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Low-head, roughing filters for enhancing recycle water treatment for aquaculture

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Low-head, roughing filters for enhancing recycle water treatment for aquaculture

By

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TABLE OF CONTENTS

LIST OF FIGURES

PAPER II. USE OF LOW-HEAD, STATIC-MEDIA FILTERS FOR CLARIFICATION AND NITRIFICATION IN A RECIRCULATING FISH CULTURE SYSTEM

PAPER III. CULTURE OF WALLEYE FROM FINGERLINGS TO FOOD-SIZE IN A RECIRCULATING SYSTEM

LIST OF TABLES

PAPER III. CULTURE OF WALLEYE FROM FINGERLINGS TO FOOD-SIZE IN A RECIRCULATING SYSTEM

NOMENCLATURE AND ABBREVIATIONS

Variable Notations

a	specific interfacial area, m^{-1}
a_{CO_2}	CO_2 produced as a proportion of feed fed, kg CO_2 per kg feed
a_t	total specific surface area of packing, m^2/m^3
a_w	wetted specific surface area of packing, m^2/m^3
A	total gas-liquid interfacial contact area, m^2
Alk	alkalinity, mg/L as $CaCO_3$
C_0	concentration of CO_2 entering the culture tank, mg/L
C_1	concentration of CO_2 within the culture tank, mg/L
C_2	concentration of CO_2 entering the air-stripping column, mg/L
C_{CO_2}	concentration of CO_2 in water, mg/L
$C_{CO_2}^{eq}$	concentration of CO_2 in water which would be in equilibrium with the CO_2 levels in the surrounding atmosphere, mg/L
$C_{CO_2}^{g}$	concentration of CO_2 in gas phase, mg/L
$C_{CO_2}^{inf}$	concentration of CO_2 in stripping column water inflow, mg/L
$[CO_2]$	aqueous carbon dioxide molarity, mol/L
$[CO_3^{=}]$	aqueous carbonate molarity, mol/L
C_{TAN}	concentration of TAN within culture tank, mg/L
$C_{TAN,0}$	concentration of TAN flowing into culture tank, mg/L
d_p	nominal packing diameter, m
D	diameter of particle, m
DF_{eff}	driving force in the stripping tower's liquid effluent, difference between actual and predicted equilibrium mol fractions, unitless
DF_{inf}	driving force in the stripping tower's liquid influent, difference between actual and predicted equilibrium mol fractions, unitless
DF_{LM}	log mean driving force across the stripping tower, log mean difference between influent and effluent driving forces, unitless
D_L	diffusivity of CO_2 in liquid phase, m^2/s
D_G	diffusivity of CO_2 in gas phase, m^2/s
ε	porosity of granular-media bed, unitless
f_{rem}	fraction of CO_2 removed from liquid phase across stripping tower, unitless

$f_{rem,1}$	fraction of TAN removed across roughing filter, unitless
$f_{rem,2}$	fraction of TAN removed across biofilter, unitless
g	acceleration due to gravity, m/s^2
G_{mass}	superficial mass flow rate of gas through stripping tower, kg sec^{-1} m^{-2}
G_{mol}	superficial molar flow rate of gas through stripping tower, mol sec^{-1} m^{-2}
G_{vol}	superficial volumetric flow rate of gas through stripping tower, m^3 sec^{-1} m^{-2}
G/L	ratio of volumetric flow of gas to volumetric flow of liquid, unitless
$[H^+]$	hydronium ion molarity, mol/L
$[HCO_3^-]$	aqueous bicarbonate molarity, mol/L
$[H_2CO_3]$	carbonic acid molarity, mol/L
$[H_2O]$	water molarity, mol/L
k	fish condition factor, g/mm^3
$k_{1/2, TAN}$	maximum TAN removal rate, g TAN per m^2 of biofilm per day
k_{CO_2}	rate constant for kinetics of CO_2 hydration, sec^{-1}
k_G	mass transfer resistance coefficient across the gas interphace, m sec^{-1}
$k_{H_2CO_3}$	rate constant for kinetics of CO_2 dehydration, sec^{-1}
k_L	mass transfer resistance coefficient across the liquid interphace, m sec^{-1}
K_0	equilibrium constant for the hydration of CO_2 into H_2CO_3, unitless
K_1	equilibrium constant for the ionization of H_2CO_3 into H^+ and HCO_3^-, mol/L
K_2	equilibrium constant for the ionization of HCO_3^- into H^+ and $CO_3^=$, mol/L
K_H	Henry's law constant when using mol fraction units in both liquid and gas phases, atm
K_H^D	Henry's law constant when using mol fraction in gas phase and concentration in liquid phase, atm L/mg
K_H^M	Henry's law constant when using mol fraction in gas phase and molarity in liquid phase, atm L/mol
K_H^u	Henry's law constant when using molarity or concentration units in both gas and liquid phases and ignoring P_T, unitless
K_L	overall mass transfer coefficient, m sec^{-1}
K_W	equilibrium constant for the ionization of H_2O into H^+ and OH^-, mol^2/L^2
J_{CO_2}	rate of mass transfer of CO_2 from liquid phase to gas phase, sec^{-1}
L	length of a fish, mm

L_{mass}	superficial mass flow rate of liquid through stripping tower, kg sec^{-1} m^{-2}
L_{mol}	superficial molar flow rate of liquid through stripping tower, mol sec^{-1} m^{-2}
L_{vol}	superficial volumetric flow rate of liquid through stripping tower, m^3 sec^{-1} m^{-2}
L:W	length to width aspect ratio
M_{CO_2}	molarity of CO_2 in the liquid phase, mol/L
MW_{air}	molecular weight of air, g/mol
MW_{CO_2}	molecular weight of air, g/mol
MW_{H_2O}	molecular weight of air, g/mol
$[OH^-]$	hydroxide ion molarity, mol/L
μ_L	viscosity of liquid, kg/m/s
pH	(-) log base 10 of the concentration of hydronium ion, unitless
pK_a	(-) log base 10 of the acids equalibrium constant, unitless
ΔP	differential of the vapor pressure of gases in water above saturation, mm Hg
$\Delta P/L$	headloss across a bed of granular media, cm of H_2O
P_{CO_2}	CO_2 production rate, mg/min
P_T	pressure of the vapor phase, atm
P_{TAN}	TAN generation rate, mg/L/d
Q	flow rate through the culture unit, L/min
ρ_1	density of particle, kg/m^3
ρ_{fish}	density of fish, kg fish per liter rearing space
ρ_G	density of gas, kg/m^3
ρ_L	density of liquid, kg/m^3
r_{feed}	feeding rate, kg feed per kg fish per day
r_{loss}	rate that CO_2 is lost from the culture tank to the atmosphere, mg/min
$r_{max, TAN}$	maximum TAN removal rate, g TAN per m^2 of biofilm per day
r_{TAN}	TAN removal rate, g TAN per m^2 of biofilm per day
R	fraction of water reused in a generalized recirculating system, unitless
R_1	fraction of water reused passing the roughing filter, unitless
R_2	fraction of water reused passing the biofilter, unitless
σ	standard deviation
σ_c	critical surface tension for the packing material, N/m
σ_L	surface tension for the liquid, N/m
S_b	bed specific surface area, cm^{-1}

S_p	particle specific surface area, cm^{-1}
SS	suspended solids, mg/L
T	temperature, °C or °K
TAN	total ammonia nitrogen, mg/L
TVS	total volatile solids, mg/L
TS	total solids, mg/L
v	settling velocity of discrete particles, m/s
v_0	superficial velocity of the fluid, cm/s
V	gas-liquid contact volume, m^3
VSS	volatile suspended solids, mg/L
V_{tank}	volume of rearing tank, L
W	weight of a fish, g
W_S	standard weight of a fish, g
X_{CO_2}	mol fraction of CO_2 in the liquid phase, unitless
$X^{eq}_{CO_2}$	mol fraction of CO_2 in the liquid phase which would be in equilibrium with the mol fraction of CO_2 in the gas phase, unitless
X_{eff}	mol fraction of CO_2 in stripping columns effluent water flow, unitless
X^{eq}_{eff}	mol fraction of CO_2 in the stripping column effluent water flow which would be in equilibrium with the CO_2 in the inflowing gas phase, unitless
X_{inf}	mol fraction of CO_2 in stripping columns influent water flow, unitless
X^{eq}_{inf}	mol fraction of CO_2 in the stripping column influent water flow which would be in equilibrium with the CO_2 in the effluent gas flow, unitless
Y_{CO_2}	mol fraction of CO_2 in the gas phase, unitless
Y_{eff}	mol fraction of CO_2 in stripping columns effluent gas flow, unitless
Y_{inf}	mol fraction of CO_2 in stripping columns influent gas flow, unitless
Z	stripping tower height, m

Chemical Notations

BOD	biochemical oxygen demand
$C_5H_7NO_2$	approximate stoichiometric estimate of cell mass
$Ca(OH)_2$	calcium hydroxide (slaked lime)
$CaCO_3$	calcium carbonate
CaO	calcium oxide (burned lime, quick lime, unslaked lime)
cBOD	carbonaceous oxygen demand
CO_2	carbon dioxide
$CO_3^=$	carbonate
H^+	hydronium ion
H_2CO_3	carbonic acid
H_2O	water
HCO_3^-	bicarbonate
HNO_2	nitrous acid
HNO_3	nitric acid
N_2	nitrogen
Na_2CO_3	sodium carbonate (soda ash)
$NaHCO_3$	sodium bicarbonate
NaOH	sodium hydroxide (caustic soda)
NH_3	ammonia
NH_4^+	ammonium
NO_2^-	nitrite
NO_3^-	nitrate
O_2	oxygen
OH^-	hydroxide ion

Other Abbreviations

APHA	American Public Health Association
AWWA	American Water Works Association
CSTR	continuous-flow stirred tank reactor
EIFAC	European Inland Fisheries Advisory Committee
EPA	Envirnmental Protection Agency
FWS	Fish and Wildlife Service
RBC	rotating biological contactor
RFS	roughing filter system
SBS	settling basin system
SECL	Sigma Environmental Consultants, Limited
USDC	Department of Commerce, Bureau of the Census
USDI	Department of Interior

GENERAL INTRODUCTION

Objective

The objective of this research project was the study of water treatment technologies required for rearing walleye in closed-systems. Specifically, the processes of clarification, nitrification and carbon dioxide removal as well as the growth of walleye in closed systems were focused on. The project was oriented towards using processes amenable for converting abandoned water and waste water treatment plants into commercial sites for culturing walleye using recycle systems.

Explanation of Dissertation Organization

This dissertation was written as a compilation of papers which will be submitted for publication.

The purpose of the "Review of Literature" chapter is to provide background relevant to the studies performed and which are reported in the "paper" chapters of this dissertation.

Papers I and II will be submittal to the Journal, *Aquacultural Engineering*. Paper III will be submittal to the journal, *The Progressive-Fish Culturist.*

There is a general summary and discussion chapter following the last paper chapter. The list of references cited in the "Review of Literature" and "General Summary and Discussion" chapters follows the "General Summary and Discussion" chapter.

