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Our File #: TC-12-03

April 4, 2013

Mr. Bruce Donald
Teck Metals Ltd.
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Kimberley, BC V1A 3E1

Dear Mr. Donald:

RE: Long-term Monitoring Program of Garrow Creek, Polaris Mine, Nunavut

Objective

The objective of this letter report is to summarize the pertinent physical, limnological, chemical and toxicological data from 10 years of post-closure monitoring of Garrow Lake and Garrow Creek to support a rational and justifiable long-term monitoring program at Garrow Creek, the former final discharge point for 'effluent' from Garrow Lake.

Introduction and Background

Garrow Lake is a small (4.2 km^2) high Arctic lake situated on Little Cornwallis Island with unique limnological, physical and chemical characteristics (BC Research, 1975; Ouellet and Dickman, 1983; Dickman and Ouellet, 1987; Fallis et al., 1987; Azimuth, 2005). At least four centuries ago when the surrounding landscape underwent isostatic rebound following the Wisconsin glaciation period, a small marine depression was uplifted from the ocean and became isolated, forming a saline lake. Over the last several centuries, Garrow Lake became permanently chemically and thermally stratified (i.e., meromictic), with a brackish surface water layer extending to about 10 m depth that is completely separated from a deep (10 – 40 m) hypersaline bottom layer. This bottom layer or monimolimnion is relatively warm, very high in salt (nearly 3x marine water), high in sulfides and completely devoid of oxygen. Despite the hostile conditions of the monimolimnion, the upper mixolimnion layer nevertheless supports a biological community, that although depauperate, includes a marine relict population of fourhorn sculpin, *Myoxocephalus quadricornis* (BC Research, 1978; Fallis et al., 1987; Azimuth, 2005).This relict population of fish and the fauna that support it has persisted in this lake since its isolation from the adjacent marine environment and despite the use of the lake bottom as a repository for mine tailings from Polaris Mine.

Garrow Lake was classified as a 'Tailings Disposal Facility' under Schedule 2 of the Metal Mining Effluent Regulations (MMER) prior to development of the Polaris Mine. As such, permission was given by Environment Canada to Cominco use this fish-bearing lake as a repository for tailings from the mine that operated between 1981 and 2002. However, although mine tailings were directly deposition into the monimolimnion, the physical and chemical isolation of this layer from the mixolimnion, prevented upward movement of metals and prevented surface water contamination of the lake and therefore Garrow Creek the 'effluent' discharge point from the disposal facility.

Operations History

Mine Operations and Tailings Disposal

The Polaris Mine was located on Little Cornwallis Island in Nunavut. It produced lead and zinc between 1981 until September 2002. Upon exhaustion of the ore body and permanent closure, immediate implementation of the Polaris Mine Detailed Decommissioning and Reclamation Plan began. Reclamation activities continued until completion in September 2004. The site has been under active surfeillance annualy through the end of 2011.

During its operations, the underground mine produced about 1,000,000 tonnes per year of ore, resulting in between 250,000 to 300,000 wet tonnes per year of zinc and lead concentrates. The processing facility, maintenance shops, warehouse and administration offices were all constructed in southern Canada on a barge which was towed to the site. Once on site the docked barge had fill placed around it resulting the barge facilities being landlocked. Tailings from the milling process were piped 4 km to a thickener building were process water was separated from the tailings. The process water recovered was pumped back to the processing facility for re-use and the thickend tailings were discharged via a pipeline into the bottom of Garrow Lake (into the monimolimnion). In 1985 and in 1989 breaks in the tailings line in the mixoimnion caused zinc concentrations to increase in the mixolimnion. As a contingency measure, a dam was constructed in 1990/1991 across the end of the lake. The Water Licence had a requirement for the installation of a dam in zinc concentrations I nteh surface layer (mixolimnion) increased o the effluent licence limits. While this did not occur, Teck installed the dam as a precaution in case zinc levels did not stabilize. As part of the site decommissioning, the Garrow Lake level was restored to its approximate original elevation and the dam was removed in the winter of 2003/2004. Since 2004 the discharge from the lake has been controlled by seasonal weather cycles.

Source of Zinc in Surface Waters of Garrow Lake

Tailings from Polaris Mine were piped to a thickener and the thickened tailings discharged directly into the monimolimnion of Garrow Lake via a pipe that extended between 600 m and 1.2 km offshore into the lake and then down to a depth of up to 30 m, at least 15 m below the pycnocline, the thin layer that separates the mixolimnion from the monimolimnion. In 1984/85 there was a leak from the tailings pike that was not detected, resulting in the discharge of tailings directly into mixolimnion that caused zinc concentrations in surface waters to rise from 10 µg/L to at least 400 µg/L (0.4 mg/L) following the spill (BC Research, 1998). Elevated zinc concentrations were then detected in water discharged from the lake via Garrow Creek, the final 'discharge point' of the tailings disposal facility to the marine receiving environment of Garrow Bay. A dam was constructed at the outlet of Garrow Lake in 1989/90 to raise water level by about 2 m. This allowed discharge from the lake to be stopped until there was confidence that zinc concentrations had stabilized and that discharge from the lake could resume without impacting the marine environment. Discharge from the lake resumed two years later where water was actively pumped over the dam and into the Garrow Creek channel. Between this time and mine closure in 2002, zinc concentrations continued to decline, partly because of initial dilution, sequestration into bottom sediments, and because of years of gradual replacement of surface water runoff from precipitation. In 2011, maximum zinc concentration of Garrow Creek was 0.06 mg/L or 62 µg/L, far less than the permit concentration of 500 µg/L.

Summary of Post-Closure Environmental Conditions of Garrow Lake and Creek

A large amount of information has been collected from Garrow Lake and Garrow Creek since mine closure in 2002. Because outflow from Garrow Creek is defined as an 'effluent' by Environment Canada and the Water Licence, it has been subject to rigorous monitoring under the MMER and Environmental Effects Monitoring (EEM) regulations which were also written into the Type A water license monitoring requirements for the Polaris Mine.

Monitoring of the effluent consisted of the following:

- Weekly monitoring of Garrow Creek for a narrow suite of parameters.
- Monthly monitoring of Garrow Creek, Garrow Bay and a reference area for a broad suite of parameters, including discharge, temperature and metals loading.
- Monthly acute toxicity testing (rainbow trout and the water flea *Daphnia magna*) of Garrow Creek during open water.

In addition to monitoring of the effluent, understanding the physical and chemical stability of Garrow Lake was also required. To do this, limnological and chemical profiling of Garrow Lake was undertaken three times annually from two independent locations. A broad suite of water quality parameters was measured at 1 m intervals between surface and 22 m depth and then ~5 m depth thereafter. Post 2004 when the mine site was not occupied, mid-winter sampling was not conducted because it was not safe to travel to the site. Consequently, post-2004, sampling was conducted twice per year (at maximum ice thickness and during ice free conditions).

All of this information is documented in quarterly (where appropriate) and annual reports and data summaries provided by Teck to the NWB. In addition, a dedicated limnological and ecological study of Garrow Lake was undertaken in 2003, one year after cessation of tailings disposal, by Azimuth Consulting Group (Azimuth, 2005). In this study the ecological health of the lake was established, including water and sediment chemistry, zooplankton, benthic invertebrate and fish community assessment.

The information presented below was gathered from these sources as well as the October 17, 2011 summary of post-closure conditions entitled '*Evaluation of*

Limnological and Chemical Conditions of Garrow Lake and Chemistry of Garrow Creek, Nunavut 2002 – 2011' by Azimuth that was submitted to Teck for submission to the report to the NWB and AANDC.

Physical Stability

The unique physical/chemical conditions of Garrow Lake have created a meromictic lake where the slightly brackish (2 – 7 ppt salinity), cold (0 – 4^{o}C) surface waters of the upper mixolimnion layer remain completely isolated from the warm (8^{o}C), anoxic, hypersaline (70 – 80 ppt) monimolimnion bottom layer. The very large difference in density due to high salt content of the monimolimnion renders the two layers as completely independent, with no possibility of mixing of any chemical parameter. This physical stability has maintained complete separation of these discrete layers for many centuries. Isotopic examination of bottom water from Garrow Lake by Page et al. (1984) revealed that this water has not been exposed to oxygen for at least 2,600 years.

To determine the long-term physical stability of the meromictic nature of Garrow Lake and integrity of the pycnocline in the post-mining era, AXYS (2001) was commissioned to determine if there was any possibility of mixing of the monimolimnion and mixolimnion. If this occurred, water chemistry of the entire lake and Garrow Creek would be considerably altered. AXYS (2001) (**Appendix A**) concluded that the density barrier of the pycnocline is so strong that no meteorological condition observed (e.g., sustained high winds for a long period over an ice-free lake) could physically mix the surface and bottom layers and overturn the lake. The essential conclusions of this study were: "the halocline is stable and will not be broken down by wind and wave action after draw-down of the lake" (i.e., after removal of the dam) and "there is no possibility of wind induced tilting of the halocline". Thus no combination of wind speed or duration is sufficient to cause loss of integrity and mixing of the two layers.

Limnological Conditions

As described above, the limnology of Garrow Lake is driven by the physical stability of the salinity and temperature differences between the monimolimnion and mixolimnion and the rapid transition that occurs within the pycnocline (or halocline) at 9 – 11 m depth. The rigid separation of the two layers results in consistent and predictable consistencies between the two layers over time. Vertical temperature and conductivity (a measure of salinity) profiles for Garrow Lake between 2002 and 2011 depicted in **Figures 1** and **2** respectively show that temperature and salinity/conductivity profiles within the two layers are very similar. The only difference is observed for temperature, as surface waters warm and cool during brief summer. Otherwise, vertical profiles are near constant.

Although oxygen concentrations are not depicted, Hydrolab® results indicate that the mixolimnion is well oxygenated while the monimolimnion is completely anoxic.

Limnological conditions have remained stable during the 10 years of monitoring since mine closure. Conditions are not expected to change in the long-term as there is no physical force (AXYS 2001) that can cause conditions to change.

Chemical Conditions

A long-term record of basic chemical parameters collected under MMER and the NWB water license show that basic chemical parameters of Garrow Lake have been very stable with no observable directional changes. This is true for pH, salinity / conductivity, anions, hardness, nutrients and most metals. This is expected given the stable physical and limnological conditions within the lake. The one exception to this pattern has been zinc concentrations, as a result of the tailings spill into the mixolimnion in 1984/85.

After the under-ice break in the tailings line in 1984, zinc concentration rose within the lake to nearly 400 µg/l or 0.4 mg/L. Zinc rich tailings deposited to the sediment provided an on-going source of dissolved zinc to the water column that is still detectable. Annual discharge from the lake has contributed to the gradual decline in zinc concentrations until the end of mine life and that have continued to this day. **Figure 3** depicts the vertical distribution of zinc in Garrow Lake between 2002 and 2011. In the mixolimnion, zinc concentrations have consistently hovered around 0.2 mg/L (200 µg/L). Between 2006 and 2011 concentrations are very similar and suggest that zinc concentrations have stabilized, or are declining very slowly. Zinc concentration in the mixolimnion has diminished by half since peak concentrations several years after the spill.

In the monimolimnion, zinc has diminished dramatically since cessation of tailings deposition, with consistent, gradual declines through 2003 – 2005 from the 2002 peak. Total zinc concentration has stabilized at 3 – 4 µg/L with no significant change between 2006 and 2011. The abundance of sulfides in the water column below the pycnocline have scavenged and precipitated the dissolved and particulate metals where they have fallen to the bottom of the lake to be sequestered there.

Figure 4 depicts zinc concentrations in Garrow Creek between 2002 and 2011 on a weekly basis during the brief open water period, between early July and early September. The intra-annual profiles of zinc between 2002 and 2011 depict a fairly repeatable pattern with very low concentrations early in the discharge period because of the large influence of snow and ice melt from the lake. As summer progresses, the influence of snowmelt diminishes and zinc concentrations increase as surface water quality of Garrow Creek becomes a better reflection of surface water quality of Garrow Lake (see October 17, 2011 Azimuth letter report to Teck). Moving through late July and into August, zinc concentrations increase from about 20 µg/L to a maximum of <100 µg/L. The only exception to this was in 2002/03 when the tailings dam was removed and the lake was being pumped lower and concentrations were slightly higher (150 µg/L).

