DEVELOPING TAILINGS PONDS AND PIT LAKES AS BIOREACTORS AND HABITAT COST-EFFECTIVE SUCCESSES AT HIGHLAND VALLEY COPPER

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ABSTRACT

Forty-five years of mining in the Highland Valley has created several completed tailings ponds and pit lakes. Efforts to enhance the development of these evolving water bodies have been underway since the mid-1990s.

Extensive yet inexpensive techniques have been successful in establishing biochemically active and ecologically valuable aquatic resources. The results obtained and the techniques used, including nutrient growth factor additions, artificial upwelling, biorafts and microfloral introductions, will be described.

The initial fertilization of a pit lake in the Highland Valley invariably results in an extensive phytoplankton bloom that is impossible to replicate in the second or subsequent years. This inability to sustain vigorous biologic production has implications to the development of productive ecosystems and imposes limitations on the metal removal potential of the phytoplankton. Recent work has led to an increased understanding of the role played by vitamins in these water bodies, and this work and some possible solutions will be presented.

INTRODUCTION

Located 80 km southwest of Kamloops, British Columbia, Highland Valley Copper (HVC) is Canada's largest base metal mine. Forty-five years of mining activity have resulted in the creation of several completed tailings ponds and developing pit lakes. Low sulphide concentrations in the tailings and pit walls limit the extent of metal dissolution, although molybdenum management will be a long-term issue.

Development of the deactivated tailings ponds and pit lakes as aquatic habitat and bioreactors began in 1995. While some reclamation is site-specific, the techniques covered in this paper have worked well at all HVC sites. Success is defined as the development of sustainable, ecologically valuable aquatic resources without large capital investments or maintenance costs.

What Every Lake Needs

A basin filled with water of suitable chemistry does not become a lake until it has been colonized by:

1. Microflora = bacteria, algae, fungi, yeasts
2. Aquatic plants and shoreline vegetation
3. Animals = zooplankton, invertebrates, fish (most people and all fishermen consider a lake incomplete if it does not contain fish)

The enzyme pathways within these organisms make possible an additional suite of chemical reactions that will not happen in the strictly chemical processes of a sterile lake.

What Every Lake Does

Beyond the pure physics of an unevenly heated fluid mass subject to wind energy, every lake hosts hundreds of intersecting biochemical pathways for nutrient cycling and energy transfer within food chains. The all-important bacteria perform thousands of chemical transformations from the upper sediment layer. A constant rain of dying algae and plant cells supply the sediment microflora with organic carbon and also deliver adsorbed metals to the sediments.

Mimicking Lake Biochemical Systems in Mine Waters

The same biochemical principles of natural lakes also apply to tailings ponds and pit lakes, but different dynamics dictate different reclamation techniques. For example, both tailings ponds and pit lakes require initial dosing with limiting macro (N, P, C, Si, K) and micro (Fe, Mn, Cu, S) nutrients to stimulate microfloral production. Once the inorganic nutrients are in place, bacterial development will commence and a nutrient/vitamin-rich organic sediment layer will begin to form. In both cases, the upper 1 cm of sediments or rock wall surface hosts 99% of all the bacteria in the water body. Organic accumulations are on the order of 1–2 mm per year, and they host secondary microflora such as the sulphate-reducing bacteria (SRB), fungi and algae (Larratt, 1990). The bioreactor concept relies on reactions between the water and cell surfaces, exudates and chemical reactions.

The array of biological surfaces and chemistry available to remove aqueous metals from mine water is impressive and is summarized in Table 1 below.

