# CHESLATTA/MURRAY LAKES and RIVER SYSTEM: The Role of Hydraulic Flushing on Lake and Stream Primary Productivity and Ecosystem Recovery

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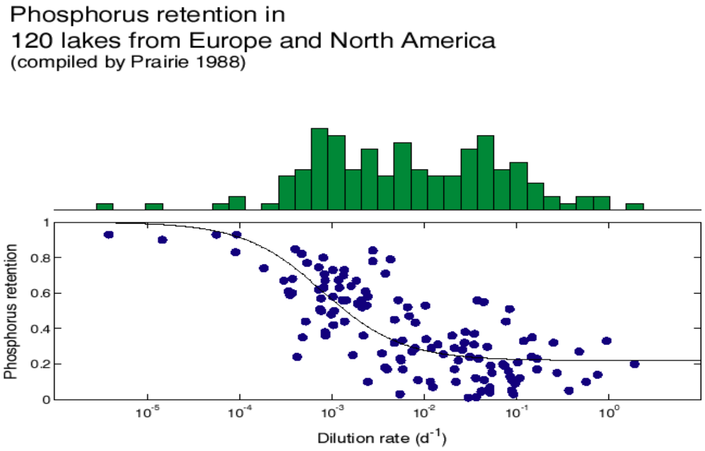
**April 30, 2006**

# 1.0 INTRODUCTION

There are several interrelated factors that collectively can cause and ultimately sustain the ultra-oligotrophic (low production) condition in lakes and streams at temperate latitudes. Among the most important of these are: 1. low ambient dissolved nitrogen (N), phosphorus (P) and carbon (C) concentrations in ground and surface water inputs to the ecosystems, and 2. large hydrologic inputs (flows) that can scour stream-beds and lakeshores of periphyton and rapidly flush the surface waters of lakes/reservoirs during prime plankton and periphyton growth periods, or May to October. Depending on the size of the lake or stream these large spring freshets usually flush (advect) both particulate and dissolved C, N, and P to lake outlets and to stream fluvial fans (deltas) and greatly reduces sedimentation and retention of particulate C, N, and P within lake or stream, creating an 'export' ecosystem. It is well documented that in 'natural' lakes sedimentation and P, C and N retention decline in concert with increased hydraulic flushing, i.e. shorter water residence times (Fig. 1). With the rapid flushing by large inflows that are now common in reservoirs/lakes like Cheslatta and Murray, these ecosystems tend to becomes 'C-export' systems with extremely short (weeks, months) surface water or epilimnetic residence times. The fast surface water flush exacerbates pelagic production by 'draining' the euphotic zone of dissolved and particulate organic C, N and P. Excessively high waters tend to scour the littoral of lakes, and the stream-beds of rivers, removing significant amounts of periphyton and their grazers, e.g. insect larvae, cladocerans, tubificids, etc. Year after year if flows are high and sustained the ecosystem quickly losses productive capacity and becomes a very low production system - ultra-oligotrophic, and this trophic status is perpetuated until more 'natural' flows can be restored (Ney 1999, Stockner et al. 2000).

**Fig.1.** The role of flushing in phosphorus retention in lakes and reservoirs (after T. Anderson, NIVA, Oslo, Norway).



Phosphorus retention in
120 lakes from Europe and North America
(compiled by Prairie 1988)

## METHODS

### 2.1. Lakes

***Model Predictions***. We will use the phosphorus loading equations of Vollenweider (1976) to determine the critical specific P loading ($L_c$) and attendant flows required for Cheslatta and Murray lakes to retain sufficient nutrient concentrations to increase rates of primary production in both phytoplankton and periphyton communities during the peak growth period. We will also attempt to address the role of hydraulic flushing (water residence time) to predict the range of flows that the ecosystems can accept so as to retain nutrients and sustain particulate C within the system to optimize C production (see Appendix 1).

***The PR Model***. The **P**hotosynthetic **R**ate model (Shortreed et al. 1999) will input current P values and proposed 'optimal' P values to estimate a range of PRs (C production) for Cheslatta and Murray lakes under present flow conditions and under predicted 'optimal' flow conditions following implementation of flow regulation. Model output will also provide a first-order prediction of the lake's carrying capacity for pelagic fishes, i.e. kokanee, under current flows and predicted 'optimal' (best for fish production) flows (Stockner 1987).

***Caveats***. There are neither current nor past data on the epilimnetic chlorophyll (CHL) content of Cheslatta or Murray lakes, only descriptive and somewhat anecdotal accounts from pre-dam lake survey of fish, plankton and littoral benthic fauna/flora by Lyons and Larkin (1952), where they report their sense of 'mesotrophic richness' and elevated productive state of both systems, especially in smaller, shallower Murray Lake (eutrophic). Since average seasonal CHL is an important variable in depicting a lake's present/past trophic state I have had to use professional judgment to estimate what past and present CHL values were likely to have been. I have used 0.0005 as 'present' mean value and the range of 0.0025 to 0.0035 $mg/m^3$ as past mean value, based largely on present mean values in larger Francois Lake of 0.002 (Shortreed et al. 2000). Epilimnetic depth is used in some calculations of water replacement and fortunately the Lyons and Larkin (1952) report published a clear temperature profile for both lakes on July 19, 1951 when the epilimnion was well developed (strongly stratified conditions), and the temperature change occurred at a depth of 8 - 8.5m, hence lacking further data I have used 8m as an estimate of 'current' mean epilimnetic depth for calculations of flushing for both lakes.

### 2.2 Streams

***Productivity of Cheslatta River***. In addition to potential effects on the productivity of Cheslatta and Murray lakes, significant flow releases from Skins Spillway can also potentially affect the productivity of the Cheslatta River. Nutrient concentrations in the river are likely to reflect that of Nechako Reservoir, which is known to be oligotrophic or unproductive. With no flow releases from Skins Spillway, nutrient concentrations of the river will revert to that of the original, smaller Cheslatta River, which is estimated to have had a mean annual discharge of 0.6 cms (Golder and Associates Ltd. 2005). Like the pre-diversion lake, the small 'historic' Cheslatta River was likely to have had much higher nutrient concentrations and thereby likely supported greater biological productivity within the Cheslatta River reaches from Skins Lake to Cheslatta Lake to Murray Lake.

It is possible to predict the effects of various flow releases on biological productivity by the use of stream productivity models, and two methods were used to estimate the effects of the proposed range of flow releases. Firstly, primary production (as gross carbon production per annum or GPP) is predicted using a multiple regression model (multiple $r^2 = 0.7$) developed by Lamberti and Steinmann (1997), using the parameters of watershed area, mean annual flow and soluble reactive phosphorus (SRP). As a second approach, two stream salmonid biomass models are applied: a nitrate-nitrogen and cover model ($r^2 = 0.96$; Rosenau and Slaney 1982), and a simple alkalinity model ($r^2 = 0.84$; Ptolemy in press). Based on these, it should be possible to estimate the potential effects on *stream productivity* of a range of flow scenarios ranging from a zero release (or a base flow 0.6 cms) to mean annual releases of 5 to 20 cms.

### 2.3 Water sampling.

Because the Cheslatta River is currently flowing from Skins Spillway, composite nutrient samples from a set of tributaries are used to approximate the nutrient water

chemistry of the original small Cheslatta River. Water chemistry parameters sampled for both lake and stream model predictions are:
Soluble reactive phosphorus (SRP),
Total dissolved phosphorus (TDP),
Total phosphorus (TP),
Dissolved nitrate-nitrogen ($NO_3N$),
Total alkalinity and TDS

***Field Sampling*** (Compiled by: Triton Environmental Consultants Ltd.)
On the 29th of March, water samples were collected from the Murray-Cheslatta watershed. Below are details pertaining to the water sample collection sites.

### Site #1- Skins Lake Spillway (Ootsa Lake) (Sample 3)

**UTM**: 10 302475 5962538
**Time**: 1005
**Water Temperature**: 1.5$^0$C
**Location Comments**: Sample was taken from Oosta Lake upstream of the spillway. The Van Dorn was lowered into the water column from a rocky outcrop along the shoreline. The water sample was taken at a depth of 0.5m.

### Site #2- Moxley Creek (Sample 4)

**UTM**: 10 317296 5961636
**Time**: 1033
**Water Temperature**: 0$^0$C
**Location Comments**: The sample site was located upstream of the confluence of Moxley Creek and the Cheslatta River because Moxley Creek itself was frozen solid and no evidence of water, frozen or not, near the Cheslatta River could be found. Upstream a large frozen ponded area was found and an auger hole was drilled into the pond to obtain a sample. Unfortunately, the pond was almost completely frozen through and the sample had to be taken from the water seeping into the auger hole.

### Site #3- Cheslatta River (upstream of Dog Creek) (Sample 5)

**UTM**: 10 318716 5960616
**Time**: 1052
**Water Temperature**: 1.5$^0$C
**Location Comments**: Sample was taken from step pool area of Cheslatta River.

### Site #4- Dog Creek (Sample 6)

**UTM**: 10 318762 5960670
**Time**: 1046
**Water Temperature**: 0$^0$C
**Location Comments**: At confluence of Dog Creek and Cheslatta River, Dog Creek was found flowing under ice, however the flow was too shallow for a sample. Therefore a deeper section of flow was found slightly upstream. The ice was broken over the stream for a sample to be taken.

### Site #5- Home Creek (Sample 7)

**UTM**: 10 321607 5958397
**Time**: 1115
**Water Temperature**: 0$^0$C
**Location Comments**: Home Creek was either dry or completely frozen from its confluence with the Cheslatta River until just downstream of its first road crossing. A sample was collected from flow found just downstream of the road culvert. Ice covering the flow was broken for sample to be collected.