This pattern is well illustrated in the 2011 weekly data from Garrow Creek that is presented in **Table 1**. All metals increase in concentration, coincident with salinity and hardness from late June, when the stream starts flowing, through early September and freeze-up. Zinc concentration increases from 11 µg/L to 62 µg/L in July and range from 41 – 51 µg/L in August and September. These values are well below the License A discharge permit level of 500 µg/L and hardness adjusted toxicity level concentrations.

Note that runoff from Garrow Lake into Garrow Creek is reflective of the chemistry in the uppermost 1 – 2 m of the lake (that has the lowest salinity and metals concentrations) and also residual water from the lingering influence of ice and snow melt, local precipitation and minor influence of shallow groundwater due to gradual thawing of the upper permafrost layer. Zinc concentrations in the mixolimnion of Garrow Lake have consistently hovered around 200 µg/L (0.2 mg/L) since 2006 and suggest that zinc concentrations have stabilized at this concentration, or are declining very slowly. Minor differences in zinc concentration among years are due to differences in timing of collection related to annual variations of precipitation, snowmelt, ice melt, causing dilution of surface waters.

Toxicity Testing

Subsequent to official ‘closed mine status’ in 2005 and as per the Water License, acute toxicity testing (LC50) was conducted on a monthly basis during the open water period (2005 – 2011) on Garrow Creek water (i.e., the final effluent discharge location) using rainbow trout (*Oncorhynchus mykiss*) and the water flea (*Daphnia magna*). **Table 2** depicts acute toxicity test results between 2001 and 2011. With the exception of a single failure of a *Daphnia* test in 2007 (despite a low zinc concentration of 0.05 mg/L), no toxicity has been observed to either species in any test.

Note that zinc toxicity would not be expected given the chemical conditions persisting within Garrow Lake. Zinc toxicity is hardness dependent, with a higher toxicity threshold at higher hardness. The BC Ambient Water Quality Guidelines (BC WQG) for the protection of aquatic life provides a range of zinc concentrations according to hardness as follows; 15 µg/L at 100 mg/L hardness, 165 µg/ at 300 mg/L hardness, 315 µg/L at 500 mg/L hardness and so on. Water hardness of in Garrow Creek during August 2011 was at least 1380 mg/L (**Table 1**). Using the BC WQG guidance for zinc assuming 1380 mg/L hardness, the toxicity threshold is 974 µg/L, which is far higher than the maximum observed zinc concentration of 100 µg/L. Given the brackish nature of Garrow Lake, water hardness will always be high.

It is noteworthy that at the time of the 2003 ecological survey of Garrow Lake by Azimuth (2005) fourhorn sculpin still persisted in the lake, despite tailings deposition to the monimolimnion and the tailings spill to the mixolimnion. Sculpin appeared healthy and had the fish sampled had a similar length-weight relationship and condition factor as observed in 1976 (Fallis et al., 1987) and 1977 (BC Research, 1978), prior to mining. Consequently, despite the sudden elevation in zinc in 1984/1985, the high hardness of the lake water prevented toxicity and is the likely cause for the survival of the fish population.

Proposed Long-Term Monitoring Program for Garrow Creek

With the expiry of the Type A water licence that regulated monitoring of the site during closure, reclamation and a period of post-reclamation monitoring, a long term post-reclamation plan is being proposed for Polaris Mine. This section provides the rationale, sampling parameters and sampling frequency for long-term monitoring of the final discharge location of Garrow Lake.

Rationale for Location and Timing

Garrow Creek has been the designated final discharge location of the Schedule 2 Tailings Disposal Facility of Garrow Lake at Polaris Mine during mine operations and post-closure since 2002. This is the final discharge location for effluent before entering the receiving environment of Garrow Bay. Based on mining and post-mining limnological and chemical data from Garrow Lake (**Figures 1, 2** and **3**) water quality of Garrow Creek (**Table 1**) is a direct reflection of surface water chemistry of Garrow Lake. The effluent quality changes once the spring freshet has passed, which consists of local snowmelt and ice melt from the lake, which is lower in all parameters. Thus sampling from Garrow Creek late in July or early August is the logical time and location from which to measure water quality discharged to the receiving environment (**Table 1**).

We do not recommend monitoring of any other location besides Garrow Creek. Given the stable chemistry of Garrow Creek, absence of toxicity and lack of exceedence of water quality parameters (including zinc) above CCME guidelines, monitoring of the historic Garrow Bay and reference locations adds no value and is unnecessary.

List of Monitoring Parameters

The list of water quality parameters recommended for long-term monitoring are derived from the 'monthly' suite of water quality parameters according to both the MMER and the Water Licence, (with a few exceptions) as follows:

Recommended Parameters:

- Field measured stream temperature (^oC), conductivity and pH using hand-held meters.
- Laboratory measured 'conventional' parameters including pH, conductivity (mS/cm), salinity, hardness, alkalinity.
- Total suspended solids (TSS). Note that the laboratory need be made aware that Garrow Creek water is slightly brackish and the filter paper needs to be rinsed with distilled water to wash through any salt or false TSS results will be recorded.
- Total metals (full suite of 30 metals) including all metals regulated under MMER.
- Dissolved metals (full suite) to determine the ratio of total to dissolved zinc and other metals. Currently, the proportion of total metals that is in the dissolved phase is about 60% in oxic water. This ratio should remain constant in the absence of changes in redox conditions in the lake.

Parameters **not** recommended for monitoring and their rationale include:

- Cyanide – Although cyanide was used in the mining process it degrades within short periods of time in the surface waters and so years after operations ceased, this is not a contaminant of potential concern.
- Nitrate, nitrite, and other nutrients – Nitrogen nutrients and ammonia were analysed during mining to monitor blast residue in waste rock and tailings. Given that blasting has long ceased, this is no longer a relevant parameter for monitoring.

- Radium 226 – Radium 226 was not detected in mine tailings from Polaris ores and was only analysed due to the Canada wide standardization of MMER monitoring.

Quality Assurance – Quality Control

Quality Assurance – Quality Control (QA/QC) is an integral part of routine water quality monitoring and consists of the following two components:

1. In addition to the routine sample for all parameters, a second complete set of water quality parameters will be collected at least 15 minutes apart. This will ensure that at least one sample is acquired in the event of a bottle breakage and confirm results of the first sample.
2. A 'trip blank' will be analysed for all undissolved parameters. A trip blank is laboratory supplied distilled water that is transported to site and back and analysed to ensure that there was no contamination that occurred prior to or after sample collection or while en route.

Monitoring Frequency

Mining and tailings disposal to Garrow Lake ceased in 2002 and completion of mine-site closure and remediation activities were completed in 2004. Weekly/monthly monitoring of Garrow Creek water quality during open water was conducted every year until 2011, a period of nine years since tailings deposition ceased and seven years since remediation was completed.

Given the physical and limnological stability of Garrow Lake and stable chemical conditions of Garrow Creek it is reasonable to considerably reduce the monitoring frequency of Garrow Creek water chemistry. Recently, the Department of Indian and Northern Affairs Canada (INAC, 2009) Contaminated Sites Program released a document entitled "Abandoned Military Site Remediation Protocol". This document lays out the rationale and schedule for long-term monitoring of northern Canadian contaminated sites, in particular the abandoned, remediated distant early warning (DEW) line sites. The objective of this document is to "provide sufficient background information to understand the environmental issues present at these sites, and to describe the guiding principles for their assessment and remediation".

To determine a reasonable long-term monitoring frequency for a remediated, stable site this document has been used as a guide. This is a reasonable approach for Polaris Mine given the high Arctic location, stable physical/chemical conditions post-remediation and precedent for an acceptable frequency of monitoring.

Post-closure monitoring of DEW line sites is proposed to take place during two phases; Phase 1 from years 1 – 5 and Phase 2 during years 7, 10, 15, and 25. Given that monitoring of Garrow Creek has already occurred for 7 straight years since remediation was completed in 2004 (year 0), it is reasonable to assume that Phase 1 monitoring has been completed and we are partially into Phase 2 monitoring. If 2004 was Year 0, 2011 is Year 7. Thus the next monitoring period would occur in Year 10 or 2014, year 15 (2019) and Year 25 (2029), consistent with the monitoring frequency laid out in the INAC (2009) protocol for northern contaminated sites.

Figure 5 is a Gant chart that depicts surface water quality monitoring frequency of Garrow Creek water chemistry in accordance with the INAC (2009) protocol and the terrestrial monitoring parameters associated with the subsidence area and other geotechnical related inspections at the former mine.

In addition to creek water quality monitoring at Year 25 (2029) we propose that vertical limnology and chemistry monitoring of Garrow Lake is conducted from the center location through ice during winter. The same parameters will be collected as from Garrow Creek (conventional parameters, total and dissolved metals) from the following depths:

- 3 m (i.e., 1 m below ice surface)
- 5 m
- 9 m
- 10 m
- 11 m
- 12 m
- 15 m
- 20 m
- 30 m
- 38 m (near bottom)

Greater sampling effort is dedicated within the depth range at the pycnocline depth (10 m), to record the chemical transition between the mixolimnion and the monimolimnion and document the integrity of the pycnocline or density layer.

Adaptive Management

A key component of water quality monitoring of Garrow Creek is adaptive management. Given that Garrow Creek water is a surrogate for the Garrow Lake mixolimnion, should water quality parameters differ such that there is reason to believe that the fundamental nature of the lake has changed, such as due to an unexpected mixing of the mixolimnion and monimolimnion, winter water sampling of Garrow Lake will be conducted the winter following the anomalous water quality result. Triggers for sampling of Garrow Lake include the following:

- Water quality conditions similar to the monimolimnion including high temperature (>6^{o}C) and high salinity (>20 ppt)
- Unusually low zinc and metals concentrations concentration (< 10 µg/L).

The NWB will be advised and results discussed with them prior to undertaking subsequent sampling efforts should any be required.

Sincerely,

Azimuth Consulting Group Inc.

