

Water and Sediment Quality in the Nechako River (British Columbia, Canada): The Synergistic Effects of Point-Source Effluents, Historic Flow Reductions and Submerged Macrophytes

By

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For

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For more information on white sturgeon-related issues and ecology, please visit the Nechako White Sturgeon Recovery Initiative website at: <http://www.nechakowhitesturgeon.org/sturgeon/>

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Sincerely,

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Summary

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the white sturgeon (*Acipenser transmontanus*) as Endangered (species facing imminent extirpation or extinction) in late November 2003. The Nechako River White Sturgeon Recovery Initiative has recently completed a draft final recovery plan for the Nechako (central British Columbia) population that identified excessive rooted macrophyte growths and associated water quality issues as one of several factors that may be having adverse effects on survival and/or reproduction of the species. The objectives of this project were to use existing databases on macrophyte distributions, water and sediment quality to describe current conditions in the Nechako River, with emphasis on the reach between the Stuart River confluence and Vanderhoof where white sturgeon have historically been most abundant.

The primary conclusions of this study were:

1. Rooted macrophytes were most abundant in the Nechako River between the Stuart River confluence and Vanderhoof (often growing to the surface for >50% of river cross section), and macrophyte cover maxima in this section of river have increased significantly over the period 1991 to 2000,
2. The Vanderhoof sewage discharge was having a measurable, and substantial, impact on water quality in terms of specific conductivity (a measure of total ionic impurities), and chloride (Cl⁻), total dissolved phosphorus (Tot-P_{diss}, P fraction that will pass through a 0.45- μ m filter), un-ionised ammonia (NH₃-N), nitrite + nitrate (NO₂+NO₃), and total chemical impurity (TCI) concentrations,
3. Medium- and high-density rooted macrophyte beds in the reach between the Stuart River confluence and Vanderhoof were substantially increasing NH₃-N and Tot-P_{diss} concentrations relative to open-water control sites (adjacent sites in the thalweg where rooted macrophytes had not established), but appeared to be reducing total dissolved zinc (Tot-Zn_{diss}, Zn fraction that will pass through a 0.45- μ m filter) concentrations,
4. Concentrations of 2-methyl-naphthalene (two fused benzene rings methylated on C-2 (likely from a petroleum source)), total oil & grease hydrocarbons, arsenic, iron and nickel in bottom sediments in the section of river between the Stuart River confluence and Vanderhoof often exceeded provincial criteria for the protection of aquatic life.

A conceptual model describing long-term changes in water and sediment quality in the Nechako River is proposed. The model is based on the succession of the macrophyte community and sediment loadings from channel avulsions in the upper watershed.

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Introduction

In 1990, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) classified white sturgeon (*Acipenser transmontanus* Richardson) federally as a Species of Special Concern (species particularly sensitive to human activities or natural events). Based on the results of recent (mid-1990s to present) population assessments, COSEWIC officially redesignated white sturgeon to Endangered status (species facing imminent extirpation or extinction) in late November 2003. This designation is more in-line with those of the U.S. Fish & Wildlife Service, who list the Columbia-Kootenai (Idaho, Washington and Montana) population as Endangered, and British Columbia (B.C.) Conservation Data Centre, who designate the upper Columbia (south-eastern B.C.) and Nechako (north-central B.C.) populations as red-listed (Critically Imperilled).

The provincial government of B.C. has recognised for more than a decade that white sturgeon populations have been declining, and has led the design and implementation of research on the biology, habitat sensitivities, and conservation of the species. In September 2000, the provincial government initiated a white sturgeon recovery planning processes for the upper Columbia and Nechako populations that are consistent with the requirements of the federal *Species at Risk Act* (SARA, Bill C-5). A recovery plan for the Nechako white sturgeon population has recently been completed, and two committees are responsible for its implementation: (1) the Recovery Team (formed in September 2000), and (2) the Action Planning Group (formed in April 2001), and together they are known as the Nechako White Sturgeon Recovery Initiative (see <http://www.nechakowhitesturgeon.org/sturgeon/>).

There is anecdotal and model-based evidence that the rooted macrophyte community in the Nechako River has expanded greatly, particularly between the Stuart River confluence and Vanderhoof where white sturgeon have historically been most abundant, since the Kenney Dam was completed in the early 1950s (French & Chambers 1997). Excessive macrophyte growths and their probable impacts on water quality have been identified as one of several factors that may be having adverse effects on white sturgeon in the Nechako River. The primary objectives of this project were:

1. To compare current (2000) macrophyte distributions in the Nechako River to past (1991) distributions,
2. To determine how dense macrophyte growths in the river segment between the Stuart River confluence and Vanderhoof are affecting water chemistry from data collected in 2000,
3. To use existing databases (1982-1995) to describe longitudinal trends in water quality in the Nechako River in relation to point-source discharges,

4. To survey bottom sediments in the Nechako River between the Stuart River confluence and Vanderhoof for organic and inorganic contaminants that may affect white sturgeon survival and reproductive success (autumn 2004 surveys).

A conceptual model describing long-term changes in water and sediment quality in the Nechako River is proposed. The model is based on the succession of the macrophyte community and sediment loadings from channel avulsions in the upper watershed.

Study Area

The Nechako River (Figure 1), being about 290 km in length and having an average annual flow of 9×10^9 m³, is one of the largest tributaries of the Fraser River which drains 25% of mainland British Columbia. The Nechako watershed lies entirely within a subboreal pine-spruce biogeoclimatic zone and has an area of about 3,131,25 ha, of which 85% is forested and 8% is farmed (Dorcey & Griggs 1991). Soils in the watershed are of sedimentary and volcanic origin (Dorcey & Griggs 1991). Following the construction of the Kenney Dam in the early 1950s, flows to the Nechako Canyon were blocked with the water being backed into a 906-km² reservoir located upstream of the canyon (Figure 1). Water required for power generation is removed from the west end of the reservoir and diverted through a tunnel to the coast and over a 792-m fall to the Pacific Ocean. Water not needed for power generation is released into the Cheslatta River via an overflow spillway (Skins Lake Spillway) (Figure 1); thus, the outflow of Cheslatta Lake is now, effectively, the beginning of the Nechako River. The present Nechako River flows northeast from the Cheslatta River inflow for 83 km to the village of Fort Fraser and then northwest for 4.5 km to where it converges with the Nautley River which drains Fraser and Francois lakes. The Nechako then flows southeast for 196 km to where it joins the Fraser River at Prince George (population 80,000). Between its confluence with the Nautley River and Prince George, the Nechako River flows through the town of Vanderhoof and is joined by its largest tributary, the Stuart River (Figure 1).

Sewage releases from Vanderhoof (population 4,000) and Fort Fraser (population 500) are presently the only significant point-source effluents to the Nechako River. French & Chambers (1995) estimated that these communities contribute, respectively, about 1,600 and 200 kg of total phosphorus and 4,000 and 6,000 kg of dissolved inorganic nitrogen (Σ NO₂, NO₃, total ammonia) to the river annually; however, full chemical characterisations of these effluents are not readily available. Fertilisers are applied to the Nechako watershed at a rate of about 4,000 tonnes/year (Dorcey and Griggs 1991). Diffuse sediment sources to the Nechako River likely include poorly-functioning road and rail crossings over the mainstem and tributaries, sparsely vegetated industrial and residential properties, and poorly-functioning riparian zones in agricultural sub-

basins; however, such sediment sources have yet to be quantified. The most-substantial mass input of sediment to the Nechako River occurred nine years after the completion of the Kenney Dam. In 1961, the Cheslatta River, which enters the Nechako River immediately downstream of the mostly-dry Nechako Canyon (Figure 1), shifted course and flowed through a previously dry gully from which it eroded about $0.9 \times 10^6 \text{ m}^3$ of sediment comprised of pebbly gravels, sands and silts (NHC 2003a,b). About $\frac{1}{2}$ of the sediment from the Cheslatta River avulsion was deposited in the Nechako Canyon to form what has been referred to as the Cheslatta Fan, with the other $\frac{1}{2}$ being transported varying distances downstream. The avulsion channel has since been blocked, so the Cheslatta River now enters the Nechako channel at its original point of entry.

Analyses of long-term flow records (Water Survey of Canada Station 08JC001 for periods 1948-1951 and 1980-2001) show that regulation by the Kenney Dam has reduced winter flows at Vanderhoof by more than 50% and spring and early summer flows by about 75% (Figure 2). Moreover, regulation has substantially altered flow periodicity. Prior to the construction of the Kenney Dam, spring flows in the Nechako River were at a maximum during spring snowmelt and early summer with this timing in flow maxima coinciding with unregulated rivers in the region (Figure 2). However, flow maxima in the Nechako River now occur from late July through August (Figure 2). There are presently concerns that flows in the Nechako River upstream of the Stuart River inflow are not high enough to effectively assimilate nutrients and other wastes entering the river at Vanderhoof, and that reduced current velocities, in combination with N- and P-based nutrient loads from Vanderhoof, have resulted in excessive rooted macrophyte growths (e.g., French & Chambers 1997). There is also evidence that low post-diversion flows could not effectively flush sediments from the Cheslatta avulsion out of the Nechako system. Surveys indicate that a high proportion of the avulsion sediments has deposited to the bottom of the Nechako River channel upstream of the Stuart River inflow. It has been suggested that these sediments have covered critical white sturgeon spawning habitat/substrates and are a primary initiating cause of recruitment failure (NWSRT 2003). As described below, the avulsion sediments may have also affected benthic invertebrate populations (including mussels, which are thought to be an important food source for white sturgeon) by direct burial and by affecting habitat quality, and worked synergistically with nutrient loads from Vanderhoof to stimulate excessive macrophyte growth.

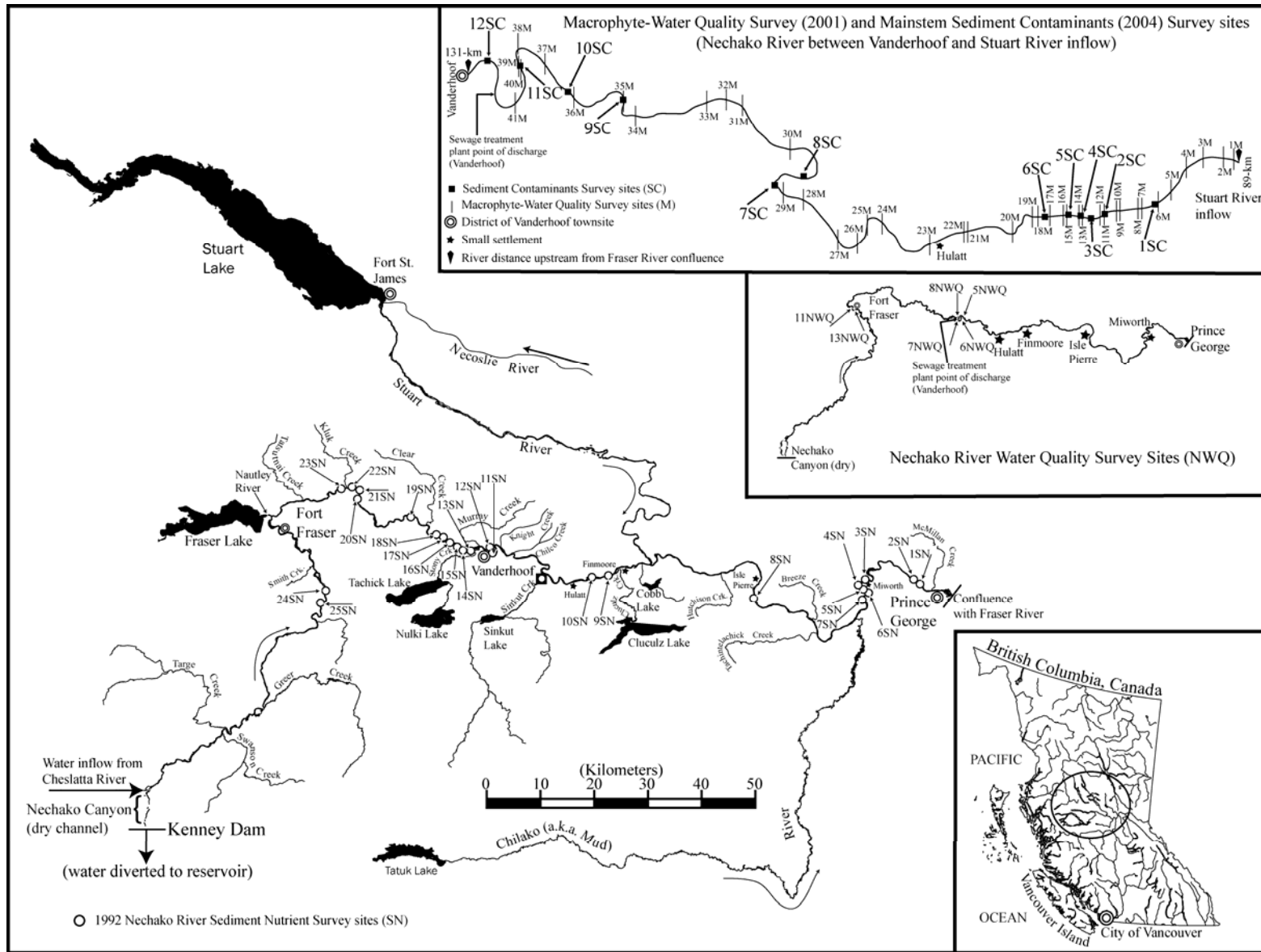


Figure 1. The Nechako River, British Columbia, showing the distribution of water and sediment monitoring sites referred to in this report.

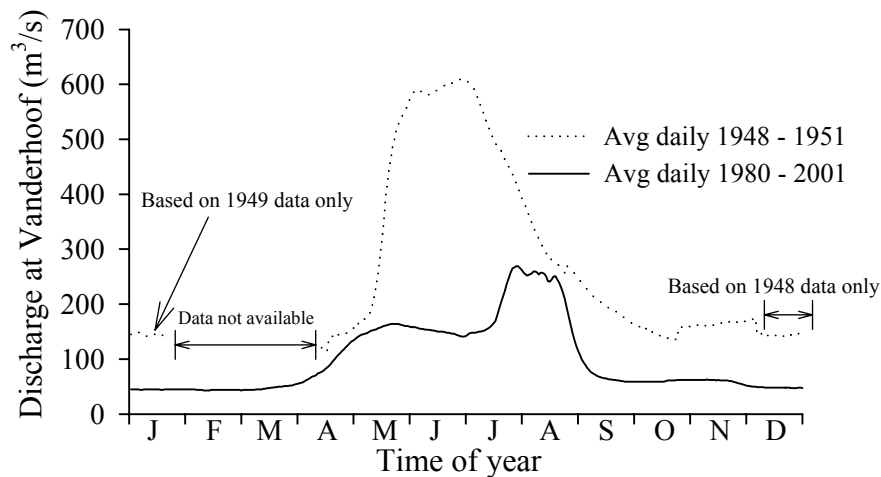


Figure 2. Discharge hydrographs of the Nechako River at Vanderhoof (Water Survey of Canada Station 08JC001) under natural conditions (1948-1951) versus present conditions (1980-2001).

Materials & Methods

Macrophyte Community

The large-scale distribution of rooted aquatic macrophytes in the Nechako River was determined from two aerial surveys done during autumn low-flows: one on September 11, 1991 (flow at Vanderhoof = 56.2 m³/s) and the other on September 15, 2000 (60.2 m³/s). In 1991, the Nechako River was filmed continuously between the Stuart River confluence and the Highway 27 bridge (10 km upstream of Vanderhoof) from a helicopter flying at a constant speed at 60-m altitude. Filming between the Highway 27 bridge and the Nautley River confluence focussed on capturing representative conditions because macrophyte densities, as observed from the air, were low in this section of the river. The surface area of the river covered by macrophytes was measured from each frame of the film with the DOS-based computer program Video Imaging Processing System (VIPS). A total of 309 frames from the 1991 aerial survey were digitised, allowing for the production of a nearly continuous overview of the macrophyte distribution for the river segments flown. In 2000, the survey focussed on the segment between the Stuart River confluence and Vanderhoof Bridge. The river was flown at a near-constant rate (100 km/hour) at an altitude of about 880 m, with the production of 85 full-channel width frames. The surface area of the river covered by macrophytes was measured from each frame with the image analysis software Northern Exposure (Empix Imaging Inc.).

Cover estimates within each survey year (1991 and 2000) were grouped by range:

- all data (cover estimates from each video frame),
- low cover (25th-50th quartile of observed covers),

- medium cover (50th-75th quartile of observed covers), and
- high cover (75th-100th quartile of observed covers).

To determine whether the extent of macrophyte coverage had changed in the river section between Vanderhoof and the Stuart River inflow over the period 1991 to 2000, t-tests ($\alpha = 0.05$) were used to compare the average covers observed within each range (SPSS Inc. 2003).

In the year following the 1991 aerial survey, ground surveys were undertaken to quantify the major environmental conditions associated with macrophyte biomass in the Nechako River between Prince George and about 1 km upstream of Fort Fraser (see French & Chambers (1996) for details). Twenty six sites (Figure 1) were selected from 1:50,000 maps to encompass a wide range of environmental conditions in terms of depth and current velocity. In August 1992, submerged macrophytes (excluding below-ground structures) were harvested using SCUBA from within three 0.1-m² quadrats placed haphazardly at 5-m intervals across the channel at each site. Collections proceeded from each bank to 10 m beyond the maximum depth of colonisation. Two sediment cores (4-cm diameter, 10-cm length) were also collected from within each quadrat. The cores were extruded on site and the top 5 cm were frozen until grain size and nutrient analyses were performed. Current velocity was measured at each collection site with a Price AA current meter. For depths > 1.5 m, velocity was measured at three depths: (1) surface (0.8 × total depth), (2) mid-depth (0.5 × total depth) and (3) bottom (0.2 × total depth). For depths < 1.5 m, velocity was measured only at mid-depth. Average current velocity was calculated at sites > 1.5-m depth as the mean of the three readings at the surface, mid-depth and bottom.