### Site #6- North Tributary (Sample 8)

**UTM**: 10 324178 5955384
**Time**: 1136
**Water Temperature**: 0$^0$C
**Location Comments**: Lower sections of the creek near the Cheslatta River were either dry or frozen; a shallow section of flow was found beneath the ice 100m upstream of the confluence. Stream was also very shallow at bridge crossing.

### Site #7- ~2km on Cheslatta Lake from inlet (Sample 9)

Upon arriving at the first lake site it became evident that the ice was too thick to simply drill through using the auger (3 holes in a triangular pattern) and chip away the remaining middle ice. As such in order to obtain samples from 2m below the ices bottom, a chain saw was used to cut out the middle section of the ice. With the Van Dorn being a completely enclosed unit and the water being taken from 2m below the ice bottom it is unlikely that any contamination from the chain oil occurred. Information on lake site locations is below, water temperature for all lake samples was 0$^0$C.
**UTM**: 10 329650 5954342
**Time**: 1332

**Site #8- Middle of Cheslatta Lake (Sample 10)**
**UTM**: 10 344020 5957149
**Time**: 1351
**Site #9- ~3km on Cheslatta Lake from outlet (Sample 11)**
**UTM**: 10 360221 5953283
**Time**: 1409
**Site #10- Middle of Murray Lake (Sample 12)**
**UTM**: 10 344020 5957149
**Time**: 1431
After retrieval water samples were placed in coolers and couriered to Environment Canada's Pacific Centre (PESC), North Vancouver, BC, for immediate analysis of requested variables.

## 3.0 RESULTS & DISCUSSION

### LAKES

**3.1.** ***Water chemistry***. Results of analyses are presented in Table 1. All nutrient concentrations were exceptionally low, most notably $NO_3N$ values that at this time of season should be close to their 'overturn' maximum, e.g. 0.030-35 mg/L in Francois Lake[1]. Average TP values were similar to values measured in Francois Lake at spring overturn – 0.0058 mg/L[1]. Chlorophyll values were not measured in Cheslatta or Murray lakes owing to winter conditions with snow-covered ice.

**Table 1.** Six location results of variables used in lake PR and TP loading calculations. Values are reported in mg/L. UD=undectable (below method level of detection).

| Location | TDS | $NO_3$ | $PO_4$ | TDP | TP |
|---|---|---|---|---|---|
| Skins Lake | 40 | 0.006 | <0.001 | 0.003 | 0.005 |
| Cheslatta R | 37 | 0.005 | <0.001 | 0.002 | 0.008 |
| C. Lake Inlet | 37 | 0.007 | 0.001 | 0.003 | 0.008 |
| C. Lake mid. | 41 | 0.008 | <0.001 | 0.003 | 0.005 |
| C. Lake Outlet | 45 | 0.011 | <0.001 | 0.003 | 0.005 |
| Murray Lake | 43 | 0.013 | <0.001 | 0.002 | 0.005 |
| Average (N=6) | **40.5** | **0.008** | **<0.001 (UD)** | **0.0027** | **0.006** |

[1] K. Shortreed, DFO, Cultus Lake Lab. Unpublished data. Data are from a 3 yr seasonal (monthly sampling) limnological study conducted in the 1990's.

Such conditions allow minimal incident light to pass to water below the ice surface with negligible photosynthesis occurring. Thus, chlorophyll values would be expected to be undectable, i.e. < 0.0005 mg/L. The seasonal average chlorophyll value for Francois Lake was 0.0019 mg/L[1], low for an interior Fraser River system lake (Shortreed et al. 2000). Soluble reactive phosphate ($PO_4$) values were, as expected, below detection levels at all stations except the inlet station on upper Cheslatta Lake, where the value (if real) was exceptionally low. Total dissolved phosphorus was also very low <0.003 mg/L. Lake TDS values increased slightly during passage through Cheslatta Lake, doubtless due to input from numerous small streams of much higher TDS, then TDS declined slightly in Murray Lake, however none of the differences were large enough to be of statistical significance or biological relevance.

**3.2.** ***TP Loading.*** The present TP loads to Cheslatta and Murray lakes are 595 and 3,048 $mgTP/m^{-2}yr^{-1}$, respectively. These values are relatively high owing to the large annual volume of input water from Skin's Lake spillway to both lakes, but especially to the smaller and shallower Murray Lake, that has basically become an input-output riverine ecosystem with little or no nutrient retention. When TP loads are plotted as a function of lake mean depth both lakes are clearly placed in the 'eutrophic' category because of their moderately shallow mean depths (Fig. 2). However, because epilimnetic flushing and TP retention are not factored into the first equation, the graph does not accurately depict the 'real' present conditions that are clearly of a low production or ultra-oligotrophic condition. When retention and flushing are factored in the true past pre-dam and present conditions of both lakes are better depicted (Fig. 3).

**Fig. 2**. Present TP loads to Cheslatta and Murray lakes as a function of mean depth.

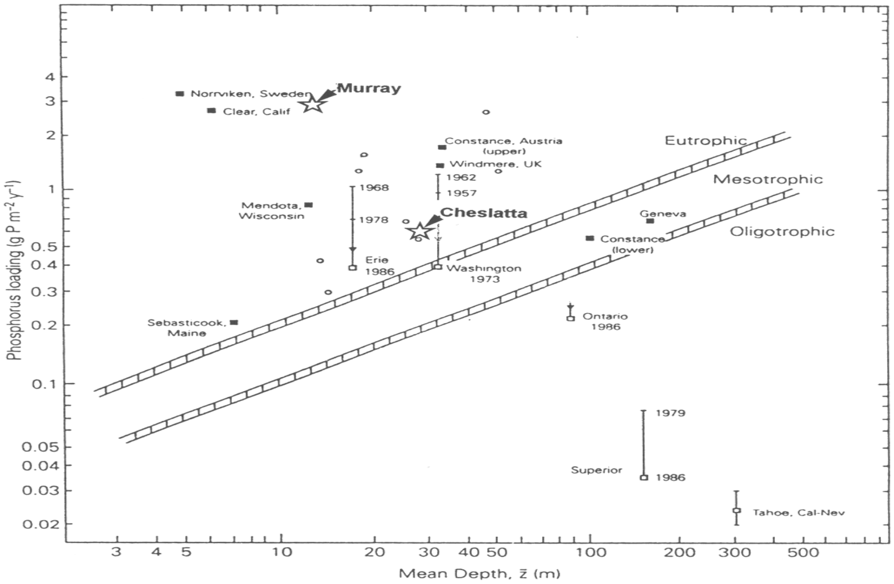
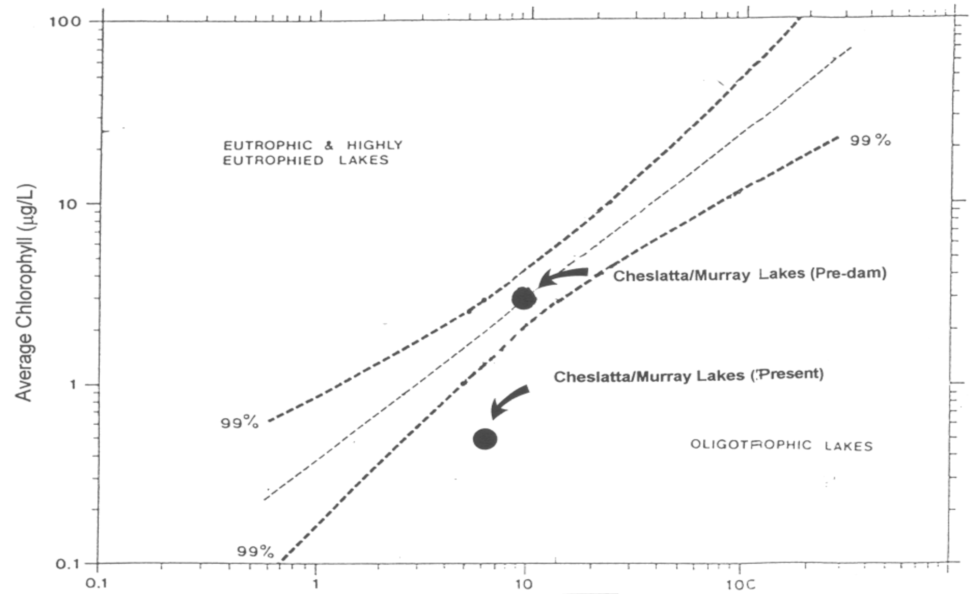


**Fig. 3**. Average TP concentration vs. mean growing season chlorophyll concentration in Cheslatta and Murray lakes, pre-dam (Skins Lake inflow) and present conditions.