REVIEW OF LITERATURE

Aquaculture

Aquaculture can be defined as the production of aquatic organisms (in this case walleye) in controlled environments. Control over the culture environment increases the reliability, predictability and intensity of fish production. Production systems include ponds, raceways, tanks, net pens, and silos. In extensive (pond) culture with multiple harvests, artificial aeration and the use of some water for flushing, annual harvests approach 5,000 lb/acre (Dupree and Huner, 1984). In intensive fish culture (raceways and tanks), channel catfish (*Ictaluras punctatus*) have been raised at densities up to 900,000 lb/acre by utilizing flowing water to supply oxygen and remove wastes. Controlling fish culture environments is expensive, however, and the specific culture requirements of different species of fish affects the economics of raising fish extensively or intensively. Currently, pond culture is used for rearing most catfish and intensive culture systems are used for rearing salmonids.

A comprehensive review of the past, present, and future of aquaculture systems is given by McCoy (1986, 1987a, and 1987b). In the U.S., the three major cultured food fish are catfish, rainbow trout (*Oncorhynchus mykiss*), and several species of salmon (Shepherd and Bromage, 1988). The cultural technology used to produce these species has traditionally been governed by three factors: the availability of water, the temperature of the water, and the amount of energy required to utilize the water. For example, the majority of catfish are raised extensively in large earthen ponds located in the southern states (Mississippi being the leader) where ambient temperatures provides long growing seasons and there is an abundance of ground water to fill the ponds. Most salmon are cultured intensively in floating net pens in coastal bays and fjords in northern climates. Rainbow trout are grown intensively in single-pass raceways situated in the Snake River valley of Idaho where there is an abundance of natural springs. They are successful, i.e., economically efficient, because they take advantage of natural sources of energy (warm climates), and abundant water supplies. The cultural methods used to produce these species sets the price which must be achieved to produce these species competitively. However, producers outside of the centers of production may rear these species profitably when they sell a fresh product directly to local (niche) markets, sometimes offering special services: live fish for fee fishing, or a fresh product to suit the local clients. Additionally, demand for regionally popular sport or commercial species (e.g., walleye--*Stizostedion vitreum*, yellow perch--*Perca flavescens*, and striped bass--*Morone saxatilis*) has generated interest in developing technology for production of new species.

Thus, interest in fish production outside of the traditional areas has been a strong incentive for investment in closed-system (i.e., recycle) aquaculture. Closed-systems have many potential advantages: (1) greater latitude in site selection, (2) siting facilities close to markets, (3) precise control over the rearing environment, (4) lower water requirements, and (5) improved waste water treatment. Because recycle systems reduce the requirement for fresh water by reusing water, they make it economical to heat water to the optimum temperature for fish growth, producing faster fish growth rates, year round growth, and a shorter production cycle from fingerling to market size. In addition, the closed environment reduces disease by limiting the introduction of pathogens.

Furthermore, traditional fish farming methods have been impacted by recent trends towards increasing and enforcing federal, state, and local regulations governing fish production system effluents which flow into navigable streams and their tributaries or into water which can enter the ground water aquifers (Hankins and Bullock, 1994; Harris, 1979). Closed-system aquaculture makes it more economical to meet water quality discharge standards as it has a small and concentrated waste stream which is much easier to treat than the large volume waste streams from traditional flowing-water (single-pass) and cage aquaculture methods.

Recycle system aquaculture

Closed system aquaculture is a type of flowing water (intensive) fish culture in which a high percentage of the volume of water in the system is treated and reused. The water treated for reuse must be sufficient in both quantity and quality to maintain water quality for the growth and health of the cultured organism. Most often, treatment systems utilized for preparing water for reuse involve unit processes designed for the reduction of fish metabolites such as suspended and settleable solids, dissolved nitrogen compounds (ammonia and ammonium), and BOD, as well as processes for controlling dissolved gases (O_2, CO_2, and N_2), pH, and pathogens, and finally processes for water recirculation, and heating of make-up water.

Although recycle aquaculture systems have many advantages, the systems have a high capital investment (fixed cost). In addition to fish rearing tanks,water reuse treatment processes and automatic failsafe components such as backup power systems are expensive and will have higher variable costs for energy than most single-pass systems. Therefore, to be successful, the water reuse treatment processes must maximize energy efficiency and minimize capital and operating costs for water treatment.

Many of the water treatment unit processes used in closed-system, reuse aquaculture systems represent adaptations of technologies from the water and waste water treatment

industries. Although a seemingly logical technology transfer, use of many technologies from the water and waste water industries for closed system aquaculture have often not been successful because the processes were not really suitable for the extremely low concentrations of contaminants required for fish growth and survival. Unfortunately, in some cases the lack of a true understanding of the function of the unit process has led to failed technology transfer.

Some commercial fish-culture facilities have been established using reuse processes; unfortunately, most have not been cost-effective. For example, use of processes such as rotating biological contactors (RBCs), hydrocyclones, and ozonation are considered to be state-of-the-art for closed-system aquaculture. However, all three processes fail in at least one regard from being ideal water reuse processes: e.g., the processes must operate as integral components of a total system, and they must be practical (i.e., with low or moderate capital costs and low operating costs). RBCs have been found to work consistently as attached-growth biological treatment units with low head requirement, important for long term stability, and low operating costs; however, commercial RBCs have extremely high capital costs. Similarly, ozonation has many useful treatment properties, yet its high capital and operating costs may not be practical for commercial aquaculture. Hydrocyclones remove large or dense particles effectively and they have a moderate capital cost. Hydrocyclones, however, require high head to operate effectively (i.e., high energy costs), do not remove small or nonsettleable particles, and may discharge more water during clarification than is desirable in reuse systems.

The fundamental factor governing the success of closed-system aquaculture is whether fish can be produced at prices equal to or less than established culture methods. To date, few U.S. fish producers have found it economically viable to culture fish where large amounts of energy must be expended for pumping or heating water. Therefore, the present research focused on small-scale, pilot plant studies of water reuse processes that combine both relatively low capital costs and low energy requirements. The research described focused on the gross removal of solids and carbonaceous oxygen demand with the use of relatively low-cost, low-head roughing filters for the purpose of stabilizing and enhancing nitrification in an attached growth biofiltration unit. Such units are normally already available in abandoned waste water treatment plants.

Water Quality Criteria

The water quality criteria required for maintaining healthy and fast growing fish environment (Table 1) are the basis for designing water reuse processes for closed-system aquaculture. Water quality parameters are of concern in fish culture if they stress the fish,

reduce the fish's growth rate, or cause fish mortality. Water quality is also of concern if the effluent characteristics (e.g., phosphorus) of the culture facility must be controlled to meet water pollution requirements. Growth rate is of primary concern to the economics of fish production; reduced growth due to water quality limitations is undesirable. As well, growth is a measure of the overall state-of-health of the fish (Meade, 1989a). However, stress, defined as the sum of all the physiological responses by which an animal tries to maintain or re-establish a normal metabolism in the face of a physical or chemical force, may not be quantified by reduced growth, but measured by stress-induced physiological changes (histological, hematological, and immunological) in the cultured organism (Meade, 1989a). The reduction in water quality which leads to stress and the deterioration of fish health will increase the risk of disease and catastrophic loss of fish, even if it does not have an immediate impact on production (Meade, 1989a).

The parameters of primary concern in recycle aquaculture are dissolved nitrogen compounds such as ammonia (NH_3), ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-); organic compounds that are dissolved or exist as suspended or settleable solids; dissolved oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2) gases; and alkalinity. These parameters are a concern because their production or reduction (Table 2) during recycle aquaculture can lead to concentrations which affect the growth and health of the fish. However, it is not only the individual components, but the aggregate of all the water quality components which affect fish growth and health (Meade, 1989a).

Alkalinity and pH

Nitrification, described in detail later, consumes approximately 7 mg of alkalinity per mg of ammonia nitrogen oxidized to nitrate, resulting in an increase in the H_2CO_3 (and thus CO_2) concentration and a decrease in pH. Alkalinity can be rate limiting for nitrification at concentrations less than 50 mg/L as $CaCO_3$ (Gujer and Boller, 1984). Nitrification rates are significantly lower at pH values below 7.

The pH controls the equilibrium of many of the chemical species important in aquaculture, in particular, pH controls the equilibrium of the ammonia and the carbonic acid systems. Taking the equilibrium of ammonia and ammonium for example:

$$NH_3 + H_20 \Leftrightarrow NH_4^+ + OH^- \quad (1)$$

Because the ammonia (NH_3) associates with water (H_2O) to form hydroxide (OH^-) and ammonium (NH_4^+), the resulting equilibrium is a function of pH,

Table 1. Water quality standards for fish culture. Unless otherwise stated, units are in mg/L. (Meade, 1989b).

Alkalinity (as $CaCO_3$)	10-400[a]
Aluminum (Al)	< 0.01[b]
Ammonia (NH_3)	<0.02[b]
Arsenic (As)	<0.05[b]
Barium (Ba)	5[b]
Cadmium	
Alkalinity < 100 ppm	0.0005[b]
Alkalinity > 100 ppm	0.005[b]
Calcium (Ca)	4-160[a]
Carbon dioxide (CO_2)	0-10[a]
Copper	
Alkalinity < 100 ppm	0.006[b]
Alkalinity > 100 ppm	0.03[b]
Dissolved oxygen (O_2)	5 mg/L to saturation[a]
Hardness, Total	10-400a
Iron (Fe)	< 0.01[b]
Lead (Pb)	< 0.02[b]
Magnesium (Mg)	< 15[b]
Manganese (Mn)	< 0.01[b]
Mercury (Hg)	< 0.2[b]
Nitrogen (N_2)	< 110 % total gas pressure[b]
	< 103% as N_2 gas[b]
Nitrate (NO_3^-)	0-3.0[a]
Nitrite (NO_2^-)	0.1 in soft water[b]
PCB (polychlorinated biphenyls)	0.002[b]
pH	6.5-8.0[a]
Potassium (K)	< 5.0[b]
Salinity	< 5 %[b]
Selenium (Se)	<0.01[b]
Sodium (Na)	75[b]
Sulfate (SO_4)	< 50[b]
Sulfur (S)	< 1.0[b]
Total dissolved solids (TDS)	< 400[b]
Total suspended solids (TSS)	< 80[b]
Zinc (Zn)	< 0.005[b]

[a]desireable range
[b]maximum

Table 2. Metabolite production and consumption.

