HYDROGEN SULFIDE IN HUDGEON LAKE, YUKON: EVALUATION AND REMEDIATION OPTIONS

By

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Abstract

Hudgeon Lake was created in 1974 by a waste rock landslide at the Clinton Creek Asbestos Mine. Previous environmental reviews identified the lake as a restrictive habitat for fish due to anoxic conditions and sulfide generation in deeper water. In order to understand the nature of the lake a water quality testing program was conducted. Water quality parameters studied included temperature, pH, conductivity, salinity, sulfides, dissolved anions and cations and metals. The lake was found to be meromictic, mixing only on the surface. Risk associated with sudden release of elevated levels of sulfide due to an overturn was considered minimal however; other risks associated with a breach of the waste rock dam were identified. Remediation options discussed include the lowering of the lake level which is recommended to address the reduction of risk, improve water quality and allow fish access to the upper Clinton Creek drainage.

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Chapter 1 – Introduction

Context

Hudgeon Lake lies within the operational area of the abandoned Clinton Creek Asbestos Mine, about 100 km northwest of Dawson City, Yukon Territory. The mine site is 9 km upstream where Clinton Creek flows into the Fortymile River. This is also the location of the former mining town of Clinton Creek. The town site is approximately 5 km upstream from the confluence of the Fortymile River and the Yukon River, where the remnants of the town of Fortymile can be found, a historic site pre-dating the Klondike Gold Rush. From there, the Yukon River winds its way for about 65 km (river kilometres) to enter the State of Alaska, making it a trans-boundary river with implications to the whole watershed in terms of the Pacific Salmon Treaty (1985) between Canada and the United States.

The mine area can be accessed seasonally from Dawson City via the Top of the World Highway and the Clinton Creek Road. The Clinton Creek Road is maintained in the summer by Yukon Government (YG), but all roads west of Dawson City, except access to West Dawson, are closed during the winter months.

Hudgeon Lake was created in 1974, when waste rock deposited on the north-facing slope of the Clinton Creek valley failed and the slide extended across the valley bottom. The blockage caused the flooding of the valley to form a lake with a calculated area of around 65 ha, an approximate total volume of 6.7×10^6 m^3, and a maximum depth of 27 m. The deepest section is near the outlet.

The site was closed in 1978. The Northern Affairs Program of Indian and Northern Affairs Canada (INAC) have monitored the mine site since then. Ownership remained with

Cassiar Asbestos Corporation Ltd. until 1991, when the company was acquired by Princeton Mining Corporation. Some remediation activities were initiated by the former and the new mine owners and studies for a closure plan were undertaken, but an agreement for closure of the mine site between the company and INAC was never reached. However, Princeton Mining Corporation eventually succeeded to have an environmental bond associated with an earlier water licence returned by INAC before the company ceased to operate in the early 1990s.

Following a study of the potential risks to human life and property associated with flooding from a catastrophic breach of the waste rock dam (UMA Engineering Ltd. [UMA], 2000), INAC Water Resources issued a directive to the former owners of the company in 2002 to undertake actions to stabilize the creek channel under Section 37 of the *Yukon Waters Act*. The corporate structure of any liable party had, however, been dissolved and no response was received. For that reason, the site was treated as abandoned and INAC Waste Management initiated the first phase of a channel stabilization program that was designed by UMA Engineering Ltd. (2002).

In 2003, the devolution of most remaining federal powers to the YG was instated. The new arrangements were documented in the *Yukon Devolution Transfer Agreement* (INAC, 2001a), and Chapter Six covered federal liabilities regarding abandoned mine sites. The Clinton Creek Mine is now a designated “Type Two” mine site, managed by the YG Energy Mines and Resources, Assessment and Abandoned Mines Office, and funded through the INAC Contaminated Sites Program with Treasury Board Contaminated Sites Funding. Over the past few years remediation and care and maintenance work has been contracted out according to INAC’s mandate to provide employment to the local First Nation and northerners and YG’s mandate to preferably contract work to Yukon based bidders if possible. The monitoring of continuing waste rock and tailings movements is also on-going (UMA, 2006). Current efforts and studies are underway to develop a final closure plan for the mine site by addressing the following environmental issues and human health hazards:

- Stability of the waste rock and asbestos tailings
- Long-term effects of air- and water borne asbestos from the unstable asbestos tailings on humans, wildlife and aquatic species
- Vulnerability of the creek channels and access roads due to erosion
- Long term viability of the waste rock dam to safely retain the waters of Hudgeon Lake
- The risk of a catastrophic breach of the waste rock dam with subsequent flooding, sedimentation and wash-outs of downstream fish habitat and road access, and the potential of the loss of property and human life.

Since the site receives funding under the Federal Contaminated Sites Action Plan (FCSAP), the Department of Fisheries and Oceans (DFO) acts as an Expert Department and carries out the monitoring of the status of aquatic habitat (DFO, 2006). Aside from the observations of effects on anadromous fish populations (juvenile Chinook salmon) and non-anadromous fish species (arctic grayling, slimy sculpins and long-nose suckers), there have not been any studies of the physical and chemical conditions of Hudgeon Lake.

The site is located within the Klondike Plateau ecoregion, an area known for placer mining since the Klondike Gold Rush of 1898. Aside from placer mining, current land uses include prospecting and mineral exploration, wilderness recreation and tourism, hunting and trapping (Environment Canada, 2008). And although the site is somewhat remote and located in a sparsely populated area of the region, the level of public, governmental and stakeholder interest is considerably high. A final closure plan is expected to be scrutinized by a wide range of stakeholders and interest groups including:

- Local residents – property owners at the Fortymile River, including a trapper
- Members of the Tr’ondëk Hwëch’in (the local First Nation) and other residents of Dawson City and area
- Local placer claim holders, including Fortymile River placer miners with an access road passing through the Clinton Creek town site
- Various Yukon Government Departments (Environment, Energy Mines and Resources, Community Services, and Highways and Public Works)
- Federal Departments (INAC, Environment Canada, DFO)
- Yukon Fish and Wildlife Management Board
- Yukon Salmon Committee
- Yukon Conservation Society
- Canadian Parks and Wilderness Society
- Yukon River Inter-Tribal Watershed Council (with members from Alaska and Yukon aboriginal groups)
- State of Alaska and some U.S. Federal Departments (U.S. Geological Survey, Hydrology Department).

The objectives of closure planning and final remediation work for the federal government are to find and implement solutions that will alleviate further liabilities, and for the Yukon government, to restore the site to a state with minimal environmental and human health risks and if possible, with no long term care and maintenance and monitoring requirements.

The Issue

In 1998, an extensive environmental review of the mine area was carried out by the Applied Research Division of Royal Roads University (1999) and UMA Engineering Ltd. (1999) for INAC, Waste Management Program, Yukon Region. Among geochemical evaluation of the mine waste materials, instability issues regarding waste rock and tailings dumps, and inventory and assessment of aquatic and terrestrial habitats, a limited sampling program was applied to determine the water quality of Hudgeon Lake. It was found that the lake was anoxic at depth and the presence of hydrogen sulfide (H_2S) was noted in samples from deeper sections (hypolimnion). Recommendations for further studies included the need to assess the chemical behaviour of the anoxic hypolimnion, the lake stratification, and “the possible effects of overturn events and downstream movement of sulfide-rich water masses” (Royal Roads University [RRU], 1999).

When INAC Waste Management Program initiated work to stabilize the stream channel of Clinton Creek at the outlet of Hudgeon Lake in 2002, the author in his capacity as Environmental Officer with INAC carried out occasional sampling at different times of the year in order to investigate the stratification and H_2S levels in the lake. Increased levels of H_2S with depth and an almost linear decrease of temperature toward 0°C at the deepest area were observed (INAC, 2003). The absence of a significant layer of water at 4°C (where freshwater is at its densest) at the bottom of the lake gave rise to the suggestion that the unusual temperature stratification of the water profile was influenced by a salinity effect, with a higher concentration of dissolved ions and anions in bottom waters. The theory of high salinity at the bottom was reinforced by temperature measurements at and slightly below 0°C that suggested a depressed freezing point. Cold water saturated sediment samples were also recovered from the deepest section of the lake without the presence of ice crystals.

The exploratory sampling did not establish certainty if the lake would turn over and release significant quantities of bottom waters that would be toxic to aquatic organisms downstream. This thesis project was developed to provide a more structured, consistent, and also economical approach to gather data approximately every six weeks for an entire year in order to capture significant seasonal changes.

Research Objectives

The main objective of the research was to study physical and chemical processes in the lake and to assess the possibility of H_2S release through turn over, large hydrological events (e.g., freshet), release to the atmosphere or a combination of the above. The data gathered could potentially be used to provide some recommendations for future monitoring, additional studies and remediation options if environmental risks associated with the release of H_2S are identified. The research question posed for this project was therefore: What is the potential for the release of toxic quantities of H_2S from the bottom of Hudgeon Lake at the abandoned Clinton Creek Asbestos Mine and how can this risk be mitigated?

A number of sub-objectives were proposed to evaluate the influence and impact of the lake on its immediate environment. One objective was the collection of invertebrates at the inflow and outflow of the lake for comparison and an assessment of possible detrimental effects from lake discharge by identifying species that may be tolerant to poor water quality below the outflow. This aspect of the research was scaled back, however, since the Assessment and Abandoned Mines Office of YG commissioned a separate study of the biological productivity of the lake in the summer of 2007. The investigation included the evaluation of fish utilization, water quality, and the extent of benthic invertebrate colonization (White Mountain Environmental Consulting [WMEC], 2008). Some of the results of the WMEC study are discussed in this thesis. Another sub-objective included the consideration of the influences this man-made lake has on permafrost in the area.

To achieve these objectives data was gathered approximately every six weeks over the year in 2007. Water samples were obtained from the inflow and outflow of the lake. Sampling at depth was also conducted at 5 m intervals. These samples were analyzed for various water quality parameters including pH, conductivity, sulfides, dissolved anions and cations. Samples collected from surface waters at all inflows and the outflow in June 2008 were also analyzed for nutrients and dissolved metals. Following data analysis and interpretation, remediation options and recommendations for a sustainable site closure have been proposed in the final chapters.

Chapter 2 – Literature Review

Asbestos Deposit and Mine Operation

According to notes from a prospecting course (Yukon Chamber of Mines, 2000), asbestos occurs in so-called regional metamorphic deposits that are pod-like to irregularly shaped, with ore consisting of stockwork veinlets that range from 1 to 10 cm in width and several meters in length. The length of the fibres and the spacing of fibre containing veinlets are crucial to evaluate such a deposit. Although there are numerous showings of asbestos in the Yukon, the Clinton Creek deposit has been the only economic viable one in the territory. Chrysotile asbestos, as mined at Clinton Creek, occurs in ultramafic metamorphic deposits; ultramafic meaning igneous (cooled magma) rocks with a high content of dark coloured minerals including magnesium and iron. The silky fibres formed through metamorphism of highly fractured ultramafic rock where circulating hot water solutions caused the mineral serpentine (magnesium iron silicate hydroxide) to re-crystallize into asbestos within the fractures (Yukon Chamber of Mines, 2000).

The discovery of asbestos in the Clinton Creek area is credited to Arthur Anderson, a native trapper from the village of Fortymile. Staking of the property was arranged in 1957 by the Dawson City merchant Fred Caley, and a Toronto based exploration company acquired the claims the same year. The property was transferred to Cassiar Asbestos Corporation Ltd. and an intermittent trenching, underground bulk sampling, diamond drilling, geological and geophysical exploration program was carried out between 1957 and 1964 (Budinski, 1984). Active asbestos mining on the Clinton Creek property was undertaken by Cassiar Asbestos Corporation Ltd. from 1968 until 1978. According to Budinski (1984), chief geologist of Cassiar Resources Limited in 1980, the mining took place in three open pits, one large (Porcupine Pit) and two smaller ones (Snowshoe Pit and Creek Pit), and averaged 1.5 million tonnes of asbestos ore annually. The removal of overburden (waste rock) amounted to 6 million tonnes per year. From the mined asbestos ore 939,887 tonnes of cement grade asbestos fibre was produced.

The waste rock was dumped over the slopes next to the open pits. The total amount of waste rock was approximately 60 million tonnes, most of which was dumped on the north-facing slope of the Clinton Creek valley, causing waste rock failure and the creation of Hudgeon Lake in 1974. The waste rock dam displaced the creek at the outflow of the lake about 25 m above the valley bottom and it cut a new channel into the interface of the waste material and the northern valley wall (Stepanek & McAlpine, 1992).

Asbestos ore from the pits was taken to the primary crusher near the largest pit (Porcupine) and then transported by an aerial tramway, 1,609 m long, to the mill on top of the hill across the Clinton Creek valley. After drying and further crushing, the material underwent “successive stages of screening, aspiration, fibrising, cleaning and grading” and the “various fibre products were then pressure packed into 45 kg bags for truck transport” (Budinski, 1984). The tailings from the milling process, amounting to approximately 14 million tonnes, were deposited over a slope to the adjacent Wolverine Creek valley. Also in 1974, the tailings pile failed and temporarily blocked Wolverine Creek, a tributary which enters Clinton Creek downstream of the waste rock area. During blockage of Wolverine Creek by tailings, a small lake formed, but the blockage was subsequently breached which released water borne tailings into the channel downstream. Channel blockages were repeated as the downhill movement of the tailings lobe (South Lobe) continued. The placement of tailings was then continued farther north with the same effect of failure, forming the North Lobe (UMA, 1999). The gradual movement of the tailings, temporary blockages, and breaches still continue to occur. The failures of both the waste rock and the tailings have been attributed to the disturbance of the slopes and the loading that caused permafrost degradation which, in turn, triggered these mass movements (Stepanek & McAlpine, 1992). A layout of the site is shown in Figure 1.

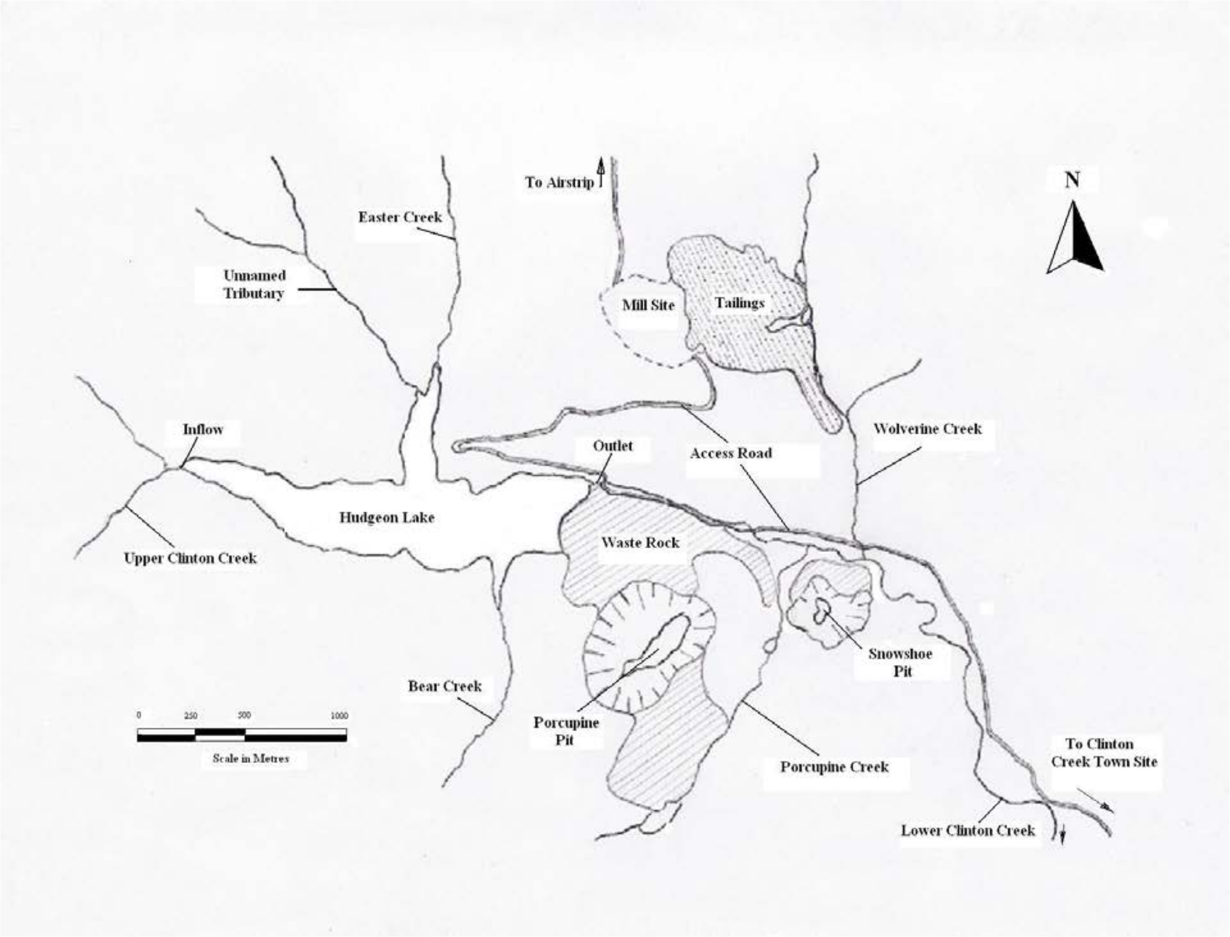

Figure 1. Site map of the Clinton Creek Asbestos Mine showing main features drawn from an airphoto (INAC, 2001b).

Local Geology and Geochemistry

The Clinton Creek area is situated near the northwest trending Tintina Fault which divides the Yukon Territory into two main geological units. The north-eastern part consists of an older sequence of sedimentary rocks, deposited on the stable geological base of the ancient North American continent. The south-western portion, of which the Clinton Creek area is a part of, is "composed of a younger, complex mosaic of varying rock types that amalgamated and accreted to the stable sedimentary package" (Hart, 2002). This region is part of the Yukon Metamorphic Complex consisting of a sedimentary and volcanic assemblage where thin bedded phyllites, graphitic and limy argillites, quartzite, limestone, quartz mica schist and gneisses, marble, greenstones and chloritic schists are found (Budinski, 1984). Locally, ultramafic, igneous and metamorphosed rocks include serpentinite, diorite, amphibolite, and schist. These rocks are overlain in most areas of the mine, including most of the Clinton Creek drainage basin, by a mantle of shale, siltstone and sandstone, with some local phyllite and phyllonite (Stepanek & McAlpine, 1992).

The surface and subsurface geology is naturally the source of geochemical constituents in surface and sub-surface water as small particles or in solution. The primary process for rocks breaking down to become subject to transport by water or mass wasting down steep slopes is mechanical weathering. The effectiveness of such weathering depends on the type of rock and its strength, the presence of fractures and pores, spacing, continuity, and orientation of joints, the infilling of the joints, and the movement of water in and out of a rock mass (Bloom, 1998). Major mechanical ways are described by Bloom (1998, pp. 120 – 127) as:

- Pressure release due to erosion of overburden over long periods of time
- Thermal expansion and contraction - including fire, sudden and seasonal temperature changes
- Growth of foreign crystals in cracks and pores, or salt weathering
- Frost cracking and hydrofracturing - freeze thaw cycles and capillary film cooling and freezing and therefore attracting more water and ice in non-confined and non-water saturated surface rocks
- Plants and animal activity – wedging action of plant roots, soil organisms, larger animals, and, of course, the excavation and mining activities of humans; making them the primary erosional agents.