Here the critical difference between tailings ponds and pit lakes becomes apparent. The contact between the substrate and the water column is:

- Continuous in a pond 5 m deep or less
- Seasonal in a thermally layered (stratified) pond or pit lake
- Very restricted in a non-mixing pit lake of 50 m deep or more

Table 1: Biochemical Aqueous Metal Removal

Type of Particle	Role in Metal Removal

Phytoplankton	• Many algal surfaces have affinity for heavy metals such as Cu(II) Pb(II) Zn(II) Cd(II) Ni(II) via surface complex formation.
	  • Gram +ve bacteria (Lipid sheath)
	  • Gram –ve bacteria (Peptidoglycan cell walls)
	  • Cyanobacteria (Mucilage sheath)
	  • Euglenoid algae (Mucous coatings)
	  • Chrysophyte algae (External gelatinous matrix)
	  • Diatom algae (Frustules (shells) made of silica dioxide)
	  • Desmid algae (Silicate and/or calcareous surfaces)
	  • Dinoflagellates (Cellulose walls)
	  • Cryptomonad algae (Periplast protein coat with mucous)
	• Aging microflora mineralizes and sediments

Biological debris	• metals adsorb to negatively charged organic particle surfaces esp. –COOH -NH3 -OH groups • metals also attach to cation/anion ligands already attached to the surface of the particles
aCO3	• Heavy metals, phosphates and B12 are adsorbed as calcium carbonate crystals grow. Their large size and therefore small surface area limits the amount of metal CaCO3 co-precipitates.
Fe(III) hydroxides and oxides	• pH dependent, ferric hydroxides/oxides have a strong affinity for heavy metals, phosphates, silicates and oxyanions of As Se Fe(III) oxides • even if ferric hydroxides/oxides are present in small proportions they can exert significant removal of trace metals • at an oxic/anoxic boundary, Fe(III) can represent a large part of settling particles
Mn(III,IV) oxides	• pH & redox-dependent, manganese oxides have a high affinity for metals and high specific surface area and are normally important in regulating trace metals in the lower layers of water columns and sediments
Aluminum Silicates Clays, oxides	• Ion exchange, binding of phosphates and metal ions (usually minor)

(Wetxzel, 2001; Wehr & Sheath, 2006; Chappell, 1973)

The products of bacterial activity in the substrate are continuously available in a shallow pond but are either seasonally replenished at spring and fall overturn in a pit lake shallower than 30 m or not at all in a non-mixing pit lake with a permanent bottom water layer. Additional steps are required to make a pit lake as productive as a tailings pond. The next two sections will detail the sequence of techniques used at HVC tailings ponds and pit lakes.

TECHNIQUES USED ON HVC TAILINGS POND RECLAMATION

Reclaimed HVC tailings ponds perform limited removal of aqueous metals and provide excellent wildlife habitat through fertilization and the introduction of native aquatic species. Aquatic plants and algae essentially create a conveyor belt delivering adsorbed metals to the sediments as they die. Their adsorption of metals is often far in excess of aqueous and sediment concentrations. The range of biochemically active surfaces is large (Table 1). We do not attempt to control the type of microflora—we create a variety of habitats and rely on microfloral diversity.

Fertilizing

In most cases, wash-in from terrestrial reclamation in HVC tailings pond drainage areas was sufficient to stimulate initial algae growth. While phosphorus recycles from the sediments, nitrogen can blow off as ammonia or nitrogen gas. This is particularly true in organic sediments with high pH where denitrifying bacteria perform bacterial nitrogen removal to the point that N often becomes the limiting nutrient. Annual small doses of N-fertilizer such as liquid 28-0-0 urea/ammonium nitrate are needed to maintain the food chain in reclaimed tailings ponds.

Bacterial Introduction

Once water chemistry is suitable, bacterial colonizing begins without assistance. Early colonizers include photosynthetic bacteria and chemotrophs (Koschorreck, 2002). After their organic carbon is available, the bacterial flora expands rapidly to include decomposers such as methanogens and sulphate reducing bacteria (SRB). The colonization process will only take 4–5 years but can be enhanced with introductions of surface substrate removed from other ponds or by introducing aquatic plants.