Metabolite	kg metabolite per kg feed fed (unless otherwise specified)	Species
Oxygen demand	0.22 (Willoughby, 1968)	Trout
	0.54 (Liao and Mayo, 1974)	Salmon
Total ammonia nitrogen produced	0.032 (Piper et al., 1982)	Nonspecific
	0.031 (Speece, 1973)	Trout
	0.029 (Liao and Mayo, 1974)	Salmon
Nitrate produced	0.087 (Piper et al., 1982)	Nonspecific
	0.024 (Liao and Mayo, 1974)	Salmon
Phosphate produced	0.005 (Piper et al., 1982)	Nonspecific
	0.016 (Liao and Mayo, 1974)	Salmon
	0.0078 (Lomax and Wheaton, 1978)	Channel catfish
Settleable solids produced	0.3 (Piper et al., 1982)	Nonspecific
	0.12 (Lomax and Wheaton, 1978)	Channel catfish
	0.52 (Liao and Mayo, 1974)	Salmon
Total solids produced	0.4 (Speece, 1973)	Catfish
cBOD produced (5-day, 20°C)	0.4 (Speece, 1973)	Catfish
	0.60 (Liao and Mayo, 1974)	Salmon
	3 g/kg fish (Bohl, 1977)	Nonspecific
COD produced	1.60 (Liao and Mayo, 1974)	Salmon
Carbon dioxide produced	0.285 (Liao and Mayo, 1974)	Coho salmon
	0.43 (Liao and Mayo, 1974)	Steelhead
Chloride produced	0.0081 (Lomax and Wheaton, 1978)	Channel catfish

$$\frac{[NH_3]}{[NH_4^+]} = 10^{(pH-pK_a)} \quad (2)$$

and temperature (@ 25°C, $pK_a = 9.245$),

$$pK_a = 0.09018 + 2729.92/T,°K \quad (3)$$

such that increasing pH or temperature shifts the equilibrium to the formation of more of the ammonia. The location of equilibrium is important because ammonia (unionized) is much more toxic to aquatic organisms than ammonium. Ammonium, however, is utilized by autotrophic bacteria for food.

The pH-equilibrium relation between the species in the carbonic acid system is equally important, though more complex, and is discussed later.

Ammonia

Ammonia is the primary nitrogenous metabolite excreted by fish (Brafield, 1985). Approximately 30 mg of ammonia are produced by fish per gram of feed consumed (Piper et al., 1982; Speece, 1973; and, Liao and Mayo, 1974). Ammonia is also produced by three additional reactions in recycle-systems using biological treatment: biological deamination of organic compounds (waste feed and feces), endogenous respiration, and cell lysis (Kruner and Rosenthal, 1987).

The total ammonia nitrogen ($NH_3 + NH_4^+ = TAN$) is an important water quality parameter in aquaculture. At high levels, un-ionized ammonia (NH_3) is toxic to fish (LD_{50} = 0.32 mg/L for rainbow trout and 3.10 mg/L for channel catfish; Meade, 1985) and at lower concentrations (0.05 to 0.2 mg/L of ammonia; Colt and Armstrong, 1981), it causes a significant reduction in growth (Colt and Tchobanoglous, 1978). For salmonid fishes, optimal conditions for growth will require an un-ionized ammonia concentration less than 0.0125 mg/L (Piper et al., 1982). Though criteria have not been established for walleye, there would be less risk of mortality or stress to assume that walleye are as sensitive as salmonids.

Carbon dioxide

One of the most severe problems encountered in high density culture systems, following oxygen depletion, is carbon dioxide toxicity (Colt and Orwicz, 1991). Carbon dioxide is the by-product of respiration, it is excreted by the fish and in recycle systems by the microorganisms growing in the biological filters. As salmon and trout respire they produce 0.3 to 0.4 mg of carbon dioxide per mg of feed consumed (Liao and Mayo, 1974). Respiration

also occurs in the biological treatment processes used in recycle systems where ammonia and organics are biologically oxidized. Based upon stoichiometry, nitrifier cell synthesis and nitrification, would produce approximately 6 mg of carbon dioxide per mg of NH_4^+-N consumed (EPA, 1975). Carbon dioxide is also produced when organics are biologically removed. The molecular composition of organic species is variable, therefore a stoichiometric relation between the quantity of organics biologically decomposed and carbon dioxide produced can not be obtained. For culturing salmon and trout, aqueous CO_2 concentrations should be maintained below 20 mg/L (SECL, 1983). Carbon dioxide is toxic to fish because it reduces the blood's ability to transport oxygen (Colt and Orwicz, 1991).

Control strategies for carbon dioxide are dependent upon the pH and the equilibrium of CO_2 with the carbonic acid system and with the atmosphere. The importance of CO_2 equilibrium and the treatment of CO_2 by either air stripping or chemical addition are addressed in Paper I.

Dissolved nitrogen gas

Nitrogen gas is biologically inert and does not react chemically. However, nitrogen gas supersaturation greater than 110% is considered detrimental to most fish (Parker and Davis, 1981). The effect of supersaturation due to all gases, represented by ΔP, varies with the species of fish, the life stage of fish, water quality and the depth in the water column of the fish (Colt and Orwicz, 1991). To avoid supersaturation problems, Colt and Orwicz (1991) suggest a general criterion of ΔP less than 10 mm Hg for maintaining fish health even during sensitive periods. A higher criterion may be possible for fish less sensitive to nitrogen supersaturation or in systems where pure oxygen is used for aeration.

Dissolved organics

Dissolved organics promote the growth of heterotrophic microorganisms. Heterotrophic microorganisms cause an increase in the total oxygen demand of the system and inhibit nitrification by competing for space and oxygen in a biofilter. Some heterotrophic (saprotrophic) microorganisms in the system may consist of facultative pathogens (i.e., *aeromonas*)which can result in epizootics when the fish are stressed by handling or sublethal water quality conditions.

Dissolved oxygen

Dissolved oxygen does not affect the growth of fish until it falls below a concentration of 5 to 6 mg/L for salmon and trout, or 3 to 4 mg/L for warm water fish. Maintaining adequate dissolved oxygen in intensive culture is challenging as there are many oxygen demands in these

systems. The cultured fish require between 220 mg (Willoughby, 1968) and 547 mg (Liao and Mayo, 1974) of oxygen per gram of feed they consume. Oxygen is also used to biologically oxidize the ammonia produced in the culture system, approximately 4.25 g of oxygen is required to oxidize 1 g of ammonia (as nitrogen). The organics produced in the culture system, if not removed, would exert an additional oxygen demand of 0.6 to 0.9 gram per gram of feed consumed if complete biological oxidation is allowed.

Nitrite

Nitrite (NO_2^-) is an intermediate product of the biological oxidation of ammonia to nitrate (nitrification). Nitrite is toxic to fish at low levels. The 96-h LC_{50} value of NO_2^- to rainbow trout is 0.20 to 0.40 mg/L as NO_2^--N (Russo and Thurston, 1977). However, the toxicity depends upon the concentration of calcium or chloride ions, which can increase the tolerance of rainbow trout by a factor of 20 to 30 times (Colt and Armstrong, 1981). To maintain a healthy, growth-promoting environment, Westin (1974) recommends a nitrite concentration of less than 0.012 mg/L. Meade (1989a,b) recommends 0.1 mg/L maximum (Table 1). Aqueous nitrite is in equilibrium with nitrous acid, which is more toxic to aquatic organisms than nitrite (Wheaton et al., 1989):

$$HNO_2 + H_2O \Leftrightarrow H_3O^+ + NO_2^- \quad (4)$$

The equilibrium of nitrite with nitrous acid ($K_a = 4.5 \times 10^{-4}$ @ 25°C) is dependent upon pH, and a shift to lower pH values shifts the equilibrium towards nitrous acid and thus increases the nitrite toxicity. At normal culture pH, however, equilibrium favors essentially only NO_2^-.

Nitrate

Nitrate, the end product of the biological oxidation of ammonia, toxicity only affects fish at high concentrations. The 96-h LC_{50} value of NO_3^--N to fish ranges from 1000 to 2000 mg/L (Colt and Tchobanoglous, 1978). The tolerance limit of rainbow trout to nitrate is about 800 mg/L (Braun, 1972). Westin (1974) observed no change in the growth and health of Chinook salmon in a recirculation system with nitrate concentrations less than 25 to 35 mg/L.

Aqueous nitrate is in equilibrium with nitric acid:

$$HNO_3 + H_2O \Leftrightarrow H_3O^+ + NO_3^- \quad (5)$$

The equilibrium of nitrate with nitric acid ($K_a = 100$ @ 25°C) is dependent upon pH, and a shift to lower pH values shifts the equilibrium towards nitric acid. However, under normal culture conditions (e.g., normal pH values) chemical equilibrium would favor essentially only NO_3^-.

Phosphorus

Phosphorus does not become growth limiting in intensive systems. Phosphorus is primarily a concern as it results in effluent discharge problems.

Suspended and settleable solids

Aquatic organisms are affected by solids in suspension and by settleable solids as they are deposited by sedimentation. The effect of the solids on fish is dependent on the species, age and stage of the reproductive cycle (Muncy et al., 1979). Suspended and settleable solids may affect reproductive behavior, gonad development, and the survival of the egg, embryo and larval stages of warmwater fishes (Muncy et al., 1979). The lowest concentration of suspended solids that showed lethal effects on adult fish in a study of over 16 species of fish did not occur until a concentration, on average, greater than 69,000 mg/L was reached (Wallen 1951). Adult mortality through reduced resistance to disease (EIFAC, 1965) may be attributed to suspended solids. Sublethal effects, such as fin rot in rainbow trout, have been observed at concentrations of 207 mg/L of diatomaceous earth (Herbert and Merkens, 1961).

Water-Reuse Unit Process Options

Water treatment in recycle aquaculture systems uses unit processes designed for the reduction of fish metabolites, such as suspended and settleable solids, dissolved nitrogen compounds (ammonia and ammonium), and BOD, as well as processes for controlling dissolved gases (O_2, CO_2, and N_2), pH, and pathogens, and finally pumping and heating of make-up water. The water treatment must be sufficient to maintain water quality for the growth and health of the cultured organism. In addition to the rearing units, four unit processes are required in a recirculating fish-culture system: oxygenation, clarification, biofiltration, and removal of carbon dioxide (Figure 1). These unit processes are reviewed below. The removal of carbon dioxide is reviewed in Paper I.

Rearing

Rearing units for the intensive culture of fish are of varied shape and flow pattern (Piper et al., 1982). They are designed with considerations for production cost, space utilization, water quality maintenance and fish managment. Geometry, water velocity and flow patterns are particularly important design considerations. The rationales for several common tank designs are reviewed as discussed by Piper et al. (1982), Watten and Beck (1987), Westers (1991), Young and Timmons (1991), and Timmons and Young (1991).

Circular tanks Circular rearing tanks are generally operated with a circular flow pattern and a center drain. Operated in this manner, approximately homogeneous water quality

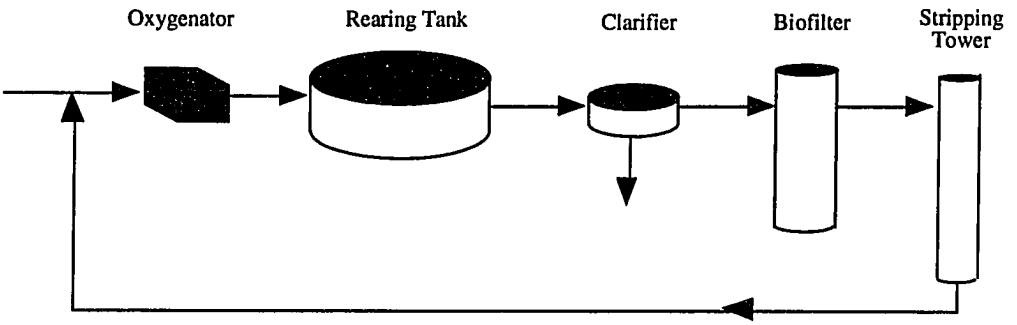


Figure 1. Illustration of the unit processes required in a generalized recirculating system.

is maintained throughout the tank as would be modeled by a continuous-flow stirred tank reactor (CSTR). Homogeneous mixing means that the concentration of a constituent in the water flowing into the tank will instantaneously change, in a step-wise manner, upon entering the tank. It also means that the concentration of the constituent in the tank will be the same as in the water leaving the tanks through the center drain. Thus, all fish within the tank are exposed to the same water quality. The tank water exchange rate (water changes per day) is generally used to maintain the water quality throughout the tank at a healthy level.

