BIOLOGICAL POLISHING

IN

ACID MINE DRAINAGE

CONTAMINANT REMOVAL CAPACITY AND APPLICATION MODEL

FINAL REPORT

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Work on this project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources, Canada.

DSS FILE #: 015SQ.23440-2-9216

DSS CONTRACT SERIAL #: 23440-2-9216

SCIENTIFIC AUTHORITY: Dr. David Koren

DATE: March 11, 1993

EXECUTIVE SUMMARY

Biological polishing is one of the natural processes used in the Ecological Engineering approach to decommissioning mine sites. An application model to determine the metal removal capacity of the process, surface area required for periphyton growth, nutrient additions, pond size and retention time, was developed based on three years of data collection.

In 1990 and 1991, the nature of the contaminant removal process and periphyton growth quantification methods were developed. Attached periphyton remove metals from waste water by: providing nucleation/precipitation sites for metals; serving as a negatively-charged surface for adsorption of cations; and providing extracellular polysaccharides for "sieving" of suspended solids.

Biological polishing design parameters were derived in circum-neutral effluents from a flooded pit of the Buchans mine in central Newfoundland. Six experimental pools were constructed to determine the ratio of substrate surface area to pond volume, periphyton biomass production on the surfaces and the effects of fertilizer applications. These parameters were tested over a period of two years. Zinc sequestration between inorganic and organic components of the biomass, along with the removal from the water, was quantified.

Biological polishing was quantified as part of the decommissioning for the South Bay mine and tailings area, a cooper-zinc concentrator which operated for ten years in northwestern Ontario. Periphyton growth was quantified on brush cuttings in a lake which had become acidic from tailings seeps. Inert demolition material was used as periphyton growth surfaces in the Decant Pond on the tailings, which previously received lime.

Indigenous periphyton were abundant in both the circum-neutral and acidic sites where the process was quantified. In a seepage from the Selminco coal waste dump in Cape Breton, periphyton populations were limited in distribution to very distinct areas. The incorporation of this site into the study added information on growth-limiting factors in acidic effluents with a high reduced iron content. Biological polishing cannot be implemented in the waste stream, until iron oxidation is largely complete.

Growth rates in the laboratory were determined for all populations used in the field. These studies quantified periphyton growth in the absence of inorganic accumulations which were present on periphyton under field conditions.

Site-specific models were developed for the application of the process at each field site. At Buchans, the model is being used to predict the performance of a 320 m^3 polishing pond. At South Bay, the model is being used to estimate reductions in contaminant loadings, which might be achieved by biological polishing in Mill Pond and in an acidic

lake, given an increased surface area for growth. At Selminco, the model is used to assess the possibility of utilizing the process to remove aluminum from the waste water.

A general application model, written in a spreadsheet format (Quattro Pro), utilizes observed periphyton growth rates and contaminant accumulations in the biomass and derives the dimensions of polishing ponds and substrate surface area required for contaminant removal. The model does not address the geochemistry of effluents and cannot be used without site-specific data on periphyton growth conditions and annual contaminant loadings. Contaminant removal was calculated by multiplying the concentrations of metals associated with the periphyton by the amount of periphyton growth. The output of the model determines the size of the polishing pond and the surface area required to remove specific contaminants. The contaminants addressed within the site-specific models are iron, zinc and aluminum.

Since the application model represents a simplified view of the biological polishing process, e.g. chemical/biological interactions are not defined, it was considered prudent to use conservative input parameters for the model to avoid producing false expectations by the users of the model. The site-specific models therefore give a range of expected performance, reflecting minimum and enhanced removal.

Laboratory measurements produced high growth estimates, which were used to calculate the high end of the growth rate range. Actual growth measurements in waste water in the field were used to represent the low end of the growth rate range. These field rates were used in the scale-up calculations.

The output of the site-specific models enable the use of a quantitative, rather than qualitative assessment of the rates of contaminant removal by biological processes, within the framework of an Ecological Engineering decommissioning technology.

SOMMAIRE

Le polissage biologique est l'un des procédés naturels utilisés dans l'approche du génie écologique afin de décommissionner les chantiers miniers. Un modèle d'application afin de déterminer la capacité d'élimination des métaux du procédé, la superficie nécessaire à la croissance des périphytons, les ajouts de nutriments, la dimension des bassins et le temps de rétention, a été mis au point en fonction de trois années de collecte de données.

En 1990 et 1991, la nature du procédé d'élimination des contaminants et les méthodes de quantification de la croissance des périphytons ont été mises au point. Les périphytons fixés éliminent les métaux des eaux usées en fournissant des sites de nucléation/précipitation pour les métaux, en servant de surface négativement chargée pour l'absorption des cations, et en fournissant des polysaccharides extracellulaires pour le «tamisage» des solides en suspension.

Les paramètres de la conception du polissage biologique ont été puisés dans des effluents circum-neutres à partir d'un chantier inondé de la mine Buchans au centre de Terre-Neuve. Six mares expérimentales ont été construites afin de déterminer le coefficient de la superficie des substrats par rapport au volume du bassin, la production de la biomasse des périphytons sur les surfaces et les effets des applications de fertilisants. Ces paramètres ont été testés sur une période de deux années. La séquestration de zinc entre les composants inorganiques et organiques de la biomasse a été quantifiée, en même temps que l'enlèvement à partir de l'eau.

Le polissage biologique a été quantifié comme partie du décommissionnement de la mine de South Bay et de l'aire des résidus, un concentrateur de cuivre-zinc qui a fonctionné pendant dix années dans le nord-ouest de l'Ontario. La croissance des périphytons a été quantifiée sur des coupes de broussailles dans un lac qui était devenu acide par les infiltrations des résidus. Les matériaux de démolition inertes ont été utilisés comme surfaces de croissance dans le Decant Pond sur les résidus, qui recevait précédemment de la chaux.

Les périphytons indigènes étaient abondants tant dans les sites circum-neutres que les sites acides où le procédé a été quantifié. Dans un suintement à partir du dépotoir des déchets du charbon de Selminco, au Cap Breton, la distribution des populations de périphytons se limitait à des zones très distinctes. L'intégration de ce site dans l'étude a ajouté des informations sur les facteurs limitant la croissance dans les effluents acides à teneur en fer grandement réduite. Le polissage biologique ne peut pas être mis en place dans le courant des déchets, avant que l'oxydation du fer ne soit largement achevée.
Les taux de croissance en laboratoire ont été déterminés pour toutes les populations utilisées sur le terrain. Ces études ont quantifié la croissance des périphytons en l'absence d'accumulations inorganiques qui étaient présentes sur les périphytons dans les conditions sur le terrain.

Les modèles spécifiques aux sites ont été mis au point pour l'application du procédé dans chaque site de terrain. À Buchans, on utilise le modèle afin de prédire la performance d'un bassin de polissage de 320 m^3. À South Bay, on utilise le modèle pour estimer les réductions des chargements des contaminants, ce qu'on peut réaliser par le polissage biologique effectué dans Mill Pond et dans un lac acide, dans le cas d'une superficie augmentée pour la croissance. À Selminco, le modèle est utilisé afin d'évaluer la possibilité d'utiliser le procédé pour enlever l'aluminium des eaux usées.

Un modèle d'application générale, rédigé sous forme de tableau électronique (Quattro Pro), utilise les taux de croissance des périphytons et des accumulations de contaminants observés dans la biomasse et tire les dimensions des bassins de polissage et de la superficie des substrats nécessaires à l'enlèvement des contaminants. Le modèle n'aborde pas la géochimie des effluents et ne peut être utilisé sans des données spécifiques aux sites sur les conditions de croissance des périphytons et des chargements annuels de contaminants. L'enlèvement des contaminants a été calculé en multipliant les concentrations des métaux associées aux périphytons par la quantité de la croissance des périphytons. Le rendement du modèle détermine la taille du bassin de polissage et la superficie nécessaire à l'enlèvement des contaminants spécifiques. Les contaminants abordés au sein des modèles spécifiques aux sites sont le fer, le zinc et l'aluminium.

Comme le modèle d'application représente une vue simplifiée du procédé de polissage biologique, par exemple, les interactions chimiques/biologiques ne sont pas définies, on a pensé qu'il était prudent d'utiliser des paramètres d'entrée conservateurs pour le modèle, afin d'éviter de susciter de faux espoirs chez les utilisateurs du modèle. Les modèles spécifiques aux sites donnent, par conséquent, une gamme des rendements espérés, reflétant l'enlèvement minimal et l'enlèvement augmenté.

Les mesures en laboratoire ont produit des estimations de croissance élevée, qu'on a utilisées pour calculer le haut de la gamme des taux de croissance. On a utilisé les mesures de la croissance réelle dans les eaux usées sur le terrain afin de représenter le bas de la gamme des taux de croissance. On a utilisé ces taux sur le terrain dans les calculs d'augmentation proportionnelle.

Le rendement des modèles spécifiques aux sites permet d'utiliser une évaluation quantitative plutôt que qualitative des taux d'enlèvement des contaminants par les procédés biologiques, dans le cadre d'une technologie de décommissionnement du génie écologique.

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1. INTRODUCTION

Decommissioning of inactive mine sites presents an economic and environmental challenge. Ecological Engineering processes are being developed to assist the mining industry in finding solutions to the decommissioning challenge. Biological polishing, one of the Ecological Engineering processes, has been quantified with data collection in three different acid generating mine sites, an abandoned coal seepage in Cape Breton, at the Buchans Mine in Central Newfoundland and in effluents from acid-generating tailings at South Bay in northwestern Ontario.

Biological polishing can assist in the improvement of AMD seepages by the following processes:

- Provide nucleation/precipitation sites for metals on periphyton surfaces,
- Provide living covers over metal-laden sediments,
- Provide extracellular polysaccharides to complex metals.

The work was funded jointly by Industry and CANMET Biotechnology. The program started in 1990 with a literature review on periphyton growth conditions and geochemical considerations of the contaminant removal process. In 1991, the study proceeded with field data collection at the three sites (Kalin and Wheeler 1992a,b,c). In 1992, periphyton growth rates were determined in the laboratory, and field collections were carried out to confirm the growth rates obtained in 1991.

The literature review carried out in 1990 indicated that biological polishing could be developed, if the basis of the contaminant removal process were understood (Kalin et al. 1991). Therefore, in 1991, periphyton biomass, which had accumulated on various suspended substrates, was collected several times during the growing season. Growth or accumulation rates of biomass were determined through destructive sampling of substrates colonized by biomass. Experiments with slow-release fertilizer were carried out at three locations to increase growth rates or establish growth.

A large data set was amassed (about 1000 biomass/ periphyton/ precipitate samples) during the first stage of investigation in 1991, of which only a fraction were analyzed for elemental composition. More samples were subjected to chemical analysis in 1992 and, together with those collected during the 1992 field season, form the input parameters for an application model.

The first two years of results suggested that there were several factors controlling the growth of periphyton at different mining sites. Many of these factors were common to all sites. It was proposed to develop an application model for biological polishing to provide a framework for the evaluation of pond size, retention time and expected contaminant removal.

The characteristics of the waste waters in which the periphyton were studied is shown in Table 1. Table 2 gives the elemental composition of the periphyton populations growing in the waste waters.

Table 1: Description of Waste Water Sites and Periphyton

Mine Site	Habitat	Main Taxa	pH	[Zn] mg/L	[Al] mg/L	[Fe] mg/L
South Bay	Lake	Ulothrix sp.	3.2-3.5	7-11	2.1	4.5
Buchans	Pond	Microspora/Ulothrix sp.	6.5-7.5	4-18	4-8	2
Selminco	Seep	Ulothrix sp.	4	0.1-0.3	24-95	100-150

Table 2: Summary Table - PPC Composition

Site	Location	Taxa	(n)	L.O.I. %	Fe %	S %	Zn %	Mn %	Al %	Ca %	Cu %
South Bay	Boomerang Lake	Ulothrix	64	47.4	18.0	1.40	0.07	0.14	0.39	0.35	0.03
Buchans	Polishing Ponds	Microspora/Ulothrix	34	29.3	10.9	0.46	7.60	1.54	1.30	1.90	0.03
Selminco	A11 Seepages	Temnogametum	6	35.5	24.4	5.60	0.03	0.04	0.89	2.20	0.02

(n) is the number of periphyton analyses from each site in 1991/1992.

L.O.I. is Loss on Ignition, or 100 - the % ash after burning at 500 C.

In order to develop the general application parameters, confirmation of the 1991 contaminant removal rates measured during the summer were needed and minimum rates for the winter time were required. An understanding of the factors controlling the removal process and the conditions under which biological polishing can be applied were needed. In order to achieve this goal, four objectives were addressed.

1. Periphyton biomass was collected from peritraps after the winter period to obtain values for the winter season. Collections were also made at the end of the growing season in 1992 to confirm 1991 accumulation rates.

2. Sedimentation traps were installed at several locations to determine sedimentation rates without periphyton growth. Contaminants can precipitate in waste water if geochemical conditions allow, and can control the effectiveness of the biological polishing process.

3. Data collected during the summer of 1991 were analyzed and summarized with respect to physical and chemical factors which may be important to the overall process of contaminant removal, rather than site-specific factors already identified.

4. Periphyton investigated in the 1991 season were collected again in 1992, and brought into the laboratory for measurement of growth under less stressful conditions. The objective here was to determine optimum periphyton growth affected by light and by additions of fertilizers.

This report is divided into sections which detail aspects of site-specific application models. In Section 2, the laboratory growth rate experiments are discussed. The results from these experiments are used to provide the upper boundary on periphyton field growth rates. In Section 3, general aspects of application modelling and biological polishing are discussed. Sections 4, 5, and 6 discuss site-specific biological polishing models. Supporting data for the input parameters are described. Section 7 describes those parameters which are in common between all sites, and uses this information in a simple biological polishing application model.

2. LAB GROWTH STUDIES

2.1 Periphyton Descriptions

Periphyton from each of the study sites (Buchans, South Bay and Selminco) were selected from locations, where periphyton were relatively free of precipitate. The waste waters from which these "clean" populations were derived were similar to those in the field study sites, but generally contained less iron.

The taxonomic grouping of the periphyton at all three sites was similar, consisting of a mixture of *Ulothrix* sp. and *Microspora* sp., with a few *Oscillatoria* sp. and small diatoms at Buchans. A *Ulothrix* sp. dominated the periphyton community at South Bay. In the coal seepage, *Ulothrix* sp. dominated the population, but, *Temnogametum* sp. was also present in large numbers.

2.2 Periphyton Sample Preparation

Reference samples, preserved in Lugols fixative, were kept for species identification. The biomass was cleaned of debris, dried, powdered, and sent for elemental analysis to a certified laboratory. There, subsamples were oxidized with a mixture of nitric and perchloric acids, and analyzed by Inductively Coupled Plasma Spectroscopy (ICP).

Fresh weight was determined by blotting the cleaned biomass dry between paper towels. To determine fresh biomass to dry biomass weight samples were oven-dried at 60° C for 24 h. Another subsample was dried to a constant weight at 110° C, and ashed in a muffle furnace at 500° C for 30 minutes. The difference between the oven dried (60 °C) weight and ashed weights gave the Loss On Ignition (LOI). LOI reflects the percentage organic versus inorganic in the PPC .

Seepage or AMD water from the nearby study sites was also collected and used as a solution in which the growth experiments were carried out. The pH, Eh, conductivity and temperature were determined in the field, and tightly capped samples brought back to the lab. The samples were filtered through 0.45 μm cellulose acetate filters, acidified with nitric acid to a pH of 1, and analyzed by ICP.

