INTENSIVE AQUACULTURE IN ABANDONED MINNESOTA IRON ORE PITS: ENVIRONMENTAL & REGULATORY PERSPECTIVES[1]

by

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Abstract. A controversy has developed on Minnesota's Iron Range over the use of two abandoned iron ore pit lakes for intensive net-pen aquaculture of salmon and trout. The pit lakes are still filling with groundwater and the two with aquaculture operations lie immediately adjacent to the Fraser pit lake, the source of Chisholm, MN's drinking water. A two year limnological assessment of these and other nearby pit lakes was conducted to impartially address the major water quality issues and develop predictive models of pit lake responses to increased nutrient loading. There are between 100 and 200 pit lakes on the Iron Range and their use for aquaculture has been promoted actively as a beneficial reclamation. This paper presents an overview of the key environmental and regulatory aspects of the use of these pit lakes for economic development.

Introduction

In the past 25 years, approximately 200 lakes have formed on the Cuyuna, Mesabi, and Vermillion Iron Ranges in Northeastern Minnesota from the gradual filling of abandoned iron mine pits with groundwater (Figure 1). The lakes are relatively small, ranging in size from about two to about one-hundred hectares. They are typically steep sided and relatively deep with maximum depths from about 20m to over 200m (Svatos 1986, IRRRB 1988, Pierce and Tomcko 1989). A few are used for drinking water by Iron Range communities (MPCA 1990) and about 20 are managed for recreation (i.e. picnicing, camping, swimming, boating, and fishing) by a cooperative effort of the Minnesota Department of Natural Resources (MDNR) and the Iron Range Resources and Rehabilitation Board (IRRRB) (Svatos 1986, Pierce and Tomcko 1989).

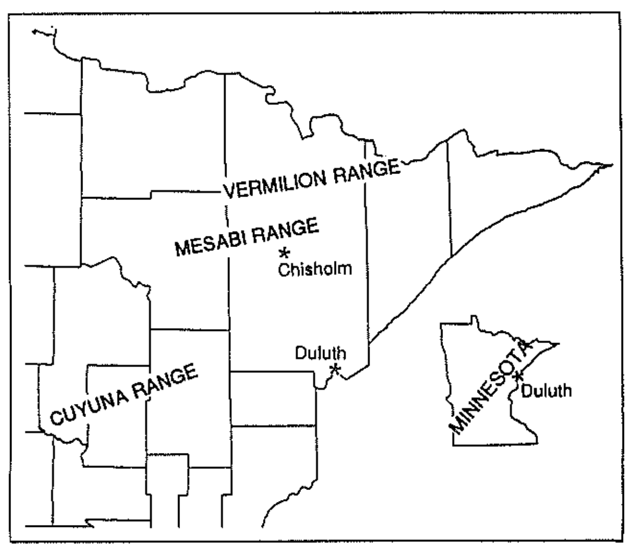

Figure 1. Northeastern Minnesota Iron Ranges where more than 200 mine pit lakes are located.

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The potential of most mine pit lakes for use as recreational trout fisheries is probably limited by their low productivity. Algal primary production is typically quite low and appears to be regulated by low inputs of phosphorus (Pierce and Tomcko 1989, Axler et al. 1992). Benthic invertebrate communities and aquatic vegetation, essential fish food and habitat, respectively, are limited by the small fraction of littoral area relative to natural lakes (Pierce and Tomcko 1989).

In the late 1980s, aquaculture entrepreneurs, the IRRRB, and the Minnesota Department of Agriculture began to actively investigate the development of an aquaculture industry in or around some of the mine pit lakes in Northeastern Minnesota (IRRRB 1987). Feasibility studies on the potential for aquaculture of salmonids in the mine pit lakes estimated that $44 million/year in primary and secondary revenues could be generated (Colt et al. 1987, 1989).

In 1988 a commercial aquaculture operation began intensive production of salmonids, primarily chinook salmon, in net-pens (also known as cage culture) near Chisholm, MN (Figure 2). A controversy soon developed regarding the potential impacts of this activity on the current and potential future beneficial uses of these lakes and on the regional aquifer. Because of conflicting opinions of

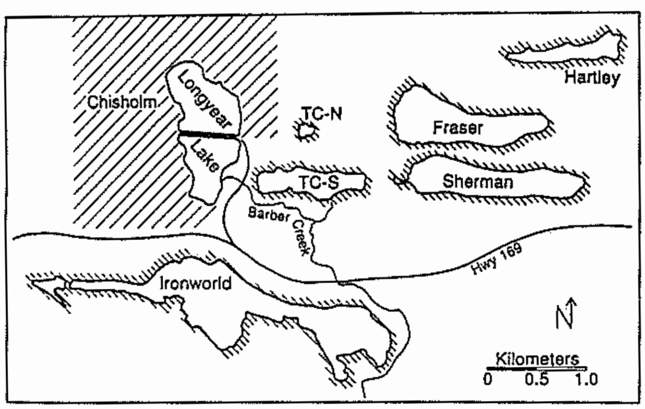

Figure 2. Mine pit study lakes, located east and southeast of the City of Chisholm. Grant pit lake (not shown) is located ~3 kilometers east-northeast of Fraser pit lake. Intensive aquaculture was initiated in Twin City-South (TC-S) in 1988 and in Sherman in 1989. Fraser pit lake is the raw water supply for Chisholm.

