structure in 1998. The lower cost was at the West Kettle River where access was readily available from adjacent roads and stream bars, large wood was donated (aside from transport), and boulders were available at no cost (aside from local transport). The higher cost was where materials were transported long distances to the stream reach by truck and then by helicopter. Using these estimates, cost is estimated to average of $2000-$3000 per LWD structure, depending on how much of the material is heli-transported. Boulder clusters typically cost $20-40 per large (0.6 m) boulder depending on ease of access. Based on early operational experience at the Keogh River, heli-transport of boulders can be less expensive if access trails must be constructed (Ward 1997).

Similar costs are associated with erosion control structures along stream banks including hybrid triangular structures or ramped-debris groynes that collect woody debris, thus moving the river/stream thalweg away from eroding banks (Slaney et al. 1997). Upstream facing rootwads or stumps, ballasted to large boulder-protected streambanks are an integrated technique used where hydraulic forces are high at large streams. Methods vary with stream gradient as described in detail in Babikaiff et al. (1997).

6.2.5 **Riparian Restoration**

Riparian restoration is another aspect of stream restoration that should be considered holistic, even in side-channel development because there is a need to ensure the riparian areas retain their functions. This is of utmost importance where trees are removed and disturbed, which is common in most side-channel development projects and some streambank stabilization projects. In side-channel projects, disturbed access areas need to be rapidly re-vegetated and largely with coniferous trees to discourage beaver activity. Such conifers must be periodically maintained until the free-to-grow stage.

Projects associated with agricultural streams offer the most benefits of riparian restoration as compensation for lotic GPP losses. These projects arrest erosion of banks and re-establish a mixture of deciduous and coniferous riparian vegetation. Livestock exclosure fencing is typically required to achieve lasting benefits. This type of compensation project, combined with streambank stabilization, is likely to be needed along streams associated with the Koocanusa and Pend d’ Oreille reservoir units where agriculture is a significant land use.

Immature and young forests within the riparian areas can also be accelerated in the rate at which they will recruit large wood to the stream channel. In this case, benefits are far in the future, which is a consideration that must be weighed in terms of project benefits. However, in some projects thinned trees can be also be utilized as “complexing materials” for LWD structures or in streambank erosion projects. Procedures for riparian restoration are described in detail in a technical circular produced by BC’s Watershed Restoration Program in the 1990s (Koning 1999). Techniques mostly involve thinning of trees within the riparian zone, resulting in benefits to both fish and wildlife, and costs vary according to technique employed and intensity of application (Koning 1999).

6.3 Wetlands

As for streams and lakes, wetland enhancement is covered by the general DFO guidelines. The preference for maintaining existing habitats is usually not an option for reservoir environments as the habitat loss occurred at the time of reservoir creation. The subsequent choice of “like for like” compensation by replacing natural habitat, at or near the site has been proven to be feasible, within existing reservoirs, at select locations. Wetland restoration/establishment options have been explored in the Revelstoke Reach area since 1990 as part of the dust-control program (AIM and Carr 2000, Carr and AIM 2002a,b, Carr et al. 1993, Moody 2002). Opportunities for re-establishing vegetation in the drawdown zones of various Columbia Basin reservoirs have also been examined as part of the Columbia Basin Water Use Plan (2005), highlights of which are covered below. This has been deemed a feasible option in select reservoir areas, with preliminary sites and estimated costs for treatments identified. Increasing the productivity of existing habitat has also been addressed within the water use plans, as increasing plant production also has the potential to enhance plant survival in the reservoir environment. Off-site wetland creation options are limited due to the mountainous nature of the terrain. The final consideration, purchase of land for habitat protection will only prevent further losses rather than enhancing the carbon contribution to the system.

Re-establishing wetlands in reservoir drawdown zones is not a simple task. There are limited sites that meet the requirements for a suitable substrate, slope, aspect, elevation and hydrologic regime that can sustain a few select plant species that are tolerant of extreme reservoir environments. However, if the objective of compensation is to restore a portion of the wetland productivity that was lost from the Columbia Basin, restoration within the drawdown zone meets that requirement. Furthermore, it has the likelihood of being self-perpetuating and self-sustaining unlike many other compensation options. If, however, the objectives are to provide habitat for waterfowl or other higher trophic levels that live and breed in wetlands, drawdown zone revegetation may not be the best choice given operational constraints.

6.3.1 Water Level Modifications

Hydrologic manipulation is the method of choice for wetland restoration, rehabilitation and recreation. Wetlands are intimately tied to their hydrologic regimes, therefore water level changes (as noted in section 2.2.1) can result in dramatic vegetation changes. Reservoir water level modifications are generally beyond the scope of most projects due to costs or corporate obligations. However, in select cases this may be feasible and cost effective. Currently, the Coursier Lake (dam - decommissioned in 2003) historic wetlands are being allowed to regenerate without external intervention other than for riparian shrub planting (Sayers 2004).

Vegetation communities that are able to survive the operating regime of a reservoir appear to have responded to long-term water level averages during the growing season. A lowering of the long-term median water level should allow the vegetation community to expand, whereas an increase in elevation will likely cause the vegetation to diminish in area and productivity over time. The recent WUP's completed in the Columbia (Kinbasket, Revelstoke, Arrow), Duncan and Whatshan reservoirs have examined operational effects on various environmental issues (Columbia Basin Water Use Plan 2005). Water level management was considered, where feasible, to enhance ecosystem components. Where possible, operational changes were recommended for the enhancement of wetland communities. Where operational changes were not deemed feasible, alternative options, such as habitat islands or water control structures were put forth. The Water Use Plans, together with monitoring recommendations, are pending approval.

6.3.2 Enhancement of Existing Vegetation Growth by Fertilization.

Establishment of native plants in extreme environments is a key issue in reservoirs. Generally, the younger the plant, the more susceptible it is to environmental stress. Although the wetland species typical of floodplain habitats are adapted to normal water level fluctuations, reservoir drawdown zones present unique conditions for plant establishment. Seedlings establishing in drawdown zones become inundated by deep water much earlier than in a normal wetland, where water levels decline over the summer period, allowing seedlings time to grow and develop. Fertilizer can be a valuable supplement for promoting plant establishment by stimulating rapid growth in seedlings, thereby providing much needed nutrient reserves for stressful periods. Existing vegetated sites can be enhanced by fertilizer applications to increase biomass and vigour of the vegetation. This represents the lowest enhancement cost per area with potentially the greatest habitat gains. Fertilization offers an opportunity to enhance existing or developing vegetation communities and to boost chances for survival. Fertilization studies at Revelstoke Reach indicated an average 20% increase in size of plants in one year as a result of year as a result of fertilizer applied to the substrate (Moody 2002). Similar results have been obtained for foliar applications of fertilizer in both Stave and Williston reservoirs. Most plant communities, once well established, will not require additional fertilizer applications.

6.3.3 Vegetation Establishment by Seeding or Planting

It has been postulated that vegetation establishment in reservoirs is limited by the ability of the plants to establish (CARR and AIM 2002a). Vegetation seeding and planting allows the establishment of vegetation in areas where natural establishment is difficult or impossible. This may be the case in creek fans or in other substrates where moisture conditions are too severe for seedlings to establish. Planting of vegetation is a labour-intensive, costly process. However, it has the potential for great success in well-chosen locations when water levels are not drastically changed. Studies at Revelstoke Reach indicated the potential to expand vegetation approximately 2m deeper into the reservoir drawdown zone than natural establishment would allow (Moody 2002, CARR and AIM 2002a, Carr et al. 1993). Site-specific assessments are required for determination of site suitability. The Columbia (Kinbasket and Arrow) and Duncan WUP's have considered vegetation-planting programs as essential components of their plans. The planning of footprint/operational issues needs to be considered in light of multiple interests and the potential for cost sharing.

6.3.4 Reservoir shoreline enhancement

Riparian enhancement has been addressed in the river/stream section. This approach is also feasible in select locations along reservoir shorelines. Due to the limited availability of suitable locations, site-specific information is necessary before embarking on such a program. Identifying candidate sites from aerial photos and then field checking to determine site characteristics (substrates, slope, aspect, hydrology) is an essential pre-requisite to any planting program.