Randy Baker, M.Sc., R.P.Bio. Principal

References

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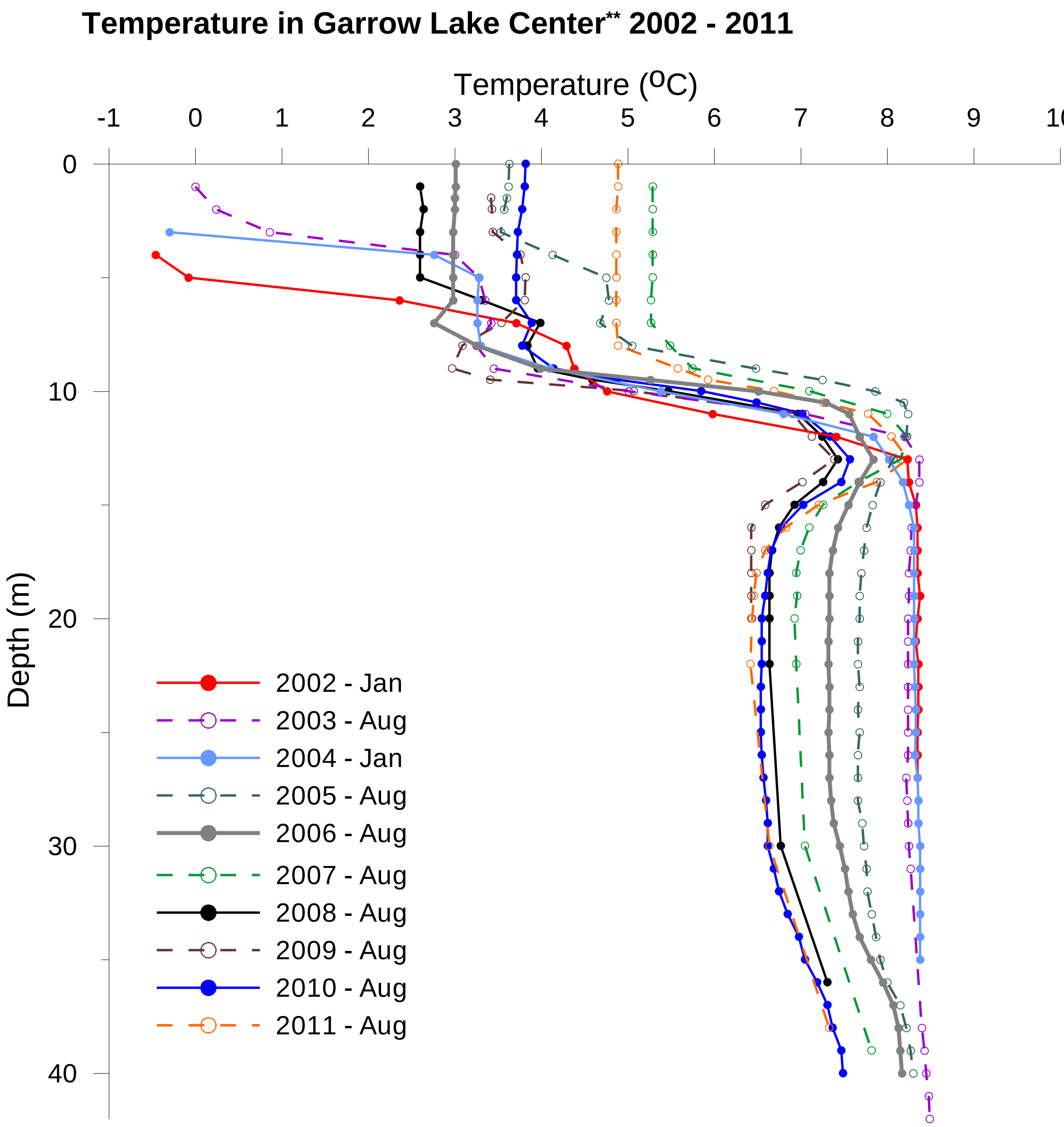
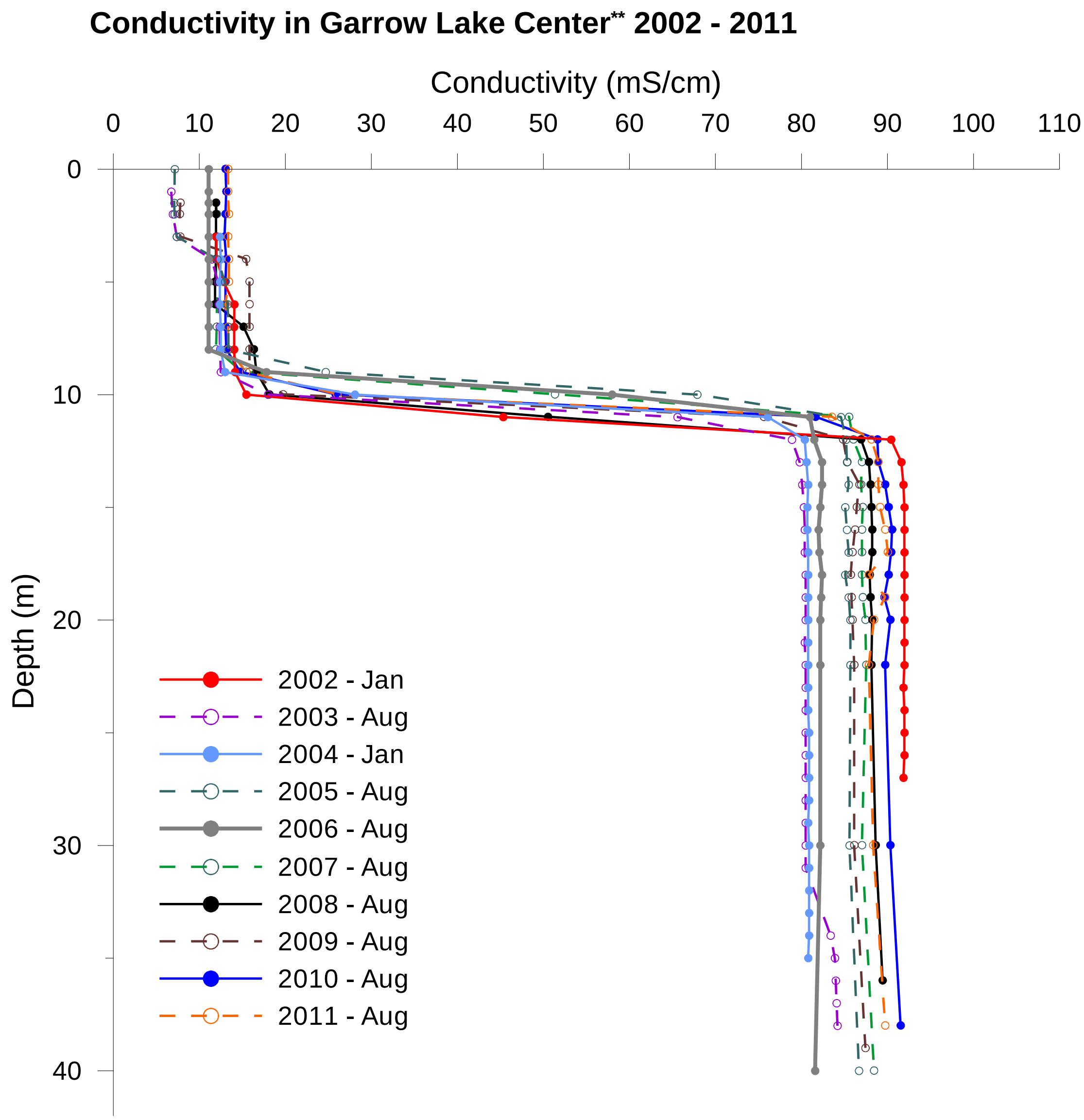
Figure 1. Vertical temperature distribution in Garrow Lake 2002 – 2011 .



**Garrow Lake South station data are shown for January 2004 due to a sampling error at the center station.

Figure 2. Vertical conductivity distribution of Garrow Lake 2002 – 2011.



**Garrow Lake South station data are shown for January 2004 due to a sampling error at the center station.

Figure 3. Vertical zinc concentration in Garrow Lake, 2002 – 2011.

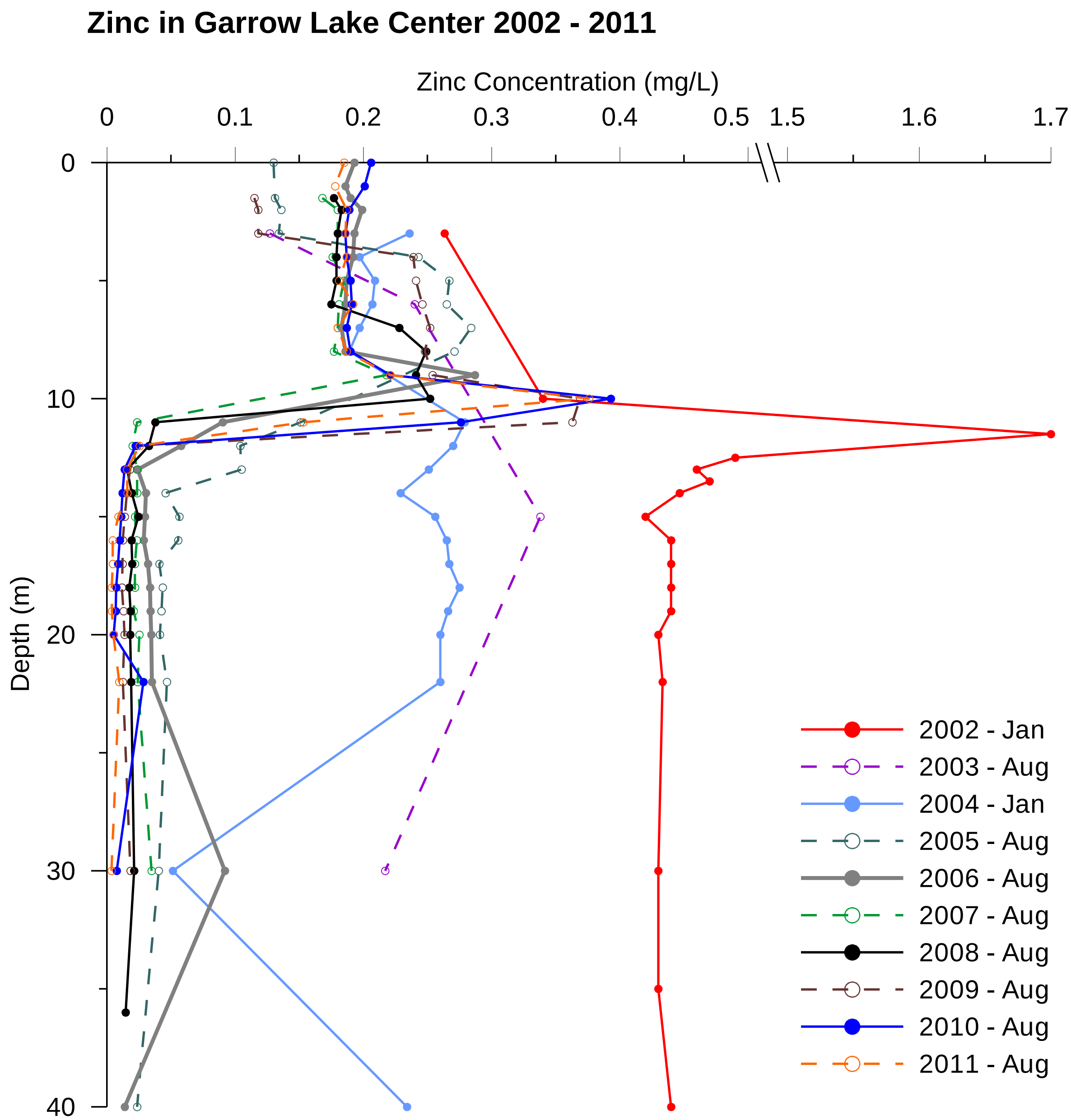
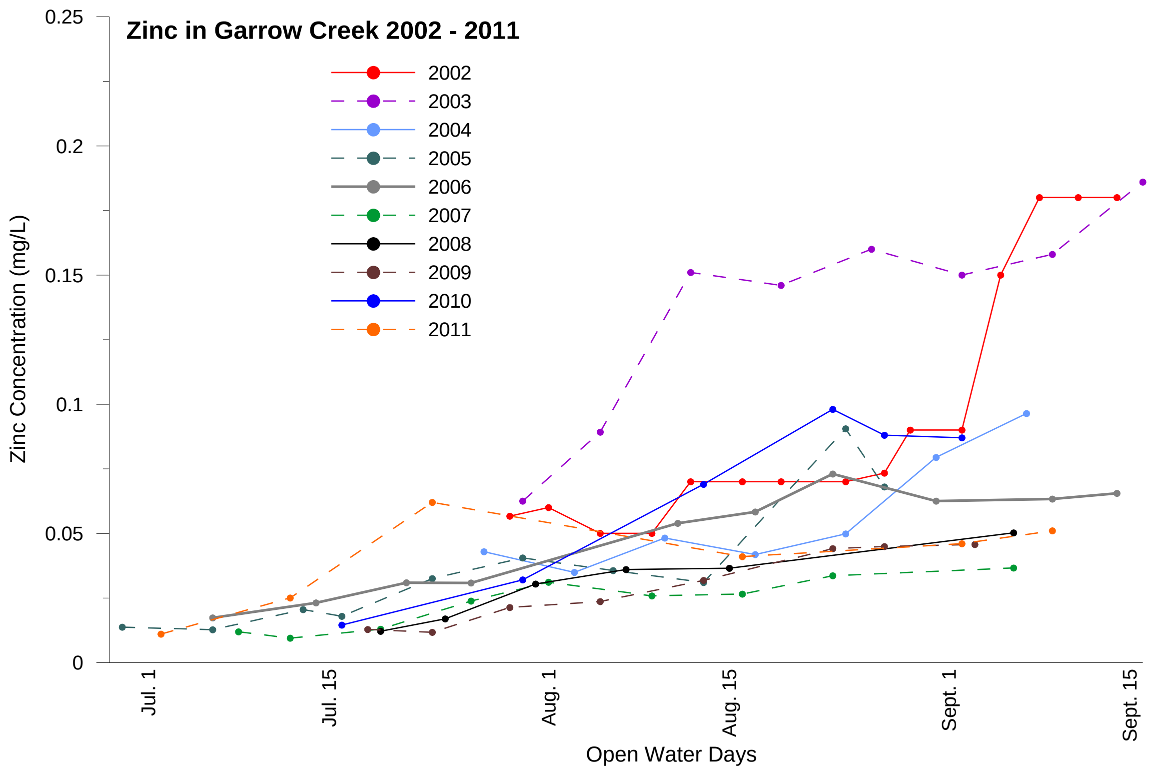


Figure 4. Zinc concentration in weekly water samples from Garrow Creek 2002 – 2011.