2.3 Methods - High Density

In the laboratory, plant material was manually cleaned of debris and 2 g of fresh weight were placed in 500 mL of field-collected water. Some of the cultures were supplemented with phosphate (0.2 g waste phosphate rock) and/or 0.2 g nitrate (Osmocote, KNO_3), placed under fluorescent lights (270 $\mu E\ m^{-2}\ s^{-1}$) with (12:12) photoperiod, and bubbled with air.

Periphyton were maintained under these conditions for 5-10 days. This was considered the adaptation phase and the periphyton under these conditions were further separated from sediments, debris, and dead material which could not be washed off manually.

After the adaptation phase, the periphyton were filtered through paper coffee filters in a Büchner funnel. Material was collected from the filters, blotted dry, and weighed. New jars were set up (1 L jars with 500 mL of field-collected water), with the following conditions.

3	Full Light	270 $\mu E\ m^{-2}\ s^{-1}$
3	1 Nitex screen	126 $\mu E\ m^{-2}\ s^{-1}$
3	2 Nitex screens	60 $\mu E\ m^{-2}\ s^{-1}$
3	3 Nitex screens	27 $\mu E\ m^{-2}\ s^{-1}$

Irradiance was measured with a Biospherical Instruments QSL-100 quantum meter. All Irradiance jars contained 0.2 g KNO_3 slow-release fertilizer and 0.2 g waste natural phosphate rock.

2 Full Light with only KNO_3
2 Full Light with only phosphate rock
2 Full Light controls with no added nutrients.

Jars were continuously bubbled, ensuring that periphyton were well mixed. The pH and water temperature were recorded before and after the experiment. Experiments ran for 15 days, long enough to give significant growth. The experiment was terminated when plant material was filtered through coffee filters in a Büchner funnel, blotted dry, and weighed.

2.4 Methods - Low Density

Periphyton culture densities of 0.1 gfw (grams fresh weight) in 500 mL water were achieved when 1.0 gfw of newly-collected periphyton material was blended for 1 minute at high speed in a Waring blender in a solution of 100 mL of tap water. A 10 mL aliquot of homogenized periphyton slurry was pipetted into each treatment jar containing 500 mL of mine waste water. Three 10 mL aliquots were filtered through glass-fibre filters and dried. These were used to determine the beginning weight of each aliquot.

Growth jars were continuously aerated and lighting was provided by high intensity cool-white fluorescent lamps on a 12:12 light cycle. Experiments ran for approximately 7 days.

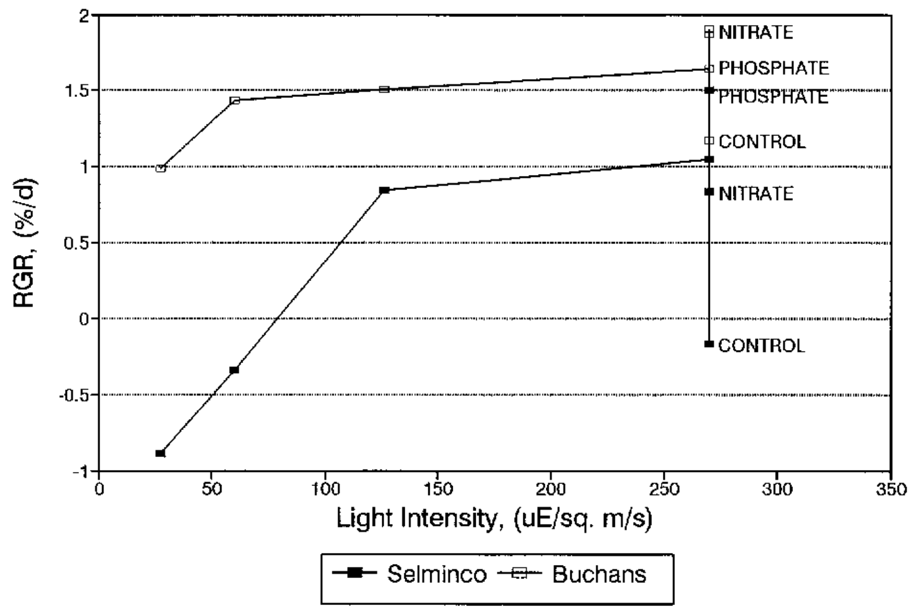
At the end of the experiment, periphytic material was washed from the culture jars through a glass-fibre filter and dried. The dried periphyton before and after the experiment were used to determine the relative growth rate (RGR; $\ln(W_2\ W_1^{-1}\ t^{-1})$).

In some cases, the filter papers were further analyzed by Inductively Coupled Plasma Spectroscopy after wet oxidation with a mixture of nitric and perchloric acids to determine elemental composition.

2.5 Results - High Density Experiments

High density growth rate experiments were performed on periphyton from Buchans and Selminco but not for South Bay (Boomerang Lake). In Figure 1, the RGRs are plotted against light intensity. The RGRs under high light, with added nutrients, produced similar results for the two sites. Both populations grew well in water from the original site, achieving rates between 1.5 and 1.9 % d^{-1} (doubling time = 42 to 36 days).

Fig. 1: Buchans and Selminco
RGR for High Density Cultures



Selminco periphyton (■) were much more light dependent than Buchans periphyton (□). Buchans periphyton produced positive growth at the lowest light intensity, while the Selminco population lost weight.

Both populations responded to nutrient additions, where growth under high light and nutrients was significantly higher than controls, with only high light. High light conditions in these experiments (270 $\mu E\ m^{-2}\ s^{-1}$) were approximately 1/6 full sunlight.

Thus, it can be expected that in the field, where periphyton are generally found in high density, growth rates would be similar or higher.

In these laboratory experiments, biomass density was high (1.5-2 gfw L^{-1}), with no water turnover. As periphyton are normally found in a slow-flowing streams, water turnover occurs continuously. It is reasonable to assume that in the high density experiments, the nutrient supply might have been limiting, thus slowing growth rates. However, these high densities were more representative of densities found in field populations, and may therefore have better represented the growth rates occurring in the waste waters.

2.6 Results - Low Density Experiments

Low density cultures were carried out with *Ulothrix* from South Bay (in Boomerang Lake water) and from Selminco (in S1 water). The growth rates achieved in Boomerang Lake water ranged from 2.7 to 5.1, depending on the strain of *Ulothrix* used, giving doubling times from 26 to 14 days (Table 3). Growth rates of *Ulothrix* from Selminco averaged 7 % d^{-1} (doubling time of 10 days), when grown in phosphate-treated Selminco S1 water. However, when grown in water from Boomerang Lake, the growth rate was only 2.6 % d^{-1} (doubling time 27 days). This suggests that the periphyton populations are adapted to growing in waste water. These results emphasize that indigenous periphyton populations should be used in the biological polishing process.

Table 3: Laboratory Derived Relative Growth Rates for Low Density Cultures

Description	Origin	Water	Water pH	W2 (gdw)	W1 (gdw)	RGR (%/d)
Ulothrix	Selminco	Selminco S1	4.3	0.0338	0.02085	6.9
Ulothrix	Selminco	Selminco S1	4.2	0.035	0.02085	7.4
Ulothrix	Selminco	Boomerang Lake	3.5	0.02503	0.02085	2.7
Ulothrix	S. Bay	Boomerang Lake	3.5	0.03654	0.02142	5.1

In summary, periphyton from a number of mining sites seem to be adapted to grow in mine waters with elevated metal content and low pH. Growth rates of periphyton in these effluents are surprisingly high and are affected by the initial periphyton density used in the cultures. Low density experiments provided conditions which produced the highest growth rates.

For the biological polishing process these results suggest that, in the beginning of the season, when biomass densities are lower in polishing ponds, higher growth rates will prevail. As the population increases over the summer season, growth rates will become more affected by the adsorption of contaminants and inorganic precipitate formation and sieving.

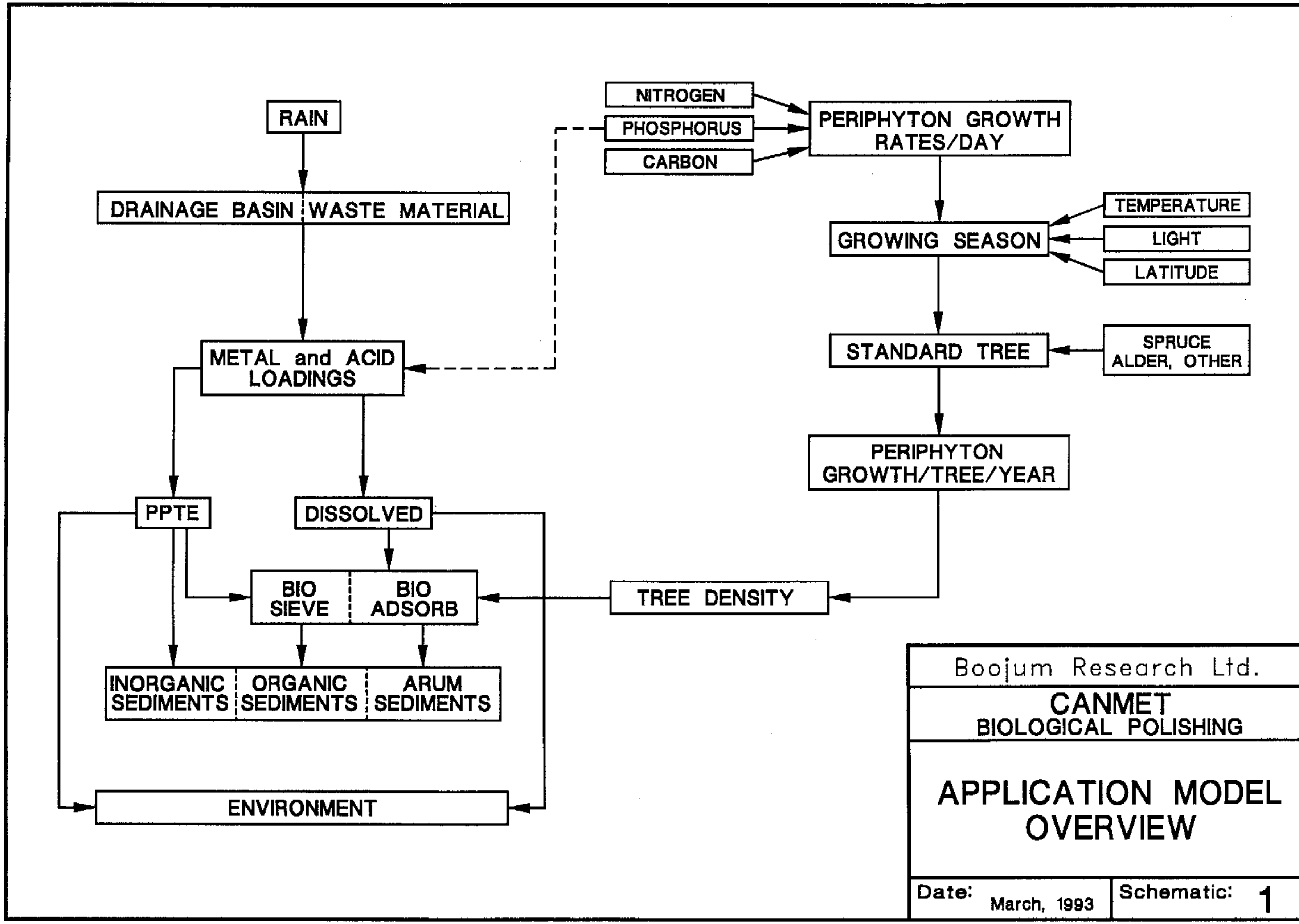
Average growth rates achieved with the different methods (high and low density, nutrients, and irradiance) are similar to those found in the field. Therefore, it is realistic to use high growth rates as input parameters for the model. The experiments also suggest, that biological polishing rates can be increased through fertilizer additions.

3. APPLICATION MODELLING

Ecological models are generally a quantitative description of relationships between biological processes and the environmental factors that affect them. A biological polishing model is not a model which describes the effect of environmental factors on periphyton growth. It takes the observed growth rates and contaminant accumulations in the biomass in the waste water and derives the dimensions of the ponds and substrate surface area for required for growth.

In Schematic 1, the major components for such a model are shown. On the left side are the factors which play a role in biological polishing process. The effluent (contaminant) characteristics are determined by the hydrological conditions (rain) which represent the transport medium of the contaminants generated in the waste material. The hydrological conditions, together with the rates at which the waste material generates contaminants, will result in the metal and acid loadings to the effluent stream. Periphyton populations grow in the resulting water. Their ability to remove contaminants is related to the quantity of precipitate which is formed chemically in the waste water, and must be "sieved", and the amount of contaminants which remain dissolved, and must be bio-adsorbed.

After death, periphyton biomass is relegated to the sediments in the polishing pond. In the waste stream, some precipitates are formed geochemically. These also settle to the sediments. The organic material provided by periphyton provides nutrition necessary to maintain reducing conditions in the sediments. In these reducing sediments, microbes transform adsorbed and precipitated metals into more stable precipitates. The microbial communities which do this transformation also generate alkalinity (ARUM; Acid Reduction Using Microbiology). The aim of the biological polishing process is to optimize the above described aspects within the polishing pond to minimize the amounts of precipitate and dissolved metals which leave the site to the environment.


RAIN
DRAINAGE BASIN
WASTE MATERIAL
METAL and ACID LOADINGS
PPTE
DISSOLVED
BIO SIEVE
BIO ADSORB
INORGANIC SEDIMENTS
ORGANIC SEDIMENTS
ARUM SEDIMENTS
ENVIRONMENT
NITROGEN
PHOSPHORUS
CARBON
PERIPHYTON GROWTH RATES/DAY
TEMPERATURE
LIGHT
LATITUDE
GROWING SEASON
SPRUCE ALDER, OTHER
STANDARD TREE
PERIPHYTON GROWTH/TREE/YEAR
TREE DENSITY
Boojum Research Ltd.
CANMET
BIOLOGICAL POLISHING
APPLICATION MODEL OVERVIEW
Date: March, 1993
Schematic: 1

Field and laboratory data were collected from several sites in which biological polishing is being scaled-up to remove contaminant loadings. These data have been used to provide the input parameters for an application model of biological polishing. The key non-biological parameters which can be manipulated in the field are: 1) the contaminant loadings, and 2) the retention time needed in the pond. Together, these parameters define the size of the pond needed, given the flow rates of the site. The key growth production parameters which can be manipulated in the field are nutrient (carbon, nitrogen and phosphorus) level and tree density (Schematic 1).

Site-specific investigations provided input parameters to the application model for scale-up of the biological polishing process. However, similar approaches were taken at each site. The first step was to define the contaminant loading to the water body in which biological polishing was to be utilized. This was done through an assessment of the base flow in the drainage basin areas, the contaminant concentrations in the waste stream and the hydrological precipitation rates (rain).

The second step was to calculate or measure the distribution of precipitated metals and dissolved metals. Periphyton are good "sieves" and can remove particulates. The concentrations of dissolved and precipitated contaminants determined how much biomass was needed for sieving and adsorption. This was followed by an assessment of the available substrate surface area, and pond volume. The growth rates or the biological polishing capacity was then derived from the number of trees in the ponds. Projections for complete contaminant removal increased the tree density in the polishing pond so that periphyton growth (and contaminant removal) matched contaminant loadings.