Somewhat less effective than mechanical weathering and even more gradual, but still of great importance, is chemical weathering or decomposition. Instrumental in chemical weathering is water with various solutes, oxygen, and organic and inorganic acids as a result of biochemical activities in the environment. Primary minerals are converted by these agents and elements are released in soluble form with water being the medium of transport. Brady & Weil (1999, pp. 34 - 37) describe six types of chemical weathering as follows:

- Hydration – the binding of water molecules to minerals with products of hydration reactions such as hydrated iron and aluminum oxides
- Hydrolysis – where molecules of water split into hydrogen and hydroxyl components and the exchange of a cation with hydrogen releases water soluble elements or molecules such as potassium or silicic acid
- Dissolution – the dissolving of minerals through hydrating of anions and cations until they are dissociated and dissolved in water (e.g., gypsum dissolving to calcium and sulfate in water)
- Carbonation and other acid reactions – chemical dissolution of minerals becomes accelerated in the presence of acids (e.g., carbonic acid can release calcium and bicarbonate into solution by reacting with the mineral calcite)
- Oxidation-Reduction – highly frequent reactions in minerals containing iron, manganese and sulfur exposed to air and water
- Complexation – organic acids from biological processes in soil are able to mobilize aluminum and silicon into solution by forming organic complexes, also known as chelates, from silicate minerals.

Physical and chemical weathering processes take place simultaneously and are complimentary in the effectiveness of releasing soluble constituents from parent rocks. Other enhancing and facilitating processes occur through microbial weathering on the surface and below surface even in the harshest climates. Bacteria, fungi and algae have the ability to dissolve elements from minerals and thereby effectively speeding up all purely physical and chemical weathering (Bloom, 1998).

Weathering of rock material and subsequent soil formation are in general dependent on the parent material, climate, organisms present, topography, and time (Bloom, 1998). The Clinton Creek watershed is located in a cold climate and annual precipitation is fairly low, yet the analysis of surface waters in the watershed confirms that weathering is effectively taking place. Major dissolved anions and cations in the water are calcium, magnesium, sulfate, and bicarbonate. To a lesser degree, sodium, chloride, potassium, and iron are also present. These constituents can be expected from the local rock types described above. Argillite, sandstone, shale, and siltstone contain aluminum, silica and several alkali and alkaline earth cations, such as potassium, sodium, and calcium. Since shale and argillite are sedimentary rocks from marine and lacustrine (lake) deposits, they are also a source of such anions as sulfates and carbonates. The ultramafic and mafic rocks associated with the asbestos ore body and found in outcrops in the watershed, such as serpentine rocks, contain high levels of iron and magnesium. The amphibole found in the area consists in addition to iron and magnesium also of aluminum and silica (Christopherson, 1992). Implications of these dissolved materials found in the Clinton Creek watershed on Hudgeon Lake and its stratification are discussed in Chapters 4 and 5.

Geography and Ecoregion

The Clinton Creek Mine is located approximately 230 km south of the Arctic Circle and 13 km from the Alaska – Yukon border with the following coordinates: 64° 26.6’ N and 140° 42.8’ W. The mine area and Hudgeon Lake lie within the unglaciated portion of the Klondike Plateau ecoregion with the characteristic terrain features of rolling plateau topography with moderate to deeply incised V- shaped valleys. Lakes are therefore highly unusual in this terrain. Mean temperatures range from 10.5 °C in the summer to -23 °C in the winter, with an annual mean of -5.5 °C (Environment Canada, 2008). The range of mean annual precipitation is 300 – 450 mm and the climate is continental with short warm summers in contrast to long, cold winters.

The Assessment and Abandoned Mines Office of YG maintained a weather station at the mine site during 2006 and 2007. However, only the 2006 data was usable and raw data of the HOBO Micro Station Logger (Model H22-002) was made available for this thesis. The sampling interval was set at 300 s and daily values for the sum of rainfall, average temperature, wind speed and direction, maximum for temperature and wind speed, and minimum for temperature were calculated from the raw data for June, July, August and September of 2006 and are shown in Appendix B (Tables B1 – B4). The average daily wind direction was graphed for each month (Figures B1 – B4) because of the importance to illustrate the main wind direction which has an influence on surface water mixing of Hudgeon Lake during the summer months. The graphs show that the prevailing wind direction is south with intermittent southeast and southwest periods but no extended periods of wind blowing from due east or west directions. Since the aspect of the lake is east/west, the lake is relatively sheltered lying between the surrounding hills.

The average elevation of the area according to Environment Canada’s ecoregion description, is between 1,000 – 1,500 m above sea level (asl), with major drainage channels extending below 1,000 m asl. The elevation of the mine site is well below that of the surrounding terrain. The outlet of Hudgeon Lake and therefore the lake level is indeed currently maintained by the installed drop structures at 411 m asl (UMA, 2006).

Forests in the region are described as consisting of black and white spruce forests with aspen and occasional lodge pole pine in warmer boreal sections. Paper birch and black spruce are found on slopes that are underlain by permafrost, and alder, willow and balsam poplar are common along drainage areas, water courses, and flood plains. Widely distributed are extensive stands of dwarf birch and willow that can be found from valley bottoms to well above the tree line.

The occurrence of permafrost is widespread but discontinuous and can be found in fine-textured valley deposits and north-facing, steep, and moss-covered slopes. Soils in association with permafrost have been identified as Turbic Cryosols, and soils that developed on loamy colluvial materials are Eutric Brunisols, while Regosols are found in sandy floodplains (Environment Canada, 2008).

Wildlife most commonly observed in the area includes caribou, moose, grizzly and black bear, wolf, fox, wolverine, hare and beaver. Avian species present have been found to be raven, magpie, gray jay, rock and willow ptarmigan, golden eagle, bald eagle, hawk and owl. Waterfowl including dabbling and diving duck species have been observed during summer and fall on the lake, the beaver ponds along Clinton Creek below the mine, the Fortymile River and Yukon River.

Drainage Basin and Water Flow

Drainage basin data was obtained from the UMA Risk Assessment Report (2000), prepared for INAC. A drawing of the drainage area including the lake and all inflowing creeks is shown in Appendix B (Figure B5). The total drainage area above the outflow of Hudgeon Lake has been calculated to be 112 km^2 and a peak outflow from the lake (a 200 year flood peak) was estimated to be 43 m^3/s according to data from Water Survey of Canada and U.S. Geological Survey hydrometric stations in the general vicinity of the mine (UMA, 2000).

Summer data for 2006 regarding the water flow through the Clinton Creek watershed from the Clinton Creek hydrometric station was made available by water survey personnel of YG (Table 5B). The hydrometric station consisted of a stilling well with a staff gauge, a shaft encoder, and a data logger (Ott Messtechnik, Germany) which was located on the lower reaches of Clinton Creek, several km below the mine site. The data showed significant variation that was dependent on precipitation. Measurements from August 2006, for example varied from a low of 0.386 m^3/s to a high of 2.260 m^3/s. Water discharge data from Hudgeon Lake was taken on July 18, 2006 with a current meter (Price) by YG personnel. This data was used to establish the relationship between the amount of water discharged from Hudgeon Lake and the readings from the hydrometric station. The result indicated that approximately 80 % of the water measured at the hydrometric station originated in the upper Clinton Creek drainage. The station is only in operation from May until early October because of freezing. Water flow by January was observed to be almost non-existent, except of groundwater seeps that result in local glaciations.

Site visits during the late fall, winter, and spring by either helicopter or snowmobile revealed unstable ice conditions on the lake. Ice has been found to vary in thickness and consistency due to enclosed bubbles (most likely nitrogen gas and some methane in shallow side arms and near shore where methanogenesis is possible in the sediment under low oxygen conditions). Some areas of the lake have only a thin ice cover possibly due to ground water upwelling. Patterns of inconsistent ice thickness have been confirmed by flying over the lake during spring thaw. In June 2005, a male moose carcass was discovered submerged at the west end of the lake (personal observation). It obviously broke through the ice and drowned. It most likely happened shortly after freeze up in late fall since the antlers were still attached. In the winter of 2006, caribou tracks on the lake led to an area on the ice where the animals licked up elemental sulfur that has formed as a yellow crust on the surface of this sulfate rich body of water (personal observation).

Limnology

Limnology is the scientific study of bodies of fresh water, as lakes, ponds, rivers and wetlands, with special reference to plant and animal life according to Funk & Wagnalls Canadian College Dictionary (Avis et al., 1989); more precisely, it is the study of fresh water bodies as systems (Kalff, 2002). As with all systems there are similarities that allow certain categorizations, but in regard to the variability of locations, size, internal composition and external influences, every system is unique. The attributes and properties of an aquatic system have been distinguished by limnologists through a hierarchy outlined in Kalff (2002, p. 9):

- Regional properties - climate, geology, and topography
- Catchment attributes - vegetation, soil, and hydrology
- System attributes – morphometry (origin and measurement of form), lake stratification, flushing rate, and sedimentation
- Physical/chemical water properties - light/temperature, turbidity, salinity, discharge, humic substrates, nutrients, and toxins

- Biological/ecological properties - biomass, productivity, trophic structure, and biodiversity
- Human Impacts - habitat destruction, harvesting, nutrient and sediment input, toxic substances, hydrological alterations, and climate change.

While several important aspects of aquatic systems from this hierarchy have been and are discussed in this chapter (e.g., regional properties and catchment attributes), some specific points, such as system attributes and physical / chemical water properties, are addressed along with data in the results section (Chapter 4), while some remaining aspects are touched upon in the discussion and recommendation sections (Chapters 5 and 6). Some components of the hierarchy, such as detailed biological and ecological evaluations are beyond the scope of this study.

One key observation of the lake is stratification which leads to the categorization of Hudgeon Lake as a meromictic lake. This is due to the observed anoxic bottom waters with the hydrogen sulfide odour, the measured increase of salinity with depth, and the unusual temperature gradient that remained constant in the deeper sections of the lake throughout the year long study. Meromixis means that a water body only mixes partially on an annual basis, in contrast to most inland fresh water lakes that are holomictic and mix completely (Kalff, 2002); or dimictic in temperate regions, mixing twice per year (during spring warm-up and autumn cool-down). Other terms used in limnology to describe the layers of a lake, or its stratification are specifically for meromictic lakes: mixolimnion, or the upper layer that is subject to mixing and temperature stratification, and the monimolimnion, the higher density layer that is not mixed and anoxic. In between is a layer where significant changes in salinity and other measurable water quality parameters take place and this layer may be variously known as chemocline, halocline, pycnocline or oxycline, depending on the subject of discussion of the particular constituents in such a lake.

Meromixis is a phenomenon mostly established by either a pronounced salinity gradient and/or a high relative depth to surface area ratio of a lake, or the location in a wind-protected basin where surface mixing is limited. This is, however, not necessarily a steady state since less pronounced salinity gradients, changes in salinity influx, density currents or extremely windy conditions can impact and upset the stratification (Kalff, 2002). Depending on the conditions, meromixis may therefore last a few years, decades, hundreds or even thousands of years. Studies of long-term meromictic lakes have mostly focussed on sediments because of their undisturbed deposition due to the lack of wind or current induced turbulence and anoxic conditions and the absence of burrowing macroscopic and aerobic organisms (bioturbation). An example is an analysis of subfossil molecular remains of purple sulfur bacteria in the lake sediment of the meromictic Mahoney Lake in British Columbia, dating the meromictic condition of this lake to more than 9,000 years (Coolen & Overmann, 1998).

Quite some attention has also been drawn to the vertical column diversity of sulfate reducing and sulfide oxidizing bacteria, methane producing *Archea*, the activities of phytoplankton, and purple and green sulfur bacteria, especially in and near the interface of the bottom of the oxygenated mixolimnion and the upper reaches of the anoxic monimolimnion. Microbial communities have been studied in several meromictic lakes, such as Mahoney Lake in British Columbia (Overmann, 2001), Lake Pavin in France by Lehours, Bardot, Thenot, Debroas and Fonty (2005), Big Soda Lake in Nevada, U.S.A. by Cloern, Cole and Oremland (1983) and the alpine Lake Cadagno in Switzerland by Lüthy, Fritz and Bachofen (2000), to name just a selected few from studies in other parts of the world.

The co-dependence of physical and chemical conditions with bacterial presence and activities appear to define the system present at Hudgeon Lake, along with apparent long-term stability and its resilience to seasonal changes.

Sulfur Bacteria

The production of hydrogen sulfide in Hudgeon Lake can be partially attributed to the decay of organic matter at the lake bottom under anoxic conditions, since dead organics constitute a relatively rapidly cycled sulfur reservoir (Atlas & Bartha, 1998, p. 425). As studies in comparative meromictic lakes have shown, however, the hydrogen sulfide generation occurs not just at the bottom of the lake but throughout the oxygen deprived sections in the water column below the chemocline and throughout the monimolimnion. The sustaining source for bacterial sulfide transformation in Hudgeon Lake is sulfate in solution. This is due to high sulfate concentrations in the streams flowing into the lake, which are based on the geochemistry in this watershed.

The sulfur cycle in an aquatic system involves aerobic and anaerobic sulfur transformations and specific groups of bacteria as shown in Figure 2. In aerobic conditions, dissolved sulfides will be oxidized spontaneously, or aerobic sulfur bacteria transform it into sulfate (SO_4^{2-}), sulfite (SO_3^{2-}), and elemental sulfur (S^0) through chemical - and photo oxidation. In anaerobic conditions the SO_4^{2-} and SO_3^{2-} will be reduced by sulfate reducing bacteria using sulfate as electron acceptor for their respiratory process, and the S^0 will be reduced by sulfur reducing bacteria, forming hydrogen sulfide in both instances.

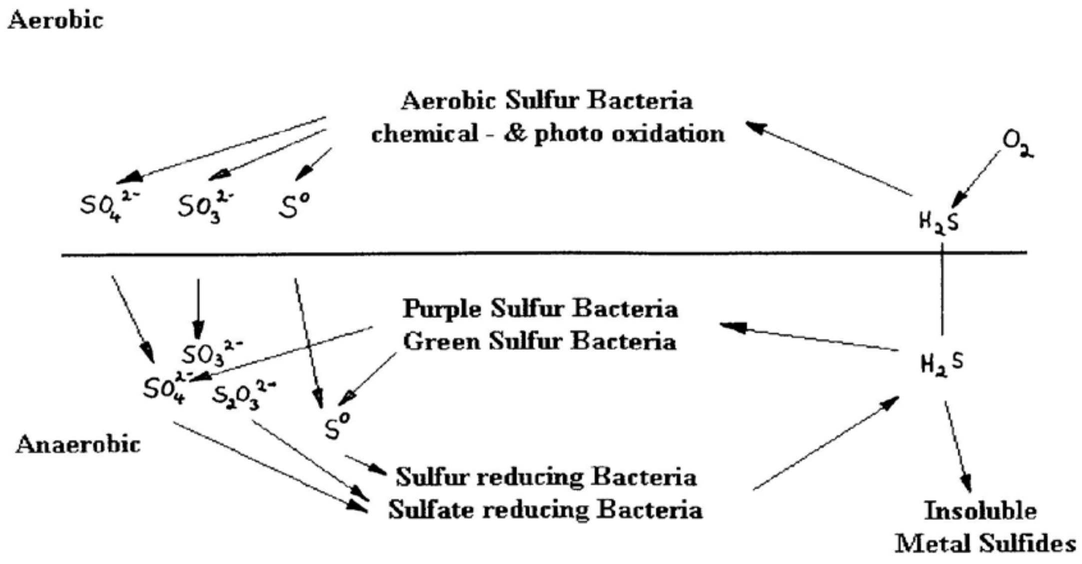

Figure 2. Sulfur cycle as facilitated by specific bacteria near the interface between oxic and anoxic conditions in the water column (modified from Kalff, 2002, p. 369).

Both, aerobic and anaerobic respiration in the biochemical sulfur cycle happen in assimilative (internal to organisms) and dissimilative (external interactions) processes (Madigan, Martinko, & Parker, 1997, pp. 573 - 575). If light can reach the anoxic zone there is also the possibility for anoxygenic photosynthesis, as carried out by purple and green sulfur bacteria, which are capable to oxidize sulfides into sulfate and elemental sulfur (see Figure 2). This has been confirmed for example in Lake Mahoney (Overmann, 2001) and Lake Cadagno (Lüthy et al, 2000). From these studies on meromictic lakes and their microbial communities, it has become apparent that the aquatic sulfur cycle and the associated bacterial communities represent dynamic as well as self-regulating systems, able to adjust to daily (day and night) and seasonal (summer and winter) changes, according to nutrient levels, light intensity and turbidity (Overmann, 2001; Tonolla, Peduzzi, Demarta, Peduzzi & Hahn, 2004).

In the oxic zone the main species found are *Beggiatoa, Thiothrix, Thiobacilli, and Sulfolobus.* In the anoxic zone the main species found are *Desulfovibrio* with approximately 12 species while species found in the chemocline include *Desulfobacter, Desulfomicrobium, Desulfovibrio, Desulfobotulus, and Desulfobulbus*. The studies on the meromictic lakes also indicated daily and seasonal changes in density and in fluctuations of the variety of species (Overmann, 2001; Tonolla et al, 2004).

In addition to limitations of irradiance into the lake the abundance of sulfur bacteria is limited by the existing pH range. To this affect the most likely variety of sulfur oxidizing bacteria that would occur in Hudgeon Lake, according to the existing pH regime, consists of sulfur oxidizing bacteria that prefer the range of pH from 6 to 8. Among those are *Thiobacillous spp*, filamentous sulfur chemolithotrophs, and other genera. Among the subspecies of *Thiobacillous spp* are also facultative aerobes, such as T. *denitrificans* being able to use NO_3^- as electron acceptor in anaerobic conditions (Madigan, Martinko, & Parker, 1997, p. 662). This connects the nitrogen cycle with the sulfur cycle, evidence of which has been observed in Hudgeon Lake where a spike in nitrate concentrations occurs at the chemocline where rapid denitrification takes place under low oxygen conditions as the concentration of sulfides gradually increases. The possible implications of denitrification near the chemocline are discussed in Chapter 4.

In Hudgeon Lake, again within the pH range 6 to 8, the most prolific sulfur and sulfate reducing species are most likely *Desulfovibrio* who can utilize lactate, pyruvate, ethanol, or certain fatty acids as carbon and energy sources from organic material suspended in the water. They are also known and common in water logged soils especially those that contain abundant organic material and sufficient levels of sulfate.

Hydrogen Sulfide

Hydrogen sulfide is produced naturally through non-specific and anaerobic bacterial reduction of sulfates and sulfur containing organic compounds in anoxic conditions. At atmospheric pressure, H_2S exists as a gas and partitioning to the air is likely when released. However, it may also partition to surface water, moist soils, and plant foliage (Agency for Toxic Substances and Disease Registry [ATSDR], 2002). H_2S solubility is one gram in 187 ml of water at 10 °C (Merck Index, 2000), or 5,347 mg/L. High water temperature and low pH increase the evaporation of H_2S.

H_2S in air is oxidized by molecular oxygen and hydroxide radicals to form the sulfhydryl radical (SH^-) and finally sulfur dioxide or sulfate compounds. These products are removed from the atmosphere through absorption by plants and soils or through precipitation. In water, H_2S oxidation occurs in oxygen rich surface waters and the sulfhydryl radical SH^- is found to be more abundant with increasing pH. SH^- is believed to be a lesser toxicological hazard, since it is not as readily absorbed across biological membranes as H_2S. There is evidence, however, that SH^- may produce toxic effects in fish in hydrogen sulfide-contaminated water at higher pH levels (ATSDR, 2002). The speciation of sulfide is pH dependent and sulfide will be present as hydrogen sulfide (H_2S) in a low pH environment, as bisulfide (HS^-) in the neutral pH environment, and as sulfide ion (S^{2-}) in a high pH environment (Madigan, Martinko, & Parker, 1997). Species of sulfide between the various pH regimes will exist in equilibrium.