In the laboratory, macrophyte samples were cleaned with tap water to remove debris, sorted to species using descriptions in Warrington (1980), dried at 80 °C to constant weight, and weighed to the nearest 1 g. Biomass at each collection site was calculated by averaging the biomass of the three replicates. The grain size distribution of bottom sediments was determined with a Malvern 2600L laser grain size analyser for 100 sediment samples selected to encompass sites covering the full range of observed current velocities. Sediment samples were wet sieved through a 1.5-mm sieve into the water bath of the laser analyser. Disaggregation of the sediment samples was achieved by both mechanical stirring and ultrasonic dispersion. Three distributions were measured on each sample and the results averaged for each collection site. Exchangeable nitrogen ($N_{\text{exch.}}$) and phosphorus ($P_{\text{exch.}}$) concentrations were determined in duplicate for the same sediment samples that were analysed for grain size distribution. $P_{\text{exch.}}$ was extracted from 0.25 g of homogenised wet sediment by shaking for 16 hr in 25 ml of 0.1N NaOH + 0.1N NaCl (after Williams *et al.* 1967) and measured spectrophotometrically (Murphy and Riley 1962). $N_{\text{exch.}}$ was extracted from 4 g of homogenised wet sediment by shaking for 1 hr in 40 ml of 2M KCl (Bremner 1965) and measured spectrophotometrically as ammonium (Solorzano 1969).

Water Chemistry & Point Source Effluents

The effects that the Vanderhoof and Fort Fraser sewage discharges are having on water chemistry were assessed by comparing the chemistry observed in the Nechako River over the period 1982 to 1995 at six sites where samples had been collected regularly by B.C. Ministry of Water, Land and Air Protection (Figure 1):

- Site 5NWQ (NWQ stands for “Nechako Water Quality” for Figure 1 site references) - Nechako River 2 km downstream of Vanderhoof sewage discharge,
- Site 6NWQ - Nechako River 500 m downstream of Vanderhoof sewage discharge,
- Site 7NWQ - Nechako River 100 m downstream of Vanderhoof sewage discharge (initial dilution zone),
- Site 8NWQ - Nechako River upstream of Vanderhoof (control site),
- Site 11NWQ - Nechako River 200 m downstream of Fort Fraser sewage discharge, and
- Site 13NWQ - Nechako River 200 m upstream of Fort Fraser sewage discharge.

As inferred from the provincial EMS (Environmental Monitoring System) database, water samples from these sites were typically collected in “runs”, when each (or most) of the sites were sample on a single day or, as sometimes occurred, over a two-day period. Although water samples from these sites were periodically analysed for metals and, very rarely, for organic compounds, only the following biologically-relevant parameters have been measured frequently enough that upstream-downstream trends could be determined: (1) sp. conductivity (conductivity @ 25 °C), (2) Cl⁻ (chloride), (3) NH₃-N (un-ionised ammonia), (4) NO₂+NO₃ (nitrite+nitrate), (5) Tot-P_{diss} (total dissolved phosphorus), and (6) pH. Water chemistry data were partitioned by month to permit the comparison of water quality at the sampling sites on a seasonal basins, and so that NWSRI biologists can infer water quality conditions that occur in association with any white sturgeon reproductive behaviour and/or events.

Sp. conductivity was used to infer upstream-downstream trends in non-specific total chemical impurities (TCI as Σ (totals fraction concentrations) F, Cl, NO₂+NO₃, P, Li, Na, Mg, Ca, Sr, Ba, Sb, As, Al, U, Cu, Fe, Pb, Mn, Mo, V and Zn) in mg/L. To permit this, a regression-based predictive relationship between sp. conductivity and TCI was developed from extensive chemistry datasets available for 31 natural waters (mixture of surface and ground waters) in the Omineca-Peace region and applied to the Nechako River. From the regression model, TCI was computed from measures of conductivity for the Nechako River sites to infer changes in total ionic impurity caused by the incompletely-characterised sewage effluents.

Water Chemistry & Macrophytes

Forty one of the year-2000 aerial-flyover sites used in the estimation of macrophyte bottom cover were randomly selected to test the hypothesis that macrophyte stands of high and medium density (relative scale) are affecting water quality in the Nechako River (Figure 1 - see sites with suffix “M” for “macrophyte study

sites”). Sp. conductivity, pH and temperature (YSI Model 63 multimeter), and O₂ concentration (OxyGuard Handy Meter MkIII) were measured at 20-cm intervals from the surface to the bottom within selected macrophyte stands (treatment groups) and at open-water control sites (adjacent sites in the thalweg where rooted macrophytes had not established) over the period September 26 to October 6/2004. Water samples were collected from mid-depth at treatment and control sites with a horizontal student-point bottle, and analysed for dissolved metals (ICP-MS), Tot-P_{diss}, NH₃-N, Tot-Hardness_{diss} using the standard methods described in Greenburg *et al.* (1992). Samples for the analysis of dissolved fractions were filtered (0.45 µm) in the field immediately following collection.

The physical and chemical properties of within-stand and control sites were compared with t-tests ($\alpha = 0.05$) (SPSS Inc. 2003).

Bottom Sediment Chemistry

Bottom sediment samples were collected from 12 littoral sites (often within macrophyte stands) between Finmoore and Vanderhoof (Figure 1) over the period November 5 to November 15/2004:

- Site 1SC (SC stands for “Sediment Contaminants” for Figure 1 site references) - Nechako River 1 km downstream of Finmoore,
- Site 2SC - Nechako River 1.5 km upstream of Finmoore,
- Site 3SC - Nechako River 2 km upstream of Finmorre,
- Site 4SC - Nechako River 2.5 km upstream of Finmoore,
- Site 5SC - Nechako River 3 km upstream of Finmoore,
- Site 6SC - Nechako River 3.5 km upstream of Finmoore,
- Site 7SC - Nechako River 100 m downstream of Sinkut Creek inflow,
- Site 8SC - Nechako River 1 km upstream of Sinkut Creek inflow,
- Site 9SC - Nechako River at km 125,
- Site 10SC - Nechako River 5 km downstream of Vanderhoof sewage discharge,
- Site 11SC - Nechako River 2 km downstream of Vanderhoof sewage discharge, and
- Site 12SC - Nechako River 1 km upstream of Vanderhoof sewage discharge.

Sediments were collected with an Ekman dredge that was cleaned with acetone at the beginning of each sampling day and rinsed with river water between each sample collection. Sediment was transferred from the dredge with clean spoons (non-contaminating materials) into one sample jar for the analysis of extractable petroleum hydrocarbons, total organic carbon and pesticides (organochlorine- and organophosphorus-based), another jar for metals, and into a tissue cup for the analysis of grain-size distribution. Silt (>0.004 mm - <0.063 mm) and clay (<0.004 mm) fractions were homogenised and analysed for the following parameter

classes using methods similar to those described in Greenburg *et al.* (1992): metals (ICP-MS), organic and inorganic carbon (loss on ignition), non-chlorinated phenols, phenoxy-acid herbicides, organochlorine and organophosphorus pesticides, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, miscellaneous semivolatile organics, volatile organics including trihalomethanes, and chlorinated aliphatics (all by GC/MS).

Mat-Sorb Contaminant Adsorption

The EMS database indicates that a trial contaminants-adsorption experiment was undertaken in storm sewer #89 (Cameron Street, Prince George) that discharges to the Nechako River near the Fraser River confluence. The experiment was undertaken over the period March 6 to December 12, 2000. From EMS, it was inferred that Mat-Sorb pads of woven materials similar to those shown in Plate 1 were placed in the storm sewer discharge for specific durations to determine whether they accumulated, by adsorption, hydrocarbon-based contaminants that may drain from the sewer and into the river (i.e., the pads were constructed of materials commonly used to clean up small petroleum spills). The experimental Mat-Sorb pads were placed in the sewer discharge for the following time periods that represent early spring, spring, early and late summer, early and late autumn, and early winter:

- March 6 - 21 (15 day trial),
- March 21 - April 6 (16 day trial),
- April 6 - April 19 (13 day trial),
- May 5 - June 7 (33 day trial),
- June 7 - June 26 (19 day trial),
- June 26 - July 19 (23 day trial),
- September 15 - October 16 (31 day trial),
- October 16 - December 12 (57 day trial).

After retrieval from the storm sewer, the Mat-Sorb pads were analysed for extractable hydrocarbons and total oil & grease hydrocarbons by GC/MS. The rate of adsorption was estimated by dividing the mass of extractable hydrocarbons/oil & grease adsorbed by the days of exposure to the storm sewer discharge. The silt + clay fraction of bottom sediments directly in the path of the storm sewer discharge were similarly analysed to determine whether the hydrocarbons adsorbed to the pads were comparable to those adsorbed to natural sediments.



Plate 1. Mat-Sorb pads used to test storm sewer waters for the presence of petroleum hydrocarbons.

Results & Discussion

Macrophyte Community

Average (± 1 S.D.) macrophyte bottom cover between the Stuart River confluence and Vanderhoof was $14 \pm 12\%$ in 1991 and $16 \pm 14\%$ in 2000 (Figure 3). The average difference of $+2\%$ was not statistically significant at $\alpha = 0.05$; however, the resulting P -value of 0.098 indicates that the difference was close to being significant. When cover estimates within each year were grouped by quartile, significant differences were detected. Average cover in the low range (25th-50th quartile) increased ($P < 0.001$) from 7% in 1991 to 9% in 2000, with this equating to an average difference of $+2\%$ (Figure 3). Average cover in the high range (75th-100th quartile) also increased ($P = 0.010$), being 30% in 1991 and 35% in 2000 ($+5\%$). While low and high range cover appears to have increased between 1991 and 2000, cover in the medium range (50th-75th quartile) appears to have decreased ($P = 0.013$) slightly (-1%) over time, being 17% in 1991 and 16% in 2000 (Figure 3). It is possible that medium sized stands expanded (by growth) into the high range category over the time period, with this explaining why the high range stands expanded the most ($+5\%$) over the time period and why cover in the medium range apparently decreased. Closer examinations of the data indicate that bottom cover has increased primarily in river segments immediately upstream of the Finmoore island and immediately downstream of the Vanderhoof sewage discharge.

The highest macrophyte biomasses in 1992 were observed in river segments having bottom sediments composed primarily of fine (440 ± 444 g/m²) and medium (431 ± 445 g/m²) silts, with the lowest biomasses typically observed in areas having sediments composed of textures larger than very fine sand ($P < 0.001$) (Figure 4a). The observed distribution of macrophyte biomass along the sediment texture gradient was largely driven by the dominant canopy-forming taxa: *Elodea canadensis*, *Potamogeton richardsonii*, *Myriophyllum exalbescens*, and *Ceratophyllum demersum* that were most predominant on silty substrates, such that some of the more minor, in terms of biomass, sub-canopy species were actually more abundant on

sandy (e.g., *Ranunculus aquatilis*, *Chara* spp., and *Potamogeton berchtoldii*) to rocky (e.g., mosses) substrates (Table 1).

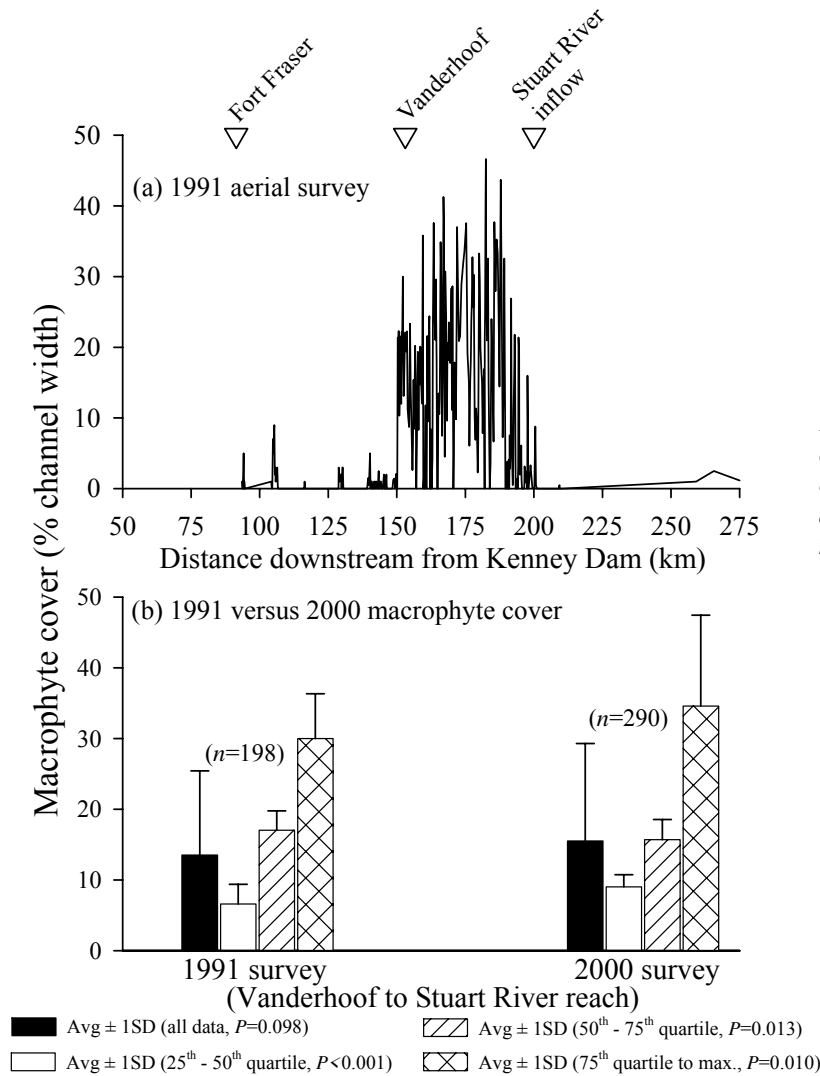


Figure 3. Percent macrophyte bottom cover in the Nechako River in 1991 (a) and changes in bottom cover between the 1991 and 2000 aerial surveys (b). Panel (a) was modified from French & Chambers (1997).

The distribution of sediment texture classes in the Nechako River were strongly associated ($P<0.001$) with current velocity profiles, such that silts were observed at sites having average velocities <0.2 m/s and textures larger than very fine sands at velocities >0.2 m/s (Figure 4b), with this sediment texture sorting most likely due to the lesser ability of slower waters to suspend and move larger particles. The high macrophyte biomasses observed in river segments having silty sediments may, therefore, be the result of the lower shear stresses (i.e., mechanical forces) applied to macrophytes from slower moving waters, but could also be related to the higher nitrogen and phosphorus (important plant nutrients) exchange capacities of fine sediments compared to coarser sediments (e.g., Chambers *et al.* 1991; Madsen *et al.* 2001) (Figure 5). However, defining the precise, or cause and effect, relationship between macrophyte distributions/biomass

and sediment texture/current velocity conditions is made somewhat spurious by the fact that the presence of macrophytes can, in turn, reduce current velocities and cause fine-sediment deposition which, in turn, results in increased substrate nutrient availability (Gregg & Rose 1982; Madsen & Warncke 1983; Machata-Wenninger & Janauer 1991; Petticrew & Kalff 1992). Thus, there is a degree of debate regarding which came first: macrophytes, or nutrient-rich habitat that is suitable for macrophyte growth.

Anecdotal information provided by long-term residents and biologists in the region indicate that the macrophyte community in the Nechako River has indeed expanded substantially since the river was dammed in the early 1950s (French & Chambers 1997). It is quite likely that the apparent expansion has been the result of the synergistic effects of severe flow reductions and nutrient inputs from Vanderhoof (see below). Based on equations provided in French & Chambers (1997), it is clear that current velocities in the Nechako River have decreased by more than ½ since the river was dammed (Figure 6). This reduction in velocity would have increased the rate of fine sediment deposition (including fine sediments contributed by Cheslatta channel avulsions), particularly in the lower gradient reaches upstream of the Stuart River confluence. Nitrogen, phosphorus and other nutrients released with Vanderhoof’s sewage could then adsorb to these fine sediments and increase the potential for macrophyte growth. As macrophytes colonised the low-gradient reach between the Stuart River and Vanderhoof, their physical presence would have further accelerated fine-sediment (and nutrient) deposition and macrophyte habitat expansion. Thus, it is highly plausible that reduced velocities caused by the Kenney Dam in combination with fine-sediment loadings from the Cheslatta avulsion and nutrient-rich effluents have been directly responsible for the present problems with macrophytes downstream of Vanderhoof.

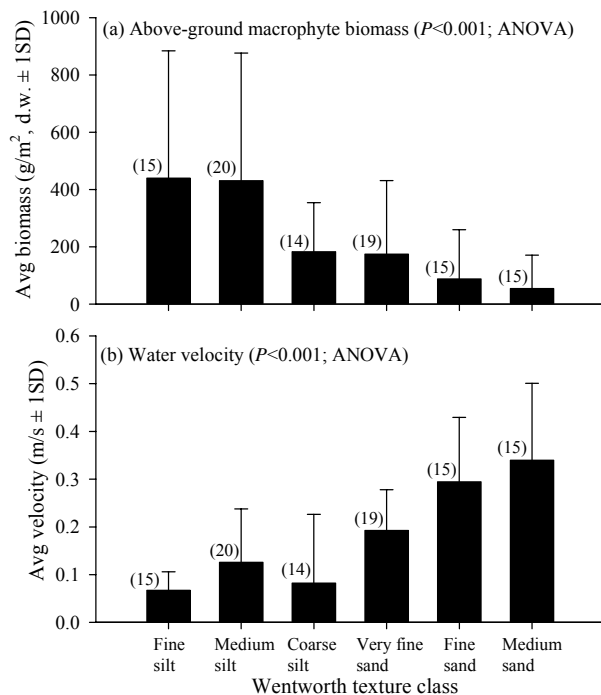


Figure 4. Macrophyte biomass in relation to Wentworth sediment texture class (a) and sediment texture class in relation to current velocity (b) in the Nechako River.

Table 1. Percentage of total mass for each observed macrophyte taxon in relation to major bottom sediment texture classes (data from French & Chambers (1996)).