4. APPLICATION MODEL - BUCHANS

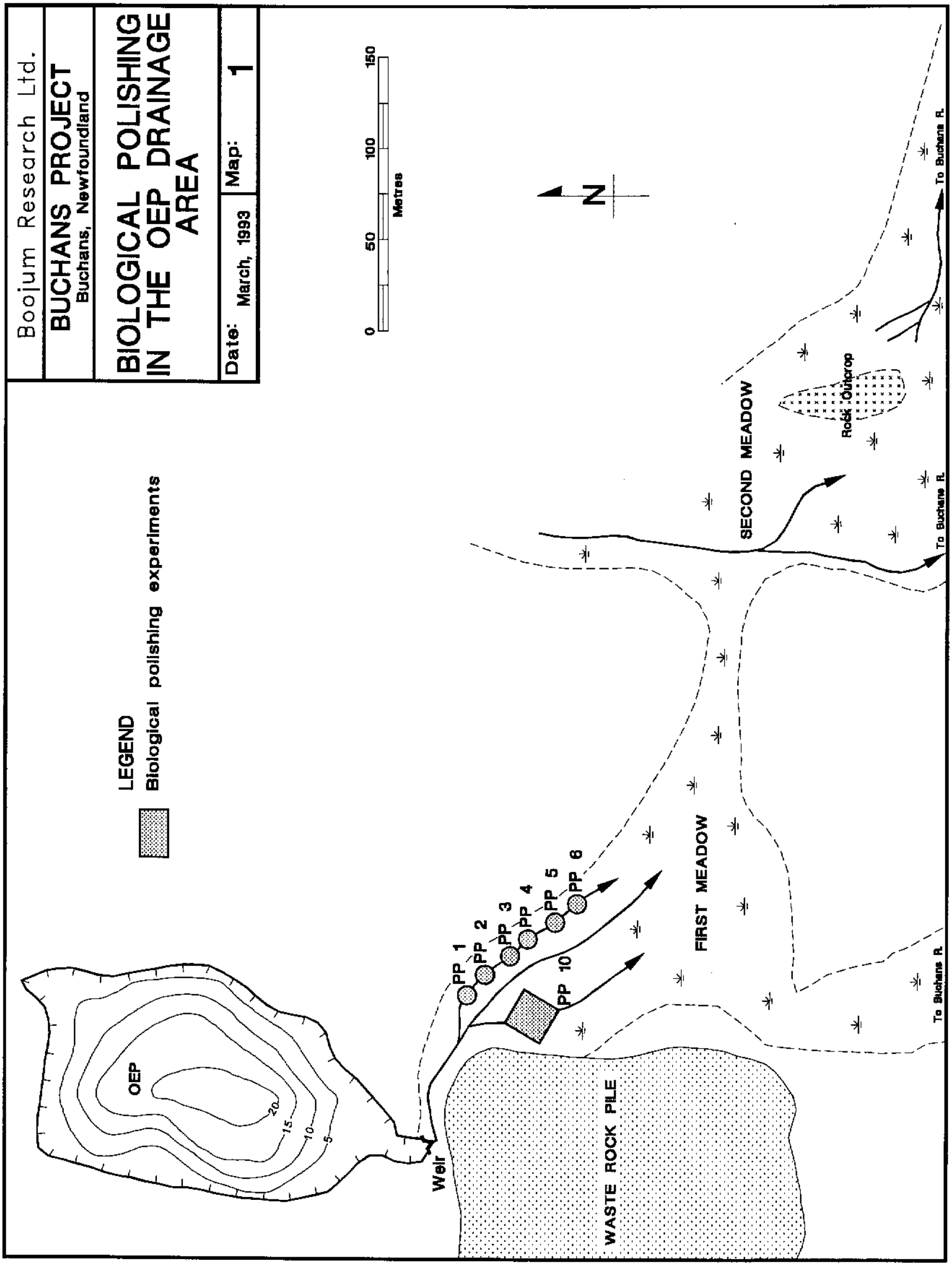
The site-specific model to scale-up the biological polishing process at Buchans is derived from a set of experimental pools, into which alder brush was placed. A brief description of the site and the origins of the effluent to be treated with biological polishing are given below.

4.1 Site Description

The Buchans mine site is located in central Newfoundland. Buchans was a base metal mine, with a number open pits (gloryholes) associated with the underground workings. After completion of the mine, several of the gloryholes, including the Oriental East were flooded. The effluent is a combination of contaminated water from the underground workings and clean highly alkaline ground water. In the pit, below the chemocline (oxic/anoxic zone), the water contains 60 mg Fe L^{-1}, which produces extensive ferric hydroxide precipitate in the outflow, when ferrous iron is oxidized and hydrolysed in the surface waters.

The effluent from the Oriental East Pit (OEP) is circum-neutral, with 20 mg Zn L^{-1}. In June of 1989, six ponds were excavated in the First Meadow below the OEP outflow, to act as experimental biological polishing ponds (MAP 1). Water was diverted from the main OEP outflow stream through the 6 ponds, in series. Between August and September 1989, 110 alder cuttings were placed in each of the pools (130 in pond 6) to act as surface area on which periphyton could grow. The ponds were, on average, about 0.6 m deep, with a diameter of 9.2 m. Pond volumes ranged from 24 m^{-3} (pond 5) to 54 m^{-3} (pond 2). The average volume was 40 m^{-3}.

Throughout 1991, flows through the polishing ponds varied from 0.035 L s^{-1} in July to 0.174 L s^{-1} in August. The average flow was 0.122 L s^{-1}. Calculated turnover



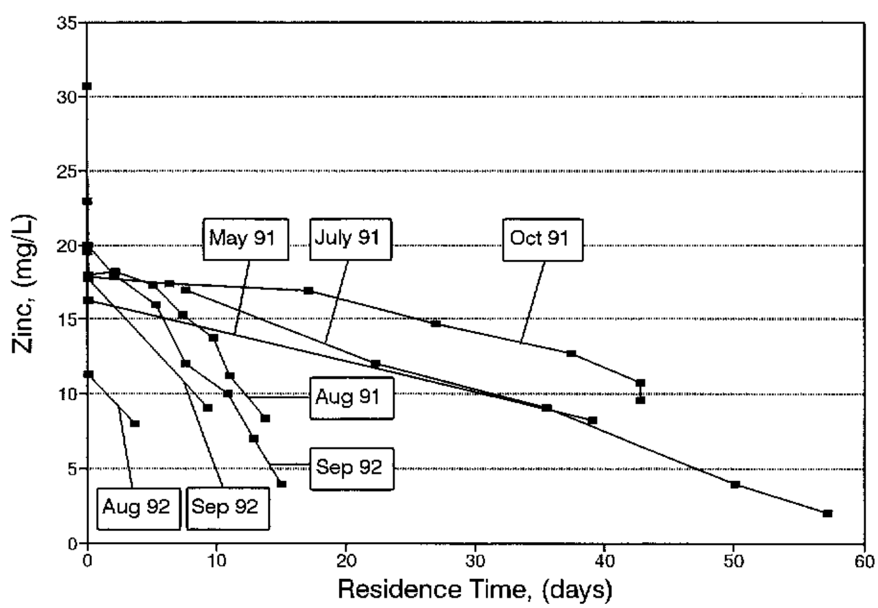
Boojum Research Ltd.
BUCHANS PROJECT
Buchans, Newfoundland
BIOLOGICAL POLISHING IN THE OEP DRAINAGE AREA
Date: March, 1993
Map: 1
0
50
100
150
Metres
N
LEGEND
Biological polishing experiments
OEP
20
15
10
5
Weir
WASTE ROCK PILE
PP 1
PP 2
PP 3
PP 4
PP 5
PP 6
PP 10
FIRST MEADOW
SECOND MEADOW
Rock Outcrop
To Buchans R.
To Buchans R.
To Buchans R.

times varied from 80 days (July) to 16 days (August). The average turnover time for the summer was 23 days.

Water passing through the ponds has been sampled and analyzed a number of times each year since the alders were added (Figure 2). On each sampling date, the zinc concentration in each pond, or in ponds 1 and 6, were measured along with flow rates. The flow rates when divided into the total pond volume (240 m^3) gave the residence of time of water in the ponds. These data indicate that zinc is being removed from the waste stream as it passes through the ponds.

The removal started several months after the cuttings were added to the ponds. Towards the end of 1989, significant biological polishing started as evidenced by a 40 % removal of zinc between pond 1 and 6 (November 1989). In 1990, the best removal was 86 % of the zinc (September), and in July 1991, over 90 % of the zinc was removed from water flowing through the 6 ponds. The increase in zinc removal was paralleled by the growth of periphyton populations (Kalin and Wheeler 1992a).

Fig. 2: Buchans Polishing Ponds
Zinc Reductions vs. Residence Time



4.2 The Application Model

The following model description provides the necessary scale-up parameters. The model was written in the form of spreadsheet (Quattro Pro 4), in which each line is calculated based on preceding information. By changing the initial conditions, the output of the spreadsheet is changed. The final lines of the spreadsheet calculate the performance of the system and the parameters which require improvement.

A model has been developed in order to determine the size of polishing pond necessary to accommodate the entire zinc loading leaving the OEP. The model utilizes the characteristics of the existing polishing ponds and the growth rates of the periphyton to predict the amount of zinc which could be removed from the waste stream, if biological polishing were scaled-up (Table 4a,b). This model uses both monitoring and derived growth data from both field and lab studies.

Line 1 of the model describes the dry to fresh weight ratio used in converting between dry biomass and wet biomass. This number was derived from OEP PPC collections in 1992. Periphyton cleaned of precipitates generally had dry to fresh weight ratios around 0.2 to 0.3. If periphyton had substantial fractions of precipitates, the ratio rose, to 0.61 gdw gfw^{-1} (or 0.61 kgdw $kgfw^{-1}$). Periphyton with high precipitate fractions were common, due to the high iron precipitates in the OEP outflow water.

Line 2 of the model describes PPC density in the polishing ponds. This was estimated by extrapolating the PPC mass measured on alder twigs to the amount of alder in the ponds. Alders placed in the pools, averaged 0.96 kgdw in mass, with 350 gdw of branches, fruits and leaves. PPC were measurements made on branches, fruits, and leaves. Therefore, the average tree mass used to quantify PPC growth was 350 gdw. PPC densities ranged from 0.37 to 4.1 gdw $gdwB^{-1}$ (gdwB = grams dry weight of branches; Table 5; page 19). The average PPC mass during the last 2 years was 2.4 gdw gdwB-1.

Table 4a: Buchans Polishing Pond Extrapolations
(Residence Time - 14 days, OEP [Zn] - 20 mg/L)

1	Dry to fresh weight	0.61	kgdw/kgfw
2	Density of PPC in lab and field	3.8	kgfw/m3
3	Growth rate	8	gdw/m2/d
4	Average PPC Zn (1992)	62	g/kg
5	Volume of Pond 10	320	m^3
6	Minimum required residence time	14	d
7a	OEP flow	12.875	L/s
7b	OEP Zn concentration	20	g/m3
7c	OEP Zn loading (1992)	8121	kg/a
7d	OEP Zn loading (1992)	22.2	Kg/d
8	Periphyton Zn removal capacity	1149.7	g Zn/m3 of pond/d
9	Periphyton Zn removal from system	279383.9	g Zn/system/d
10	Periphyton Zn removal from system	50289.1	kg Zn/system/a
11	Average Zn loading Pool 1-6 (1992)	166.7	kg/a
12	Average Zn leaving Pool 1-6 (1992)	88.8	kg/a
13	Average Zn remaining in Pools 1-6 (1992)	77.9	kg/a
14	Zinc removal rate	320.4	g Zn/m3/a
15	Zinc removal rate	114.5	g Zn/tree/a
16	Trees required to remove Zn load		
17	Projected pond volume	25,342	m^3
18	Projected pond area	42,236	m^2
19	Maximum flow into pond	0.3	L/s
20	Maximum Zn loading to Pond 10	0.4	kg Zn/d
21	Maximum Zn loading to Pond 10	150	kg Zn/a
22	Percentage of total flow treated	1.8	% of total flow
23	Pond 10 Zn removal	102.5	kg Zn removed/a
24	Percentage of Pond 10 Zn load	68.36	% of loading

Table 4b: Buchans Polishing Pond 10 Fertilizer Requirements
(Residence Time - 14 days, OEP [Zn] - 20 mg/L)

FERTILIZER REQUIREMENTS: PLANT-BASED			
25	Biomass production to remove load	6.7	kgdw/d
26	Healthy plants require approx. 0.5% P	0.005	g P/gdw
27	Phosphorus requirement for biomass	33.28	g P/d
28	P content of nutricote (19:6:12)	0.06	P
29	Fertilizer requirement	99.84	kg fertilizer over 180 d growing season
FERTILIZER REQUIREMENTS: WATER-BASED			
30	Flow through Pond 10	15.9	L/min
31	Need about 4 mg/L for eutrophic pond	30.5	g P/d
32	Using a 6% P fertilizer	507.9	g fertilizer/d
33	Fertilizer requirement	91.4	kg fertilizer over 180 d growing season

Table 5: Buchans PPC Mass on Branches in Polishing Ponds

	1991 (gdw/gdwB)				1992 (gdw/gdwB)		
Pond	May	July	Aug	Oct	Jun	Aug	Sep
1	1.14	3.06	6.50	3.66	0.88	1.77	3.64
2	1.15	1.49	3.42	1.53	0.98	1.72	3.50
3	1.00	4.82	4.35	2.00	3.04	1.21	1.79
4	1.82	3.86	3.10	3.28	0.91	1.03	4.06
5	0.66	2.94	5.12	4.10	1.30	1.24	2.39
6	0.66	3.24	2.40	1.36	0.38	1.01	2.60
Avg	1.07	3.24	4.15	2.66	1.25	1.33	3.00

When the average density is multiplied by the mass of branches per tree (350 gdw), the number of trees per pond (110), and divided by the volume of pond (40 m^3), a value of 2.3 kgdw m^{-3} is produced. If this number is further divided by the dry/fresh weight ratio (0.61), a value of 3.8 kgfw m^{-3} is produced.

The periphyton growth rate used in the model is shown on Line 3. Growth rates of PPCs were difficult to measure. There are several ways to estimate growth, all of which produced widely spaced estimates. Growth was calculated both in the laboratory (see Section 2) and in the field (see Kalin and Wheeler 1992a). With peritraps, a linear estimation of growth was obtained, as opposed to the relative growth rates (RGR) obtained in the laboratory or from periphyton colonization of alder twigs in the polishing ponds.

Typically, growth was measured as a function of substrate surface area (sub; substrate) or weight of substrate (gdwB). If biomass was measured both before and after a given time interval, then growth was calculated using RGR (as in laboratory studies), which calculated growth logarithmically (e.g. $RGR = 100*\ln(W_2 W_1^{-1})t^{-1}$).

Periphyton growth rates measured in the lab produced estimates which were high. Peritraps, which were cleaned every few months, produced a conservative growth estimate. Mass accumulations by PPCs over the summer period, produced a third estimate, which resulted in an intermediate growth rate.