the acquaculture industry, local citizens, and the Minnesota Pollution Control Agency (MPCA) about the effects of aquaculture on mine pit lakes, an impartial limnological assessment and modeling of the actual and potential impact of aquaculture on these lakes was commissioned. This two year study was conducted by the Natural Resources Research Institute (NRRI). It focused on the changes in water quality which occurred in two mine pit lakes used for intensive aquaculture in comparison to two reference mine pit lakes without aquaculture (Axler et al. 1992). One of these reference lakes is the raw drinking water supply for Chisholm (a city of about 5000) and it lies adjacent to the aquaculture lakes. The study also developed empirical models for water quality and a fish bioenergetics/mass balance model for estimating aquaculture waste loads and their relative impact on receiving waters.

Concurrent with the establishment of net-pen aquaculture in Minnesota, the legislature mandated the MPCA to develop rules prescribing water quality permit requirements for aquaculture facilities (H.F. 958 [11/07/91]). This process has been controversial and is still in progress as of March 1992. The legislature charged the MDNR with providing rules to protect the genetic integrity of natural fish communities and to prevent the transmission of diseases from cultured fishes to wild populations.

General Water Quality and Limnology

The pit lakes can be generally characterized as hardwater, alkaline lakes with low levels of phosphorus and high levels of nitrate relative to natural lakes in the region (Table 1 and MPCA 1990). The major ion characteristics are generally similar to those of the Biwabik Iron Formation Aquifer which is assumed to be the source of most of the water seeping into the pits (Anderson 1986). Algal productivity during the growing season is likely limited by available phosphorus and occassionally by reductions in light penetration due to high turbidity from direct surface runoff following spring snowmelt and rainstorms.

Ice typically forms by early December and persists until late April. Thermal stratification is rapid and pronounced with a thermocline in the

Table 1. General chemical characteristics of Northeastern Minnesota mine pit lakes. Median values and ranges are surface water annual means (major ions) or May - September means (TP, DIN, chlorophyll) for 18 lakes based on data summarized from Pierce and Tomcko (1989) and Axler et al. (1992). Dissolved inorganic nitrogen (DIN) means for Pierce and Tomcko (1989) lakes assumed an ammonia concentration of 20 µg N/L (ammonia was not measured). Alk (alkalinity), TP (total phosphorus), TDS (total dissolved solids).

	Median	Range		Median	Range
pH (std)	8.0	7.5 - 8.5	TDS* (mg/L)	268	159 - 478
Alk (mg $CaCO_3$/L)	155	82 - 216	SO_4^{2-} (mg/L)	57	12 - 165
TP** (µg/L)	6	1 - 42	Cl^- (mg/L)	5.6	2 - 17
DIN** (µg/L)	87	28 - 2107	Ca^{2+} (mg/L)	47	30 - 90
Chlor-a** (µg/L)	<5	<1 - 12	Mg^{2+} (mg/L)	23	13 - 44
Secchi** (m)	6	2 - 11	Na^+ (mg/L)	7.7	3.9 - 14
			K^+ (mg/L)	2.8	0.4 - 3.4

* calculated from ion sum ** excludes two lakes with intensive aquaculture

range of 5-7m throughout the summer growing season. Although there are spring and fall mixing periods, some mine pit lakes do not mix completely to the bottom every year because they are extremely deep relative to their surface area and because they often lie in sheltered, steep-sided basins. This results in incomplete reoxygenation of hypolimnetic water and/or incomplete redistribution of solutes.

As a consequence of incomplete mixing, the oxygen demand of inundated terrestrial soil and vegetation, and perhaps occasional inputs of domestic wastewater, some mine pit lakes may "naturally" develop anoxic hypolimnia. However, most water in the deeper lakes would be expected to have relatively high levels of dissolved oxygen (>5 ppm) and relatively cool temperatures, both of which are prerequisites for salmonid culture and growth.