COMPARISON OF AANDC TYPICAL NORTHERN CONTAMINATED SITES MONITORING PROGRAM FOR DND COMPARED TO PROPOSED MONITORING PROGRAM FOR POLARIS

CALENDAR YEAR	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	+ 2031
YEARS FROM COMPLETION OF REMEDIAL WORK	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	+ 27
	Phase 1 Monitoring						Phase 2 Monitoring																				Phase 3 Monitoring		
AANDC Typical Monitoring Program Frequency for Northern Contaminated Sites		x		x		x		x			x					x										x			?
Actual Polaris Mine Monitoring Under 2003 Water Licence (expired)	x	x	x	x	x	x	x	x																					
Proposed Polaris Mine New Water Licence Monitoring Schedule											x					x										x		Report	?

Notes:

?	Need for further future sampling to be determined at the end of the Phase 2 Monitoring Phase
Report	A year after final Phase 2 monitoring event, a review report of monitoring to date and recommendations regarding potential Phase 3 monitoring

Table 1. Water Chemistry from Garrow Creek Final Discharge Point (Garrow Lake Former Dam / Syphons), Garrow Bay (Esposure Station), and Reference Station in Garrow Bay, Little Cornwallis Island, Nunavut, 2011

FDP Coordinates:
Northing: 75°22'32"
Easting: 96°48'37"

		Garrow Creek Former Dam/Syphons (Final Discharge Point)*									Garrow Bay - Exposure			Reference Area		
		Garrow Creek	**Garrow Creek**	**Garrow Creek**	**Garrow Creek**	**Garrow Creek**	**Garrow Creek**	**Garrow Creek**	**Garrow Creek**	**Garrow Creek**	**Garrow Bay**	**Garrow Bay**	**Garrow Bay**	**Reference**	**Reference**	**Reference**
		GC-070211	**GC-071211**	**GC-071811**	**GC-July23**	**GC-July31^**	**GC-081611**	**GB-082711**	**GC-090211**	**GC-091012**	**GB-072311**	**GB-082711**	**GB-191011**	**GC-072311**	**GC-082711**	**GC-191011**
Parameters	**Units**	**02-Jul-11**	**12-Jul-11**	**18-Jul-11**	**23-Jul-11**	**31-Jul-11**	**16-Aug-11**	**27-Aug-11**	**02-Sep-11**	**10-Sep-11**	**23-Jul-11**	**27-Aug-11**	**10-Sep-11**	**23-Jul-11**	**27-Aug-11**	**10-Sep-11**
Nitrite (N) [1]	mg/L	n/m	n/m	n/m	*<0.005*	*<0.005*	*<0.005*	*<0.005*	n/m	n/m	*<0.005*	*<0.005*	*<0.005*	*<0.005*	n/m	*<0.005*
Nitrate (N) [1]	mg/L	n/m	n/m	n/m	0.28	n/m	n/m	0.29	n/m	n/m	0.23	0.12	0.07	*<0.02*	*<0.02*	*<0.02*
Cyanide + Thiocyanate	mg/L	*<0.0005*	*<0.0005*	0.0001	0.0006	*<0.0005*	*<0.0005*	*<0.0005*	*<0.0005*	*<0.0005*	*<0.0005*	*<0.0005*	*<0.0005*	0.015	n/m	*<0.0005*
Total Hardness (CaCO3)	mg/L	365	n/m	n/m	n/m	n/m	1380	1530	n/m	n/m	n/m	2810	3430	n/m	5230	5220
Salinity	g/L	1.65	2.64	4.43	5.94	6.37	6.97	7.08	n/m	7.72	8.66	18.6	19.9	29	30.5	31.4
Alkalinity (Total as CaCO3)	mg/L	n/m	n/m	n/m	94	n/m	n/m	110	n/m	n/m	95	110	110	98	93	100
Alkalinity (PP as CaCO3)	mg/L	n/m	n/m	n/m	*<0.5*	n/m	n/m	*<0.5*	n/m	n/m	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*
Bicarbonate (HCO3)	mg/L	n/m	n/m	n/m	110	n/m	n/m	140	n/m	n/m	120	130	130	120	110	140
Carbonate (CO3)	mg/L	n/m	n/m	n/m	*<0.5*	n/m	n/m	*<0.5*	n/m	n/m	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*
Hydroxide (OH)	mg/L	n/m	n/m	n/m	*<0.5*	n/m	n/m	*<0.5*	n/m	n/m	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*
Ammonia (NH4)	mg/L	0.017	0.011	0.068	0.019	0.25	0.036	0.059	0.042	0.42	0.19	0.083	0.015	0.028	0.036	0.13
Nitrate plus Nitrite (N)	mg/L	n/m	n/m	n/m	0.28	n/m	n/m	0.29	n/m	n/m	0.28	0.12	0.12	*<0.02*	*<0.02*	*<0.02*
Conductivity	uS/cm	n/m	n/m	n/m	10400	n/m	n/m	12100	n/m	n/m	10400	29200	3400	44200	45800	47200
pH	pH Units	7.81	8.01	7.73	7.94	7.9	n/m	8.06	7.94	7.94	7.94	7.97	7.9	7.85	7.83	7.83
Total Suspended Solids [1]	mg/L	*<1*	1	1	1	*<1*	1	3	1	1	1	12	12	9	15	11
Total Calcium (Ca)	mg/L	36	52	92	106	n/m	140	147	129	129	130	214.0	245	373	350	344
Total Magnesium (Mg)	mg/L	66	105	177	238	n/m	251	299	270	270	299	554	263	1140	1060	1060
Total Aluminum (Al)	ug/L	n/m	n/m	n/m	*<10*	n/m	n/m	n/m	n/m	*<10*	*<10*	n/m	*<10*	*<10*	*<10*	*<10*
Total Arsenic (As)	ug/L	*<0.5*	*<0.5*	*<0.5*	*<0.5*	n/m	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*	*<0.5*	1.4	1.5	*<0.5*
Total Cadmium (Cd)	ug/L	0.07	0.14	0.21	0.32	n/m	0.27	0.28	0.3	0.38	0.29	0.24	0.21	*<0.05*	0.12	0.07
Total Copper (Cu)	ug/L	1	0.5	0.6	*<0.5*	n/m	*<0.5*	*<0.5*	0.9	0.8	1.8	0.8	0.8	*<0.5*	0.5	*<0.5*
Total Iron (Fe)	ug/L	n/m	n/m	n/m	11	n/m	n/m	n/m	n/m	18	102	n/m	18	3	n/m	7
Total Lead (Pb)	ug/L	0.3	0.2	0.2	0.1	n/m	0.2	0.2	0.2	0.3	0.4	0.20	0.3	0.1	0.1	0.1
Total Mercury (Hg)	ug/L	*<0.3*	*<0.3*	*<0.3*	*<0.3*	n/m	*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*	*<0.3*
Total Nickel (Ni)	ug/L	1.4	*<0.2*	3.1	4.5	n/m	5.5	6.2	6.1	9.3	4.4	4.8	5.6	0.4	0.8	0.8
Total Molybdenum (Mo)	ug/L	n/m	n/m	n/m	2	n/m	n/m	n/m	n/m	n/m	9	n/m	n/m	9	n/m	n/m
Total Zinc (Zn)	ug/L	11	25	57	62	n/m	41	41	46	51	57	24	22	*<1*	1	1
Total Potassium (K)	mg/L	15	24	43	55	n/m	60	64	63	63	75	150	208	346	309	334
Total Sodium (Na)	mg/L	448	719	1250	1650	n/m	1730	2100	1820	1820	2330	4530	5390	9810	8860	8430
Total Sulphur (S)	mg/L	62	79	150	183	n/m	201	223	230	230	248	430	553	857	818	860

Note that TSS and nitrite/nitrate samples arrived at laboratory beyond the recommended holding time

Values shown in red italicized font are less than the detection limit reported.

[1] Parameters arrived at laboratory past holding time

^ Metals inadvertently not analysed for by lab on July 31

* Aircraft not availble to samplers on July 10 and August 13

n/m = not measured

Table 2. Summary of acute toxicity test results for Garrow Creek, 2003 - 2011.

Test Date	Species Tested	Test Type	Sample Method	Consultant Laboratory	LC50 (% effluent)	LC50 Lower Confidence Limit (% effluent)	LC50 Upper Confidence Limit (% effluent)
Rainbow Trout 96-hr LC50							
29-Jul-03	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants, North Vancouver, BC	> 100	-	-
19-Aug-03	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants, North Vancouver, BC	> 100	-	-
16-Sep-03	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants, North Vancouver, BC	> 100	-	-
7-Jul-04	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants, North Vancouver, BC	> 100	-	-
27-Jul-04	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants, North Vancouver, BC	> 100	-	-
24-Aug-04	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
16-Jul-05	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
6-Aug-05	*Oncorhynchus mykiss*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
15-Jul-06	*Oncorhynchus mykiss*	Survival	Grab	Golder Associates, North Vancouver, BC	> 100	-	-
23-Aug-06	*Oncorhynchus mykiss*	Survival	Grab	Golder Associates, North Vancouver, BC	> 100	-	-
9-Sep-06	Sample lost due to laboratory error						
26-Jul-07	*Oncorhynchus mykiss*	Survival	Grab	ALS Environmental, Winnipeg, MB	PASS	-	-
23-Aug-07	*Oncorhynchus mykiss*	Survival	Grab	ALS Environmental, Winnipeg, MB	> 100	-	-
6-Sep-07	*Oncorhynchus mykiss*	Survival	Grab	ALS Environmental, Winnipeg, MB	> 100	-	-
30-Aug-08	*Oncorhynchus mykiss*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
9-Sep-08	*Oncorhynchus mykiss*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
18-Jul-09	*Oncorhynchus mykiss*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
16-Jul-10	*Oncorhynchus mykiss*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
23-Aug-10	*Oncorhynchus mykiss*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
23-Jul-11	*Oncorhynchus mykiss*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
7-Sep-11	*Oncorhynchus mykiss*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
***Daphnia magna* 48-hr LC50**							
29-Jul-03	*Daphnia magna*	Survival	Grab	EVS Consultants, North Vancouver, BC	> 100	-	-
19-Aug-03	*Daphnia magna*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
16-Sep-03	*Daphnia magna*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
7-Jul-04	*Daphnia magna*	Survival	Grab	EVS Consultants, North Vancouver, BC	> 100	-	-
27-Jul-04	*Daphnia magna*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
24-Aug-04	*Daphnia magna*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
16-Jul-05	*Daphnia magna*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
6-Aug-05	*Daphnia magna*	Survival	Grab	EVS Consultants North Vancouver, BC	> 100	-	-
15-Jul-06	*Daphnia magna*	Survival	Grab	Golder Associates, North Vancouver, BC	> 100	-	-
23-Aug-06	*Daphnia magna*	Survival	Grab	Golder Associates, North Vancouver, BC	> 100	-	-
9-Sep-06	*Daphnia magna*	Survival	Grab	Golder Associates, North Vancouver, BC	> 100	-	-
26-Jul-07	*Daphnia magna*	Survival	Grab	ALS Environmental, Winnipeg, MB	PASS	-	-
23-Aug-07	*Daphnia magna*	Survival	Grab	ALS Environmental, Winnipeg, MB	67.4	59.7	76.1
6-Sep-07	*Daphnia magna*	Survival	Grab	ALS Environmental, Winnipeg, MB	86.6	-	-
30-Aug-08	*Daphnia magna*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
9-Sep-08	*Daphnia magna*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
18-Jul-09	*Daphnia magna*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
16-Jul-10	*Daphnia magna*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
23-Aug-10	*Daphnia magna*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
23-Jul-11	*Daphnia magna*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-
7-Sep-11	*Daphnia magna*	Survival	Grab	Nautilus Environmental, Burnaby, BC	> 100	-	-

APPENDIX A

GARROW LAKE DAM

EFFECT OF REMOVAL ON LAKE STABILITY

AND

OUTFLOW WATER QUALITY

By

Paul Erickson,

AXYS Environmental Consulting

March 12, 2001

Garrow Lake Dam

Effect of Removal on Lake Stability and Outflow Water Quality

A report prepared for

Cominco Ltd.
Polaris Operations

By

Paul Erickson
AXYS Environmental Consulting

and

Edward Bennett
Applied Ocean Sciences

March 12, 2001

SUMMARY

This report assesses the effect that Garrow Lake draw-down and decommissioning of the dam might have on the zinc content of the siphon discharge and natural lake outflow. Of particular concern are conditions following lake draw-down when surface layer depth has been reduced to a minimum (estimated at 7.5 m). The model of zinc concentrations developed previously was modified on the basis of the last 4 years of actual observations and used to predict zinc concentrations. The feasibility of mixing the upper part of the halocline, the only source of water in Garrow Lake with zinc concentrations in excess of permit limits, was reviewed under different wind-wave scenarios. On the basis of this review, we have concluded that:

1. The halocline is stable and will not be broken down by wind and wave action after the draw-down of the lake and decommissioning of the dam.