Two examples can indicate the importance of homogeneous mixing: (1) oxygen addition--a high density fish tank receives oxgyen at 23 mg/L in the inlet; however, the oxygen concentration throughout the tank is approximately 7 to 8 mg/L; (2) carbon dioxide production--a high density fish tank receives aqueous CO_2 at only 15 mg/L; however, the aqueous CO_2 concentration throughout the tank can be greater than 30 mg/L.

If the velocity of the current within the tank is not too great, and generally it is not, the settleable solids will stratify along the bottom of the tank. A properly designed inlet control structure can be used to direct the incoming flow and create optimum velocities for the swimming fish and also generate centrifugal forces to drive solids along the bottom to the center of the tank, where they can be removed.

Circular tanks range in diameter from less than 1 m (1 ft) to greater than 20 m (60 ft) and in depth from less than 1 m (3 ft) to greater than 5 m (16 ft). Circular tanks have less wall length and can structurally better handle the pressure generated by the confined water (and use thinner walls and require less concrete or fiberglass) than rectangular tanks.

Rectangular tanks Raceways are generally long and narrow and are operated in a plug-flow manner. Water enters the raceway at one end and flows axially through the raceway with minimal back mixing. The plug-flow produces a concentration gradient along the axis in

dissolved metabolites such as oxygen, ammonia, and carbon dioxide. The best water quality exists at the head of the tank, where the water enters, and deteriorates along the axis of the raceway towards the outlet. As oxygen is often the limiting environmental quality criteria, fish may congregate at the head of the raceways and cause an unequal distribution of fish density throughout the tank.

The velocity of water through the raceway is generally too low for solids removal and another mechanism for solids removal must be used: e.g., bottom-scouring baffles or periodic vacuum removal of the settled solids.

Because of their aspect ratios, raceways serve as convenient culture tanks for managing fish when crowding or grading. Crowders or graders can be placed in the raceway at one end and slowly worked down the axis of the tank.

Raceways can be constructed side-by-side, with common walls, for maximizing the utilization of floor space and reducing construction costs. However, when constructed without common walls, because of their large aspect ratio (L:W), raceways require 1.5 to 2.0 times as much wall length as do circular tanks.

Cross-flow tanks have geometry similar to raceways, but function much differently. Due to water distribution mechanisms, cross-flow tanks exhibit mixing characteristics approximated by a CSTR, rather than a plug-flow reactor (which characterizes raceways). Water is uniformly distributed along one side of the tanks long axis through a manifold, and collected within another manifold or drain gutter along the opposite side. The influent is injected with sufficient force to establish rotary circulation about the longitudinal axis. The cross-flow tank thus has the same advantages of homogeneous mixing as does the circular tank and also has the same fish management advantages as does the raceway.

Cross-flow tanks tend to resuspend solids due to the rotary circulation along the longitudinal axis. Circulating the solids may cause increased solids break-down and increase the probability of disease transmittance.

Aeration/oxygenation

Oxygen, critical to the health and growth of fish, is often the limiting water quality factor in intensive aquaculture (Colt et al., 1988; Colt and Watten, 1988). Aeration and oxygenation are unit processes used for maintaining adequate levels of oxygen within recirculating fish-culture systems. Fortunately, aeration and oxygenation are two of the most well-understood unit processes used in intensive aquaculture, with outstanding reviews written by Speece (1981), Visscher and Godby (1987), Colt and Watten (1988), Speece et al. (1988), Westers (1989), and many others. In the aeration process, air is contacted with water so that

oxygen transfers from the air into the water. In the oxygenation unit process, pure oxygen gas is used (instead of air) to achieve oxygen levels in the water flow which are much greater than standard atmospheric saturation levels. Increased available oxygen in the flow increases the system's carrying capacity, resulting in an economical means of boosting system production.

There are many types of oxygen transfer equipment described in the literature: U-tubes, packed columns, spray columns, pressurized columns, oxygenation cones, oxygen injection aspirators, bubble diffusers and enclosed mechanical-surface mixers. High oxygen absorption efficiencies are required due the expense of pure oxygen.

Oxygen transfer is controlled by the mass transfer of oxygen from the gas-phase into the liquid-phase, and is proportional to the area of the gas-liquid interface and the gradient between the saturation and existing concentrations of the gas in the water. When absorbing pure oxygen, the saturation concentration is increased over atmospheric saturation due to the increased partial pressure exerted by the oxygen gas. The saturation concentration can also be increased by increasing the total pressure in which the transfer occurs (e.g., via a pump or hydrostatic head). Increasing the absorption pressure to increase the oxygen transfer, however, may also increase the operating costs and these costs must be considered when selecting an oxygenation unit.

The absorption of oxygen increases the ΔP (gas pressure) of the water and mechanisms for stripping/venting nitrogen gas released during the absorption of oxygen are important for both reducing the ΔP and also increasing the efficiency of oxygen transfer.

Clarification

According to the most recent work in the field, biosolids control is the most pressing and difficult parameter to manage in recirculating system design (Tetzlaff, 1991; Chen and Malone, 1991). The ability to control and isolate such solids in the production system water influences the efficiency of all the other component functions and the effluent water quality (Rakocy et al., 1991; Westers, 1991; Stechey and Trudell, 1990; Bouvendeur et al., 1990). Suspended solids (TSS) in aquaculture systems are a major source of carbonaceous oxygen demand, and if not reduced before biofiltration will inhibit both nitrification (Figueroa and Silverstein, 1992; Bovendeur et al., 1990; Kruner and Rosenthal, 1987; and McHarness and McCarty, 1973;) and the heterotrophic oxidation of organics (Kruner and Rosenthal, 1987; and Sarner and Marklund, 1984). Solids control and specifically solids particle size have been associated with environmentally-induced disease problems (Chapman et al., 1987).

Equipment manufacturers are marketing a variety of new screening and filtering components that are being adopted by private producers. Little research has been published on

the cost-effectiveness or efficiency of this equipment (Mäkinen et al., 1988). Work that has been done has limited distribution or is often reported or supported by equipment manufacturers, e.g., Robertson (1992) and Anon (1989).

Generation of suspended solids Production of TSS in finfish systems is proportional (~ 30 to 60 %) to the feeding rate (Chen and Malone, 1991) and is extremely sensitive to wasted feed (Westers, 1992). The suspended solids are generated as (1) waste (uneaten) feed, (2) feed fines, (3) fish fecal matter, and (4) when recirculating systems are used, sloughed biofilter cell mass. If feeding is improperly handled, uneaten feed may be the largest contributor to suspended solids (Westers, 1992). Feeding fines can be reduced by careful handling and separation techniques. Both uneaten feed and feed fines must be removed as soon as feasible, at they will break down and partially solubilize with time and shear. The fecal matter of trout (and many other fish) is contained within a mucous sheath which can remain intact if the feces is removed soon after deposition (Farrell, 1990). Soon after being deposited, shear forces (water turbulence, fish motion, pumps, etc.) can break apart the mucous sheath allowing the fecal matter to disintegrate into much finer and more soluble particles (Clark et al., 1985). In recirculating systems, sloughed biofilter cell mass is typically generated erratically, may range in size from several micrometers to several millimeters, and may or may not be settleable.

The mechanisms which function in any clarification process are entirely dependent upon the characteristics of the particulates. To characterize the particulate stream properly requires knowledge of the flow and the particulate concentration, size range, specific gravity, strength or shear resistance, and chemical make-up. The clarification process selected to treat a particulate stream must (1) have the functioning mechanisms which can act effectively on removing the particulates, (2) fit in the space available on-site, and (3) be economical in both capital and operating costs.

Particulate size Solids are classified according to size, e.g.: soluble (<0.001 μm); colloidal (0.001 - 1.0 μm), supra-colloidal (1.0-100 μm); and settlable (>100 μm). Dissolved solids can be removed by biological conversion to cell mass or by chemical oxidation. Colloidal solids can be clarified if they can be flocculated by chemical addition (aluminum and iron salts, polymers, or ozone) or if they can be floated. (However, with the exception of ozone, which shows great promise, the use of flocculant aids for enabling clarification of colloids has not been practical in aquaculture.) Larger supra-colloidal solids can be clarified by filtration or flotation, and their removal efficiency can be increased by flocculation. Settleable solids can be removed with or without flocculation by simple sedimentation or by filtration.

Shear resistance The shear resistance of aquaculture solids is generally better than that of flocculant particles found in water and waste water treatment plants. The shear resistance of aquaculture solids, however, is still low enough to cause serious consideration when selecting the best clarification process (Clark et al., 1985).

Specific Gravity The specific gravity of fish fecal matter is likely to vary depending upon conditions. Suspended solid specific gravity values of 1.005, 1.13 to 1.20, and 1.19 were reported by Robertsen (1992), Timmons and Young (1991), and Chen (1991), respectively.

Chemical make-up The general chemical make-up of the particulate stream should be known to select the clarification process properly. The process selection can depend greatly on whether the particulates are relatively organic or inorganic, hydrophobic or hydrophilic, protein or fat, reactive or inert, positively or negatively charged, temperature stabilized, or pH stabilized. Knowledge of the particulate composition can provide insight into which clarification mechanisms are beneficial (precipitation, flocculation, flotation) or warn of problems which may occur (biofouling, scale deposition, corrosion, abrasion, flotation).

Sedimentation The process of clarification by sedimentation occurs when particles having a specific gravity greater than the surrounding water are acted on by gravity so that the particles settle out and are removed from the water column. Sedimentation is typically designed to occur in basins with hydraulics that minimize turbulence and provide time for interception of the particle with the bottom of the clarifier (Figure 2). The solids collect on the bottom of the basin, forming a sludge blanket, while clarified water passes out of the basin.

