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Effect of Drawdown on Ammonium and Iron Concentrations in a Coastal Mountain Reservoir

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Part way through a year-long water quality field survey, the Capilano Reservoir, located in the Greater Vancouver Water District, was drawn down to accommodate earthquake reinforcement work on the Cleveland Dam. This paper reports observations of the effect of drawdown on water quality in the reservoir, in the context of the original study. The drawdown exposed a large zone of deltaic material through which the Capilano River eroded a path up to 2.5 m deep. The deltaic material contained substantial amounts of nitrogen and iron (TKN, 4,470 mg · kg^{-1}; total iron, 21,800 mg · kg^{-1}). During drawdown, turbidity in the reservoir increased up to 25 times as compared to prior conditions. Ammonium (NH_4^+–N) and dissolved and particulate iron concentrations in the drawdown zone were up to two orders of magnitude higher than concentrations upstream. Both NH_4^+–N and dissolved iron were observed to travel the length of the reservoir. Persistence of NH_4^+–N in the highly oxygenated conditions may be explained by the presence of factors that inhibit nitrification. Persistence of NH_4^+–N and particularly dissolved iron may be due to adsorption and complexation reactions. Seasonally high concentrations of iron and ammonium at the water intake corresponded to the timing of complaints of taste, odour, turbid water, and staining in the distribution system. Observations made during this extreme drawdown suggest that transport of N and Fe from exposed deltaic sediments may play a role in the periodic increases in ammonium and iron observed in the Capilano Reservoir. Further understanding of the impacts associated with changing reservoir elevation should lead to the development of appropriate management strategies to maintain the high quality of GVWD water.

Key words: **iron, ammonium, reservoir drawdown, turbidity**

Introduction

In 1991, the Greater Vancouver Water District (GVWD) initiated a limnological field survey of the Capilano Reservoir to identify processes contributing to seasonal increases in iron and ammonia concentrations in the reservoir waters. This study was launched in response to taste, odour, turbid water and staining complaints in the distribution system of the GVWD fed by the Capilano Reservoir. Taste and odour were specifically

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to be addressed as part of a water quality improvement plan (Economic and Engineering Services Ltd. 1990). While historical water quality data was available for years prior to 1991, this field survey was the first in the GWVD to collect water samples directly from the reservoir (as opposed to the dam wall).

Iron, nitrogen and turbidity were the focus of the field survey since they were directly linked to reported problems in the distribution system. Consumer complaints of turbid water and iron staining of plumbing fixtures were predominant in fall months (GVWD 1992a), coincident with peak total iron concentrations at the intake (up to 950 $\mu g \cdot L^{-1}$ [GVWD 1992b]) and episodic high turbidity (Gerath and Smith 1993). From 1989 to 1991, turbidity exceeded the 5 NTU federal drinking water guideline (Department of Health and Welfare 1995) an average of 91 days per year in the Capilano Reservoir (GVWD 1992b). Consumer complaints of chlorinous odour, most prevalent in September through November (GVWD 1992a), were coincident with annual peak ammonium (NH_4^+) concentrations at the intake to the distribution system (up to 70 $\mu g \cdot N \cdot L^{-1}$ [GVWD 1992b]). When chlorinated at the low pH of GVWD water (6.1 [Perrin et al. 1994]), ammonium can react to form taste and odour causing chloramines (threshold 130–150 $\mu g \cdot L^{-1}$ [Mallevialle and Suffet 1987]). Biological activity is low in the oligotrophic reservoir (total organic carbon 1–3 $mg \cdot L^{-1}$; summer mean epilimnetic total phosphorus 5.3–5.8 $\mu g \cdot L^{-1}$ [GVWD 1992b; Perrin et al. 1994]), and therefore organic precursors of other taste and odour causing compounds are uncommon (i.e., chlorophenols, trihalomethanes [Kruithof 1986; Mallevialle and Suffet 1987; AWWA 1990]). Because chloramination is not used for disinfection of the GVWD water supply, the presence of chloramines in the distribution system indicates that ammonium concentrations in the reservoir water are sufficient to react with the chlorine used in disinfection to potentially generate the taste and odour problems.