As organic sediments develop on tailings, they become a sink for aqueous metals through biochemical reactions and they block upward diffusion of metal ions. If the tailings pond is deeper than 8 m, an anaerobic zone can form and support SRB right to the sediment surface and result in faster metal removal. Metal-sulphide precipitation creates a flux of metals to the sediments, coupled with delivery of metal via adsorption onto microflora (Wetzel 2001; Kendorf and Schnitzer, 1981). In passive pond systems, metal removal is usually a slow, gradual process and can be overwhelmed by large metal contributions. These reactions are summarized in Figure 1, which also demonstrates the sharp decline in diffusion of aqueous metals within a substrate and the consequent anoxic conditions 0.5 mm beneath an organic layer (McKee et al.,

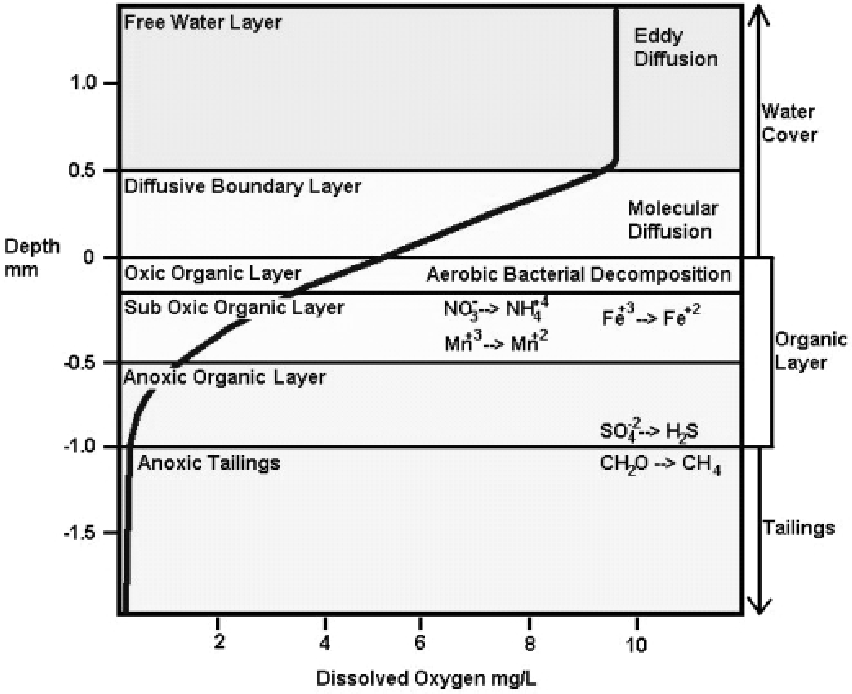


Figure 1: Oxic/Anoxic Layers and Reactions at the Sediment Surface in HVC Tailings Ponds

2002). Algae and aquatic plant detritus deliver adsorbed metals to the substrate, accelerating metal binding reactions in the sediment that would otherwise be restricted by diffusion.

Algae

While algae will volunteer in a tailings pond, many more species are capable of growing in a given pond than will develop there unaided. Introductions of filamentous algae enclosed in netting have been very successful and provide significant amounts of organic carbon to the aquatic system. The addition of natural sediments and aquatic plants will also introduce hitchhiking algae species and accelerate reclamation.

Aquatic Macrophytes

A tailings pond with vigorous bacterial and algal production is ready for aquatic macrophyte introductions.

Large quantities of rooted macrophytes can be introduced using “weed sandwiches”—2 m^2 sections of stucco wire folded over native milfoil and/or pondweeds that have developed adventitious roots. For some plants, collecting seeds (pondweeds) or turions (Elodea) and tossing them in over soft sediments is successful. Another effective means of introducing local aquatic macrophytes is by transferring the upper sediments from weed beds. While the plants may not survive the transfer, root fragments and the seed bank in the mud will.

Riparian Vegetation

The shoreline or riparian area is as critical to the pond as it is to the wildlife. Shoreline vegetation donates as much as 30% of the organic carbon, nutrients and vitamins to a pond annually.