The general approach proposed for riparian vegetation enhancement in reservoirs has been a multi-year revegetation program, with the first year in planning and acquisition of plant material (willow and native wetland plants) followed by implementation of various planting programs (treatments) and a subsequent monitoring program. It must be recognized that the development of a ‘permanent’ riparian/wetland cover in reservoirs is not a single year operation, but one of intervention (planting) over several years that facilitates the long-term vegetation cover.

6.3.5 Wetland restoration - Control Structures (Dykes/Impoundments)

Water control structures are routinely used for waterfowl enhancement and to create stable water levels for rehabilitation of degraded wetlands. These are usually relatively small areas where a previously existing wetland has been degraded through drainage or alteration of water level. Restoration and rehabilitation procedures need to be designed specifically for each site. Engineering requirements and pre-design studies can result in extremely high implementation costs. Site-specific assessments are required for determination of area suitability. Consideration of potential conflicts such as fish passage or stranding issues is important. Consultation with Ducks Unlimited confirmed that all such projects need to be planned on a site by site basis and that costs can be highly variable depending on local conditions. One of the major concerns is the availability of sites that have potential for enhancement. A very rough cost of $1000 per acre (± 50%) has been provided by DU as an indication of the range of possible costs (Brad Arner, Ducks Unlimited e-mail: b_arner@ducks.ca). This does not include costs for the purchase of land.

6.3.6 Wetland creation

The choice of moving “off-site” for creating wetlands has limited opportunity in steep mountainous terrain. Costs for wetland creation can be an order of magnitude greater than wetland restoration and are therefore not undertaken by Ducks Unlimited (B. Arner pers. comm.). Creation of pocket wetlands is much simpler on relatively flat terrain, where expanding an existing pond or stream is a possibility. Headwater streams have steep gradients and present few opportunities for wetland creation. The floodplain wetlands disrupted by the reservoirs existed in their locations due to a unique combination of hydrology, gradient and substrates. Creating wetlands in such conditions would require extensive site preparation (i.e. contouring, damming, changing watercourses etc.) and would require extensive engineering and geotechnical expertise for large-scale projects. Costs are extremely difficult to determine for such projects because there are so many variables involved. Given the steep slopes of the Columbia valley, opportunities for created wetlands outside the floodplain are very limited.

6.3.7 Off site habitat protection/land acquisition

Although not a preferred option in the list of DFO choices, protection of off-site resources may provide opportunities for ensuring continued carbon supply to the river system. The upper Columbia River between Invermere and Golden is an ideal candidate for protection as rapid land development for residential, agricultural, recreational and industrial development is gradually encroaching on floodplain habitat. The example below illustrates sawdust and wood debris being used as landfill in the floodplain (Figure 79).

Figure 79: Example of industrial infringement on floodplain habitats, upper Columbia River (photo A. Moody).

Land purchase prices vary greatly depending on market conditions, proximity to major centers and perceived aesthetics of the parcels. The Columbia valley has recently been experiencing rapid residential and recreational development and it is likely that land prices will continue to escalate as the area develops. Land acquisition costs have been estimated at $900-$7000/hectare (J.Krebs, pers comm.) to which costs for maintenance and management need to be added.

It should be noted that protection of existing resources will not replace lost production in the Columbia Basin, but will help in minimizing further losses. Consideration should be given to developing partnerships with other organizations involved in acquisition or protection of endangered habitats (e.g. Nature Trust, Ducks Unlimited, Habitat Conservation Fund etc.).

6.3.8 Reservoir Vegetation Re-establishment, Treatment Options and Costing Assumptions

As part of the Columbia WUP, five basic treatments have been recommended to expand and enhance shoreline vegetation communities in Kinbasket, Arrow Lakes and Duncan Reservoirs.

- Fall rye seeding to promote surface substrate stabilization, provides organic matter for improvement of soil fertility, and promotes native species colonization via ‘accidental’ incorporation of seed trapped in fall rye stubble. This approach has been highly successful in Upper Arrow Reservoir.
- Direct seeding of lenticulate sedge (*Carex lenticularis*) in conjunction with fall rye drill seeding application. Direct seeding of lenticulate sedge at Upper Arrow and Williston Reservoirs was successful on smaller trials and is viewed as having significant potential for more widespread use. Fall-rye functioned as a nurse-crop, creating a more beneficial microclimate for the emerging native plant material.
- Willow planting using either hardwood cuttings and/or container stock. Willow has been successfully established in Upper Arrow, Upper Campbell and Carpenter Reservoirs in higher elevation areas.
- Wetland planting using container grown native species from locally collected seed. This technique has been successful in promoting native wetland development in numerous BCH reservoirs, but is the most costly option. However, in difficult substrates or in areas of archaeological sensitivity, this may be the only option.

- Aerial foliar fertilization of existing vegetation areas to promote a more vigorous plant community in this nutritionally stressed environment. This approach was successful in Williston and Stave Reservoirs.

The following section summarizes reservoir shoreline treatments proposed for WUP purposes (Columbia Water Use Plan 2005). Further discussion of options is necessary to avoid conflicts between footprint and operational programs. It should be noted that the costs cited here were determined in 2003 and may have changed since then.

6.3.8.1 **Fall Rye Seeding**

- Fall rye seeding (at 100 kg/ha plus 10 kg/ha of a permanent grass mix) recommended for microsite modification (control of wind erosion and enhancement of soil characteristics) is seen as an initial step in a long-term vegetation enhancement program. Due to issues of scale, access and site specific considerations (stumps, substrate etc.), this cost is very difficult to estimate.
- Basic seeding –100 kg/ha fall rye seed plus 10 kg/ha of a permanent grass seed mix (inundation tolerant agronomic species), 100 kg/ha fertilizer with seed drill application – estimated average basic cost of $150/ha.
- Barging or mobilization to sites could increase costs by 100%

6.3.8.2 **Lenticulate Sedge Seeding (with Fall Rye as carrier)**

- Direct lenticulate sedge seeding with fall rye seeding (at 100 kg/ha plus 10 kg/ha of a permanent grass mix) as a carrier for drill seeding application. This is a one-time application to get the sedge seed into the soil substrate where it will stay until suitable conditions occur for germination and growth. This may take several years, but the seed will remain viable for many years. The fall rye application is needed to facilitate the drilling operation.
- Lenticulate sedge seed cost (custom collection as none is available commercially) is projected at $500/ha (10 kg/ha application rate). Revelstoke Reach is a prime seed source for reservoir adapted species.
- Fall rye seeding cost for each year is estimated at $150/ha.

6.3.8.3 **Willow Planting**

- Willow planting can be applied in reservoirs, only in the upper 3-4 meters assuming water levels are appropriate. Native willow needs to be collected each year, for planting the following year. This planting would be a progressive program with:
  Year One - cutting collection and propagation
  Year Two through Four - planting of previous year's material and collection (for next year)
  Year Five - planting only of material from previous year.
- Only 20% of the enhancement area would be affected by the willow planting (but high density planting in that portion, with linear bands spaced 3m apart and cuttings spaced 2m apart in the bands).
- With the estimated average cost of this type of planting at $5000/ha plus 25% for fill planting in second year, the cost is estimated at $7500/ha for planting.
- A reasonable mobilization cost is included in the $5000, and could be higher if areas are very remote.
  - This treatment was recommended for only 20% of the identified treatment site.

6.3.8.4 **Sedges and Wetland Plants**

- For sedges and wetland planting, the type of planting and total percentage of affected areas will determine costs. In small areas, employing high-density plantings on a portion of the total area (the inoculation approach) will result in a smaller cost on a treatment area basis compared to an expansive planting approach.
- The basic cost is $15,000/ha using 1m spacing of custom container stock.
- To achieve an inoculation level of establishment that will provide a material base for expansion throughout the treatment area, only 20% of total treatment site will be planted.