Pre-dam Cheslatta/Murray lakes are on the mesotrophic line of the plot and fall to the far less productive oligotrophic state when plotted as a function of average growing season chlorophyll concentrations. If you compare the pre-dam vs. current conditions in both lakes with a series of BC, Yukon Territory and Alberta lakes again it is apparent that pre-dam conditions were meso-oligotrophic while present are clearing ultra oligotrophic (Fig. 4). Pre-dam conditions were likely more like present day Shuswap Lake, or Williston Reservoir during its 'boom' cycle the decade immediately following impoundment. These comparisons and depictions mirror the early observations of Lyons and Larkin (1952) who after completing a bio-reconnaissance of both lakes said of…

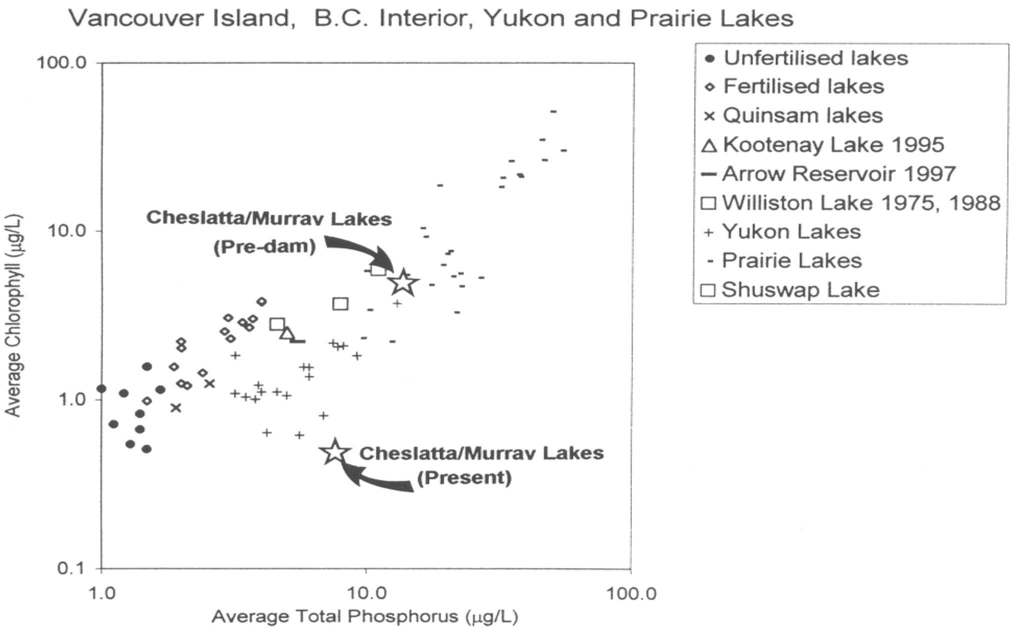
Cheslatta Lake:

> " *of moderate mean depth and large area suggests a condition best classified as mesotrophic with the favorable combination of relatively high productivity and high efficiency of food utilization"* and

of Murray Lake:

> "*the low mean depth and small area are characteristic of the eutrophic or highly productive type of lake in which the large quantities of food organisms are not efficiently utilized."*

**Fig. 4**. Comparison of Cheslatta and Murray lakes average Chlorophyll vs. average TP with several BC , Yukon and Alberta lakes (after Stockner & Beer 2004).



It is clear that both ecosystems were quite productive at all trophic levels including fish, as it is reported the fisheries of these lakes were utilized for centuries by first nation's people as traditional fishing grounds (Golder & Associates 2005). The Lyons and Larkin survey also found in early July an abundant quantity *Aphanizomenon* sp., a $N_2$-fixing blue-green alga capable of growth in N-limited ecosystems. The present (March 29, 2006) lake $NO_3$-N values are extraordinarily low, corroborating the conjecture of earlier reports that both ecosystems are severely N-limited and may require N supplementation to kick-start the production process after flows are stabilized. Current levels of biotic production are now exceptionally low as anecdotally reported by several mid-1980's and 90's surveys of current conditions with comment on possible ways of restoring lost production in both systems (Ableson 1985, 1990, 1995).

**3.3*. Production cycle of 'natural' lakes***. It is important to review how and when 'natural' lakes produce most of their autochthonous C so as to better understand why these lakes are so changed by excessive flow. Cheslatta and Murray lakes are dimictic (2 periods of circulation), temperate lakes and their active C production from phytoplankton photosynthesis begins in May, peaks in June/July and declines to negligible values by early November (Fig. 5). The epilimnion usually stably stratifies by mid-May and as freshet peaks in June some C production is advected within the epilimnion but is unlikely to be exported from the system. Inflow epilimnetic dilution volume rapidly declines through summer and fall months and owing to some phytoplankton sinking at 1-1.5 m/d (Jackson et al. 1989), much of this biogenic C either sinks to the sediment surface (sediment retention) or is consumed and transformed into faunal C, e.g. zooplankton or fish. The peak growth (2-3 doublings/wk) period of phytoplankton normally occurs in late June or early July then slows through August and September as the dissolved nutrients N and P become low and limiting to further growth. If the epilimnion of a lake is rapidly replaced within weeks or even months during this time, most of the phytoplankton C is <u>not</u> retained within the lake but shunted to the outlet and exported. Without C retention, the system remains unproductive! Even biogenic C on the shorelines as littoral C attached to substrata is usually exported from the system during 'freshet' periods by flow-current scouring.

**Fig. 5**. Typical seasonal growth cycle of major classes of phytoplankton in Henderson Lake, Vancouver Island, BC (Stockner & Shortreed 1979).

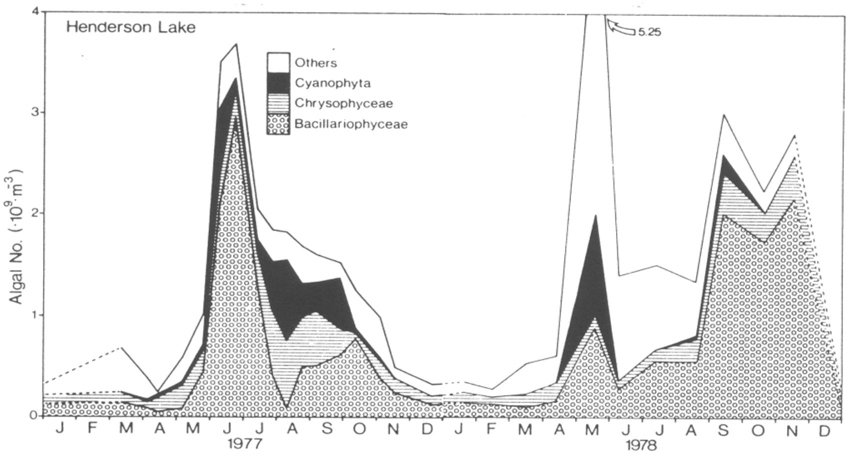
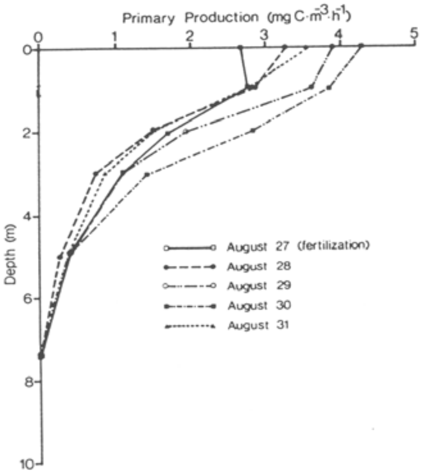


**Fig. 6**. Typical vertical profile of C production over a five day period following fertilization in a dimictic lake, North Coast, BC (after Stockner 1987).



A typical vertical profile of primary production in a stratified epilimnion is illustrated in Figure 6. This series of vertical profiles of photosynthetic production taken over a 5-day period (clear, calm weather) is closely related to light attenuation within the water column, and in the example shown the daily photosynthetic rate (**PR**) increases to a maximum on the third day following the fertilization with N and P added to the surface of the lake (Fig. 6) (Stockner 1987). It is important to remember that the surface layer or epilimnion of a lake in summer is the 'euphotic' C production zone of the ecosystem. Thus, if it is rapidly exported or frequently exchanged, little C can be retained within the lake and as a result production plummets.

**3.4. *PR model prediction.*** There are no extant data on what average daily PR was pre-dam or might be at present in either lake, so I have attempted to relate pre-dam Cheslatta and Murray lakes to a surrogate 'natural' dimictic lake of similar size, mean depths and residence times with measured PRs. I then used professional judgment to estimate what the most 'likely' PR values were in both lakes pre-dam and present condition. For current PRs I used measured PR rates from surrogate fast-flushing, low production lakes and reservoirs (e.g. Stave Reservoir, Kitlope Lake) with similar fast, hydraulic flushing rates. I used a slightly higher daily average PR than was measured in adjacent Francois Lake over a 3-yr period by Shortreed et al. (2000) as the 'natural' pre-dam lake surrogate for Cheslatta, and increased the Francois value slightly to compensate for smaller size, smaller mean depth and a more extensive littoral production in Murray Lake. Values of note are metric tones of C (tC) produced in both systems 'pre-dam' and how rapid flushing has impacted tC and the predicted capacity of the lakes to support pelagic kokanee (Table 2).

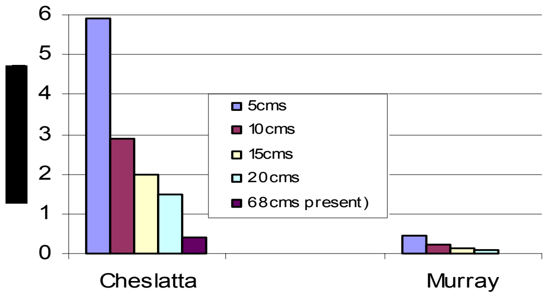
**Table 2.** PR model predictions of productive capacity of Cheslatta and Murray lakes pre-dam (1950's) and in their 'current' state to support pelagic fishes, namely kokanee salmon.

| Lake | Lake area ($km^2$) | Mean PR ($mgC \cdot m^{-2}$) Hourly | Daily | Total PR ($tC \cdot lake^{-1}$) | Adult Kokanee Opt. esc. | Maximum Kokanee juveniles biomass (kg) | number |
|---|---|---|---|---|---|---|---|
| Cheslatta (current) | 35.0 | 5 | 25 | 158 | 29,500 | 7,320 | 3,950,000 |
| Cheslatta (pre-dam) | 34.0 | 15 | 185 | 1,132 | 212,000 | 52,600 | 26,300,000 |
| Murray (current) | 5.6 | 5 | 19 | 19 | 3,580 | 891 | 445,000 |
| Murray (pre-dam) | 5.5 | 16 | 200 | 198 | 37,000 | 9,210 | 4,600,000 |

The model shows a 7-fold decline in C production in Cheslatta and a >10-fold decline in Murray Lake and a similar decline in both lake's ability to support pelagic fishes since diversion of water from Skin's Lake Spillway. Clearly, both lakes need restorative measures to increase nutrient retention and rebuild and retain higher rates of annual C production!