2. Zinc concentrations in the surface layer will remain below 0.3 ppm for the remainder of mine operations and will decrease gradually once disposal of tailings stops.

3. There is a very low probability of wind caused mixing of the top 1 m of the halocline. However, even if the top 2 m of the halocline were mixed into the surface layer, zinc concentrations in the surface layer would still be below permit levels.

4. There is no possibility of wind induced 'tilting' of the halocline sufficient to influence siphon or natural outflow zinc concentrations.

1. INTRODUCTION

1.1 Background

Tailings from the Polaris mine have been deposited into nearby Garrow Lake since the start of mining operations in 1981. Garrow Lake is permanently stratified (meromictic) on the basis of salt content. In the several thousand years since its separation from the adjacent marine waters, the annual freeze thaw cycle at the lake's surface had transferred and concentrated salt in the deeper parts of the lake. As a result prior to the start of mine operations, a vertical profile through the lake showed three well defined layers of different salt content:

1. An active, well mixed aerobic surface layer extending to a depth of about 12 m with slightly brackish water
2. A deep anaerobic bottom layer originally extending from about 30 m to the bottom with salinities almost three times that of the adjacent marine water and high concentrations of dissolved sulphide, and
3. A transition zone between the surface and bottom layer called the halocline, a region of rapidly increasing salinity.

The intense vertical stratification of the lake combined with its depth (48 m) and close proximity to the mine made Garrow Lake an ideal place to deposit mine tailings. Tailings have been discharged below a depth of 26 m in the lower part of the halocline. It was determined that the density of the tailings and the stratification of the lake would confine tailings to the bottom portion of the lake. This would prevent metals associated with tailings from entering the surface layer and ultimately, the water draining from Garrow Lake during the summer.

Overall, the system has performed as planned. There have, however been a few instances where the tailings line has broken and tailings have been discharged in the surface layer. The most significant of these events occurred in 1985. The result was the introduction of high Zn content water in and just above the halocline and increased Zn concentrations in the surface layer. In the years following this discharge, the Zn concentration in the surface layer continued to increase and threatened to exceed the original discharge permit limits of 0.1 ppm Zn in the outflow in Garrow Creek. As a result, the mine constructed a dam across the outlet of the lake in 1989/1990 and engaged Axys Environmental Consulting to develop a model to try and understand the processes controlling the concentration of zinc and predict future trends. A model was developed which has allowed predictions to be made and on-going monitoring has tracked the changes in Zn concentration and lake levels. In 1992 the mine's discharge permit was renewed and the permitted maximum level in the lake discharge increased to 0.5 ppm Zn (concentrations of Zn in the surface layer of the lake have never exceeded this concentration and have decreased gradually since 1991). In 1994, a summer siphoning programme was initiated to minimize the rise in lake level and gradually lower the surface of the lake.

It is anticipated that the Polaris mine will cease operations in 2002. One of the issues to be addressed in any abandonment scenario is the fate of the Garrow Lake dam. If the dam were to remain in place, on-going monitoring and annual siphoning of the lake would be required to ensure failure of the dam does not occur. The preferred option is to return the lake to its previous level, then remove a portion of the dam and allow natural seasonal drainage. Before removing the dam, Cominco must be confident that the water discharged from the lake will never exceed the current permit levels.

The present level of the lake is about 2.5 m above the pre-dam level. Removing the excess water (about 10 million cubic metres) would thin the surface layer and bring the top of the halocline to a depth of about 7.5 m from the surface. While the present concentrations of Zn in the surface layer (0.3 ppm) are well within the permit levels of 0.5 ppm for discharge from Garrow Lake, the halocline has Zn concentrations in excess of 1.0 ppm.

1.2 Objectives

This report attempts to answer the question regarding the effect of lake draw-down and decommissioning the dam on zinc content of the siphon and lake discharge. To accomplish this, we looked at:

- **the expected concentrations of zinc in the surface mixed layer over the next two years and after mine closure,**
- **the stability of the halocline when the surface layer is reduced to 7.5 m, and**
- **the conditions during siphon or natural discharge at the south end of the lake that would allow high zinc content water in the halocline to enter the discharge.**

The current model for zinc concentrations in the surface layer provides an answer to the first question while the question of halocline stability can be answered by comparing the density gradient present in the halocline with possible wind conditions and mixing scenarios.

We felt that prior to looking at model predictions, the models should be reviewed and modified in light of data collected since the last model modifications in 1995. The Surveillance Network monitoring Programme (SNP) data from the last three years has shown that:

1. Zinc concentrations in the surface layer are **lower** than predicted in the 1995 model, and
2. Salinity is **higher in the bottom water** and **lower in the surface layer** than predicted by the 1995 models.

These differences suggested that the source terms in the surface layer related to the upward diffusion of salt and zinc were overestimated. The models were modified to account for these observations (see Appendix I).

2. EFFECT OF LAKE DRAW DOWN ON ZINC CONCENTRATIONS IN SIPHON OR LAKE DISCHARGE

2.1 Model predictions

The revised model output (Appendix I) for zinc concentrations in the surface layer independent of any significant wind mixing events indicates that **surface layer concentrations will remain well below 0.5 ppm for the remainder of mine operations (**figure 1**).** The only source of greater than 0.5 ppm zinc water is in the halocline (figure 2).

2.2 Stability of the Halocline

We considered what conditions would be required to bring halocline water close enough to the surface to influence siphon or lake discharge or to mix all or part of the halocline into the surface layer. **The energy required to either mix or tilt the halocline sufficiently can only be supplied by wind over open water**. Winds create waves which can induce mixing and also induce a "tilt" in the lake surface. As background, a discussion of wind generated waves and their properties is provided in Appendix II. In the following discussion the maximum summer wind speed recorded at nearby Resolute Bay from 1961 to 1990 (29 m/s or 105 km/h) has been used as an assumed maximum wind speed for Garrow Lake.

The most significant feature of the vertical structure of Garrow Lake is the persistent, strong halocline that separates the low salinity surface layer from the hypersaline deep layer. This can be seen in a comparison of the salinity profiles observed in 1982 and 1999 (Figure 3). The upper parts of the halocline are identical, although in 1999 the halocline has been displaced upward about 2 m because of the tailings input at depth. The nearly fresh tailings water discharged at 26-m depth has caused the changes evident in the deep water. The tailings water formed an upward moving plume that admixed surrounding deep water until the plume was arrested at the bottom of the halocline. After a number of years the result of this mixing activity is the homogeneous deep layer evident in the 1999 profile. Plume-caused mixing has eroded the lower part of the halocline. However, the strong upper part is unchanged. Once mining operations cease, erosion of the halocline from below will cease. The long term stability of the halocline is therefore dependent on whether there is erosion of the halocline from the surface.

The following discussion examines the magnitude and duration of winds over Garrow Lake in the short ice-free season (the lake does not completely clear of ice in some years) required to erode the halocline from the top, and eventually eliminate all structure in the lake. We have considered both the energy requirements to reduce or eliminate the stratification, and the rate at which energy could be supplied which is a function of the effective power of the wind blowing on the lake surface.

[1]In a 1973 paper, Edwards and Darbyshire[1] showed that in stratified lakes, on average, about 3.9 percent of the wind/wave energy supplied to the surface is available to stir the region of maximum density gradient (halocline in Garrow Lake) at a depth of 7.5 m. The wind induced energy at the surface (P) is supplied at a rate which is the product of the wind stress and the wind-caused surface current:

$$P = \rho_A c W^2 \times kW$$

where ρ_A is density of air (1.29 x 10^{-3} g/cm^3), c is the drag coefficient for air blowing over water (2.6 x 10^{-3}), k is the coefficient relating wind-induced current speed to wind speed (.0145), and W is wind speed. Wind power is proportional to the cube of wind speed. When the above values for the constants are inserted, and when wind speed is in meters per second, then wind power at the surface is

$$P = .0486\ W^3 \quad \text{ergs/cm}^2\text{s} \quad = \quad 4.86 \times 10^{-5}\ W^3 \quad \text{watts/m}^2$$

Four percent of this power would be available to stir the halocline at 7.5 m depth.

When a stratified water column is mixed to homogeneity, its center of gravity is raised, increasing its potential energy. The initial state is said to have a potential energy deficit with respect to the homogeneous mixed state. The potential energy deficit is the net amount of work required to eliminate the stratification, and therefore is a measure of the stability of the stratification. Consider a water column comprised of an upper layer of depth h_U and density ρ_U, and a lower layer of thickness h_L and density ρ_L. The potential energy deficit for this situation is

$$E' = 0.5\ g(\rho_L - \rho_U) h_U h_L$$

The potential energy deficit is larger the greater the difference in density between the two layers, and the thicker the layers. This expression can be used to calculate the work required to deepen the surface layer of Garrow Lake by entraining water from the top of the halocline, but an additional term is needed to account for the density gradient in the entrained halocline layer:

$$\Delta E = g \Delta\rho h_L^2 / 12$$

where $\Delta\rho$ is the density increase through the layer of thickness h_L. The entrainment is treated as a two step process: first the stratified layer that is to be entrained is mixed to homogeneity (ΔE), and then mixed with the surface layer (E'). The average density of the layer to be entrained, ρ_L, equals $\rho_U + \Delta\rho/2$, so the total work needed for entrainment into the surface layer is

$$E = E' + \Delta E = g \Delta\rho h_L (3h_U + h_L)/12$$

If the halocline has a linear density gradient then $\Delta\rho$ is proportional to the thickness of

[1] Edwards, A. and J. Darbyshire. 1973. Models of a lacustrine thermocline. Mem. Soc. Roy. des Sciences des Lieges. 6 series, vol 4, pp 81 - 101.

the entrained layer h_L, and thus E varies essentially as h_L^2. It follows that, compared to the entraining of a 1-m thick layer from the top of a halocline, **entraining a 2-m thick layer would require four times as much energy, while a 3-m layer would need nine times as much.**

The **duration** of wind needed to deepen the surface mixed layer is

$$D = E/.04P = 4862\ \Delta\rho h_L(3h_U + h_L) / W^3 \quad \text{days}$$

where the density difference is in g/cm^3, layer thickness is in m, and wind speed is in m/s. The duration required to entrain the upper 1-m, 2-m, and 3-m of the Garrow Lake halocline are shown in Figure 4 for wind speeds up to 40 m/s, along with the duration needed to mix the entire lake to homogeneity. The 1999 SNP density profiles were used for the calculations, with the surface mixed layer depth reduced to 7.5m in accord with the post-operations, draw-down prediction. The results show that a 13.5 m/s wind (49 km/h) blowing for 1day could mix the upper 1-m of the halocline into the surface layer, making it 8.5m deep. Another 8 days of the same wind would be required to further deepen the surface layer by 2m, to 10.5m. Stronger winds would accomplish the same mixing in shorter times. The region is characterized by relatively weak winds however. For instance in the summer of the years 1961-1990 at Resolute, the maximum observed hourly wind speed was only 29 m/s (105 km/h). Further this wind speed was of short duration (1 hour). A wind speed of this magnitude aligned along the lake would entrain the first meter of the halocline in 2.5 hours, the upper 3-m in a day, and, if it persisted for ten days, would eliminate all stratification in Garrow Lake. **Given that winds average less than 6 m/s during the open water season, and the historically short duration of maximum winds, there is a very low probability of even the upper 1 meter of the halocline being mixed into the surface layer.** It is noteworthy that in the 18 years of mine operations, there has been no wind induced mixing of the main halocline.