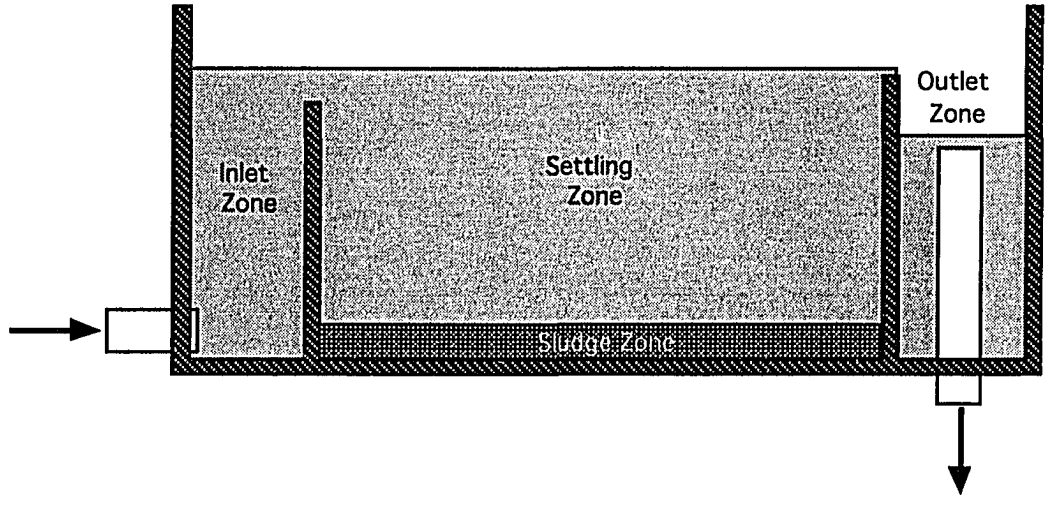


Figure 2. Illustration of a settling basin.

Solids in aquaculture typically settle as discrete particles; i.e., they do not change in size, shape, or density and thus settle at a constant rate. The settling velocity of very small discrete particles can be modeled by Stoke's law:

$$v = \frac{g \cdot (\rho_1 - \rho_L) \cdot D^2}{18 \cdot \mu_L} \tag{6}$$

where v is the settling velocity, ρ_1 is the particle density, D is the diameter of the particle, ρ_L is the water density, μ_L is viscosity of the water, and g is acceleration due to gravity. Stoke's law holds only if the settling velocity of the particle is in the laminar region. Once the characteristic settling velocity is known the removal of discrete particulate suspended matter in an ideal settling basin can be related to it's flow rate and horizontal plan area of the tank (Camp, 1936). The design of settling basins for clarification in aquaculture is discussed by Robertson (1992), Stechey and Trudell (1990), Chisholm (1990), Boersen and Westers (1986) and others. The compression and removal of solids once settled is discussed by Robertson (1992), Chisholm and Schmidtke (1991) and others.

Sedimentation is not an ideal method for removing suspended solids encountered in recirculating aquaculture systems, because: (1) in general, suspended solids have specific gravity's not much greater than water; and (2) a large portion of the suspended solids is too small to settle well (<100 μm). As a result of the solid settling characteristics, sedimentation alone may not provide adequate clarification required in recirculating systems (Tetzlaff, 1991; Chen and Malone, 1991).

Chiang and Lee (1988) investigated the use of calcium hydroxide, ferric chloride, aluminum hydroxide and filter alum for the coagulation of eel pond water. Filter alum was reported as the most effective coagulant. They warn, however, that the toxicity of alum to fish should be determined before its use in recycle systems can be assessed. Bohl (1977) reports that solids are precipitated with ferrous sulfate at a water-reuse fish culture plant when poor settling occurs; no information was given on the toxicity and accumulation of sulfates or iron hydroxides.

Two variations on the principle of clarification by sedimentation have been used in an attempt to increase the efficiency of solids removal: (1) hydrocylcones, and (2) tube or plate settlers.

Hydrocyclones Hydrocyclones (Figure 3) are also called tea-cup settlers and swirl separators, and operate by injecting the water at the outer radius of a conical tank such that the water spins around the tank's center axis. The spinning creates a centrifugal force (radial

acceleration) which moves the larger and/or denser particulates towards the wall where they settle and can be removed. To obtain strong centrifugal forces in hydrocyclones requires water injection at high velocities and results in high pressure losses (3 - 45 psi) (Landine, 1975). Hydrocyclones also result in considerable loss of water in the solids-bearing underflow (~5-10% of flow). Hydrocyclones have primarily been used for treating waste flows which contain particles of high specific gravity, e.g., sand and grit (Sullivan et al., 1974). The use of hydrocylones in aquaculture has been reported (Mäkinen, 1985; Scott and Allard, 1983 & 1984), but are generally considered to be too energy consumptive for commercial use in US aquaculture.

Tube or plate settlers Tube or plate settlers consist of a sequence of inclined tubes or plates which are stacked several inches apart (Figure 4). Use of tube or plate settlers increases the effective settling area per unit volume and reduce the depth a particle must settle to contact a surface (Yao, 1970 and 1973). These settlers have been used to increase solids removal (particularly when space is limiting) in the drinking water treatment industry (Smethurst, 1979), and occasionally in the waste water treatment industry (Yao, 1970) and in aquaculture facilities (Libey, 1992; McLaughlin, 1981; and Van Gorder and Strange, 1981).

Flotation Flotation can be used for clarification of solids, particularly biosolids, grease, hydrocarbons, fibers and algae (Montgomery, 1985). The solids attach to air bubbles, float to the surface, become concentrated and are removed. There are three basic mechanisms for producing bubbles for thickening: dispersed air, dissolved gas and electrolytic flotation. The primary difference in the three flotation mechanisms is the bubble diameter produced; systems using dispersed air (often called foam fractionation) generate bubbles larger than 100 μm; and, systems using either supersaturations of dissolved gas or electrolytic cleavage of H_2O can precipitate bubbles in the 10 to 100 μm size range (Kemmer, 1979).

Flotation of biosolids is often a better clarification technique than settling because flotation can provide a greater density difference between the water and the rising air-entrained sludge than what is obtained between water and the sinking biosolid. The flotation of solids is highly dependent upon the solids concentration, air to water ratio, surface chemistry of the solids and surfactant concentration in the water (Montgomery, 1985). Chemical addition (a strong oxidant such as ozone, salt or polymers) can aid in the formation of a cohesive froth to improve the quality of the treated water.

Clarification of solids with flotation has been demonstrated in recirculating aquaculture systems using dispersed air (Figure 5) (Chen and Malone, 1992; Chen, 1991; Huguenin and

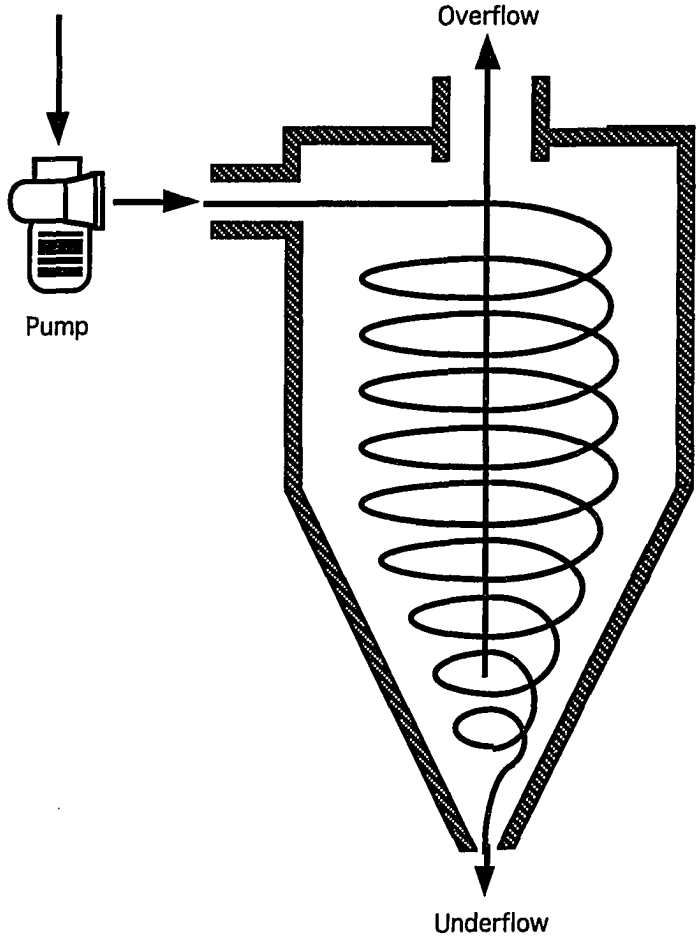


Figure 3. Illustration of a hydrocyclone.

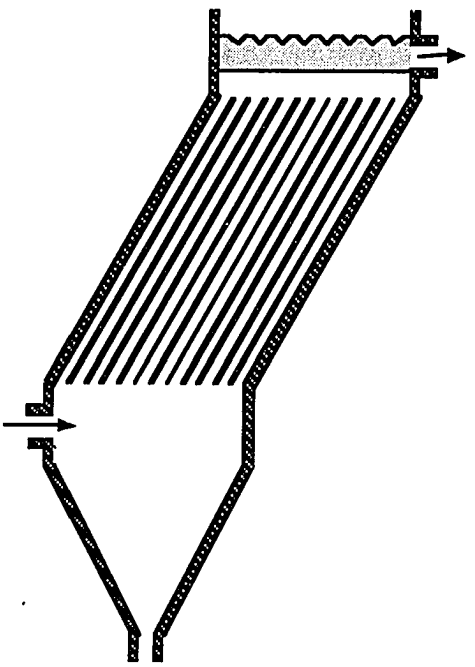


Figure 4. Illustration of a plate settler.

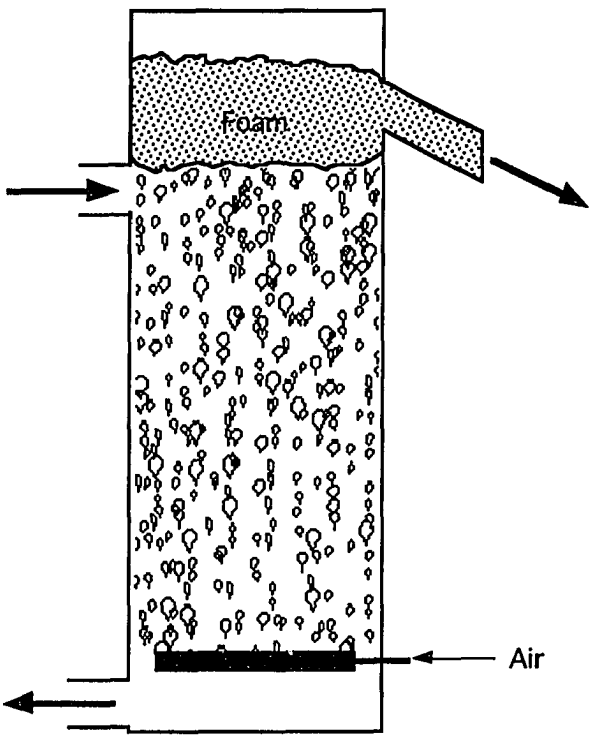


Figure 5. Illustration of dispersed air flotation (foam fractionator).

Colt, 1989; and Dwivedy, 1973). Typically, dispersed air flotation removes mostly particles smaller than 30 μm (Chen, 1991).

Filtration Filtration is used for removing particulate matter in waters. In addition, filtration may become obligatory to remove total phosphorus levels in waste water discharges down to 1 mg P per liter (Kavanaugh et al., 1977). Filtration can be achieved by either depth filtration or straining, which occurs on the surface of a media.