H_2S is extremely toxic to aerobic organism, because it reacts with the heavy metal groups of the cytochrome systems (Atlas and Bartha, 1998). Cytochromes are complex protein respiratory pigments within cells, functioning as electron carriers in biological oxidation.

If H_2S or other forms of sulfide would be released from the lake in large quantities in an instant or gradually over time, their toxicity could be perceived as risk to wildlife or humans. Toxic gas eruptions from water bodies have been documented in the past. Examples are Lake Nyos in Cameroon (Zumdahl, 1993, p. 511), and the Namibia coast (Lass, Siegel, Endler, Brüchert & Schiedek, 2005). In the case of Lake Nyos, however, the toxic gas was CO_2 from volcanic activity. In the Namibian coastal upwelling ecosystem the gases involved are methane and H_2S. The mechanisms of the gas eruptions are still under study but are believed to be either facilitated by the methane gas which builds up below the mats of decaying biomass on the ocean floor as a driving force (Killergase vor Namibia, 2007), or by cross currents as part of the physical nature of the Benguela upwelling system that brings H_2S rich waters to the surface (Lass et al., 2005). Other than in this instance H_2S is generally not released from anoxic environments quickly, but rather released gradually and transformed immediately through oxidation.

A risk at Hudgeon Lake may develop if large amounts of sulfide rich water are suddenly released. This could occur in the case of seismic activity, potentially causing a breach of the waste rock dam, displacement of water masses by landslides, or in an intense flood due to an unusual sudden freshet or extreme precipitation event. Short term high concentrations of sulfides in the water would result in detrimental effects for organisms in the downstream aquatic environment, i.e., invertebrates and fish species.

Invertebrates

It has long been recognized that biodiversity in surface waters is directly related to water quality. The variety of invertebrates found in a stream is an indicator for the quality of fish habitat. The classification of invertebrates into various classes has become a useful tool for biologists or even laymen volunteering for organizations such as Stream Keepers, to observe water quality in streams near communities. Three categories of taxa have been grouped to summarize species that are pollution sensitive, somewhat pollution tolerant, and pollution tolerant (Pacific Streamkeepers Federation, 2003 – 2009). A sampling and evaluation protocol has been developed and can be accessed on line in Module 4 of the Streamkeepers Handbook. The water quality assessment protocol was used for a preliminary evaluation of the tributaries to Hudgeon Lake and the outflow based on the results of the benthic invertebrate sampling (WMEC, 2008) and the identification of species (Table C1).

Chapter 3 – Methodology

Overview of Field Investigations

Data collection was carried out in excess of an entire year and was originally planned for June 2006 to September 2007 with site visits every 5 to 6 weeks apart to capture seasonal changes in the water column and water quality of surface water entering and leaving the lake, as well as at depth at the deepest part of the lake. However, irregularities with dissolved oxygen measurements and the safety issues associated with freeze-up in the late fall and winter of 2006 prompted additional site visits. A satisfactory data set was completed for the entire year of 2007. In order to obtain a snapshot of biological activity dissolved metals, total nitrogen, and total phosphorous in the lake, additional samples were taken from the lake in June 2008. Sediment samples were obtained with a Ponar grab sampler and analyzed for metals in July 2006 and August 2007.

Bathymetry and Calculation of Lake Volume

The volume of the lake was calculated using a methodology described by Kalff (2002). Bathymetry lines for the lake were drawn in 5-meter increments based on the shape and shorelines from an air photo (INAC, 2001). For the calculation of the lake area the shape and the bathymetry lines were transferred by carbon paper onto 4-ply coated poster board. Three different area squares (representing 4 ha, 25 ha, and 400 ha) at scale with the lake drawing were cut out and weighed. The shape of the lake and each depth contour shape were also cut out and weighed. All shapes were calculated according to the ratio of their weight in comparison to the weight of the known areas. There were some inherent errors in the methodology including errors arising from the quality of the poster board, the transfer of a geographic shape from the air photo onto the board, the cutting out of the shapes with scissors, and the weighing of the cut out shapes. Two sets of cut outs and weighing were conducted. A simple statistical analysis for the mean standard deviation, standard error (68% confidence), and a 95 % confidence error was completed. The result closest to the obtained mean value was used for the determination of the lake volume. Each 5-metre contour line was then cut from the original lake shape. The remaining cardboard piece was weighed and the ratio of the new area and the original lake shape resulted in the area at the particular depths. The volume was then calculated using the area average and depths increments in the following formula (Kalff, 2002, p.86), where $V(x_1x_2)$ is the volume of one depth section, Ax_1 and Ax_2 are the areas comprised by subsequent depth contour lines, and $(x_2\text{-}x_1)$ indicates the depth interval:

$$V(x_1x_2) = ((Ax_1 + Ax_2)/2)\ (x_2-x_1)$$

Sampling Locations

Samples were collected from three locations for the year long study in 2007, and from an additional four locations for the surface water study in 2008 as shown in Figure 3.

Sample Location A was chosen as the prime location for depth sampling because it was the deepest section of the lake with a maximum depth of approximately 27 meters with slight variations arising from seasonal water level fluctuations. Samples were taken at the surface, 1 m, 5m, and then every subsequent 5 m. The sediment samples (2006 and 2007) and surface water samples in 2008 were also taken at this location.

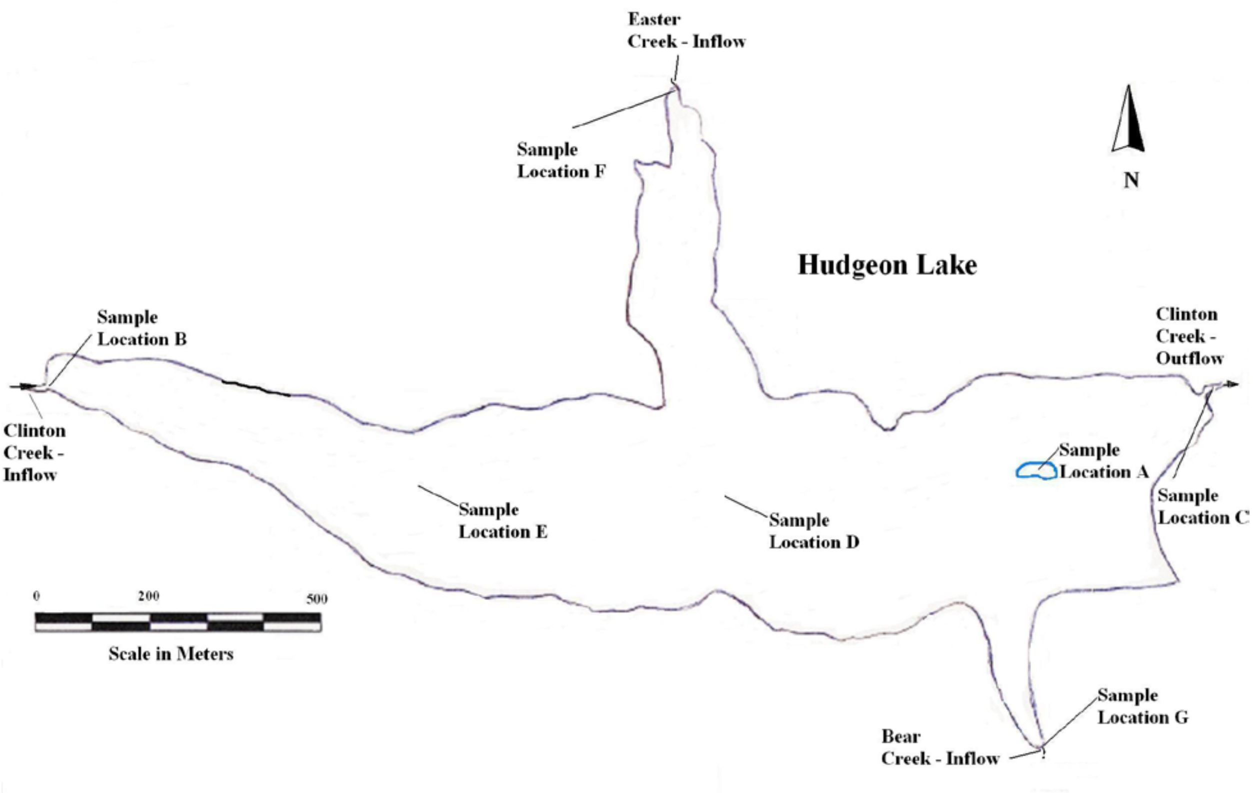

Figure 3. Sampling locations on Hudgeon Lake (A, D and E), the inflowing creeks (B, F and G) and the outflow (C).

Sample Location B was chosen because it is the upper Clinton Creek branch and the main inflow into Hudgeon Lake. Surface water samples were taken at this location in 2007 and 2008.

Sample Location C is at the outflow of Hudgeon Lake where the lower portion of Clinton Creek begins. Surface water samples were taken at this location in 2007 and 2008.

Sample Location D is at the midsection of Hudgeon Lake and was chosen as a second location (after location **A**) for the surface water study on the lake in 2008. Depth samples were taken in 1 m increments to 7 meters only.

Sample Location E is in the upper lake area of Hudgeon Lake and was chosen as the third location for the surface water study on the lake surface in 2008. Depth samples were taken in 1 m increments to 7 meters only.

Sample Location F is the inflow of Easter Creek, entering Hudgeon Lake from the north. Surface water samples were taken from this location as part of the surface water study in 2008.

Sample Location G is the inflow of Bear Creek into Hudgeon Lake from the south.

Surface water samples were taken from this location as part of the surface water study in 2008.

Sampling and Analytical Protocols

The lake was accessed by either a 14 foot aluminum boat or a small Zodiac™ with a 5 hp Honda™ outboard motor. In windy conditions, an anchor was used to maintain same sample location for adequate depths samples. Surface water samples were obtained by grab sampling directly into the containers. The bottle was held near the base and the neck plunged below the surface (25 – 40 cm). The jar was tilted such that the neck pointed to the water flow during filling. Water sampling at depth (in 5 m intervals) was carried out with a 1.5 liter Van Dorn water sampler (The Science Source – Waldoboro, Maine: Model # 15010).

Water quality data was obtained at the time of sampling with a submersible YSI 6600 Bulkhead Sonde equipped with YSI 650 Multiparameter Display System (Yellow Springs Instruments Co. Inc.). This included temperature, pH, dissolved oxygen, conductivity, total dissolved solids, and salinity.

Water samples for general water quality parameters, dissolved ions, and total dissolved solids were sent unpreserved to Bodycote Testing Group, formally known as Norwest Labs, Surrey, BC for analysis. Samples designated for hydrogen sulfide analysis were preserved with zinc acetate and sent to the Bodycote laboratory for total sulfide in water analysis using Gas Dialysis, Automated Methylene Blue Method, 4500-S2-E. Surface water samples collected in June 2008 from all major inflows and the outflow were analyzed at Bodycote for routine water quality parameters, nutrients, chlorophyll *a*, dissolved metals (filtered and preserved with nitric acid), total nitrates and total phosphates (preserved with sulfuric acid) (see Tables 6 and A9). A Secchi disc was also used to investigate water transparency during the June 2008 survey. Sediment samples were obtained with an Eckman dredge sampler on July 20, 2006 and August 30, 2007. The sediment samples were placed into glass jars and shipped to Bodycote Testing Group for total metal analysis by strong acid digestion and Strong Acid Leachable Metals (SALM) in Soil, V 1.0, analysis.

Aquatic and Terrestrial Habitat Assessment

A fisheries and benthic invertebrate assessment was commissioned by the YG Assessment and Abandoned Mines Office to establish the presence of benthic invertebrates near the inflows and the outflow of the lake and the level of fish utilization in 2007. This was carried out by WMEC (2008). Standardized methods were used to evaluate fish habitat, fish utilization, and benthic colonization. At the completion of sampling, sorting, enumeration and identification the benthic samples were sent to Dr. Charles Low, an entomologist in Victoria, BC for confirmation. The results from the fisheries and benthic survey are included in the discussions of results for this thesis.

An assessment of site use by potential mammalian and avian wildlife was also conducted on a qualitative basis using observations and sightings.

Quality Assurance and Quality Control

Equipment performance monitoring

All equipment used to obtain water samples was routinely checked and calibrated. Prior to sampling the multiparameter probe was calibrated on site every time. Clean water bottles and preservatives, specific for analytes tested, along with coolers and chain of custody forms were obtained from the laboratory. Sample locations, time, field conditions, and multiparameter probe data were recorded in the field note book.

Laboratory analysis

All samples were analyzed at the Bodycote Testing Group laboratory in Surrey, BC. The laboratory is accredited by the Canadian Association for Environmental Analytical Laboratories (CAEAL) and also by Standards Council of Canada (SCC) in accordance to international standard ISO 17025. For each sample set for sulfides and routine water analysis a duplicate was obtained. The results of the duplicate analysis were mathematically evaluated, using the relative percent difference (RPD) method.

$$RPD = 100\ (x_1 - x_2)/\{(x_1 + x_2)/2\}$$

Where x_1 is the sample concentration and x_2 is the duplicate concentrations of a chosen analyte.

Values of RPD less than 30% indicate reasonable to good precision, while those exceeding this value are considered fair to poor (see chapter 4 and Table A8). With all sample sets the laboratory also produced the results of its quality control protocol for each analytical process.

Data Presentation and Analysis

The data for temperature, dissolved oxygen, pH, conductivity, total dissolved solids, salinity and the laboratory results for most sampling locations are organized in tables in Appendix A. Some tables complement the discussions within the results section. The parameters are discussed individually in the following chapter and descriptive statistics were used to show how some selected parameters correlate to each other (Figures 5 and 6).

Chapter 4 - Results

Lake Morphometry and Volume

The bathymetry of the lake is illustrated in Figure 4. The total lake area was determined to be 64.7 ha ± 0.8 ha. The 68 % confidence interval was calculated to range between 63.9 ha to 65.5 ha and the 95% confidence interval was found to range between 62.6 ha and 66.8 ha (standard error $xt_{df;\ 0.05}$). The calculated lake area of approximately 65 ha compares to previous estimates as follows:

1999 Royal Roads University	115 ha
2000 UMA	74 ha

Using the method described by Kalff (2002) and the 400 ha square cut out comparison the volumes of the 5-m layers were calculated as given in Table 1.

Table 1

Calculated Areas and Volumes of 5-m Layers, and Total Lake Volume.

Depth Layers (m)	Ax_1 (m^2)	Ax_2 (m^2)	Volume (m^3)
0 – 5	653,406.6	455,952.5	2,773,397.75
5 – 10	455,952.5	298,423.2	1,885,939.25
10 – 15	298,423.2	166,208.6	1,161,579.50
15 – 20	166,208.6	82.308.7	621,293.25
20 – 25	82,308.7	22,132.2	261,102.25
25 – 27	22,132.2	1,735.9	23,868.10
		Total Volume:	6,727,180.10

From the values in Table 1 almost 70 % of the total water volume of Hudgeon Lake can be calculated to be contained within the 10 m surface layer. This observation may be of importance for the evaluation of future risk if the current lake level is to be maintained or altered.

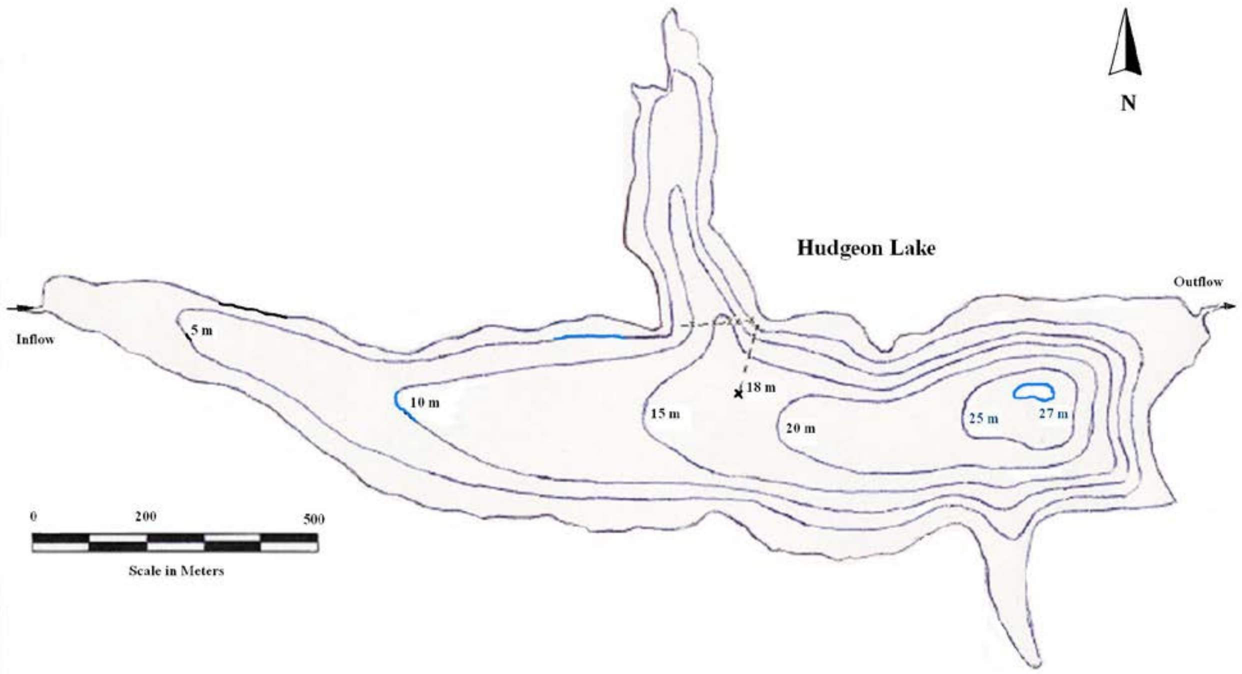

Figure 4. Bathymetry drawing modified from the Clinton Creek Environmental Review Report, (RRU, 1999) and air photo (INAC, 2001b).

Sample Location A

Sample Location A (see Figure 3) provided depth sampling results for all water quality parameters at the deepest section of the lake. The complete data for 2007 are organized in separate tables in Appendix A and individual parameters are addressed below. A graph was drawn to illustrate the approximate location of the chemocline (around 7 - 9 m) and the character of the water column representative for the whole lake (Figure 5). The graph includes temperature, dissolved oxygen, pH, conductivity, and sulfide concentrations from the mean of results for the summer months of June, July and August 2007. The data used for the graph are listed in Table 2.

Table 2

Mean water quality parameters and sulfide concentrations at Sample Location A for June, July, and August 2007

Depth	Temperature °C	Dissolved Oxygen (%)	pH	Conductivity µS/cm	Sulfides mg/L
Surface	17.9	94.0	7.80	450	-
5 m	4.6	12.1	7.21	712	-
10 m	1.9	0.0	6.95	1167	0.27
15 m	1.1	0.0	6.89	1377	0.51
20 m	0.7	0.0	6.84	1829	1.24
25 m	0.0	0.0	6.80	2873	1.46

Temperature

Significant temperature changes were only observed in the top layers during the year with a maximum of 21.95ºC in the summer and a minimum of 0.22 ºC in the winter below the ice. Aside from seasonal changes in the surface layers, temperature decreased gradually with depth below 5 m to a minimum of -0.04ºC at the bottom. Some energy transfer to deeper layers occurred during the summer (Table A1), becoming more benign below the 10 m level.