Willows are an important shrub and are readily introduced as 2–3 cm diameter stakes or wattling. They must be planted in damp but not water-covered areas. Planting dormant stakes as soon as the tailings thawed provided the best results while summer/fall planting gave lower survival.

Of the typical riparian vegetation, sedges are the most tolerant of drought and inundation. They are readily introduced by digging from a donor wetland and installing as 20 cm^2 plugs in early fall during low water.

We found pressing cattail seed heads into the mud in the fall resulted in thousands of seedlings per square meter the following summer, and a typical fringe of cattails developed within three summers.

It is important to retain mud flats for waterfowl and shorebirds to prey on invertebrates. Areas away from viewpoints should not be planted but kept as essential but somewhat unsightly mud flats.

Aquatic Invertebrates

Like algae, aquatic invertebrates seem to “show up” during reclamation when conditions are suitable. Immigration occurs through inflowing water, via waterfowl and as hitchhikers on plant or sediment introductions.

Hay bales are a time-tested means of transferring invertebrates from one system to another, but permits are required if the donor site is not on the mine property. Bound hay chunks are left to soak for a month in a natural system to be colonized by invertebrates, then transferred in a water-filled tub to the new site with a minimum of draining. Live-trapping with nets and screen buckets is also possible.

Specialized habitat development

Once the core planting and introduced species are established, specialized habitat development based on the characteristics of each pond can commence. Features such as spawning channels, nesting islands or boxes, shelter belts and shade rafts are all options. The HVC mine site is located in an area with limited natural water bodies, so the reclaimed ponds are very popular, and use by over 95 species of birds has been documented.

TECHNIQUES USED IN HVC PIT LAKE RECLAMATION

Pit lakes can be used for aqueous metal removal from the surface water and as fish habitat. As bioreactors, summer-long algae blooms have removed as much as 10% of the dissolved molybdenum and 4% of the dissolved copper from HVC pit surface layer in a single season. Depending on the rate of metal introduction into the pit lake waters and the ability to maintain prolonged blooms, algal remediation may be a significant future water management technique at HVC as it is at other operations such as Island Copper.

Thermodynamics and Metal Cycling

All HVC pit lakes develop high, stable thermoclines due to limited turbulence. This limited turbulence also restricts algae cell suspension. Only small species and those that can adjust their buoyancy or swim were able to maintain their position in the water column.

HVC pit lakes deeper than 50 m also form a non-mixing bottom layer. Aqueous metals and nutrients can be biochemically removed from the surface water and concentrated in the non-mixing layer. Pit lakes shallower than 30 m fully mix in the spring and fall as most natural lakes do. Aqueous nutrients and metals re-circulate from deep water in mixing pits while the fraction associated with dead cells accumulates as a sediment organic layer.

Pits with a permanent non-mixing bottom layer may be useful for metal storage, but regular fertilization would be needed to maintain productivity (Stevens & Lawrence, 1996). Loss of growth factors to the non-mixing zone poses a serious barrier to continuous blooms on which the pit passive bioreactor scheme relies.