6.3.8.5 **Aerial Fertilization of existing plant communities**

- Enhancement of existing wetlands can be conducted using aerial fertilization (AgAir Enhanced Foliar Fertilizer) Conducted early in the growing season, this approach has been shown to improve performance of reservoir remnant wetlands significantly (over 40% in height and 25% in biomass). Increases in plant size and biomass improve plant survival under stressful conditions and increase nutrient contributions to the adjacent ecosystems.

- The operation is $50/ha per treatment, with a 10 ha minimum per site.
- Fertilizer should be applied for three years to effectively change site production, yielding a treatment cost of $150/ha.

6.4 Effectiveness Monitoring of Compensation Projects

Performance measures of a compensation program are typically based on effectiveness monitoring of the set of compensation projects that comprise the program. The project objectives set the stage for measurement of performance by monitoring how well projects have met such objectives. However, this does not mean that all compensation projects need to be intensively evaluated, which would be costly in any program. Provided there is published evidence that applications of a compensation technique are effective, there is not a compelling a need for intensive effectiveness monitoring on all projects, but rather only a sample subset. Regardless, low intensity or "routine" monitoring, based on visual ratings/scorings, should be conducted on all compensation projects to ensure projects meet design criteria and are functional and durable. In addition, both routine-level and intensive-level effective monitoring should be maintained as adaptive management to guide further compensation/restoration activities. Effectiveness monitoring should focus on the reach and site level because very few compensation projects are likely to be conducted at the watershed or whole-stream level, although they may be conducted at a whole-lake or reservoir-level (e.g., fertilization).

There are design challenges of conducting intensive or validation effectiveness monitoring on compensation projects. Roni (2005) reviewed monitoring results of habitat restoration and improvement projects and concluded that although many studies report increases in salmonids, few of the responses were statistically significant as stand alone treatments. Under-funded or weakly designed attempts to conduct intensive monitoring without adequate design rigor are likely to be inconclusive, or at least equivocal, and greatly risk type-2 errors (i.e., accepting the null hypothesis of no effect when there was an effect), which can be highly misleading. Accordingly, an appropriate study design must govern any subset of projects selected for intensive effectiveness monitoring.

There are three physical scales of effectiveness monitoring, which require decisions at the outset of planning effectiveness monitoring: watershed, reach and site levels (Roni 2005). Whole lakes or individual lake basins equate to reaches. The *watershed or whole-stream or whole- lake level* is typically associated with intensive validation/research-level monitoring and typically includes extensive population estimation or juvenile migrant yields at a watershed level, or multiple trophic level monitoring, especially in lakes. The *reach level* is a relatively homogeneous segment of a stream but requires that its size is large enough to capture treatment variation. The *site level* is the lowest level and it is best used for making inferences about the relative effectiveness of specific replicated types of treatments.

Effectiveness monitoring is of two primary types with associated monitoring objectives:

- *Routine effectiveness evaluation*: using rapid visual estimates to evaluate if the treatment meets basic physical and biological objectives;
- *Intensive effectiveness monitoring* (includes validation or research-level monitoring): using more rigorous measures to evaluate significant physical and/or biological responses or long-term trends.

Operational refinement of techniques can also fall within the intensive level, and answers question whether there are refinements in a technique that would increase effectiveness or cost efficiency. These types of effectiveness monitoring differ from compliance monitoring, which is contract management to assess whether a compensation project was completed as paid for by the compensation program.

6.4.1 Routine Effectiveness Evaluations

Routine effectiveness monitoring/evaluation was well developed in BC's Watershed Restoration Program and provided a mechanism to judge how proponents' projects were performing after major storm events. Monitoring involved rating of all projects using a four point scoring of performance (success to failure) in meeting project physical and biological objectives, structural stability and condition, and maintenance needs (Koning et al. 1997). Late in the Program, 25 % were also independently sub-sampled more intensively and re-rated with the addition of half point ratings within the four-point scoring system. This latter evaluation indicated >90 % durability of instream and off-channel projects after 1 to 5 years since project completion (Wilson et al. 2002).

Guidelines for in-stream and off-channel effectiveness evaluation as routine effectiveness monitoring are available from the BC Ministry of Forest's FIA- Land-Based Investment web site (MOF). The instream and off-channel rating forms in this guide should be used for visual ratings of structures in terms of meeting physical and biological objectives of their placements (Anonymous 2003). Further, identification of maintenance needs is made for each structure site. Generally, the ratings from 1-4 in meeting objectives should be completed at base flows after the spring-melt season, whereby a score of 1 is a failure and a score of 4 is beyond expectations. Half point ratings should be used to improve accuracies of the 4-point rating protocol (Anonymous 2003).

6.4.2 **Intensive Effectiveness Monitoring**

A selected sub-set of compensation projects are more intensively monitored, which may range from as few as 25 % of multiple small compensation projects to 100 % of large compensation projects. The selection of a potential study design is the key step in conducting intensive effectiveness monitoring of a compensation project. These can be summarized as designs that: (1) collect data before and after treatment, or (2) only collect data post-treatment. Both are dependent on adequate replication to statistically test for significant differences. Frequently in compensation/restoration projects, it is not possible to collect before-treatment data, which often requires several years to be adequate for statistical analysis. Thus, post-treatment designs are frequently required where collection of before data is difficult or impossible.

Occasionally, fish responses to treatments can be of a large enough magnitude that effects are obvious and convincing, and a simple before and after design can be effective (e.g., West Kettle River LWD restoration, and upper Salmon River fertilization). However, these cases are not always predictable, and an adequate design needs to be selected.

6.4.3 **Before and after studies**

The simplest before and after design involves the collection of data within a single stream site, a stream reach or even an entire stream/river/watershed. The approach is commonly utilized for monitoring an individual restoration or compensation project. The most frequently used design is the before and after controlled impact (BACI) design, of which a good example is that of Solazzi (2000) where coho, steelhead and cutthroat migrants were monitored for 3-4 years before and 4-5 years after treatment in a control and treatment stream; results are summarized in section 6.2. A less used design is an uncontrolled before and after study, which is less powerful. However, a BACI design with a poorly chosen control can be less powerful than a simple before/after design (Korman and Higgins 1997). In the absence of replication spatially, before/after and BACI studies should be considered case studies, and results applied cautiously to other areas (Roni et al. 2005). Typically, a minimum of four years of before data and four year of after data is required in BACI studies to detect a difference, but replication temporally depends on the natural variability of the parameter being monitoring. A more rigorous BACI design with broader inferences involves replication. For example, at the site level, reservoir/lake shoal fertilization could be conducted at multiple paired sites where one or more trophic levels would be monitored to evaluate effectiveness of the slow-release enrichment.

There are variants on the before/after and controlled before and after designs. These are the pulsed monitoring system and the staircase design proposed by Bryant (1995) and Walters (1988), respectively. In the pulsed system, data is collected intensively for a short period of time, separated by longer periods of low-intensity data collection. In the staircase design, a sequential treatment of study sections or reaches is required over time, with untreated sections or reaches acting as controls until eventually treated.

6.4.4 **Post-treatment design studies**

Frequently it is not possible to collect before-treatment data, and in these cases, a post-treatment design is an alternative, which is retrospective, with replication mainly spatial rather than temporal as in before-after designs. This design applies to where compensation/restoration projects are being implemented too rapidly to acquire pre-treatment data, which is common in programs. In this design, a control or reference section/reach is selected that is thought to be similar to the treated section/reach before it was treated.

Two post-treatment designs have been defined: intensive post-treatment (IPT) in which multiple years of data are collected at one or a few paired treatment and control sites, and extensive post treatment (EPT) in which many paired control and treatment sites are monitored over a 1-3 year period. The EPT has been found to be effective at the reach level for examining differences in juvenile abundances (Roni and Quinn 2001; see tabled results in section 6.2). As emphasized by Roni et al. (2005) an advantage of the EPT design is that it facilitates regression analysis of factors that may be affecting treatment effects, which can be used to modify techniques. The obvious weaknesses in these designs are the lack of pre-project data and the assumption that the control is equivalent to the pre-treatment condition. The latter can be minimized by a careful selection process. In a published EPT study on stream-rearing salmonids, a sample size of 30 paired sites was required to detect differences after instream LWD restoration (Roni and Quinn 2001). A requirement of relatively large paired sample sizes is to be expected in streams because of variable hydraulic conditions.