Taxon	Wentworth texture class		
	Silts (14-56 μm)	Sands (63-470 μm)	Bare rock
I. Group A taxa (pioneers ¹)			
Mosses	4%	19%	76%
<i>Ranunculus aquatilis</i>	26%	71%	4%
<i>Chara spp.</i>	35%	65%	0%
II. Group B taxa (intermediates ²)			
<i>Potamogeton berchtoldii</i>	49%	51%	0%
<i>Callitriche hermaphroditica</i>	57%	43%	0%
<i>Potamogeton gramineus</i>	66%	34%	0%
<i>Potamogeton pectinatus</i>	69%	31%	0%
III. Group C taxa (climax ³)			
<i>Elodea canadensis</i>	83%	17%	0%
<i>Potamogeton richardsonii</i>	84%	16%	0%
<i>Myriophyllum exalbescens</i>	86%	14%	0%
<i>Ceratophyllum demersum</i>	99%	1%	0%

In the context of this report:

¹pioneer taxa are defined as those that live primarily on coarse substrates (establish before bottom substrates have developed high silt/clay content)

²intermediate taxa are defined as those that live primarily on a mixture of silts and sands (establish after substrates have increased in silt content via deposition)

³climax taxa are defined as those that grow from the bottom to surface (canopy formers) and live mostly on very fine (silts) sediments (species are unlikely to be displaced by others as they form dense canopies that block light penetration)

A conceptual framework of macrophyte succession in the Nechako River is as follows:

- *Pioneers (Group A taxa)* - prior to the construction of the Kenney Dam in the early 1950s, current velocities in the Nechako River were substantially higher (Figure 6). Thus, based on relationships between current velocity and sediment texture (Figure 4), the texture of bottom sediments would have also been coarser prior to the construction of the dam. On the basis of this information, it would seem likely that the Nechako River macrophyte community would have been dominated by taxa that are most-associated with sandy substrates and bare rock, e.g., *Ranunculus aquatilis*, *Chara* and mosses (Table 1).
- *Intermediates (Group B taxa)* - Following the construction of the Kenney Dam, current velocities in the Nechako River decreased substantially (Figure 6). With decreased velocities, the river's ability to transport sediment would have declined exponentially. As a result, sedimentation rates would have

increased along the length of the river, but most substantially in wider segments of the river upstream of the Stuart River confluence. The Cheslatta avulsion occurred about 10 years after the Kenney Dam was completed. Therefore, sedimentation rates should have been particularly high for a few years following 1961 during which time the avulsion materials would have been sorted in an upstream-downstream gradient according to density. During the 1991 aerial macrophyte survey, extensive silty-sandy dunes were observed between the Stuart River confluence and Vanderhoof, and these dunes may have been associated with previous avulsions in the Cheslatta River channel. During the decades following the construction of the Kenney Dam and Cheslatta avulsions, the structure of bottom sediments in the Nechako River would have changed gradually over time. As indicated above, substrates composed of sands and rock would have been most common prior to 1952; however, after velocities were reduced and sediments were loaded to the system via the Cheslatta River, the dominant substrates would have gradually transformed to a mixture of silts and sands. Given this, the species composition of the Nechako River macrophyte community would have gradually shifted to favour species associated with silt-sand mixtures, e.g., *Potamogeton berchtoldii*, *Callitriche hermaphroditica*, *Potamogeton gramineus*, and *Potamogeton pectinatus* (Table 1).

- *Climax (Group C taxa)* - The physical presence of dense stands of Group B taxa (above) would have, in turn, further reduced current velocities. Reductions in current velocity associated with Group B species would have accelerated the deposition rate of very fine sediments (silts and clays) that have high nutrient adsorption capacities (Figure 5). As sediment textures within stands of Group B species changed from silt-sand mixtures to silts, canopy-forming, silt-associated species would have started to colonise and, over time, would have shaded out the Group B taxa. The Nechako River macrophyte community between Vanderhoof and the Stuart River confluence is now dominated by dense growths of four Group C taxa: *Elodea canadensis*, *Potamogeton richardsonii*, *Myriophyllum exalbescens*, and *Ceratophyllum demersum* (Table 1).

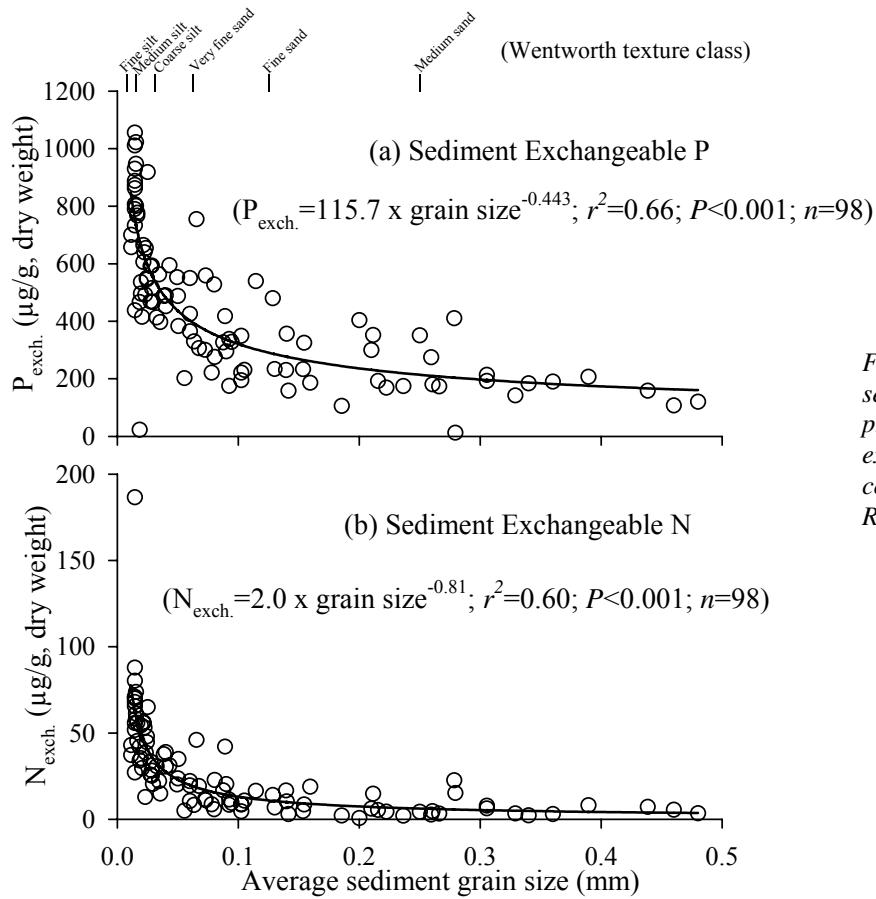


Figure 5. Relationship between sediment texture and exchangeable phosphorus ($P_{\text{exch.}}$) (a) and exchangeable nitrogen ($N_{\text{exch.}}$) (b) concentrations in the Nechako River.

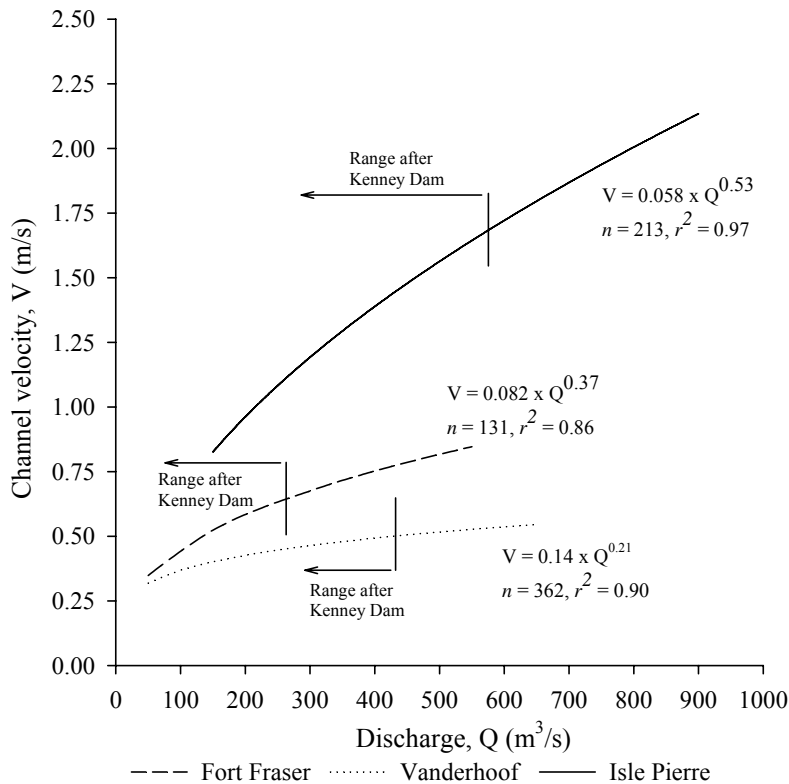


Figure 6. Modelled current velocity profiles in the Nechako River at Fort Fraser, Vanderhoof and Isle Pierre before and after the construction of the Kenney Dam (based on equations in French & Chambers (1997)).

The physical presence of dense and spatially extensive macrophyte stands in the Nechako River between the Stuart River confluence and Vanderhoof and their associated effects on sedimentation rates may be affecting white sturgeon success in the following ways:

1. By reducing current velocities, dense macrophyte stands are undoubtedly increasing sedimentation rates. The long-term settling of fine sediments is likely, over time, burying a proportion of the available hard substrates that white sturgeon eggs adhere to.
2. Observations by the author indicate that sediment deposited in littoral areas of the river have a tendency to cover over freshwater mussels (and possibly other sessile invertebrates) in the reach between the Stuart River and Vanderhoof. If these mussels (and other benthic organisms) are important food sources for juvenile and/or adult white sturgeon, such sediment deposition may be reducing available food resources.
3. Given points 1 and 2 (above) regarding increased sedimentation rates, it is possible that the increased rates of fine sediment deposition resulting from the physical presence of dense macrophyte beds are burying a proportion of viable white sturgeon eggs and/or are increasing the probability of egg and larvae suffocation.
4. Since fine sediments (i.e., silts and clays) have higher ion exchange capacities than coarse sediments, it is possible that the fine sediments deposited in dense macrophyte stands are increasing the storage of chemical contaminants in the reach (see below). This, in turn, has the potential to adversely affect white sturgeon eggs and larval development.
5. The presence of extensive macrophyte stands in the reach between the Stuart River confluence and Vanderhoof has likely reduced the availability of physical space for adult and juvenile white sturgeon, particularly during periods of low flow and during the winter months.

Water Chemistry & Point Source Effluents

The long-term longitudinal water chemistry profiles suggest that sewage from Fort Fraser is not having a measurable effect on water quality with respect to the regularly measured parameters (Figures 7-12). However, it is clear that the Vanderhoof sewage discharge is having a substantial effect on water chemistry, such that sp. conductivity (Figure 7), and Cl⁻ (Figure 8), NH₃-N (Figure 9), NO₂+NO₃ (Figure 10), and Tot-P_{diss} (Figure 11) concentrations were typically elevated 2- to 3-fold in the initial dilution zone of the Vanderhoof discharge at almost all times of the year, but particularly during periods of low flow (Figure 2). In contrast, the Vanderhoof sewage release does not appear to be having a measurable effect on pH (Figure 12).

By using sp. conductivity as a predictor of TCI (Figure 13), it was further determined that the Vanderhoof sewage discharge is substantially elevating ionic parameters in addition to those that have been measured on a regular basis. As shown in Figure 7, sp. conductivity upstream of Vanderhoof was typically about 70 $\mu\text{S}/\text{cm}$, with this equating to a TCI of 15 mg/L based on the regression equation shown on Figure 13. In comparison, sp. conductivity was typically about 140 $\mu\text{S}/\text{cm}$ in the initial dilution zone of the Vanderhoof sewage discharge, with this equating to a TCI of 29 mg/L (or nearly 2-fold that observed upstream). Increases in the concentrations of the regularly measured chemical parameters (ΣCl^- , $\text{NH}_3\text{-N}$, NO_2+NO_3 , and $\text{Tot-P}_{\text{diss}}$) account for about 30% of the increase in sp. conductivity observed in the initial dilution zone; thus, 70% of the TCI contributed at Vanderhoof are presently not quantified.

It has been argued (Pers. Comms. to T.D. French) that the chemical effects of the Vanderhoof sewage release are insignificant since the concentrations of released chemicals are similar to background concentrations downstream of the initial dilution zone (Figures 7-12). However, it is the author's belief that this argument is not valid in view of the potential adverse effects that these chemicals may be having at an ecosystem level. It must be acknowledged that Vanderhoof has been discharging sewage to the Nechako River for several decades, and the constituents of this sewage are not being exported (i.e., "disappearing") from the channel. Rather, it is a certainty that they are being transformed (either through organic or inorganic reactions) and stored within the channel. The reduced concentrations in contributed elements observed downstream of the initial dilution zone may be, in part, to dilution; however, it is also likely that some, if not most, of the constituents discharged from Vanderhoof are being stored within fine bottom sediments and/or within biota (e.g., macrophytes, filter-feeding invertebrates, fish, etc.) - many simplistic contaminant-fate models do not account for biological and physical uptake and storage. The dense macrophyte stands downstream of Vanderhoof provide direct evidence that materials discharged from Vanderhoof are being stored to some degree within biota (i.e., nutrients; however, toxic chemicals also have the potential for storage) and are being "scrubbed" out of the water column via sedimentation (i.e., why they are not measured in the water column downstream of the initial dilution zone). It is the contention of the author that present flow levels in the Nechako River upstream of the Stuart River inflow are insufficient to effectively flush and process effluent from Vanderhoof, particularly during low summer, autumn and winter flows.

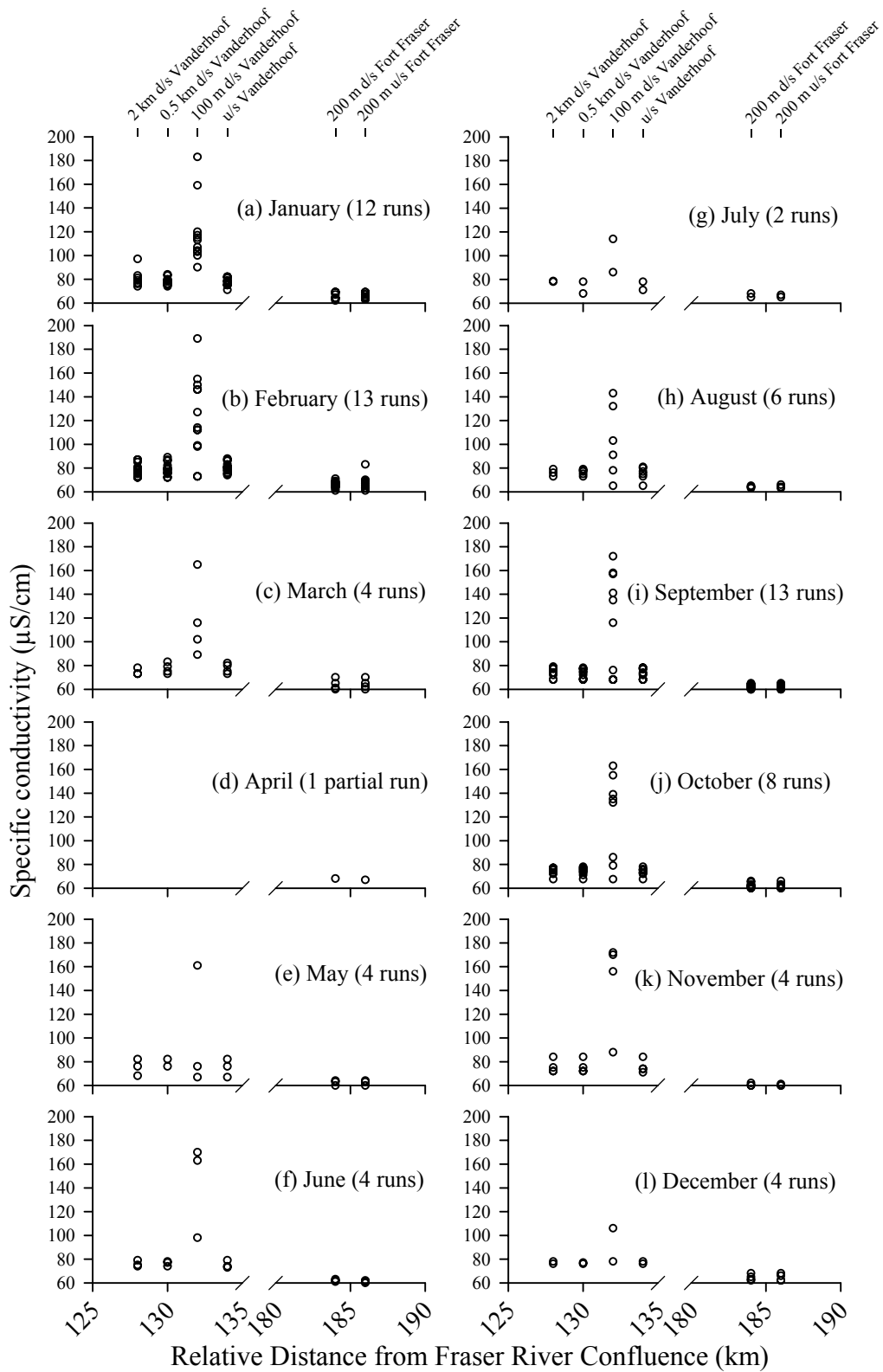


Figure 7. Upstream-downstream trends in *sp.* conductivity in the Nechako River over the period 1982 to 1995 (N = 378).