The iron and ammonia problems in the GVWD appear to be unique among comparable water districts. Perrin et al. (1994) surveyed seven water districts in the U.S. Pacific Northwest and Southwestern BC within similar high gradient watersheds in high rainfall climatic regions (Bellingham, Bremerton, Everett, Portland, Seattle, Tacoma and Victoria). Of the seven water districts, none reported any ammonia-related water quality problems. Two utilities reported iron problems, one of which was related to the chemical (soda ash) used for pH adjustment. The Tolt River supply for Seattle was the only utility that experienced seasonally elevated concentrations of iron, and they were unsure of the iron source. Since the Capilano Reservoir is oligotrophic, water districts where eutrophic conditions present chronic problems of high ammonia and iron concentrations were not surveyed.

Part way through the year-long field survey, the Capilano Reservoir was drawn down more than usual to accommodate earthquake reinforcement work on the Cleveland Dam. The drawdown exposed a large zone of deltaic material at the north end of the reservoir, through which the

Capilano River eroded a path that roughly conformed to the original river channel before impoundment (Gerath and Smith 1993). Additional stations were added to the original sampling regime to observe the effect of change in water surface elevation on water quality. This paper reports observations of the effect of extreme drawdown on water quality in the Capilano Reservoir, in the context of the original study.

Reservoir Description and Operating Regime

The Capilano Reservoir is situated at an elevation of 198.4 m in a steep mountain watershed immediately north of the city of Vancouver, located on the southwest coast of British Columbia, Canada. The reservoir is in a protected watershed of second-growth cedar and hemlock forest in which public access is prohibited except on guided tours.

Construction of the Cleveland Dam formed the Capilano Reservoir in 1954. At full pool, the storage of the reservoir is 7.5×10^7 m^3 with a surface area of 271 ha. The reservoir is long (5000 m) and narrow (600 m), and has a maximum depth of 91.4 m located within the dam embayment. The drainage basin area upstream of the Cleveland Dam is 198 km^2. One main inflow river, the Capilano River, and many first- and second- order streams drain directly into the reservoir (Fig. 1). Average pH of reservoir water is 6.1, and the reservoir thermally stratifies in the summer.

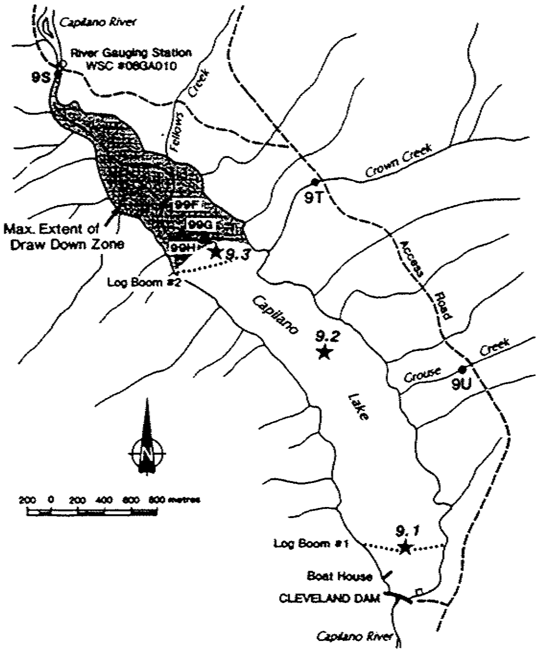

Fig. 1. Capilano Reservoir showing road access routes, drainage streams and locations of the Cleveland Dam, reservoir and river sampling sites.