Aquaculture

The Minnesota Department of Agriculture (MDA) has noted that aquaculture is currently the fastest growing sector of agriculture in the U.S., averaging 15% annual growth since 1988 (MDA 1990). A similar trend is occurring worldwide in response to an increase in the per capita consumption of both wild and farmed fish (e.g. Beveridge 1987, Robinette et al. 1991). Per capita consumption increased 20% over the period 1975-1988 and is projected to increase another 100% by the year 2020 (Robinette et al. 1991). The importation of fish and fishery products represented about 4% of the total U.S. trade deficit in 1987. In response, the federal and many state governments are actively encouraging commercial aquaculture while at the same time developing regulations specific to the industry for protecting water quality and safeguarding wild fish populations from escaped aquaculture species and disease-causing agents.

There are three primary methods of culturing salmonids: extensive (no exogenous feeding), semi-intensive (low protein supplements to natural foods), and intensive (relying entirely on external additions of high protein [>20%] fishfood). Several of these aquaculture systems could potentially use mine pit water (Table 2). Currently, only one company in Minnesota uses an intensive system. They raise salmon and trout in net pens (with some incidental semi-intensive culture) in each of two mine pit lakes, with a combined volume of 33 x 10^6 m^3. The company has produced about 500-1000 metric tonnes of chinook salmon and trout in its first three years of operation (total fish production, actual harvest is proprietary). The state (MDNR and IRRRB) has attempted to develop put-grow-

Table 2. Potential mine pit lake aquaculture systems for salmonids. √ denotes an existing facility or program in Minnesota.

Type	Options	Manager
EXTENSIVE	put-grow-and-take sport fishery	Government (√) (Resource/Development Agency)
"	put-and-take sport fishery (stock catchable size, little or no growth prior to harvest)	"
SEMI-INTENSIVE	ranching (may be associated with net-pens to utilize wasted food and algal production from pens)	Private (√)
INTENSIVE	net-pens	Private (√)
"	floating raceways / bags	Private
"	land-based raceways / tanks / ponds / etc...	Government Private (proposed)

and-take trout fisheries (i.e. extensive aquaculture) in another twenty pit lakes for recreational fishing. However, success in some lakes has been unsatisfactory due to slow growth rates, presumably a result of low productivity and subsequent low forage bases (Pierce and Tomcko 1989).

Environmental Considerations

General Impacts of Aquaculture

All aquaculture systems which involve the use of exogenous feed (intensive and semi-intensive) or nutrients (some extensive systems) have the potential to impact water quality. Organic enrichment comes primarily from uneaten food and fish feces. In a commercial operation, as much as 30% of dry feed remains uneaten (Rosenthal et al. 1988), and 25 - 30% of the consumed food is egested as feces (NCC 1990). Numerous studies have demonstrated hypolimnetic and sediment anoxia due to organic enrichment from both net-pens and land-based systems (Enell 1982, Leonardsson and Näslund 1983, Brown et al. 1987, NCC 1990, Axler et al. 1992).

Severe oxygen depletion generally results in an accumulation of chemically reduced substances such as ammonium, methane, hydrogen sulfide, and ferrous (iron) and manganous (manganese) ions due to anaerobic bacterial metabolism (Wetzel 1983, Gowen and Bradbury 1987, Bergheim et al. 1990). Hydrogen sulfide is particularly toxic to aquatic life, and in high enough concentrations it may reduce the amount of habitat suitable for aquatic organisms (Wetzel 1983). Unionized ammonia generated at higher pH is also extremely toxic to fish and many other aquatic organisms. Anoxic conditions may also enhance the exchange of nutrients between the sediments and the overlying water. Phosphorus, in particular, is typically released from the sediments at faster rates under anaerobic conditions (Wetzel 1983).

Organic enrichment of the sediments may also affect bottom fauna. Directly under net-pen operations, benthic macro-invertebrates may be absent due to oxygen depletion or excessive sedimentation. Areas near the pens, where the food supply is increased, may be inhabited by only a few opportunistic species. Reduced biodiversity near net-pen facilities is similar to that observed for other types of organic loading (Brown et al. 1987, Bergheim et al. 1990, Weston 1990).

Increased suspended sediment concentrations in the water column from wasted food, feces, and algae can decrease water clarity, interfere with invertebrate and vertebrate feeding, and potentially affect the cost of water treatment for drinking water use. Wasted nitrogen and phosphorus may also contribute to eutrophication problems in nutrient-limited lakes. At salmonid aquaculture facilities, only about 20-25% of the nitrogen and phosphorus from feed is typically retained in the fish (Bergheim et al. 1990). Nitrogen is excreted primarily as unionized ammonia which is toxic to aquatic life. However, at normal pH and temperature most ammonia is rapidly converted to the non-toxic ammonium ion. Ammonium is readily available to algae and could increase algal growth in an N-deficient system. The oxidation of ammonium to nitrate by aerobic nitrifying bacteria will reduce ammonium concentrations but the nitrate is also readily available to algae. Further, the nitrogenous oxygen demand associated with this process may also contribute to dissolved oxygen (DO) problems in the receiving water. Because both ammonium and nitrate are soluble, their removal in a treatment system is particularly difficult.