The impact summer temperatures had on the lake and its biological productivity was significant. It appeared that humic substances suspended in the lake water absorbed most of the incoming sunlight, heating up the surface water to a temperature range that was not conducive for local fish species. The higher temperatures also prevented optimal uptake of atmospheric oxygen during the ice free months; the solubility of oxygen in water has been shown to increase with decreasing water temperature (Hemond & Fechner, 1994). Also notable was the absence of a significant layer of 4ºC water, where water is normally at its densest. This can be attributed to the salinity effect caused by increasing levels of dissolved solids towards the bottom.

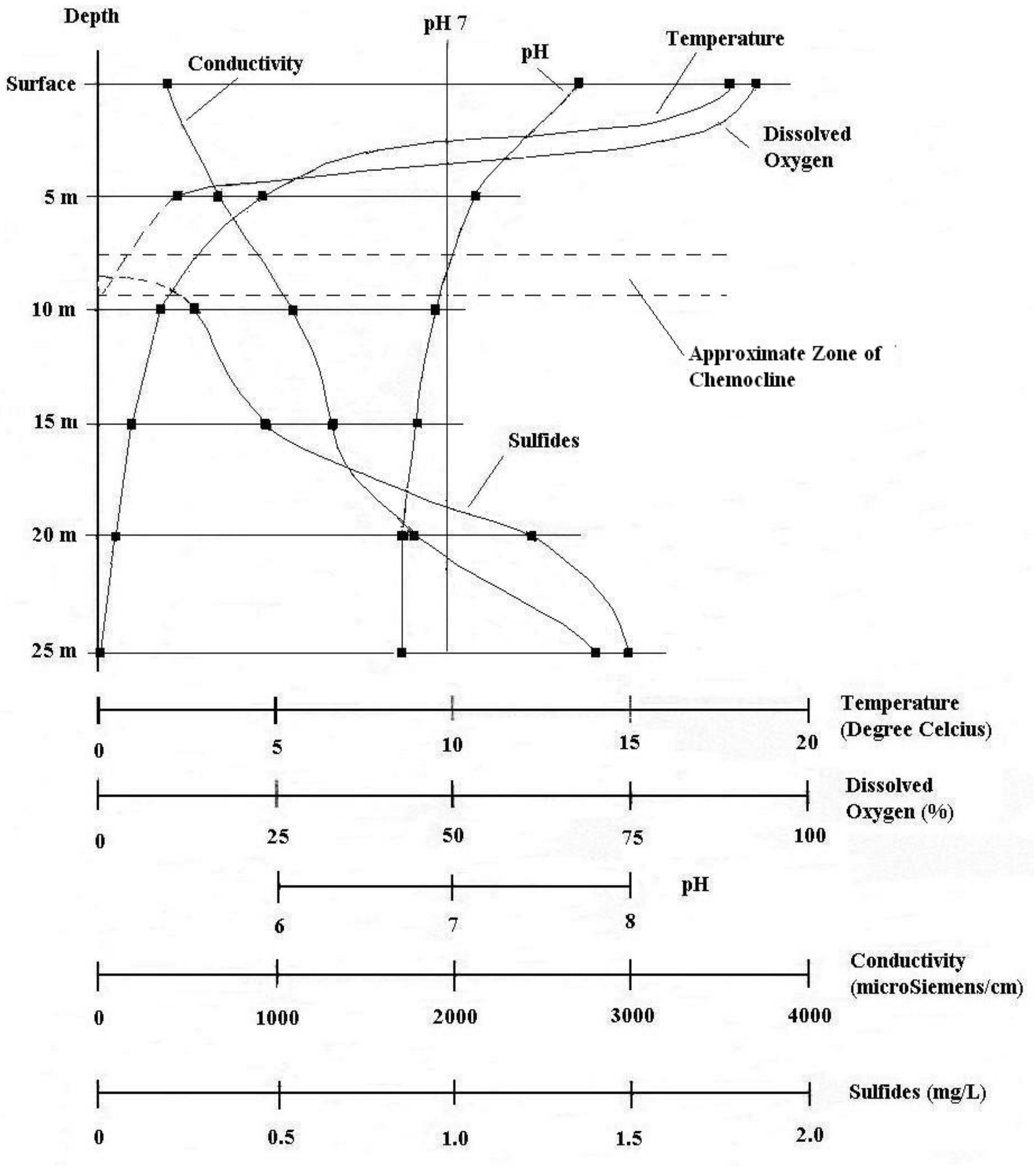

Figure 5. Mean water quality parameters and sulfide concentrations for June, July, and August 2007 at Sample Location A. The chemocline appears to be between 7 m and 9 m where oxygen becomes depleted, sulfides are being generated and where pH is neutral, changing from slightly basic to slightly acidic. Note: Scales correspond to individual parameters.

Dissolved oxygen

As indicated above, oxygen transfer to the lake through surface water interaction with the atmosphere was limited due to high surface water temperatures in the summer and a possible high biological oxygen demand caused by the humic contents and naturally occurring biological activity of phytoplankton and algae. Additional limitations included the short summer season, the prolonged frozen state of the lake tributaries, and ice coverage of the lake in the winter.

Maximum dissolved oxygen content was measured in July 2007 reaching 97.5% on the surface. The oxygen content correlated with temperature decrease as shown in Figure 5 and approached 0% at a depth at 10 m. The significant change from oxic to anoxic conditions also indicated the location of the chemocline which is discussed further below. Both temperature and dissolved oxygen measurements indicated the meromictic character and the stability of the lake’s stratification. Gradual oxygen depletion in the surface layer was observed during the winter months (December to March) while dissolved oxygen uptake and transfer into deeper levels occurred from late August into the winter (Table A2).

pH

The surface water samples collected from the lake were slightly alkaline with a pH range of 7.25 in late winter to 7.97 in August 2007. The pH at Location A gradually decreased with depth, reaching a summer average of 7.00 at 10 m depth. The minimum pH recorded was 6.33 in January at 25 m depth (Table A3). The gradual decrease of pH to slightly acidic levels coincided with depletion of dissolved oxygen and sulfide generation by bacteria under anoxic conditions (see Figure 5). Dissolved sulfide in the water column also depressed pH values as indicated in the year long depth sampling at Sampling Location A.

Conductivity, total dissolved solids, and salinity

Conductivity, total dissolved solids, and salinity are intrinsic indicators of dissolved ions and anions in natural waters. They confirmed the stability and the stratification of the lake by steadily increasing towards the bottom (see Table 3 and Figure 6). The increases were not linear and corresponded to electron transfer during chemical transformations in the chemocline. The three parameters correlated well since dissolved solids and salinity were derived from the conductivity measurements by programmed calculations provided by the YSI 650 Multiparameter Display System (Yellow Springs Instruments Co. Inc., 2009).

Table 3
Mean conductivity, total dissolved solids (TDS), and salinity for January, March, and December 2007 at Sample Location A

Depth	Conductivity (µS/cm)	TDS (g/L)	Salinity (‰)
Surface	640	0.415	0.30
5 m	750	0.488	0.37
10 m	1,211	0.787	0.60
15 m	1,411	0.917	0.70
20 m	2,077	1.350	1.04
25 m	2,867	1.863	1.45

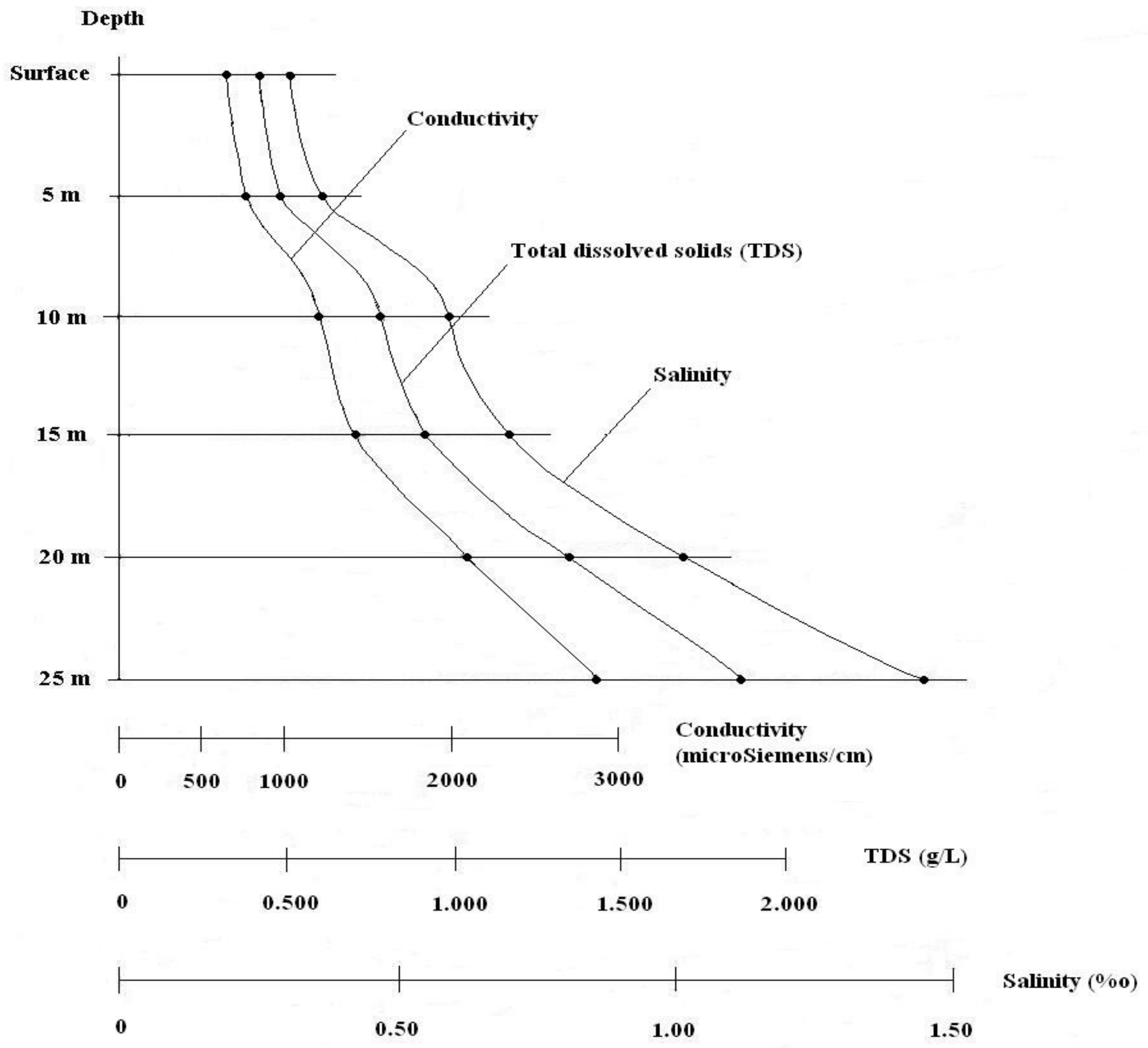

Figure 6. Variation of the mean conductivity, total dissolved solids, and salinity with depth from January, March, and December 2007 at Sample Location A.

Annual fluctuations corresponded to the movement of water (dilution) through the watershed with high volumes occurring during the annual freshet and occasional high precipitation events. The highest measured salinity (1.47‰) was at 25 m depth. To put this into perspective, salt content in natural waters has been classified into four categories (New World Encyclopedia, 2009): freshwater (<0.5‰); brackish (0.5 – 30‰); saline (30 – 50‰) and brine

(>50‰). Hudgeon Lake and its stratification, although defined substantially by its salinity, can thus be categorized as containing fresh water on the surface but turning brackish or slightly saline below the chemocline.

Dissolved ions

The concentrations of the dissolved ions determined at Sample Location A are listed in Table A7. They include calcium, magnesium, sodium, potassium, iron, manganese, chlorite, nitrate, sulfate, and bicarbonate. As with changes in conductivity, TDS, and salinity, annual fluctuations of the dissolved ions correlated with the flow of water and time of release from the upstream watershed. The changes in concentration with increasing depths were influenced by chemical and biological transformations. While most of the ion concentrations increased gradually towards the bottom of the lake, the nitrate (NO_3^-) and iron ions (Fe^{2+} or Fe^{3+}) undergo dramatic transformations. This is illustrated for nitrate, sulfate, iron and manganese in Figure 7 using the mean concentrations for June, July, and August, 2007 (Table 4).

Table 4
Mean concentrations (mg/L) of selected dissolved ions for June, July, and August, 2007 at Sample Location A

Depth	Iron	Nitrate	Manganese	Sulfate
Surface	0.16	0.05	0.06	132
1 m	0.16	0.11	0.12	132
5 m	0.10	0.26	0.44	217
10 m	0.72	0.01	3.37	323
15 m	0.30	0.01	4.14	394
20 m	0.18	0.01	5.74	651
25 m	0.19	0.01	8.68	1,103

There was an increase in iron concentration at the chemocline. Once it reached anoxic depths, where sulfide concentrations increase, a large portion of the iron ions were removed from the water column to the sediment as insoluble iron sulfides.

As indicated in Chapter 2 *Thiobacillous denitrificans* are able to use NO_3^- as electron acceptor in anaerobic conditions (Madigan, Martinko, & Parker, 1997, p. 662). This is observable in Figure 7 where a spike in nitrate concentrations is indicated at 5 m near the chemocline. Under low oxygen conditions and at the beginning of the anoxic zone rapid denitrification occurred with nitrate concentrations diminishing to near or below detection limits at the depth of 10 m. This process appeared to be sustained throughout the year (see Table A7). The end product of denitrification is N_2, with intermediate products NO and N_2O (Kalff, 2002, p. 275), gases that may either dissolve in the water or bubble up to be released into the atmosphere. They may also form bubbles in the ice as the lake freezes and ice builds on the surface over the winter. These conditions were noted in Hudgeon Lake as discussed previous under Drainage Basin and Water Flow.

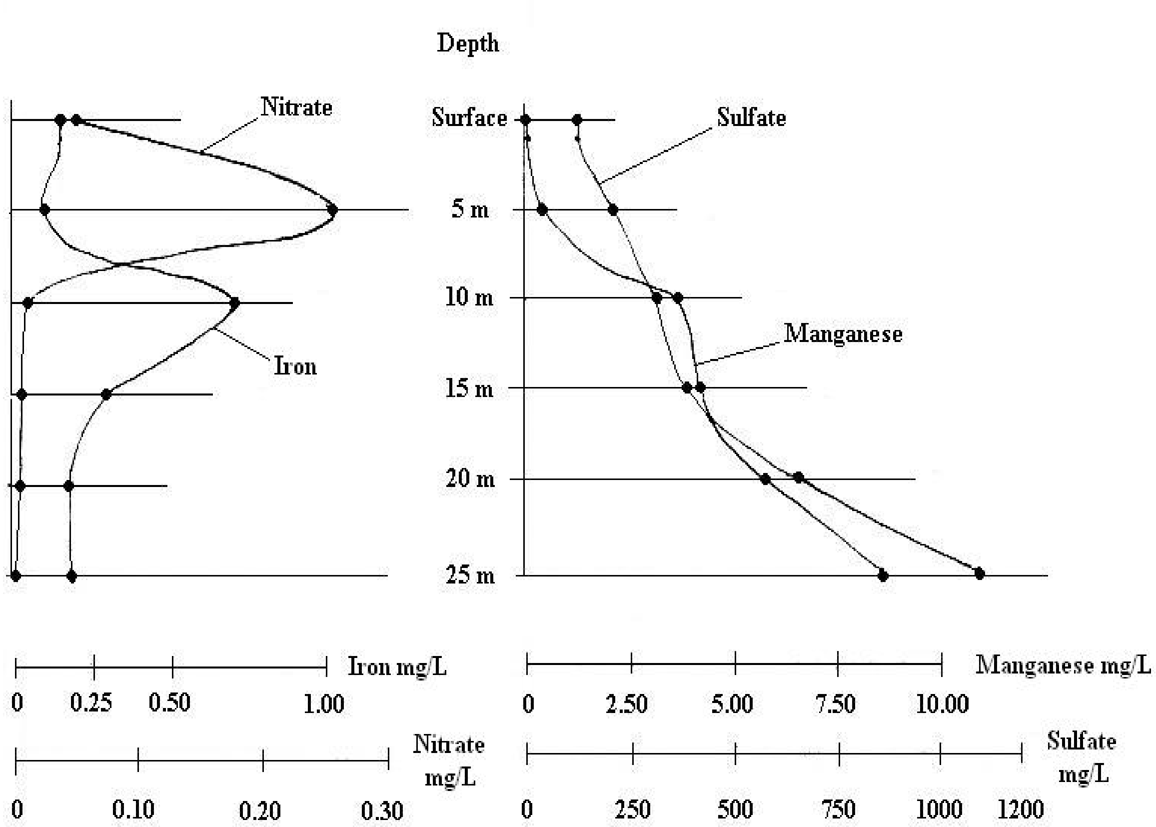

Figure 7. Variation of the mean dissolved nitrate, iron, sulfate, and manganese concentrations with depth for June, July, and August 2007 at Sample Location A. Note: Scales correspond to individual concentrations.

Sulfides

The results of sulfide analysis for Sample Location A in 2007 are given in Table 5. Sulfide generation by bacteria began in the water column approximately at the same depths marked by the depletion of oxygen. This layer, the chemocline, fluctuated slightly due to the seasonal changes and was estimated at 7.5 m during June, July, and August (see Figure 5). The highest concentration of sulfides occurred near the bottom of the lake. The concentration detected in January was significantly higher and was difficult to explain; it was statistically categorized as an outlier.

Table 5
Sulfides Concentration in mg/L at Sample Location A in 2007

Depth	January	March	June	July	August	October	December
10 m	0.35	0.37	0.31	0.36	0.13	0.51	0.57
15 m	0.51	0.48	0.70	0.63	0.19	0.75	0.81
20 m	1.04	1.03	1.29	1.23	1.21	1.30	1.45
25 m	12.40	4.50	0.96	1.45	1.98	1.49	2.40

Sulfide concentrations presented in Table 5 exceeded the water quality standards for aquatic life (0.020 mg/L) and drinking water (0.050 mg/L) as listed in the Yukon Contaminated Sites Regulations (2002). The concentrations also exceeded the aesthetic objective of $\leq$0.050 mg/L for drinking water for sulfide in water (as H_2S) established by the Canadian Council of Ministers of the Environment (2002) in the Canadian Environmental Quality Guidelines, and the safe level of undissociated H_2S in fresh and marine water for fish and other aquatic life set by the U.S. Environmental Protection Agency (1986) at 0.002 mg/L.

As previously discussed in Chapter 2, the speciation of sulfides in solutions is pH dependent. Under the given pH regime in the water column which was between 6.33 and 7.92 SH^- sulfide would be the dominant species since H_2S only exists below the pH 6 range. The increase of sulfide concentrations below the chemocline was not linear as shown in Figure 5, and may be influenced by the interaction of sulfides with metals in solution. Evidence of these interactions was suggested by the presence of elevated levels of insoluble metal sulfides in the sediment (Table A9).

Quality Control of Laboratory Results

For each sample set during the 2007 sampling program at Sample Location A, duplicates were taken at 20 m depth, one for sulfide and one for dissolved ion analysis. Results for various analytes were checked for precision using the Relative Percent Difference Method and the outcome is listed in Table A8. All tests resulted in percent values well below the 30 % bar for good and reasonable precision.