Techniques refinement can also be evaluated using a post-treatment design to compare the effectiveness of differing treatments. Comparisons of several well-replicated sites of one treatment can be made to several well-replicated sites of an alternate treatment. If possible, the study should include sites within different reaches. Two examples are the comparisons of two treatments where fish abundance is enumerated by underwater counts, and the comparison of two nutrient treatments where mean fish size-at-age is monitored at the end of the growth season by electrofishing.

Some compensation techniques are difficult to evaluate because controls are unavailable, but they can still be evaluated using post-treatment monitoring. Side-channel developments are of this type, and these are typically evaluated by monitoring numbers of adult spawners and juvenile out-migrants. These counts per unit of channel are compared to established benchmark data from naturally producing channels in the ecoregion, or alternately to monitored channels considered successful for which “biostandards” have been developed (Koning and Keeley 1997).

6.4.5 Effectiveness Monitoring by Project Type and Costs

Roni (2005) provides detailed guidance in several chapters on monitoring projects. Some examples are floodplains/bars, riparian areas, stream enhancement and stream enrichment including use of fish carcasses. Monitoring includes both controlled before and after studies and controlled post-treatment studies targeting habitat characteristics, fish abundance, fish growth and macro-invertebrates. These chapters should be reviewed in advance of establishing intensive effectiveness monitoring on a subset of compensation projects within the Columbia Basin BCHydro reservoir units. Several representative compensation projects and monitoring projects, including respective costs, are provided for three of the BCH reservoir units as examples (Appendix 4 tables 1-3).

7.0 SUMMARY

Our principal conclusions from this study are summarized below.

7.1 Lakes/Reservoirs

- Annual total lake C production, including littoral, was higher than river and stream tC production but much less than wetland production.
- C production per km^2 was higher in historic lakes than in post-dam reservoirs largely owing to the integrity of bio-diverse and therefore greater C production of the littoral and macrophyte habitats.
- Littoral C production is very low < 1-3 % of pelagic C production in post-dam reservoirs due to large water level fluctuations (drawdown) that destroy communities by desiccation with resultant low periphyton biomass and diversity.
- The C production of phytoplankton in historic lakes was light-limited through much of the growing season by turbidity from Columbia and Duncan rivers and by several large tributary inflows through peak periods of the growing season.
- Though turbidity levels are less extensive now and euphotic depths have increased in post-dam reservoirs, oligotrophication has occurred as the reservoirs and Kootenay Lake have aged and present low concentrations of available nutrients indicate that in most reservoirs/lakes, P-limitation of phytoplankton or co-limitation by both N and P now set the limits on annual tC production, not light as in historic lakes.
- Dam construction created about a 3-fold increase in pelagic habitat compared to historic lakes with Arrow Lakes, Revelstoke and Kinbasket reservoirs comprising > 85 % of the total, and Duncan, Koocanusa and Whatshan contributing most of the remainder. Kootenay Lake was largely unaffected by impoundment and lake elevational changes are now only moderate at freshet periods owing to Duncan and Libby dams.
- Despite a 3 fold increase in pelagic habitat present pelagic C production is only 2- fold higher than historic C production , (and when tC production is normalized to a km^2 basis it is clear that it is now lower than in historic natural lakes).

7.2 Rivers and Streams

- River and stream losses in habitat areas from footprint impacts were exceptionally large, or 12,000 hectares. They are dominated by Donald Mica and Mica Revelstoke, followed equally by Wardner-USA and Arrowhead-Keenleyside.
- Rivers and large streams (97 %) by far dominated habitat losses versus streams (3 %), because only small lengths of streams were flooded owing to their greater gradients.
- Extent of losses of wetted side-channel areas remain an uncertainty related to difficult detection from 1-50,000 scale floodline-maps, and detailed air-photo interpretation with some ground truthing is needed. Undetected side-channel losses are likely significant (area +10-20 %), with substantially elevated primary and heterotrophic production.
- A methodology was developed to estimate pre-dam lotic gross primary production (GPP) in the various reservoir units, but there remains considerable uncertainty associated with light attenuation under riverine glacial conditions. River-stream losses of GPP were largely proportional to habitat area losses, although glacial condition upstream of Kinbasket Lake and upper Duncan River reduced their weighting to a moderate degree. Estimated lotic GPP losses totaled 5500 t C y^{-1}. There remains some uncertainty in estimated lotic GPP, which is associated with light attenuation resulting from variable seasonal glacial conditions within the pre-dam Columbia River upstream of Arrowhead. Some field sampling could be used to refine GPP estimates to account more accurately for a broad range of lotic glacial conditions within Columbia Basin.
- As a scoping exercise, estimated lotic salmonid losses were approximated from a biomass-alkalinity relation, adjusted for estimated weighted useable area; standing crop or biomass losses was estimated to range from

56,000 to 112,000 kg as a first approximation, requiring further refinement by population assessments designed to construct a region-based habitat-biomass model.

- Lotic productivity losses within Columbia Basin have received only limited compensation effort to date, and fragmentation of lotic and lentic habitats by dams as barriers is a compensation challenge, which is dealt with elsewhere.

7.3 Wetlands

- According to the WREC classification scheme, the total wetland area lost to reservoirs was 15,973 ha. This was comprised of 10,621 ha in the wetland group, 5,325 ha in the Flood Group and 28 ha in the Transitional Group. The overwhelming majority of these habitats, 61% occurred in the Donald-Mica Dam Unit. No wetlands or floodplain habitats were identified for Dam units C2, K2 or K3, and only minimal areas occurred in C8, C10 and K9.

- From a functional perspective, all floodplain habitats (areas additional to those classified within the WREC classification) were included in the production assessments. This resulted in the inclusion of an additional 23,340 ha of floodplain habitats being considered part of the hydroriparian complex. Shallow water was tallied separately from other floodplain habitats

- Present-day vegetation mapping data from the Water Use Planning process was available for Kinbasket, Arrow Lakes and Duncan reservoirs for comparisons of pre-dam and present day wetland areas. The only unknown present day vegetated area is Koocanusa Reservoir.

- Only 13% of the historic wetland/floodplain habitats remain within the Columbia basin footprint area. The most significant losses occurred in the Donald-Mica reach where 18,971 ha (89%) of these habitats were lost. The Duncan reach lost 93% of its historic wetland and floodplain habitat (3,009 ha). Revelstoke-Arrowhead Reach, has a re-created wetland area, approximating 54% of its historic floodplain area. This recent vegetation development, is in large part due to the annual fall rye seeding of the dust control program, which has facilitated the expansion of a perennial vegetation cover in the drawdown zone.

- Historic GPP carbon production from floodplain habitats is estimated at 75,315 metric tons yr^{-1} , contrasted with the present day estimate of 10,322 metric tons yr^{-1}. This was dominated by the Donald-Mica reservoir unit with 58% of the total followed by Arrow at 16%, Revelstoke (9%), Duncan (9%), and Koocanusa (8%).

- The total carbon export of the post dam reservoir wetlands is estimated at less than 14% of the pre-dam export. Over 48% of the present-day production comes from Revelstoke Reach. Kinbasket reservoir shorelines contain a larger total area of vegetated habitats than Revelstoke Reach but are relatively impoverished.

7.4 Synthesis

- The production of carbon among major aquatic habitats of the upper Columbia basin has changed since the construction of hydroelectric dams and reservoir impoundments. Both lake and river/stream C production pre-dam was seriously affected by glacial and particulate turbidity that resulted in shallow euphotic zones and light-limited photosynthesis through much of the peak growth period.
- Present (post-dam) autotrophic C production is dominated by reservoir pelagic C production and by some limited wetland production. River/stream production within the ‘footprint’ post–dam has been reduced to a very minor component of the total C template of the upper Columbia basin.
- Total amounts of heterotrophic C production are less than half of autotrophic C production in both pre- and post-dam eras, and wetland habitats support the highest levels of heterotrophic C production with moderate levels in river and littoral periphyton communities and lowest amounts in lake pelagic.
- Because of the significant loss of wetland habitat post-dam and the present supremacy of reservoir pelagic habitat with the lowest heterotrophic C component, there is now less heterotrophic C production in the present

basin than in the historic pre-dam era across all 3 habitat types. The most ‘areal’ C productive habitat area within the basin was and remains today the wetlands. They have changed from a C retention habitat to largely an export C habitat today.