The phosphorus load from net-pen aquaculture is 70 - 80% solid and settles relatively quickly to the bottom. However, much of this may be released back into the water column during mixing events, particularly if bottom water has become anoxic (Ackefors and Enell 1990). Since most treatment systems focus on solids removal (NCC 1990, FishPro 1991), significant removal of phosphorus is possible.

The generation of noxious algal blooms (particularly scum-forming bluegreen species) due to nutrient enrichment (eutrophication) from aquacultural wastes is another serious concern. Potential effects of algal blooms include: DO depletion from excessive organic matter production and nighttime respiration; aesthetic/recreational value loss; food web alterations; taste and odor problems in both fish and drinking water; and animal/human toxicity (see review by Paerl 1988).

Some aquaculture facilities have caused concern because of the potential for increased human pathogens and/or the spread of disease to wild stocks. However, most studies have shown no significant increase in the numbers of human pathogens or indicator (coliform) bacteria (NCC 1990). Austin and Allen-Austin (1985) suggest that fish at freshwater aquaculture facilities would probably become impacted by microbial pollutants before the microbial pollution was detrimental to the surrounding aquatic environment. Further, there is virtually no evidence to support the suggestion that microbes pathogenic to fish are a health risk to humans, especially since fish are cold-blooded. It is likely that where an association between fish farms and human pathogens (or indicator organisms) has been suggested, the problem was due to the use of animal manure used to stimulate production, or improper handling of fish feed (WDF 1990).

Wild populations of fish may be affected by the introduction of disease and parasites with farmed fish, especially if the cultured fish are of exotic origin. Farmed fish may escape into the environment and compete with native populations for habitat and resources. In addition, the genetic diversity of wild populations may be decreased or contaminated by farmed fish breeding with wild fish (Bergheim et al. 1990, NCC 1990). However, aquaculture in nutrient poor waters may potentially benefit indigenous fish species if the wild fish eat wasted food. Fertilization of the water from aquaculture may also enhance the overall productivity of the system, allowing more native fish species to survive (Phillips et al. 1985).

Antibiotics used in aquaculture are administered through food additives, injection, or as baths or dips. Antibiotic use is a concern because it may inhibit natural populations of bacteria, thus reducing the breakdown of organic wastes. Persistence of antibiotics could lead to increased bacterial resistance, ultimately leading to reduced antibiotic efficacy (Austin 1985, NCC 1990, WDF 1990). Antifoulants and chemicals leached from construction materials may also show some toxic effects on aquatic organisms (Rosenthal et al. 1988).

Impacts Related To Mine Pit Lakes

An assessment of the potential impacts associated with aquaculture in Northeastern Minnesota's pit lakes can be organized around three general areas: (1) public health issues; (2) ecological impacts; and (3) impacts on water quality/beneficial uses.

Public Health. Both direct chemical additions and indirect eutrophication effects continue to be central issues for Minnesota net-pen aquaculture (Axler et al. 1992). The key public health issues for the net-pen facility near Chisholm, MN have been the potential for degradation of nearby, public, drinking water supplies and the regional aquifer. Since the public was prohibited from recreational use of the aquaculture lakes, and since no aquaculture was permitted in a nearby pit lake used by the city as a domestic water supply, degradation of water supplies due to aquaculture activities could occur only via seepage to groundwater. Assessments of long-term degradation of an aquifer depend upon the local and regional hydrogeology and are often difficult, expensive, and imprecise. Arguably, during the current filling phase of these pit lakes, the gradient of water movement is into the pits. However, after pit lake levels stabilize (generally estimated to be 10-20 years), some migration of solutes may occur (depending upon the direction of groundwater flow and concentration gradients).

Nitrate-nitrogen, produced from the nitrification of ammonia excreted by fish, and from ammonium mineralized from wasted food and fish feces, is the only chemical directly derived from aquaculture that we found to pose a potential long-term public health concern. Since it is very mobile in water, aquaculturally-generated nitrate could potentially increase the existing nitrate concentrations in the drinking water pit lake and in the local aquifer. However, the federal primary drinking water standard is 10,000 µg N/L, and the highest concentrations observed to date in these lakes were about one order of magnitude below this level. Since the rate of increase over the past three years has been 300 µg (NO_3-N)/L per year, it is likely that dissolved oxygen depletion or other problems will likely limit fish production well before the nitrate standard (in the aquaculture lake) is approached.