The full supply elevation of 174 m (height above datum [27.85 m geodetic]) at the Capilano Reservoir is drawn down on a seasonal basis between 8.4 and 12.6 m. The annual drawdown usually begins in late June or early July and reaches a minimum water surface elevation in October. Recharge is usually complete by the end of November due to increased precipitation from coastal storm systems. Drawdown can also occur in midwinter when freezing reduces water inflows. This drawdown did not occur in this project due to the warming influence of the El Niño ocean current present off the British Columbia coast in 1991–92. In December of 1991, an extreme drawdown of the reservoir was initiated to accommodate earthquake reinforcement work on the dam wall. The water surface reached a minimum elevation in February 1992 (drawdown of 21.6 m), and was back to full pool in May 1992.

Field Investigation

The sampling plan implemented for the original study started October 29, 1991, and involved the collection of water samples every 2 weeks (spring through fall) or 3 weeks (winter) using a transparent 3-L van Dorn water bottle lowered from a boat. Two sampling sites were initially established: station 9.1 was located 300 m north of the dam wall and station 9.2 was located approximately mid-basin at maximum annual drawdown in October 1991 (Fig. 1). Samples were obtained at the surface and at depths of 5, 10, 20, 40 and 65 m. When samples were collected from shallower sites, the deepest samples were collected in approximately 10-m intervals. Water samples were placed in coolers at 4°C and delivered to the GVWD laboratory within 6 hours of collection. Samples were analyzed according to standard methods (APHA et al. 1985) for ammonium nitrogen (NH_4^+–N), nitrate nitrogen (NO_3^-–N), total and dissolved iron, and turbidity. Detection limits for these parameters were $10\ \mu g \cdot L^{-1}$, $5\ \mu g \cdot L^{-1}$, $20\ \mu g \cdot L^{-1}$, $20\ \mu g \cdot L^{-1}$ and 0.1 NTU, respectively. Randomly assigned duplicate water samples revealed a range of error between 0.4% for NO_3^-–N and 18% for NH_4^+–N. Error in measurements of all other parameters was between these extremes with most values <5%. Field blanks indicated no contamination in the field and lab, with the exception of NH_4^+–N that was found at concentrations up to $2\ \mu g \cdot L^{-1}$ in field blanks. These errors were small and not important in relation to the magnitude of change in values that were encountered during drawdown in this study. Temperature and dissolved oxygen (DO) concentrations were measured at 1-m intervals with an air-calibrated dissolved oxygen/temperature meter (YSI Model 57).

To better document the drawdown event, station 9.3, in the drawdown zone intersected by the mainstem Capilano River, was added to the sampling program in February 1992. This site was located in <10 m of water near the northern reservoir margin at maximum drawdown (Fig. 1). Sampling sites were also established on the Capilano River mainstem within the drawdown zone near the new reservoir margin (stations 99F, 99G, 99H). River sampling (station 9S) also started in late February and was synchronized with ongoing reservoir water sampling.

The drawdown exposed a large zone of organic and inorganic deltaic material at the north end of the Capilano Reservoir. Sediment samples were collected from 13 strata in topset and foreset beds of the vertical profile, dried to constant weight, and analyzed for total organic content (weight loss on ignition at 550°C), total Kjeldahl nitrogen (TKN) and total iron (APHA et al. 1985).

The field sampling concluded on November 23, 1992. The Capilano River discharge during the study period was obtained from the Water Survey of Canada data for Station 08GA010, located 800 m upstream of the reservoir margin at full pool.

Data Presentation

Chemical concentrations by depth and time are presented as chemical isopleths, using the contouring method in SYSTAT 7.0 (Wilkinson 1997). A square grid of linearly interpolated values was computed from measured values. Contours were drawn using linear interpolation and procedures reported by Lodwick and Whittle (1970). With the use of linear interpolations, actual maximum and minimum values occurring on certain days and depths are smoothed out in the plot and may not appear in hard copy. Where necessary, these data are shown or quoted separately. A total of 139 measured values of each parameter spanning all dates and depths were used in the production of each plot.