- The historic total C production (auto + heterotrophic) of the basin pre-dams was clearly driven by wetland production that in the post-dam setting has been replaced largely by reservoir pelagic C production.
- We surmise that much of the highly productive wetland C was annually transported by river and stream flow and a portion deposited in river and lake habitats where reduced flow and increased water residence times permitted sedimentation.
- The Columbia River has been changed from a C export system to a less productive lacustrine C production system where both autochthonous and allochthonous organic and inorganic particulate C now sediments within reservoirs initially at higher rates than in the pre-dam period.
- The higher C sedimentation rate in some reservoirs has led to stronger pelagic/benthic coupling in the present reservoirs than we surmise occurred in pre-dam historic lakes.
- Littoral margins of the shorelines of large Columbia River reservoirs are largely dysfunctional due to large water level fluctuations (drawdown) and what communities do exist are marginal and ineffective producers of carbon.
- Both river/stream C production pre-dam was seriously affected by turbidity that resulted in shallow euphotic zones and light limited photosynthesis.
- Autotrophic C production presently is dominated by lake pelagic production and by wetland production with river production at negligible levels. Autotrophic C production pre-dam was dominated by wetland production and natural lake pelagic and littoral production was 4-fold lower and only slightly higher than rivers
- Heterotrophic C production makes up less than half of autotrophic C and is highest in wetland habitats and lowest in lakes and rivers. There is less heterotrophic C production in the present basin than in the past pre-dam era in all habitat types. The total C (auto + heterotrophic) of the basin pre-dams was clearly wetlands dominated and presently is co-dominated by lakes and wetlands. Rivers have been reduced to a minor component of the total C template of the upper Columbia basin.
- The C production and strong export patterns of the Columbia River ‘spiraling’ have been changed to what today is largely a pelagic C production system where both organic and inorganic particulate sediments are accumulating at higher rates than in the pre-dam period.
- Stronger pelagic/benthic coupling now occurs in the present reservoirs than in pre-dam lakes. Littoral margins of the multi-reservoir dominated Columbia basin are largely dysfunctional and marginal and ineffective producers of carbon.

8.0 CONCLUSIONS

The production of carbon among major aquatic habitats of the upper Columbia basin has changed, over the past several decades, since construction of the large Columbia Basin hydroelectric dams and reservoir impoundments. The strong seasonal flow of the ‘natural’ Columbia River transported large quantities of allochthonous C from large areas of very productive wetlands, floodplains, tributary streams and forested terrestrial riparian habitats within the Columbia’s immense drainage basin. Columbia River’s turbid ‘freshet’ flow, comprised largely of glacial silt and allochthonous particulate inorganic and organic C loads, was an important seasonal event, scouring river and lakeshore habitats wetlands and picking up woody debris and other large particulate debris in transit through the basin. With only a few lakes in the headwater’s region and neither Bush or Kinbasket lakes large enough to provide sufficient residence time for settlement of much of its inherent turbidity, the large, deep Arrow lakes became the major depositional basins for not only Columbia River’s input of silt, clay and particulate C, but also sediment coming from several glacially turbid tributary inflows (Powertech 1992, Pieters et al. 1998). During the freshet period, water residence time in Arrow lakes was short (weeks, months), and with more turbidity gathered from several glacially turbid tributary inflow as the water transited the lakes, the emergent Columbia River below Lower Arrow was still characterized as moderately turbid river during the peak summer months.

In stark contrast, today the Columbia River upon emergence from the Keenleyside dam, flows with low turbidity as a moderately clear river, having left behind a major portion of its particulate load within each of the 3 major reservoirs (Kinbasket, Revelstoke, Arrow Lakes reservoirs). In the post-dam period, these have become the depositional basins for much of the inorganic and organic C load that had heretofore been transported out of the basin. The ‘new’ lacustrine pelagic habitat, created for water storage and hydroelectric generation, now dominants the landscape of the upper Columbia basin. However, it is the least productive aquatic habitat in terms of tC km $^{-2}$, replacing far more productive historic wetlands and river and stream habitats.

The total annual carbon production (GPP) from the hydroriparian environments (lakes, rivers, floodplain/wetlands) of the historic Columbia Basin was calculated as 180,445 tC yr $^{-1}$. In contrast, the current carbon production from the reservoir environments has been assessed at 53,506 tC yr $^{-1}$, or approximately 30% of historic .

Compensation for production losses should follow the Canadian Habitat Policy of “no-net loss”. Priority is for compensatory approaches that are “like for like” by replacing natural habitat at or near the site of loss. However, if “like for like” compensation is not possible, then secondly it may be possible to move “off-site” with replacement habitat, or by increasing the productivity of existing habitat, utilizing several proven and a few experimental compensation options. Lentic techniques include reservoir/lake nutrient supplementation, embayment fertilization, and littoral (shoal) fertilization. Lotic techniques include stream/river productivity augmentation, fish access improvements, off-channel habitat development, instream habitat rehabilitation and riparian restoration. Wetland techniques include water level modifications, water control structures, vegetative establishment by seeding/planting, enhancement of existing vegetation by fertilization and reservoir shoreline enhancement. Ecosystem strategies, which apply a diversity of compensation options are likely to maximize biodiversity and be most effective, whilst also generating substantial resource user benefits.

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10.0 APPENDICES

10.1 Appendix 1– Definition of Footprint Impacts

These definitions of operational and footprint impacts associated with BC Hydro's hydroelectrical facilities in B.C. have been proposed to provide clarification to the Fisheries Technical Committees as well as committees involved in Water-Use Planning (WUP) and the BC Hydro Fish & Wildlife Bridge Coastal Restoration Program.

Footprint Impacts:

These impacts would occur primarily as a result of inactive storage and construction of dam structures, and are largely irreversible. Some impacts are re-occurring but the causative agent is usually a one-time action or event. Any footprint impacts should be considered when reservoir is at full pool.

1. Construction impacts (e.g. sediment, water quality) temporary events associated with building and construction.
2. Habitat loss from facilities or structures (e.g. habitat inundation by reservoir): includes loss of riparian area for LWD recruitment and permanent lotic - lentic habitat change and impact.
3. Permanent loss of upland and riparian terrestrial habitats within the full pool footprint and their associated impacts on biodiversity.
4. Fragmentation and loss of habitat connectivity at landscape scale.
5. Changes in the amount and spatial extent of aquatic-terrestrial species interactions due to loss of seasonal habitats, shifts in primary productivity or habitat fragmentation.
6. Nutrient or contaminant effects (e.g. trapping, downstream release, methylation) related to flows released from the reservoir.
7. Water quality in reservoir (e.g. temperature, TGP, DO) related to water quality within the water column of the reservoir.
8. Erosion, sediment transport, erosion and morphological change due to reservoir could include effects of interception of bed load and increased earth slides and instabilities caused by reservoir drawdowns.
9. Impacts to fish movement and migration often due to structures like dams or barriers exposed during reservoir drawdown.
10. Fish entrainment and loss of fish includes loss of fish from reservoir populations with the inability to return to natal areas resulting in a loss of fishing potential or damage to the population numbers, dynamics, etc.
11. Ice regime impacts due to reservoir and effects on tributary systems and ice effects within the reservoir or due to the thermal action of the stored water.
12. Local hydrological effects increased snow or precipitation due to thermal effects of reservoir, evaporative water losses, long-term groundwater effects, greenhouse gas release, cumulative effects from other uses (i.e. increased water withdrawal due to proximity to reservoir).

Operational Impacts:

Operation impacts tend to occur over restricted temporal and spatial, and typically represent the seasonal or operational variation in reservoir elevation and downstream flows within a matter of hours, days, within season or recurring over a multi-year period.