Additional human health concerns included the use of alum and the production of trihalomethanes (THM's). Alum was used to reduce phosphorus concentrations to permit levels. Although public concerns continue over potential links between aluminum and Alzheimer's disease, the scientific concensus appears to be "no causative link," at least at the levels encountered in natural waters or in mine pits used for aquaculture (Axler et al. 1992). Further, salmonids are among the most sensitive organisms to toxic forms of aluminum. The highest levels suggested as a proposed drinking water standard (50 ug/L dissolved) would pose a much greater threat to the salmonid fish stock than to humans (Axler et al. 1992).

THM's were identified as a human health concern because they are suspected carcinogens, they are created during the chlorination of natural water, and because recent studies suggest that their precursor concentrations may increase with increased levels of organic matter derived from eutrophication (e.g. Pope et al. 1988). THM's are typically present in natural waters at only very low levels but form during the disinfection process with free chlorine. The amount formed depends upon the type and concentrations of precursors, the chlorine dose and contact time, water temperature, and pH. The most common precursors, humic substances derived from the decomposition of plant and animal tissue, constitute at least half of the dissolved organic carbon (DOC) in natural waters (Wetzel 1983). As a result, DOC and TOC (total organic carbon) have been suggested to be useful for estimating the levels of THM precursors in a water body (Edzwald et al. 1985).

It is clear that intensive organic matter loading associated with aquaculture, especially net-pen culture, has the potential to increase THM's if the water is subsequently chlorinated for disinfection. THM production could be avoided by using forms of disinfection other than free chlorine, although additional costs may be incurred. We did <u>not</u> observe a significant buildup of TOC in our study lakes used for aquaculture (Axler et al. 1992). However, since "carcinogens" generate extra (and very emotional) concerns, we believe that intensive, economically viable, aquaculture operations and public drinking water supplies are incompatible.

The growth of potentially toxic forms of scum-forming bluegreen algae was not a problem in our study lakes because of the recirculation/reaeration systems used to maintain DO levels required for salmonid survival (Axler et al. 1992). The intensive aeration system vertically mixed phytoplankton out of the euphotic zone for much of the day; therefore, they were light-limited for much of the time. However, in the absence of this intensive management, scum-forming algal blooms could have produced an "off-taste" in the fish as well as secondary effects on water quality.

Ecological Impacts. Ecological impacts are largely related to eutrophication effects (i.e. algal blooms, DO depletion, water clarity reduction, H_2S buildup, etc.), rapid sediment (muck) buildup on the bottom, and impacts on indigenous aquatic, and perhaps terrestrial, species. The magnitude of eutrophication effects is clearly a function of the rate of fish production in relation to the size of the receiving water body (Beveridge 1987, NCC 1990, Axler et al. 1992).

The relative change induced in the system by fish wastes also depends upon the "natural" rate of nutrient inflow. In Northern Minnesota pit lakes, phosphorus inflow is likely to be very low, and relatively dramatic increases in nutrient levels may result from aquaculture (Figure 3). Severe eutrophication effects may be mitigated by intensive management techniques such as vertical mixing, reaeration, and sediment collection. Direct collection of fish wastes for treatment may be the most desirable mitigation technique, but it has not been shown to be cost-effective for commercial net-pen culture (FishPro 1991).

The collection of solids can be accomplished relatively easily in land-based systems and in totally enclosed floating systems by using filters and sedimentation ponds. For these operations where the effluent is an end-of-pipe discharge, a variety of technologies developed for fish hatcheries and domestic and industrial waste streams are potentially available (FishPro 1991, NCC 1990).

Net-pen wastes are more difficult to collect and treat because the waste load is rapidly diluted in the receiving water. This precludes removal of soluble wastes (such as ammonia and dissolved organic matter), although collection of particulate fecal material and wasted food would be possible.

The Minnesota net-pen operation near Chisholm is currently designing a prototype waste-

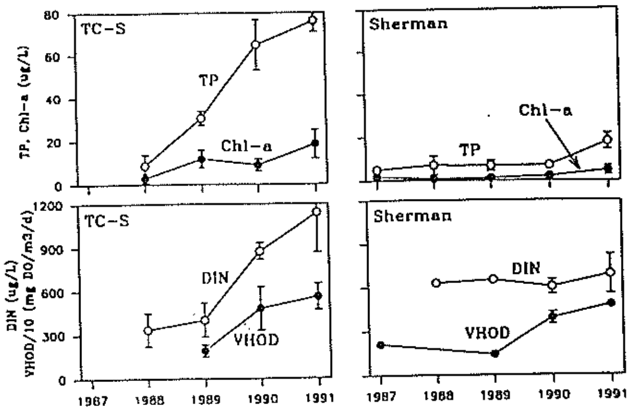

Figure 3. Trends of mean summer (May-September) total phosphorus (TP), chlorophyll-a (Chl-a) and dissolved inorganic nitrogen (DIN) in surface water, and the volumetric hypolimnetic oxygen deficit (VHOD) in Twin City-South (TC-S; intensive aquaculture initiated in 1988) and in Sherman (intensive aquaculture initiated in late 1989) pit lakes. Values plotted with 95% confidence intervals.

collection system and may be required by the MPCA to install a full-scale collection system. Such a collection system could remove a significant fraction of the lake's phosphorus load, which is predominantly particulate, and could reduce bottom sediment accumulation. However, inorganic nitrogen and overall biochemical oxygen demand (BOD), which are predominantly soluble, would not be greatly reduced (Axler et al. 1992, FishPro 1991).