2.3 Wind Set-up and Halocline Displacement

Wind blowing over a lake exerts a shearing stress at the air-water interface that moves water in the downwind direction. When the wind has been blowing steadily, the water movement results in the "piling up" of water at the downwind end of the lake, and a lowering of lake level at the upwind end, creating a slightly sloped or tilted lake surface. The difference in lake level between the upwind and downwind ends is the wind set-up. The surface slope (s) is a measure of the pressure gradient induced to balance the wind stress, which is roughly proportional to the square of the wind speed:

$$s = \rho_A c W^2/\rho g h$$

where ρ_A is air density, ρ is water density, c is the drag coefficient, W is wind speed, and h is the water depth. In stratified lakes like Garrow Lake h is the depth of the surface mixed layer. The set-up pressure gradient exists through the surface mixed layer, but vanishes for all deeper levels, because the interface at the bottom of the surface layer acquires an opposite slope. But the slope of the interface (halocline) is much larger than that of the lake surface; the ratio of these slopes is determined mostly by the density ratio $\rho/\Delta\rho$, where $\Delta\rho$ is the difference in density between the surface layer and the deeper layer:

$$dh/dx = -s\ \rho/\Delta\rho$$

where x is the distance in the downwind direction. It follows that h is a quadratic function of distance:

$$h^2(x) = h_O^2 + 2\rho_A c W^2(x - F/2) / g\Delta\rho$$

where h_O is the surface layer depth in the absence of wind, and F is the maximum fetch. In Garrow Lake the second term, which accounts for displacement of the halocline, is relatively small because the density difference $\Delta\rho$ is so large (0.05 g/cm^3), resulting in small displacements from h_O. In the post-mill scenario the total surface layer depth will be about 7.5m, so potential discharge of water from the halocline would require a halocline tilt or set-down of at least 12m in 2400m (in the above equation x = 2400 and h = 6.5 m to bring the halocline to within 1 metre of the surface). **The wind speed required to produce this slope would be 208 km/h almost twice the maximum speed recorded at Resolute Bay. For the maximum wind speed of 29 m/s observed at Resolute, the mixed layer depth would be 6.5 m at the upwind end and 8.4 m at the downwind end of the lake, a set-down of only 1.9 m. The probability of a wind induced tilting of the halocline sufficient to influence siphoning or natural lake discharge is therefore very remote.**

The effect of tilting of the halocline also serves to offset somewhat the effects of wave induced mixing described in the previous section as there will be a downwind increase of the surface layer depth during strong wind events. For instance, for the case of maximum wind speed (29 m/sec), at the downwind end of the lake the top of the halocline would be 8.4 m deep rather than 7.5 m and the time required to mix the upper 1 m of the halocline increased by about 12 %.

3. RECOMMENDATIONS FOR ON-GOING MONITORING

After mine operations cease, there will no longer be tailings introduced into the deep layer of Garrow Lake and no further erosion of the bottom of the halocline. The only source of high zinc content water (outside permit limits) will be in the halocline. Monitoring after mine operations cease should therefore focus on halocline stability. We would recommend that the monitoring concentrate on:

1. Assessing annual changes in lake structure (vertical profiles of salinity/conductivity and depth of the surface layer), and
2. Monitoring zinc concentrations in the surface, halocline and deep layers of the lake.

It should not be necessary to monitor the siphon discharge from the lake if surface layer concentrations of zinc are below permit levels. Once the dam has been decommissioned, natural outflow in the absence of wind mixing will be primarily melt water and zinc concentrations in the outflow will be typically a third to a quarter of the mean concentrations in the surface layer (based on observations prior to 1990).

Annual changes in conductivity and zinc profiles could be assessed by sampling once a year at station 262-3. Sampling in late May or early June prior to ice melt would probably be most reliable since it may not be possible to sample in the summer if the lake does not clear of ice.

Wind speed and direction observations at nearby Resolute Bay should be reviewed from late July through freeze-up to determine if there is a wind event of sufficient magnitude and duration to cause mixing of the top of the halocline. Sampling through the surface and halocline layers should be conducted as soon as practical after such an event to assess whether there has been any measureable mixing. This should include a conductivity profile to determine the depth to the top of the halocline, halocline thickness and measurements of zinc content of the surface and halocline layers. A significant wind event could be defined as one capable of mixing at least the top metre of the halocline (see figure 4).

To be conservative it is suggested that monitoring should continue until the the zinc content of the surface layer and the top 2 m of the halocline are such that even if they were mixed, the mean zinc concentration in the deepened surface layer would not exceed 0.5 ppm.

4. CONCLUSIONS:

In summary, **it is our opinion that the level of Garrow Lake can be safely lowered to pre-dam levels and the dam decommissioned without zinc concentrations exceeding permit levels for the discharge and without affecting the stability of the halocline.**

This opinion assumes that the lake level would be lowered gradually over a period of at least three years before the dam is decommissioned. This would allow at least one complete freeze - thaw cycle on the lake after the mine has stopped operations.

Cominco started to draw down the lake in the summer of 2000 and plans to lower the lake to its pre-dam elevation by the late fall of 2002. The dam would then be decommissioned in 2003 and natural drainage would start in the summer of 2004. This will allow two complete freeze-thaw cycles on the lake after the mine ceases operations.

Highest concentrations of zinc in the siphon discharge and after decommissioning of the dam will occur when the lake is ice free and there is a strong wind aligned along the length of the lake. Under these conditions, the concentrations of zinc in the discharge will approximate the mean concentrations of the upper mixed layer.

The strong halocline will remain intact. There is a very low probability that there will be any significant mixing of the upper portion of the halocline into the surface layer as a result of wind induced mixing. Winds of sufficient magnitude and duration to mix even the top metre of the halocline into the surface layer are rare. The most sensitive time in this regard will be after the dam is decommissioned and the surface layer thickness is at its minimum. A worst case analysis (wind speed and duration sufficient to mix the top 2 m of the halocline with a surface layer thickness of 7.5 m) suggests that zinc concentrations in the surface layer would increase by approximately 0.13 ppm based on present halocline zinc concentrations. This would result in surface layer zinc concentrations that would be still be within the permit limit based on the revised model predictions. Concentrations of zinc in the outflow from Garrow Lake after decommissioning of the dam should be 3 to 4 times lower than the mean surface layer concentrations in the absence of significant wind mixing.

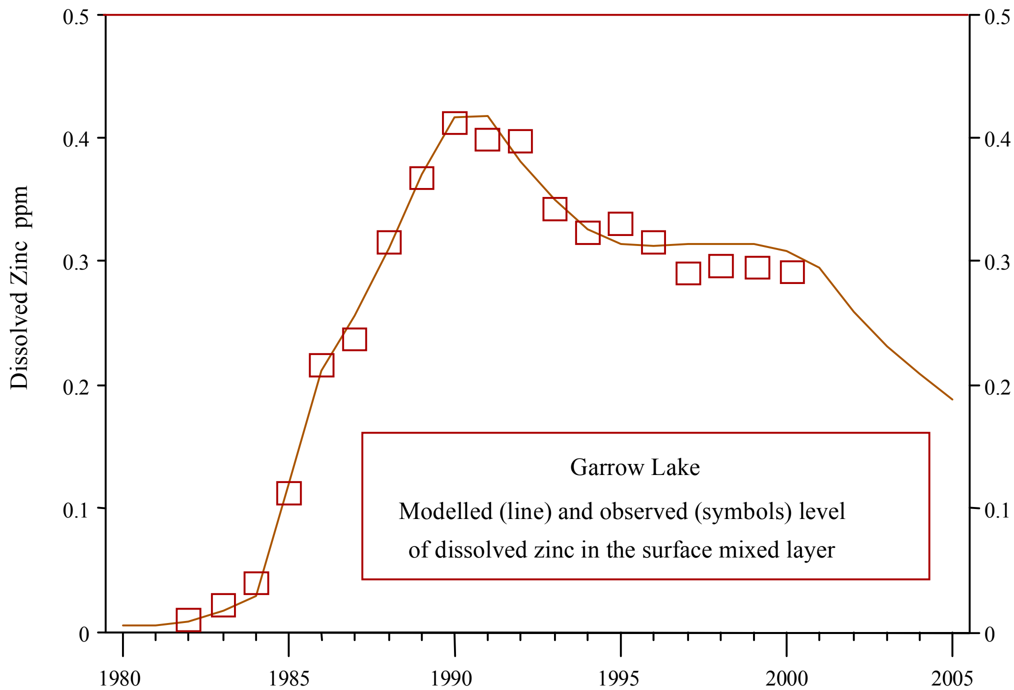


Figure 1. Revised model predictions and observations for zinc concentrations in the surface layer.

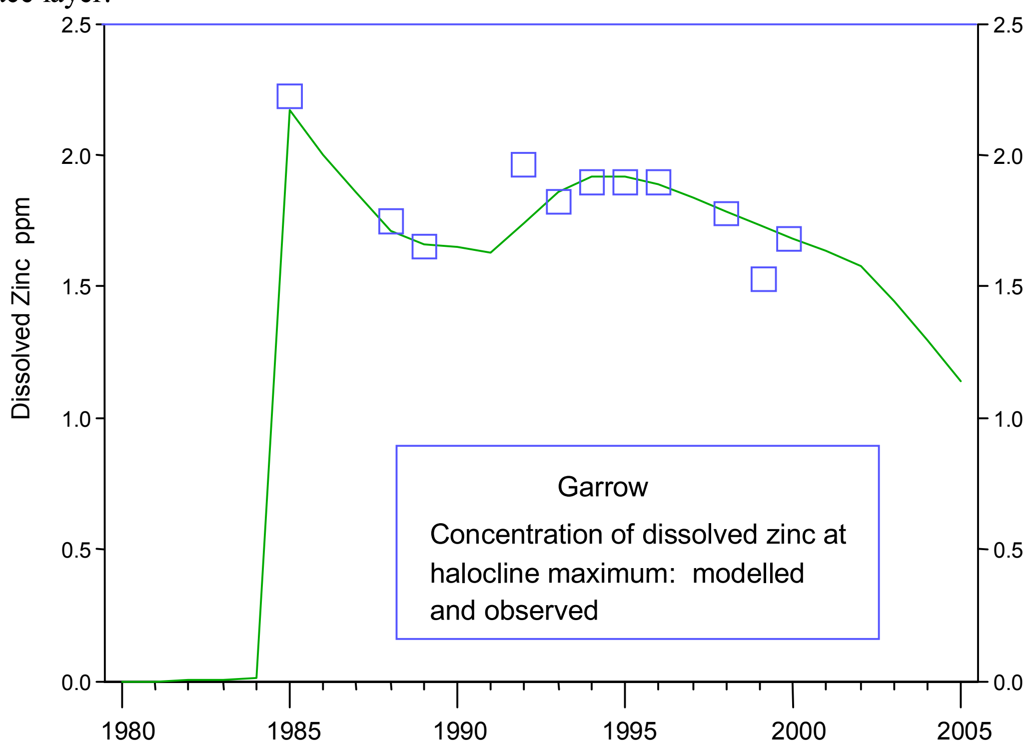


Figure 2. Revised model predictions and observations for zinc concentrations in the halocline