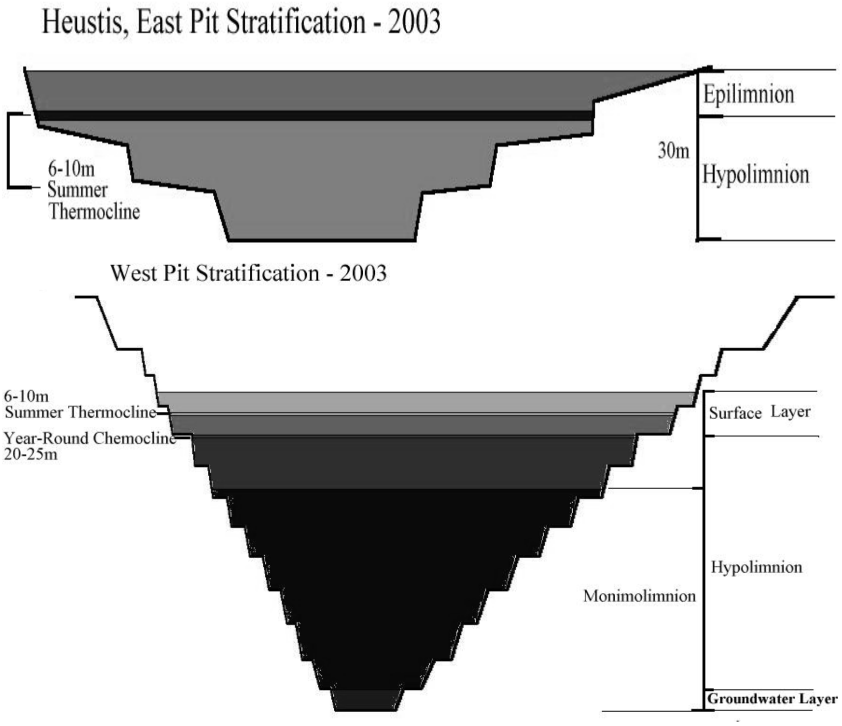


Figure 2: Schematic of Mixing and Non-mixing Pit Lake Thermal Structures

Fertilizing Pit Lakes

Initially HVC pit lakes were strongly phosphorus limited. We used standard agricultural fertilizer 11-52-0 pellets over shallow benches at a rate of 1 to 2 tons per annual application. On deeper pit lakes we used liquid Agrium 10-34-0 and 28-0-0 urea/ammonium nitrate 3–4 times per growing season to achieve >0.2 mg/L diss-N and >0.01 mg/L diss-P. These fertilizers stimulated algae and photosynthetic bacteria growth, and in turn, they encouraged metal precipitation and adsorption onto particulates.

Low metal biosolids (4-2-60C) proved to be an attractive alternate to commercial fertilizer for pit lake development because it also contains carbon compounds. At HVC, two dump truck loads of biosolids applied to a pit ramp out-performed chemical fertilizer. Although biosolids can release Cu, Cd, Zn etc., they did not significantly increase aqueous metal concentrations, and concentrations returned to pre-application levels within three years (Larratt, 2003).

Algae and Microflora

Plankton blooms of one or two species were easily induced by adding high P fertilizer for a few seasons, but subsequent plankton production diminished. Benthic algae growth continued unhindered but unfortunately had limited impact on water chemistry.

Restricted recycling of growth factors from the bottom water was suspected. What wasn’t apparent, however, was the identity of the missing growth factors. All of the major and minor inorganic nutrient requirements for algae were met, but without stimulating plankton algae growth.

As the pit lake plant diversity and benthic communities expanded over time, the spring algae bloom after ice-off grew in intensity and duration. For example, in 28 m deep Heustis pit, intense blooms developed from ice-off to mid-May initially and now extend to mid-June. When the bloom collapses, the pit water clarity goes from very murky (secchi depth of less than 1 m) to very clear (secchi depth of more than 7 m) within four days. No abrupt change in water chemistry induces this sudden loss of productivity.

The pit surface water clears to mirror that of a crater lake. The exceptionally clear water during the summer means that peak microfloral production occurs between 5 and 15 m, not near the surface where sunlight is too intense. Fertilized pit lakes often experience a bloom of photosynthetic bacteria and/or nannoplankton near the thermocline and chemocline, rather than a surface algae bloom. This is not ideal because the surface water has the greatest volume and heat budget.

A missing ingredient

Clearly there is a missing ingredient beyond the major and minor nutrient requirements that limits algae production in the upper waters for most of the summer.