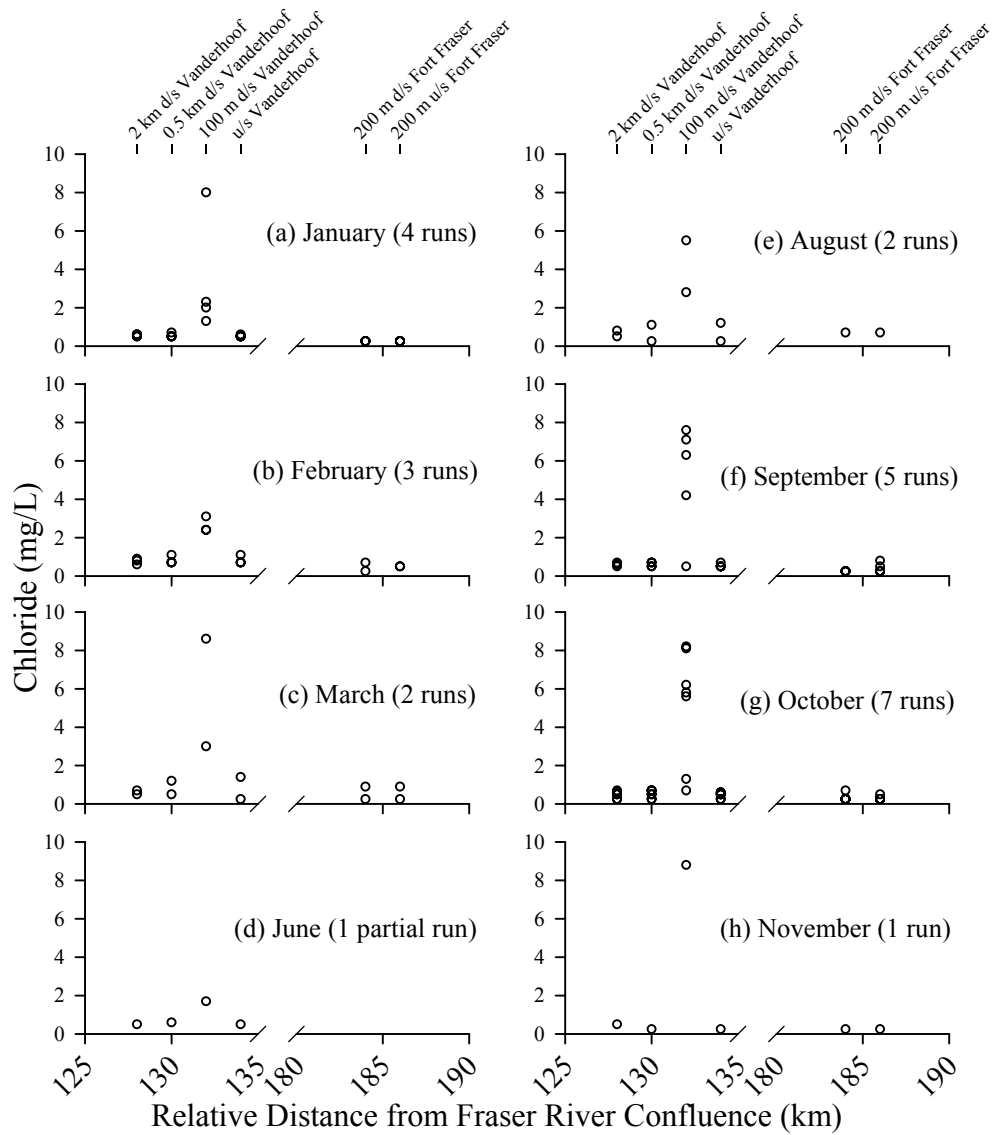


Figure 8. Upstream-downstream trends in Cl^- in the Nechako River over the period 1982 to 1993 (N = 146).

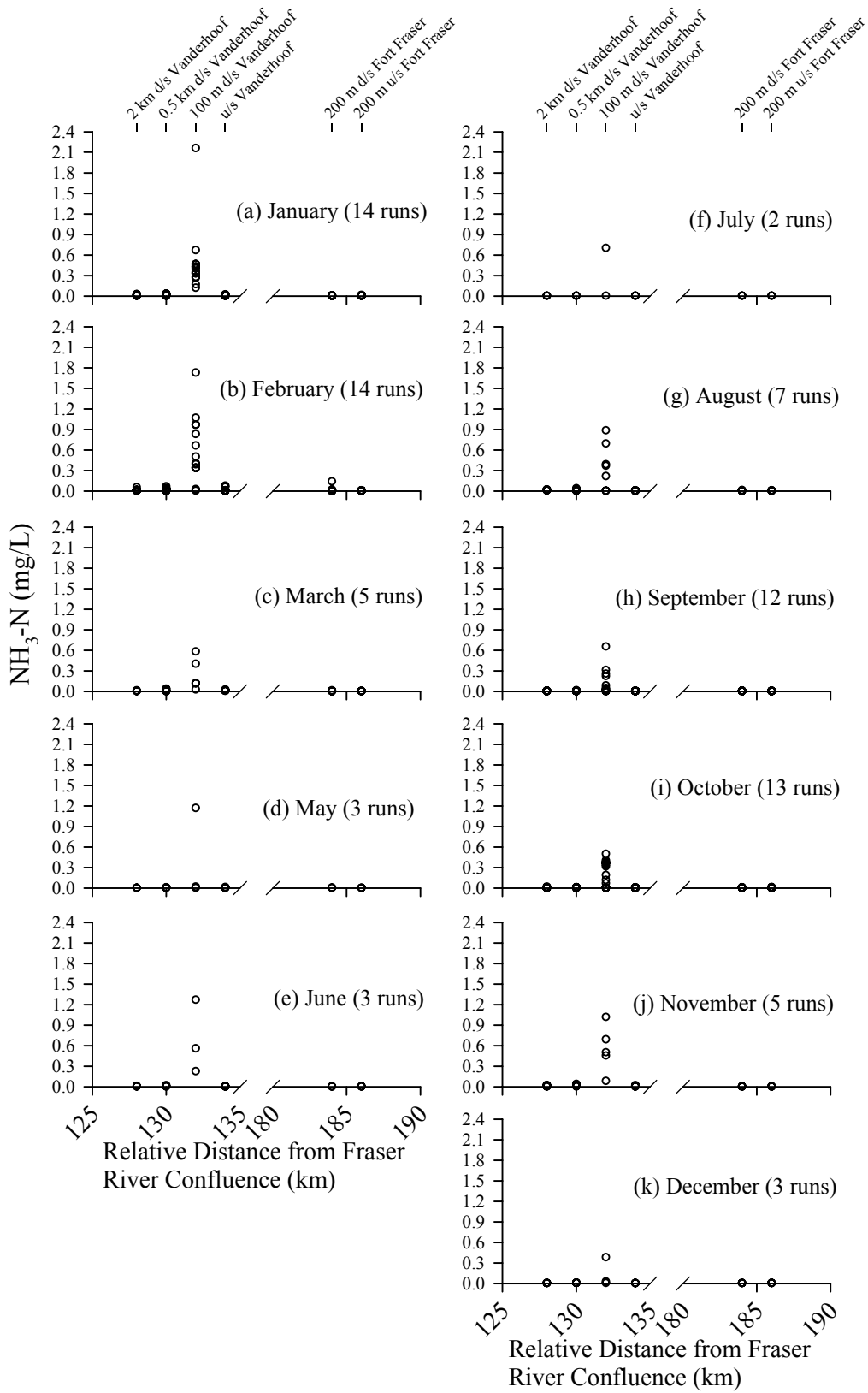


Figure 9. Upstream-downstream trends in $\text{NH}_3\text{-N}$ in the Nechako River over the period 1982 to 1995 (N = 470).

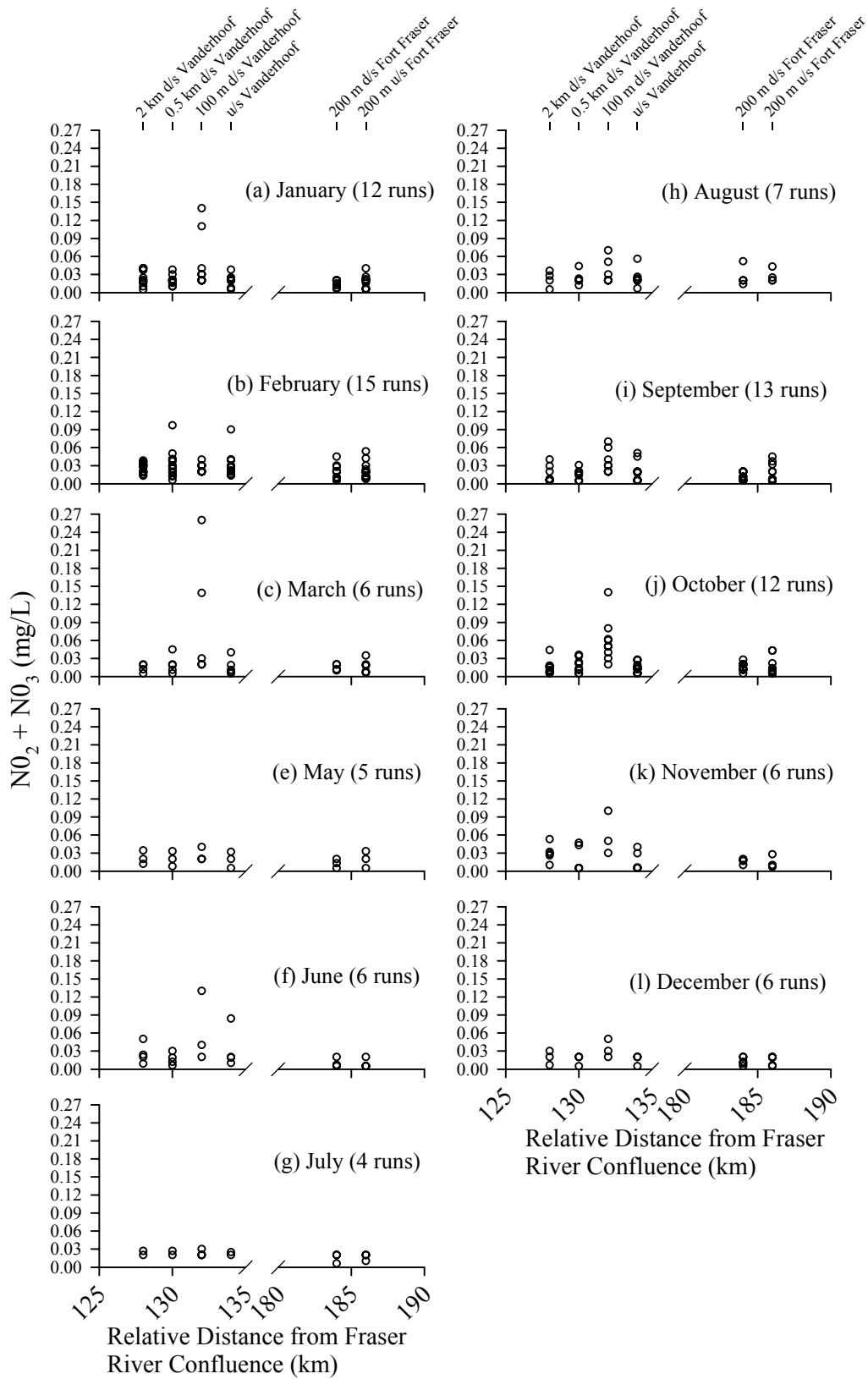


Figure 10. Upstream-downstream trends in $\text{NO}_2 + \text{NO}_3$ in the Nechako River over the period 1982 to 1995 (N = 420).

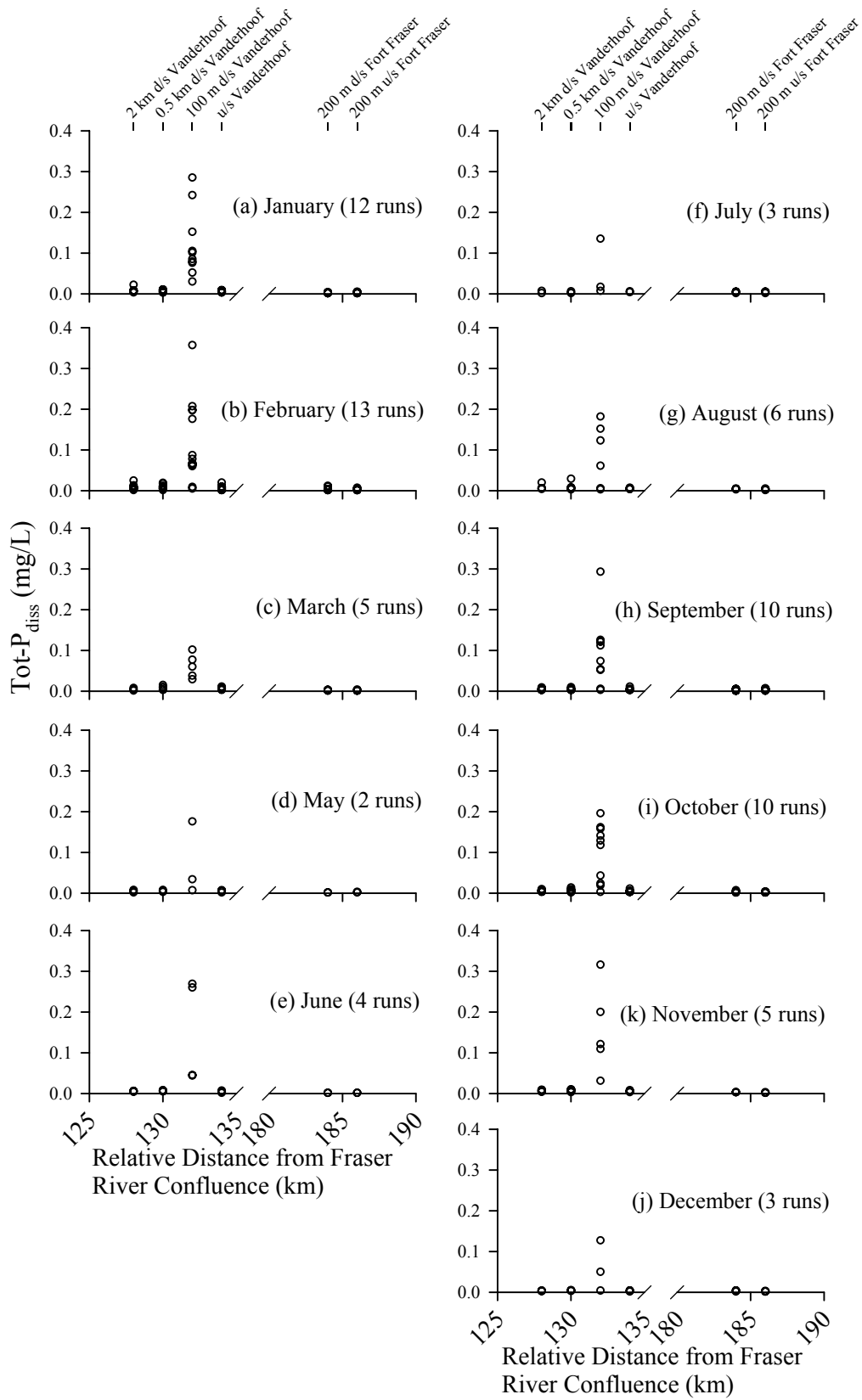


Figure 11. Upstream-downstream trends in $Tot-P_{diss}$ in the Nechako River over the period 1982 to 1995 (N = 393).

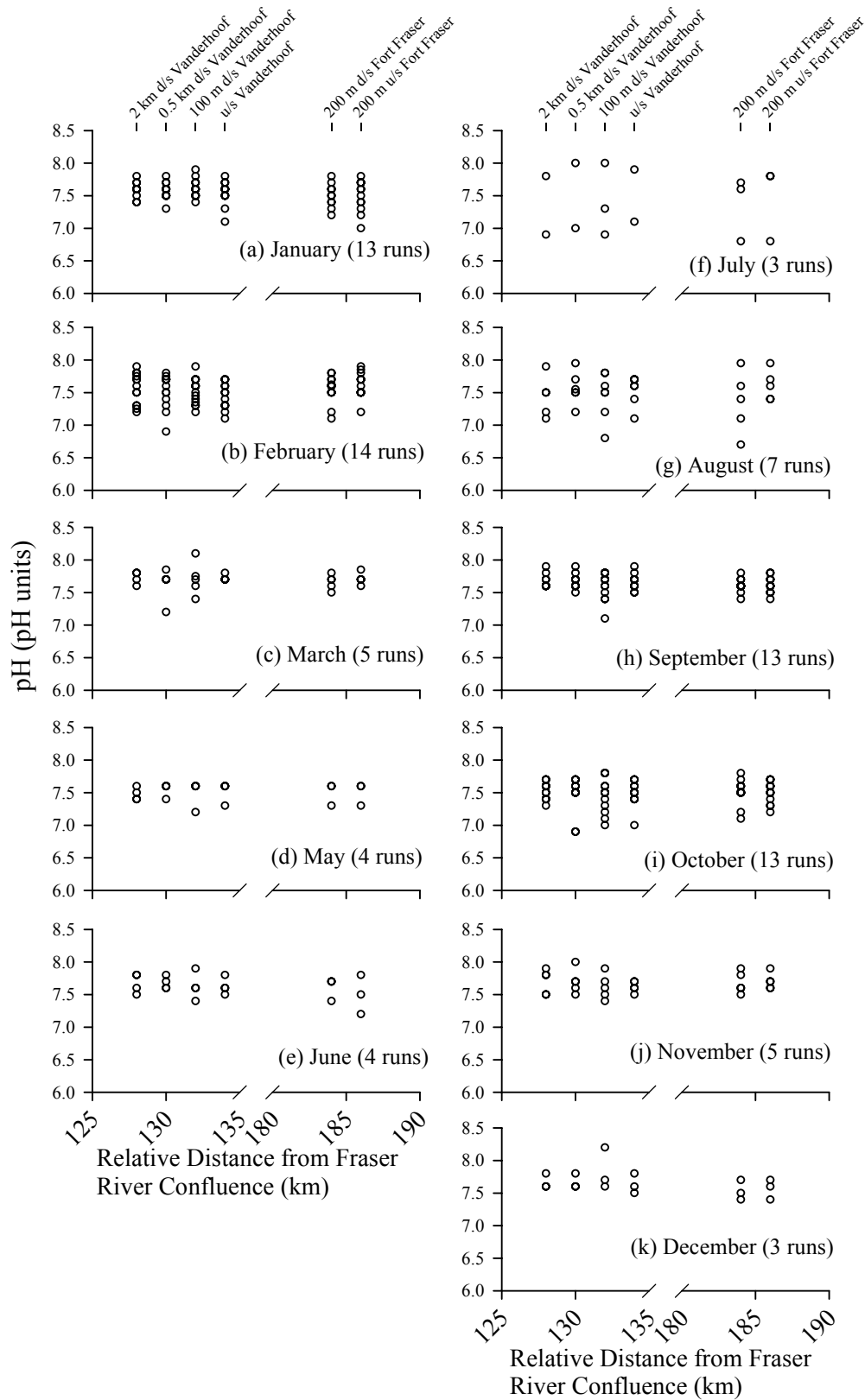


Figure 12. Upstream-downstream trends in pH in the Nechako River over the period 1982 to 1995 (N = 473).