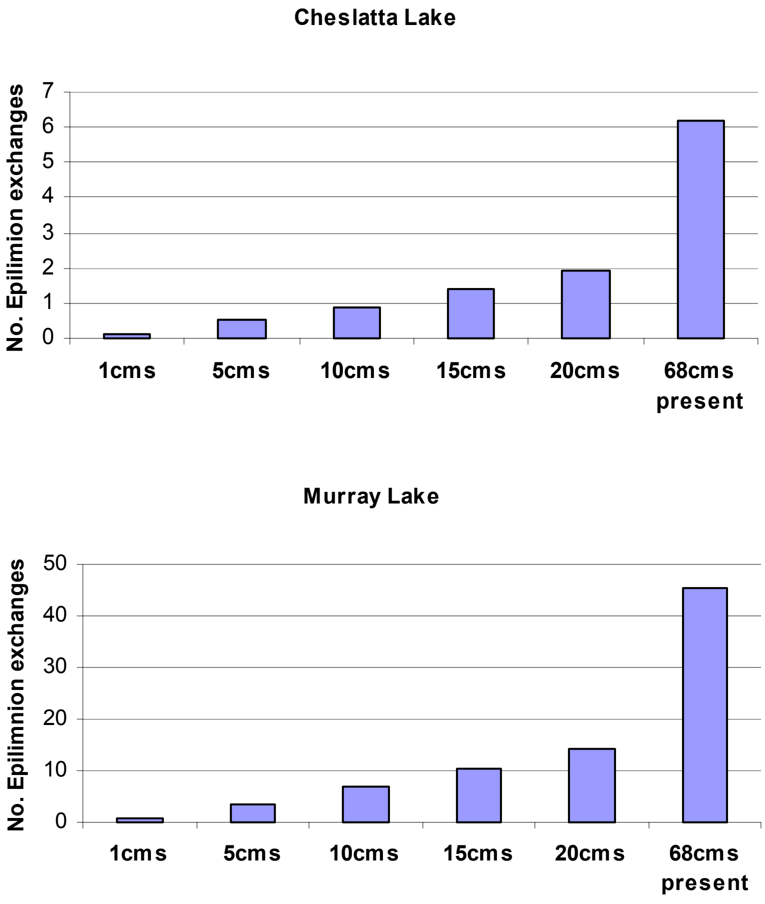
**3.5. *Flushing Rates*.** Under past 'pre-dam' water inputs the annual hydraulic flushing time of Cheslatta was about 6 yrs and for much smaller Murray Lake about 6 months.

**Fig. 7.** Hydraulic residence times of Cheslatta and Murray lakes and various annual inflow rates



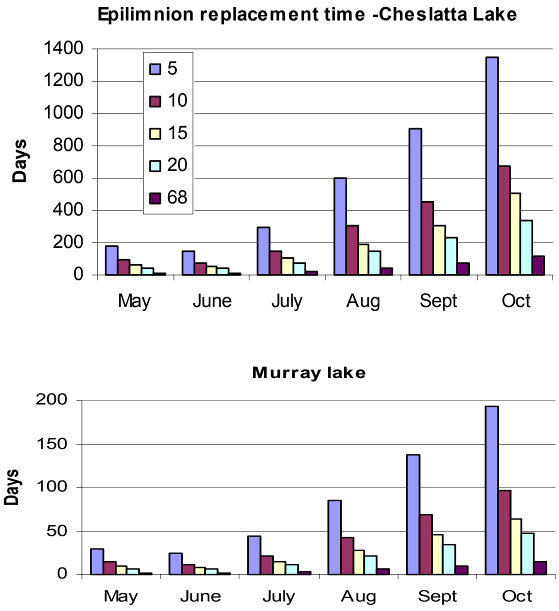
As water flow increases, residence times become shorter, and at present average 'Skin's Lake diversion' flows residence times are about 4-5 months in Cheslatta to a few weeks in Murray (Fig 7). Even at 20m$^3$/s (cms) flows residence time falls to only a 1.5 yrs in Cheslatta and a few months in Murray (Fig. 7). But a much more important measure that determines whether lakes retain or lose C (i.e. become import or export systems) is the rate at which the productive surface layer or epilimnion is replaced by inflow velocities during the plankton growing season – May to October (Figs. 8). Both lakes have an average epilimnetic depth of 8 m (Lyons and Larkin 1952). The measure of epilimnetic volume during the growing season is of particular relevance in these lakes since the inflow comes from the surface (epilimnion) of larger lakes and likely has the same or similar temperatures and density, and hence will directly flush the surface layer (epilimnion) of Cheslatta and Murray lakes. However, if the input came from a cold, deep dam discharge then the cold inflow would create an 'interflow' and would plunge beneath the epilimnion and only marginally impact the epilimnion. It is clear from Fig. 8 that the 'average' high inflows from Skin's Lake discharge can replace the Cheslatta epilimnion 6 times and Murray Lake's epilimnion 45 times between May and the end of October. An average inflow from Skin's Lake of 10-20 cms would replace Cheslatta's epilimnion 1 and 2 times and Murray's 7 and 14, with the greatest impact on Murray Lake and with some reduction of C retention in Cheslatta. In pre-dam periods inflows of between 1 and 5 cms had little effect on Cheslatta's epilimnion but 5 cms would replace Murray's 2-3 times, i.e. once every 65 to 90 days. These are not major replacements and would likely result in good C retention and import of carbon fauna and to sediments.

**Fig. 8** Number of epilimnion replacements (exchanges) through the growing season (May to October- 184 days) in Cheslatta and Murray lakes at 5 average low flow and present high flow scenario.



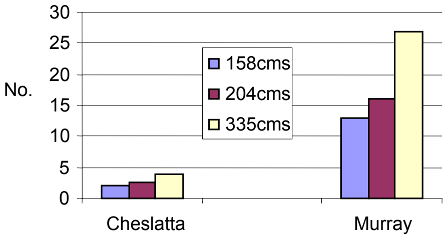
The impact of the 'freshet' inflow in May, June and July (the Stellako River hydrograph was used) and the rapid fall from August to October on 'monthly' epilimnetic replacement is depicted in Fig. 9 (below), and illustrates the importance of keeping flows as low as possible during the growing season to enable biogenic C to accumulate and sink to the hypolimnion to be retained/recycled within the lakes and/or flow through faunal components of the food-web and be retained as overwintering biomass. Present day high flows allow little biogenic C to settle and be retained, creating what are quite clearly rapid 'export' systems, i.e. riverine-like.

**Fig. 9**. Epilimnetic replacement times (days) each month during the growing season (185 days) using the surrogate Stellako River hydrograph for determination of monthly average flows (cms).



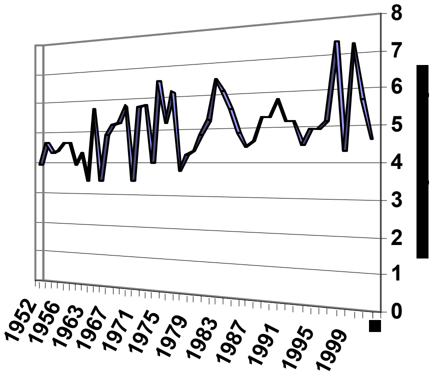
The NFCP Technical data review 1988-2002 published a time series of annual releases from the Skin's Lake Spillway with max, min and average flows from July 10 to August 30 from 1983-2000. This is a period of 'peak' carbon production in most dimictic lakes of the interior of Northern BC, of similar size to Cheslatta and Murray lakes (Stockner and Shortreed 1975, Stockner 1987). By selecting three average flows common during this period above and below the mean, one can readily see the major effects of flow augmentation as a sockeye cooling flow in the Nechako River on epilimnetic volume replacement (C export) on the Cheslatta/Murray lake ecosystem (Fig. 10). The Cheslatta Lake epilimnion is replaced 3 to 4 times while Murray's is replaced from 13-27 times!

**Fig. 10.** Epilimnetic replacement under present conditions of flow from July 10 to August 30.



Stave/Hayward Reservoir ecosystem is similar in many respects to Cheslatta Lake, both are fast-flushing systems with rapid epilimnetic volume replacement and each with smaller, shallower even faster flushed lakes below. Stave has one the lowest daily C pelagic production rates (16.4 mgC/m$^2$/day) yet measured in BC (Stockner and Beer 2004) and the principal causal agent for such low production was attributed first to the number of whole lake volume replacements each year (Fig. 11), and second to large water level fluctuations (drawdown) resulting in a disrupted and dysfunctional littoral zone resulting in negligible periphyton C production rates (Stockner and Beer 2004).