Sediments

The lake sediments obtained in 2006 and 2007 consisted of very a fine almost jelly-like black mass with a strong sulfide smell. The highest concentrations of metals are shown in Table A9 with aluminum (14.8 mg/g and 12.1 mg/g), iron (27.9 mg/g and 39.9 mg/g), and magnesium (12.2 mg/g and 14.0 mg/g). These levels of metals are the result of sulfides reacting in the water column and precipitating insoluble metal sulfides into the sediment.

Surface Water Survey June 2008

The results of the surface water survey for temperature, dissolved oxygen, pH, conductivity, total dissolved solids, and salinity are compiled in Table A10. Nutrient, selected dissolved metal, and chlorophyll *a* concentrations for all sample locations are listed in Table 6. The purpose of this survey was to re-evaluate the aerobic layer of the lake in relation to the chemocline at Sample Locations A, D, and E (Figure 3) and to collect some data regarding the biological productivity in the oxygen rich surface. Also, all major inflows and the outflow (Sample Locations B, F, G, and C) were sampled to evaluate the water quality of the water flowing through the system.

The major influence on water flowing through the lake was temperature. Water entering the lake had a temperature range of 5.39°C to 7.97°C compared to the outflow temperature of 17.12°C (Table A10). While the pH level at the outflow did not vary significantly from that of the inflows, changes in dissolved oxygen concentration were noted. The dissolved oxygen content of the inflows range from 87.8% to 101.0%, compared to 106.7% at the outflow. A noticeable change in conductivity, TDS, and salinity between the inflows and the outflow confirmed that the lake acted as a sink for dissolved and suspended substances. This was also illustrated in the increase in conductivity with depth in the lake which ranged from 467 µS/cm at the surface to 829 µS/cm at 7 m (Table A10).

The analysis for nutrients resulted in low levels of nitrate and nitrite in the inflowing streams and below detection limit (<0.01 mg/L) at Sample Location A in the lake (Table 6). Phosphate as the limiting factor for nutrient dependent biological activity in the lake was found to be below the detection limit (<0.01 mg/L) at all sampled locations.

Table 6
Nutrient, Selected Dissolved Metal (mg/L), and Chlorophyll a (µg/L) Concentrations at Sample Locations of the Surface Water Survey June 2008 in Order from Inflow to Outflow of Lake (West to East)

Analytes	Sample Location						
	B	E	F	D	G	A	C
Nitrate	0.11	-	0.02	-	0.04	<0.01	<0.01
Nitrite	0.09	-	0.05	-	0.09	0.09	0.06
Orthophosphate	<0.01	-	<0.01	-	<0.01	<0.01	<0.01
Calcium	67.6	-	72.8	-	61.1	48.4	50.3
Barium	0.033	-	0.045	-	0.072	0.037	0.038
Iron	0.11	-	0.11	-	0.71	0.12	0.13
Magnesium	37.0	-	58.2	-	23.7	26.8	27.9
Manganese	0.0416	-	0.1140	-	0.0801	0.0469	0.0459
Potassium	0.59	-	0.96	-	0.47	0.82	0.81
Sodium	3.45	-	3.66	-	2.66	2.62	2.85
Chlorophyll a	-	0.8	-	0.5	-	0.5	-
Phaeophytin	-	1	-	2	-	2	-

Dissolved metals listed in the table varied in concentrations at the inflows (Sample Locations B, F & G) but showed generally higher values than those at the outflow (Sample Location C). This supported the observation that Hudgeon Lake acted as a sink for metals and some dissolved ions.

For the analysis of biological productivity in water bodies chlorophyll *a* is commonly used as a surrogate for the estimation of biomass present (Kalff, 2002, p. 328). Phaeophytin as a degradation product of chlorophyll *a* is normally reported by the laboratory as well since both values are derived from the spectrophotometric method of detection and subsequent calculations. Both pigments are detected by the same absorption and fluorescence bands and need to be accounted for by finding optical density at different wavelengths of pure extracts and acidified extracts as outlined in the Standard Methods for the Examination of Water and Wastewater Method 10200H (American Public Health Association, 1999). The ratio of the results for chlorophyll *a* and phaeophytin show the presence of living versus dead algal cells and the concentration of chlorophyll *a* in the sample suggest the level of biological productivity at hand. For Hudgeon Lake the results as listed in Table 6 indicated that the lake falls into the category of an oligotrophic, or poorly nourished lake with a chlorophyll *a* concentration of <3µg/L (Kalff, 2002, p. 353). The ratio of living versus dead biomass may partially be explained by the humic nature of the water where a lot of un-decayed plant material was present. However, the determination of the lake’s biological productivity from a one time sampling and analysis for chlorophyll *a* is not conclusive and a snapshot only, since various species of algae may peak at different times of the year.

Secchi disc measurements were taken at all three lake sample locations and found to be 1.25 m. This confirmed that the water in the lake was humic and therefore significantly reduced light attenuation in the oxygenated surface water, at least in the range of visible light. Most sun energy appears therefore to be retained in the water surface by surface water warming. In regard to the retention of oxygen by surface water gas exchange with the atmosphere, this is counter productive since less oxygen is retained in warmer waters.

In contrast to other meromictic lakes such as Lake Cadagno, Switzerland, and Lake Mahoney, BC, the presence of phototrophic sulfur and sulfate-reducing green and purple bacteria could not be verified at Hudgeon Lake. Water samples taken with a clear Van Dorn bottle at 7 m depths did not show evidence of this group of bacteria. This could be attributed to the highly humic nature of the water which prohibits adequate irradiance in the infrared spectrum at that depth (Overmann, 2001).

Sample Locations B (Inflow) and C (Outflow)

Temperature, Conductivity and Dissolved Oxygen

Inflow and outflow measurements varied seasonally and correlated with the amount of water flowing through the system. The temperatures varied from 0.26ºC in January to 22.25ºC in July at the inflow and 0.18ºC in March to 18.47ºC in July at the outflow. The conductivity level at both sample locations was generally lower during the summer compared to the winter. The opposite was true for dissolved oxygen content due to open water and surface mixing in the summer and ice cover and oxygen depletion in the winter (Table A11).

pH

The pH levels were lower during the late winter months (Table A11) indicating the influence of sulfides under the ice and increase during the summer and late fall due to the mobilization of alkaline constituents of local soils and rocks.

Dissolved Ions

As discussed in the previous section, the lake acted as a sink for dissolved ions. Throughout the sample year the concentrations of ions in water flowing into the lake were consistently higher compared to the concentrations in water at the outflow (see Table A12). Substances with this noted effect include calcium, magnesium, sodium, sulfate, and bicarbonate. This continuously maintained the stratification of the lake and the increase in salinity towards its deepest sections. Furthermore, the steady supply of sulfate to the water column appeared to support the ongoing production of sulfides by anaerobic bacteria in the anoxic parts of the lake.

Inventory and Habitat Assessment of Aquatic and Terrestrial Environments

Site Useage

Due to its remote location, the site is visited only regularly by a few locals, including one trapper, government officials, and occasionally by tourists and hunters. Access to the mine site is restricted to 4x4 vehicles due to the necessity to ford Clinton Creek below the mine site and the outflow at Hudgeon Lake in order to continue on the road to the mill site and the now overgrown air strip. Road access to the waste rock and the open pits has been closed off by the YG to prevent the public from entering due to safety concerns around steep and unstable slopes around the open pit area.

Wildlife

Several wildlife species including black and grizzly bear, moose, caribou, wolf, foxes, and birds of prey were sighted during site visits. The following duck species were identified on

Hudgeon Lake during the lake survey in June 2008:

- Dabbling Ducks - 30 Northern Shovelers, 2 Green Winged Teals and 2 American Wigeons;
- Diving Ducks - 40 Buffleheads, 8 Scaups spp, 6 Horned Greebes (3 pairs), 5 White Winged Scoters and 1 Long-Tailed Duck;
- The carcass of a juvenile American Coot was found approximately 75 meters from the lake's shore.

Aquatic Life

From ongoing fish monitoring and fish habitat studies in the Clinton Creek area carried out by the Department of Fisheries and Oceans (DFO, 2007) and the Fisheries and Benthic Invertebrate Assessment Monitoring study commissioned by YG (WMEC, 2008), it is apparent that there are no fish in Hudgeon Lake. Fish in abundance are found only below the outflow of Hudgeon Lake and the entire length of lower Clinton Creek to its confluence with the Forty Mile River. The most common species were juvenile chinook salmon, slimy sculpins, and to a lesser degree long nosed suckers. Very few juvenile arctic grayling were also present and according to studies by DFO the grayling population appeared to be on the decline in Clinton Creek (DFO, 2007).

Benthic invertebrate collection at all inflows and the outflow of Hudgeon Lake resulted in the observation of different communities. A total of 2,737 individuals were collected consisting of 66 different taxonomic groups (Table C1). A significant difference was found in the species present in the inflows versus the outflow. The species dominant in the outflow were pollution and low dissolved oxygen tolerant in comparison to moderately pollution tolerant species found in the inflowing tributaries. Dominant species found in the inflows were

Plecoptera, whereas the dominant species in the outflow consisted of Diptera. Subdominant species in the inflows were Diptera, Ephemeroptera, Ostracoda, and Plecoptera while subdominant species in the outflow were Gastropoda. The highest abundance of benthic communities was found in Easter Creek (Sample Location F) while the highest diversity was actually found at the outflow followed by Easter Creek. The lower abundance and diversity found in the other streams maybe attributed to their location, length and channel characteristics.

According to water quality assessment based on Module 4 of the Pacific Streamkeepers Federation (2003 – 2009) the presence of specific invertebrate communities suggested acceptable water quality with a score of 3.00 for Easter Creek only. The main tributary to Upper Clinton Creek scored 2.75 and Upper Clinton Creek 2.50, indicating marginal to acceptable water quality. Bear Creek and Clinton Creek below the outflow had only a score of 2.00 (Table C2). A low score in the water quality assessment usually refers to low oxygen content and/or the presence of pollution. Other reasons may be of a physical nature, such as streambed shape, irregular water flow, or quality of substrate. In the case of the low scoring Bear Creek, the streambed was described as containing very few small pebble gravel sections but consisting mostly of mud, fine sand and organic material (WMEC, 2008). The invertebrate sampling at the outflow was conducted by WMEC below the gabion basket structures and described as having low flow on the surface and consisting of a straight channel overgrown with weeds and with lose rock in netted structures as streambed.

Chapter 5 – Analysis & Discussion

Findings in Perspective

Referring to the notion of fresh water bodies as systems, Hudgeon Lake is a unique system from a number of aspects. The main influencing circumstances are the location of the lake in an area where lakes are uncommon, the geochemistry, and the topography. Due to its location, the climatic conditions limit surface gas exchange to approximately five months of the year. The local geology and the resulting geochemistry contributing to the water quality of inflowing streams define the physical and chemical stability of the water column. The morphometry of the lake is based on the local topography. This means that the lake has filled previous creek beds in V- shaped valleys. The depth of the lake gradually increases over the length of approximately 2 km toward the outflow where waste rock has blocked the path of the creek. Even at high flows the incoming water is slowed down with ample retention time allowing heavier dissolved and suspended constituents to settle into deeper layers of the lake before reaching the outlet. This is based on the observations that lower strata of the lake do not show significant seasonal changes in their physical and chemical makeup. It appears that incoming water is unable to mix the lake by the force of water flowing through the system. In essence, the current lake volume is too large for the flow of water to maintain fresh water status throughout.

Data for the inflow and outflow of Hudgeon Lake indicate that the lake is a sink for substances, especially ions such as calcium, magnesium, sodium, iron, sulfate, and bicarbonate. These ions also contribute significantly to the stratification of the lake and the increase in total dissolved solids, salinity, and conductivity. Hence, the hypolimnion does not experience instability; the lake is indeed meromictic and appears to be stable and unaffected by seasonal weather changes on the surface.

Contributing to the state of the lake and its meromictic character is surface water mixing by wind is limited. This is due to the topography since the lake is located in a valley, surrounded by steep slopes, and its aspect is east/west with the predominant wind direction during the summer months being south (Figures B1 – B4).

Catchment attributes, such as vegetation and soil contribute significantly to the humic water quality. This has consequences for the biological productivity in the surface water of the lake. First, the humic characteristics reduce the range of visible light that reaches the oxygenated surface layer and thereby limits the activity and development of phytoplankton. Second, the humic substances absorb most of the sun’s energy and cause the surface water to heat up during the summer months and thereby reduce the uptake of oxygen. Both the higher temperatures and lower oxygen levels contribute to unfavourable habitat for northern fish species, such as arctic grayling and juvenile Chinook salmon.

Seasonal temperature changes in the water column were recorded only in the surface layers and it appears that heat transfer toward the bottom of the lake is very gradual. Temperatures near and around zero degrees at the bottom are most likely attributable to underlying permafrost. The extent of permafrost is not known but heat exchange over a long period of time would suggest that the presence of the lake will eventually cause the permafrost to degrade over time. This may result in slope instability especially on the north facing side of the valley. Some slumping has been observed near the water surface around the lake’s perimeter. Although the lake provides some stability to the waste rock near the outflow, the interaction of the lake as an effective heat sink with the present permafrost may add to the overall instability of slopes in the mine area.

Measured pH levels have shown that the sulfide speciation limits the actual amount of the highly toxic hydrogen sulfide. The presence of hydrogen sulfide is also limited by the oxygenated surface layer, where sulfides are oxidized immediately by sulfur oxidizing bacteria and the oxygen in solution. It therefore appears that the presence of sulfides is limited by self-regulating processes and the fluctuating equilibria that are inherent to the system. This means that the risk of any detrimental release of sulfides would be negligible under normal circumstances since the lake is not turning over and any sudden displacements of water by landslides are likely of a small nature.

Based on the Fisheries and Benthic Invertebrate Assessment Monitoring study carried out by WMEC (2008), invertebrate communities varied in low oxygen tolerant and low oxygen intolerant groups of species according to location. The outflow location revealed the preference of low oxygen and pollution tolerant species (Diptera and Gastropoda). This may be attributed to water temperatures from the heated lake surface, the nature of the drop structures (gabion baskets), the water flow, or the type of substrate rather than low oxygen content or pollution.

Within the ecosystems of the immediate surroundings, Hudgeon Lake could be characterized as a body of water with low productivity adding to the other low productive terrestrial areas, being the waste rock and tailing piles, created by human mining activities.

Risk Analysis

Due to the stratification and the temperature gradient of the lake the sulfide concentration increases with depths and the oxygen rich surface waters are virtually free of sulfides. Since the stratification and the temperature gradient of the lake appear not to be influenced by seasonal changes, the water column with its content of dissolved gases appears to be stable. Therefore an eruptive release of sulfides or lake turnover is not expected and the risk of intoxication of living beings in the vicinity or downstream can be considered extremely low.

The main outstanding risk with the lake is that of a breach of the waste rock dam. Although the dam is currently risk managed with the installed gabion structures, requiring some annual care and maintenance, the risk of release of large quantities of water and sulfide rich water masses is fairly high. If care and maintenance were to be suspended, the occurrence of an extreme spring run-off or several high precipitation events may cause the lake outlet structures to be damaged and severely compromised. This may eventually lead to further down cutting of the stream channel near the outlet and a catastrophic breach.

Sustainability

There is probably no debate that the mining practices that led to the current state at the abandoned Clinton Creek Asbestos Mine have been unsustainable. The failed waste rock and tailings piles, the unstable slopes and a perched lake, harboring anoxic and sulfide rich water in its depths behind millions of tonnes of normally unsuitable dam material (argillite), left a costly legacy for current government to deal with. The mining created a scenario that makes it difficult for decision makers to find reasonable, cost effective and sustainable solutions for site remediation. And a debate may arise as to what is sustainable and what to do? Do nothing, continue to risk manage, monitor and provide for care and maintenance in perpetuity, or make great efforts to remediate?

Since Clinton Creek is a salmon rearing stream, a look at a big picture scenario such as the fate of the Pacific salmon may provide some inspiration. As an example to understand the meaning of sustainability Doppelt (2003) in his book *Leading Change toward Sustainability* puts forward the notion of ‘options’. The necessity for species to have options in order to thrive and survive is exemplified by Doppelt with the Pacific salmon having been plentiful along the North American coast from California to Alaska up until the early 1900s with a marked decline in recent decades. Salmon spawning and juvenile rearing streams have over thousands of years experienced dramatic changes with landslides, flooding, droughts and forest fires. Yet the species have continued to thrive despite the challenges of constantly changing habitats, because there were options of utilizing intact waterways when others became temporarily destroyed. Decades of human development with mines like Clinton Creek, hydro dams, logging and alterations of stream channels to meet the needs of growing human infrastructure have changed the landscape along the North American Coast and reduced the options for salmon species. Once we include equally detrimental influences such as overfishing, pollution and changes in the Pacific due to climate change it is not surprising why salmon are in decline.

The mine workings and current conditions at Clinton Creek have removed the option for juvenile salmon and other fish to access the other half of the original habitat (see Figure B5), that is access to the Upper Clinton Creek drainage. To restore this access as option would be a sustainable approach.

Doppelt (2003) extends the notion of options from healthy habitats for fish to the human economy, and argues that we should protect our options by adjusting our economic and community development to ensure the stocks and flows of our natural capital (e.g., clean water, clean air, biodiversity, etc.) can naturally regenerate themselves. Only then will humans and other species have a sustainable future.

Chapter 6 – Remediation Considerations

Habitat Access

As the Fisheries and Benthic Invertebrate Assessment (WMC, 2008) has confirmed, fish are not found in Hudgeon Lake, fish are not able to access the upper Clinton Creek drainage area crossing the gabion structures, but high bio-diversity of invertebrates is present in the upper Clinton Creek area. Furthermore, the inhospitable water quality of Hudgeon Lake during all seasons rules out permanent residency of fish and could only serve as temporary migration route. Overwintering in the lake is impossible under current conditions due to lack of oxygen and the stratification of the lake. Furthermore, the inflowing creeks are too shallow to provide overwintering habitat.

To remediate this situation and allow seasonal access of fish to utilize the upper Clinton Creek drainage area some work would have to be done on the gabion structures. This could be a restructuring of the baskets to allow water pools to form for fish to migrate upstream or the installation of a fish ladder. Other remediation options that could improve water quality and/or fish access in general are discussed below.

Lake Aeration

The overloading of reservoirs with nutrients and resulting problems of high sulfide levels are resolved elsewhere through artificial aeration and circulation systems, also called destratifiers (Hudson & Kirschner, 2000). A lake aeration system could be installed in order to supply oxygen to the deeper layers of the lake and effectively break down the current static stratification. This could be achieved through physical mixing of the water. The oxidation process would lower high concentrations of reduced sulfur, methane, manganese, and iron compounds and would effectively oxidize odorous and toxic sulfides to sulfate (Kalff, 2002. p. 260).

A variety of aeration systems are available. In use are pneumatic diffusers, hydraulic diffusers, and various bubbling systems that are usually operated by pumps or compressors. Some of these systems are highly efficient but also costly. A simpler and more sustainable system could be constructed by a wind mill driven pump or compressor to diffuse oxygen rich water into the monimolimnion or to bubble compressed ambient air into the lake. A system like this would have to be maintained and monitored and would probably only be operational during the summer months, when access and operational conditions are favourable. The operation costs would include monitoring of the oxygen levels in the lake to verify the effectiveness of this method. If no other physical changes to the lake are planned as part of the site closure, the aeration process would have to be continued over a long term since the lake would re-stratify to the current conditions within a very short time, due to the geochemical constituents of the inflowing waters.