Depth filtration The process of clarification by depth filtration occurs when particles are smaller than the pore openings at the granular media surface, or are too weak to sustain the hydraulic shear at the pore entrance, and pass into the void spaces occurring within the granular media bed. Once within the bed the particles can be removed by straining, sedimentation, absorption or chemical bridging mechanisms. Periodically, the granular media bed must be flushed of entrapped particles, which involves backwashing with water possibly supplemented with a prior air wash.

Depth filtration is commonly used in drinking water treatment plants, and following the secondary clarifiers in waste water treatment. Depth filtration is used in some fish hatcheries for reducing the entry of pathogens and often follows a chemical oxidation process used for disinfection (Cryer, 1992).

Straining The straining process occurs when water-bound particles are larger than the openings in sieves or pores of the granular media. Straining at the surface of granular media filters is an important mechanism in systems removing large particulates and in pressurized systems with fine media operating at high hydraulic loading rates, e.g., diatomaceous earth filters. Particles smaller than the sieve or pore openings are removed by sieving after an accumulation of strained particles effectively reduces the size of the openings. When the accumulation of particles have effectively reduced the size of the openings through the sieve or pore, the resistance to flow (headloss) increases. To maintain flow through the sieve or pore, the accumulation of particles must be removed by some cleaning mechanism, which can occur continuously, periodically, or on demand. Surface straining granular media filters are cleaned by hydraulic and/or air back-wash systems. Sieve filters, depending upon type (Figure 6), are cleaned by either hydraulic flushing, pneumatic suction, mechanical vibration or hand raking. Most sieving filters are operated to maintain a low headloss (<15 cm) across the sieve and the headloss across the whole filter less than 30 cm (Kemmer, 1979). However, some sieve filters, such as the sieve bend, rely on gravity (possibly coupled with periodic raking) to maintain sieve openings. Sieve bends can require as much as two meters of hydraulic headloss.

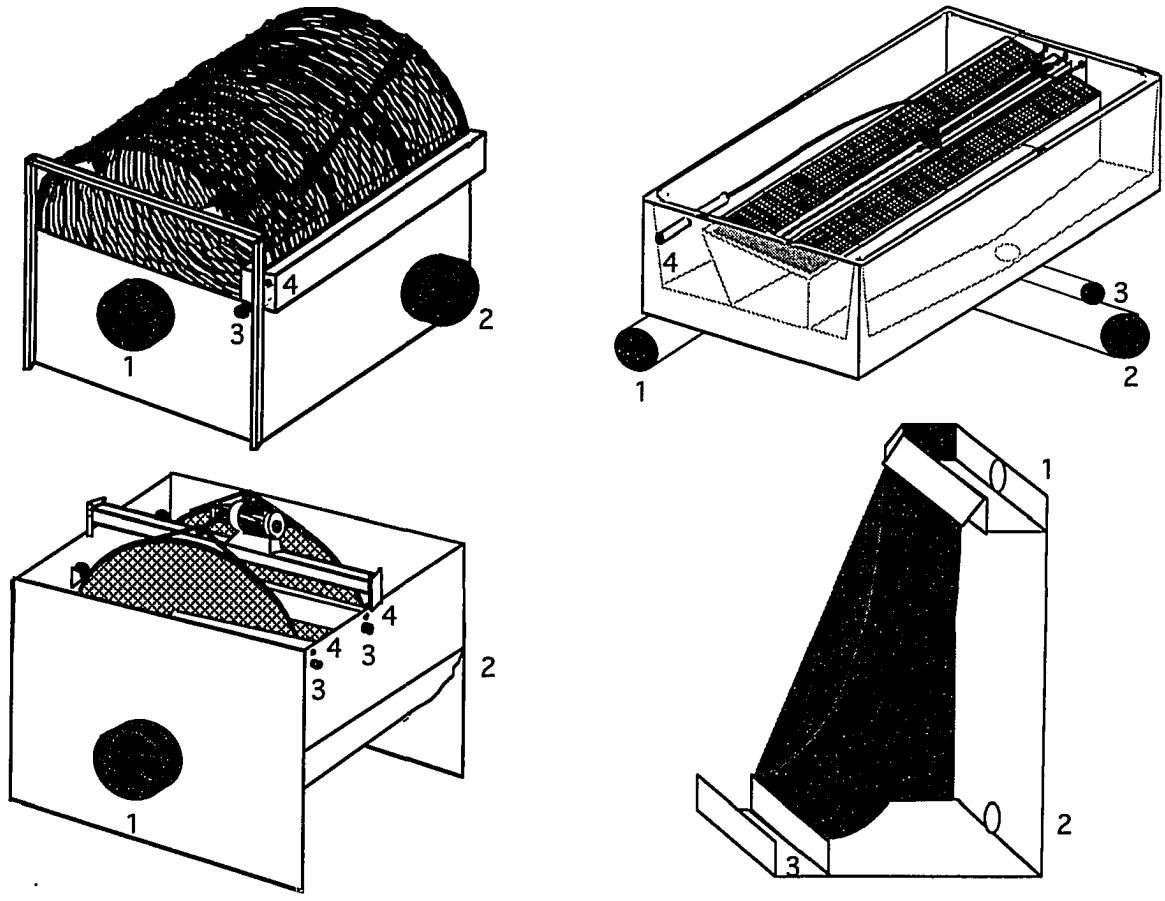


Figure 6. Illustration of four variations of sieve filters, starting from the top-left and moving clockwise they are: drum filter, triangle filter, sieve bend filter, and disk filter. (1 = Inlet, 2 = Outlet, 3 = Sludge Outlet, 4 = Wash Water Inlet).

Granular media systems which function by straining are used in many industries: drinking water, waste water, food-processing, pharmaceutical, swimming pool and others. Granular media filters which function by straining are used occasionally in aquaculture, particularly when disease control is critical and cost is of less concern.

Bar screens, a much coarser application of sieving filters, have been used as water intake structures at both water treatment plants and fish hatcheries which use surface water, and at waste water treatment plants. Sieving filters (also called microscreens) are commonly used at water-intakes for removal of algae and other fine particulates and are used in the food-processing, metals-processing, and pulp wood industries. Sieving filters are also used in waste water treatment plants as secondary clarifiers. Although the sieving process has been known of for years, it has recently come under increasing consideration for use as the clarifier for treating hatchery effluents (Robertson, 1992; Anon, 1989; and Mäkinen et al., 1988) and in commercial recirculating systems (Summerfelt et al., 1994; Libey, 1993). Sieving filters are especially attractive to users of commercial recirculating systems because these filters are not permanently fixed to one spot (as concrete settling basins are); additional advantages are a high hydraulic capacity, a low space requirement, an acceptable headloss, and a relatively easy installation (because they come as a complete package).

The problem encountered by all potential microscreen users, and in particular the users with commercial recirculating systems, is the complete lack of unbiased data and criteria on the performance of sieving filters. A reason for the lack of published data is the capacity and cost of the sieving filters available commercially. Not many research facilities have the capacity to test full-scale models, particularly facilities researching recirculating aquaculture systems. And it is unlikely that small-scale sieves fabricated for research would result in data that scale-up well.

Biofiltration

Biofiltration is a term coined for labeling attached growth biological treatment processes. Biofiltration is not a process for removal of suspended solids, but is a process where heterotrophic and autotrophic microbes attached to a support medium biologically oxidize (by metabolism) a portion of the ammonia nitrogen and the biodegradable organics (the oxygen required for this oxidation is called the biochemical oxygen demand, or BOD) in a waste stream. Retention of the microbe population is obtained by their attachment to the wetted or submerged surfaces of the biofilter medium, providing the long solids retention time required for good biological oxidation. Ammonia is oxidized by autotrophic bacteria (called nitrifying bacteria) and biologically degradable organic compounds are oxidized by

heterotrophic microbes. Typically, the autotrophic and heterotrophic microbes coexist on the the media surface in the biofilter.

The ammonia and organics oxidation capacity of biological filters is largely dependent upon the total surface area available for biological growth and the efficiency of the area utilization. Greater ammonia removal capacity results from an increase in biofilm surface area. The efficiency of nitrification per unit surface area is dependent upon the accessibility of the media surface, the mass transfer rate into the biofilm, the growth phase of the biofilm (lag, log, stationary, and death phases), and by the competition with heterotrophic microbes for space and oxygen (Alleman and Preston, 1991; Manem and Rittman, 1992).

The removal of ammonia in the nitrification step of the biofiltration process is one of the most important functions of the water reconditioning system because it is critical to the continued health and growth of the fish. Therefore, in aquaculture recycle systems, biofilters are typically designed based entirely on nitrification.

There are several problems and inefficiencies with many of the biofiltration unit processes currently used in recycle aquaculture systems. Primarily, systems are being designed incorrectly because of one or several of the following inadequacies:

- they utilize expensive and low specific surface area media resulting in large and excessively costly units;
- they utilize insufficient media surface area to (1) provide nitrification of ammonia all of the way to nitrate, and avoid accumulation of nitrite, and (2) provide space for the slow-growing autotrophic nitrifiers which compete poorly with the fast-growing heterotrophic microbes for the available surface area (Wanner and Gujer, 1984; Harremoes, 1982; and Schlegel, 1988);
- they do not utilize an operating procedure that can maintain sufficient oxygen for microbial oxidation through-out the biofilter, in some cases, because of unplanned for carbonaceous oxygen demand exerted by the heterotrophic organisms located upstream of the autotrophic nitrifiers (Liao and Mayo, 1974; Bovendeur et al., 1990; Wanner and Gujer, 1984; Harremoes, 1982);
- they do not utilize an operating procedure for maintaining thin, aerobic, high-efficiency, log-growth phase biofilms; or
- they do not utilize operating procedures for maintaining unplugged media or for preventing short circuiting.

Biofilter media The media used in attached growth systems must have a relatively high specific surface area (i.e., surface per unit volume) and an appreciable voids ratio. The

specific surface area is important as it controls the amount of bacterial growth that can be supported in a unit volume. The voids ratio is critical for adequate hydraulic performance of the systems since it must allow the water to pass through the media in close contact with the biofilm yet must also provide for contact with oxygen within the media. In addition, media must be inert, non-compressible, and non-biologically degradable on a relative time scale.

Media is classified according to its packing characteristics, i.e., random packing versus structured packing. Random packing can be crushed rock or river gravel, or some form of plastic or ceramic material shaped as spheres, rings, or saddles. Structured media can be crossed stacks of redwood slats, or more commonly plastic blocks composed of corrugated plates or tubes.

Trickling filters Trickling filters, using biofilm grown on gravel-size stones, were the first attached growth biological contact units utilized for waste water treatment. Trickling filters have been used extensively in waste water treatment throughout the twentieth century. The most important reason for the popularity of the trickling filters is their ease of operation, self aerating action, and low capital cost. The technical innovation that impacted trickling filters the most was the development of plastic media. Plastic media is light, offers high specific surface areas, and void ratios of 90 percent or more.

As with most of the attached growth biofilters, trickling filters with high specific surface areas may be less efficient than filters of lower specific surface areas due to channeling or a hydraulic load that is not sufficient to moisten all the area of the densely packed media (Rusten, 1984). An additional problem with the trickling filter is the inadequate control over the hydraulic detention time (Haug and McCarty, 1972).