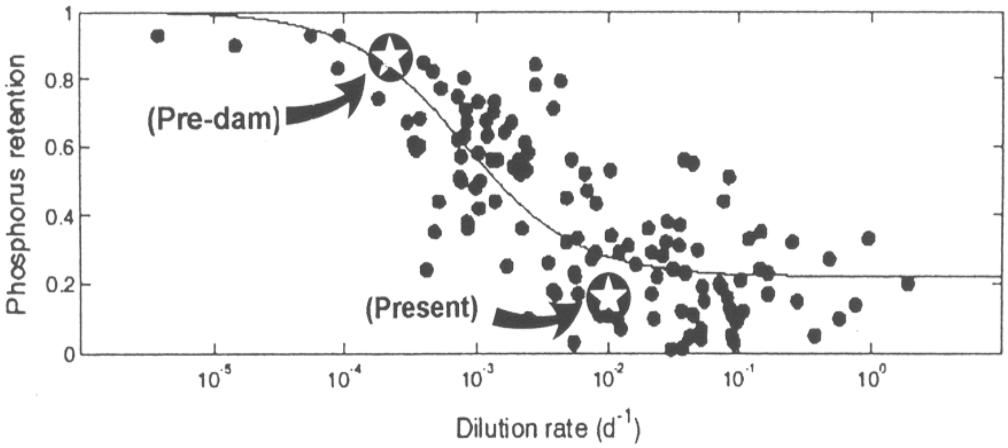
**Fig. 11.** Stave reservoir volume replacements/yr (after Stockner and Beer 2004)



### 3.6. *Retention*

There were insufficient hydrologic data as well as limnological assessments of sedimentation rates to directly measure rates of retention. However, knowing the rate of dilution of the lake volume and with an estimate of the replacement rate of the epilimnion some first order estimate of the TP retention could be obtained using the relationship of Prairie (1988) (Fig. 12).

**Fig. 12.** Pre-dam and present estimates of P retention based on dilution rate (After Prairie 1988)



Based on dilution rate from natural flows (1950's) the rate of nutrient retention in Cheslatta and Murray lakes was likely on the order of 70-90 %, but in the current state, especially with high mid-summer flows, the retention rate is likely in the 10-15 % range or lower, and clearly these ecosystems are now basically a 'export' systems, losing at outflow most of what little autochthonous C, N or P, is produced/yr.

### 3.7. *Optimal flows for Cheslatta/Murray lakes C production/retention.*

From a carbon production perspective, the lower the mean annual inflow and the smaller the spring 'freshet' peak, the higher the C retention and C gain to each lake. It is likely that with fertilization to jump-start the C production the gains at an average inflow range of between 10 and 15 cms could potentially double annual C production. The Cheslatta Lake epilimnetic replacement rate of twice/yr under the 20 cms hydrograph could lead to only a 1.5 fold C increase with nutrient addition, and even at 15 cms Cheslatta's epilimnion is replaced 1.4x a growing season which is on the edge of increasing export and slowing potential annual C gains by C retention within systems. Murray Lake by virtue of its small size and quickly replaceable epilimnion is much more perceptible to higher C export at higher mean annual flow regimes, e.g. 15-20 cms.

**Table 3.** Estimates of salient variables affecting C retention and potential C gains from 4 flow scenarios being considered and change from 'current' state (68 cms).

**Cheslatta Lake**

| Flows (cms) | Volume replacements[1] | Epilimnion replacements[2] | Retention[1] (%) | Carbon gain[3,4] |
|---|---|---|---|---|
| **5** | 5.9 | 0.5 | 85-95 | 1166 |
| **10** | 2.9 | 0.9 | 75-85 | 1103 |
| **15** | 2.0 | 1.4 | 65-75 | 914 |
| **20** | 1.5 | 2.0 | 45-55 | 725 |
| **68** | 0.4 | 6.2 | 0.5-10 | 158 |

**Murray Lake**

| Flows (cms) | Volume replacements[1] | Epilimnion replacements[2] | Retention[1] (%) | Carbon gain[3,4] |
|---|---|---|---|---|
| **5** | 0.43 | 3.4 | 75-80 | 207 |
| **10** | 0.22 | 6.8 | 55-65 | 151 |
| **15** | 0.15 | 10.2 | 40-50 | 106 |
| **20** | 0.11 | 14.1 | 25-30 | 76 |
| **68** | 0.003 | 45.2 | 0.1- 1 | 19 |

[1]Yearly; [2]growing season (May-Oct); [3]professional judgment + Shortreed et al. 1999, 2000, appendix database; [4]without nutrient supplementation (fertilization); tC/yr.

## 4. 0. Upper Cheslatta River

**4.1. *Water chemistry.*** Historically, dissolved nutrients of the upper Cheslatta River can be expected to have changed substantially pre- and post-diversion of flows from Nechako Reservoir, a source of low nutrient water. Prior to the diversion of water from Nechako Reservoir to the Cheslatta system, the upper Cheslatta River was a small torturously meandering single thread channel which was only about 5 m in channel width (Lyons and Larkin 1952, Golder Associates Ltd. 2005), and had a mean annual flow of 0.6 cms. In this dry zone of the Nechako Plateau, nutrient-rich watershed groundwater would be expected to provide a primary source of flow for much of the year, aside from the spring melt season. Thus, the average water chemistry of four of the river's four tributaries should provide an approximation of pre-diversion conditions at low flows (Table 4).

**Table 4.** Total alkalinity, total dissolved solids (TDS) and nutrient concentrations (mg/L) of four upper Cheslatta River tributaries, Cheslatta River at Skins Lake and near Cheslatta Lake during late March, 2006.

| Stream | T. Alkalinity mg/L | TDS mg/L | NO3N mg/L | SRP mg/L | TDP mg/L | TP mg/L |
|---|---|---|---|---|---|---|
| Moxley Creek | 227 | 308 | 0.09 | 0.014 | 0.023 | 0.215 |
| Dog Creek | 84.9 | 166 | 0.062 | 0.13 | 0.164 | 0.2 |
| Home Creek | 82.3 | 148 | 0.194 | 0.087 | 0.115 | 0.128 |
| North Tributary | 82.1 | 151 | 0.052 | 0.013 | 0.017 | 0.072 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Arithmetic Mean | 119.1 | 193 | 0.1 | 0.061 | 0.08 | 0.154 |
| Geometric Mean | 106.5 | 184 | 0.087 | 0.038 | 0.052 | 0.141 |
| | | | | | | |
| Skins Lake | 24.6 | 40 | 0.006 | <0.001 | 0.003 | 0.005 |
| Cheslatta River | 28.4 | 37 | 0.005 | <0.001 | 0.002 | 0.008 |
| Mean | 26.5 | 38.5 | 0.0055 | <0.001 | 0.0025 | 0.0065 |

Among the upper Cheslatta River tributaries, mean alkalinity and TDS was 119 mg/L and 193 mg/L, respectively, which as indicators of productivity are relatively high. Similarly, mean values of SRP, TDP and TP are high, whereas mean nitrate nitrogen is a more moderate value, compared to values elsewhere in the Interior of British Columbia. Values at upper Cheslatta River at both Skins Lake and the Cheslatta River near Cheslatta Lake were similar, but both were substantially less than the nutrient-rich tributaries. Total alkalinity and TDS were low, and about 20 % of the tributary means. On average, nutrient values at upper Cheslatta River were about 3 % (TDP) to 5 % (NO3N) of mean tributary nutrient values, and SRP was below the detection level.

Existing nutrient values were collected at a late March release flow approaching 28 cms. This is close to the maximum proposed mean annual release flow of 25 cms, post-construction of a cold-water release facility at Kenney Dam (Golder and Associates Ltd. 2005).

**4.2. *Primary Production.*** Lamberti and Steinman's (1997) primary production model for gross primary production (GPP) is applicable to various potential cases of flow releases post-Kenney Dam diversion:

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

where: $r^2 = 0.7$ and $n = 30$
GPP is g C $m^2$/y
Area is watershed area in hectares
Discharge is mean annual discharge in L/s
SRP is soluble reactive phosphorus in µg/L

For GPP calculations, the geometric mean of SRP was applied (Table 3) because of high variability in SRP among upper Cheslatta River tributaries. In addition, SRP concentrations were adjusted proportionally to account for Skins Spillway releases (Table 5), assuming the SRP concentration was near zero from the reservoir (< 0.001 mg/L, Table 4). Watershed area was assumed to be 190 $km^2$ in all flow release cases, even though additional releases accounted for an unknown proportion of the Nechako Reservoir watershed.

**Table 5**. Estimated gross primary production (GPP, g/$m^2$/y) predicted from the Lamberti and Steinman's (1997) multiple regression model, and based on four mean annual flow cases (natural flow of 0.6 cms, and release flows of 5, 15 and 25 cms).

| Mean Annual Flow (cms) | Watershed Area (ha) | SRP (ug/L) | GPP (g C $m^2$/y) |
|---|---|---|---|
| 0.6 | 19,000 | 38 | 802 |
| 5 | 19,000 | 4.6 | 124 |
| 15 | 19,000 | 1.5 | 47 |
| 25 | 19,000 | 0.9 | 30 |

To place these GPP values in perspective, the assumed GPP value at a natural mean annual flow of 0.6 cms is high among those published in a summary by Webster and Myer (1997) and Lamberti and Steinman (1997). The 800 value is similar to the most productive of eastern US deciduous streams and about 3 times that of productive boreal rivers in Quebec (Naiman and Link 1997). In comparison, a maximum value of 150-300 g C $m^2$/y is evident among several boreal and coniferous forest streams (Lamberti and Steinman 1997). The values of 30 and 47 g C $m^2$/y at higher release flows are more typical of high precipitation zones, including the BC

Coast and West Kootenays, respectively (Moody et al. 2006). Compared to boreal forests, the 800 value is likely overestimated because SRP concentrations from tributaries in late winter are apt to be above the average annual SRP concentration. Furthermore, higher flow cases may be underestimated because a greater proportion of watershed area is not incorporated. However, the positive association of GPP with watershed area is based on accumulation and transport of greater amounts of nutrients and organic matter from larger watersheds (Lamberti and Steinman 1997), which are not generated from large oligotrophic reservoirs. Thus, the predicted GPP values for the various potential flow releases examined fall well within the range of published values for north temperate areas.