Partial Infilling of Lake

An option to remediate water quality issues in Hudgeon Lake would be to fill in the deep section with waste rock. This could potentially serve two purposes. One is to replace the monimolimnion in the deep section along with the high concentrations of sulfides and other ions currently causing the static stratification. This may also enable the lake system to be flushed if the current volume is drastically reduced and the current capability of the lake to act as a sink for organic matter and dissolved inorganic substances minimized.

The second benefit could be to remove waste rock from the upper layers of the waste rock pile which would reduce downward and lateral pressure and waste rock movement, which is still recorded to happen, albeit, at a slow rate (UMA, 2006).

Technically this could be achieved with a floating conveyer belt that would have to be moved as the filling progresses. In order to minimize detrimental effects on the downstream environment this work would have to proceed during late fall and winter months. Also a protective curtain would have to be placed near the outflow to prevent suspended solids and fines from the filling process to reach the outflow and allow the material to settle on the lake bottom. The desired lake depth and amounts of material needed could be derived from a bathymetry map.

According to the calculations presented here (see Table 1), the filling of the lake to a uniform depth of 20 m would require approximately 300,000 m^3 of material.

The cost of this measure would be considerable, not only in dollars but also by the greenhouse gas emissions that would be released by this operation. This type of remediation along with more waste rock being moved back into the Porcupine Pit would only be feasible if the removal of a certain amount from the waste rock pile would guarantee its long term stability.

Chapter 7 – Recommendations

The recommendations suggested here are based on the findings of this research and government objectives for site closure referred to in Chapter 1. The recommendations are to reduce the risk of a catastrophic breach, improve the water quality of the lake and provide access for fish to the upper Clinton Creek drainage area. To accomplish this requires the lowering of the lake level as this measure would remove a significant volume of water that could potentially unleash destructive forces and severe damage downstream. A target level would be approximately 10 m that is where the current outflow channel comes in contact with the bedrock of the northern hillside of the valley below the gabion drop structures (UMA, 2006). The volume of approximately 4.7 x 10^6 m^3 of water would be removed, accounting for nearly 70% of the current water volume of Hudgeon Lake (see Table 1). There is a possibility that this measure could solve the anoxic conditions and the current level of sulfide generation. Based on the observations of the current system in the lake and its stratification, the through flowing water can only maintain oxygenated water in the top 5 m water layer whereby contact with the air on the surface does not seem to translate into mixing to deeper levels. Once the lake level is dropped by 10 m, the surface area of the lake would be reduced by more than half; leaving a 5 m surface layer of 1.2 x 10^6 m^3 instead of the current 2.7 x 10^6 m^3 (Table 1). This gives rise to the expectation that oxygen rich through flowing water will be better able to mix and enrich surface waters with oxygen and push the chemocline deeper. Also, the more favourable water flow to lake volume ratio may make it possible to destabilize the current stratification with the occasional flushing during high precipitation events or during the annual freshet.

The lowering of the lake would have to be done over two to three years with the installation of a siphoning system to lower the lake level gradually to be able to re-modify the lake outlet and supply continued water flow to the downstream environment. Waste rock at and near the outlet could be pushed into the mid- and southeast corner of the lake as a partial filling of the deepest section (see Figure 3) to further reduce the lake volume and decrease the chances of stratification based on salinity. With a significant decrease of water volume the generation of sulfides in the lake is also expected to be strongly reduced and as a side effect of the reduction of lake area, less methane gas will be produced in the shallow parts currently under water.

Once the desired lake level has been reached, fish should have the option to access the lake and the upper Clinton Creek area again as they have done before.

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Appendix A

Table A1

Water Temperatures in °C at Sample Location A in 2007

Depth	January	March	June	July	August	October	December
Surface	0.22	0.26	17.16	21.95	14.46	3.03	0.44
1 m	0.52	0.36	16.86	16.09	13.70	3.11	1.28
5 m	3.45	3.13	3.14	4.18	6.48	3.36	3.33
10 m	1.85	1.92	1.77	2.04	1.95	1.93	1.89
15 m	1.09	1.05	1.03	1.18	1.16	1.11	1.18
20 m	0.56	0.50	0.56	0.83	0.66	0.65	0.55
25 m	-0.01	-0.03	0.02	0.05	0.03	0.01	-0.04

Table A2

Dissolved Oxygen Levels in Percent (DO %) at Sample Location A in 2007

Depth	January	March	June	July	August	October	December
Surface	82.2	78.3	89.5	97.5	94.9	94.4	86.9
1 m	79.7	77.1	90.7	84.5	93.3	92.4	94.0
5 m	35.0	13.4	18.4	10.4	7.4	91.7	9.3
10 m	3.8	0.5	0.0	0.1	0.0	8.3	4.0
15 m	0.4	0.0	0.0	0.0	0.0	3.5	8.6
20 m	0.2	0.0	0.0	0.0	0.0	2.9	3.0
25 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A3

The pH Measurements at Sample Location A in 2007

Depth	January	March	June	July	August	October	December
Surface	7.49	7.25	7.56	7.88	7.97	7.92	7.53
1 m	7.36	7.31	7.59	7.65	7.97	7.87	7.79
5 m	6.97	7.03	7.08	7.25	7.31	7.83	7.51
10 m	6.52	6.74	6.91	6.97	6.98	7.11	7.09
15 m	6.46	6.86	6.87	6.89	6.92	7.01	6.93
20 m	6.39	6.86	6.84	6.85	6.84	6.91	6.80
25 m	6.33	6.81	6.80	6.78	6.81	6.84	6.75

Table A4

Conductivity (µS/cm) at Sample Location A in 2007

Depth	January	March	June	July	August	October	December
Surface	631	691	380	465	509	545	597
1 m	618	688	376	475	510	545	583
5 m	673	779	733	722	681	545	798
10 m	1,184	1,266	1,197	1,152	1,153	1,167	1,182
15 m	1,388	1,496	1,405	1,363	1,363	1,360	1,348
20 m	1,939	2,183	1,954	1,610	1,928	1,924	2,109
25 m	2,850	2,890	2,890	2,859	2,869	2,863	2,862

Table A5

Total dissolved solids (g/L) at Sample Location A in 2007

Depth	January	March	June	July	August	October	December
Surface	0.410	0.449	0.247	0.302	0.331	0.355	0.387
1 m	0.402	0.448	0.245	0.309	0.331	0.354	0.377
5 m	0.439	0.506	0.477	0.469	0.442	0.354	0.519
10 m	0.770	0.823	0.779	0.750	0.751	0.760	0.769
15 m	0.902	0.973	0.913	0.887	0.886	0.884	0.877
20 m	1.261	1.419	1.270	1.046	1.254	1.251	1.371
25 m	1.852	1.877	1.878	1.859	1.865	1.860	1.861

Table A6

Salinity (‰) at Sample Location A in 2007

Depth	January	March	June	July	August	October	December
Surface	0.30	0.33	0.18	0.22	0.25	0.26	0.28
1 m	0.30	0.33	0.18	0.23	0.25	0.26	0.27
5 m	0.33	0.38	0.36	0.35	0.33	0.26	0.39
10 m	0.58	0.63	0.59	0.57	0.57	0.57	0.58
15 m	0.68	0.74	0.69	0.67	0.67	0.67	0.67
20 m	0.97	1.10	0.98	0.80	0.96	0.96	1.06
25 m	1.45	1.46	1.47	1.45	1.46	1.45	1.45

Table A7

Dissolved ions (mg/L) at Sample Location A in 2007

Depth	Analyte	January	March	June	July	August	October	December
Surface	Calcium	71.5	-	40.7	49.6	43.3	61.2	61.5
	Magnesium	43.8	-	23.2	29.9	34.8	35.7	36.1
	Sodium	3.5	-	2.4	5.1	3.1	3.1	3.3
	Potassium	0.8	-	0.9	0.8	0.6	0.6	0.64
	Iron	0.12	-	0.18	0.17	0.13	0.17	-
	Manganese	0.092	-	0.027	0.072	0.068	0.172	-
	Chloride	1	1.3	<0.4	3.9	0.7	1.2	0.62
	Nitrate	0.28	0.4	0.06	0.08	0.2	0.16	0.17
	Sulfate	193	192	110	133	152	159	170
	Bicarbonate	170	-	105	128	159	161	176
1 m	Calcium	70.9	41.2	49.7	78.7	78.7	61.7	56.3
	Magnesium	43.3	-	23.3	30.2	47.8	36.1	33.8
	Sodium	3.4	-	2.4	4.0	4.0	3.1	3.1
	Potassium	0.7	-	0.9	0.9	0.9	0.6	0.58
	Iron	0.12	-	0.18	0.18	0.13	0.16	-
	Manganese	0.092	-	0.005	0.071	0.292	0.176	-
	Chloride	<0.4	1.1	<0.4	2.6	0.7	1.0	0.65
	Nitrate	0.30	0.4	0.05	0.08	0.2	0.15	0.15
	Sulfate	192	190	109	134	153	157	171
	Bicarbonate	175	-	104	130	159	163	174
5 m	Calcium	80.8	-	80.8	78.2	78.5	58.8	68.5
	Magnesium	51.4	-	48.7	47.6	48	34.4	41.0
	Sodium	4.0	-	4.4	4.8	4.0	2.9	3.7
	Potassium	0.9	-	0.9	0.9	0.8	0.4	0.72
	Iron	0.13	-	0.03	0.15	0.13	0.16	-
	Manganese	0.427	-	0.605	0.410	0.293	0.165	-
	Chloride	0.9	1.2	<0.4	1.9	1.2	1.4	1.0
	Nitrate	0.22	0.12	0.20	0.27	0.3	0.16	0.17
	Sulfate	217	209	223	208	219	151	214
	Bicarbonate	208	-	862	216	226	159	219
10 m	Calcium	138	-	142	133	138	132	130
	Magnesium	81.4	-	81.0	76.1	78.3	75.2	72.0
	Sodium	6.9	-	7.6	7.7	7.0	6.5	6.6
	Potassium	1.3	-	1.5	1.4	1.5	1.3	1.26
	Iron	0.87	-	0.72	0.72	0.73	0.50	-
	Manganese	3.36	-	3.43	3.18	3.50	3.14	-
	Chloride	2.8	3.9	1.5	5.4	3.0	3.1	3.31
	Nitrate	<0.01	<0.1	<0.01	0.01	<0.2	<0.01	<0.04
	Sulfate	332	320	338	322	310	309	285
	Bicarbonate	415	-	426	410	437	414	417

Table A7 (continued)

Dissolved ions (mg/L) at Sample Location A in 2007

Depth	Analyte	January	March	June	July	August	October	December
15 m	Calcium	172	-	172	164	168	158	145
	Magnesium	99.2	-	97.0	92.3	93.7	87.5	79.6
	Sodium	8.9	-	9.3	10.6	8.4	7.5	7.5
	Potassium	1.8	-	1.9	1.9	1.8	1.5	1.48
	Iron	0.37	-	0.29	0.32	0.30	0.33	-
	Manganese	4.21	-	4.19	3.92	4.31	3.72	-
	Chloride	4.3	<0.1	2.6	6.8	4.1	4.4	4.18
	Nitrate	0.01	<0.1	0.01	0.02	>0.2	<0.01	<0.04
	Sulfate	416	440	421	390	370	362	346
	Bicarbonate	509	-	512	503	534	501	486
20 m	Calcium	271	-	261	229	260	248	226
	Magnesium	148	-	140	126	138	136	115
	Sodium	10.1	-	10.6	10.9	10.4	10.0	8.5
	Potassium	2.5	-	2.5	2.3	2.7	2.5	2.1
	Iron	0.24	-	0.17	0.20	0.28	0.19	-
	Manganese	5.99	-	5.75	5.19	6.28	5.56	-
	Chloride	4.7	5.0	3.2	7.1	4.7	5.4	4.06
	Nitrate	<0.01	<0.1	<0.01	0.02	<0.2	0.01	<0.04
	Sulfate	732	670	687	596	670	655	568
	Bicarbonate	690	-	659	617	708	660	596
25 m	Calcium	396	-	380	388	328	400	474
	Magnesium	525	-	239	233	202	240	278
	Sodium	12.0	-	12.0	13.0	11.7	13.0	11.6
	Potassium	<4	-	<4	<4	3.2	<4	3.0
	Iron	0.55	-	0.19	0.20	0.17	0.18	-
	Manganese	9.50	-	9.07	8.99	7.99	9.54	-
	Chloride	3.9	4.6	2.4	4.3	3.8	4.1	3.51
	Nitrate	<0.01	<0.1	<0.05	<0.05	<0.2	<0.05	<0.04
	Sulfate	1,150	1,110	1,240	1,130	940	1,160	1,120
	Bicarbonate	946	-	913	922	878	953	930

Table A8

Quality Control of Laboratory Results (2007) for Sample Location A using the Relative Percent Difference (RPD) Method for Various Analytes

Month	Analyte	Sample x_1 (mg/L)	Duplicate x_2 mg/L	RPD (%)	Rating
March	Sulfide	1.03	1.20	15.3	Reasonable
	Sulfate	670	670	0	Good
	Chloride	5.0	4.8	4.1	Good
June	Sulfide	1.29	1.14	12.35	Reasonable
	Sulfate	687	663	4	Good
	Calcium	261	258	1	Good
July	Sulfide	1.23	1.54	22.38	Reasonable
	Iron	0.20	0.19	5.13	Good
	Bicarbonate	617	621	<1	Good
August	Sulfide	1.21	1.05	14.2	Reasonable
	Sodium	10.4	10.2	1.9	Good
	Manganese	6.28	6.18	1.61	Good
October	Sulfide	1.45	1.51	4.05	Good
	Sulfate	655	658	<1	Good
	Magnesium	136	136	0	Good
December	Sulfide	1.45	1.51	4.05	Good
	Calcium	226	244	9	Good
	Bicarbonate	596	653	9	Good

Table A9

Metals (µg/g) in Lake Sediment at Sample Location A, 2006 and 2007

Analyte	July 20, 2006	August 30, 2007
Aluminum	14,800	12,100
Antimony	<10	3.9
Arsenic	<5	10.3
Barium	265	99
Beryllium	<0.4	0.48
Bismuth	<10	1.2
Cadmium	4	1.8
Calcium	2,320	9,700
Chromium	103	76.2
Cobalt	43	21.3
Copper	411	56.8
Iron	27,900	39,900
Lead	16	27.7
Lithium	24	15.2
Magnesium	12,200	14,000
Manganese	450	784
Mercury	-	0.27
Molybdenum	18	9.22
Nickel	166	156
Phosphorus	888	766
Potassium	600	985
Selenium	75	<0.3
Silicon	-	78
Silver	<4	<0.2
Sodium	300	102
Strontium	26.8	68.2
Thallium	36	1.4
Tin	20	0.6
Titanium	73	88.5
Uranium	130	-
Vanadium	19	38.2
Zinc	398	170
Zirconium	<1	11.2

Table A10

Water Quality Parameters at all Sample Locations from Surface Water Survey June 2008 in order from Inflow to Outflow of Lake (West to East)

Sample Location	Depth	Temperature °C	Dissolved Oxygen %	pH	Conductivity µS/cm	Total Dissolved Solids g/L	Salinity ‰
B	Surface	7.97	101.0	7.87	578	0.365	0.28
E	Surface	16.16	103.2	7.85	470	0.306	0.23
	1 m	15.15	97.9	7.77	472	0.307	0.23
	2 m	12.91	87.2	7.70	490	0.319	0.24
	3 m	9.05	70.1	7.60	554	0.354	0.26
	4 m	5.09	38.1	7.46	645	0.419	0.31
	5 m	3.40	11.6	7.30	752	0.491	0.37
	6 m	2.86	1.80	7.23	806	0.524	0.39
	7 m	2.58	0.00	7.19	829	0.537	0.40
F	Surface	5.50	94.7	7.92	756	0.491	0.37
D	Surface	17.12	106.3	7.84	469	0.305	0.23
	1 m	16.50	104.6	7.83	469	0.305	0.23
	2 m	13.41	88.0	7.77	486	0.316	0.24
	3 m	10.09	73.7	7.68	532	0.345	0.26
	4 m	6.52	49.3	7.56	592	0.395	0.29
	5 m	3.25	9.8	7.39	756	0.495	0.37
	6 m	2.83	2.80	7.31	789	0.514	0.38
	7 m	2.56	0.00	7.24	829	0.539	0.40
G	Surface	5.87	87.8	8.73	503	0.327	0.24
A	Surface	17.86	106.5	8.06	467	0.304	0.23
	1 m	16.73	105.4	8.02	468	0.304	0.23
	2 m	14.75	93.0	7.94	475	0.308	0.23
	3 m	9.90	71.4	7.84	530	0.344	0.26
	4 m	5.49	43.9	7.70	632	0.407	0.30
	5 m	3.78	20.5	7.60	719	0.467	0.35
	6 m	2.85	3.1	7.44	788	0.512	0.38
	7 m	2.57	0.00	7.39	820	0.524	0.40
C	Surface	17.12	106.7	7.97	467	0.304	0.23

Table A11

Water Quality Parameters at Sample Locations B(Inflow) and C (Outflow) in 2007

Parameter	Location	January	March	June	July	August	October	December
Temperature °C	B	0.26	0.26	17.29	22.25	4.85	0.01	0.32
	C	0.39	0.18	16.91	18.47	14.08	3.05	0.28
Dissolved Oxygen %	B	70.6	64.1	92.7	99.0	100.6	95.7	74.8
	C	77.0	72.6	90.6	84.2	97.9	96.4	81.6
pH	B	6.79	6.38	7.64	7.88	7.88	8.08	8.28
	C	7.08	7.18	7.61	7.75	8.08	7.92	8.09
Conductivity µS/cm	B	637	712	386	466	651	637	633
	C	562	693	380	474	509	545	600
Total Dissolved Solids g/L	B	0.414	0.463	0.251	0.303	0.428	0.414	0.411
	C	0.336	0.450	0.247	0.308	0.331	0.354	0.390
Salinity ‰	B	0.30	0.34	0.19	0.22	0.32	0.30	0.30
	C	0.27	0.33	0.18	0.23	0.25	0.26	0.29

Table A12

Dissolved Ions (mg/L) at Sample Locations B(Inflow) and C (Outflow) in 2007

Analyte	Location	January	March	June	July	August	October	December
Calcium	B	74.0	-	41.8	55.0	65.2	71.7	60.7
	C	71.0	-	39.7	50.6	53.6	58.3	57.1
Magnesium	B	45.6	-	24.0	31.0	43.5	42.0	34.9
	C	43.3	-	22.6	30.6	35.0	34.9	33.0
Sodium	B	3.6	-	2.4	6.0	3.4	3.5	3.3
	C	3.4	-	2.4	3.7	3.0	3.1	3.0
Iron	B	0.17	-	0.19	0.12	0.38	0.38	-
	C	0.12	-	0.18	0.19	0.12	0.16	-
Sulfate	B	203	190	113	140	209	190	182
	C	190	180	107	137	152	166	171
Bicarbonate	B	181	-	108	136	197	183	186
	C	179	-	103	131	159	165	176

Appendix B

Table B1

Weather Data for June 2006. Daily Sum of Rainfall, Averages for Temperature, Windspeed and Direction (in degrees), Maximum for Temperature and Windspeed and Minimum for Temperature