Additional, economic removal of nutrients from either land-based or net-pen systems could be accomplished using artificial wetlands (e.g. Gersberg et al. 1984), especially if the water levels in the mine pit lakes stabilize near their rims. The effluent water from an aquaculture operation could also be used as irrigation water for agriculture or mineland revegetation, in which case its "pollutant load" would become a valuable resource - fertilizer.

Mine pit lakes have an advantage over natural lakes for *in situ* aquaculture or aquacultural discharges since they are artificially created and do not contain indigenous species of fish. A major issue for coastal marine salmon aquafarming involves the effects of these farms on existing natural fish stocks (e.g. Rosenthall et al. 1988, NCC 1990, Beveridge 1987). Concerns relate to the spread of disease from farmed fish to wild populations, dilution of genetic diversity from genetically altered culture species, and the spread of exotic species (Robinette et al. 1991). User conflicts regarding mine pit lakes could arise between fish farmers and sport fishing interests, although this could be avoided by careful planning. A moderate organic enrichment of the invertebrate-depauperate bottom sediments and of the water column could prove beneficial in developing and supporting a sport fishery in these unproductive lakes.

Generally, impacts on birds or mammals by aquaculture facilities are likely to be positive unless predator control measures are taken. Aquaculture wastes, unlike domestic waste loads from sewage treatment plants, urban runoff, and industrial effluents, do not contain pathogens (to warm blooded animals), pesticides (as do agricultural discharges), solvents, heavy metals, or persistent organic toxicants.

The potential for inducing long-term or irreversible changes in the pit lakes is also an issue of concern in Minnesota. Clearly, some relatively long-term changes will occur as a result of high loads of organic matter and nutrients from intensive fish farming. However, the situation differs in several respects from more typical "eutrophication scenarios" that involve sewage inputs or land development effects.

First, the discharger (i.e. the aquaculture operator) may depend upon the quality of the water to which he is discharging, i.e. a system which recycles receiving water. The product (salmonid fish) is one of the most sensitive water quality monitors. Second, if the business fails, the external load is eliminated almost instantly. The mine pit basins are typically steep sided and comprised of bare mineral soils, and so erosional inputs of silt and clay are relatively high compared to natural lakes. Therefore, burial of the organic fish wastes may occur more quickly than in natural lakes. Although periodic infusions of phosphorus released from the sediment will likely support enhanced algal growth, this effect could be expected to decrease over a period of years as the muck is buried and the more labile organic matter in the water column is mineralized. In addition, lake restoration techniques such as phosphorus precipitation/inactivation can be used to more quickly reduce sediment nutrient release.

The long-term legacy of fish farming is likely to be higher concentrations of nitrate relative to the baseline condition. Denitrification in anoxic bottom water and surficial sediments will remove some of this load, depending upon the degree and extent of oxygen depletion in the deep hypolimnion. Continued inflow of groundwater, precipitation, and runoff which are lower in nitrate would act to dilute nitrate levels in the pit lakes.

Regulatory Issues

Permits

Considerable confusion over the procedure for obtaining environmental permits has arisen in Minnesota in recent years. This problem is not unique to Minnesota (e.g. McCoy 1989, Robinette et al. 1991, Rubino 1992, Barinaga 1990, Stephenson 1990) and reflects a combination of the occassionally conflicting responsibilities of numerous state and federal agencies, in addition to philosophical differences regarding the balance between developing this new form of agriculture and minimizing water quality changes.

The Minnesota Pollution Control Agency is authorized by the US EPA to set state water quality standards under the provisions of the federal Clean Water Act and its amendments to prevent pollution and protect water quality. As regards aquaculture, the Minnesota Department of Natural Resources is responsible for managing the state's fisheries resources, controlling aquatic nuisances, and regulating water appropriations. The Minnesota Department of Agriculture actively promotes and coordinates the aquaculture industry statewide, and has programs to assure the quality of the state's agricultural products. The Minnesota Department of Health is also involved in various aquaculture/water quality issues because it is authorized by the US EPA to administer the provisions of the federal Safe Drinking Water Act and its amendments.