Results and Discussion

Effects of Drawdown on the Capilano River and Delta

The drawdown event resulted in the exposure of deltaic material at the north end of the Capilano Reservoir (estimated at 500,000 m^3 [R. Gerath, Thurber Engineering Ltd., Vancouver, BC, pers. comm.]). This accumulated volume corresponds to an average annual bulk deposition rate from the Capilano River of approximately 13,000 $m^3 \cdot year^{-1}$. Sediment and other debris in the path cut by the Capilano River were resuspended, a process that continued for about 4 weeks. During this time, the water flow cut a path up to 2.5 m deep through the deposited material to cobble and boulder substrata that formed the original river channel.

Considerable suspension of particulates along lake margins was also observed during the drawdown. Small tributary streams resuspended organic matter and clays as they drained through the drawdown zone. Those particulates remained suspended on the lake margins and did not appear to readily settle. Wind-induced wave action on the lake margins also disturbed very finely divided particles. Similar mobilization of suspended sediments was reported in Lake Powell after prolonged drought conditions lowered the reservoir level and the Colorado River eroded and resuspended deltaic sediments (Vernieu 1997).

Within the Capilano Reservoir, turbidity increased up to 25 times compared to conditions before drawdown (Fig. 2). On the day of maximum drawdown, turbidity reached a peak of 50 NTU at the sediment water interface. Turbidity throughout the year, exclusive of the few weeks surrounding maximum drawdown, was predominantly below 5 NTU.

In a characterization of turbid water samples from the Capilano Reservoir, Bacon Donaldson and Assoc. (1991) found that 98% of suspended particles had a diameter <0.005 mm, the mid-range of fine silt, and most were smaller than 0.001 mm, or less than clay size. These suspended particles are small enough to have colloidal properties and they are commonly lyophobic (hydrophobic, never dissolving in solution [Pankow 1991]).

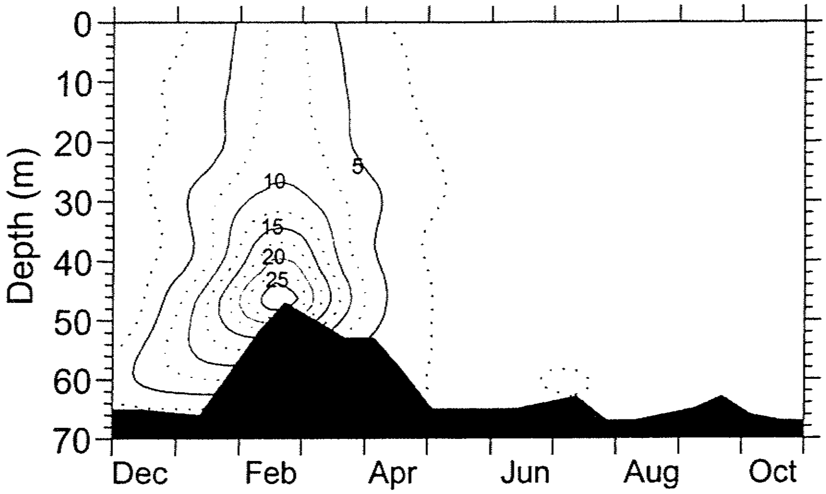

Fig. 2. Isopleths of turbidity (NTU) in Capilano Reservoir (station 9.1), December 1991 through October 1992. The top of the shaded portion of the figure indicates time course change in water depth associated with drawdown.