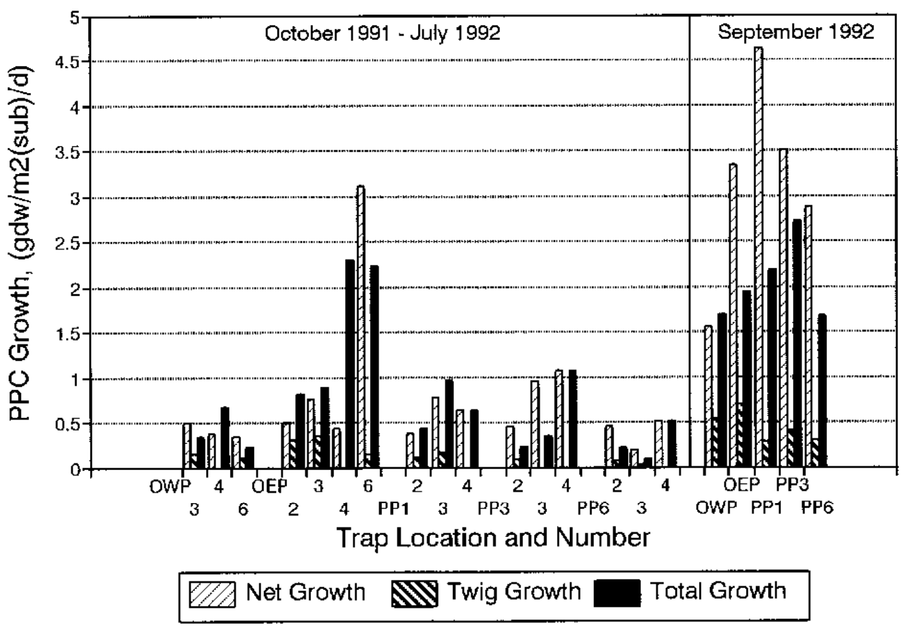
On the high end of the growth measurement range were the lab results (1.9 % d^{-1}; Figure 1). At this rate, periphytic biomass would double in about 36 days. Such biomass growth estimates, however, might be an overestimate of field growth rates. When multiplied by the average density of PPCs in the ponds (2.3 kgdw m^{-3}), this growth rate extrapolated to a biomass production of 44 gdw m^{-3} d^{-1}. By multiplying the RGR (0.019 d^{-1}) by the PPC mass per branch (2.4 gdw $gdwB^{-1}$) and dividing by the surface area to mass ratio for branches (0.00272 m^2 $gdwB^{-1}$), this RGR can be converted to a growth rate on a substrate surface area basis (16.8 gdw m^{-2} (sub) d^{-1}).

Growth rates were also calculated using peritrap PPC accumulations. Peritraps are artificial substrates, consisting of a buoyant wooden frame covered in plastic netting. The netting enclosed several alder branch "substrates". A plastic bag was hooked below the frame to catch any biomass which "sloughed" off the net and substrates.

Peritraps were placed in the OEP and the polishing ponds in June of 1991. Traps were removed at different times throughout 1991 and 1992, and the accumulated PPCs, removed, dried and weighed. The average biomass accumulation rate by peritraps in pools 1-6 over the winter and spring of 1991-1992 was 0.5 gdw m^{-2}(sub) d^{-1} (Figure 3). Between July and September of 1992, the rate increased to 2.2 gdw m^{-2}(sub) d^{-1}. These data represent the average total growth on peritraps, based on net, substrate, and bag biomass changes. Also shown in Figure 3 are the individual components of the growth, i.e. growth on nets and branches.

Growth rates were also calculated from the increase in the PPC biomass found on branches in the polishing pools. Average PPC mass increased from 1.24 in May, to 1.33 in August 1991, to 3.00 gdw $gdwB^{-1}$ in late September 1991 (Table 5). If the RGR formula is applied to these data, the growth rates varied from 0.08 % d^{-1} for the period May through August, and 1.9 % d^{-1} for the period from August to the end of September. The translated rates were 0.7 gdw m^{-2} (sub) d^{-1} to 16.6 gdw m^{-2} (sub) d^{-1}). It is interesting to note that field growth rates during the latter part of the

Fig. 3: Buchans Peritraps
PPC Growth



summer were the same as measured in the laboratory in 1992, suggesting that ideal conditions can be found in the field during at least part of the year.

To summarize, lab studies produced growth rates of about 1.9 % d^{-1}, as did summer 1991 field data (16.8 gdw m^{-2} (sub) d^{-1}). PPCs on peritraps grew at winter/spring rates of 0.5 gdw m^{-2} d^{-1} and summer rates of 2.2 gdw m^{-2} d^{-1}. PPC accumulation rates on alder branches varied between, an early summer low of 0.7 gdw m^{-2} d^{-1} and a late summer high of 16.6 gdw m^{-2} d^{-1}. Thus, winter/early summer values of 0.5 gdw m^{-2} d^{-1} were considered conservative, while good summer rates were probably at least 50 % of the max, i.e. 8 gdw m^{-2} d^{-1}. A summary of the growth rates obtained is given in Table 6.

Table 6: Buchans Growth Rate Estimates

Description	RGR (%/d)	Linear (gdw/m2(sub)/d)
Lab High Density	1.9	16.8
Peritraps: Winter/Spring	-	0.5
Summer	-	2.2
PPC/Alder: Early Spring	0.08	0.7
Late Summer	1.9	16.6
Average		8

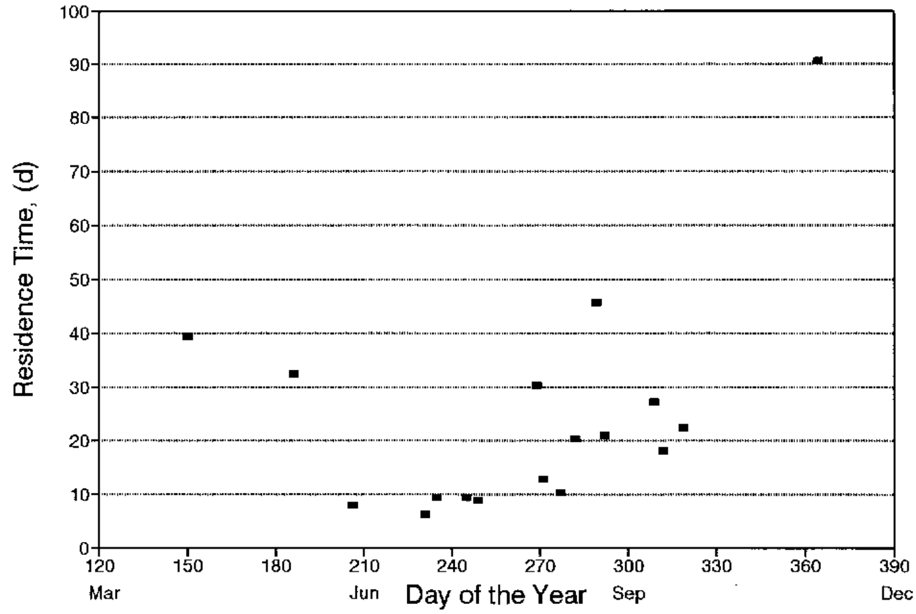
4.3 Metal Removal

Line 4 of the model describes the zinc content of the PPCs measured over the summer of 1992. The average zinc concentration in PPCs in May was 4.9 % of dry weight (Table 2). In August, the percentage climbed to 7.9. In 1991, the % of zinc in PPCs rose from 5.9% in May to 10.9% in August. The concentrations used in the model are the average of 12 samples from 1992, giving 6.2 % zinc, or 62000 μg gdw^{-1}, or 62 g Zn kgdw^{-1}. This is slightly lower than the average for the last 2 years shown in Table 2.

Line 5 of the model sets the volume of the expanded polishing pond. Since physical conditions of the areas below the outflow dictate the size of the next scale-up pond, the volume of the pond was fixed at 320 cubic meters, which is the size of the new polishing pond 10.

In line 6 of the model, the minimum residence time for water in the pool is entered. The minimum residence time was based on an assessment of measured residence times, and was defined as the time required to remove 1/2 of the zinc from the system (Figure 4).

Fig. 4: Buchans Polishing Ponds
Residence Times



This minimum residence time varied depending on the time of year. It was shortest in mid summer (August; 8 days) and longest in winter (90 days; Figure 4). For most of the summer, therefore, the residence time was quite low. For purposes of this model, a minimum residence time of 14 days was chosen.

Lines 7a-7d are the inputs for the zinc loading to the polishing ponds. This number can either be the current yearly average, 19.8 g Zn m^{-3} or a lower number, if other removal mechanisms are employed upstream of the polishing pond.

Lines, 8, 9 and 10 compute the biomass production, and zinc sequestration by the biomass production, on both a daily and yearly basis.

To make these calculations, all 6 ponds were added together. Thus, the volume of the "system" was 243 cubic meters, and the total number of alders placed in the ponds was 680. During the winter, the ponds are frozen over and therefore little flow enters the pools and the residence time is high. To estimate annual growth a growing season of 180 days (6 mo.) was used, over which time, the growth rate in Line 3 of 8 gdw m^{-2} d^{-1} was in effect.

Lines 11-15 approach the zinc removal capacity from the measured zinc reductions in the water as it passes through all six pools. In 1992, intensive water sampling was carried out, and thus a good data set exists. The calculations were broken up into estimating the average zinc loading to the pools and the average zinc "loading" leaving the pools.

The difference between Lines 11 and 12 gives the mass of zinc which actually remained in the pools, both from biological sequestration and chemical precipitation. The mass of zinc removed in all six ponds, over the year gave an annual biological and chemical removal rate.

The zinc removal rate extrapolated from the actual zinc concentrations and flows should be reasonably close to the zinc removal rates extrapolated from the zinc found in the PPCs and their growth rate. In 1991, in August, PPCs accounted for 40 % of the zinc removal. These calculations indicated that the current year's removal would be higher.

4.4 Biological Polishing Scale-Up

Using these zinc removal estimates, it is possible to extrapolate from the pools to encompass the entire outflow loading of the OEP. To remove all of the zinc from the OEP outflow would require a much bigger pond, with more substrate surface area. The number of trees needed (Line 16), the projected pond volume (Line 17) and the projected pond area (Line 18) are calculated using straight line extrapolations. The pond area was based on an assumed water depth of 0.6 m.

4.4.1 Pond 10 Extrapolations

The first step in expanding biological polishing in the First Meadow was to build an expanded retention pond. Pond 10 was constructed to have a volume of 320 m^3. If a residence time limitation of 14 days is imposed, then the volume entering Pond 10 must be equal to or less than 0.3 L s^{-1} (Line 19). At this flow, the zinc loading can be calculated, and is shown in Lines 20-21. The percentage of the total OEP outflow being treated in given in Line 22.

Multiplying the zinc removal rate per cubic meter of pond by the volume of Pond 10 gives the number of kilograms of zinc removed by the bigger pond. This can also be expressed as the percentage of the zinc loading removed (Line 24). It is worth noting that Pond 10 has a volume that is only 1.3 x larger than the existing pools.

4.5 Fertilizer Requirements

Laboratory investigations with periphyton suggest that better growth rates require both nitrogen and phosphorus (Figure 1). Calculating the addition of fertilizers to the waste water is difficult, because the phosphate in the fertilizer reacts with metals in the water, forming metal phosphates. Furthermore, in a flow-through system, slow release formulations had to be found and tested, as single applications of quickly dissolving fertilizer would be diluted and lost from the system.

Based on the literature, a healthy plant requires about 0.5 % of its dry weight as phosphorus. One way to calculate the fertilizer requirement, then, is to calculate how much phosphorus is required to bring all PPCs up to the 0.5 % level (based on dry weight; Line 26; Table 4b). For Pond 10, the total biomass required is calculated by multiplying the growth rate in Line 3 by the ratio of branch area to pond volume (2.6

m^2 m^{-3}), resulting in a biomass production rate (20.8 gdw m^{-3} d^{-1}). When this number is further multiplied by the volume of Pond 10 (320 m^3), the daily biomass production estimate for Pond 10 is calculated (6.7 kgdw d^{-1}; Line 25). If the periphyton biomass has to have a phosphorus concentration of 0.5 %, then the total amount of phosphorus required is 33.3 g phosphorus d^{-1} (Line 27), and the weight of the fertilizer is 555 g fert. d^{-1}, or 99.9 kg of fertilizer per growing season.

A second way to calculate the fertilizer requirement is to provide hyper-eutrophic nutrient conditions in the pools, by adding enough phosphorus to the water to bring phosphate concentration up to about 4 mg L^{-1}. If the 4 mg phosphate L^{-1} level can be maintained, periphyton will be able to take up enough phosphorus for optimum growth. Any excess phosphorus will also be available for precipitation with zinc and iron. Line 30 shows the flow through Pond 10. This is the same number as shown in Line 19. By multiplying the 4 mg phosphate L^{-1} times the flow and the number of minutes in a day, the amount of phosphate per day can be estimated (91.6 g phosphate d-1). When divided by 3, to convert phosphate to phosphorus, the amount of phosphorus per day is calculated (30.5 g P d^{-1}). If a 19:6:12 fertilizer is used, then the amount of fertilizer is: 508 g fertilizer d^{-1}. When this is multiplied over the 180 day growing season, the amount of fertilizer becomes: 91.5 kg fertilizer per year (growing season).

The two calculation approaches should result in a similar requirements, since both are based on ecological factors, either healthy plant content or nutrient-rich water.

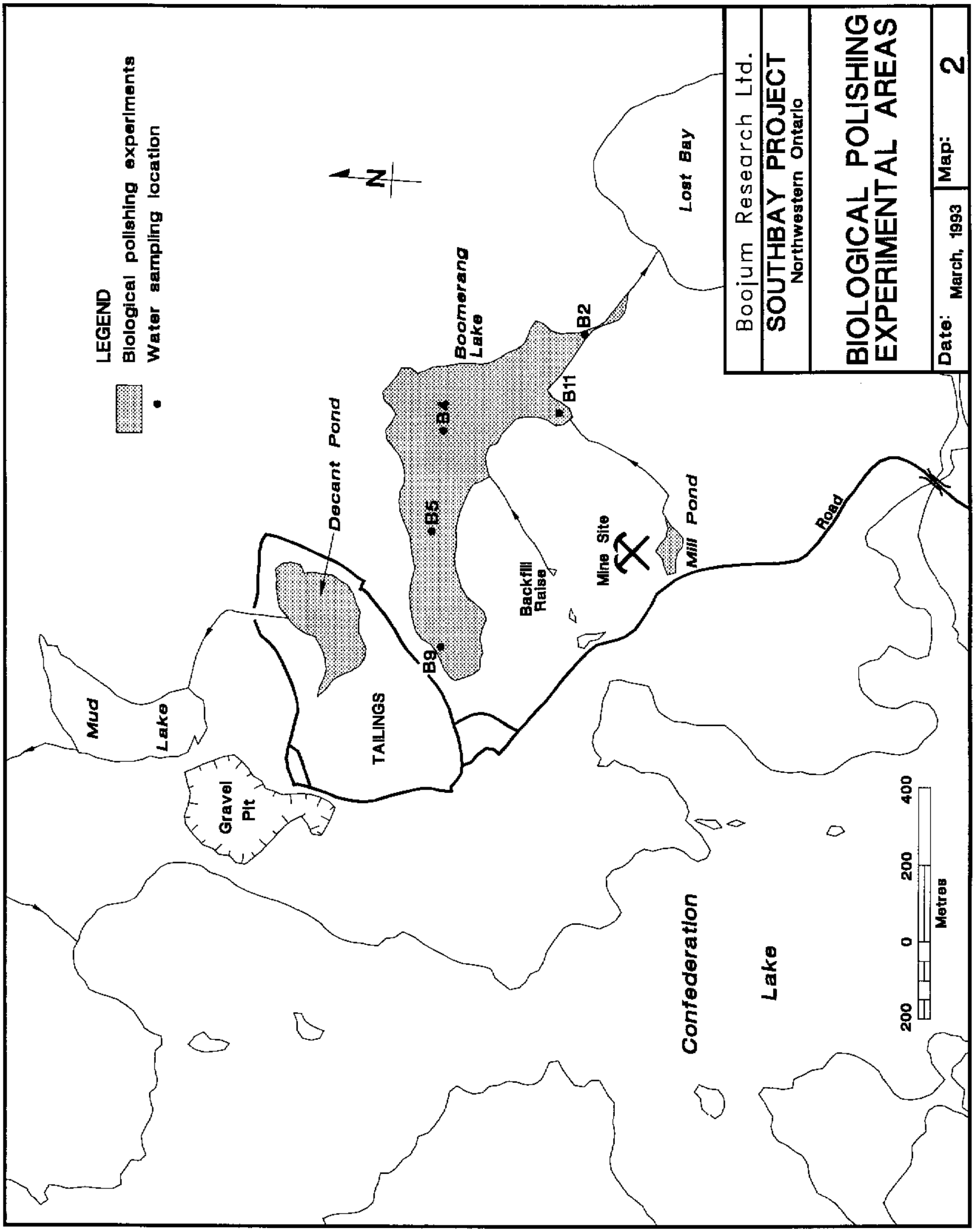
5.0 APPLICATION MODEL - SOUTH BAY

5.1 Site Description

The South Bay mine site is located in northwestern Ontario (49° N, 94° W). A copper/zinc concentrator operated at the site from 1971 to 1981. After the mine closed down, ground water plumes and seepage paths were intercepted, both from the mine site and from the tailings, and directed to Boomerang Lake. Boomerang Lake was relegated to the role of main polishing pond or treatment area (Map 2).