**4.3. *Salmonid Standing Crop.*** Another means of estimating the effects of flow releases is by applying regression models for fish standing crop, including (1) a NO3N-cover habitat capability model (HCM, Rosenau and Slaney 1983) and (2) an alkalinity model (Ptolemy in press), with equations as follows:

(1) Salmonid Standing Crop in kg/ha = $190C + 13{,}900\,(NO_3\text{-}N)^2$

Where: C is trout cover as area of cover/total wetted area,
$NO_3$-N is nitrate nitrogen in mg/L measured at low flows

(2) Trout Standing Crop in g/100 $m^2$ = $45\,(T.\ Alk)^{0.6}$

Where: T. Alk is total alkalinity in mg/L, and to convert to kg/ha, g/100 $m^2$ is divided by 10.

For HCM, cover was estimated from 2005 air-photos at a flow of approximately 58 cms, using deeper pool and run water, which was estimated at 20 % and assumed to be 20 % at all flows. The latter may be an underestimate, particularly under the natural condition where width was only about 5 m. Only standing crops at flows of 0.6 cms and 25 cms were estimated directly from water chemistry determinations, and standing crops for flows of 5 and 15 cms were estimated proportionally from the former.

As for GPP, estimated salmonid and trout standing decreased with increasing flow releases from Nechako Reservoir, although maximum differences between flows were less than GPP, and ranged from 2.3 to 3.7 times (Table 6).

**Table 6.** Estimated salmonid standing crop capacity (kg/ha) of upper Cheslatta River, based on four mean annual flow cases (natural flow of 0.6 cms, and release flows of 5, 15 and 25 cms).

| Mean Annual Flow (cms) | Predicted Salmonid Standing Crop Capacity (kg/ha) | |
|---|---|---|
| | HCM | T. Alkalinity |
| 0.6 | 142 | 74 |
| 5 | 123 | 67 |
| 15 | 82 | 50 |
| 25 | 38 | 32 |

**4.4. *Flow-Production Area Effects.*** In contrast to the lakes where lake area only changes marginally with a potential range of release flows from 5 to 25 cms, changes in river area are more substantial. Thus, another factor that must be accounted for at the upper Cheslatta River is the increase in wetted area resulting from higher release flows. A zero release from Skins Lake spillway is not considered an option because sections of the river would be dry under the existing geomorphology at a mean annual flow of 0.6 cms (Golder and Associates Ltd. 2005).

Changes in productive area have the potential to offset low GPP, particularly at the low to intermediate releases flows. Unfortunately there is little information to estimate wetted widths at various flows, aside from the 2005 photo set taken at about 58 cms in mid-June, 2005. At this flow, average wetted width is estimated at about 65 m, based on map measurements of wetted width. There is also an observed wetted width of 5 m at the mean annual flow of 0.6 cms (Lyons and Larkin 1952). Based on an asymptotic shaped curve, if 58 cms equates to a wetted width of 65 m, then 5 cms, 15 cms and 25 cms are estimated to equate to wetted widths of about 20 m, 40 m and 50 m, respectively. Using these widths, GPP can be calculated per linear m distance of the Cheslatta River (Table 7). Accordingly, wetted width-adjusted GPP is reduced much less by release flows than unadjusted GPP (Table 6). As an instructive example, the reduction in width-adjusted GPP at a release flow of 5 cms versus 15 cms was small, or only 25 %. However, there was a 40 % GPP reduction at from 5 to 25 cms.

**Table 7.** Estimated gross primary production (GPP, g/$m^2$/y) and wetted width-adjusted GPP, based on four mean annual flow cases (natural flow of 0.6 cms, and release flows of 5, 15 and 25 cms).

| MAF (cms) | GPP (g C $m^2$/y ) | Est. Production Width (m) | Width-adjusted GPP (g C lineal m/y) |
|---|---|---|---|
| 0.6 | 802 | 5 | 4,010 |
| 5 | 124 | 20 | 2,480 |
| 15 | 47 | 40 | 1,880 |
| 25 | 30 | 50 | 1,500 |

Similar application to the HCM standing crop would need to account for habitat area, and not only wetted area. However, if salmonid habitat doubled with an increase in mean annual flow of 5 cms to 25 cms (e.g., Slaney et al. 1984), then HCM standing crop would only decrease 38 % instead of 70 %, and even less so with the Alkalinity model. However, both GPP and salmonid standing crop would also depend on how the flow was distributed over the growth season from mid-spring to mid-fall. Application of a semi-natural freshet would likely result in a temporary reduction in useable salmonid habitat in order to accommodate additional ecological considerations.

**4.5.** ***Caveats.*** There are caveats to these conclusions. The primary one, is that the tributaries in composite are representative of what the same conditions were in the historic Cheslatta River, which was small (width 5 m). In addition, it is assumed that the exceptionally low flows of the tributaries in late March may have elevated nutrients beyond that of low flow conditions. However, even if nutrient concentration were elevated 2-fold, a similar range of effects on GPP would be expected. Finally, the shape of the wetted area versus flow curve for the river was crudely estimated and may be flatter or steeper, which would either decrease or increase effects on width-adjusted GPP.

## 5.0. RECOMMENDATIONS

**5.1.** ***Optimal flows***. An average inflow from Skin's Lake of 10-20 cms would replace Cheslatta's epilimnion 1 and 2 times and Murray's 7 and 14, with the greatest impact on Murray Lake and some reduction of C retention in Cheslatta. In pre-dam periods, inflows of between 1 and 5 cms had little effect on Cheslatta's epilimnion, but even average flows of 5 cms would replace Murray's epilimnion 2-3 times, i.e. once every 65 to 90 days. These are not major replacements and would lead to the best or 'optimal' retention of carbon and nutrients within the ecosystem and the lowest exports out of the system. Exchanges at 10-15-20 cms are incremental and bring moderate (10 cms) to more severe (15-20 cms) reductions in C and nutrient retention and increase flushing and export within both systems. Thus, if a primary goal is to achieve moderately high fish production in Cheslatta Lake, a lower rather than higher release flow in this range should be selected.

At upper Cheslatta River, there is a substantial effect of increasing release flows on primary production per unit area of the river. However, once wetted area is incorporated, negative overall effects of increased flows on total GPP are dampened. A release flow as high as 25 cms is excessive in terms of productivity losses, yet negative effects on primary productivity at 5 cms are small and only moderate at up to 15 cms. This indicates that although flow releases within the range of 10-15 cms are not optional, they may be adequate when gauged according to overall primary production of the river. Yet, significantly reduced salmonid growth with increasing release flows will occur in the river regardless of an offsetting affect of an expanded wetted area. Monitoring of chlorophyll a biomass and mean trout size-at-age would be instructive in fine-tuning flow releases in the upper Cheslatta River.

**5.2. *Data collection***. There is an *urgent* need to gather some limnological information on the 'present' state of the lakes. Monthly sampling for phytoplankton, zooplankton and chlorophyll together with the nutrients TP, TDP and $NO_3$-N. Once this database is established the assessment of change with changing hydrographs and mean annual flows will be 'science' based and changes to improve production and retention made with statistical confidence.

**5.3. *Hydrology-limnology Modeling.*** The nutrient retention in Cheslatta and Murray lakes is a function of the hydraulic and hydrologic variability that in turn are functions of flow into the lakes regulated by the Skin's Lake dam and the controlling elevations at the outfall of both lakes. Optimal retention of nutrients can only be achieved by discovering a balance between water surface elevation in the lake and flow rates in and out during and between growing seasons. Variation in these factors will, in turn, change the nutrient loss rate by changing loading, water temperature in the epilimnion, and sedimentation rate. A model incorporating the hydrology and limnology of this system could be developed that allows the user to solve for the optimal flow regime by viewing the impacts of changes to each of these loss variables (outflow and retention) given various annual flow scenarios. The key to restoration of this system in a timely manner lies in finding the 'optimum' hydrograph and annual mean flow (cms)!

### 5.4. *Lake Rehabilitation Measures*

#### 5.4.1 *Lake 'Pelagic' Nutrient supplementation (fertilization).*

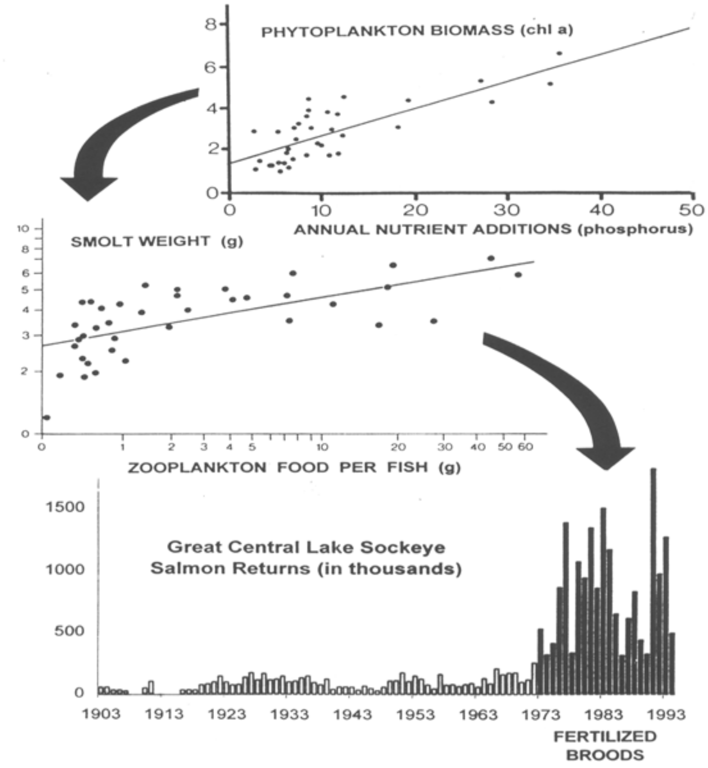


**Fig. 13.** Schematic of fertilization of Great Central lake and processes responsible for rapid stock recovery (after Stockner and MacIsaac 1996).