Analysis of the deltaic material indicated a sediment organic content ranging from 1–9.2%, excluding twigs and other large organic debris. Several seeps with $Fe(OH)_3$ staining were also apparent at drawdown. Sediment had high concentrations of TKN (up to 4470 $mg \cdot kg^{-1}$) and total iron (up to 21,800 $mg \cdot kg^{-1}$) (Table 1). The mean TKN and iron concentrations in the sediment profile, excluding samples that contained large particulate organic matter, were 1095 $mg \cdot kg^{-1}$ and 16,443 $mg \cdot kg^{-1}$, respectively. Using these mean concentrations, an approximate bulk density of

Table 1. Characterization of the sediment profile exposed in the drawdown zone of the Capilano River delta in February 1992

Depth range (cm)	Volatile organic matter (%)	TKN ($mg \cdot kg^{-1}$)	Total Fe ($mg \cdot kg^{-1}$)	Comment
5–10	26.5	3,160	17,600	LPOM[a] present
25	1.0	96	10,000	
40 (no fine sediment, only bark fragments, twigs and sand)				
55	2.5	268	14,300	
65–69	6.6	1,190	17,900	
82–84	8.9	1,600	18,800	
90–99	9.2	1,590	19,800	
106–114	17.1	2,890	19,000	LPOM present
130–132	30.8	4,470	17,500	LPOM present
132–140	7.6	1,220	18,800	
150–170	8.7	1,700	15,500	
193–197	15.0	1,370	19,300	LPOM present
199–209	11.5	2,030	21,800	LPOM present

[a] LPOM refers to large particulate organic matter.

1.33 $g \cdot cm^{-3}$ (assumed value [Brady 1974]) and a deltaic material volume of 500,000 m^3, the mass of TKN and total iron exposed from the delta can be estimated at 715 Mg and 10,660 Mg, respectively.

Reservoir Water Quality

Ammonium

Within the drawdown zone, ammonium (NH_4^+–N) concentrations were up to two orders of magnitude higher than concentrations upstream (Table 2). The effect continued from February 26, when in-river sampling started, through the third week of April, a month past the time when the original substrata was exposed in the river channel.

Ammonium–N concentrations in the Capilano Reservoir prior to the drawdown event were 30 $\mu g \cdot L^{-1}$ throughout the water column (Fig. 3). During drawdown, concentrations at station 9.1 increased to 40–50 $\mu g \cdot L^{-1}$ near the surface, reaching a peak of 80 $\mu g \cdot L^{-1}$ on the day of maximum drawdown. The NH_4^+–N concentration within 5 m of the bottom was 110 $\mu g \cdot L^{-1}$. NH_4^+–N concentrations declined directly with reservoir filling, but by the end of the study (November 1992) had still not returned to concentrations found prior to the drawdown event.

These high concentrations near the Cleveland Dam intake indicate that NH_4^+–N released from the delta or other exposed sediments traveled the length of the reservoir in solution. Nitrogen released from the delta as NH_4^+–N was not completely nitrified to NO_3^- (e.g., Richey et al. 1985)

Table 2. Ammonium (NH_4^+–N) and dissolved and particulate iron (Fe) concentrations in the Capilano River upstream of the drawdown zone (Station 9S), within the drawdown zone at Station 99H, and near the intake that draws water from the Capilano Reservoir (Station 9.1 at a depth of 10 m), at full drawdown and during reservoir recharge

	NH_4^+–N ($\mu g \cdot L^{-1}$)			Dissolved Fe ($\mu g \cdot L^{-1}$)			Particulate Fe ($\mu g \cdot L^{-1}$)		
Sample date	Upstream	Within	Intake	Upstream	Within	Intake	Upstream	Within	Intake
23–26 Feb 92	10	230	80	20	3510	150	80	3680	980
9 Mar 92	10	760	50	20	560	100	20	5640	420
23–24 Mar 92	10	1080	30	20	6550	100	10	700	170
6 Apr 92	10	210	50	30	630	70	20	290	230
21 Apr 92	10	10	30	30	40	80	20	20	170