By 1986, the pH in Boomerang Lake had dropped gradually for 10 years from a pH of about 7 to a pH of 4. Attached periphyton, which contained high iron and high zinc concentrations, were found growing on tree branches suspended in the lake. It was proposed that, by increasing the growing surface area for periphyton, biological polishing could remove enough zinc to maintain the zinc concentration at constant level, and, as the population increased with time, even reduce the zinc concentrations in the lake.

For Boomerang Lake, the contaminants come from 3 primary sources; Mill Pond, the tailings, and Backfill Raise. There may be further contributions from some tailings spill areas, but contaminant loadings from these could not be quantified. Boomerang Lake is 1.2 km long and 400 m wide, along its widest transect. The lake is shallow, the maximum depth is about 5.2 m near station B4. The lake has a mean depth of about 4 m (Map 2).


LEGEND
Biological polishing experiments
Water sampling location
N
Boojum Research Ltd.
SOUTHBAY PROJECT
Northwestern Ontario
BIOLOGICAL POLISHING
EXPERIMENTAL AREAS
Date: March, 1993
Map: 2
Lost Bay
Boomerang Lake
Decant Pond
B2
B11
B4
B5
B9
Backfill Raise
Mine Site
Mill Pond
Road
TAILINGS
Mud Lake
Gravel Pit
Confederation Lake
200 0 200 400
Metres

5.2 The Application Model

The model is written in the form of a spreadsheet (Quattro Pro 4), in which each line is calculated based on preceding information. By changing the initial conditions, the output of the spreadsheet is changed (2nd copy of model at back cover).

In Table 7a, the starting conditions (dimensions) of Boomerang Lake are given. These form the basis for the model calculations. The lake has a volume of just over 1 million m^3 and a surface area of 24 ha (Lines 1,3). Because the lake is shallow, the water is well mixed through-out the ice-free season. The annual base flow from the drainage basin to Boomerang Lake is estimated at approximately 344,000 m^3 a^{-1} which results in a retention time of approximately 3 years (Line 2).

Contaminant loadings were derived from hydrogeological studies and water sampling in piezometers. Within Boomerang Lake, at suspected points of contaminant entry, log booms were constructed to restrain the spruce brush cuttings which were used as substrate for biological polishing in the lake. The areas for these are given in Lines 4 to 7. Only 3.5 % of the lake area is currently being used for biological polishing.

5.3 Contaminant Loadings to Boomerang Lake

At South Bay, the application of biological polishing is quite different than at Buchans. At Buchans, contaminants came from the OEP effluent, a point source. The effluent is treated in a series of ponds. In South Bay, biological polishing is used to reduce contaminant loadings to Boomerang Lake, and to remove the annual contaminant loadings coming from the tailings and several other sites. Thus, the contaminant loadings are diffuse. Therefore, to model the biological polishing capacity of Boomerang Lake, the loadings must first be quantified. Since the sources are diffuse, this is a complex task. A brief description of South Bay sites is given below.

Table 7a: Boomerang Lake Starting Conditions

	BOOMERANG LAKE STARTING POSITIONS		
1	Lake volume	1,043,419	m3
2	Base flow	342,854	m3/a
3	Lake area	238,861	m2
4	B11 boomed area	2,837	m2
5	B7 boomed area	486	m2
6	B8 boomed area	1,000	m2
7	B2 boomed area	4,050	m2
8	Total boomed area	8,373	m2
9	% boomed to lake	3.5	
10	Zinc concentration	7.49	mg/L
11	Aluminium concentration	1.46	mg/L
12	Iron concentration	1.56	mg/L
13	Copper concentration	0.13	mg/L
14	Sulphur concentration	73.9	mg/L
15	Sodium concentration	1.92	mg/L
16	pH	3.5	

Table 7b: Boomerang Lake Contaminant Loadings - Mill Pond

	MILL POND		
17	Zinc concentration	50	mg/L
18	Aluminium concentration	6	mg/L
19	Iron concentration	1	mg/L
20	Copper concentration	1	mg/L
21	Sulphur concentration	109	mg/L
22	Sodium concentration	4	mg/L
23	pH	4.26	
24	Base flow	65,526	m3/a
25	Zinc loading	3,276	kg/a
26	Aluminum loading	393	kg/a
27	Iron loading	66	kg/a
28	Copper loading	66	kg/a
29	Sulphur loading	7,142	kg/a
30	Sodium loading	262	kg/a
31	H+ loading	5,948	mol/a

Table 7c: Boomerang Lake Contaminant Loadings - Tailings

	TAILINGS		
32	Zinc concentration	227	mg/L
33	Aluminium concentration	53	mg/L
34	Iron concentration	2,064	mg/L
35	Copper concentration	7.2	mg/L
36	Sulphur concentration	2,072	mg/L
37	Sodium concentration	8.6	mg/L
38	pH	3.0	
39	Base flow	1,200	m3/a
40	Zinc loading	272.4	kg/a
41	Aluminum loading	63.6	kg/a
42	Iron loading	2,476.8	kg/a
43	Copper loading	8.64	kg/a
44	Sulphur loading	2,487	kg/a
45	Sodium loading	10.32	kg/a
46	H+ loading	90,015	mol/a

Table 7d: Boomerang Lake Contaminant Loadings - Backfill Raise

	BACKFILL RAISE		
47	Zinc concentration	6.9	mg/L
48	Aluminium concentration	3.2	mg/L
49	Iron concentration	2.9	mg/L
50	Copper concentration	1	mg/L
51	Sulphur concentration	49.3	mg/L
52	Sodium concentration	2.34	mg/L
53	pH	3.87	
54	Base flow	34,788	m3/a
55	Zinc loading	240	kg/a
56	Aluminum loading	111	kg/a
57	Iron loading	101	kg/a
58	Copper loading	35	kg/a
59	Sulphur loading	1,715	kg/a
60	Sodium loading	81	kg/a
61	H+ loading	8,306	mol/a

Table 7e: Boomerang Lake Contaminant Loadings - Clean Water

	CLEAN WATER LOADINGS		
62	Zinc concentration	0.29	mg/L
63	Aluminum concentration	0.03	mg/L
64	Iron concentration	0.03	mg/L
65	Copper concentration	0	mg/L
66	Sulphur concentration	2.22	mg/L
67	Sodium concentration	0.84	mg/L
68	pH	6.33	
69	Base flow	242,089	m3/a
70	Zinc loading	70.2	kg/a
71	Aluminum loading	7.3	kg/a
72	Iron loading	7.3	kg/a
73	Copper loading	0.0	kg/a
74	Sulphur loading	537.4	kg/a
75	Sodium loading	203.4	kg/a
76	H+ loading	373	mol/a

Table 7f: Boomerang Lake Contaminant Loadings - Summary

	TOTAL LOADING INPUT		
77	Zinc loading	3,859	kg/a
78	Aluminum loading	575	kg/a
79	Iron Loading	2,650	kg/a
80	Copper loading	109	kg/a
81	Sulphur loading	11,882	kg/a
82	Sodium loading	557	kg/a
83	H+ loading	104,642	mol/a
	TOTAL LOADING OUTPUT		
84	Zinc loading	2,568	kg/a
85	Aluminum loading	501	kg/a
86	Iron Loading	535	kg/a
87	Copper loading	45	kg/a
88	Sulphur loading	17,652	kg/a
89	Sodium loading	658	kg/a
90	H+ loading	108,420	mol/a
	TOTAL LOADING REMAINING		
91	Zinc loading	1,291	kg/a
92	Aluminum loading	75	kg/a
93	Iron Loading	2,116	kg/a
94	Copper loading	64	kg/a
95	Sulphur loading	-5770	kg/a
96	Sodium loading	-101	kg/a
97	H+ loading	-3778	mol/a

Table 7g: Boomerang Lake Biological Polishing

	BIOLOGICAL POLISHING		
98	Current algal % of PPC	20	%
99	PPC dry to fresh weight	0.61	gdw/gfw
100	Area per unit branch	0.0089	m2/gdwB
101	Mass per spruce branch	200	g
102	Spruce branches per tree	200	
103	Usable mass/spruce tree	40,000	g
104	Growth area per tree	356	m2
105	# trees in lake	4,000	
	GROWTH RATES - PPC		
107	Peritraps - summers only	1.43	gdw/m2(sub)/d
108	Peritraps - data slope	0.35	gdw/m2(sub)/d
109	Lab GR w/field density	0.03	gdwPPC/gdwB/d
110	Peritraps - summers only	0.0127	gdwPPC/gdwB/d
111	Peritraps - data slope	0.0031	gdwPPC/gdwB/d
112	Peritraps - best guess	0.0127	gdwPPC/gdwB/d

Table 7h: Boomerang Lake Biological Polishing

	PRODUCTIVITY		
113	Current production	1.9	gdwPPC/gdwB/a
114	Current production	76.2	kgdwPPC/tree/a
115	Enhanced production	180	kgdwPPC/tree/a
116	Current production/current trees	305	tonnesPPC/lake/a
117	Enhanced production/current trees	720	tonnesPPC/lake/a

Table 7i: Boomerang Lake Metal Removal

	METAL REMOVAL		
		Metal Content of PPC	
118	Zn	473	ug/gdw
119	Cu	243	ug/gdw
120	Fe	270,556	ug/gdw
121	Al	1,353	ug/gdw
122	Zn	6.0	ug Zn/gdwb/d
123	Cu	3.1	ug Cu/gdwb/d
124	Fe	3,436	ug Fe/gdwb/d
125	Al	17.2	ug Al/gdwb/d
126	Zn	901.1	ug Zn/gdwb/a
127	Cu	462.9	ug Cu/gdwb/a
128	Fe	515,409.2	ug Fe/gdwb/a
129	Al	2,577.5	ug Al/gdwb/a
			Mass Based
130	Zn	36.0	g Zn/tree/a
131	Cu	18.5	g Cu/tree/a
132	Fe	20,616.4	g Fe/tree/a
133	Al	103.1	g Al/tree/a
134	Zn	144.2	kg Zn/lake/a
135	Cu	74.1	kg Cu/lake/a
136	Fe	82,465.5	kg Fe/lake/a
137	Al	412.4	kg Al/lake/a
138	Zn loading in PPCs	144.2	kg/a
139	Zn loading in PPTs	395.2	kg/a
140	Cu loading in PPCs	74.1	kg/a
141	Cu loading in PPT	39.8	
140	Fe loading in PPCs	82,465	kg/a
141	Fe loading in PPT	11,927	kg/a
142	Al loading in PPCs	412.4	kg/a
143	Al loading in PPT	248	kg/a
144	Fe concentration of PPT	177,666	ug/gdw
145	Zn concentration of PPT	5,887	ug/gdw
146	Cu concentration of PPT	593	ug/gdw
147	Al concentration of PPT	3,687	ug/gdw

Table 7j: Boomerang Lake Tree and Fertilizer Requirements

148	# trees required using current GR to remove total Zn load	71,248	
149	# trees required using enhanced GR to remove Zn leaving lake	30,162	
150	Average P in PPCs	939	ug/gdw
151	1992 unfertilized P level	630	ug/gdw
152	Necessary P for good growth	5,000	ug/gdw
153	Periphyton as % of PPC	20	
154	Necessary PPC amount for removal	5,429	t PPCs/lake/a
155	Necessary annual P for lake	2,009	kg P
156	Necessary annual PO4 for lake	6,026	kg PO4
157	Concentration in water	6	mg/L PO4
158	Necessary annual nitrogen	6,026	kg N
159	Necessary annual potassium	4,018	kg K

Mill Pond Drainage Basin: Table 7b describes the starting conditions for Mill Pond. Mill Pond sits in a drainage basin which occupies 24.2 ha. In the drainage basin, three dams were constructed below Mill Pond, creating polishing ponds. In Lines 17-22 the concentrations of contaminants in the second of the three dams, just before water enters Boomerang Lake, are given. Line 23 gives the pH of the water at the second dam. Based on precipitation, the drainage basin has a base flow of 65,526 cubic meters per annum (Line 24). The resulting loadings are listed in Lines 25-31.

Tailings: In Table 7c the contaminant loadings to Boomerang Lake, from the tailings, are given. Ground water, from the tailings, enters Boomerang Lake in the region of B9 (Map 2). Loadings from the tailings were calculated, based on the metal concentrations in, and hydraulic conductivity of, piezometers along the Boomerang Lake shore. Contaminant concentrations used in Lines 32-38 were produced from average concentrations in piezometers along the lake shore, measured between 1989 and 1992. A base flow of 1,200 m^3 a^{-1} was estimated (Line 39), which resulted in an average annual zinc loading of 0.27 t of zinc (Line 40), 2.5 t of iron (Line 42), and 2.5 t of sulphur (Line 44), along with a loading of 90 kg of hydrogen ions (Line 46) from the tailings to Boomerang Lake.

Backfill Raise Drainage Basin: The Backfill Raise ditch drains part of the mine site along with some of the contaminants generated by the mine development rock. The diversion ditch was enlarged in l992 to capture surface seepages from the underground workings, which were flowing because of the unusually high water levels in l992. The base flow was calculated from the drainage basin and precipitation records. This annual base flow (Line 54) was multiplied by the concentrations of contaminants found in the most recent samples from the diversion ditch, prior to construction of the extended ditch. The calculated loadings are shown in Table 7d (Lines 55-61).

Clean Water Drainage Basin: Essentially all contaminant sources to Boomerang Lake are located on the west side, while the east side contributes clean base flow. The concentration of elements in Confederation Lake was used to represent the clean water. The estimated contribution to the lake is given in Table 7e, following the same logic as used in the contaminated areas. The concentrations in the water are given in Lines 62 to 68, which are multiplied by the base flow (Line 69) to arrive at the loadings (Lines 70 to 76).

The Sum of the Loadings: In Table 7f the total calculated loadings from all four sources are shown in Lines 77-83, and represent 3,860 kg Zn, 575 kg Al, 2,650 kg Fe, and 109 kg Cu per annum.

At this point, it is possible to project what the lake contaminant concentrations would be, given these loadings. The degree to which these projected concentrations match the actual concentrations measured, provides an assessment of the accuracy of the loadings. Thus, by dividing these loadings by the total base flow for Boomerang Lake (Line 2), the concentrations of contaminants in the lake can be calculated. The lake should contain 11.3 mg L^{-1} zinc, 1.7 mg Al L^{-1}, 7.7 mg Fe L^{-1}, and 0.3 mg Cu L^{-1}, if loadings are correct. The concentrations are in reasonable agreement with the lake concentrations.

Using five water samples from 1992 the following were the average concentrations of aluminum, copper, iron, and zinc leaving Boomerang Lake: Al - 1.5 mg L^{-1}; Cu - 0.1 mg L^{-1}; Fe - 1.6 mg L^{-1}; and Zn - 7.5 mg L^{-1}. The measured concentrations were used to calculate the annual outflow of contaminants from Boomerang Lake. The base flow multiplied by the concentrations results in the "loadings" leaving Boomerang Lake: 501 kg Al a^{-1}; 45 kg Cu a^{-1}; 535 kg Fe a^{-1}; 2,568 kg Zn a^{-1} (Lines 84-90).