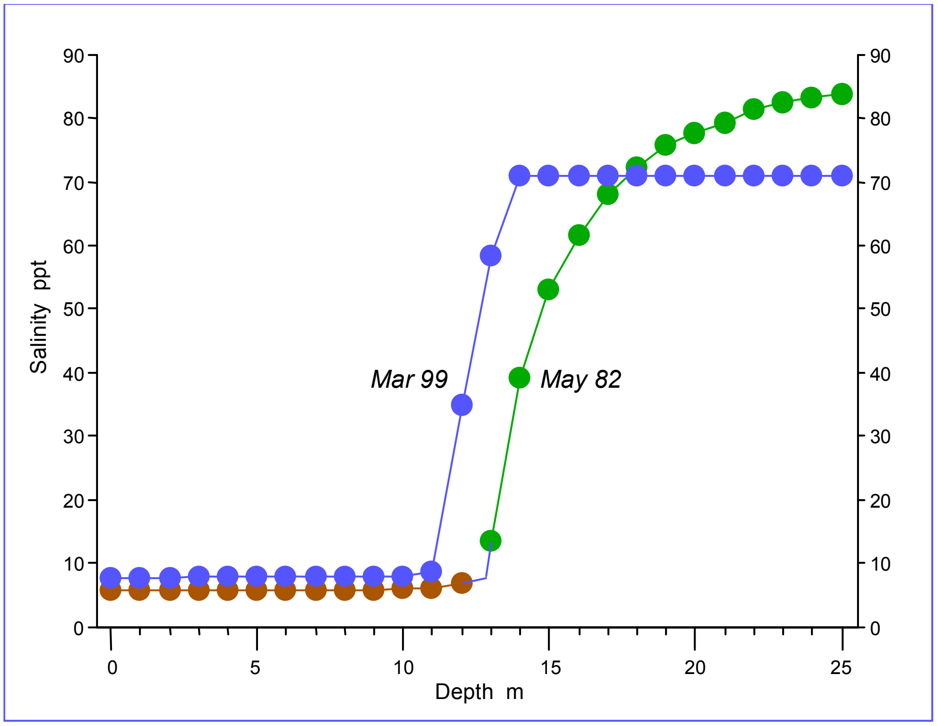


Figure 3. Salinity/depth profiles in Garrow Lake in May 1982 and May 1999

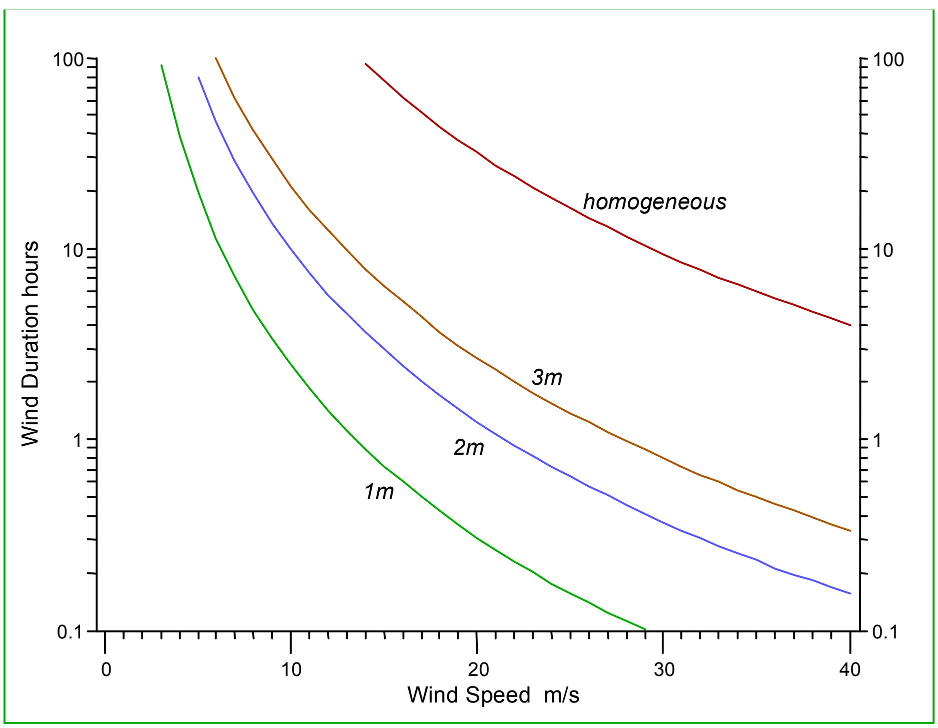


Figure 4. Wind duration as a function of wind speed required to mix the top 1, 2 and 3 m of Garrow Lake and to mix the lake to homogeneity.

Appendix I. Model Adjustments

Physical Model:

The rate of upward salt diffusion into the surface layer was reduced by about 20 percent, and the amount of salt discharged during siphoning was increased slightly. The salinity of the bottom layer predicted by the model is increased by about 1 ppt for years after 2001. These changes had essentially no effect on the outputs from the plume behaviour and bubble transport models (important inputs for the zinc/sulphide model).

Revised model outputs for surface and bottom layer salinity are shown in figures I-1 and I-2. Both surface and bottom layer salinity more closely track the observations in recent SNP reports although observed bottom water salinity in the past two years is still higher than predicted.

Zinc Model:

Several modifications were made to the zinc model to match observed concentrations in the surface and halocline. These included:

- the turbulent flux of zinc from the halocline to the surface layer was decreased by about a factor of 2
- the rate of input of zinc to the surface layer via flotation was increased by 25 percent but decreased to the halocline by 20 percent
- the rate of zinc precipitation due to rising lake levels after damming was reduced 70 percent
- the rate of loss of zinc due to siphoning was increased slightly
- the downward turbulent flux of zinc from the zinc maximum in the halocline was increased by 40 percent
- the addition of zinc to the halocline due to zinc precipitation events in the surface layer was reduced by 30 percent
- the turbulent flux of sulphide from the bottom layer to the halocline (where it is consumed) was increased by about 40 percent

Making these changes resulted in a model output which closely tracks the surface layer and halocline zinc concentrations (see figures 1 and 2). While the previous model predicted gradually rising zinc concentrations to the end of mine operations, the revised model predicts that zinc concentrations will remain nearly constant at about 0.3 ppm for the remainder of mine operations.

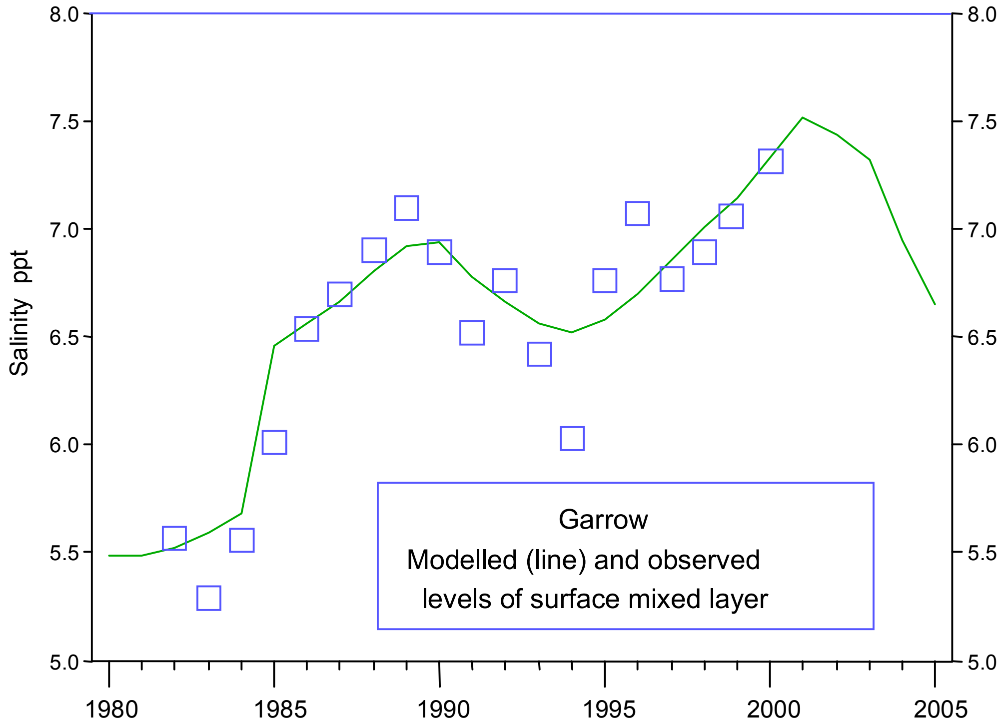


Figure I-1. Revised model predictions of surface layer salinity and observations

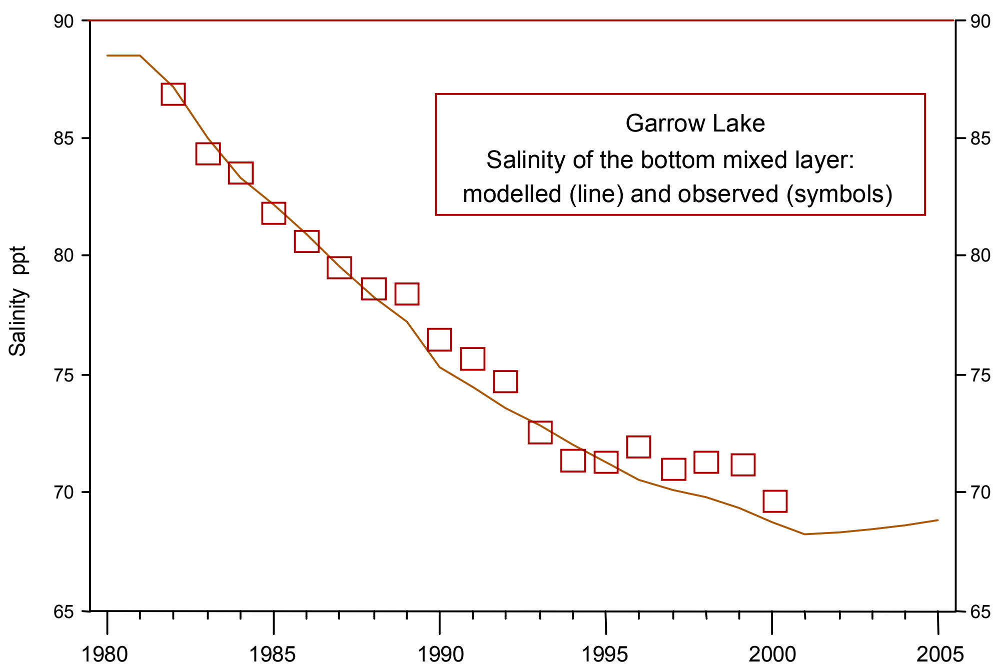


Figure I-2. Revised model predictions of bottom layer salinity and observations

Appendix II. Wind Wave Features

The four defining characteristics of a wave are its height, speed, length, and period. For waves produced by the action of wind blowing across the sea surface, all characteristics generally increase with wind speed, wind duration, and fetch (downwind distance from shore). Fetch plays a significant and restrictive role in wave growth in Garrow Lake, which has a maximum dimension of only 2400 m. The relationships that wave height, wave speed, and minimum duration have to fetch are presented graphically in Defant (1961, Figure 43). The corresponding empirical relations, expressed in terms of the same non-dimensional parameters used for the graphs, are discussed below and used to develop significant features of wind waves in Garrow Lake.

Minimum Duration: The minimum time required for the establishment of a steady fetch - limited wave field is given by the non-dimensioned relation

$$DW/F = 45\ (gF/W^2)^{-.32}$$

It follows that

$$D = .006\ F^{.68} W^{-.36} \quad \text{hr}$$

where D is duration in hours, F is fetch in meters, W is wind speed in meters per second, and where the constant value of 9.8 m/s^2 was used for the acceleration of gravity g. The minimum duration increases with fetch, but decreases with wind speed. The longest duration would be for maximum fetch and lowest wind speed. In Garrow Lake which has a 2400-m fetch, the duration for 1 m/s wind is only 1.2 hr, and is lower for higher speeds. The duration would be 0.5 hr for 10 m/s wind and 0.35 hr for 30 m/s wind. Thus the length of time for establishment of a steady wave field in fetch-limited Garrow Lake would be less than an hour for any significant wind event.

Wave Height: For wind speeds 2 m/s and higher, the relationship among wave height H, wind speed W and fetch F is

$$gH/W^2 = .0028\ (gF/W^2)^{3/7}$$

It follows that

$$H = .00076\ F^{3/7} W^{8/7} \quad \text{m}$$

Thus wave height varies approximately linearly with wind speed, and approximately as the square root of the fetch. Wave heights were calculated for Garrow Lake for wind speeds up to 40 m/s (144 km/h), and for fetches of 1200 m (mid lake) and 2400 m (at the downwind end). The results are presented in Figure II-1. Waves 0.5 m high require winds exceeding 16 m/s (58 km/h), while those 1.0 m high need winds above 28 m/s (101 km/h).