An extensive literature review of the nutritional requirements of the blooming algae species in HVC pit lakes indicated that some species need more than light and the right mixture of inorganic nutrients. Research found algal species that required different combinations of three B vitamins: B12 (cobalanine) B1 (thiamine) and B7 (biotin). While some algae can produce/release biotin and thiamin, cobalamin synthesis is completely absent from algae altogether (Aaronson et al., 1977; Croft et al., 2005; Smith, 2007).

The research found that vertical distribution patterns for the B vitamins changed markedly with the season, apparently in relation to the succession of dominant species of phytoplankton. In Table 2, below, the smallest overall vitamin concentrations are from large lakes where water contact with the bacteria-rich sediments is minimal, while the largest concentrations are from small ponds where the water circulation past the bacteria-rich sediments is continuous. These values provide targets for dosing non-productive pit lake water. Bench testing can determine which combination of B vitamin additions stimulates the best algae growth.

Table 2: Ranges of Vitamin Concentrations in Natural Lakes and Ponds

Vitamin	Concentration in ug/L or mg/m^3
B12 colbalamin	0.0004 – 0.85
B1 thiamin	<0.001 – 0.44
B7 boitin	0.0001 – 0.068
B3 niacin	<0.001 – 3.3
B5 pantothenic acid	<0.01 – 0.26
B9 folic acid	<0.01 – 0.48

(After Wetzel, 2001)

The restricted contact between the benthic coatings rich in bacterial B vitamins and pit lake water effectively limits the range of potential species that a pit lake can produce.

In order to test whether vitamin deficiencies were a factor in the HVC pit lakes, we decided to try biosolids (a suspected source of B vitamins) and eggs (a known source of B vitamins that also floats). These materials were added to 19 L collapsible clear plastic containers, filled with fertilized but non-productive pit water and floated in the pit lake. Within two weeks, intense algae blooms developed in the containers while the pit lake remained non-productive as did a control container. Since both the biosolids and eggs are very complex, we subsequently tried multi-vitamin and pure B12 vitamin pills and got the same bloom intensity but with fewer species. The final and best trial involved a combination of biosolids and garden compost (McCullough & Lund, 2006). It apparently delivered the most complete mixture of inorganic and organic compounds to the microflora. Our informal in-situ bench trial is a critical step in pit lake bioreactor planning.

How to supply B vitamins?

The question then becomes one of how to practically deliver those vitamins to the surface water. Bacterial products can be restored to the surface water via partial destratification where water adjacent to bacteria-rich sediments is pumped or lifted on compressed air bubbles to the surface. Alternately, the water can be passed through biosolids which will dissolve B vitamins and other valuable organic molecules. Ultimately we hope to expand the zones where bacteria and algae can grow in close proximity. The use of the following structures is considered in addition to destratification and biosolids additions:

- Biorafts—floating permeable platforms enclosing filamentous algae and/or duckweed
- Large “teabags” made of biosolids + compost enclosed in erosion-control fabric
- Partially submersed artificial reefs growing aquatic plants where water can circulate past bacterial biofilms on plant roots, rocks woody debris, biosolids, compost, etc.

Benthic algae

Benthic algae coated every surface we submersed in otherwise unproductive pit lake water. The reason for this apparent contradiction lay once again with bacteria. Once a biofilm of bacteria colonized a submersed surface, the algae had the growth factors they needed to colonize it within two weeks. The only practical way to expand the benthic contribution to pit lake productivity is to expand the surface area available for their attachment.

We submersed wood, styrofoam, cotton rope, nylon rope and metal at various depths, and each grew the same biofilm and dominant algae species, but the minor algae species were different, suggesting that a wide variety of substrates would increase the pool of species available to the pit lake. The best substrate by far was live material—large filamentous algae and macrophytes such as pondweed or duckweed. These biological surfaces present the added benefit of supplying carbohydrates and vitamins directly to the microflora.

A range of substrates were also tested in 100 L enclosures. Calcium carbonate precipitated in the enclosures with the highest photosynthetic rate such as the submerged aquatic macrophytes, the duckweed and the filamentous green algae enclosures. Calcium carbonate co-precipitates other metals and molecules and raises pH.