The end result is that 1291 kg of zinc per annum remain in Boomerang Lake (Line 91), along with 2091 kg of iron and 181 kg of copper (Lines 93,94). The aluminum loading remaining in the lake was 75 kg a^{-1} (Line 92). If the contaminant concentrations in the lake were rising each year due to the remaining loading, then this fraction would be targeted by biological polishing. However, the major contaminant concentrations in the lake are not increasing (data not shown). Therefore, the loadings that remain are those that are already being removed by biological polishing and other removal mechanisms. Since it is the aim of Ecological Engineering to set up a self-sustaining ecosystem which will remove annual loadings of contaminants, it appears that major steps have already been taken toward that end.

5.4 Growth Rate Calculations

The most difficult parameter to derive in a biological polishing model is the relationship between brush surface area and periphyton. The complex geometry of natural surfaces, and the deciduousness of leaves, needles and bark makes calculating surface areas difficult. Nevertheless, a number of spruce branches were carefully analyzed for surface area and mass, including needles. Lines 100-102 (Table 7g) detail the surface area and mass relationships found for black spruce (avg. mass 40 kg; avg. surface area 356 m^2).

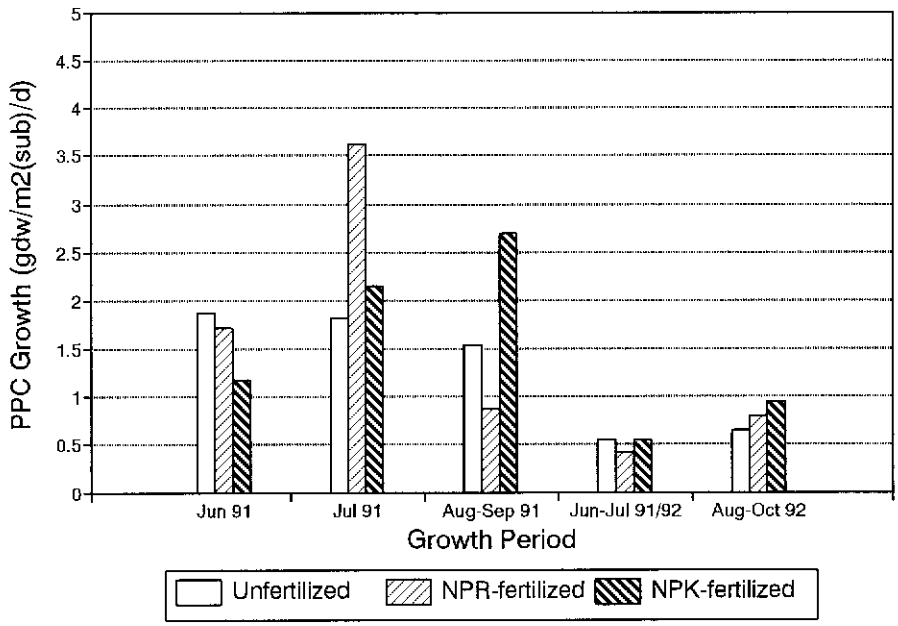
According to aerial photographs, approximately 600 brush/trees were placed behind booms at B11 and B2 in 1987. In the winter of 1990, an additional 41 tuck loads of brush cuttings were placed in the lake behind booms at B8, B9, and B10. In Plate 1, a portion of the truck loads with brush cuttings can be seen. Each truck load was spread apart with a backhoe and left to sink in the lake after spring melt. To estimate the surface area of the brush and trees, the number of "standard" spruce trees in each of the piles were estimated.

A consensus among several knowledgable people was reached, and the number of trees per pile was set at 75 standard spruce trees. Therefore, a total of 4000 brush/standard trees were estimated to have been placed in the lake overall (Line 105).

Plate 1: Placement of brush/trees into Boomerang Lake, winter 1991.

PPCs on peritraps (biomass on nets, branches, and in bags) grew at rates ranging from a high of 3.6 gdw m^{-2} (sub) d^{-1} during July 1991, to a minimum of 0.4 gdw m^{-2} (sub) d^{-1} over the winter of 1991/1992 (Figure 5). The average of all PPC growth rates for the two years was 1.43 gdw m^{-2} (sub) d^{-1} (Line 107). The average growth over the winter and part of the summer of 1991/1992 was 0.47 gdw PPC m^{-2} (sub) d^{-1}.

Fig. 5: Boomerang Lake Peritraps
PPC Growth



Another way to calculate a minimum, year-round growth is to plot the mass of PPCs accumulated on the peritraps (and in the bags) against submergence time. The results are presented in Figure 6. The regression line through these points suggests that overall growth rates were around 0.35 gdw PPC m^{-2} (sub) d^{-1} (Line 108).

The upside growth rate calculation can be made using the laboratory growth rate of 5.1 % d^{-1} (Table 3). If this rate is multiplied by the average density of PPCs on branches (0.4 gdw $gdwB^{-1}$; Figure 7), a rate of 0.03 gdw $gdwB^{-1}$ d^{-1} is calculated (Line 109). Growth rates, thus, vary between 0.03 and 0.0031 gdw $gdwB^{-1}$ d^{-1}. The growth of PPCs on peritraps over the summer (Line 110) seemed to be the most reasonable of the calculations, and was used in further extrapolations (Line 112).

Fig. 6: Boomerang Lake Peritraps
PPC Mass vs. Submergence Time

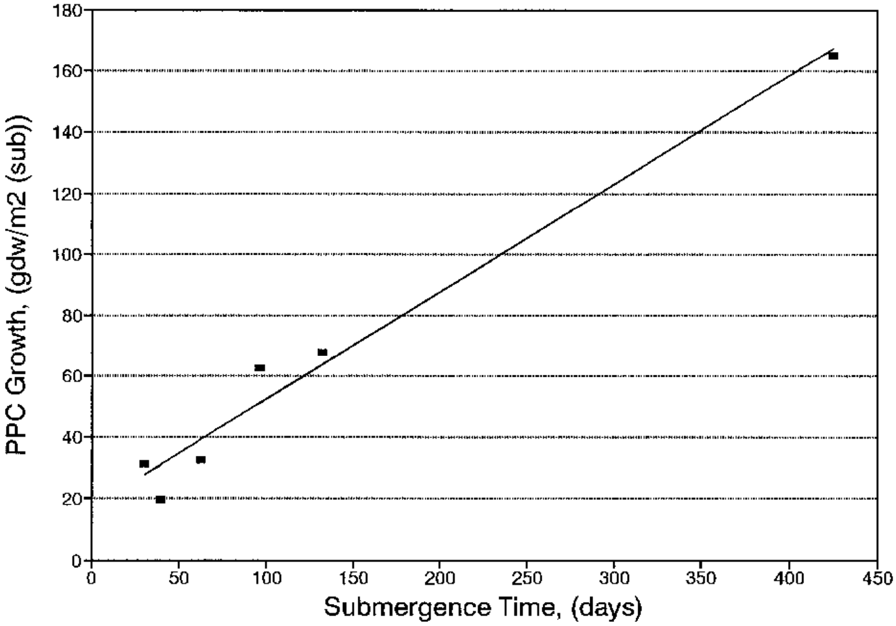
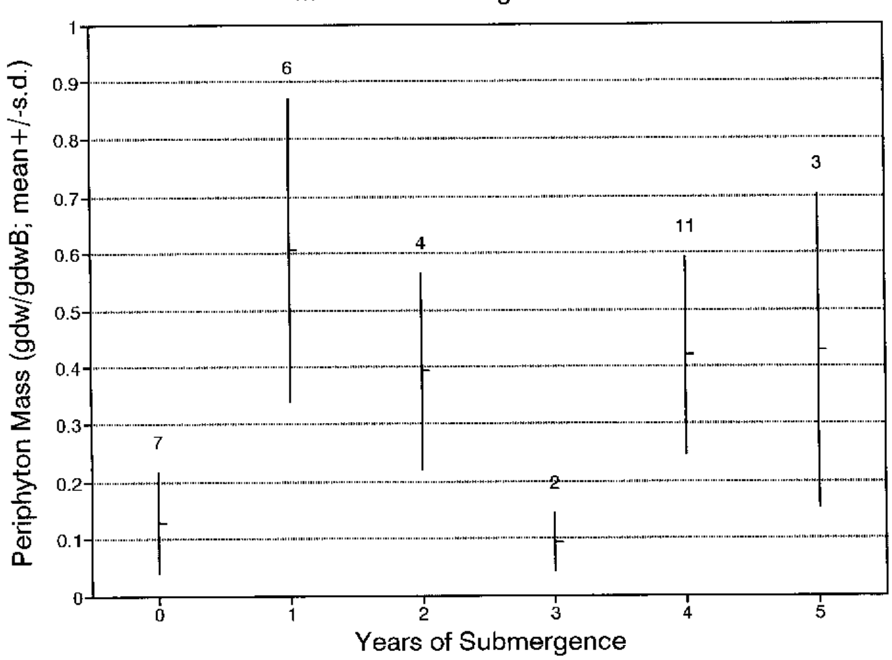


Fig. 7: Boomerang Lake PPCs
Mass vs. Submergence Time



The data in Lines 110 and 111 are the same data as Lines 107 and 108, but converted to different units. All growth data were converted to equivalent mass per branch weight per day, so that the scale-up per tree would be more meaningful.

In Table 7h, the growth rates are used to calculate biomass production in Boomerang lake on the placed brush. The growing season at South Bay is approximately 150 days. Thus, by multiplying the daily production rate by the number of growing days per year, an annual primary productivity figure can be calculated (Line 113). If the mass of branches per tree (Lines 101,102) is multiplied by the per branch data, the primary production per tree per year can be calculated (Line 114).

When these primary production estimates are multiplied by the current estimate of the number of brush/trees in the lake (4000; Line 105), then approximately 300 tonnes of PPCs have been produced in Boomerang Lake on an annual basis (Line 116). If the growth rates of PPCs in Boomerang Lake could be enhanced to the point where they produced at rates measured in the laboratory (Line 109), then the annual primary productivity would climb to 180 kgdw PPC $tree^{-1}$ a^{-1} (line 115). Using the enhanced growth rate estimate, this annual production climbs to 720 tonnes of PPCs.

5.5 Metal Removal Calculations

At this point, the stage has been reached where the biological polishing capacity of the periphyton on branches in the lake can be estimated (Table 7i). Lines 118-121 detail the elemental composition of peritrap and other PPCs collected and processed during the summer of 1992. Although all elements which are of interest are presented in Table 7i, detailed discussion is provided for only two elements, namely iron and zinc. Zinc concentrations averaged only 473 μg gdw^{-1} (Line 118), while iron made up almost 27% of the mass, at 270,556 μg gdw^{-1} (Line 120).

To calculate the metal removal abilities of the periphyton, the concentration of iron in the PPCs was multiplied by the growth rate of the PPCs. This gave the result in Line 124, 3,436 μg Fe gdwB^{-1} d^{-1}. If this result is multiplied by 150 days per growing season per year, the result is that shown in Line 128 (0.52 g Fe gdwB^{-1} a^{-1}).

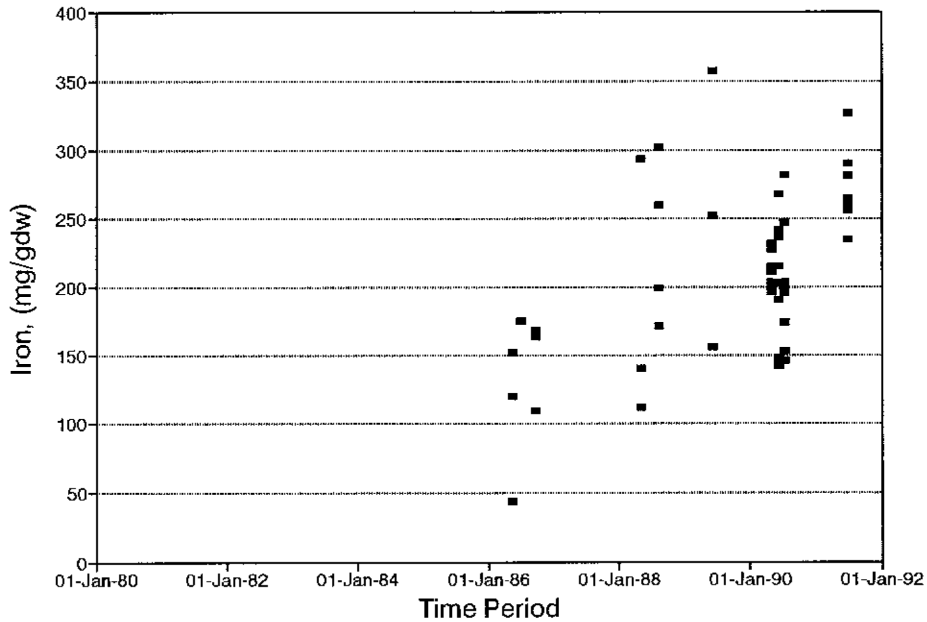
Multiplying the mass of brush/tree by the amount of PPCs per branch gives the mass of Fe removed per tree. The result is shown in Line 132 (20.6 kg Fe tree^{-1} a^{-1}).

If the estimated number of brush/trees already in the lake is multiplied by the mass of iron per tree per year, the result is the annual mass of iron accounted for by the PPCs in Boomerang Lake. This result is 82.4 tonnes of Fe per year (Line 136).

The amount of iron presently being "fixed" by PPCs is roughly 41x the amount of iron which remains in the lake based on loading calculations (Line 93). Clearly, these biological polishing estimates for iron require some explanation.

In oxidizing conditions, iron precipitates, and with time, forms a relatively hard crust on any submerged surface. With time, then, periphyton biomass becomes incorporated in iron crusts, becoming less likely to slough off at the end of the growing season. The amount of iron associated with the periphyton, then, increases with time as shown in Figure 8. In this figure, the iron concentration in the PPCs (μg gdw^{-1}) is plotted against submergence time. It is evident that the total amount of iron in the biomass is increasing from year to year. The concentration used in the model (Line 120), then, is far too high, and represents the accumulation of iron over at least five years. A more reasonable annual estimate for iron removal, therefore, would be to take the number in Line 136 (82.4 t lake^{-1} a^{-1}) and divide it by 5 (minimum number of years iron has been accumulating).

Fig. 8: Boomerang Lake Peritraps
Iron Concentrations vs. Time



In Section 5.5.1, sedimentation rates of iron are discussed in detail. Sedimentation traps were found to account for about 11.9 tonnes of iron (Line 141), suggesting that iron in the sediments is being resuspended. However, resuspension, at this point, has not been quantified. These observations suggest that the geochemistry of sediments and the hydrology of the lake are important components of modelling the biological polishing process, at least in Boomerang Lake. It further emphasizes that an underwater meadow covering the sediments, as originally envisaged for Boomerang Lake, is essential for the achievement of an effective biological polishing system, particularly with respect to iron.

The same calculations, as were carried out for iron, can be performed for zinc. Here, Line 122 calculates the amount of zinc sequestered per gram of branch per day (6.0 μg Zn gdwB^{-1} d^{-1}). Line 126 calculates this on an annual basis (901 μg Zn gdwB^{-1} a^{-1}). The amount of zinc sequestered per tree per year is extrapolated in Line 130 (36 g Zn tree^{-1} a^{-1}). Finally, based on the number of brush/trees estimated to be in the lake, about 144 kg Zn lake^{-1} a^{-1}, is sequestered (Line 134).