<u>Wave Age:</u> The age of a wave is defined as V/W, the ratio of the wave speed V to the wind speed W, both in the same units. Wave age as a function of fetch F and wind speed is given by

$$V/W = .07\ (gF/W^2)^{2/7}$$

Wave age increases from zero with the onset of wind, and with sufficient duration and fetch, can exceed 1.0 (wave speed faster than wind). This situation would happen in Garrow Lake only for winds less than 2 m/s. For all other wind speeds wave age would be less than 1.0. At 10 m/s wind speed wave age would be 0.33 at 2400 m fetch; while at 20 m/s the age would be 0.22.

<u>Wave Speed:</u> Wave speed as a function of fetch and wind speed can be derived from the wave age relation:

$$V = .1344\ F^{2/7}W^{3/7}\ \text{m/s}$$

Wave speed varies approximately as the cube root of fetch, and approximately as the square root of wind speed, with the proviso that wind duration is long enough for a steady condition to have been established. In Figure II-2, which shows wave speed as a function of wind speed, calculated at mid lake and the downwind end, the dependency of wave speed on the root of wind speed is evident. Wave speed is about 3 m/s for 10 m/s wind, and about 5 m/s for 30 m/s wind.

<u>Wave Length:</u> Surface waves on Garrow Lake can be treated as deep water waves, for which the wave length L depends on the square of the wave speed V:

$$L = 2\pi V^2/g$$

Introducing the expression given above for wave speed:

$$L = .01158\ F^{4/7}W^{6/7}\ \text{m}$$

Wave length is roughly proportional to the square root of fetch, and is nearly a linear function of wind speed. Calculations of wave lengths for wind speeds up to 40 m/s for the 1200-m and 2400-m fetches are presented in Figure I-3. The calculations show that a wind of 40 m/s (144 km/h) would produce a wave length of 23 m at the downwind end of Garrow Lake; and that weaker winds and shorter fetches would produce shorter waves.

A surface wave is considered to be a deep water wave if the water depth exceeds one quarter of the wave length. Thus the 23-m wave that is associated with a 40 m/s wind would be deep in nature for water depths of 6 m or more (93 percent of maximum fetch in Garrow Lake is deeper than 6 m). **This means that the fetch limitation on wave length permits only deep water waves for essentially all wind events on Garrow Lake.**

Wave Period: The period of a wave T is the time required to travel one wave length:

$$T = L/V = 2\pi V/g$$

Introducing the expression given above for wave speed,

$$T = .0862\ F^{2/7}W^{3/7}$$

Wave period varies with fetch and wind speed in the same way as wave speed, or approximately as the square root of wind speed and as the cube root of fetch. Calculations of wave periods were made for wind speeds up to 40 m/s and for the 1200-m and 2400-m fetches of Garrow Lake (Figure I-4). Periods are 1 to 2 s for weak winds, and are 3 to 4 s for 30 to 40 m/s winds.

Wave Orbital Velocity: The trajectory of water particles in a deep water wave is a circle that, at the surface, has a diameter H related to wave height, and that is traced once during each wave period T. Accordingly the orbital velocity is $U = \pi H/T$ m/s at the surface. Introducing the wave height and wave period functions,

$$U = .0277\ F^{1/7}W^{5/7}$$

Orbital velocity has little dependency on fetch; a doubling of fetch increases the velocity by only 10 percent. The surface orbital velocity of wind waves in Garrow Lake would be about 1 m/s for winds of 40 m/s, and would be smaller for weaker winds.

The orbital velocity decreases exponentially with depth according to $\exp(-2\pi Z/L)$, where Z is the depth below the surface. The decrease with depth is rapid. At depths equal to one-quarter, one-half and one wave length the velocity is, respectively, 21.8, 4.3, and 0.2 percent of the value at the surface. In turn, there is a corresponding diminution with depth of energy that might be available for entraining halocline water into the surface layer of Garrow Lake.

Reference:

Defant, Albert. 1961. Physical Oceanography. Vol II. Pergamon Press, Oxford. 598p.

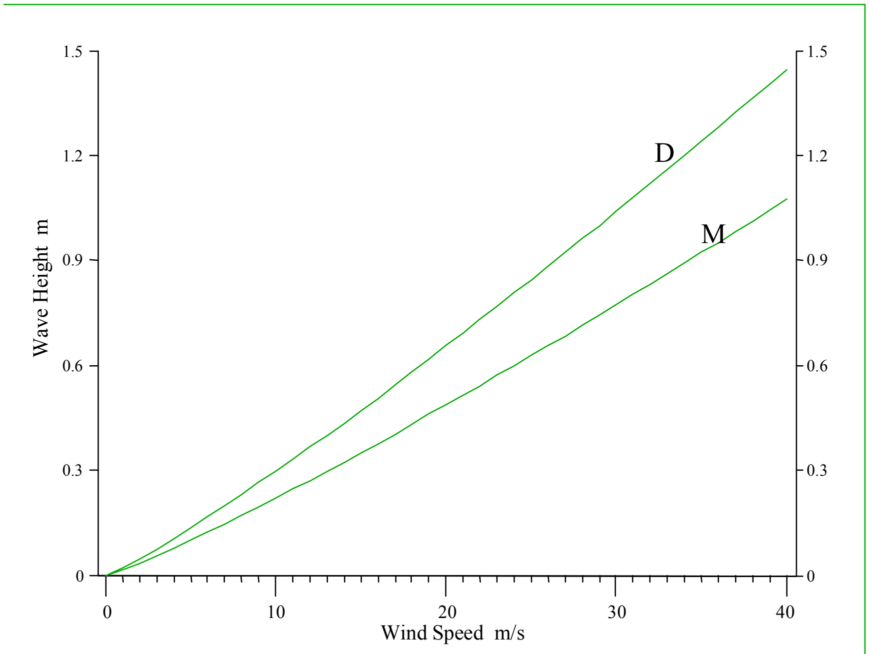


Figure II-1. Wave height as a function of wind speed at the downwind end of the lake or maximum fetch (D) and at mid-lake (M).

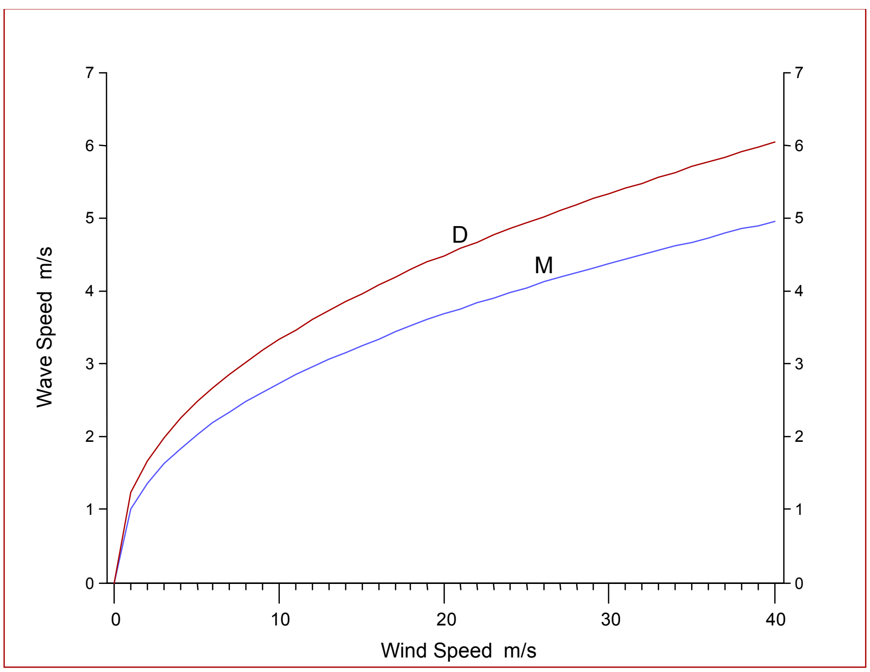


Figure II-2. Wave speed as a function of wind speed at the downwind end of the lake (D) and at mid-lake (M).

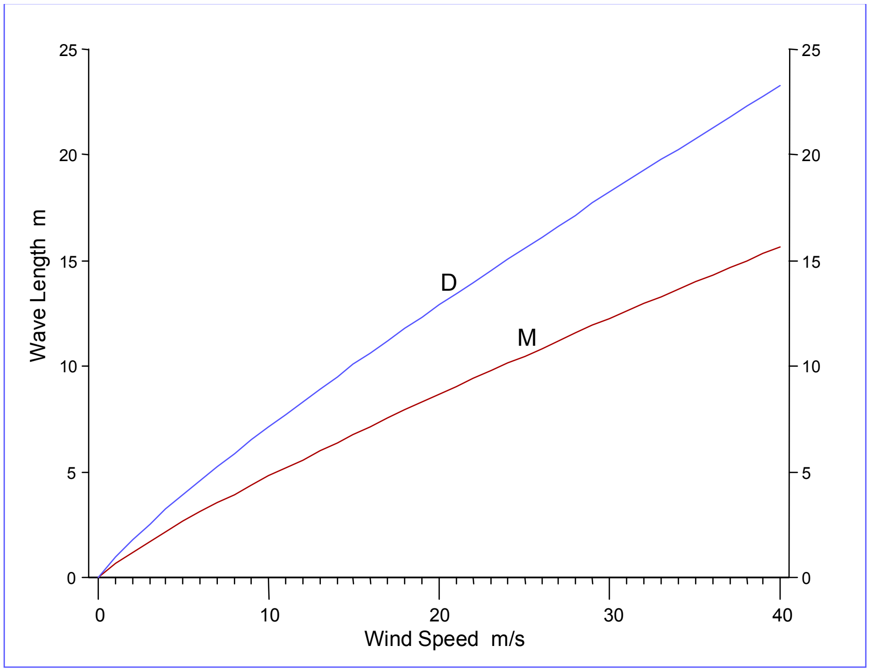


Figure II-3. Wave Length as a function of wind speed at the downwind end of the lake (D) and at mid-lake (M).

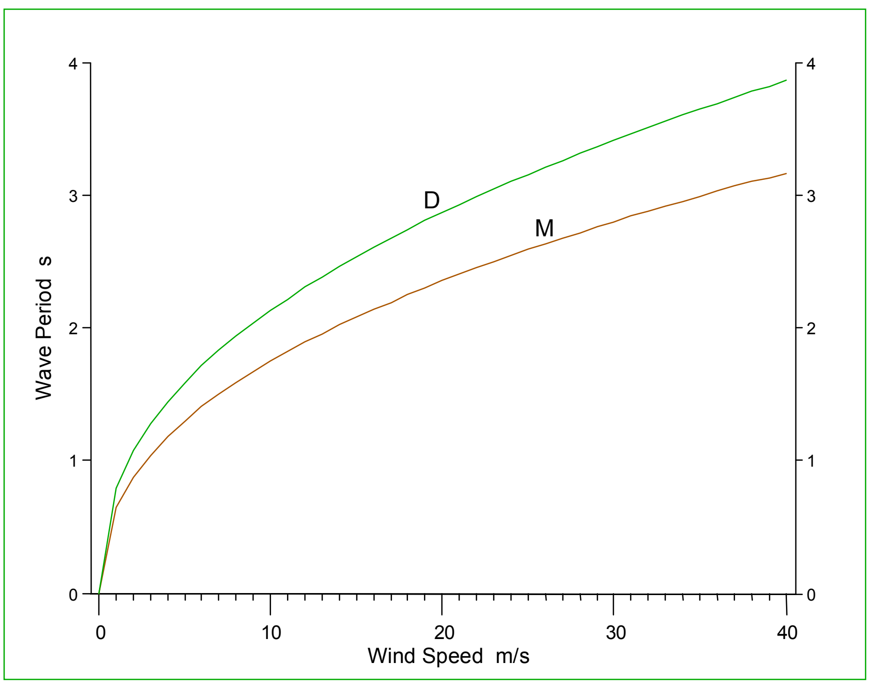


Figure II-4. Wind period as a function of wind speed at the downwind end of the lake (D) and at mid-lake (M).