Benthic mats contribute most of the organic production in HVC pit lakes, and are crucial to invertebrate production. With fluctuating water levels and small littoral areas, algae will be the base of the food chain in most pit lakes. A small fishery can be supported in many reclaimed pit lakes.

Habitat Diversity

At HVC, submerged aquatic plants were introduced with plant sandwiches dropped into place on benches shallower than 4 m. Native plant mixes from adjacent lakes were employed. These live plant transfers also introduce hitchhiking microflora and invertebrates.

Fertilizing raised nutrient concentrations to the levels required by duckweed. Both filamentous algae and duckweed are not rooted so do not require a stable water level, but they do not tolerate wind throw. We enclosed them in floating log booms that also created additional invertebrate habitat and shade for fish.

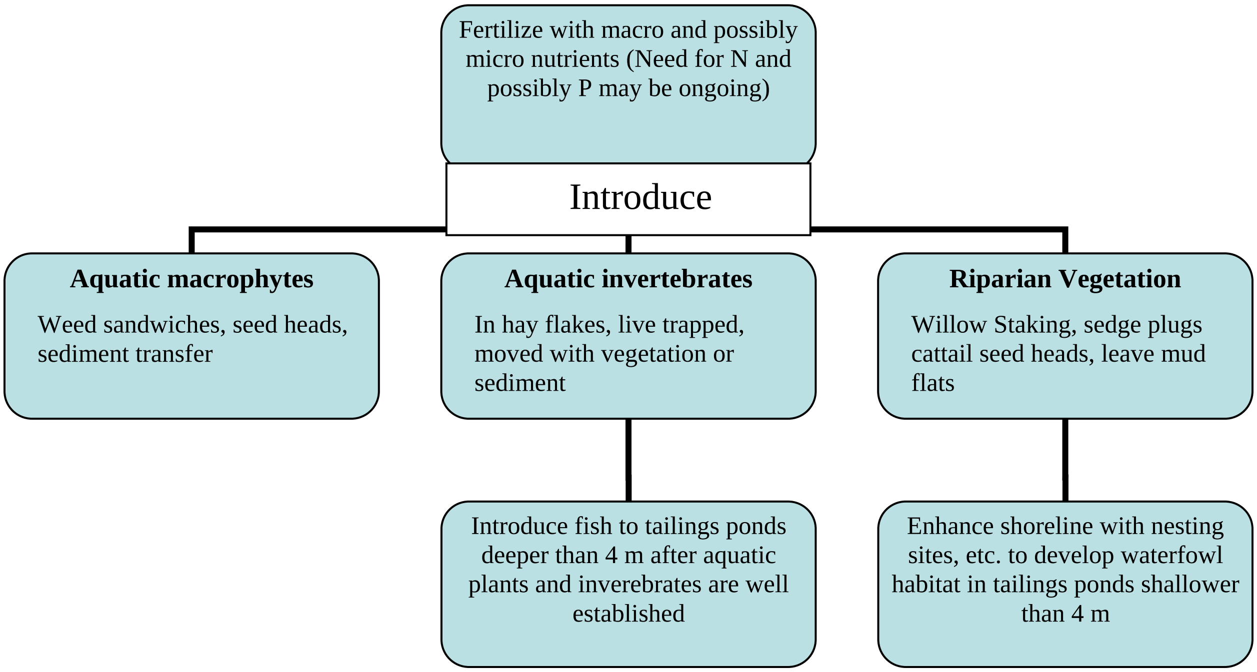
We also added substrate salvaged from a seepage pond clean-out for one pit lake and biosolids in another; both substrates were applied to the old ramps.