1. Habitat impacts due to hydrological/hydraulic changes: impact on habitats due to fluctuations in flows, velocities or water levels in riverine habitats related to biological suitability, food production, etc.
2. Littoral zone/ shoreline or riparian habitat and vegetation impacts: impact on habitats due to water levels or hydroperiod
3. Erosion, sediment transport and morphological habitat effects related to flow: includes erosion scour-deposition, sediment quality and geomorphological habitat changes caused by diversions or re-regulation of flows from facilities
4. Entrainment and destruction of fish: includes entrainment and destruction of fish in turbines, stranding due to flow fluctuations
5. Water quality in discharge operations (e.g. temperature, TGP, DO): water quality related to the timing, location and nature of release from reservoirs or operations
6. Impacts to fish movement and migration: includes blockage and delays in upstream and downstream migrations of fish due to operations, flows and water quality impacts
7. Seasonal lentic/lotic habitat change and impact: seasonal, within-year changes in habitat due to operational changes and conditions (i.e. drawdown zones, exposed creek fans)
8. Ice regime impacts: ice effects due to operational changes such as flows and temperature
9. Local hydrological effects: includes seasonal groundwater effects, flooding and seasonal inundation

10.2 Appendix 2. A check list to achieve effective development of side-channel compensation projects within Columbia Basin BCH reservoir units.

- Confirm targeted species and life stages. Where possible, kokanee should be a target life stage to enhance side-channel productivity and provide a carbon source for rearing salmons in the form of eggs, colonizing insects and flesh. Confirm local populations (as at the Lardeau River) make use of such side channels.

- Select a site with a high water quality source (preferably pond- or lake-headed) that is low in suspended and bed load sediments and relatively high in water temperature. Primary and heterotrophic production is strongly a function of water temperature; GPP alone is 2.5 fold higher at 15 C than 5 C (Morin et al. 1999). The nature of the water source must guide site identification, rather than visa versa.

- To avoid excessive sedimentation, a successful intake must be located at the outside of a stream bend, and relatively stable sections of a stream such as a lake outlet are the most favourable maintenance-free locations. Alternative diversion through a very large pond site can provide the equivalent while providing minor warming of the source flow. Aerial photo analyses, followed by helicopter-assisted inspections, are common practices to pre-identify suitable channel tracks and intake sites. Most promising sites are then viewed on the ground to confirm their suitability for side-channel development.

- It is important to minimize intrusion of the floodplain which was an early criticism of side-channel developments in the Lower Mainland. A naturally functioning floodplain is necessary to accommodate extreme flood events in natural systems. Exposure to flood risk is a design aspect, and it is best to design the side channel so that it may overtop in an extreme flood event (a 1 in 30 recurrence interval) as a "safe-fail" philosophy. A common practice is to use the granular material that is excavated from the side-channel track, as a low berm for flood protection. An existing adjoining road or railway bed may operate as an existing dyke providing additional flood protection, which is a common coastal practice.

- A site elevation survey is required to ensure that a suitable elevation profile is available for drawings of the plan and cross-sectional view of the proposed side-channel project. This is necessary for assuring an adequate channel gradient and bank heights to accommodate the flushing flow. It is also necessary for obtain regulatory approvals including site construction and the right to divert water, which requires a provincial water license.

- The intake is the *heart* of the project and must be designed to accommodate large floods without in-filling with bedload. Details of suitable intake designs are provided by Lister and Finnigan (1997). One of the more maintenance-free designs is a double-cedar log intake set parallel to the mainstem flow. A boulder apron in the mainstem is often used to ensure a constant proportional diversion under varying flow stages. Where there is sufficient bed load movement that it could reduce the viability of the side-channel by infilling spawning and rearing habitats, a large excavated or flooded settling pond may be necessary, which would usually require maintenance (i.e., excavator removal of deposited sediments at 5-10 year intervals). An alternate design that has had a high level of success is the manifold-type intake (Figure 7-13 and Table 7-1 in Lister and Finnigan 1997) which is elevated 30 cm above the bed to eliminate bedload inputs, although it does not exclude suspended sediment inflows.

- The channel design is key to providing prime spawning and rearing habitat and must be adequate to withstand flushing flows. Frequent meanders will enhance pool formation at outside bends, as in natural channels, which is where pools are excavated and large woody debris with rootwads is secured for scour and cover. Boulder clusters are concentrated in the riffles and pool entrances and gravels at pool tail-outs. Adequate gradient is important for trout rearing, with 1 % as a good target (range 0.5 to 2 %). A riffle:pool ratio of 1:1 is commonly selected with short riffles and pools much more conducive to both spawning and rearing then long extended riffles and pools. This is because the upper part of a pool supports much higher densities of rearing salmonids and the prime spawning area is concentrated at pools tail-outs. "Bovee curves" of species and life-stage velocities and depths, are used to ensure preferred velocities and depths, which can be achieved by manipulations of slopes, boulders and LWD materials. Lining of the channel margin with coarse rock and boulder weighted logs/rootwads increases salmonid carrying-capacity, as does vegetative plantings that overhang water surfaces. To accommodate flushing flows, securing of LWD is typically required, and attachments/weights include: deadheads, boulders, epoxi-cabling, tree bases, duck-bill anchors, and wedging of materials (Slaney et al. 1997). Maintaining a small tote trail for excavator access is advised, as well as a road access to the intake and settling pond.

- Beaver management is a requirement by use of a “beaver control box” at the outlet of the settling pond at the entrance of the side-channel (Finnigan and Marshall 1997). Planting of access areas with conifers is crucial to discourage beavers; otherwise deciduous tress will overtake the access tote trail and berm, and will attract beavers. Beaver-proof fencing is a frequent requirement at the intake and the settling pond as well as any other areas that become attractive for damning activities. Low gradient side channel sites with extended pool sections should be avoided because they are more attractive to beavers and are not suitable spawning rearing habitats for the native salmonid species complex that inhabits the Kootenay ecoregion.

- Unless side-channels are well used by kokanee, slow release fertilizer should incorporated because infertile waters are ubiquitous in Columbia Basin, and this measure directly compensates for lotic losses of GPP within BCH reservoir units.

10.3 Appendix 3: Example of Vegetation Enhancement Overview Prepared for Columbia Water Use Plan

AREA	*Site*	*Loc.*	*Vegetated (ha)*	*Potential (ha)*	*Description*	*FERTILIZE*	*ENHANCE LOW ELEV. PLANT VIGOUR*	*SHRUB & WETLAND PLANTING*	*TOTAL*	*Potential for Enhance -ment*	*Field observations*	*Special Concerns*
RR	M		154.5	99	Natural colonization could be accelerated by fertilization & seeding, on M1, M2	$23,175	$47,025	$34,763	$104,963	H	Part of potential vegetation area has become vegetated	Part of potential vegetation area has become vegetated
RR	N		3.8	130.3	Low elev. could be accelerated by fertilization & seeding	$570		$855	$1,425	H	Much of the potential area is sparsely vegetated	low elevation in most areas (430-432m)
RR	S		38.5	22.2	partially/sparsely vegetated, could be accelerated by fertilization & seeding	$5,775	$10,545	$8,663	$24,983	H	much of the potential area is vegetated	public sensitivity; resort
UA	1	A	29.8		very sparsely vegetated area, delta mouth	$4,470		$6,705	$11,175	H	well vegetated	
UA	1	B	46.9		well vegetated delta area, potential for fertilizer enhancement	$7,035		$10,553	$17,588	H	well vegetated	
UA	1	D	9.5		well vegetated delta area, potential for fertilizer enhancement	$1,425		$2,138	$3,563	H	well vegetated	
UA	1	F		15.6	unvegetated, post-impoundment deposits in old river channel, may be high energy, sediments need to be examined		$7,410		$7,410	H	part of potential vegetation area has become vegetated	
UA	8	F		101.2	current swept beach, may have incipient vegetation, combination seeding, selective planting		$48,070		$48,070	H	hard substrates, lots of annuals, patchy sedge and RCG - excellent potential	public sensitivity
LA	10	G		80.5	lower slope below F, some veg. patches, substrate may be relatively coarse, low elevation?		$38,238		$38,238	H	establishing vegetation, has great potential for expansion	public sensitivity
						$42,450	***$171,998***	***$63,675***	***$278,123***	***H Total***		

10.4 Appendix 4. Table 1. Compensation option and monitoring examples for Donald-Mica Dam Unit.

Rationale: Owing to a dominance of glacial conditions outside of Canoe Arm, on-site projects are focused on Canoe Arm as like (lotic and floodplain) and unlike (lentic) compensation. To achieve significant like-for-like compensation of river habitat/production, large streams are targeted elsewhere in Columbia Basin, expanded as like-for-like off-site compensation as benefits are confirmed by effectiveness monitoring. Floodplain compensation options are presented as enhancements of existing but impoverished relict wetlands and as planting options for degraded drawdown zones where vegetation distribution is limited by challenges of establishment.