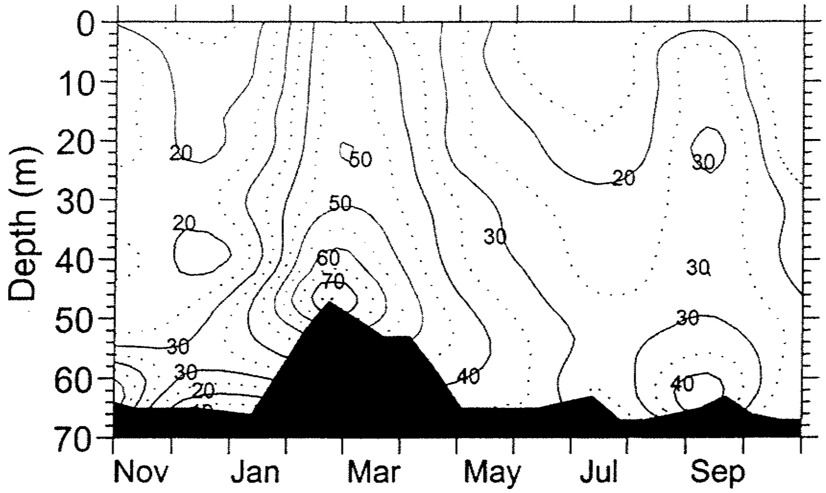

Fig. 3. Isopleths of NH_4^+–N ($\mu g \cdot L^{-1}$) concentrations in Capilano Reservoir (station 9.1), November 1991 through October 1992. The top of the shaded portion of the figure indicates time course change in water depth associated with drawdown.

despite high DO saturation throughout the reservoir (DO concentrations at all depths were >11 $mg \cdot L^{-1}$ (90% saturated) during and after drawdown; Perrin et al. 1994). Higher concentrations of NH_4^+– N than expected based on redox conditions can persist particularly when temperatures are low (5C), pH is less than 7, and concentration of humates is high enough to produce visible colour of surface water (e.g., Perrin et al. 1984). These conditions, which can be characteristic of coastal lakes such as the Capilano Reservoir in early winter, may inhibit the growth of nitrifying bacteria (Rice and Pancholy 1972; Wetzel 1983; Tisdale et al. 1985). In addition, mobilization of particulate and colloidal matter could result in downstream transport and precipitation of NH_4^+–N as part of uncharged aggregates. At pH 6, clays, most insoluble oxides and naturally occurring particulates in reservoirs are characterized by negative surface potentials (Stumm and Morgan 1981). The ammonium ion, albeit a weak cation, can be attracted and adsorbed to these substrates. Ammonium adsorption has been documented in lake sediments (Rosenfeld 1979) and in oxic stream sediments (Newbold et al. 1983; Richey et al. 1985). The increase in turbidity that accompanied the N release from the delta sediments provided a tremendous increase in reactive substrates with the potential to produce a sink for the ammonium ion.

Dissolved and particulate iron

Dissolved and particulate iron concentrations were both up to two orders of magnitude higher in the drawdown zone than concentrations upstream (Table 2). Relatively high concentrations of dissolved and especially particulate iron were also noted at the intake. Total iron concentrations in the Capilano Reservoir were above 500 µg · L^{-1} in early November 1991, but stabilized to 100–200 µg · L^{-1} prior to the onset of drawdown (Fig. 4). Dissolved iron concentrations prior to drawdown were <100 µg · L^{-1} (Fig. 5). On the day of maximum drawdown, total iron concentration reached 1130 µg · L^{-1} at 10-m depth (station 9.1, Table 2) and 2840 µg · L^{-1} at the sediment-water interface. These extreme concentrations on the one day do not show on Fig. 4 because of the effect of smoothing to generate the isopleth image. Peak concentrations of dissolved iron were 150 µg · L^{-1} at a depth of 10 m (Table 2) and 180 µg · L^{-1} at the sediment-water interface. Total iron concentrations declined directly with reservoir filling, and returned to background concentrations when the reservoir returned to full pool.