Specialized Habitats

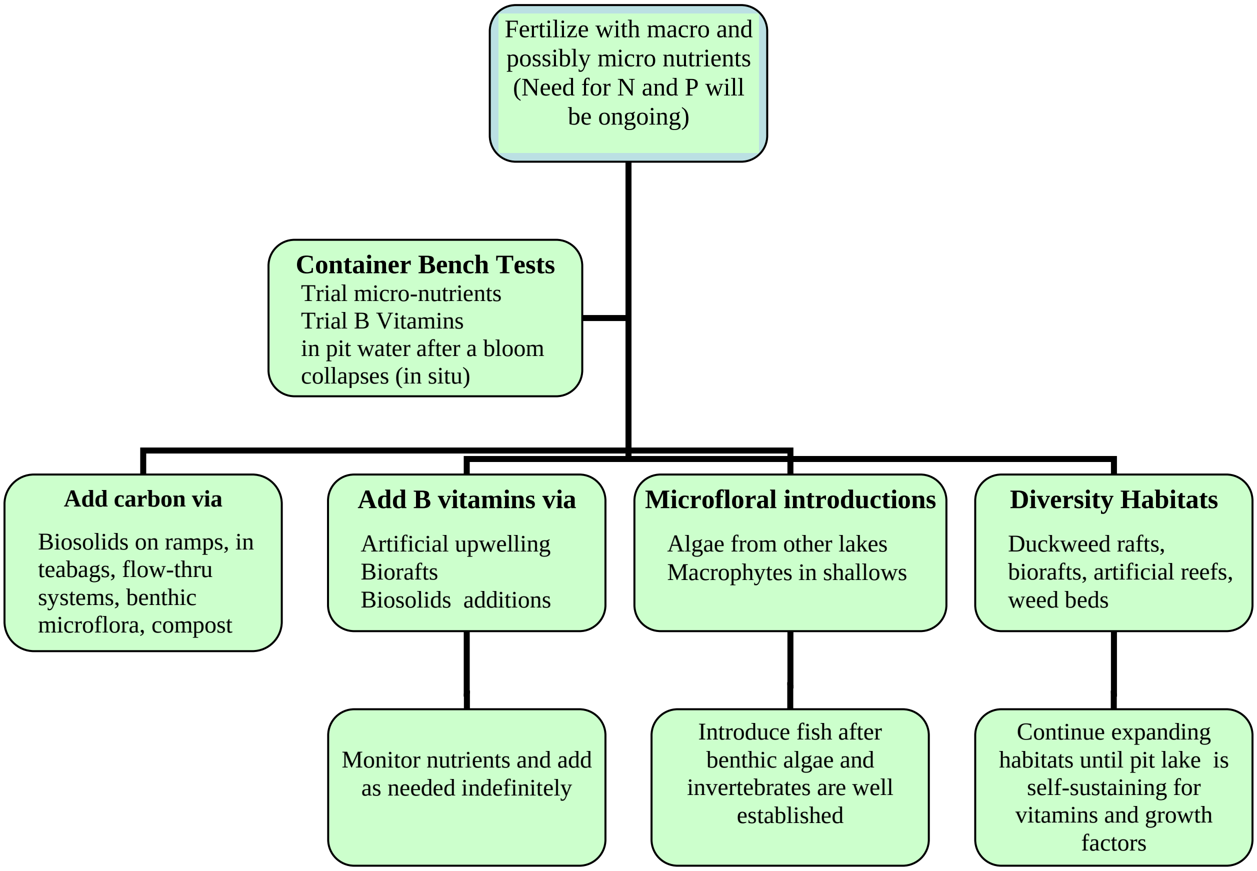
As with tailings ponds, once the food web is established in a pit lake, not only will it function as a bioreactor, it has fishery and waterfowl potential as well. The addition of a selection of clean-out channels, biorafts, nesting rafts, shoreline planting, etc. where practical will enhance wildlife use.

SUMMARY

Flow Chart for Tailings pond Conversion to Aquatic Habitat Plus Bioreactor



Flow Chart for Pit Lake Conversion to Bioreactor Plus Aquatic Habitat



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