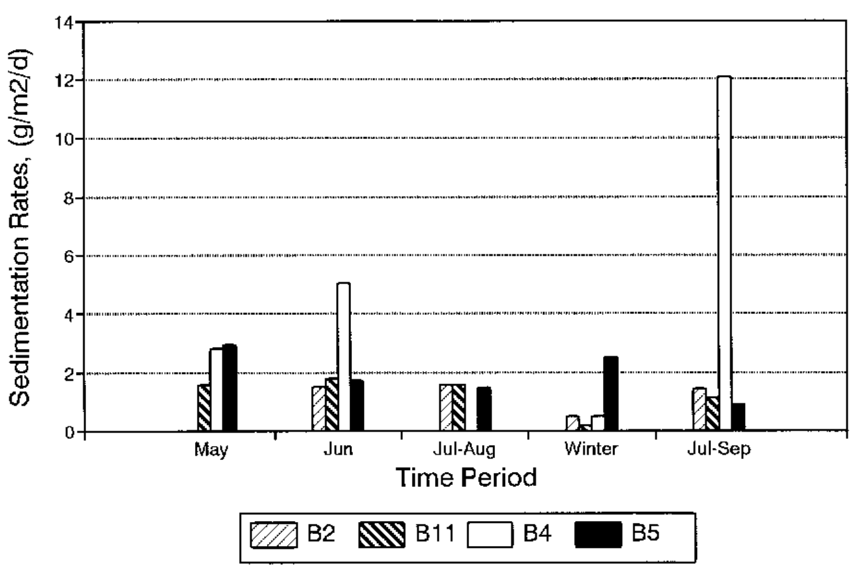
5.5.1 Sediment Trap Iron and Zinc Data

It became apparent in the second year of data collection, that iron concentrations in the periphyton and the iron loadings estimated to the Lake were orders of magnitude apart. Therefore, another mechanism must exist, which either, increases the iron loadings to the lake, or enhances the amount of iron on the periphyton.

In 1991 and 1992, 3-4 sediment traps collected sediment (precipitate) in the lake at 4 locations. Traps were placed at B2, near the boom, at B11, near the boom, at B4 in the deepest part of the lake (trap lost mid summer 1991, replaced midsummer 1992); and in the narrows near B5 (Map 2).

Over the summer of 1991, the winter of 1991/1992, and the summer of 1992, these traps collected sediment at the following rates: B2- 1.2 g m^{-2} d^{-1}; B11 - 1.2 g m^{-2} d^{-1}; B4 - 5.1 g m^{-2} d^{-1}; and B5 - 1.9 g m-2 d^{-1} (Figure 9). The time-averaged rate for the two years of data was 0.77 g m^{-2} d^{-1}. The time averaged rate was lower than summer means, due to the low overwinter rates.

Fig. 9: Boomerang Lake
Sedimentation Rates



Since this time-averaged rate included overwinter data, the daily rate was multiplied by 365 days to give an annual sedimentation rate of 281 g m^{-2} a^{-1}. ICP data show that the sediments caught in the traps had an average iron concentration of 0.17 g gdw^{-1}. When this average is multiplied by the annual sediment /precipitate loading, an iron loading of 50 g m^{-2} a^{-1} is calculated. When this is further multiplied by the area of the lake (Line 3), 11.9 tonnes of iron are projected to sediment/precipitate in Boomerang Lake each year. This is 4 times the iron loading calculated entering from the contaminant sources previously.

Because the lake is shallow and long, it is quite possible that lake sediments, especially those at the north end of the lake could be resuspended, allowing the sediment traps to pick up more than the calculated loading. The highest sedimentation rates were found in B4 and B6 sediment traps in the north and west end of the lake. Prevailing winds are from the north and west. Such wind-driven resuspension of sediments is common in shallow lakes (Ten Hulscher et al. 1992).

The same calculation can be applied to zinc in the precipitate. In this case, the zinc content of the sediment/precipitate (5887 μg Zn gdw^{-1}) was multiplied by the mass of sediment in the traps over 1 year and lake area. The result is a removal of 395 kg Zn per annum with sediment/precipitates in the lake.

In summary, the amount of iron collected in the sediment traps is about 4 x the amount of iron that is thought to enter the lake. Most of the iron enters the lake in ground water from the tailings. This iron is probably in the ferrous form. Oxidation of the iron in Boomerang Lake, depresses the pH of the lake, and causes the precipitation of iron hydroxide. Since very little iron leaves the lake, it is probable that most of the iron has oxidized and precipitated. This is also evidenced by the high concentration of iron in the sediments around B9.

The iron hydroxide that is formed at the upper end of the lake can adsorb/coprecipitate zinc and copper. About 60 % of the zinc and 33 % of the copper are found associated with the sediment/precipitate.

The evaluation of biological polishing is based on several parameters, where large measurement variables can be introduced. Two of the most important variables are the estimate of surface area and the methods used to measure PPC growth. These two variables will be discussed below.

5.6 Biological Polishing Scale-Up

In order to remove a significant fraction of the incoming zinc loading, more substrate surface area is required. This can be provided by adding more brush/trees or some other suitable surface area such as netting. The current model, however, uses the standard tree for scale-up. Table 7j uses previous data to calculate the required number of trees. If the total zinc loading leaving the lake is divided by the total zinc accumulated by PPCs, and the growth rate per tree, the total number of trees required is calculated - 71,250 (Line 148). If the growth rate of the PPCs were enhanced with the use of fertilizers, the number of trees required would drop to 30,160 (Line 149). These scale up estimates are 10-20 times the number of trees which are in the lake at present, estimated at 4000 trees.

Zinc concentrations in Boomerang Lake have not increased in the last 4 years (data not shown), as would have been expected, if biological polishing utilized at the present rate with 4000 trees would not have been effective. These 4000 trees have been placed into a small fraction of the lake (3.5 % of the lake surface area). Based on the substrate surface area required for full scale-up, only about 62 % of the surface area of the lake needs to be used for biological polishing. In general, it can be concluded that a better surface area estimate per cut brush tree is required and possibly more effective surface areas for periphyton growth should be used.

The model calculations used 1992 field data. A second approach to estimating biological polishing capacity, not pursued to date, is to calculate the difference between lake concentrations both with, and without, Ecological Engineering. The projected concentrations without E.E. can be extrapolated from the rate of increase in contaminant concentration (e.g. zinc), over the 5 year period before E.E. measures were implemented. The difference between the two lake concentrations would give a credible estimate of the capacity of periphyton on 4000 trees in Boomerang Lake and in Mill Pond to biologically polish contaminants.

5.7 Fertilizer Requirements

To achieve these enhanced growth rates, the plants must be fertilized. The average phosphorus concentration in the PPCs from Boomerang Lake was only 939 $\mu g\ gdw^{-1}$ (Table 7j; Line 150), although the 1992 average was only 630 μg P gdw^{-1} (Line 151). Since the periphyton in Boomerang Lake are only about 20 % of the mass of the PPC (Line 153), the periphyton fraction had a phosphorus content of only about 188 μg P gdw^{-1}. Healthy periphyton have a phosphorus content of about 5000 $\mu g\ gdw^{-1}$ (Line 152; Hutchinson 1975). The amount of periphyton (PPC) necessary to remove all zinc, would require about 5400 tonnes (Line 154). The amount of phosphorus needed to keep this amount of PPC healthy, would require about 2 tonnes of phosphorus (Line 155). To convert this to phosphate, Line 153 is multiplied by 3 (Line 156). This corresponds to a concentration of 6 mg L^{-1} (Line 157), which is slightly higher than the eutrophic concentrations used for estimating the fertilizer requirements for Buchans.

Phosphate may be the limiting nutrient, but on such a scale, nitrogen and potassium must also be added to the lake. The usual ratio of N:P:K is 3:1:2 (or 19:6:12). Thus, the N and K amounts are calculated in Lines 158 and 159. The total quantity of fertilizer would depend on the choice of the NPK mixture.

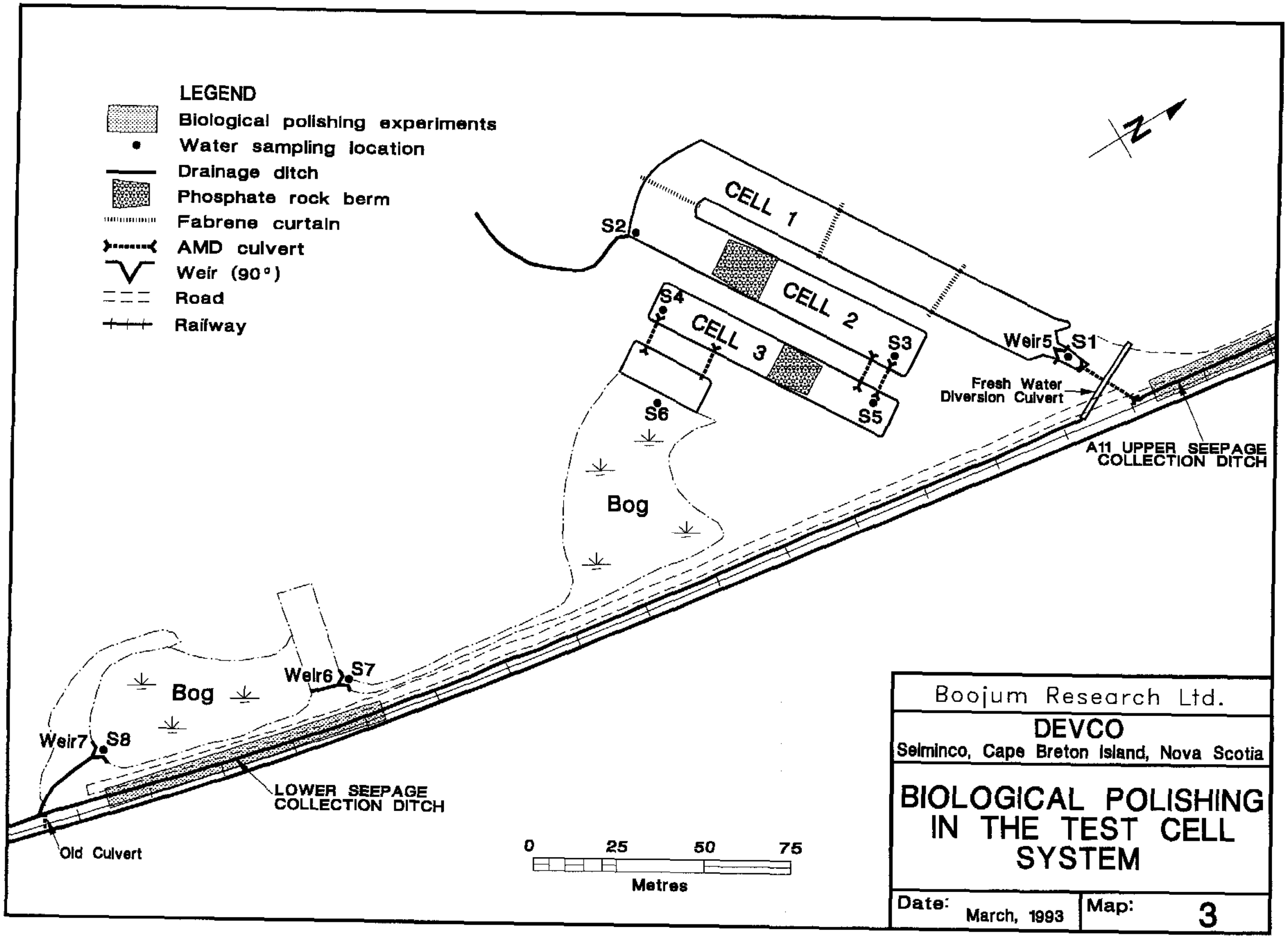
6. APPLICATION MODEL - SELMINCO

At the previous two sites, the data for the biological polishing process were derived from on-site collections. At the third site, biological polishing has not been initiated, but the hydrological, geochemical and biological criteria necessary for biological polishing are known. Indigenous periphyton have been collected from the site, and their presence and absence have been studied in detail (Kalin and Wheeler 1992c). The primary question which an application model can answer, is: If biological polishing were implemented, what effluent quality can be expected? To provide the appropriate background, the activities which have been carried out under the project to implement Ecological Engineering are briefly described below.

6.1 Site Description and Project History

Selminco Summit is an abandoned coal waste dump on Cape Breton Island in Nova Scotia. AMD seeps from the toe of the dump. In 1989, an ecologically engineered treatment system was implemented at the site. The treatment system consisted of a series of precipitation ponds, followed by two ponds in which biological water cleansing processes would be developed (Map 3). Two biological processes were envisaged for the system, ARUM (Acid Reduction Using Microbiology) and biological polishing. ARUM is a sediment-based process in which microbes, under reducing redox conditions, generate alkalinity and precipitate metals.

In 1991, Boojum Research, with the aid of Cape Breton Development Corp. and CANMET, studied the conditions necessary to initiate the growth of periphyton in the E.E. system (Kalin and Wheeler 1992c). The primary criteria for the establishment of periphyton populations were: 1) an elevation of pH above 3.5, and 2) a reduction in iron content of the water.


LEGEND
Biological polishing experiments
Water sampling location
Drainage ditch
Phosphate rock berm
Fabrene curtain
AMD culvert
Weir (90°)
Road
Railway
N
CELL 1
CELL 2
CELL 3
S1
S2
S3
S4
S5
S6
S7
S8
Weir5
Weir6
Weir7
Fresh Water Diversion Culvert
A11 UPPER SEEPAGE COLLECTION DITCH
Bog
Bog
LOWER SEEPAGE COLLECTION DITCH
Old Culvert
0
25
50
75
Metres
Boojum Research Ltd.
DEVCO
Selminco, Cape Breton Island, Nova Scotia
BIOLOGICAL POLISHING IN THE TEST CELL SYSTEM
Date: March, 1993
Map: 3

The high iron content and oxidizing conditions in the ditches and system, provided the conditions necessary for rapid changes in the redox state of the water. The rapid oxidation of the iron, precipitated any available phosphorus, and dropped pH below the tolerance limit.

Seepage water emerges from the waste rock pile at station A11, and several other points as the AMD travels down a drainage ditch (Map 3). The water enters the system at station S1 (weir 5). The system consists of three cells designed to provide surface area and retention time for the oxidization and precipitation of iron hydroxide.

With the establishment of phosphate rock berms in the system in 1992, and the proposed implementation of more phosphate treatment in other parts of the system, not only has the iron concentration in the system significantly decreased, but acidity has decreased as well. With these implementations, it is likely that periphyton can be established in areas that have been treated with phosphate rock.

6.2 Application Model

In order to determine the steps necessary to scale-up biological polishing of the effluent, a model was developed using the hydrology and geochemistry of the site and biological data from Selminco and other biological polishing sites (Table 8). The model is written in the same format as the models for the two previous sites.

The dimensions of the ecologically engineered system are shown in the first box. These dimensions are required for model calculations. The estimated volume of the seepage ditch is given in line 1. The volumes of the cells are shown in Lines 2-5. The biological treatment area "bog" has a volume of about 4000 m^3. The surface areas of the component parts of the system are shown in Lines 7-12.