Dam Unit Location	Impact or Loss	Compensation Example	Compensation Cost	Performance Monitoring	Compensation Gains
Donald-Mica Canoe Arm	1680 t C y^{-1} at 4900 ha lotic losses	30 barrier removals in Canoe Arm tributaries and extensive side-channels: -like for like (lotic) -on-site	$600,000 ($20k/proj.) 3 barriers per year	Fish species Use by snorkeling and electrofishing: extensive post-project (EPM) $5000/project	150 ha
Donald-Mica Canoe Arm	as above	Annual slow-release stream fertilization of 10 Canoe Arm tributaries 50 ha treated/yr -like for like -on- site	$50,000/yr at 0.5 t per 5 km per stream at $3500/t; helicopter application	EPM salmonid growth as mean size at age; subset of 5 of 10 control & treated at $2000/pe r stream	50 ha 50 t C y^{-1} (at 1 t C $y^{-1}ha^{-1}$)
Donald-Mica Valemount	as above	Habitat Complexing 100 km of tributaries and side-channel developments -like for like -on-site	$130,000 per year at 2 km/year	25 % EPM and IPM combined; night-snorkel salmonid counts at 5 cm sizes $2000 project	100 ha
Donald-Mica off-site	as above	Annual slow-release Fertilization of the Salmo River via six tribs: $62,000/yr incl. shipping and placement of pellets; 350 ha treated/yr -like for like -offsite	$62,000/year plus monitoring costs	EPM salmonid growth as mean size at age; six trib. and 12 mainstem sites $20,000/year for 3 years	350 ha 350 t C y^{-1} (at 1.5 t C y^{-1} ha^{-1})

Dam Unit Location	Impact or Loss	Compensation Example	Compensation Cost	Performance Monitoring	Compensation Gains
Donald-Mica off-site	as above	Habitat Complexing 50 km Salmo River 10 km of tributaries and side-channel developments -like for like, off-site	$120,000/yr at 2km/yr	25 % EPM and IPM combined; day-snorkel salmonid counts $2000/km/year 3 years/project	200 ha
Donald-Mica Canoe Arm Onsite	as above	Canoe River and Arm fertilization as equivalent to a river/embayment-strategy. - like and unlike -on-site (Note: an annual migrant whitefish fishery exists at L.Canoe R.)	$125,000/yr monitoring cost included	BACI –paired Canoe River nutrient input: - River: as above - Reservoir: N. reach versus S. reach control: $25,000/yr (20 % of total project cost)	10 ha of river 1000 ha of reservoir: 10 km 10 t C y^{-1} as like GPP river gain & 165 t c y^{-1} as unlike reservoir GPP gain (experimental)
Donald-Mica Canoe Arm Onsite	19,991 t C y^{-1} loss of Floodplain production in **Donald-Mica**; productivity of this site has probably decreased by approx 50% from pre-dam	Fertilize relict wetland to enhance survival & production like for like, enhancement -on- site	Approx. $25,000 ($50/ha) for each year of fertilization, plus monitoring costs	Baseline biomass monitoring, post treatment biomass harvest to test vegetation response $15,000 (2 dates & lab fees)	454ha, 20% increase in GPP, estimated annual increase in yield - 213 tC for area, gains will decrease once fertilization is stopped
Donald-Mica Canoe Arm Onsite	19,991 t C y^{-1} loss of Floodplain production in **Donald-Mica**; Unvegetated upper drawdown zone	drill-seed with lenticulate sedge, fertilize; like for like, on-site	Approx. $17,500, ($700/ha) plus monitoring costs	Baseline vegetation density and biomass monitoring, post treatment assessment to test vegetation response $10,000 (2 dates & lab fees)	25 ha- estimated annual yield =100tC for area once vegetation is established
Donald-Mica Canoe Arm Onsite	19,991 t C y^{-1} loss of Floodplain production in **Donald-Mica**; Unvegetated upper drawdown zone	steep slope but located between vegetated sites- container shrub/ wetland planting, like for like, on-site	Approx. $150,000, ($15,000/ha) plus monitoring costs	Baseline vegetation density and biomass monitoring, post treatment assessment to test vegetation response $10,000 (2 dates & lab fees)	10 ha - estimated annual yield = 47 tC for area once vegetation is established

10.5 Appendix 4. Table 2. Compensation and monitoring option examples for Mica-Revelstoke Dam Unit.

Rationale: In Mica-Revelstoke unit, there are several tributary streams of varying sizes and fish use to target replacement of river productivity losses. To achieve adequate like-for-like compensation of river habitat/production, large streams are targeted elsewhere in Columbia Basin, expanded as like-for-like off-site compensation as benefits are confirmed by effectiveness monitoring. The embayment fertilization has potentially wide reaching implications; macrophytes are known to currently occupy embayments within the reservoir. Fertilization may increase macrophyte production, area and density. Due to reservoir operations, establishment of floodplain/wetland vegetation is extremely limited on site. Further recommendations can only be made with the aid of current aerial photo interpretation and site inspections to determine the feasibility of creating impoundments for wetland enhancement.

Dam Unit Location	Impact or Loss	Compensation Example	Compensation Cost	Performance Monitoring	Compensation Gains
Mica-Revelstoke On-site	1580 tCy^{-1} at 2700 ha	Scotland pipe-type 2-way fish elevators on each side of 175 m Revelstoke Dam as on-site compensation	$100,000 bioengineering feasibility study	Fish species Use: intensive post-project fish IPM; electronic and video $50,000/year	Eliminate habitat fragmentation: Re-open spawning/rearing habitats:potential lotic gain of 500 ha re-connected
Mica-Revelstoke On-site	as above	Annual slow-release stream fertilization targeting 10 large tributaries; 200 ha treated/yr - on-site - like for like	$150,000/yr at 2 t per 15 km per stream at $3500/t (50% cost = fertilizer)	EPM salmonid growth as mean size at age; subset of 5 of 10 control & treated $2000/pe r stream	200 ha 200 t C y^{-1} at 1.5 t C $y^{-1}ha^{-1}$
Mica-Revelstoke On-site	as above	Habitat Complexing 100 km of tributaries and side channel devlopments - on-site - like for like	$180,000/yr at 3 km per year	25 % EPM and IPM combined; night-snorkel salmonid counts at 5 cm sizes $2000 project	200 ha
Mica-Revelstoke Off-site	as above	Annual low-level slow-release fertilization of the Moyie and Goat Rivers: 30 km or 100 ha treated/yr - off-site: like-like	$150,000/yr at 2 t/15 km per stream $3500/t (50% cost = fertilizer)	EPM salmonid growth as mean size at age; at tributary and mainstem sites $20,000/year for 3 years	100 ha 150 t c y^{-1} at 1.5 t C $y^{-1}ha^{-1}$
Mica-Revelstoke off-site	as above	Habitat Complexing 100 km Slocan River 20 km of tributaries and side-channel developments - off-site: unlike-like	$120,000/yr at 2 km/yr	25 % EPM and IPM combined; day-snorkel salmonid counts $2000/km/year 3 years/project	400 ha