Several other agencies are important members of the aquaculture community in Minnesota. The

Iron Range Resources and Rehabilitation Board (IRRRB) is a state agency set up in 1941 to enhance and diversify the economy of northeastern Minnesota from its reliance on iron-ore mining and forest products. It has financially encouraged the use of mine pit lakes for aquaculture, for both commercial and recreational fisheries, as a form of reclamation. More recently, Minnesota Technology, Inc., formerly the Greater Minnesota Corporation, was formed by the State as a public, nonprofit corporation which supports the development and adoption of technology by Minnesota industry. The Minnesota Extension Service and Minnesota Sea Grant also have important roles, especially with regard to technology development and transfer from the University systems to aquaculturists.

Minnesota's development of salmonid aquaculture in pit lakes has provided a unique model to the rest of the country in terms of potential problems (environmental and political) associated with the "reclamation" of these newly created freshwater resources. Aquaculturists would prefer minimal regulations and would prefer that the principal factor limiting their waste discharges be the economic cost of wasted fish food. This parallels arguments made by farmers regarding excess fertilizer usage on farmland. Further, a net-pen system is inherently dependent upon reasonable water quality for the health of its fish.

This contrasts strongly with the views of regulatory agency staff who view nutrient discharges as pollution and who are committed to reducing pollution at the source. The US EPA has ruled that all net-pen operations are to be treated as point source discharges of pollutants, similar to land-based systems, and therefore, must apply for a National Pollutant Discharge Elimination System (NPDES) Permit. This applies to all facilities harvesting more than 20,000 lbs of coldwater fish per year or feeding more than 5000 lbs of food per month during the month of maximal feeding. These criteria for coldwater species (trout, salmon) essentially exempt only small, part-time operations since gross annual income would be expected to be only about $40,000 maximum. A similar exemption exists for facilities harvesting less than 100,0000 lbs of warm/coolwater fish per year.

In the case of the salmon farm in Chisholm, MN, an NPDES permit was written which, in addition to a suite of other water quality and limnological parameters, set "trigger" (i.e. warning) and "action" (implementation of a remedial action plan) levels of 20 and 33 µg TP/L, respectively, in the farmed lakes. These values were based on reasonable expectations of water quality for the ecoregion in which the aquaculture facilities were located (see Heiskary and Walker 1988 and Wilson and Walker 1989). This was an attempt to set an upper bound to phosphorus loading in relation to the highest expected loads in the region, although it would also curtail the potential magnitude of the farming operation.

In fact, these phosphorous standards have been routinely exceeded since 1988. In 1990 the company used alum to precipitate phosphorus from the water column in an attempt to meet its permit requirement for in-lake phosphorus concentration. This routine lake management technique worked temporarily but "precipitated" additional public protest over the potential harmful effects of aluminum in the aquifer. Although these concerns are unlikely to be substantive (Axler et al. 1992), they have political impact.

Presumably, if the pit lakes were located in a different ecoregion within the state, such as the North Central Hardwoods Forest or Western Corn Belt Plains, then NPDES permit levels for phosphorus might have been less stringent, since lakes in those ecoregions tend to be more productive than lakes in the Northern Lakes and Forests ecoregion (presumably due to agricultural and urban runoff; MPCA 1990).

"Public vs Private Waters"

Another source of disagreement regarded the terms "waters of the State" and "public waters." "Waters of the State" includes essentially all lakes, ponds, marshes, rivers, streams, ditches, springs, and waters from underground aquifers, regardless of their size or location (Minnesota Statutes sections 115.01 and 115.41). This authorizes the MPCA to set water quality standards for abandoned mine pit lakes, irrespective of their shoreline ownership. Considerable confusion and controversy arose over the term "public waters," which was previously used by the MDNR to denote lakes with publicly-owned access. The aquaculture company in Chisholm asserted that since it controlled the shoreline of the pit lakes, and the public was legally forbidden to trespass, the MPCA (and the Clean Water Act) had no authority over the water quality of its "private waters." In fact, MDNR is now listing "public waters" as "Protected Waters" to help avoid future confusion, since technically in Minnesota there are no "private waters."

Nondegradation Of Groundwater

Since the pit lakes have formed primarily from groundwater seepage back into the cone of depression created by historical mine dewatering, they clearly are connected to the underlying aquifer. Minnesota, along with many other states, is currently in the process of developing a strategy for long-term protection and monitoring of its groundwater resources (1989 Groundwater Protection Act). The impetus for this resulted largely from concerns about consumptive use (overdrafting), degradation from agrochemical residues (i.e. toxic pesticides and nitrate fertilizer) in Central and Southern Minnesota where farming predominates, and controversies regarding the siting of waste disposal facilities. However, the issue of non-degradation or anti-degradation can be emotionally charged wherever the aquifer is the primary source of a community's drinking water, as is the case on the Iron Range.