***Background.*** The efficacy of an annual lake nutrient supplementation to increase a lake's productive capacity and zooplankton forage for planktivorous juvenile sockeye and/or kokanee has been repeatedly demonstrated over the past 3 decades in over 20 BC lakes (Fig.

13) (Stockner 1987, Stockner and MacIsaac 1996, Stockner and Ashley 2003). The fertilization of Kootenay Lake and Arrow Lakes Reservoir to restore kokanee and rainbow trout production has been an on-going program for the past decade in the Kootenays, and has been viewed as the most feasible compensation option available to restore lost production, caused by upstream dam creation and very low nutrient inputs due to nutrient trapping (Ashley et al. 1996, Pieters et al. 2000). Model simulations that remove the two dams and restore 'natural' hydrographs suggest that Kootenay Lake TP concentrations could be elevated by nearly 60 % (Perrin and Korman 1997). The productive capacity of Cheslatta and Murray lakes is exceptionally low owing to excessive flows and the negative consequences of rapid flushing. Lake pelagic-zone nutrient supplementation would be a very effective means of 'jump-starting' the carbon production cycle of Cheslatta Lake, especially when coupled with the restoration of a 'natural' seasonal hydrograph that would assure adequate 'nutrient retention' during treatment. These two factors together would definitely hasten the recovery of the badly damaged pelagic and littoral ecosystems of the lake.

#### 5.4.2 *Sector or embayment fertilization*.

Fertilization of select embayments of larger lakes and reservoirs was first done successfully on a pilot-scale in a northern Swedish lake/reservoir (Stockner and Milbrink 1999), where bags of slow release fertilizer were place strategically in small inflow streams of one large embayment (bay) while a second, contiguous bay was used as a control. Char and trout migrated from great distances (20-30 km) to the fertilized bay with its greatly enhanced zooplankton forage base (4-fold control) and the char increased 2-fold in size during the open-water growth period compared to sizes in a control bay. The technique of embayment fertilization is currently an operational compensation mechanism on two moderate sized reservoirs in northern Sweden (G. Milbrink, Univ. of Uppsala, Zoology Dept., unpublished data, and J. Stockner personal observation). Both lakes may be candidates for trials of embayment fertilization, but especially Murray where slow-release fertilizer pellets could be placed in the Cheslatta River delta before entry into Murray Lake.

### 5.5. *Lake Littoral or 'shoal' fertilization*.

***Background.*** Water temperature, nutrient levels, and duration of optimum conditions (drawdown frequency) in the littoral zone of lakes/reservoirs are key determinants of littoral productivity. Among Pacific Northwest reservoirs and in rapidly flushed lakes like Cheslatta and Murray, 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), while Cheslatta's lake level may vary by as much as 2-3 m (Golder and Associates 2005). Such wide fluctuations dewater and destabilize large expanses of littoral substrate, which severely limits suitable littoral habitats for aquatic biota and decreases benthic insect production (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, Stockner and Beer 2004). Clearly reservoir and lake drawdown has a profound impact on littoral C production by periphyton and macrophytes, as well as benthic invertebrates. Thus, the substantial reductions in macro-benthic insect production concomitant with a loss of littoral C production are major impacts of reservoirs and lakes 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).

#### 5.5.1.*'Shoal' fertilization*.

A compensatory measure for offsetting some of the negative impacts of high flows and elevated water levels in both Cheslatta and Murray lakes is *'shoal fertilization'*, which could be targeted at the lower-end of the new lake elevation range that lies within the euphotic zone for much of the year. 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, e.g. 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 currents. These techniques 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 lake/reservoir bays. 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, a small applied research pilot-phase is necessary before this potentially effective compensation measure is widely applied.

### 5.6. *Cheslatta River Fertilization*

During the initial recovery period, trophic productivity of the river will lag, largely because of "cooling flow" releases that have highly scoured river substrates and their biota. Associated with channel scour, there will be little instream woody debris to trap organic matter and retain nutrients, and there will be sparsely developed streambank vegetation to contribute abundant leaf litter. Furthermore, kokanee spawning runs from the lakes will initially be too small to contribute nutrients and carbon to the Cheslatta River system. Under these conditions, an initial period of stream fertilization is a useful option to accelerate recovery.

At the same time, downstream spiraling of nutrients can be utilized to fertilize the upper portion of Cheslatta Lake, to "kick-start" lake productivity, increasing both lake nutrient and carbon retention, as discussed earlier. Whole-river fertilization has been used as a restoration option and improved growth rates of salmonids are well documented on the Coast (Johnston et al. 1990, Slaney et al. 2005) and in the Northern Interior (Slaney and Ashley 1999). Given the remoteness of the Cheslatta River, slow-release fertilization using coated fertilizers post spring freshet is a viable option as a short-term measure to speed recovery, and as well to provide the equivalent of embayment enrichment in Cheslatta Lake.

### 5.7. *Kokanee Spawning Habitat Rehabilitation*

Kokanee will eventually provide a natural equivalent source of nutrients as well as carbon, similar to that documented at the Lardeau River in the West Kootenays (Slaney and Andrusak 2003). There, a large spawning run of kokanee from late summer to autumn drives the productivity of mainstem and side-channel habitats, similar to runs of salmon at many coastal rivers. Positive effects of sockeye carcasses on the productivity of northern streams are documented by Johnston et al. (2004).

Measures to ensure there are adequate spawning areas for kokanee in the Cheslatta River are likely needed because of flushing of gravels by annual "cooling flow" releases from Skins Spillway. Selected placements of spawning gravels in the river may be required at suitable wide sites where gravel stability can be assured during the spring freshet. It may also be feasible and cost effective to construct a 1.5 km spawning channel that diverts flow from above the falls barrier in the Cheslatta River to a point where a tributary, Dog Creek, enters the river. Such a channel would also provide migratory fish access above the barrier, and key nursery stream habitat for rainbow trout and bull trout.

### 5.8. *River Habitat Rehabilitation*

Fish habitat rehabilitation in the Cheslatta River is also of importance in accelerating recovery of salmonid populations. In particular, the existing river is lacking in large woody debris (LWD) which provide important in-stream cover and over-winter refugia for rearing salmonids. LWD as lateral log jams also generates sediment sorting, which creates prime spawning gravel areas for kokanee and other salmonids. In addition, there are no natural trapping devices for storage of organic matter in the Cheslatta River. The latter is a key role of LWD that is often under-estimated, as emphasized by Minshall et al. (1983) from a long-term inter-biome study of ecosystem processes.

Riverbank attachments of LWD should be implemented early in operational recovery plans to assure these ecological functions are re-established in the Cheslatta River. Restoration of large wood should progress from downstream to upstream over several years. Strong evidence for the effectiveness of large wood restoration on yields of salmonid migrants is available from long-term controlled before and after studies, including Solazzi et al (2000).

## 6.0. REFERENCES CITED

Ashley, K.I., L. C. Thompson, L. Haywood-Farmer, J-R Yang, F.R. Pick. P.B. Hamilton, D.C. Lasenby, K. E.Smokorowski, L. McEachern, D. Sebastian and G. Scholten. 1996. Kootenay Lake fertilization experiment . year 3 (1994-95) report. Province of BC Fisheries Project Report No. RD 49: 100p.

Beer, J.A. 2004. Littoral zone primary production in a coastal reservoir ecosystem, MSc Thesis, Univ. of BC, Vancouver, BC

Benson, N.G. and P.H. Hudson. 1975. Effects of reduced fall drawdown on benthos abundance in Lake Francis.Transactions of the American Fisheries Society 3; 526-528.

Golder and Associates Ltd. 1998. Review of the effects of reservoir operation on productivity of Lower Kananaskis Lake. Fisheries and Recreation Enhancement Working Group, Calgary, Alberta. pp 942-2268.

Golder and Associates Ltd. 2005. Background information report: Murray-Cheslatta River system. Contract report prepared for the Nechako Enhancement Society. 29p.

Jackson, L.J, J.G. Stockner, and P.J. Harrison. 1989. Contribution of *Rhizosolenia eriensis* and *Cyclotella* spp to the deep chlorophyll maximum of Sproat Lake, British Columbia. Can. J. Fish. Aquat. Sci. 47: 128-135.

Johnston, N.T., C.J. Perrin, P.A. Slaney, and B.R. Ward. 1990. Increased juvenile salmonid growth by whole river fertilization. Canadian Journal of Fisheries and Aquatic Sciences 47:862-872.

Johnston, N.T., M.D. Stamford, K.I. Ashley, and K. Tsumura. 1999. Responses of rainbow trout (*Oncorhynchus mykiss*) and their prey to inorganic fertilization of an oligotrophic montane lake. Can. J. Fish. Aquat. Sci. 56: 1011-1025.

Johnston, N.T., E.A. MacIsaac, P.J. Tschaplinski and K.J. Hall. Effects of the abundance of spawning sockeye salmon (Oncorhynchus nerka) on nutrients and algal biomass in forested streams. Canadian Journal of Fisheries and Aquatic Sciences 61: 384-403.