Weather Station - Clinton Creek Mine										MAX	Max
	Raw Data Rows		Rainfall	Temp	Wind	Wind	Direction	Max Temp	MIN Temp	Wind	Wind
Date	Start	End	mm	ºC	m/s	km/h	ø	ºC	ºC	m/s	km/h
21-Jun-06	3	148	5.8	13.74	1.92	6.90	154.2	16.76	11.38	5.01	18.04
22-Jun-06	149	436	2.2	12.25	1.87	6.73	131.9	16.38	9.03	6.12	22.03
23-Jun-06	437	724	0	10.81	2.37	8.52	164.1	15.62	2.89	6.49	23.36
24-Jun-06	725	1012	0	11.76	1.10	3.95	218.6	18.66	5.4	3.71	13.36
25-Jun-06	1013	1300	0.2	13.11	2.24	8.05	213.9	20.95	4.57	7.98	28.73
26-Jun-06	1301	1588	9.4	10.72	1.31	4.70	231.4	14.47	8.23	6.31	22.72
27-Jun-06	1589	1876	1.2	12.68	2.91	10.46	184.0	17.14	9.03	6.31	22.72
28-Jun-06	1877	2164	2.2	12.84	1.76	6.32	141.0	17.52	9.03	8.16	29.38
29-Jun-06	2165	2452	2.4	14.15	1.44	5.17	152.0	22.09	9.82	4.64	16.70
30-Jun-06	2453	2738	0	16.33	1.93	6.97	183.6	24.01	9.03	6.12	22.03

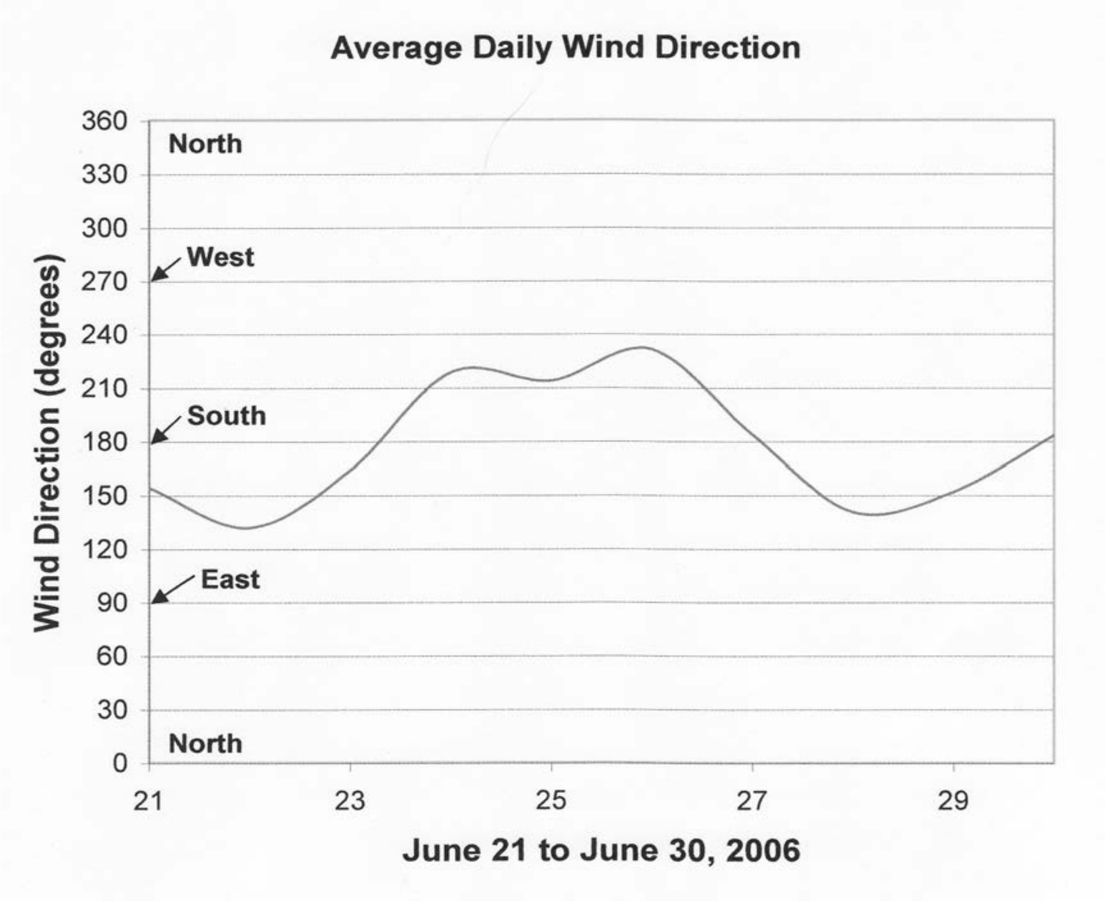

Figure B1. Calculated average daily wind direction from June 21 to June 30, 2006.

Table B2

Weather Data for July 2006. Daily Sum of Rainfall, Averages for Temperature, Windspeed and Direction (in degrees), Maximum for Temperature and Windspeed and Minimum for Temperature

Weather Station Clinton Creek Mine									
Date	Raw Data Rows		Rainfall	Temp	Wind	Direction	Max Temp	MIN Temp	Max Wind
	Start	End	mm	ºC	km/h	ø	ºC	ºC	(km/h)
01-Jul-06	3	290	0	14.2	9.2	195.2	20.2	5.4	26.7
02-Jul-06	291	578	0	15.2	11.6	123.2	21.0	8.23	30.1
03-Jul-06	579	866	0.6	14.4	5.8	158.1	19.0	9.42	14.0
04-Jul-06	867	1154	0	15.8	5.0	134.7	22.5	5.81	14.0
05-Jul-06	1155	1442	1.6	16.7	8.0	141.4	21.7	9.82	25.4
06-Jul-06	1443	1730	0.2	15.7	6.6	162.1	21.0	9.03	26.7
07-Jul-06	1731	2018	2	15.3	5.1	161.7	21.0	10.6	18.0
08-Jul-06	2019	2306	0	15.8	7.9	180.8	18.3	8.23	20.1
09-Jul-06	2307	2594	0	15.2	8.8	188.3	21.3	6.22	18.0
10-Jul-06	2595	2882	0	16.4	5.8	172.4	24.8	4.99	14.7
11-Jul-06	2883	3170	0	17.5	7.5	185.5	26.7	7.03	27.4
12-Jul-06	3171	3458	0.6	16.1	6.1	172.4	22.5	9.03	22.0
13-Jul-06	3459	3746	0	17.1	6.1	162.4	23.2	9.42	23.4
14-Jul-06	3747	4034	0.8	16.2	6.6	194.5	24.4	9.82	22.7
15-Jul-06	4035	4322	0.8	13.6	7.6	206.3	21.7	6.62	28.0
16-Jul-06	4323	4610	0	12.3	6.2	173.2	21.0	4.57	22.0
17-Jul-06	4611	4898	0	14.0	5.6	187.0	19.0	6.62	18.0
18-Jul-06	4899	5186	0	14.7	5.1	167.8	19.8	8.63	24.0
19-Jul-06	5187	5474	0	15.2	5.7	197.9	21.3	4.99	20.1
20-Jul-06	5475	5762	0	16.7	7.9	177.2	24.8	5.81	19.4
21-Jul-06	5763	6050	0.2	15.4	6.3	169.8	22.5	7.83	24.7
22-Jul-06	6051	6338	0	16.5	5.5	186.5	22.9	11.38	17.4
23-Jul-06	6339	6626	0	17.2	5.2	96.6	24.8	7.43	14.0
24-Jul-06	6627	6914	0	18.1	7.7	145.8	26.7	6.62	20.1
25-Jul-06	6915	7202	0	18.2	12.2	172.2	22.5	12.55	26.7
26-Jul-06	7203	7490	0	15.5	5.2	147.7	17.9	11.77	15.4
27-Jul-06	7491	7778	5.2	16.3	9.0	213.4	21.0	12.93	19.4
28-Jul-06	7779	8066	0	18.2	6.4	177.2	26.7	8.23	18.0
29-Jul-06	8067	8354	12.2	16.3	7.2	130.1	26.0	9.03	22.0
30-Jul-06	8355	8642	2.2	13.3	7.2	169.4	15.2	11.38	18.7
31-Jul-06	8643	8930	0.8	13.4	6.5	169.2	19.0	9.03	14.0

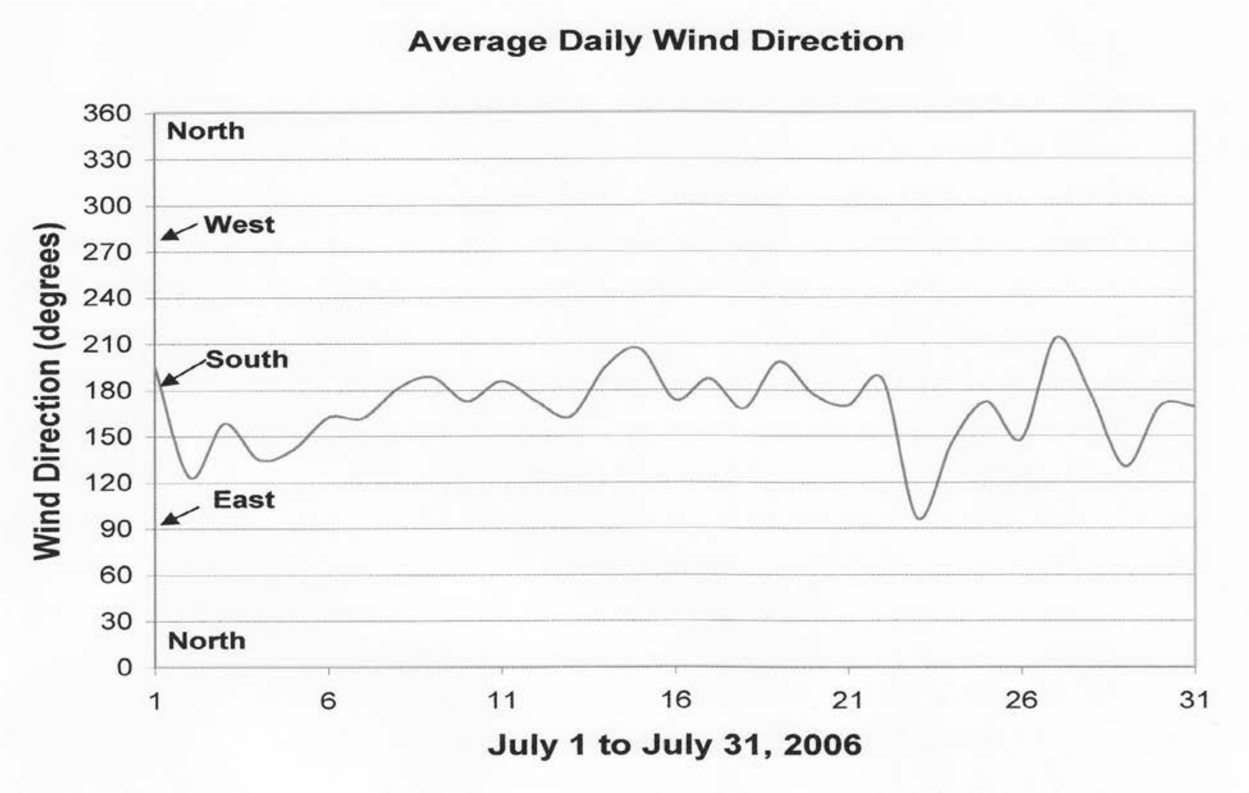

Figure B2. Calculated average daily wind direction from July 1 to July 31, 2006.

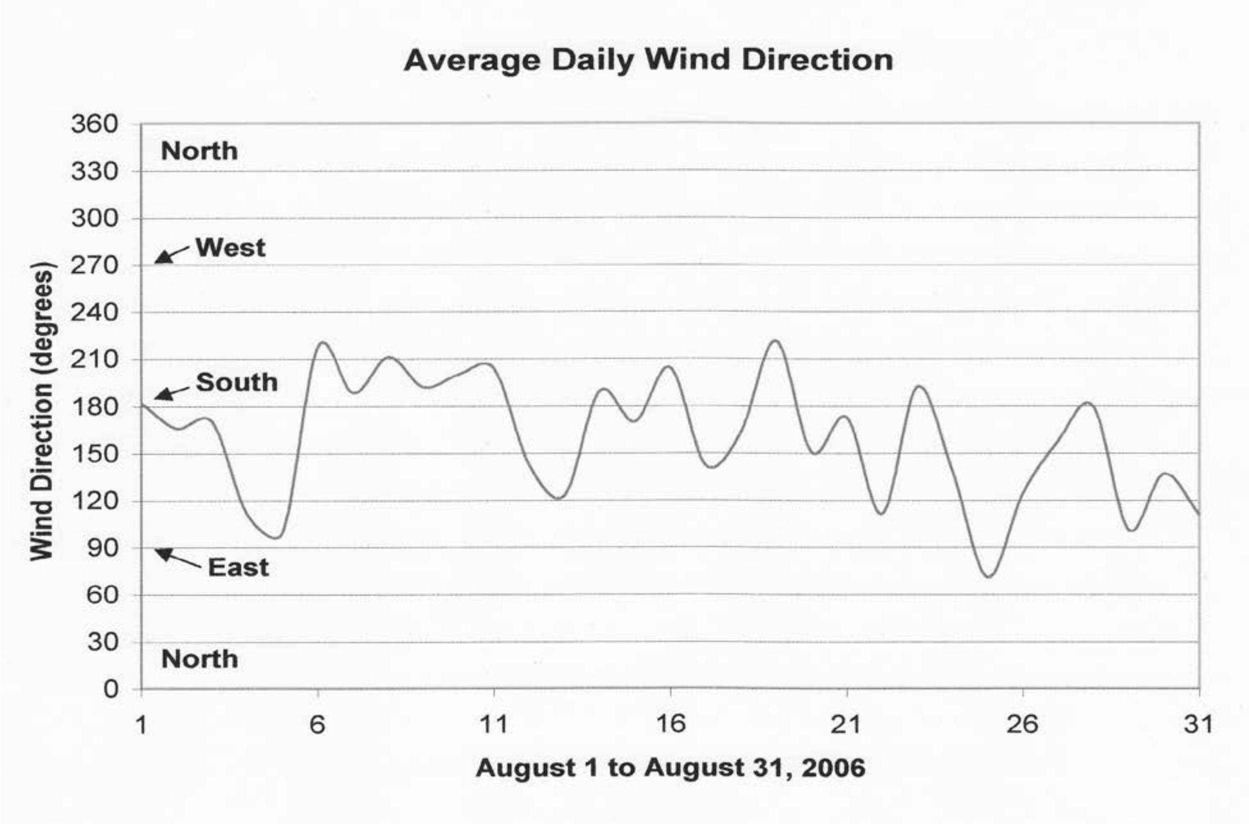

Figure B3. Calculated average daily wind direction from August 1 to August 31, 2006.

Table B3

Weather Data for August 2006. Daily Sum of Rainfall, Averages for Temperature, Windspeed and Direction (in degrees), Maximum for Temperature and Windspeed and Minimum for Temperature

Weather Station Clinton Creek Mine

Date	Raw Data Rows Start	End	Rainfall mm	Temp ºC	Wind km/h	Direction ø	Max Temp ºC	MIN Temp ºC	Max Wind (km/h)
01-Aug-06	3	290	0	15.0	5.4	181.8	22.1	7.8	20.1
02-Aug-06	291	578	4.2	13.2	4.1	165.6	17.9	10.2	17.4
03-Aug-06	579	866	0	14.1	5.8	170.0	22.5	4.2	18.0
04-Aug-06	867	1154	0	14.5	10.4	110.7	21.7	5.8	26.1
05-Aug-06	1155	1442	0	15.4	5.4	99.4	21.3	0.0	17.4
06-Aug-06	1443	1730	1.4	13.8	4.2	217.5	18.3	9.4	11.3
07-Aug-06	1731	2018	0	16.0	5.3	188.2	21.7	10.6	16.7
08-Aug-06	2019	2306	0.2	13.5	7.1	211.0	17.5	8.2	18.7
09-Aug-06	2307	2594	0	12.7	5.0	191.9	21.0	3.3	14.0
10-Aug-06	2595	2882	1.2	12.5	5.9	200.0	21.7	2.5	20.7
11-Aug-06	2883	3170	3	12.0	6.1	203.6	20.6	4.6	16.7
12-Aug-06	3171	3458	1.6	12.0	4.0	142.3	16.4	9.0	16.0
13-Aug-06	3459	3746	1.6	12.1	4.7	122.8	17.5	5.8	18.7
14-Aug-06	3747	4034	0	12.2	3.9	189.3	19.4	4.6	11.3
15-Aug-06	4035	4322	1.4	10.2	3.7	169.8	12.9	6.6	14.7
16-Aug-06	4323	4610	0.2	11.9	4.0	204.0	17.1	7.8	20.1
17-Aug-06	4611	4898	1.2	11.9	5.6	141.9	16.0	8.2	24.7
18-Aug-06	4899	5186	0.6	11.1	7.4	163.2	16.0	7.0	22.7
19-Aug-06	5187	5474	7	11.2	6.9	221.4	18.3	7.0	24.7
20-Aug-06	5475	5762	2.8	7.1	5.3	150.7	11.4	1.2	18.0
21-Aug-06	5763	6050	18.4	9.3	4.1	172.7	11.4	4.2	31.4
22-Aug-06	6051	6338	0	7.0	6.3	111.4	14.1	0.7	16.0
23-Aug-06	6339	6626	5.8	10.3	4.3	192.1	14.5	7.8	19.4
24-Aug-06	6627	6914	0	9.0	4.9	139.3	16.8	1.2	14.0
25-Aug-06	6915	7202	4.4	9.1	3.6	70.9	12.9	6.2	13.4
26-Aug-06	7203	7490	1	9.0	3.0	124.1	14.9	5.4	9.4
27-Aug-06	7491	7778	0	8.5	7.1	157.7	15.2	0.7	18.0
28-Aug-06	7779	8066	0	9.0	6.3	179.7	14.1	3.3	18.0
29-Aug-06	8067	8354	0	6.7	5.1	101.0	13.7	-1.1	12.7
30-Aug-06	8355	8642	0	6.9	5.6	136.9	15.6	-0.6	14.0
31-Aug-06	8643	8930	1	5.8	6.5	110.5	10.6	0.3	22.0

Table B4

Weather Data for September 2006. Daily Sum of Rainfall, Averages for Temperature, Windspeed and Direction (in degrees), Maximum for Temperature and Windspeed and Minimum for Temperature