The coincidence of high Fe concentrations produced in the deltaic zone of the Capilano River and high concentrations near the Cleveland Dam intake indicate that dissolved Fe released from the delta or other exposed sediments also traveled the length of the reservoir. DO concentrations throughout the depth of the Capilano Reservoir at the time of drawdown would preclude the transport of dissolved iron as Fe^{2+} and favour ferric iron (Wetzel 1975; Hesslein 1987; Jackson et al. 1993). Adsorption processes, similar to those for ammonia, may therefore also have controlled iron fluxes. Within the drawdown zone, the concentration of dissolved iron was usually greater than or comparable to the particulate iron concentration. In the reservoir, however, concentrations of the

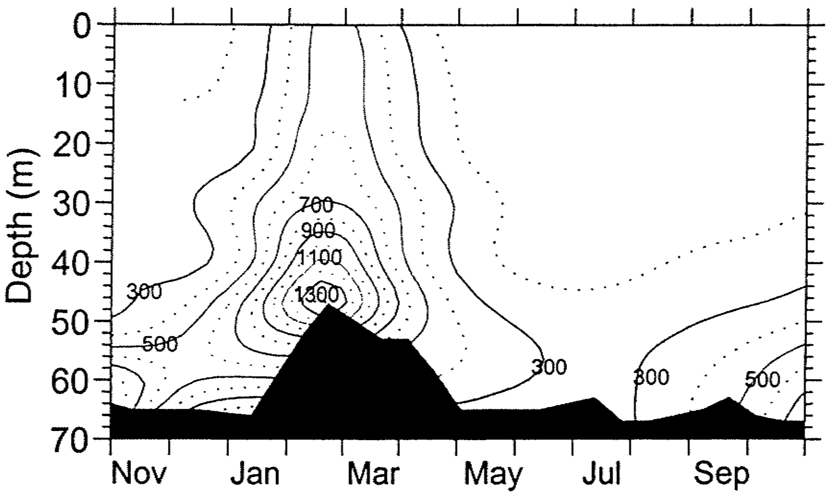

Fig. 4. Isopleths of total iron (µg · L^{-1}) concentrations in Capilano Reservoir (station 9.1), November 1991 through October 1992. The top of the shaded portion of the figure indicates time course change in water depth associated with drawdown.

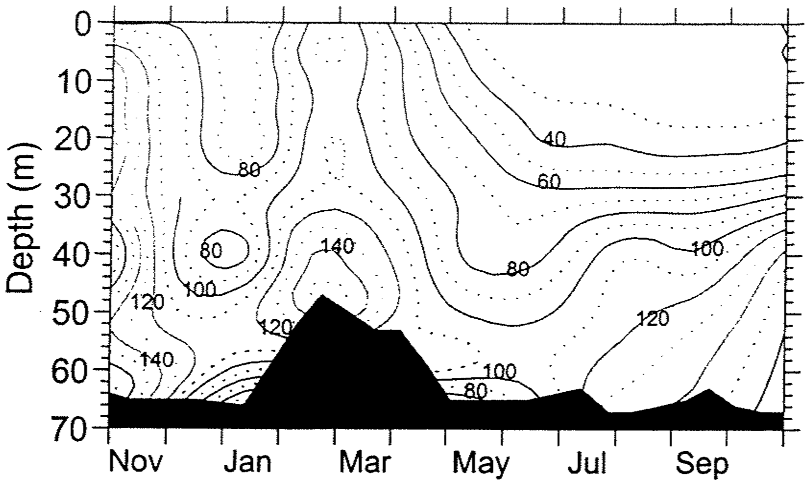

Fig. 5. Isopleths of dissolved iron ($\mu g \cdot L^{-1}$) concentrations in Capilano Reservoir (station 9.1), November 1991 through October 1992. The top of the shaded portion of the figure indicates time course change in water depth associated with drawdown.