Kaster, J. L. and G.Z Jacobi. 1978. Benthic invertebrates of a fluctuating reservoir. Freshwater Biology 8: 283-290.

Knotek, W.L., M. Deleray, and B. Marotz. 1997. Hungry Horse Dam Fisheries Mitigation Program: fish passage and habitat improvement in the upper Flathead basin. Prepared for the US Department of Energy, Bonneville Power Administration.

Lamberti, G.W. and A.D. Steinman. 1997. A comparison of primary production in stream ecosystems. North American Benthological Society 16: 95-104.

Lyons, J. C. and P.A. Larkin. 1952. The effects on sport fisheries of the Aluminnum Company of Canada Limited Development in the Nechako Drainage. British Columbia Game Department, Game Commission Office Vancouver, B.C. Fisheries Management Report No. 10.

Moody, A, P.A. Slaney, and J. Stockner. 2006. Footprint impact of BC Hydro Dams on aquatic and wetland primary productivity in the Columbia Basin. Contract report prepared by Aim Ecological Consultants Ltd., Eco-logic Ltd. and PSlaney Aquatic Science Ltd. for the Columbia Basin Fish and Wildlife Compensation Program. 200p.

Naiman, R.J. and G.L. Link. 1997. Organic matter dynamics in five subarctic streams, Quebec, Canada. Journal of North American Benthological Society 16: 33-39.

Perrin, C.J. and J. Korman. 1997. A phosphorus budget and limnological description for Duncan Lake Reservoir, 1994-95. Report to BC Hydro, Kootenay Generation Area, Castlegar, BC, by Limnotek R. & D. Vancouver, BC.

Pieters, R. + others, 2000. Arrow Reservoir fertilization experiment year 1 (1999/2000) report. Province of BC Ministry of Environment, Lands and Parks Fisheries Project Report No. RD 82: 400 p.

Prairie, Y.T. 1988. A test of the sedimentation assumptions of phosphorus input-output models. Arch. Hydrobiol. 111: 321-327.

Ptolemy, R. P. (in press). Biostandards for coastal cutthroat trout (*Onchorychus clarki clarki*): can ecoregions be used as a place-based standard for abundance. 16 p.

Rosenau, M. L. and P.A. Slaney. 1983. A preliminary capability model for estimating standing crop of resident salmonids in streams. Province of BC Fisheries Project Report No. RD10: 19p.

Shortreed, K.S., J.M.B. Hume, and J.G. Stockner. 1999. Using photosynthetic rates to estimate the juvenile sockeye salmon rearing capacity of British Columbia lakes. P. 505-521. *In* E.E. Knudsen, C.R. Steward, D.D. MacDonald, J.E. Williams and D.W. Reiser [eds.]. Sustainable Fisheries Management: Pacific Salmon. CRC Press LLC, Boca Raton, New York.

Shortreed, K.S., K.F. Morton, K. Malange and J.M.B. Hume. 2000. Factors limiting juvenile sockeye production and enhancement potential for selected B.C. nursery lakes. Can. Stock Assessment Sec. Res. Doc. 2001., Ottawa, Canada.

Slaney, P.A., M.L Rosenau, D. H.G. Ableson and R.L. Morely 1984. Habitat capability of the Nechako River for rainbow trout and char, and the effects of various flow regimes. BC Fisheries Branch Fisheries Technical Circular No. 63: 34p.

Slaney, P.A. and H. Andrusak. 2003. Lardeau River fish habitat assessments (2002) and Preliminary Gerrard Rainbow trout production capability modeling. Contract report Redfish Consulting Ltd.

Slaney, P.A., B.R. Ward, and J. C. Wightman. 2003. Experimental nutrient addition to the Keogh River and application to the Salmon River in coastal British Columbia. Page 11-126 In J.G. Stockner (ed.) Nutrients in salmonid ecosystems: sustaining production and biodiversity. American Fisheries Society Symposium. 285p.

Slaney, P.A and K.I. Ashley. 1999. Case studies of whole-stream fertilization in British Columbia, pp 83-98. In: J.G. Stockner and G. Milbrink eds. Restoration of fisheries by enrichment of aquatic ecosystems. Symposium Proc. Uppsala Univ., Instit. of Limnology, Univ. of Uppsala Press, 219 p.

Stockner, J.G. 1987. Lake fertilization: The enrichment cycle and lake sockeye salmon (Oncorhynchus nerka) production, p. 198-215. In: H.D. Smith, L. Margolis and C.C. Wood (eds.). Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96, 486 p.

Stockner, J.G. and K. I. Ashley. 2003 Salmonid nutrients: closing the circle. Page 3-16. In J. G. Stockner (ed.) Nutrients in salmonid ecosystems: sustaining production and biodiversity. American Fisheries Society Symposium 34: 285p.

Stockner, J.G. and J. Beer. 2004. The limnology of Stave/Hayward reservoirs: with a perspective on carbon production. Rept. To BC Hydro, Environmental Services, Burnaby, BC.

Stockner, J.G. and G. Milbrink. 1999. Restoration of fisheries by enrichment of aquatic ecosystems. Uppsala Univ. Press, Uppsala, Sweden, 220 p.

Stockner, J.G., and E.A. MacIsaac. 1996. The British Columbia Lake fertilization program: overview after two decades of salmon enhancement. Reg. Rivers. 12: 344-356.

Stockner, J.G., and K.R.S. Shortreed. 1979. Limnological surveys of 13 sockeye salmon (Oncorhynchus nerka) nursery lakes in British Columbia. Fish Mar. Serv. Tech. Rep. No. 865, 125 p.

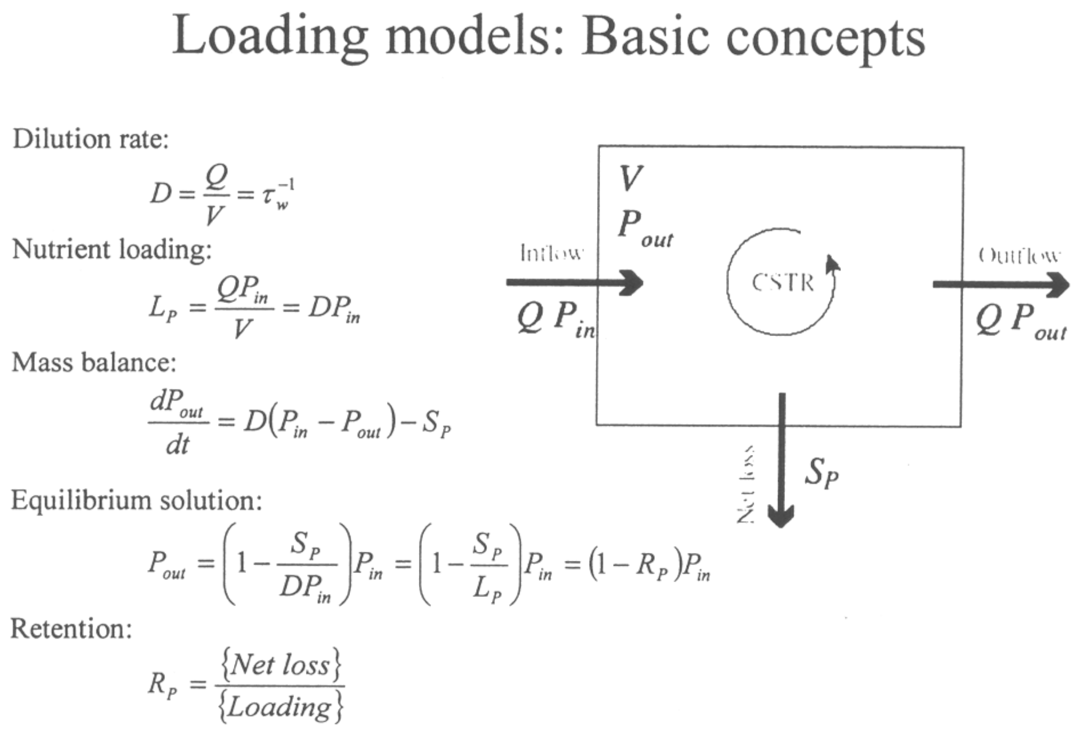
Stockner, J.G., K.S. Shortreed, E.A. MacIsaac , and B.H. Nidle. 1993. The limnology of Kitlope lake: a cold, glacially-turbid, sockeye salmon (*Oncorhynchus nerka*) nursery lake. Can. Tech. Rep. Fish. Aquat. Sci. 1909: 35p.

Stockner, J.G., E. Rydin, P. Hyenstrand. 2000. Cultural Oligotrophication. Fisheries 25: 7-14.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Inst. Ital. Idrobiol. 33: 53-83

Webster, J. R. and J.L. Meyer. 1997. (ed.) Stream organic matter budgets. Journal of North American Benthological Society 16: 4-161).

**7.0 Appendix 1.**



# Loading models: Basic concepts

Dilution rate:

$$D = \frac{Q}{V} = \tau_w^{-1}$$

Nutrient loading:

$$L_P = \frac{QP_{in}}{V} = DP_{in}$$

Mass balance:

$$\frac{dP_{out}}{dt} = D\left(P_{in} - P_{out}\right) - S_P$$

Equilibrium solution:

$$P_{out} = \left(1 - \frac{S_P}{DP_{in}}\right)P_{in} = \left(1 - \frac{S_P}{L_P}\right)P_{in} = \left(1 - R_P\right)P_{in}$$

Retention:

$$R_P = \frac{\{Net\ loss\}}{\{Loading\}}$$