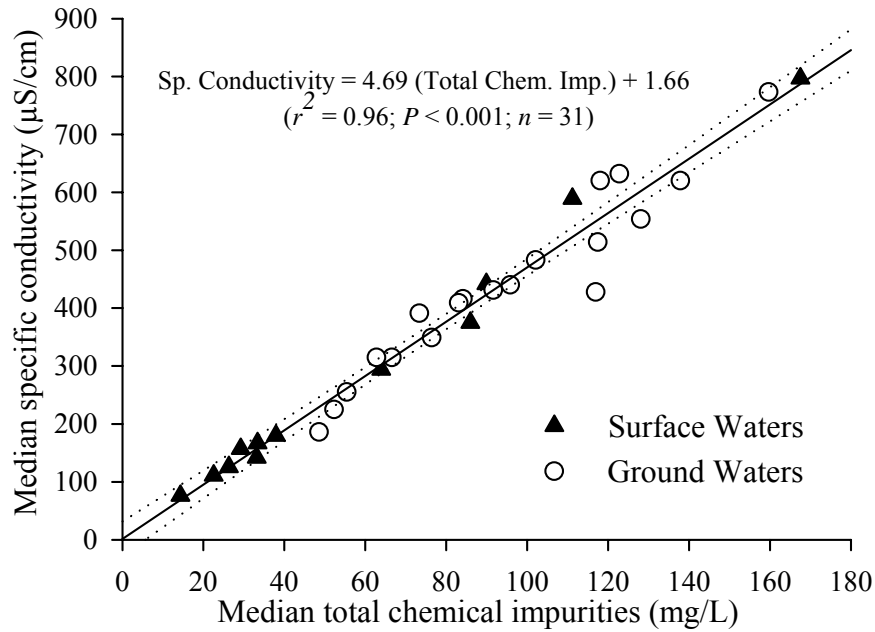


Figure 13. The relationship between total chemical impurities (TCI) and sp. conductivity as determined from 31 sites in the Omineca-Peace Region of British Columbia.

The Vanderhoof discharge may be affecting white sturgeon success in the following ways:

1. Nitrification processes that occur in fresh water can rapidly oxidise $\text{NH}_3\text{-N}$ to $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ under aerobic conditions (Wetzel 2001). Thus, the $\text{NH}_3\text{-N}$ released with Vanderhoof sewage could be reducing O_2 concentrations in the Nechako River, particularly during the winter months when the river is frozen over (i.e., when river water is not in contact with the atmosphere). Unaccounted for organics released with Vanderhoof sewage may also reduce under-ice O_2 concentrations through oxidative reactions (e.g., Carpenter *et al.* 1979). It is clear, however, that many white sturgeon do survive through the winter; thus, there are definitely areas, or refugia, that maintain sufficient O_2 concentrations. But, given that flows are very low under ice, the oxidation of sewage constituents could be substantially reducing the total area of supportive physical and chemical habitat, particularly during the winter. It is also possible that the effects of low winter O_2 concentrations are age-class specific. Stress caused by low O_2 concentrations might affect reproductive physiology (e.g., egg development, vitellogenesis, spawning periodicity).
2. Some constituents of Vanderhoof sewage may have direct toxic effects on white sturgeon eggs, embryos and juveniles (e.g., $\text{NH}_3\text{-N}$ and chlorine used for disinfection). Given that the increase in TCI downstream of Vanderhoof has only been 30% accounted for, it is possible that unidentified toxins are entering the river at Vanderhoof.

3. Growth of attached algae on the valves of mussels resulting from nutrient enrichment may adversely affect the success of mussels which could be an important food source of juvenile and adult white sturgeon. The physical presence of filamentous algae on mussel valves might also be accelerating sediment deposition in microhabitats.
4. Mixtures of NaCl with urea and tannic acids have been shown to decrease the adhesiveness of fertilised sturgeon eggs by changing the chemical properties of the external glycoprotein matrix (jelly coating) (Kowtal *et al.* 1986; Bouchard *et al.* 2002; King & Farrell 2002). While such mixtures have an application in sturgeon aquaculture, similar mixtures in natural environments could adversely affect the reproductive ecology of white sturgeon. As indicated above, Cl⁻ concentrations downstream of Vanderhoof are elevated, presumably because of effluent disinfection processes. Given that there is a large amount of organic material downstream of Vanderhoof (i.e., from sewage and decomposing macrophyte tissues) it could, in theory, be possible that compounds are forming *in situ* that decrease the adhesive properties of white sturgeon eggs. Eggs that do not adhere to firm substrates in natural environments would be susceptible to downstream transport and burial. During transport, the eggs may also be subject to increased risk of predation.

Water Chemistry & Macrophytes

Table 2 lists the parameters that were never, or very rarely, detected either within high- and medium-density macrophyte stands or within the open-channel control sites. Concentrations of the vast majority of measured parameters, including metals, were similar within high- and medium-density macrophyte stands and open channel ($P>0.05$) (Tables 3 & 4). However, the concentration of some parameters varied significantly in relation to the present or absence of macrophytes. For example, NH₃-N concentrations were, on average, 3-fold greater within high- and medium-density macrophyte stands than in the open-water control sites (Tables 3 & 4). Similarly, Tot-P_{diss} concentrations and pH were typically 3 µg/L and 0.1 to 0.3 units, respectively, greater within high- and medium-density macrophyte stands than in the open channel (Tables 3 & 4). O₂ concentrations were also, albeit slightly, greater in high-density macrophyte beds than in the open channel (Table 3), but were not in medium-density stands. Conversely, Tot-Zn_{diss} concentrations appeared to be reduced by the presence of dense macrophyte stands ($P=0.015$), such that average concentrations were 3.6 ± 1.9 µg/L within high density stands versus 5.3 µg/L in the open channel (Table 3).

Elevated levels of NH₃-N within macrophyte stands were likely the result of the direct translocation from sediments and out leaves to the water column, as has been shown to occur by Toetz (1974). Similarly, the elevated Tot-P_{diss} concentrations observed within high- and medium-density macrophyte stands may have been the result of translocation through plant tissues to the water column (Welsh & Denny 1979; Gabrielson

et al. 1984), but P loss through decomposition was also likely occurring simultaneously since the survey was undertaken during the autumn when macrophyte communities in the region are usually senescing (Carpenter 1980; Ogburn *et al.* 1987; Rørslett *et al.* 1986). The slightly elevated pH and O₂ concentrations observed within macrophyte stands was likely the direct result of photosynthesis and O₂ release directly from the rhizosphere (Prins *et al.* 1980; Sand-Jensen *et al.* 1982; Ondok *et al.* 1984). The observation that Tot-Zn_{diss} concentrations were lower within high- and medium-density macrophyte beds might be consistent with Fayed & Abd-El-Shafy's (1985) finding that macrophytes accumulate metals like Zn, Cu, Cd and Pb in their tissues. In this view, Zn would be extracted from the environment at a higher rate within macrophyte stands than outside macrophyte stands and eliminated at a proportionately slower rate.

Table 2. Parameters measured as part of the macrophyte-water quality survey that had a high proportion of observations <DL (detection limit) and, thus, were omitted from further discussion.

Parameter	DL (µg/L)	N	Maximum (µg/L)	%N<DL
<i>I. Control Sites</i>				
Tot-Ag _{Diss}	0.02	3	<0.02	100%
Tot-Be _{Diss}	0.002	3	0.005	67%
Tot-Se _{Diss}	0.2	3	<0.2	100%
Tot-Ti _{Diss}	0.002	3	<0.002	100%
Tot-Tl _{Diss}	0.002	3	<0.002	100%
<i>II. High-density macrophyte beds</i>				
Tot-Ag _{Diss}	0.02	11	<0.02	100%
Tot-Be _{Diss}	0.002	11	0.016	64%
Tot-Se _{Diss}	0.2	11	<0.2	100%
Tot-Ti _{Diss}	0.002	11	0.004	82%
Tot-Tl _{Diss}	0.002	11	<0.002	100%

The finding that O₂ concentrations were slightly elevated in medium- and high-density macrophyte stands as compared to open-channel sites should be interpreted cautiously since O₂ consumption rates versus production rates are a function of time of day and season. The O₂ measures were taken during the daytime when O₂ production via photosynthesis was likely greater than O₂ consumption by respiration; however, during the nighttime when respiration rates would have exceeded photosynthesis rates O₂ concentrations within macrophyte stands would have probably been much lower than those in open-water control sites (e.g., McDonnell 1982; Carter *et al.* 1991). Brooker *et al.* (1977) have observed major fish (salmon) die-offs caused by O₂ depletion during periods of macrophyte decomposition.

Table 3. Comparison of water chemistry within high-density macrophyte beds versus water chemistry at control sites during the 2000 Nechako River survey.

Parameter	Within macrophyte bed		Outside macrophyte bed (control)		P-value (t-test)
	Avg ± 1SD	n	Avg ± 1SD	n	
<i>I. Significant at $\alpha = 0.05$</i>					
Tot-Bi _{Diss} (µg/L)	0.02 ± 0.02	11	0.01 ± 0.00	3	0.04
NH ₃ -N (µg/L)	42 ± 36	43	14 ± 2	40	<0.001
O ₂ (mg/L)	10.8 ± 1.0	281	10.3 ± 0.5	304	<0.001
pH	8.2 ± 0.5	281	7.9 ± 0.3	304	<0.001
Tot-P _{diss} (µg/L)	11 ± 3	21	9 ± 2	23	0.046
Tot-Sb _{Diss} (µg/L)	0.154 ± 0.059	11	0.081 ± 0.024	3	0.011
Tot-Zn _{Diss} (µg/L)	3.6 ± 1.9	11	5.3 ± 0.0	3	0.015
<i>II. Insignificant at $\alpha = 0.05$</i>					
Tot-As _{Diss} (µg/L)	0.4 ± 0.1	11	0.4 ± 0.1	3	0.595
Tot-B _{Diss} (µg/L)	3 ± 1	11	2 ± 1	3	0.106
Tot-Ba _{Diss} (µg/L)	9.44 ± 1.02	11	9.87 ± 0.70	3	0.512
Tot-Ca _{Diss} (mg/L)	10.1 ± 0.2	11	10.1 ± 0.7	3	0.801
Tot-Cd _{Diss} (µg/L)	0.02 ± 0.01	11	0.04 ± 0.05	3	0.228
Tot-Co _{Diss} (µg/L)	0.038 ± 0.007	11	0.038 ± 0.002	3	0.921
Conductivity @ 25 °C	87.3 ± 4.0	281	87.2 ± 3.4	304	0.608
Tot-Cr _{Diss} (µg/L)	0.2 ± 0.1	11	0.2 ± 0.1	3	0.328
Tot-Cu _{Diss} (µg/L)	0.73 ± 0.04	11	0.78 ± 0.08	3	0.579
Tot-Fe _{Diss} (µg/L)	49 ± 24	11	50 ± 4	3	0.963
Tot-Hardness _{diss} (mg/L)	36.8 ± 1.3	10	36.5 ± 1.2	3	0.762
Tot-K _{Diss} (µg/L)	700 ± 0	11	600 ± 100	3	0.115
Tot-Li _{Diss} (µg/L)	0.43 ± 0.09	11	0.41 ± 0.13	3	0.748
Tot-Mg _{Diss} (mg/L)	3056 ± 191	11	3063 ± 140	3	0.957
Tot-Mn _{Diss} (µg/L)	22.2 ± 17.5	11	23.3 ± 0.1	3	0.912
Tot-Mo _{Diss} (µg/L)	3.3 ± 0.1	11	3.3 ± 0.0	3	0.290
Tot-Na _{Diss} (mg/L)	2.1 ± 0.3	11	2.1 ± 0.3	3	1.000
Tot-Pb _{Diss} (µg/L)	0.69 ± 0.94	11	0.79 ± 0.64	3	0.864
Tot-S _{Diss} (mg/L)	1.4 ± 0.1	11	1.4 ± 0.0	3	0.951
Tot-Si _{Diss} (mg/L)	1.96 ± 0.09	11	2.01 ± 0.08	3	0.424
Tot-Sn _{Diss} (µg/L)	1.14 ± 0.44	11	1.16 ± 0.09	3	0.951
Temperature (°C)	10.1 ± 0.2	281	10.3 ± 0.1	304	0.331
Tot-U _{Diss} (µg/L)	0.110 ± 0.030	11	0.111 ± 0.028	3	0.946
Tot-V _{Diss} (µg/L)	0.64 ± 0.22	11	0.40 ± 0.29	3	0.147

Table 4. Comparison of water chemistry within medium-density macrophyte beds versus water chemistry of control sites during the 2000 Nechako River survey.

Parameter	Within macrophyte bed		Outside macrophyte bed (control)		P-value (t-test)
	Avg ± 1SD	n	Avg ± 1SD	n	
<i>I. Significant at $\alpha = 0.05$</i>					
NH ₃ -N (µg/L)	61 ± 37	7	24 ± 10	6	0.040
pH	8.0 ± 0.4	65	7.9 ± 0.3	70	0.010
Tot-P _{diss} (µg/L)	12 ± 2	6	9 ± 0	6	0.011
<i>II. Insignificant at $\alpha = 0.05$</i>					
Conductivity @ 25 °C	87.5 ± 4.5	65	86.4 ± 2.8	75	0.091
O ₂ (mg/L)	10.5 ± 0.7	65	10.4 ± 0.3	70	0.249
Temperature (°C)	9.6 ± 2.3	65	9.7 ± 2.2	70	0.752

Macrophytes in the Nechako River between the Stuart River inflow and Vanderhoof might be adversely effecting white sturgeon via their affects on water chemistry in the following ways:

1. Elevated NH₃-N concentrations within medium- and high-density macrophyte beds could be transformed to NO₂+NO₃ (denitrification, as described above). This chemical transformation could depress O₂ concentrations, particularly during the winter months when river water is not in contact with the atmosphere. NH₃-N and oxidised species (e.g., NO₂) can also be directly toxic to adult and early-life stages (see Cameron & Heisler 1983; Cooper & Plum 1987; Mugiya & Sugano 1991; Paley *et al.* 1993; Wright *et al.* 1993; Wilson *et al.* 1994; Person-Le Ruyet *et al.* 1997; Rani *et al.* 1998; Luckenbach *et al.* 2001; Huertas *et al.* 2002; Gisbert *et al.* 2004).
2. Diurnal and seasonal fluctuations in O₂ concentrations within dense macrophyte stands associated with disbalances in respiration and photosynthesis rates could have an effect on white sturgeon and other fishes and reduce the total availability of supportive chemical habitat.
3. Phosphorus excretion by submerged macrophytes can stimulate the growth of epiphytic algae which can exacerbate diurnal fluctuations in O₂ concentration and accelerate sedimentation rates.
4. The decomposition of macrophytes (and associated epiphytes) might deplete O₂ levels in some locations during the winter months. Clearly, there are suitable overwintering locations in the Nechako River where white sturgeon can live out the winter months; however, the loss in O₂ in river segments rich with macrophytes would result could result in a loss of critical physical habitat which may limit the number of sturgeon that can survive through winters.

As suggested above, the finding that Tot-Zn_{diss} concentrations within medium- and high-density macrophyte stands were lower than those at open-water control sites might mean that macrophytes are actually extracting Zn from the water column via an unidentified process. The significance of this observation is that the tissue-

concentrated Zn might be re-liberated to the water column during periods of rapid decomposition that likely occur in the Nechako River in late autumn and during the winter months under ice. It is interesting to note that MacDonald *et al.* (1997) observed elevated levels of Zn in the muscle and liver tissues of three white sturgeon from the Fraser River near Prince George, and that Kruse & Scarnecchia (2002) indicated that Zn concentrations in the ovaries of some Kootenai River white sturgeon (another population that is suffering from an apparent reproductive failure) were high enough to inhibit reproduction in other fish species.

Bottom Sediment Chemistry

Sediment parameters that were mostly at concentrations \leq the detection limit are listed in Appendix B. 2-methyl-naphthalene (2-benzene ring polycyclic aromatic hydrocarbons found naturally in fossil fuels such as petroleum and coal, and that can be formed via the combustion of wood products) and total oil & grease hydrocarbons were almost always detected in bottom sediments between the Stuart River confluence and Vanderhoof at concentrations $>$ provincial criteria for aquatic life (Figure 14). 2-methyl-naphthalene ($r^2=0.95$), total oil & grease hydrocarbons ($r^2=0.40$), and total metals ($r^2=0.98$) were positively associated with total organic carbon concentrations (Figure 15), with this association suggesting that organic materials contributed to bottom sediment from decomposing macrophytes would increase the potential for in-channel storage of these environmental contaminants. While several PAHs are well known to have mutagenic, carcinogenic and endocrine-disrupting properties that can affect fish survival and, possibly, reproduction (Krahn *et al.* 1986; Van Veld *et al.* 1992; Swartz *et al.* 2003; Thomas & Doughty 2004), and petroleum-based hydrocarbons are readily taken up by fish (Gagnon & Holdway 2000), more research will need to be undertaken to fully understand the implications of finding these compounds in Nechako River sediments. In particular, it would be of value to determine how these compounds effect egg/embryo survival, egg adhesive properties and sexual development.

The relative distributions of sediment-sorbed metals in the Nechako River between the Stuart River confluence and Vanderhoof are shown in Figures 16-19. The sediment-sorbed metals that often exceeded provincial criteria for aquatic life were arsenic (Figure 18a), iron (Figure 16c), and nickel (Figure 17d); however, more research on this topic will need to be undertaken to fully understand the implications of these findings in view of white sturgeon success.