particulate fraction were always greater than the dissolved fraction, both during and after the drawdown event. The shift from dissolved iron to particulate iron in transition from the river delta through the reservoir indicates net complexation of iron into aggregates. More detailed laboratory work would be required to determine the relative abundance of the different species of iron in the reservoir. In lakes having a pH range of 6–8, ferric iron can occur as the unreactive precipitate, $Fe(OH)_3$, but can also be complexed with colloidal organic acids (Wetzel 1975). The latter mechanism is recognized as a peptization in which $Fe(OH)_3$ is solubilized by adsorption of organic acids onto the surface of the hydroxide particles (Shapiro 1967; Stumm and Morgan 1981). Positively charged colloidal $Fe(OH)_3$ can also be abundant in well-oxygenated systems (Wetzel 1983), and it readily combines with negatively charged clays, ions and other suspended solids, forming aggregates that then precipitate to bottom sediments. In lakes having pH <6, coordination of iron with OH^- is less important, and at pH 4–5, it is virtually non-existent, even in the presence of oxygen (Koenings 1976). Rather than OH^- being the ligand for Fe^{3+}, Koenings (1976) showed that colloidal organic matter (COM) contains ligands capable of complexing reactive iron. Since the Capilano Reservoir contained DO concentrations near saturation, the main form of iron in the reservoir was likely $Fe(OH)_3$, present as both a precipitate (by complexation with inorganic matter) and a colloid (a $Fe(OH)_3$ sol with organic acids). Since the pH of the reservoir was near the lower end of the range where these complexes can occur (6.1 [Perrin et al. 1994]), COM may have provided ligands capable of complexing reactive ferric and possibly ferrous iron.

Conclusions

This paper reports water quality and visual observations made during an extreme drawdown of the Capilano Reservoir. The deltaic material exposed due to the drawdown contained substantial amounts of iron and nitrogen. Water samples taken above and below the drawdown zone indicated that large amounts of N and Fe were released into the reservoir water during the drawdown and subsequent refilling. Both NH_4^+–N and dissolved iron were observed to travel the length of the Capilano Reservoir to the GVWD intake at the Cleveland Dam. Persistence of the ammonium ion in the highly oxygenated conditions may be explained by the presence of factors that inhibit nitrification. Persistence of NH_4^+ –N, and particularly dissolved iron through the length of the reservoir, may be due to adsorption and complexation reactions, possibly with matter that has colloidal properties.

Since mobilization of the deltaic material should have declined after the Capilano River flow reached relatively immobile cobble, extended effects may have been due to periodic sloughing of unstable banks along the mainstem margins within the drawdown zone, as well as erosion by side channels which developed during the drawdown event. Such processes were observed during field sampling and may regularly be active on a much smaller scale in the deltas of the small tributary streams that enter the Capilano Reservoir. Wind-induced wave action may also contribute to the sediment mobilization around reservoir perimeters. Turbidity events are known to occur in the GVWD reservoirs (Gerath and Smith 1993), and geotechnical studies suggest that landslides along the shorelines and erosion in the reservoir tributaries at low water surface elevations can be important particle sources (Smith and Gerath 1991).

Observations made during this extreme drawdown event indicate that lowering the water surface elevation can lead to high turbidity and high concentrations of NH_4^+–N and dissolved iron in the reservoir. The annual drawdown of the Capilano Reservoir usually produces a minimum water surface elevation in October with recharge complete by the end of November. Hence, rising Capilano River flows in autumn months (due to seasonal coastal storm systems) would reach the reservoir at its annual minimum elevation. Typically, consumer complaints of taste, odour, turbidity and staining in the GVWD peak in September through November. Additional studies are clearly needed to further define any relationship between water surface elevation, Capilano River flow and dissolved iron and NH_4^+–N concentrations at the intake. In particular, studies would be required to identify the forms of iron and ammonia that occur in the reservoir. Further understanding of the impacts associated with changing water surface elevation in reservoirs should lead to the development of appropriate management strategies to maintain high quality water in the GVWD. One of these strategies may be to establish a minimum water surface elevation to minimize the episodic transport of large amounts of deltaic-derived iron, ammonia and turbidity into the Capilano Reservoir.

Acknowledgments

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