Submerged filters The submerged filter consists of a bed of media through which the waste water passes in an upward direction. It is patterned after the anaerobic filter originally developed for methane fermentation and later used for denitrification. Bacteria growing on the submerged surfaces allow long solids retention times and the upward (or submerged downward) flow allows control of the hydraulic detention time.

The submerged filter also captures most of the biological solids so that long solids retention times are possible (Haug and McCarty, 1972). Still, special attention must be paid to the hydraulic requirements to avoid flow conditions which allow the filter to plug (Schlegel, 1988) or to exhaust the dissolved oxygen that is available in the water.

Two innovative modifications of submerged filters have been developed to reduce two of their most common operational problems. The operational problems, low available dissolved oxygen and plugging problems, can be alleviated with supplemental oxygenation and

bubble aeration. Both modifications raise the level of available oxygen, and both serve to break up clogging to a variable extent. Introducing air into the base of the filter has considerable hydraulic significance. The vigorous aeration strips off thick growths of biofilm thus preventing these growths from clogging the pores in the filter media (Rusten, 1984).

According to tracer studies, the strong turbulence ensures that the substrate is evenly distributed to all parts of the filter (Rusten, 1984). Because the aerated submerged filter is a completely mixed reactor, and its reaction order is greater than zero, it would be more favorably operated as a multi-stage process (Rusten, 1984).

Rotating biological contactors Rotating biological contactors (RBCs) were first used in Europe and have been in continuous operation since 1958 (Calvin et al., 1979). RBCs have attracted attention because of their low head requirement, competitive capital cost with activated sludge, and relatively low operating costs (Tanaka et al., 1987). However, the RBCs capital cost is typically much more than that of trickling filters, submerged filters or fluidized beds.

RBCs function by rotating honeycombed or corrugated disks or tubes on a shaft through a tank containing the waste water. The microbial mass functions the same as the other attached growth systems described above; however, the oxygen transfer to the microbial film is enhanced by the rotation of the media through the atmosphere.

Typical RBCs have disks submerged to 40 % of the diameter, rotational speeds of 1.5 to 2 rpms, lengths of 8 m (25 ft), and total surface areas of approximately 8400 m^2 (85,000 ft^2) (Tchobanoglous, 1985). Catastrophic failure of either the disks or the shaft due to heavy biomass growth were major problems in early units. However, most of the problems were mechanical and recent RBCs have been more reliable.

Fluidized beds Fluidized sand-bed biological filters have been shown to be both space and capital cost-efficient methods of providing nitrification in recirculating aquaculture systems (Burden, 1988; Losordo and Westerman, 1991). The performance of fluidized beds as nitrifying biofilters within recirculating aquaculture systems has been studied considerably, particularly during the last five years (Bullock et al., 1993; Heinen and Hankins, 1991; Wimberly, 1990; Owsley, et al., 1988; Burden, 1988; Paller and Lewis, 1988; Cooley, 1979). Recently, Summerfelt and Cleasby (1993) reviewed the hydraulic design of fluidized-beds. Currently, there are several large-scale commercial fish producers using fluidized-bed biological filters in their recirculating systems.

Efficient use of the media surface area is provided in fluidized beds by the suspension and rolling of the media grains such that all portions are exposed to the solution. Mass transfer efficiency is increased at the biofilm surface on the particles within the fluidized bed because

the high velocities and turbulence required for bed expansion decreases the thickness of the stagnant boundary layer surrounding the biofilm. Microorganism growth is a function of substrate loading and can be selected to be at or near the log phase (the most efficient microbial phase for nutrient up-take) by the continuous physical shearing of the thickening biofilm due to hydraulic forces and physical particle-particle or particle-wall interactions. In addition, the proportion of decaying organic matter within the biofilm is reduced by continuous shearing forces, which reduces the substrate available to heterotrophic organisms.

Fluidized-bed biofilters use granular media of small diameter, generally less than 3 mm, which allows for high bed surface areas per unit volume. Sand and plastic beads are the media primarily used in fluidized biofilters. Sands have a specific gravity 2.65 times that of water (1.0) and for biofilters are typically utilized in sizes ranging from 0.1 to 1 mm. Plastic pellets used in the plastic molding industry can be obtained from suppliers of bulk plastics. The pellets are roughly spherical or cylindrical, and range in size from 1 to 3 mm. Plastic pellets can be used unmodified, although surface modified pellets are available. Plastic pellets can be purchased in different molecular formulations, or in formulations containing a heavy filler such as silica. Such pellets will have a specific gravity equal to, just greater than, or just less than 1.0. Using plastic beads having specific gravities greater than or less than water allows for either up-flow expanded ($\rho_p > 1$) or down-flow expanded ($\rho_p < 1$) beds. Fluidized plastic bead filters have lower headlosses (<1 psi) and somewhat lower requirements for expansion velocity and for delivering oxygen due to their lower specific surface area (relative to sand).

Because of their relatively high nitrification rate, high specific surface area and low media cost relative to other types of biofilters, fluidized bed biological filters have become attractive to commercial aquaculture producers with large recirculating systems. In addition, fluidized beds can be circular or rectangular in shape, can be contained within plastic, fiberglass, concrete, or enamel-coated steel tanks, and can generally be constructed by personnel on site. However, fluidized sand-beds have the disadvantages of significant headlosses (2 to 6 psi) and high flow rates required for fluidization. The high flow rates are necessary for providing both the velocity necessary for bed expansion and for delivering sufficient oxygen for maintaining nitrification.

Summary--Aquaculture Review

Aquaculture production within recirculating systems is being driven by the needs for conservation of water resources, control of the culture environment, alternative site locations, reduction in production cost through intensification and economies of scale, and an increased

emphasis to reduce, manage and control effluents. Recirculating technology allows aquaculture to be market and demand driven rather than limited by natural resource factors. Technological advances now make it possible to culture a wide variety of species in almost any location. The present challenge, however, is to develop, integrate, and refine recirculating aquaculture production technology so that it is economically feasible for commercial production of food products.

Recirculating systems must contain unit processes which function for fish rearing, clarification, ammonia and BOD reduction, aeration/oxygenation, CO_2 and pH control, and sometimes disinfection. Most successful, large-scale, commercial aquaculture producers using recirculating technologies have gone to deep (2 to 5 m) round culture tanks, microsieve filters for clarification, fluidized-bed biological reactors for ammonia and BOD control, pure oxygen injection systems for oxygenation, and air-stripping columns and/or chemical treatment for CO_2 control. Many researchers and producers agree that the clarification process is the most critical for making recirculating systems successful, because solids control influences the efficiency of all other unit processes within these systems. Clarification has also generally turned out to be the most capital and operational costly unit process, particularly with the introduction of fluidized-bed biofilters which have been demonstrating relatively low capital and operational costs.

Study of the literature and communication with producers indicated that little was known and less published on the understanding and control of CO_2 problems within recirculated systems. For this reason, paper I of this dissertation was devoted to the issues of CO_2.

This project was oriented towards using unit processes amenable for converting abandoned water and waste water treatment plants into commercial sites for culturing food fish within recirculating systems. The abandoned facilities typically contain large, deep, circular and/or rectangular tanks which had been used as clarifiers and, in the case of waste water treatment plants, often contained large trickling filters. Some of these empty tanks could function well for culturing food-fish on a large-scale. It was thought that other empty tanks could be converted into settling basins for clarifying the recirculating water and that the old trickling filters could be used as submerged biofilters or possibly roughing filters. Review of the field indicated that although better unit processes might be available, the unit processes available at abandoned water and waste water treatment facilities might function adequately for use within recirculating-aquaculture production systems and at low cost. Paper II describes research conducted on the performance of static-media filters for nitrification and clarification

and on the performance of either settling basins or static-media roughing filters in maintaining nitrification efficiency within the biofilter downstream.

High retail prices and limited supplies of walleye have provided the economic incentive for developing culture techniques for the commercial production of food size walleye. Closed system aquaculture appears to be the method of choice for culturing walleye to food size because it provides opportunity to maintain culture at high fish densities and at a temperature for maximizing growth. The purpose of paper III is to define the growth of walleye to food size at a fairly constant temperature (~24 °C) in recirculated systems.

PAPER I. UNDERSTANDING AND TREATING CARBON DIOXIDE PROBLEMS IN RECIRCULATING AQUACULTURE SYSTEMS

ABSTRACT

Carbon dioxide toxicity problems are being encountered in aquaculture systems in which oxygen injection is used to increase fish production in recirculating systems. Fish excretion, low water exchange and lack of air-water contact for stripping are responsible for the accumulation of carbon dioxide in a recirculating aquaculture system. The equilibrium relationships and rate processes related to carbon dioxide removal are discussed in this paper. The mechanisms for air-stripping carbon dioxide are discussed and equations based on steady-state mass balances are developed. The importance of proper ventilation of carbon dioxide from aquaculture systems within buildings is demonstrated. In addition, chemical treatment for carbon dioxide neutralization is discussed.

INTRODUCTION

Pure molecular oxygen is widely used to supplement oxygen levels and boost fish production in intensive recirculating aquaculture systems. Trout densities of 267 kg/m^3 (16 lb/ft^3) have been attained with no significant deterioration of fish health (Kebus et al., 1992). However, accumulation of high levels of carbon dioxide can become a limiting toxicity factor with high fish densities and inadequate water exchange, i.e., high fish loadings (Colt and Tchobanoglous, 1981; and Colt et al., 1991). It is not only the high fish loadings which are responsible for accumulation of toxic levels of CO_2, it is also the nature of pure oxygen injection systems which become a problem when water is being oxygenated for reuse. Pure oxygen injection systems operate with insufficient gas exchange for stripping off sufficient CO_2 to hold down its accumulation, as illustrated by Watten et al. (1991). When oxygen is supplied via aeration, adequate air-water contact is generally provided to keep CO_2 from accumulating to toxic levels (Speece, 1973).

To understand and treat the problem of CO_2 accumulation in aquaculture requires that CO_2 toxicity to fish, method of generation, equilibrium, kinetics and treatment be defined. The primary strategies for controlling carbon dioxide are air stripping and chemical neutralization. All aeration processes remove some carbon dioxide from water but forced-draft gravity air strippers seem to work the best (Colt and Orwicz, 1991). The performance of CO_2 strippers has been characterized by others (Piedrahita and Grace, 1989). Strategies for controlling pH in aquaculture systems have been discussed by Bisogni and Timmons (1991), but they do not address the problem of controlling carbon dioxide. This paper will provide a theoretical basis and strategy for controlling carbon dioxide in a recirculating aquaculture system. Such systems generally include a rearing tank, a solids removal unit, a biological filter, and a stripping/oxygenation process or processes.