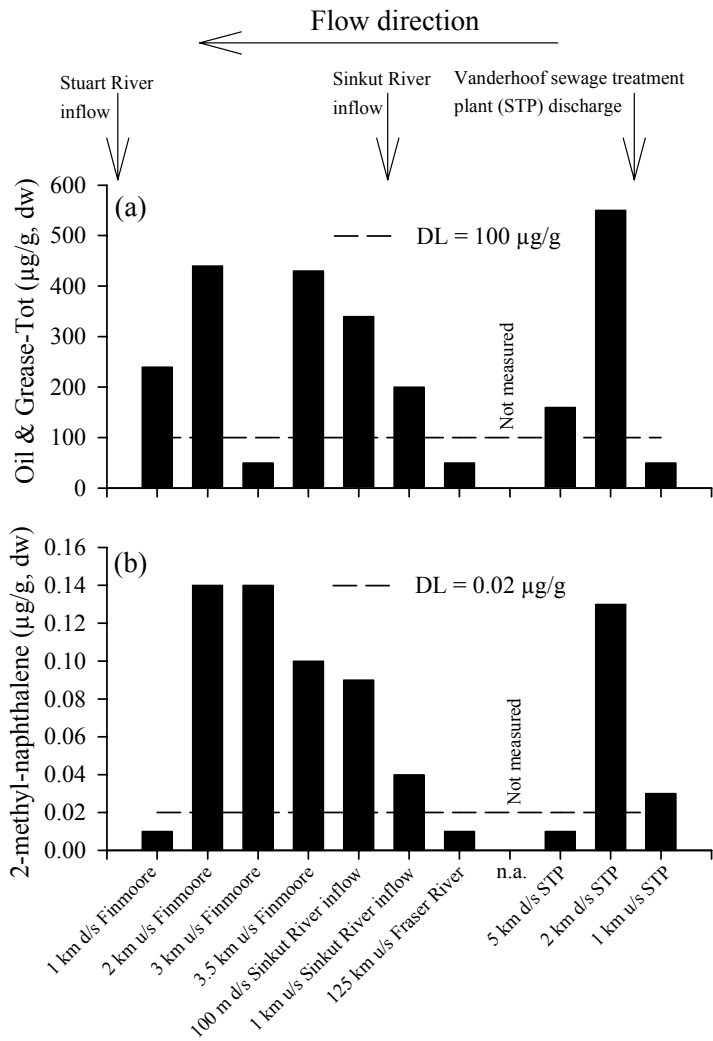


Figure 14. Oil & grease (a) and 2-methyl-naphthalene concentrations in Nechako River bottom sediments between the Stuart River confluence and Vanderhoof.

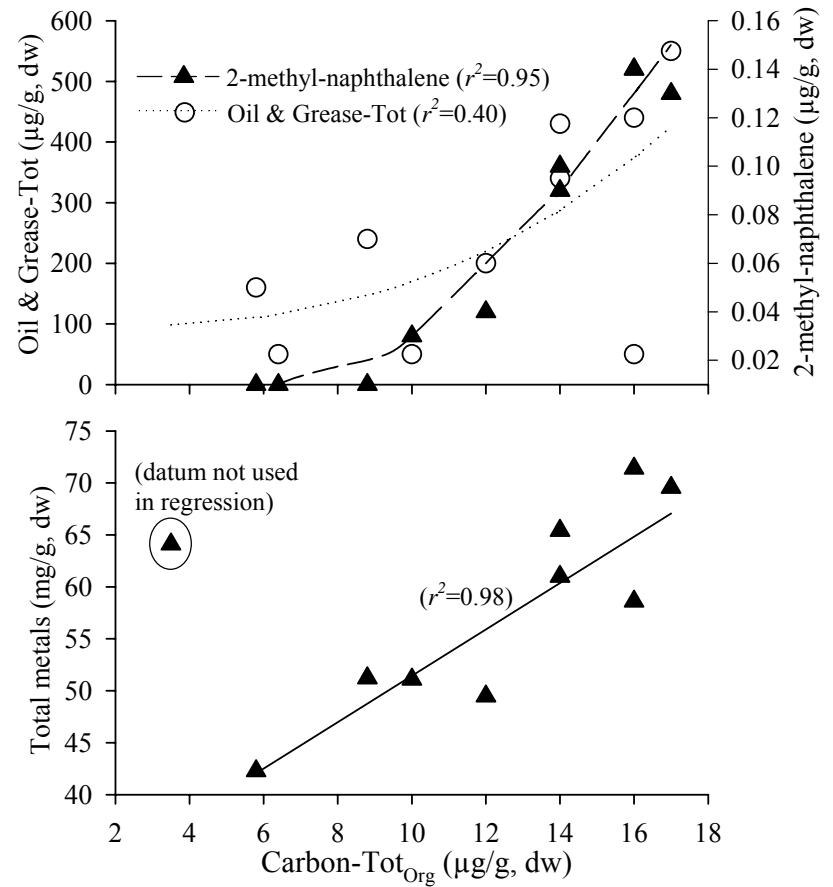


Figure 15. Association between sediment organic carbon and oil & grease and 2-methyl-naphthalene concentrations (a) and total metals concentration (b) for the Nechako River between the Stuart River confluence and Vanderhoof.

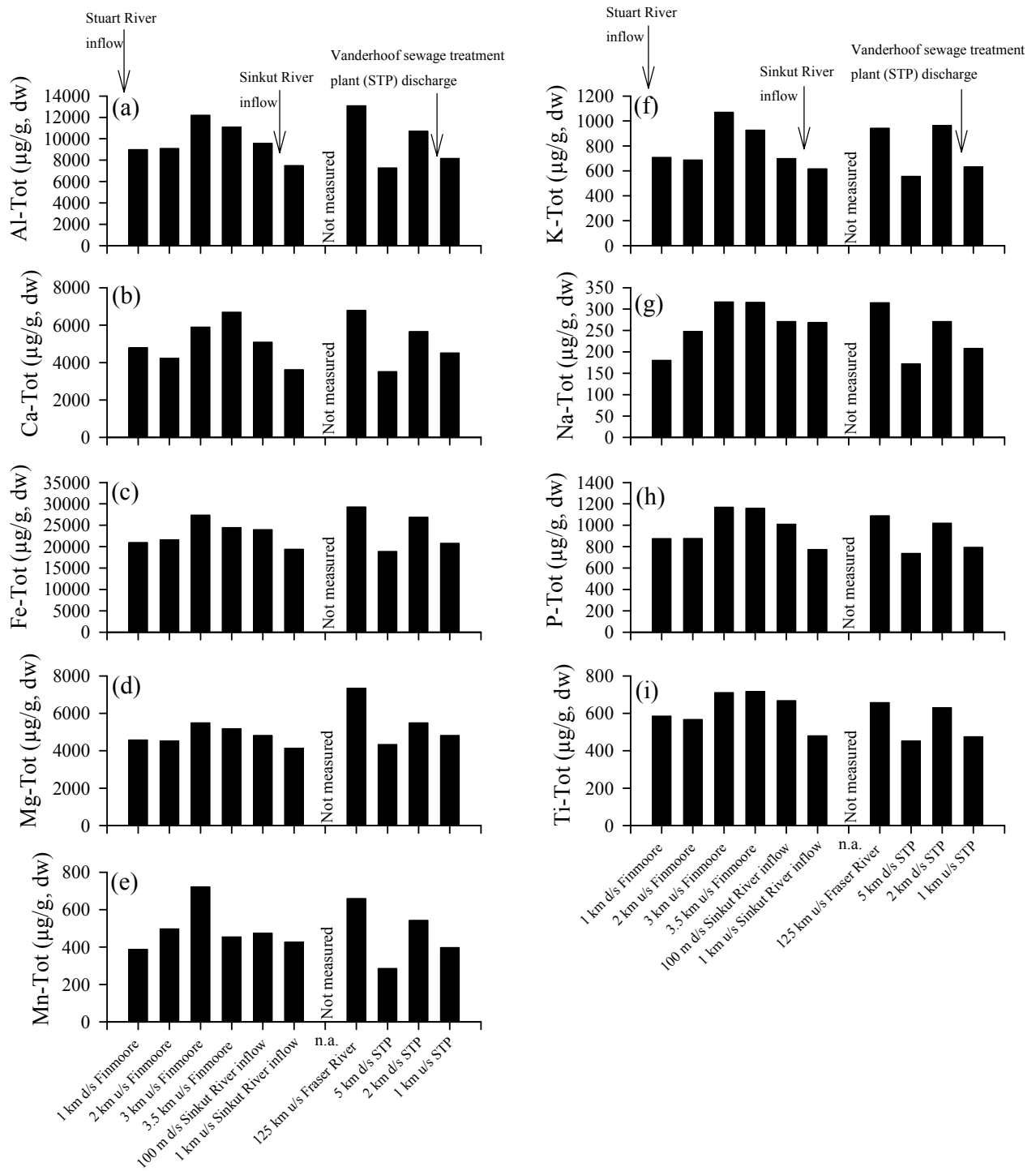


Figure 16. Concentrations of “abundant” metals observed in bottom sediments in the Nechako River between the Stuart River confluence and Vanderhoof.

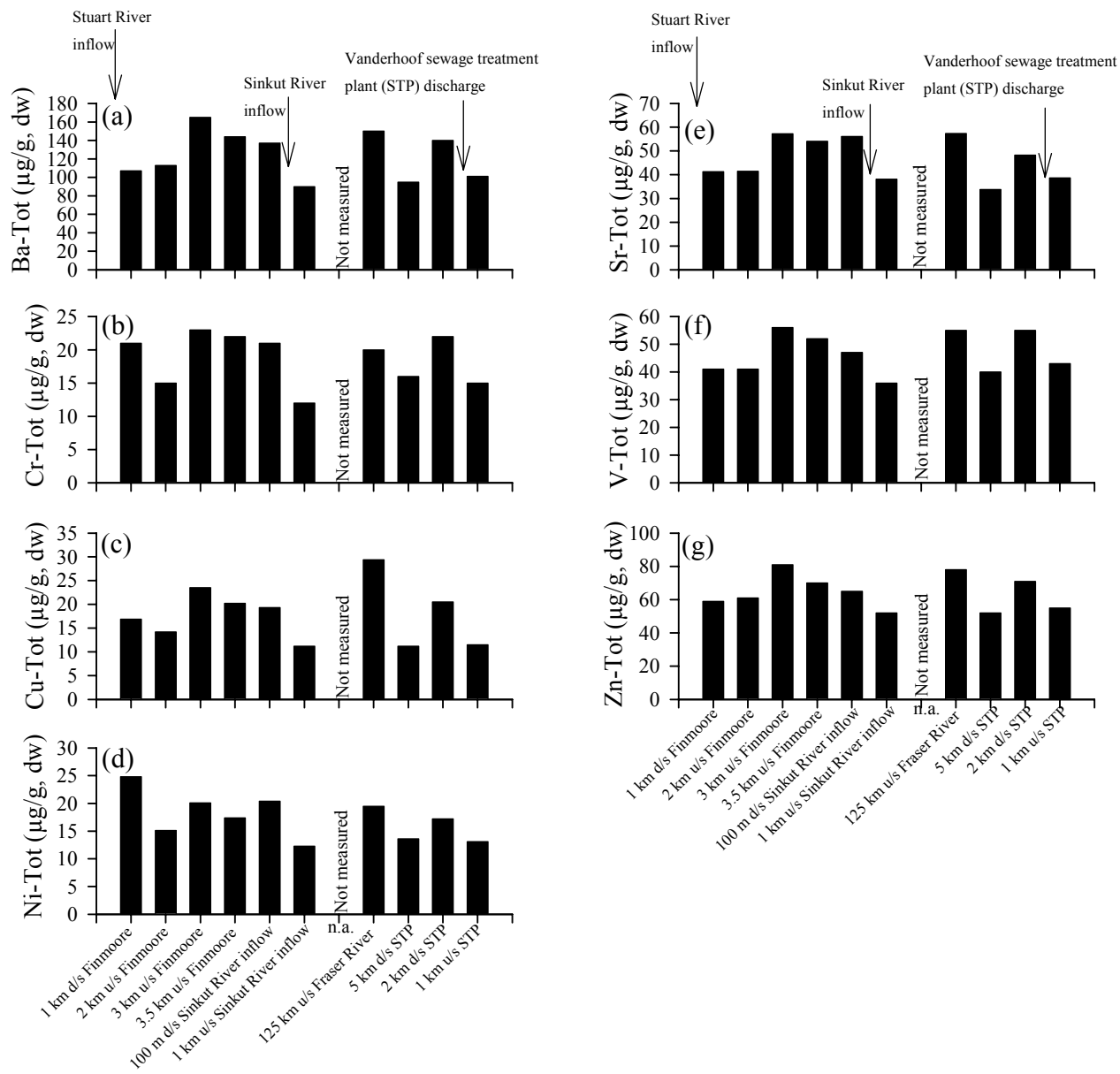


Figure 17. Concentrations of “moderately abundant” metals observed in bottom sediments in the Nechako River between the Stuart River confluence and Vanderhoof.

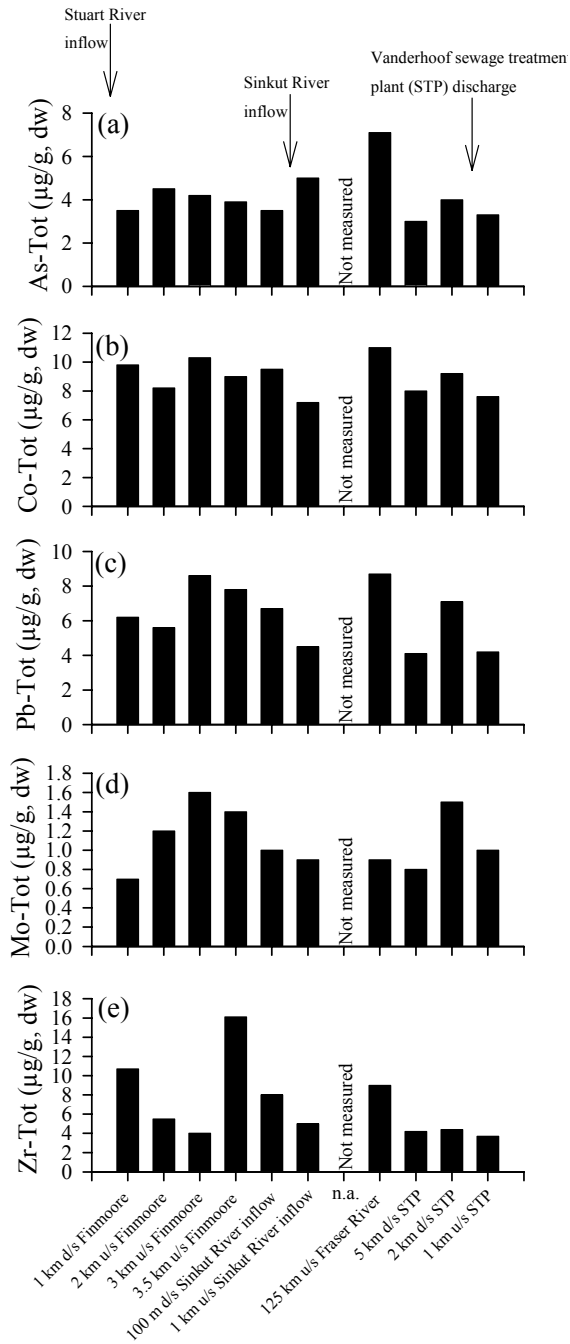


Figure 18. Concentrations of “moderately rare” metals observed in bottom sediments in the Nechako River between the Stuart River confluence and Vanderhoof.

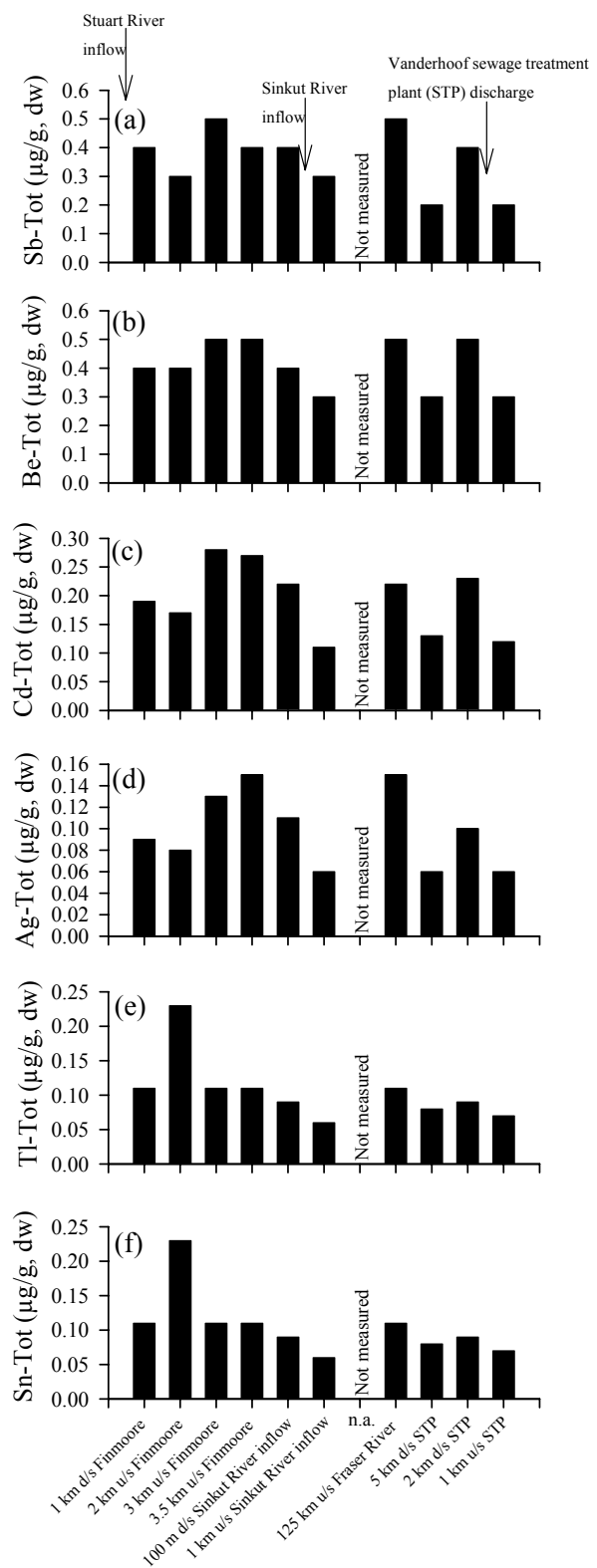


Figure 19. Concentrations of “very rare” metals observed in bottom sediments in the Nechako River between the Stuart River confluence and Vanderhoof.