The situation in Chisholm, MN appears to have been initially polarized by plans to farm fish in the Fraser pit, the raw water supply for Chisholm. Although intensive aquaculture was never officially permitted in Fraser, approximately 100,000 rainbow trout were stocked in July 1988 and about 17,000 kg of fish food were added over the next 5 months. The ration was for minimal maintenance but because of the public outcry it was terminated and an effort was made to recapture the fish. Despite no change in Fraser's water quality attributable to adjacent farmed pit lakes (Figure 2), strong opposition to the existing operation remains. Nitrate appears to be the only contaminant which could eventually approach a drinking water standard, and this only in the aquaculture lakes, not in Chisholm's water supply.

Beneficial Uses

An important outcome of the aquaculture controversy will undoubtedly be the need for the State (and County) to more clearly specify the beneficial uses of the pit lakes dotting the landscape of northern Minnesota. Pit lakes used as drinking water supplies, or very near to other surface waters or deep well shafts used for domestic supply should be clearly identified and protected. Similar protection could be designated for pit lakes being managed for recreational fisheries and water contact sports if water clarity and an unproductive trophic status are deemed desirable. A subset of lakes might be found for which nutrient enrichment poses little threat to potential beneficial uses.

In fact, the Draft St. Louis County, MN Water Plan (Sept. 1991, Summary and Action Plan) currently incorporates these suggestions. Clearly, a policy of total non-degradation of the pit lakes or the underlying aquifer is likely to make it very difficult for an aquaculture industry to survive economically, be it in-lake or land-based.

Proposed Aquaculture Rules

In 1991 the Minnesota Legislature passed the Aquaculture Development Act (H.F. 958) which in part mandated the MPCA to formulate new administrative rules for aquaculture. The intent was to balance the developing new industry with adequate protection of human and environmental health. The Act specifically provided that the rules consider: (1) Best Available Technologies (BAT's) and Best Management Practices (BMP's) that minimize the degradation of the waters of the state while considering economic factors, technical feasibility, and environmental impacts; (2) different types of aquaculture; (3) temporary reversible impacts versus long-term impacts on water quality; (4) effects on drinking water supplies; and (5) aquacultural therapeutics (MN 1991).

In drafting the rules, the MPCA reviewed standards developed by other states and countries for similar facilities. However, few guidelines are available for freshwater aquaculture, particularly for net-pen culture (BC 1990, Ontario 1990, Washington 1990, SAIC 1987). Most net-pen operations are marine, where regulations are generally based on siting and sizing criteria (Washington 1990, BC 1990, FishPro 1991). Effluent discharge limits for land-based systems appear to have been based primarily on BAT's, essentially sedimentation ponds to remove solids before discharge.

The proposed Minnesota rules treat aquaculture in a manner similar to a "concentrated animal production facility," i.e. a feed lot. Effluent discharge standards are specified for BOD, total suspended solids (TSS), fecal coliforms, oil, pH, and total phosphorus, and are identical to those for new domestic wastewater treatment facilities. The proposed standards appear somewhat less restrictive than those previously developed in the US and Canada (cited above), since the TSS standard is 30 mg TSS/L for monthly means as opposed to the daily standard of 15 mg TSS/L used by the other states or provinces. However, there are permit provisions for setting more stringent phosphorus (or other) limits where a receiving water body would be impacted.

The Minnesota draft rules make no distinction between land-based and *in situ* facilities. This apparently would require net-pen facilities to install expensive waste removal systems which would impair their economic viability. This requirement was justified economically because initial capital construction costs are expected to be much lower for a net-pen operation than for a land-based facility (MPCA 1991). Stringent requirements for baseline and operational monitoring of important limnological parameters are also included.

The rules require that a "closure plan [with]... financial assurances for closure, post-closure monitoring, and corrective actions for restoration of the receiving waters to baseline water quality..." would be a permit condition. This is unique in that the State would thereby have the authority to allow some "temporary" degradation of water quality, provided a feasible method for restoring baseline quality would be assured. Additional Minnesota rules currently being prepared by the MDNR will deal with the issues of importation of "exotic" species, use of genetically altered aquatic species, transportation of live fish, and the potential impacts of the escape of cultured organisms on native wild species.

It is somewhat ironic that a reclamation fund will be needed for mitigating the potential impacts of what was originally thought of as a reclamation industry - an economic use for abandoned mine pits. Clearly, any project proposing to use land in the pit basins or the pit water itself should plan to prepare a detailed environmental assessment with preoperational baseline data, and possibly a full EIS, in addition to implementing a long-term monitoring program. The aquaculture controversy in Minnesota has highlighted the concern of citizens for their water quality, particulary if a drinking water aquifer can potentially be impacted. It has important implications for any future use of the water, or the watersheds of the mine pits.

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