Table 8: Selminco Biological Polishing of Aluminum and Iron

	SELMINCO STARTING POSITIONS		
1	A11 ditch	12	m3
2	Cell 1	1,142	m3
3	Cell 2	1,075	m3
4	Cell 3	693	m3
5	System volume	2,910	m3
6	Bog volume	3,968	m3
7	A11 ditch	120	m2
8	Cell 1	1,730	m2
9	Cell 2	1,344	m2
10	Cell 3	866	m2
11	System area	3,940	m2
12	Bog area	3,968	m2

	WEIR 5 (S1)		
13	Aluminium concentration	48.2	mg/L
14	Iron concentration	120.9	mg/L
15	Seepage flow	85,084	m3/a
16	Aluminum loading	4,548	kg/a
17	Iron Loading	10,287	kg/a

18	PPC dry to fresh weight	0.61	gdw/gfw
19	Area per unit branch	0.0089	m2/gdw
20	Mass per spruce branch	200	g
21	Spruce branches per tree	200	g
22	Usable spruce mass	1	g
23	Usable mass/spruce tree	40,000	g
24	Growth area per tree	356	m2
	GROWTH RATES - PPC		
25	Peritraps - summers only	1.43	gdw/m2(sub)/d
26	Density in A11 ditch	199	g/m2
27	Lab low density	14.7	gdw/m2(sub)/d
28	Lab high density	3.0	gdw/m2(sub)/d

	METAL REMOVAL		
29	Al	13,336	ug/gdw
30	Fe	361,991	ug/gdw
31	Al	19.1	mg Al/m2 (sub)/d
32	Fe	518	mg Fe/m2 (sub)/d
33	Al	3.4	g Al/m2 (sub)/a
34	Fe	93.2	g Fe/m2 (sub)/a
			Tree Based
35	Al	1.2	kg Al/tree/a
36	Fe	33.2	kg Fe/tree/a
37	Al	3,722	# of trees
38	Fe	310	# of trees
39	Al	0.5	trees/m3
40	Fe	0.05	trees/m3

The two major contaminants emerging from the seep are aluminum and iron. Average aluminum and iron concentrations from 1992 were 48.2 mg Al L^{-1} and 121 mg Fe L^{-1} (Lines 13 and 14). These are based both on Boojum and CBDC data. This application model uses these two elements, rather than zinc, to calculate scale-up factors.

6.3 Contaminant Loadings

The seepage flow rates, measured at station S1, are shown in Figure 10. These data were compiled over a period of 3 years, and excluded any periods of high flow caused by run-off. As the run-off events in Cape Breton can produce very high flows, a storm diversion ditch was installed, to prevent structural stability problems.

The regression lines through these data points were used to extrapolate the annual flows. The area under the curve in Figure 10 was used to compute the annual seepage flow (Line 15). When multiplied by the annual seepage flow, annual aluminum and iron loadings can be estimated. These loadings are shown in Lines 16 and 17, and graphed in Figure 11.

Fig. 10: Selminco Summit
Flows at S1

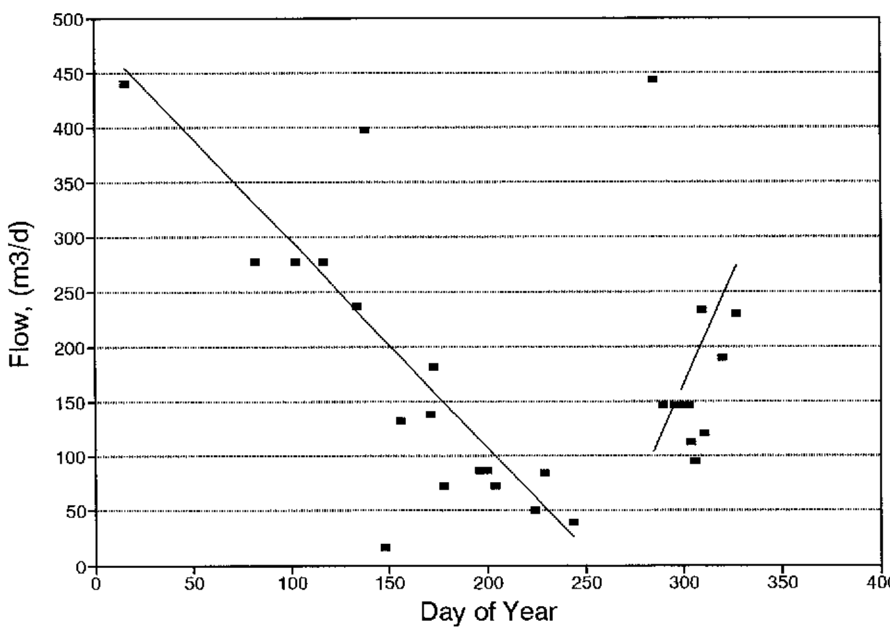
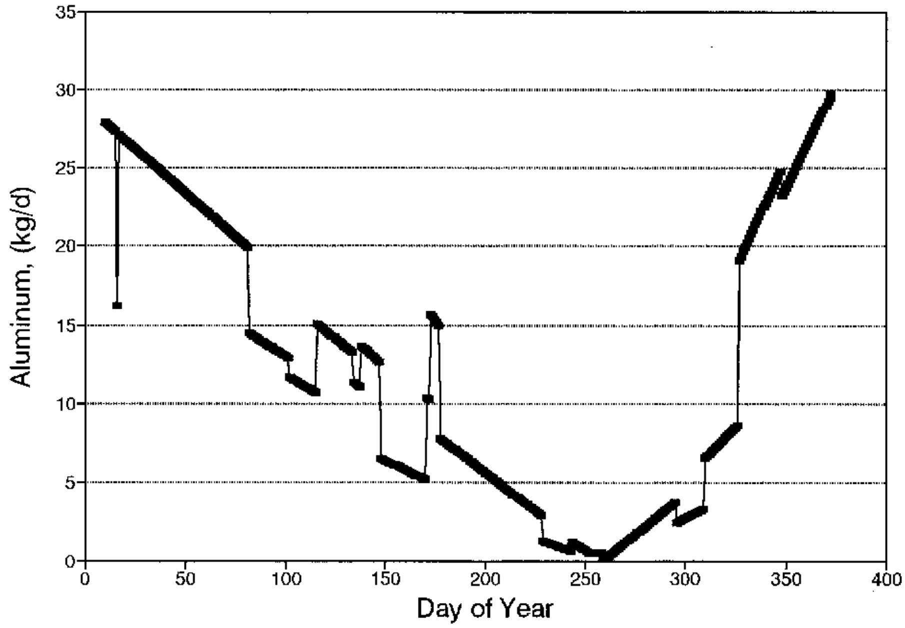


Fig. 11: Selminco Summit
Aluminum Loading at S1



6.4 Growth Rate Calculations

Once the metal loadings have been estimated, the biomass necessary to significantly reduce these loadings can also be calculated. Since field growth rates of periphyton were not measured at Selminco, field growth measurements from Buchans were used. There, peritraps produced summer PPC growth rates of 1.4 gdw m^{-2} (sub) d^{-1} (Line 25). Laboratory growth measurements suggest that growth rates of Selminco periphyton as high as 7.4 % d-1 are possible under the proper conditions (Table 3). If this maximum rate is multiplied by the density of periphyton found in the A11 ditch (Line 26; Table 9), then a maximum growth rate of 14.7 gdw m^{-2} d^{-1} is calculated (Line 27). From high density cultures in the lab, growth rates of 1.5 % d^{-1} are possible (Figure 1). Multiplying this through with average densities in the A11 ditch, produces a growth rate of 3.0 gdw m^{-2} d^{-1} (Line 28). Thus, to be on the conservative side, the Buchans field growth rate of 1.4 gdw m^{-2} d^{-1} was used for further calculations.

The area around Selminco is forested with spruce and alder. However, since the surface area of the spruce is greater, it was used in the scale-up calculations. The spruce tree data are shown in Lines 19-24.

Table 9: Selminco A11 Ditch Periphyton Density

Seepage (m from A11)	Density (g/m2)
0.0	96
4.2	216
9.2	179
12.4	199
14.4	199
18.5	306
Average	199

6.5 Metal Removal Calculations

The concentrations of metals in PPCs from the A11 ditch indicate that both aluminum and iron are accumulated by PPCs above water concentrations. Boojum Assay #3473 and 3474 were used as the basis for removal calculations. Thus, PPCs from the Selminco A11 ditch accumulated 13.3 mg Al gdw^{-1} and 362 mg Fe gdw^{-1} (Lines 19,20).

If the metal in the PPCs is multiplied by the growth rate (1.4 gdw m^{-2} d^{-1}; Line 25), the aluminum removal rate can be calculated, 19.1 mg Al m^{-2} (sub) d^{-1} (Line 31). Again, if a 180 day growing season is imposed on biological polishing, the annual removal rate becomes 3.4 g Al m^{-2} (sub) d^{-1} and 93.2 g Fe m^{-2} (sub) d^{-1} (Lines 33,34). When the conversions from substrate area to trees are used (Lines 19-21), biological polishing via periphyton can be expected to remove 1.2 kg Al $tree^{-1}$ a^{-1} and 33.2 kg Fe $tree^{-1}$ a^{-1} (Lines 35,36).

6.6 Biological Polishing Scale-up

Lines 37-40 scale-up the above calculations to remove all of the aluminum and iron loadings. Thus, to remove all of the zinc loading to the system, 3722 trees would have be added to the precipitation cells and bog. This would give about 0.5 trees per cubic meter. If the high growth rates from the lab were used in scale-up calculations, the number of trees necessary would drop to 361.

With the appropriate phosphate rock added to the system, and fully-functional ARUM sediments, further alkalinity will be generated, and dissolved metals precipitated. It is not possible, yet, to assess the contribution of these other processes. The net result, however, would be a significant decrease in the contaminant loadings. This decrease would mean that fewer trees and lower periphyton biomass would have to used to clean the effluent.

7.0 GENERAL APPLICATIONS MODEL

The biological polishing models developed for each site serve as a tool to scale up the process for a given site or project or allow an assessment of expected performance if the process is implemented. The site specific models, however, are of little use to a more general application, where, for example, a mining company would like to apply biological polishing to their effluent or waste management areas. A general spreadsheet was developed which requires only a few parameters. The output of which gives a rough estimate of the potential usefulness of the process. The output, which calculates the removal of zinc per cubic meter of waste water, can only be regarded as an estimate, accurate only to the given order of magnitude.

The general model, presented below, can only be used to assess the potential usefulness of the process. Under no circumstances is the model to be interpreted to mean that, through the addition of x number of trees and some quantity of fertilizer, the process can be implemented. That may well be the case in some circumstances, but it can not be considered as a general rule. The model has not been developed to the stage that periphyton growth conditions and the interactions between periphyton, effluent, and fertilizer can be generalized. The model output is a tool, which indicates whether or not a feasibility study might be appropriate.

7.1 What Might Be Expected From the Use of Biological Polishing?

A spreadsheet has been developed which incorporates many of the features described above for the specific sites. The spreadsheet was written in Quattro Pro 4, and was designed to calculate periphyton biomass production after answering a few basic questions (see enclosed diskette). It will be amplified as time and resources permit.

Line 1 of the model asks the user to input the pH of the waste water under consideration. The waste water is either acidic, or neutral to alkaline. If the pH is above 6.5, then zinc will precipitate geochemically. In this case, the periphyton act more as "sieves" and can sequester large quantities of zinc. For this scenario, the sequestration abilities of periphyton from Buchans were used. If the water body is acidic, then zinc removal occurs by adsorption. For this scenario, South Bay (Boomerang Lake) data were used.

Line 2 of the model asks the user to input the growth rate of the periphyton. Biological data gathered in the field from both northwestern Ontario and Newfoundland are very similar. Growth rates of periphyton were compared between sites with a circum-neutral pH and found to be similar (Kalin and Wheeler 1992a,b). Growth rates measured between acidic sites (e.g. Boomerang Lake vs. OWP), seemed to be more related to acidity than metal content. Those sites with low acidity (e.g. Boomerang Lake) had growth rates similar to more circum-neutral sites (OEP outflow). For example, peritraps in Buchans OEP ponds produced an overwinter/spring growth rate of 0.5 gdw m^{-2} (sub) d^{-1} and a summer rate of 2.2 gdw m^{-2} (sub) d^{-1}. Using similar peritraps, periphyton in Boomerang Lake grew at an overwinter/spring rate of 0.4 gdw m^{-2} d^{-1} and a summer rate of 1.4 gdw m^{-2} (sub) d^{-1}. It is not unreasonable, therefore, to assume that the *Ulothrix* -dominated periphyton populations were growing at relatively similar rates, regardless of water pH. For modelling purposes, then, a standard growth rate can probably be applied. However, growth rates have been shown to be improved, in both field and lab experiments, with fertilizer.

Line 3 of the model asks the user to input the length of the growing season. The number of days in the ice-free season gives the outer boundary on the growing season for periphyton growth. Due to storms, and other adverse conditions, the program takes the number of ice-free days, and subtracts 30. The growing season is then set at ice-free minus 30 days.

Line 4 asks the user to input the brush type. Currently, there are only two choices; either alder or spruce. Both are commonly found at most of the Canadian mine sites. In the Buchans polishing ponds, alder trees were used. In Boomerang Lake, spruce trees have been used to add surface area. Alder produces a surface area to mass of 0.0027 m^2 $gdwB^{-1}$, and spruce provides approximately 0.0089 m^2 $gdwB^{-1}$. Because of the spruce needles, then, the surface area provided by spruce is about 3.3 x the surface area of the alder.

The last line of the question section asks the user to input the brush density. Since the tree type and density together provide the total amount of surface area; this is an important parameter. In the Buchans polishing ponds, 110 alders were placed in ponds with an average volume of 40 m^3, thus providing about 2.6 m^2 of surface area per m^3 of pond. In Boomerang Lake, the scale-up process has just begun, and the surface area to volume ratio in Boomerang Lake is about 1.36 m^2 m^{-3}.

As the user inputs data, the lower, projection, section automatically changes. This allows the user to ask "what if" questions. The removal rates indicated in Lines 9 and 10 can be used to determine how large the polishing pond must be, and with which density the periphyton must be grown.

This model has been developed for use in mining waste water where periphyton are already growing. The idea is to enhance the growth of existing populations to the point where they can remove significant amounts of contaminants. If periphyton are not growing in a particular waste water, then establishment of the population may require special consideration. For example, in the Selminco system, periphyton were found growing in seeps, but absent from locations further downstream. It was discovered that oxidation/reduction reactions on or near the periphyton were precipitating iron on the periphyton which inhibited growth. To apply the model to Selminco, therefore, the location of application of the process will be changed, or the effluent will be improved using other Ecological Engineering measures.

8. REFERENCES

Hutchinson G.E. 1975. A Treatise on Limnology. Vol. III. Limnological Botany. John Wiley & Sons, N.Y., 660 p.

Kalin M., W.N. Wheeler, and R.O. van Everdingen. 1991. Periphyton communities as biological polishing agents in mine waste waters and the precipitation process in tailings. Final Report to Canada Centre for Mining and Energy Technology, Energy, Mines and Resources, Canada (CANMET), DSS Contract # 23440-0-9182/01SQ. 54 p. + appendices.

Kalin M. and W.N. Wheeler. 1992a. A study on algal bio-polishing of zinc. Final Report to Canada Centre for Mining and Energy Technology, Energy, Mines and Resources, Canada (CANMET), DSS Contract # 23440-1-9009/01-SQ. 50 p.

Kalin M. and W.N. Wheeler. 1992b. A study of algae-precipitate interactions. Final Report to Canada Centre for Mining and Energy Technology, Energy, Mines and Resources, Canada (CANMET), DSS Contract # 23440-1-9011/SQ. 58 p.

Kalin M. and W.N. Wheeler. 1992c. A study of algal establishment and growth in acid mine drainage (AMD) seeps and precipitation ponds. Final Report to Canada Centre for Mining and Energy Technology, Energy, Mines and Resources, Canada (CANMET), DSS Contract # 23440-1-9010/01-SQ. 37 p. + appendices.

Ten Hulscher T.E.M., G.A.J. Mol, and F. Luers. 1992. Release of metals from polluted sediments in a shallow lake: quantifying resuspension. Hydrobiologia 235/236: 97-105.