Weather Station - Clinton Creek Mine

Date	Raw Data Rows		Rainfall	Temp	Wind	Direction	Max Temp	MIN Temp	Max Wind
	Start	End	mm	ºC	km/h	ø	ºC	ºC	km/h
01-Sep-06	3	290	0	8.28	5.6	226.4	13.32	4.99	16.7
02-Sep-06	291	578	0	8.89	6.6	234.2	13.7	4.99	16.7
03-Sep-06	579	866	1.2	9.49	5.8	164.3	16	4.57	21.4
04-Sep-06	867	1154	0.2	7.12	3.9	230.1	14.47	0.29	11.3
05-Sep-06	1155	1442	2.2	10.42	6.5	248.4	16.38	6.22	20.1
06-Sep-06	1443	1730	0	7.41	7.5	162.4	12.93	0.73	30.1
07-Sep-06	1731	2018	0	8.58	5.4	223.6	14.85	1.6	14.0
08-Sep-06	2019	2306	0	8.52	6.9	236.9	16.76	1.17	17.4
09-Sep-06	2307	2594	0	7.26	4.2	273.8	16.38	0.29	10.0
10-Sep-06	2595	2882	0	7.81	3.6	254.2	18.28	-0.6	8.7
11-Sep-06	2883	3170	2.2	8.63	3.2	207.8	14.85	5.4	20.7
12-Sep-06	3171	3458	0	7.95	3.8	226.4	14.85	2.46	18.0
13-Sep-06	3459	3746	0.2	7.87	5.2	204.6	16	2.46	16.0
14-Sep-06	3747	4034	0	7.36	9.6	202.5	16.38	-1.05	26.7
15-Sep-06	4035	4322	0	8.37	13.7	195.5	15.62	1.17	31.4
16-Sep-06	4323	4610	11.2	3.23	9.0	187.1	9.82	-1.51	24.7
17-Sep-06	4611	4898	4.2	3.58	5.8	128.9	6.62	1.17	9.4
18-Sep-06	4899	5186	0	5.66	4.5	136.5	14.47	-0.15	12.0
19-Sep-06	5187	5474	0	5.69	8.1	165.3	11.77	0.29	23.4
20-Sep-06	5475	5762	1	7.49	5.6	164.4	13.32	3.74	12.7
21-Sep-06	5763	6050	0.2	6.01	5.8	172.4	14.09	0.29	22.0
22-Sep-06	6051	6338	0.4	7.87	9.3	159.3	11.38	2.89	27.4
23-Sep-06	6339	6626	0	5.22	5.0	110.0	11.77	1.6	15.4
24-Sep-06	6627	6914	0	3.71	4.1	115.5	12.16	-1.97	10.7
25-Sep-06	6915	7202	0	2.61	4.5	130.3	11.38	-2.9	10.7
26-Sep-06	7203	7490	0	2.52	8.8	115.0	9.03	-3.37	24.0
27-Sep-06	7491	7778	3.2	7.41	4.3	152.9	11.77	3.31	18.0
28-Sep-06	7779	8066	2	5.51	5.3	190.6	10.21	1.6	16.0
29-Sep-06	8067	8354	1	2.70	2.7	185.6	5.81	-0.6	7.3
30-Sep-06	8355	8642	0.2	3.68	7.6	261.9	4.99	-1.05	19.4

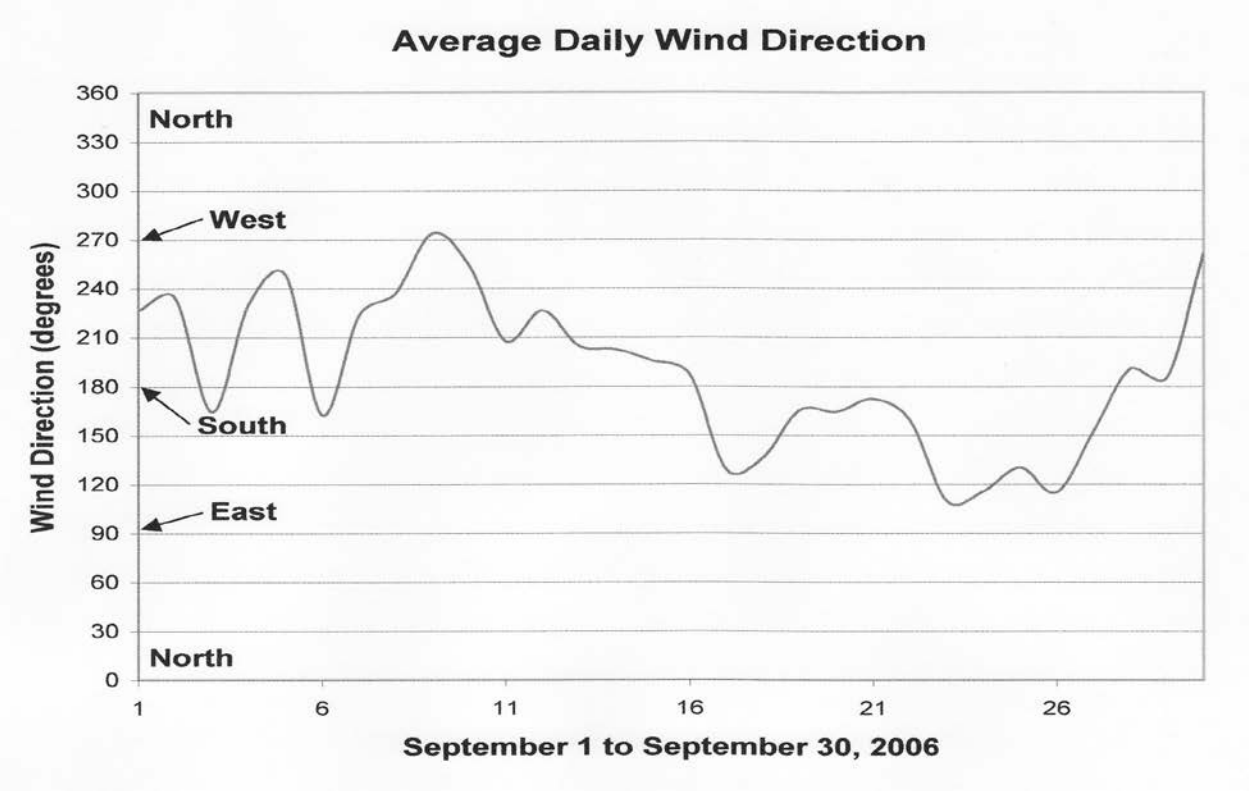

Figure B4. Calculated average daily wind direction from September 1 to September 30, 2006.

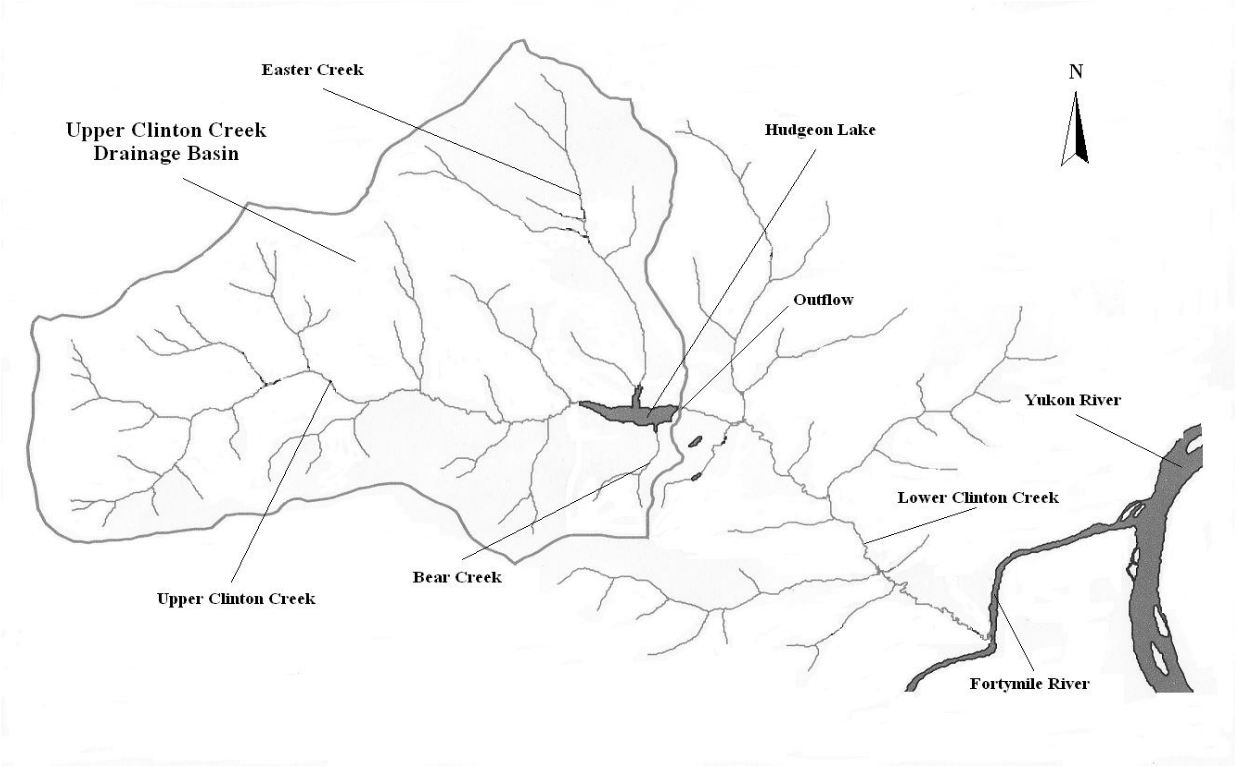

Figure B5. Upper Clinton Creek drainage basin modified from UMA Risk Assessment Report (2000).

Table B5

Daily Discharge (m^3/s) for 2006 at Lower Clinton Creek Hydrometric Station 29EC001 (YG, Department of Environment)

Day	May	June	July	August	September	October
1	-	0.610	1.63	0.497	1.11	1.55
2	-	0.598	1.29	0.537	0.993	1.45
3	-	0.561	1.02	0.567	0.927	1.30
4	-	0.506	0.864	0.546	0.883	1.80
5	-	0.399	0.780	0.506	0.855	-
6	-	0.335	0.717	0.470	0.857	-
7	-	0.288	0.637	0.452	0.842	-
8	-	0.253	0.662	0.430	0.825	-
9	-	0.231	0.632	0.431	0.800	-
10	6.29	0.224	0.528	0.400	0.797	-
11	6.17	0.207	0.453	0.389	0.782	-
12	5.68	0.196	0.422	0.424	0.783	-
13	5.47	0.187	0.407	0.417	0.769	-
14	5.29	0.175	0.389	0.421	0.759	-
15	6.04	0.175	0.373	0.442	0.735	-
16	6.65	0.230	0.363	0.485	0.727	-
17	11.3 E	0.336	0.348	0.521	1.27	-
18	10.4 E	0.417	0.359	0.559	1.56	-
19	8.86 E	0.441	0.359	0.562	1.74	-
20	7.44 E	0.419	0.345	0.756	1.84	-
21	6.19 E	0.418	0.330	1.29	1.79	-
22	5.09 E	0.706	0.333	2.54	1.66	-
23	4.14 E	0.944	0.323	2.62	1.53	-
24	3.32 E	0.859	0.311	2.49	1.39	-
25	2.62 E	0.760	0.304	2.20	1.24	-
26	2.06 E	0.782	0.302	2.20	1.11	-
27	1.59 E	1.81	0.323	2.09	1.12	-
28	1.22 E	2.21	0.320	1.84	1.24	-
29	0.926 E	2.16	0.353	1.60	1.38	-
30	0.715 E	2.02	0.408	1.40	1.50	-
31	0.570 E	-	0.470	1.22	-	-

Note. E = estimated since station equipment was impacted by extreme spring run-off.

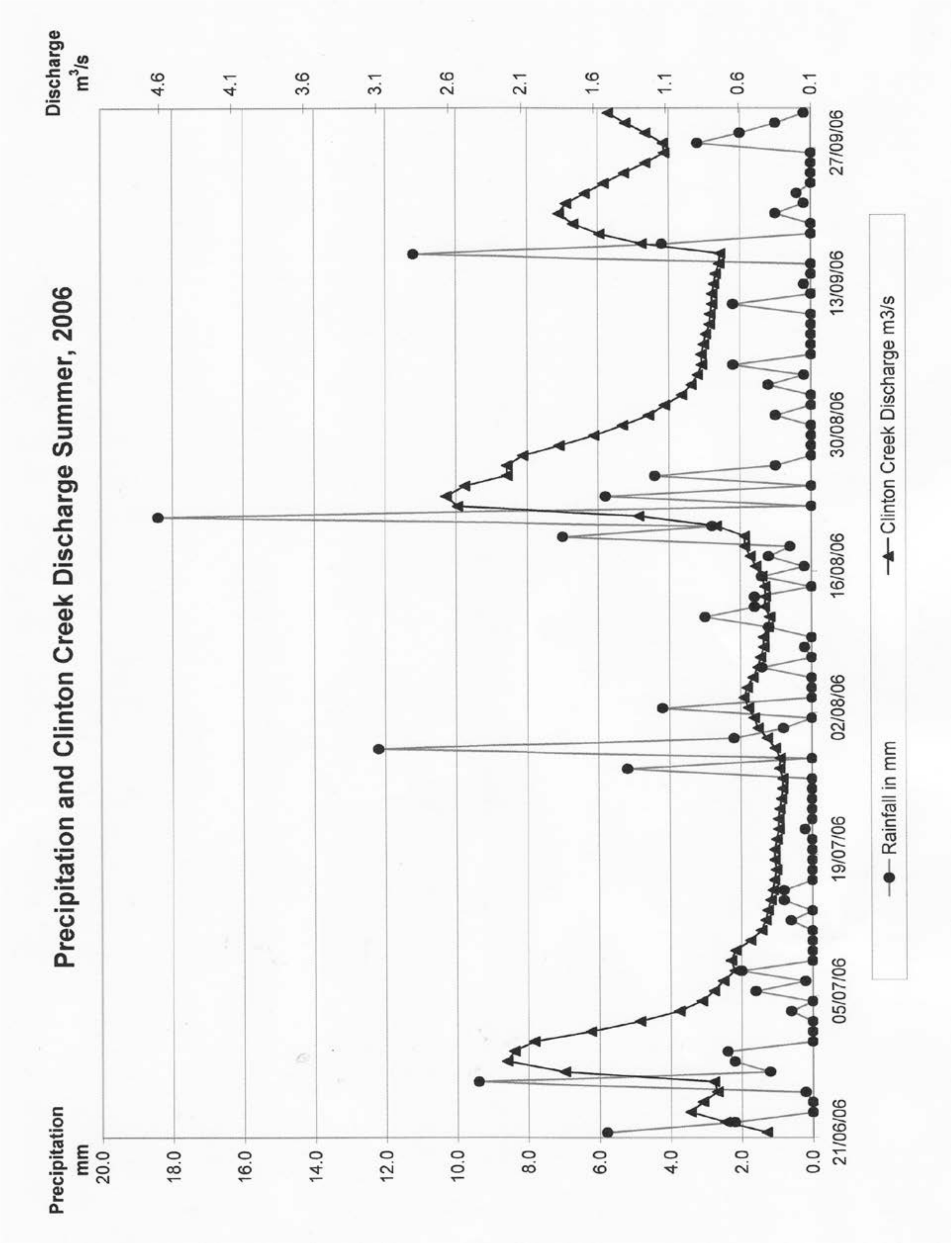

Figure B6. Precipitation from weather station data and discharge of Clinton Creek from hydrometric station data for the period 21 June to 30 September 2006.

Appendix C

Table C1

Data from the 2007 Fisheries and Benthic Invertebrate Assessment, carried out by White Mountain Environmental Consulting (2008) for the YG Assessment and Abandoned Mines Office

	Tributary to Upper Clinton Creek	Upper Clinton Creek	Bear Creek	Easter Creek	Clinton Creek below Outflow
Phylum Arthropoda **Class Insecta**					
Order Ephemeroptera					
Ameletus sp	-	-	-	2	-
Baetis sp	53	-	1	10	-
Cinygmula sp	21	3	-	15	-
Order Plecoptera					
Capnia sp	51	1	-	130	-
Leuctra sp	-	-	-	1	-
Podmosta sp	174	86	111	2	
Zapada sp	5	-	-	4	1
Skwala paralella	-	-	-	1	-
Sweltsa Grp	1	-	-	-	-
Order Trichoptera					
Trichoptera unidentified	1	-	-	-	-
Brachycentrus sp	-	-	-	-	4
Dicosmoecus	6	6	-	1	-
Limnephilus sp	-	-	-	1	-
Order Diptera					
Diptera unidentified	-	-	-	-	22
Chironomidae juvenile	6	4	-	1	22
Chironomidae pupae	8	1	-	12	50
Brillia sp	-	2	-	-	-
Cardiocladius sp	-	-	-	-	1
Corynoneura sp	-	-	-	21	-
Cricotopus sp	19	4	2	289	55
Thienemanniella sp	-	1	-	-	-
Diamesa sp	39	2	1	461	7
Eukiefferiella sp	2	29	1	7	59
Euryhapsis sp	9	-	-	11	1
Rheotanytarsus sp	1	-	-	-	18
Thienemannimyia	-	-	-	4	67
Empididae pupae	-	-	-	-	2
Weidemannia sp	-	-	-	-	18
Muscidae pupae	-	-	-	-	1

Table C1 (continued)

	Tributary to Upper Clinton Creek	Upper Clinton Creek	Bear Creek	Easter Creek	Clinton Creek below Outflow
Order Diptera (continued)					
Limnophora sp	-	-	-	-	22
Pericoma sp	-	-	-	5	-
Phoridae larvae	-	-	-	-	1
Cnephia larvae	-	-	-	4	9
Prosimulium larvae	-	-	1	196	-
Prosimulium pupae	-	-	-	42	1
Simulium sp larvae	1	-	-	46	140
Simulium sp pupae	-	1	-	3	16
Family Syrphidae larvae	-	-	-	-	1
Dicronata sp	5	3	5	10	-
Tipula sp	-	3	-	-	-
Order Coleoptera					
Coleoptera unidentified larvae (terrestrial)	-	-	1	-	-
Dytiscidae adult	-	-	-	-	1
Hydaticus sp larvae	-	-	-	-	2
Haliplidae adult	1	-	-	-	-
Staphylinidae adult (terrestrial)	-	-	-	-	2
Staphylinidae larvae (terrestrial)	-	-	-	-	19
Order Homoptera					
Aphididae (terrestrial)	-	-	1	-	-
Cicadellidae (terrestrial)	2	1	-	-	-
Order Hymenoptera					
adult (terrestrial)	-	-	1	-	-
Order Araneae					
(terrestrial)	-	-	2	-	2
Order Hydracarina					
Lebertia	-	-	-	-	1
Sperchon	-	-	-	4	1
Oribatei	1	-	-	-	-
Class Crustacea					
Order Amphipoda					
Hyalella azteca	-	-	-	-	5
Order Cladocera					
Daphnia sp	-	-	-	4	-
Sub Class Copepoda					
Sub Order Cyclopoida	-	-	-	4	-

Table C1 (continued)

	Tributary to Upper Clinton Creek	Upper Clinton Creek	Bear Creek	Easter Creek	Clinton Creek below Outflow
Sub Class Ostracoda					
Candona sp	1	-	24	4	2
Phylum Mollusca **Class Gastropoda**					
Gyraulus parvus	-	-	-	-	125
Fossaria sp	-	-	-	-	8
Phylum Annilida **Class Oligochaeta**					
Enchytraeidae juvenile	1	-	1	21	8
Kincaidiana hexatheca	-	-	1	1	-
Nais sp	-	-	1	1	-
Family Tubificidae juvenile	-	1	3	6	-
Class Hirudinea					
Helobdella stagnalis	-	-	-	-	1
Phylum Platyhelminthes					
Polycelis coronata	3	-	-	-	-
Abundance / Site	411	148	157	1,325	696
Taxonomic Richness	23	16	16	34	35

Table C2

Water Quality Evaluation using Streamkeepers Module 4 and Data from Table C1

Water Quality Assessment	Tributary to Upper Clinton Creek	Upper Clinton Creek	Bear Creek	Easter Creek	Clinton Creek below Outflow
Pollution Tolerant Index	12	11	8	12	15
EPT Index (total of Ephmeroptera, Plecoptera and Trichoptera taxa)	8	4	2	10	2
EPT To Total Ratio	0.99	0.98	0.94	0.32	0.02
Predominant Taxon Ratio	0.73	0.89	0.93	0.29	0.51
Total Point Rating	11	10	8	12	8
Average General Site Assessment Rating (out of 4)	2.75	2.50	2.00	3.00	2.00
4 = Good; 3 = Acceptable; 2 = Marginal; 1 = Poor					