Dam Unit Location	Impact or Loss	Compensation Example	Compensation Cost	Performance Monitoring	Compensation Gains
Mica-Revelstoke On-site at Revelstoke Reservoir	as above	Revelstoke Reservoir Embayment Fertilization -on-site: like for like	\$200,000/yr two-stream-embayment sets vs. one control set	Replicated BACI design to monitor fish size at age and standardized angler CPUE; 10 yr at \$50k/yr	500 ha GPP gain uncertain (experimental)
Mica-Revelstoke On-site at Revelstoke Reservoir	3,412 t C y^{-1} loss of Floodplain production in **Mica-Revelstoke**	Revelstoke Reservoir Embayment Fertilization On-site: like for like	As above- vegetation benefits are likely to accrue from embayment fertilization, incremental costs for monitoring only.	Macrophyte baseline and biomass monitoring 10 yr at \$25k/yr	GPP gain uncertain (experimental)
Mica-Revelstoke Adjacent to Revelstoke Reservoir	3,412 t C y^{-1} loss of Floodplain production in **Mica-Revelstoke**	Revelstoke Reservoir – Creation of impoundments at appropriate inflow streams. On-site: unlike.	Depends on site characteristics, engineering costs, earth moving, planting, access etc.	Monitoring of wetland development success, plant size, survival, infilling, water retention etc. Costs uncertain.	GPP gain uncertain (experimental)
Mica-Revelstoke	3,412 t C y^{-1} loss of Floodplain production in **Mica-Revelstoke**	Purchase of privately owned wetlands to protect Upper Columbia River wetlands. Off-site: like for like	\$900-\$7000/ha	Depending on site, remediation may be necessary, monitoring would be required to assess success.	Securing habitat at risk. No GPP gain

10.6 Appendix 4. Table 3. Compensation and monitoring examples for Arrowhead-Keenleyside, Kootenay, and Duncan Dam Units.

Rationale: Pelagic fertilization of Arrow Reservoir provides enhancement of lentic trophic conditions, as well as for loss of a functional littoral zone post-dam. Experimental shoal fertilization is like-for-like on-site compensation targeted at the remaining lower littoral zone within the photic zone for biodiversity gains. To achieve some like-for-like compensation of lost river habitat/production, several rivers and streams that flow into Arrow Reservoir are also targeted to increase salmonid spawning and rearing nursery habitat productivity. A riverine project is targeted on the mainstem Columbia downstream of Keenleyside Dam as a nearby like-for-like pilot compensation project, expanded if successful.

Arrow reservoir offers numerous options for establishment and enhancement of vegetation in drawdown zones. Existing mapping and information regarding vegetation establishment in the current operating regime facilitate planning of such programs. Vegetation that has established in Revelstoke Reach contributes significantly to the calculated carbon production in the present-day reservoir.

Dam Unit Location	Impact or Loss	Compensation Example	Compensation Cost	Performance Monitoring	Compensation Gains
Arrowhead-Keenleyside Arrow Reservoir	Rivers loss 800 t C y^{-1} at 1400 ha, functional loss of 60% reservoir littoral zone	Arrow Reservoir fertilization as kokanee-piscivorous rainbow/char strategy. -unlike pelagic for river and littoral losses; on-site	$850,000/yr including monitoring*	BACI –paired basin comparisons: approximate monitoring costs $153,000/year	lentic GPP gain of 3086 t C y^{-1} (no lotic compensation)
Arrowhead-Keenleyside Arrow Reservoir Littoral: biodiversity objective	as above	Annual slow-release fertilization of 10 Arrow reservoir lower littoral shoals 200 ha treated/yr -like for like lentic onsite compensation	$60,000/yr at 1.0 t per 15 km of shoreline at $3500/t	EPM salmonid growth as mean size at age; subset of 5 of 10 control & treated $2000/pe r stream	200 ha GPP gain unknown (experimental)
Arrowhead-Keenleyside Arrow Reservoir tributaries	as above	Annual slow-release stream fertilization of 10 Arrow reservoir tributaries (e.g., Mosquito Cr.) 200 ha treated/yr -like for like lotic , onsite compensation	$60,000/yr at 1.0 t per 15 km of stream at $3500/t	EPM salmonid growth as mean size at age; subset of 5 of 10 control & treated $2000/pe r stream	200 ha GPP gain of 200 t C y^{-1} at 1 t C y^{-1} ha^{-1}
Arrowhead-Keenleyside Arrow Reservoir tributaries	as above	Stream habitat complexing and side-channel developments in 50 km of tributaries -like for like lotic, onsite compensation	$130,000 per year at 2 km/year	25 % EPM and IPM combined; night-snorkel salmonid counts at 5 cm sizes $2000 project	100 ha

Dam Unit Location	Impact or Loss	Compensation Example	Compensation Cost	Performance Monitoring	Compensation Gains
Arrowhead-Keenleyside Arrow Reservoir tributaries	as above	10 barrier removals in Arrow Reservoir tributaries (e.g., Cranberry Cr) and side-channels: -like for like lotic onsite compensation	$200,000 ($30k/proj.) 2 barriers per year	Fish species Use by snorkeling and electrofishing: extensive post-project (EPM) $4000/project	50 ha
Arrowhead-Keenleyside Lower Columbia River	as above	Assess tributary and side channel trout & char recruitment limitations to mainstem; Add nursery habitat; Like for like lotic	$60,000 per year; 1 km of tributary or side-chan. per year for 10 years	25 % EPM and IPM combined; day-snorkel salmonid counts $2000/km/year 3 years/project	20
Arrowhead-Keenleyside Onsite	3,207 t C y^{-1} loss of Floodplain production in Arrowhead-Keenleyside	Fertilize to enhance survival and production at several partially vegetated upper drawdown zone sites. Like-for-like: onsite	Approx. $10,000 ($50/ha), plus monitoring costs	Baseline vegetation density and biomass monitoring, post treatment assessment to test vegetation response $50,000 (2 dates & lab fees) to evaluate range of treatment sites	200 ha- estimated increase in annual yield =0.8tC ha^{-1} or 160 t C for total area once vegetation is established
Arrowhead-Keenleyside Onsite	3,207 t C y^{-1} loss of Floodplain production in Arrowhead-Keenleyside	Riparian/shoreline enhancement – site specific studies required to determine appropriate locations. Like-for-like: onsite	Approx $7500/ha	Post treatment assessment to assess vegetation success and GPP. Costs uncertain.	GPP gain uncertain
Arrowhead-Keenleyside Onsite	3,207 t C y^{-1} loss of Floodplain production in Arrowhead-Keenleyside	Variable planting sites for seeding with lenticulate seed in unvegetated mid-elevation drawdown zone. Like-for-like: onsite	Approx. $175,000 ($700 ha^{-1}) plus monitoring costs	Baseline vegetation density and biomass monitoring, post treatment assessment to test vegetation response $50,000 (2 dates & lab fees)	250 ha - estimated annual yield = 4.7 t/ha^{-1} or 1175 tC for area once vegetation is established
Arrowhead-Keenleyside Onsite	3,207 t C y^{-1} loss of Floodplain production in Arrowhead-Keenleyside	Creation of impoundments at appropriate inflow streams. On-site: unlike.	Depends on site characteristics, engineering costs, earth moving, planting, access etc.	Monitoring of wetland development success, plant size, survival, infilling, water retention etc. Costs uncertain.	GPP gain uncertain (experimental)

Dam Unit Location	**Impact or Loss**	**Compensation Example**	**Compensation Cost**	**Performance Monitoring**	**Compensation Gains**
Duncan Dam	127 tC y^{-1} from Duncan River and tributaries	Off channel (Lardeau side channels) and instream habitat rehabilitation (restoration of side channel access; large woody debris). Like for like: on-site (Duncan-Lardeau system)	$60,000/km	Fish species use by snorkeling and electrofishing: extensive post-project (EPM) $4000/project	GPP gain uncertain
Kootenay Lake	Nutrient reduction due to upstream dams	Lake fertilization as kokanee-piscivorous rainbow/char strategy.	$713,400/annually for North Arm* (2007/08 fiscal)	Before/after comparisons at several trophic levels	3093 tC yr^{-1} (Table 11)

*current monitoring programs do not include upper trophic levels (e.g., bull trout, rainbow trout) except for a creel survey on Arrow Lakes Reservoir.