Mat-Sorb Contaminant Adsorption

Extractable petroleum hydrocarbons and oil & grease were detected in bottom sediments in the path of the discharge of storm sewer #89, Cameron Street, Prince George, and in the experimental Mat-Sorb pads (Table 5a,b). As shown in Figure 20a, the highest rates of hydrocarbon adsorption to the Mat-Sorb pads coincided with spring snowmelt when contaminants (including oil & grease hydrocarbons) would runoff from urban areas and impermeable surfaces at the highest rate. While hydrocarbon adsorption rates were comparatively low during the summer and autumn (Figure 20a), rates were positively associated with rainfall volumes (Figure 20b), suggesting that rain waters draining from urban areas transport synthetic organic compounds to the Nechako River.

Table 5a. Extractable and oil & grease hydrocarbons observed in bottom sediments from storm sewer #89 (Cameron Street, Prince George) that drains into the Nechako River. Samples were collected on July 12, 2000.

Replicate	Extractable Hydrocarbons ($\mu\text{g/g, dw}$)	Total Oil & Grease ($\mu\text{g/g, dw}$)
1	4460	6720
2	3110	4860

Table 5b. Time composite hydrocarbons adsorbed to MatSorb pads placed in water draining from storm sewer #89 (Cameron Street, Prince George) that drains into the Nechako River (see Figure 18a which shows standardised adsorption rates). Experiment was undertaken over period March through December 2000.

Period	# Days	Extractable Hydrocarbons (mg/L)	Total Oil & Grease (mg/L)
Mar 6 - Mar 21	15	2590	5180
Mar 21 - Apr 6	16	1140	2460
Apr 6 - Apr 19	13	2620	5210
May 5 - Jun 7	33	2390	3600
Jun 7 - Jun 26	19	1260	2630
Jun 26 - Jul 19	23	1510	3780
Sep 15 - Oct 16	31	549	780
Oct 16 - Dec 12	57	4240	5780

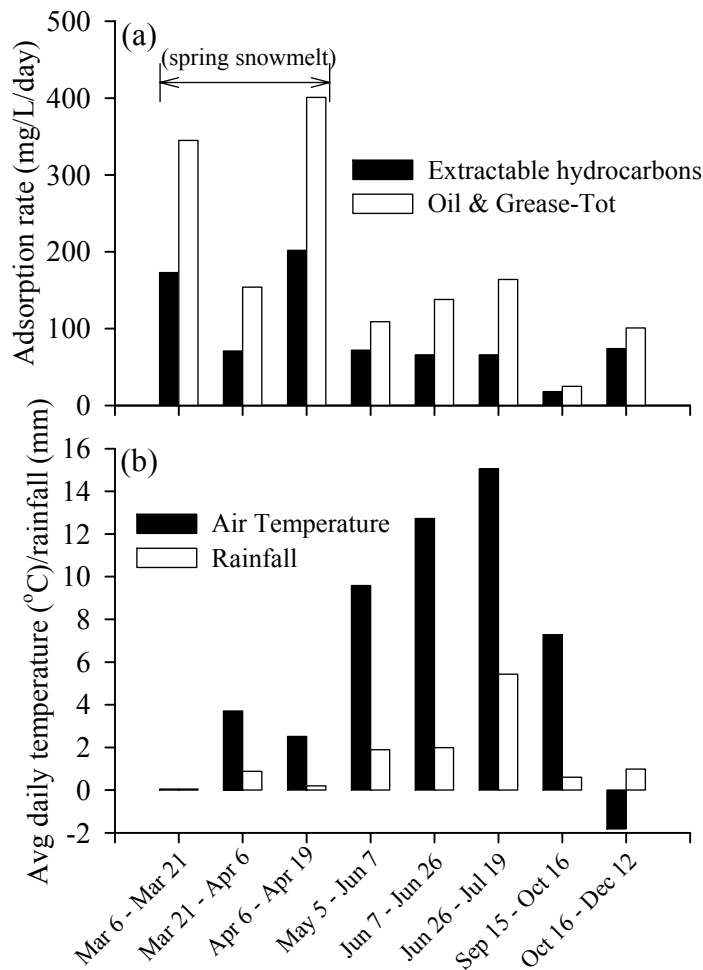


Figure 20. Extractable petroleum hydrocarbons and oil & grease adsorption rates to Mat-Sorb pads exposed to discharges from storm sewer #89, Prince George in relation to season (a) and air temperature/precipitation patterns (b).

The results of this experiment are not directly relevant to white sturgeon that may not frequent this area of the lower Nechako River; however, it does demonstrate that hydrocarbons from urban areas can enter the Nechako River with overland runoff. It is also possible that such storm-sewer related contamination is occurring upstream in the Vanderhoof area. If it is, it is possible that such runoff may be contributing to the hydrocarbon load to the Nechako River between the Stuart River inflow and Vanderhoof. As suggested above, research should be undertaken to determine how such organic contaminants affect white sturgeon survival through all life stages.

Conclusions

In this study it was shown that macrophyte abundance has increased slightly in the Nechako River between Vanderhoof and the Stuart River confluence over the period 1991 to 2000, and that macrophyte biomass increases with decreasing current velocity and increasing sediment nutrient concentrations. It was determined that mosses, *R. aquatilis*, and *Chara* were most abundant at sites having coarse substrates (sands and bare rock), with *E. canadensis*, *P. richardsonii*, *M. exalbescens*, and *C. demersum* being associated with silty substrates. In comparison, *P. berchtoldii*, *C. hermaphroditica*, *P. gramineus*, and *P. pectinatus* were found at sites having more intermediate-type substrate textures (mixtures of silts and sands). Since bottom sediments in the Nechako River were likely composed mostly of coarse substrates prior to the construction of the Kenney Dam and that dominant bottom sediment textures in the river having been becoming finer over time, it was suggested based on observed sediment-texture associations that mosses, *R. aquatilis*, and *Chara* are early seral (pioneer) species, and that *E. canadensis*, *P. richardsonii*, *M. exalbescens*, and *C. demersum* are climax community species. In this view, *P. berchtoldii*, *C. hermaphroditica*, *P. gramineus*, and *P. pectinatus* were classified as intermediate seral species.

It was determined that the Vanderhoof sewage discharge is increasing sp. conductivity and chloride, NH_3 , $\text{NO}_2 + \text{NO}_3$, and $\text{Tot-P}_{\text{diss}}$ concentrations and that the discharge is not affecting pH. High and medium density macrophyte beds in the Nechako River have also increased NH_3 and $\text{Tot-P}_{\text{diss}}$ concentrations. The results of bottom sediment surveys indicated that concentrations of 2-methyl-naphthalene, oil & grease, arsenic, iron, and nickel often exceeded provincial criteria for the protection of aquatic life; however, further work will need to be undertaken to determine the direct relevance of this finding to white sturgeon. Figure 21 illustrates a conceptual model for water quality changes in the Nechako River over the past 50 years and the relevance of these changes to the white sturgeon population.

Approx. timeline (year)

1945

1952

1960

1970

1980

1990

2000

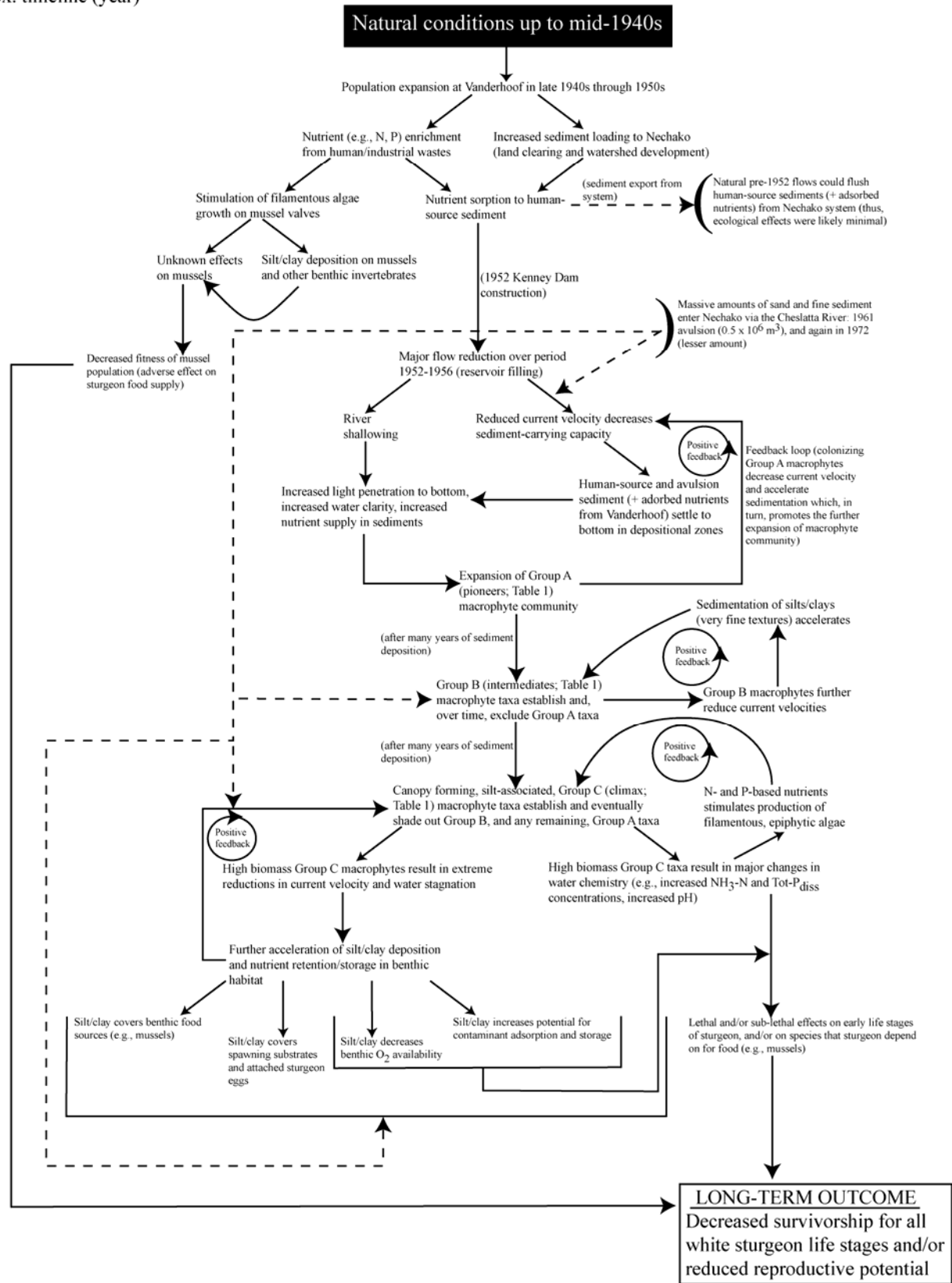


Figure 21. Flow chart illustrating proposed conceptual model of water quality changes in the Nechako River over the past 50+ years.

Recommendations

The results of this preliminary investigation of water quality trends in the Nechako River and associated provide insights into the ways in which current environmental conditions may be affecting white sturgeon success. Some key recommendations for future work are as follows:

1. Studies should be undertaken to quantify how rooted aquatic macrophytes are affecting the deposition rates of fine sediment and the locations in the river where such deposition is occurring most significantly in relation to white sturgeon distributions. As part of this study, it should be possible to determine whether deposition caused by macrophytes is resulting in the burying of egg-adhesion substrates, freshwater mussels (possibly a major food source of white sturgeon) and white sturgeon eggs.
2. This report referred to the possibility of under-ice O₂ depletion on several occasions. It is clear that there are refugia in the river where white sturgeon can successfully overwinter; however, it is possible that this space may be limiting population numbers. Although it would be a difficult study, it is recommended that a project be undertaken to quantify habitat availability (both physical space and chemically-suitable habitats) during winter periods when the river is typically froze over. This would involve surveys of a large proportion of the river area, not just areas where sturgeon are presently known to over winter successfully.
3. It was notable that PAHs (e.g., C2-naphthalenes), oil & grease hydrocarbons, and some metals (e.g., arsenic, iron and nickel) were observed in bottom sediments above provincial criteria for aquatic life. It is recommended that further studies be undertaken to determine the potential for these contaminants to affect survival, growth and reproductive development.
4. More than 90% of lumber produced in British Columbia is treated with didecyldimethylammonium chloride (DDAC), with about 400 tonnes being produced annually in the province (Farrell *et al.* 1998; Teh *et al.* 2003). In a multispecies comparison, it was determined DDAC is particularly toxic to juvenile white sturgeon (Farrell *et al.* 1998). Given that that DDAC is mass produced in British Columbia, and widely used in the interior of the province, the NWSRI should consider testing bottom sediments in the Nechako River for this compound.
5. Although not an advocacy group, the Nechako White Sturgeon Recovery Initiative should consider working with the District of Vanderhoof to see what steps can be undertaken to convert their sewage treatment plant to a zero-discharge facility as the current flows in the Nechako River at Vanderhoof are insufficient to process current loads to the river.

References Cited

- Bouchard, H.J. III & D.B. Aloisi. 2002. Investigations in concurrent disinfection and de-adhesion of lake sturgeon eggs. *North American Journal of Aquaculture* 64: 212-216.
- Bremner, J.M. 1965. Inorganic forms of nitrogen, p. 1179-1237 *In*: C.A. Black (Editor), *Methods of soil analysis*. American Society of Agronomy, Inc., Madison, WI, USA.
- Brooker, M.P., D.L. Morris & R.J. Hemsworth. Mass mortalities of adult salmon, *Salmo salar*, in the R. Wye, 1976. *Journal of Applied Ecology* 14: 409-417.
- Cameron, J.N. & N. Heisler. 1983. Studies of ammonia in the rainbow trout: physico-chemical parameters, acid-base behaviour and respiratory clearance. *Journal of Experimental Biology* 105: 107-125.
- Cooper, A.J.L. & F. Plum. 1987. Biochemistry and physiology of brain ammonia. *Physiological Reviews* 67: 440-519.
- Dorcey, A.H.J. & J.R. Griggs (Editors). 1991. *Water is sustainable development: exploring our common future in the Fraser River basin*. Westwater Research Centre, University of British Columbia, Vancouver, BC, Canada.
- Carpenter, S.R. 1980. Enrichment of Lake Wingra, Wisconsin, by submersed macrophyte decay. *Ecology* 61: 1145-1155.
- Carpenter, S.R., A. Gurevitch & M.S. Adams. 1979. Factors causing elevated biological oxygen demand in the littoral zone of Lake Wingra, Wisconsin. *Hydrobiologia* 67: 3-9.
- Carter, V., N.B. Rybicki & R. Hammerschlag. 1991. Effects of submerged macrophytes on dissolved oxygen, pH, and temperature under different conditions of wind, tide, and bed structure. *Journal of Freshwater Ecology* 6: 121-133.
- Chambers, P.A., E.E. Prepas, H.R. Hamilton & M.L. Bothwell. 1991. Current velocity and its effect on aquatic macrophytes. *Ecological Applications* 1: 249-257.
- Farrell, A.P., C.J. Kennedy, A. Wood, B.D. Johnston & W.R. Bennett. Acute toxicity of a didecyldimethylammonium chloride-based wood preservative, Bardac 2280, to aquatic species. *Environmental Toxicology and Chemistry* 17: 1552-1557.
- Fayed, S.E. & H.I. Abd-El-Shafy. 1985. Accumulation of Cu, Zn, Cd, and Pb by aquatic macrophytes. *Environment International* 11: 77-87.
- French, T.D. & P.A. Chambers. 1995. Nitrogen and phosphorus in the upper Fraser River in relation to point and diffuse source loadings. DOE/FRAP Report 1995-09, Environment Canada, Environmental Conservation Branch, 224 West Esplanade, North Vancouver, BC, Canada, V7M 3H7.
- French, T.D. & P.A. Chambers. 1996. Habitat partitioning in riverine macrophyte communities. *Freshwater Biology* 36: 509-520.

- French, T.D. & P.A. Chambers. 1997. Reducing flows in the Nechako River (British Columbia, Canada): potential response of the macrophyte community. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 2247-2254.
- Gabrielson, J.O., M.A. Perkins & E.B. Welch. 1984. The uptake, translocation and release of phosphorus by *Elodea densa*. *Hydrobiologia* 111: 43-48.
- Gagnon, M.M. & D.A. Holdway. 2000. EROD induction and biliary metabolite excretion following exposure to the water accommodated fraction of crude oil and to chemically dispersed crude oil. *Archives of Environmental Contamination and Toxicology* 38: 70-77.
- Gisbert, E., A. Rodriguez, L. Cardona, M. Huertas, M.A. Gallardo, C. Sarasquete, M. Sala-Rabanal, A. Ibarz, J. Sanchez & F. Castello-Orvay. *Aquaculture* 239: 141-154.
- Greenburg, L.S., L.S. Clesceri & A.D. Eaton (Editors). 1992. Standard methods for the examination of water and wastewater (18th edition). American Public Health Association, American Water Works Association, and Water Environment Association, 1015 15th Street, NW, Washington, DC, USA, 20005.
- Gregg, W.W. & F.L. Rose. 1982. The effects of aquatic macrophytes on the stream microenvironment. *Aquatic Botany* 14: 309-324.
- Huertas, M., E. Gisbert, A. Rodriguez, L. Cardona, P. Wiiliot & F. Castello. Acute exposure of Siberian sturgeon (*Acipenser baeri*, Brandt) yearlings to nitrite: median-lethal concentration (LC₅₀) determination, haematological changes and nitrite accumulation in selected tissues. *Aquatic Toxicology* 57: 257-266.
- King, K. & P. Farrell. 2002. Sensitivity of juvenile Atlantic sturgeon to three therapeutic chemicals used in aquaculture. *North American Journal of Aquaculture* 64: 60-65.
- Kowtal, G.V., W.H. Clark & G.N. Cherr. 1986. Elimination of adhesiveness in eggs from the white sturgeon, *Acipenser transmontanus*: chemical treatment of fertilized eggs. *Aquaculture* 55: 139-143.
- Krahn, M.M., L.D. Rhodes, M.S. Myers, L.K. Moore, W.D. MacLeod & D.C. Malins. 1986. Associations between metabolites of aromatic compounds in bile and the occurrence of hepatic lesions in English sole (*Parophyrus vetulus*) from Puget Sound, Washington. *Archives of Environmental Contamination and Toxicology* 15: 61-67.
- Kruse, G.O. & D.L. Scarnecchia. 2002. Assessment of bioaccumulated metal and organochlorine compounds in relation to physiological biomarkers in Kootenai River white sturgeon. *Journal of Applied Ichthyology* 18: 430-438.
- Luckenbach, T., R. Triebkorn, E. Muller & A. Oberemm. 2001. Toxicity of waters from two streams to early life stages of brown trout (*Salmo trutta* f. *fario* L.), tested under semi-field conditions. *Chemosphere* 45: 571-579.
- MacDonald, D.D., M.G. Ikonomou, A.L. Rantaline, I.H. Rogers, D. Sutherland & J. V. Oostdam. 1997. Contaminants in white sturgeon (*Acipenser transmontanus*) from the upper Fraser River, British Columbia, Canada. *Environmental Toxicology and Chemistry* 16: 479-490.

- Machata-Wenninger, C. & G.A. Janauer. 1991. The measurement of current velocities in macrophyte beds. *Aquatic Botany* 39: 221-230.
- Madsen, J.D., P.A. Chambers, W.F. James, E.W. Koch & D.F. Westlake. 2001. The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia* 444: 71-84.
- Madsen, T.V. & E. Warncke. 1983. Velocities of currents around and within submerged aquatic vegetation. *Archiv fuer Hydrobiologie* 97: 389-394.
- McDonnell, A.J. 1982. Oxygen budgets in macrophyte impacted streams. *Water Research* 16: 1037-1046.
- Mugiya, Y. & K. Sugano. 1991. Short- and long-term effects of ammonium chloride on RNA, DNA and protein concentrations in muscle and serum in the rainbow trout, *Oncorhynchus mykiss*. *Comparative Biochemistry and Physiology* 99B: 899-902.
- Murphy, J.A. & J.L. Riley. 1962. A modified single solution method for the determination of inorganic phosphate in natural waters. *Analytica Chimica Acta* 27: 31-36.
- NHC. 2003a. Nechako River geomorphic assessment phase I: historical analysis of lower Nechako River. Prepared for B.C. Ministry of Water, Land and Air Protection, 2975 Jutland Road (4th Floor), Victoria, B.C., Canada, V8T 5J9, by Northwest Hydraulic Consultants Ltd., North Vancouver, B.C., Canada. 31 pp. (+ appendices).
- NHC. 2003b. Nechako River geomorphic assessment phase II: detailed analysis of potential white sturgeon habitat sites. Prepared for B.C. Ministry of Water, Land and Air Protection, 2975 Jutland Road (4th Floor), Victoria, B.C., Canada, V8T 5J9, by Northwest Hydraulic Consultants Ltd., North Vancouver, B.C., Canada. 17 pp. (+ appendices).
- NWSRT. 2003. Recovery plan for Nechako white sturgeon. Prepared for the Nechako White Sturgeon Recovery Initiative's Recovery Team, c/o 4051-18th Avenue, Prince George, B.C., Canada, V2N 1B3, by Golder Associates Ltd., Edmonton, Alberta, Canada. 73 pp. (draft report).
- Ogburn, R.W. (III), P.L. Brezonik & J.J. Delfino. Effect of pH on phosphorus release during macrophyte (*Eleocharis* sp.) decomposition. *Water Resources Bulletin* 23: 829-831.
- Ondok, J.P., J. Pokorný & J. Kvét. 1984. Model of diurnal changes in oxygen, carbon dioxide and bicarbonate concentrations in a stand of *Elodea canadensis* Michx. *Aquatic Botany* 19: 293-305.
- Paley, P.K., I.D. Twitchen & F.B. Eddy. 1993. Ammonia, Na⁺, K⁺ and Cl⁻ levels in rainbow trout yolk-sac fry in response to external ammonia. *Journal of Experimental Biology* 180: 273-284.
- Person-Le Ruyet, J., R. Galland, A. Le Roux & H. Chartois. 1997. Chronic ammonia toxicity in juvenile turbot (*Scophthalmus maximus*). *Aquaculture* 154: 155-171.
- Petticrew, E.L. & J. Kalf. 1992. Water flow and clay retention in submerged macrophyte beds. *Canadian Journal of Fisheries and Aquatic Sciences* 49: 2483-2489.
- Prins, H.B.A., J.F.H. Snel, R.J. Helder & P.E. Zanstra. Photosynthetic HCO₃⁻ utilization and OH⁻ excretion in aquatic angiosperms. *Plant Physiology* 66: 818-822.

- Rani, E.F., M. Elumalai & M.P. Balasubramanian. 1998. Toxic and sublethal effects of ammonium chloride on a freshwater fish *Oreochromis mossambicus*. *Water, Air, and Soil Pollution* 104: 1-8.
- Rørslett, B., D. Berge & S.W. Johansen. 1986. Lake enrichment by submersed macrophytes: a Norwegian whole-lake experience with *Elodea canadensis*. *Aquatic Botany* 26: 325-340.
- Sand-Jensen, K., C. Prahl & H. Stokholm. 1982. Oxygen release from roots of submerged aquatic macrophytes. *Oikos* 38: 349-354.
- Solorzano, L. 1969. Determination of ammonia in natural waters by phenolhypochlorite method. *Limnology and Oceanography* 14: 799-801.
- SPSS Inc. 2003. Statistical software. Chicago, IL, USA.
- Swartz, C.D., K.C. Donnelly, A. Islamzadeh, G.T. Rowe, W.J. Rogers, G.M. Palatnikov, A.A. Mekhtiev, R. Kasimov, T.J. McDonald, J.K. Wickliffe, B.J. Presley & J.W. Bickham. Chemical contaminants and their effects in fish and wildlife from the industrial zone of Sumagayit, Republic of Azerbaijan. *Ecotoxicology* 12: 509-521.
- Teh, S.J., C. Wong, V. Furtula & F-C. Teh. 2003. Lethal and sublethal toxicity of didecyldimethylammonium chloride in early life stages of white sturgeon, *Acipenser transmontanus*. *Environmental Toxicology and Chemistry* 22: 2152-2158.
- Thomas, T. & K. Doughty. 2004. Disruption of rapid, nongenomic steroid actions by environmental chemicals: interference with progestin stimulation of sperm motility in Atlantic croaker. *Environmental Science and Technology* 38: 6328-6332.
- Toetz, D.W. 1974. Uptake and translocation of ammonia by freshwater hydrophytes. *Ecology* 55: 199-201.
- Van Veld, P.A., W.K. Vogelbein, R. Smolowitz, B.R. Woodin & J.J. Stegeman. 1992. Cytochrome P450IA1 in hepatic lesions of a teleost fish (*Fundulus heteroclitus*) collected from a polycyclic aromatic hydrocarbon-contaminated site. *Carcinogenesis* 13: 505-507.
- Warrington, P.D. 1980. Studies on aquatic macrophytes part XXXIII: aquatic plants of British Columbia. Province of British Columbia, Ministry of Environment, Inventory and Engineering Branch, Victoria, BC, Canada.
- Welsh, R.P.H. & P. Denny. The translocation of ^{32}P in two submerged aquatic angiosperm species. *New Phytologist* 82: 645-656.
- Wetzel, R.G. 2001. *Limnology: lake and river ecosystems*. Academic Press, New York, NY, USA.
- Williams, J.D.H., J.K. Syers & T.W. Walker. 1967. Fractionation of soil inorganic phosphate by a modification of Chang and Jackson's procedure. *Proceedings of the Soil Science Society of America* 31: 736-739.
- Wilson, R.W., P.M. Wright, S. Munger & C.M. Wood. 1994. Ammonia excretion in freshwater rainbow trout (*Oncorhynchus mykiss*) and the importance of gill boundary layer acidification: lack of evidence of $\text{Na}^+/\text{NH}_4^+$ exchange. *Journal of Experimental Biology* 191: 37-58.

Wright, P.A., G.K. Iwama & C.M. Wood. 1993. Ammonia and urea excretion in Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*) adapted to the highly alkaline Pyramid Lake. *Journal of Experimental Biology* 175: 153-172.

APPENDIX A

(Bottom Sediment Parameters Consistently <DL, Detection Limit)

Parameter	DL (ng/g)	N	%N<DL
<i>I. Metals</i>			
Bi-Tot	0.1	10	100%
Se-Tot	0.5	10	100%
Te-Tot	0.1	10	100%
<i>II. Carbon</i>			
C-Tot _{inorg}	500	10	100%
<i>III. Non-chlorinated phenols</i>			
Phenols	0.05	10	100%
2-Methylphenol	0.05	10	100%
4-Methylphenol+3-Methylphenol	0.05	10	100%
2,4-Dimethylphenol	0.05	10	100%
2-Nitrophenol	0.05	10	100%
4-Nitrophenol	0.05	10	100%
2-Methyl-4,6-dinitrophenol	0.05	10	100%
2,4-Dinitrophenol	0.05	10	100%
<i>IV. Herbicides</i>			
2,4-D	0.5	10	100%
2,4-DB	0.5	10	100%
2,4-D (BEE)	1.0	10	100%
2,4-DP (Dichloroprop)	0.5	10	100%
2,4,5-T	0.5	10	100%
2,4,5-TP (Silvex)	0.5	10	100%
Atrazine	0.03	10	100%
De-ethyl Atrazine	0.03	10	100%
Butylate	0.02	10	100%
Cyanazine	0.03	10	100%
Desmetryn	0.03	10	100%
Dicamba	1.0	10	100%
Diphenylamine	0.05	10	100%
Eptam	0.05	10	100%
Ethalfuralin	0.05	10	100%
Hexazinone	0.05	10	100%
MCPA	1.0	10	100%
MCPP	1.0	10	100%
Metalaxyl	0.02	10	100%
Metribuzin	0.05	10	100%
Metolachlor	0.02	10	100%
Picloram	1.0	10	100%
Pirimicarb	0.05	10	100%
Profluralin	0.02	10	100%
Prometryn	0.03	10	100%
Propazine	0.02	10	100%
Simazine	0.01	10	100%
Terbutylazine	0.02	10	100%
Terbutryn	0.02	10	100%
Triallate	0.02	10	100%
Triadimefon	0.05	10	100%
Trifluralin	0.05	10	100%

Parameter	DL (µg/L)	N	%N<DL
<i>V. Organochlorine pesticides</i>			
Alachlor	0.05	10	100%
Aldrin	0.05	10	100%
BHC, alpha-	0.01	10	100%
BHC, beta-	0.01	10	100%
Captan	0.1	10	100%
Chlorbenside	0.05	10	100%
Chlordane, alpha-	0.01	10	100%
Chlordane, gamma-	0.01	10	100%
Chlorfenson	0.02	10	100%
Chlorothalonil	0.02	10	100%
Chlorpropham	0.02	10	100%
Dacthal (DCPA)	0.05	10	100%
DDE, p,p'-	0.05	10	100%
DDT, o,p'-	0.02	10	100%
DDT, p,p'-	0.02	10	100%
Diallate(e/z)	0.01	10	100%
Dichlobenil	0.05	10	100%
Dichloran	0.05	10	100%
Dichlofluanid	0.02	10	100%
Dicofol	0.05	10	100%
Dieldrin	0.02	10	100%
Endosulfan I	0.1	10	100%
Endosulfan II	0.02	10	100%
Endosulfan Sulphate	0.01	10	100%
Endrin	0.1	10	100%
Folpet	0.1	10	100%
Heptachlor	0.02	10	100%
Lindane, BHC, gamma-	0.01	10	100%
Methidathion	0.02	10	100%
Methoxychlor	0.05	10	100%
Mirex	0.02	10	100%
Nitrofen	0.05	10	100%
Permethrin-cis/trans	0.05	10	100%
Procymidone	0.05	10	100%
Pronamide	0.05	10	100%
Quintozene	0.05	10	100%
Tecnazene	0.05	10	100%
Tetradifon	0.02	10	100%
Tolyfluanid	0.05	10	100%
Vinclozolin	0.02	10	100%

Parameter	DL (µg/L)	N	%N<DL
<i>VI. Organophosphorus pesticides</i>			
Acephate	0.05	10	100%
Aspon	0.01	10	100%
Azinphos Ethyl	0.05	10	100%
Azinphos Methyl	0.05	10	100%
Bromacil	0.02	10	100%
Benfluralin	0.02	10	100%
Bromophos	0.01	10	100%
Bromophos Ethyl	0.05	10	100%
Carbophenothion	0.01	10	100%
Chlorfenvinphos(e/z)	0.01	10	100%
Chlormephos	0.05	10	100%
Chlorpyrifos	0.01	10	100%
Chlorpyrifos Methyl	0.03	10	100%
Chlorthiophos	0.03	10	100%
Cyanophos	0.05	10	100%
Demeton	0.02	10	100%
Diazinon	0.02	10	100%
Dichlofenthion	0.02	10	100%
Dichlorvos/Naled	0.05	10	100%
Dicrotophos	0.05	10	100%
Dimethoate	0.02	10	100%
Dioxathion	0.02	10	100%
Disulfoton	0.02	10	100%
EPN	0.05	10	100%
Ethion	0.05	10	100%
Fenchlorphos(Ronnel)	0.05	10	100%
Fenitrothion	0.02	10	100%
Fensulfothion	0.02	10	100%
Fenthion	0.02	10	100%
Fonofos	0.05	10	100%
Iodofenphos	0.01	10	100%
Isofenphos	0.02	10	100%
Malaoxon	0.1	10	100%
Malathion	0.01	10	100%
Methamidophos	0.05	10	100%
Mevinphos-cis/trans	0.05	10	100%
Omethoate	0.05	10	100%
Parathion	0.05	10	100%
Parathion Methyl	0.02	10	100%
Phorate	0.02	10	100%
Phosalone	0.05	10	100%
Phosmet	0.03	10	100%
Phosphamidon	0.05	10	100%
Pirimiphos Ethyl	0.02	10	100%
Pirimiphos-methyl	0.02	10	100%
Profenophos	0.05	10	100%
Pyrazophos	0.02	10	100%
Quinalphos	0.03	10	100%
Sulfotep	0.02	10	100%
Terbufos	0.05	10	100%
Tetrachlorvinphos	0.02	10	100%

Parameter	DL (µg/L)	N	%N<DL
<i>VI. Hydrocarbons</i>			
VH C6-C10	15	10	100%
EPHs C10-19	100	10	100%
LEPHs	100	10	100%
EPHs C19-32	100	10	100%
HEPHs	100	10	100%
VPHs	15	10	100%
<i>VII. Polycyclic Aromatic Hydrocarbons</i>			
Acenaphthene	0.01	10	100%
Acenaphthylene	0.01	10	100%
Anthracene	0.01	10	100%
Benzo(a)anthracene	0.01	10	100%
Benzo(b+j)fluoranthene	0.01	10	100%
Benzo(k)fluoranthene	0.01	10	100%
Benzo(g,h,i)perylene	0.02	10	100%
Benzo(a)pyrene	0.01	10	100%
Chrysene	0.01	10	100%
Dibenz(a,h)anthracene	0.02	10	100%
Fluoranthene	0.01	10	100%
Fluorene	0.01	10	100%
Indeno(1,2,3-c,d)pyrene	0.02	10	100%
Naphthalene	0.01	10	100%
1-Methylnaphthalene	0.01	10	100%
C3-Naphthalenes	0.02	10	100%
Phenanthrene	0.01	10	100%
C1-Phen/Anthracene	0.02	10	100%
C2-Phen/Anthracene	0.02	10	100%
Pyrene	0.01	10	100%
Total PAH's	0.02	10	100%
Total Low MW PAH's	0.02	10	100%
Total High MW PAH's	0.02	10	100%
<i>VIII. Miscellaneous semivolatile organics</i>			
Hexachlorobenzene	0.03	10	100%
<i>IX. Volatile organics-MAH</i>			
Benzene	0.08	10	100%
Chlorobenzene	0.10	10	100%
1,2-Dichlorobenzene	0.06	10	100%
1,3-Dichlorobenzene	0.06	10	100%
1,4-Dichlorobenzene	0.04	10	100%
Ethylbenzene	0.20	10	100%
Styrene	0.20	10	100%
Toluene	0.20	10	100%
Xylenes	0.2	10	100%
m,p - Xylene	0.20	10	100%
o - Xylene	0.20	10	100%

Parameter	DL (µg/L)	N	%N<DL
<i>X. Chlorinated organics - chlorinated aliphatics</i>			
Bromomethane	0.6	10	100%
Carbon tetrachloride	0.06	10	100%
Chloroethane	0.2	10	100%
Chloromethane	0.2	10	100%
1,1-Dichloroethane	0.10	10	100%
1,2-Dichloroethane	0.06	10	100%
1,1-Dichloroethene	0.06	10	100%
cis-1,2-Dichloroethene	0.06	10	100%
trans-1,2-Dichloroethene	0.08	10	100%
Dichloromethane	0.20	10	100%
1,2-Dichloropropane	0.10	10	100%
cis-1,3-Dichloropropene	0.10	10	100%
trans-1,3-Dichloropropene	0.2	10	100%
1,2-Dibromoethane	0.06	10	100%
1,1,2,2-Tetrachloroethane	0.06	10	100%
Tetrachloroethene	0.04	10	100%
1,1,1-Trichloroethane	0.10	10	100%
1,1,2-Trichloroethane	0.10	10	100%
Trichloroethene	0.06	10	100%
Trichlorofluoromethane	0.4	10	100%
Vinyl Chloride	0.16	10	100%
<i>XI. Volatile organics - trihalomethanes</i>			
Bromodichloromethane	0.06	10	100%
Bromoform	0.06	10	100%
Chloroform	0.06	10	100%
Dibromochloromethane	0.06	10	100%