CARBON DIOXIDE TOXICITY AND PRODUCTION

Although CO_2 is a gas, it does not contribute significantly to the water's gas supersaturation, and thus is not a major contributor to gas bubble disease (Colt and Orwicz, 1991). Carbon dioxide is toxic to fish because it reduces the capacity of their blood to transport oxygen (significantly at 20 to 40 mg/L [Basu, 1959]) and contributes to the deposition of calcium in their kidneys, with higher CO_2 concentrations corresponding to increasing deposition (Smart et al., 1979). Smart et al. (1979) found reduced growth and higher feed conversion ratios in rainbow trout reared at concentrations of 55 mg/L CO_2. Others have found CO_2 concentrations in excess of 60 mg/L to be lethal to rainbow trout. Good tolerance to CO_2 concentrations of 30-35 mg/L have been observed in rainbow trout, while concentrations of 55 mg/L were found to be incipient to mortality (J. M. Heinen and J. A. Hankins, Freshwater Institute, personal communication). However, actual toxicity levels vary according to fish species, fish age, and other water quality variables. The recommended limit on the carbon dioxide concentration in trout or salmon culture is 20 mg/L (SECL, 1983).

Interactions between CO_2 and bicarbonate (HCO_3^-) are important, both within the fish's external environment (discussed later) and within the fish itself. Within fish tissue, CO_2 is the end-product of most catabolic pathways while HCO_3^- is the initial substrate of many biosynthetic pathways. The mechanism for elimination of CO_2 (Figure 1) was developed by the contributions of many (Swenson and Maren, 1987; Henry et al., 1988; and Perry and Wood, 1989) and has been summarized by Walsh and Henry (1991). Within fish tissue, carbon dioxide diffuses into passing red blood cells, where the enzyme carbonic anhydrase converts the CO_2 into HCO_3^-. As the blood is pumped through the gill epithilial, the enzyme mediated process reverses and HCO_3^- is converted back into CO_2. A large portion of the CO_2 diffuses out of the plasma and across the cell membrane into the mucous layer coating the outsides of the epithilial. Swenson and Maren (1987) further demonstrated that extracellular carbonic anhydrase contained within the mucous layer catalyzes the conversion of the CO_2 into HCO_3^- to maintain a low boundary layer concentration of CO_2 and an outward directed concentration gradient. Fish move relatively large volumes of their surrounding water over their gills to obtain sufficient oxygen to sustain aerobic metabolism and to ventilate ammonia and CO_2 (Wright, Randall and Perry, 1989; Perry, 1986; Randall and Daxboeck, 1984). If surrounding levels of CO_2 are elevated, less CO_2 can be transferred from the gills into the bulk solution (similar to the mass transfer described in the air-stripping section, below). Fish like trout control the rate water is pumped through their gills and the blood loading on portions of

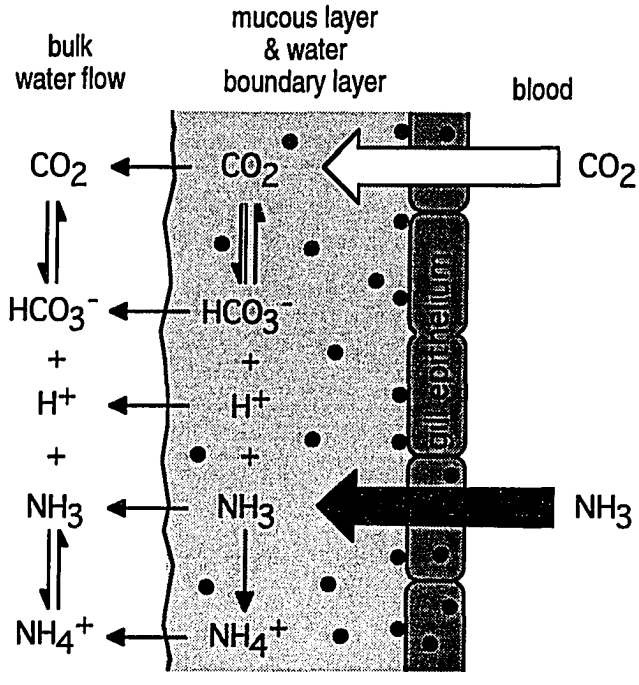


Figure 1. Illustration of the excretion of CO_2 and NH_3 through the gill epithelium. The CO_2 and NH_3 freely diffuse through the cell membrane into the mucous layer coating the gill. Carbonic anhydrase (●) within the mucous layer catalyzes the hydration of CO_2 into HCO_3^- and H^+, promoting the removal of CO_2 and NH_3 by preventing their accumulation. Thus, CO_2 and NH_3 diffusion gradients are maintained in a direction away from the gill epithelium (from Wright et al., 1989).

the gills based upon the blood's oxygen content. Elevated levels of CO_2 in the fish's environment results in a reduction in the fish's blood oxygen content, which is countered by pumping more water through the gills and by utilizing more of the gills for blood flow (author's hypothesis). The bright marachino-red gill lamella, observed in fish exposed to high-levels of CO_2 (J. M. Heinen, J. A. Hankins & G. Bullock, Freshwater Institute, personal communication), can be explained as resulting from blood loading more portions of the gills (author's hypothesis).

The volume of carbon dioxide produced in respiration is about the same as the volume of oxygen consumed (Kutty, 1968). Based on the molecular weights of carbon dioxide (44 gm/mole) and oxygen (32 gm/mole), the weight of carbon dioxide produced is about 38 percent greater than the weight of oxygen consumed — about 0.3 to 0.4 gm of carbon dioxide per gm of feed for salmon and trout (Liao and Mayo, 1974).

Respiration and hence CO_2 production also occurs in the biological treatment processes used to control ammonia and organic matter. The bacterial cell mass generated during treatment can be consumed by other heterotrophic microorganisms, producing additional carbon dioxide and releasing nutrients. Carbon dioxide is also produced during nitrification, the two step process in which ammonia is oxidized to nitrite and nitrate. Autotrophic organisms are mainly responsible for nitrification and carbon dioxide is their primary carbon source. However, the free acid produced during nitrification reacts with bicarbonate alkalinity in the water releasing more carbon dioxide than the autotrophs consume (EPA, 1975).

CARBON DIOXIDE MODELING

The concentration of carbon dioxide in water is controlled in part by the water pH and alkalinity. Dissolved carbon dioxide can combine with water in a hydrolysis reaction to form carbonic acid:

$$CO_2\,(aq) + H_2O\,(l) \Leftrightarrow H_2CO_3\,(aq) \qquad (1)$$

The hydrolysis of carbon dioxide is described by the following equilibrium relationship:

$$K_0 = \frac{[H_2CO_3]}{[CO_2]} \qquad (2)$$

$$= 1.58 \times 10^{-3} \text{ @ } 25°C$$

This relationship indicates that there is about 633 times as much carbon dioxide in water as carbonic acid under equilibrium conditions.

Carbonic acid dissociates releasing hydrogen ions and bicarbonate ions. Bicarbonate ions dissociate releasing additional hydrogen ions and carbonate ions:

$$H_2CO_3\,(aq) \Leftrightarrow H^+\,(aq) + HCO_3^-\,(aq) \qquad (3)$$

$$HCO_3^-\,(aq) \Leftrightarrow H^+\,(aq) + CO_3^{=}\,(aq) \qquad (4)$$

The ionization of carbonic acid into the bicarbonate ion is described by the following equilibrium relationship:

$$K_1 = \frac{[H^+][HCO_3^-]}{[H_2CO_3]} \qquad (5)$$

$$= 2.56 \times 10^{-4} \text{ mol/L @ } 20°C \text{ (Larson \& Buswell, 1942)}$$

The hydrogen ion concentration is equal to the ionization constant, K_1, when the bicarbonate concentration is equal to the carbonic acid concentration. The ionization of the bicarbonate ion into the carbonate ion is described by the following equilibrium relationship:

$$K_2 = \frac{\left[H^+\right]\left[CO_3^{=}\right]}{\left[HCO_3^-\right]} \qquad (6)$$

$= 4.20 \times 10^{-11}$ mol/L @ 20°C (Larson & Buswell, 1942)

Open System Equilibria

When water is in contact with the atmosphere, the equilibrium concentration (C_{CO_2}) of carbon dioxide in water will depend on the amount of carbon dioxide in the air. At standard temperature and pressure, air contains about 0.032 percent carbon dioxide by volume (320 ppm, Giddings, 1973) -- a mole fraction of about 0.00032 and a partial pressure (P) of 0.00032 atm. Henry's law can be assumed to predict gas-liquid equilibrium because for dilute solutions, the gas-liquid equilibrium relationship is linear. The Henry's law proportionalilty constant (K_H) has been expressed many ways depending upon which concentration units are of interest:

- mol fractions in both gas (Y_{CO_2}) and liquid (X_{CO_2}) phases at pressure, P_T,

$$K_H = \frac{P_T \cdot Y_{CO_2}}{X_{CO_2}} = 1.43 \times 10^3 \text{ atm @ 20°C (Tchobanoglous \& Schroeder, 1985)} \qquad (7)$$

- mol fraction in gas phase (Y_{CO_2}) and molarity (M_{CO_2}) in liquid phase,

$$K_H^M = \frac{P_T \cdot Y_{CO_2}}{M_{CO_2}} = 25.8 \text{ atm} \cdot \frac{L}{\text{mol}} \text{ @ 20°C (as in Cornwell, 1990)} \qquad (8)$$

- mol fraction in gas phase and mg/L (C_{CO_2}) in liquid phase,

$$K_H^D = \frac{P_T \cdot Y_{CO_2}}{C_{CO_2}} = 5.84 \times 10^{-4} \text{ atm} \cdot \frac{L}{\text{mg}} \text{ @ 20°C (as in Cornwell, 1990)} \qquad (9)$$

- molarity or mg/L in both gas ($C_{CO_2}^g$) and liquid phases, and ignoring P_T (=1),

$$K_H^u = \frac{C_{CO_2}^g}{C_{CO_2}} = 1.07 \text{ @ 20°C (as in Cornwell, 1990)} \qquad (10)$$

Henry's law constant, strongly dependent upon temperature, decreases with increasing temperature according to (for the first unit system, Equation 7 [Cornwell, 1990]):

$$K_H = 10^{\left(6.73 - \frac{1042}{T}\right)} \tag{11}$$

Where T is temperature in °K.

Water in contact with the atmosphere, therefore, would normally have an equilibrium concentration of 10^{-5} mol carbon dioxide per liter — about 0.5 mg/L at 20°C.

The equilibrium concentration of the other carbonate species can be estimated by substituting into equations 2, 5 and 6. If the concentration of carbon dioxide is 10^{-5} mol/L, the concentration of carbonic acid will be about 1.6×10^{-8} mol/L. At pH of 6.3, the bicarbonate concentration will be the same as the concentration of carbon dioxide and the carbonate concentration will be about 10^{-9} mol/L. At this pH, the bicarbonate ion is the main source of alkalinity and it would have a value of about 0.5 mg/L as $CaCO_3$.

Alkalinity is a measure of the acid neutralizing capacity of a solution. It depends on the concentrations of the bicarbonate, carbonate, hydroxide and hydrogen ions:

$$\frac{Alk}{50000} = \left[HCO_3^-\right] + 2\left[CO_3^=\right] + \left[OH^-\right] - \left[H^+\right] \tag{12}$$

where the alkalinity is expressed in mg/L as $CaCO_3$.

The concentrations of the hydroxide and hydrogen ions can be related to each other through the ion product, K_W, for the dissociation of water:

$$H_2O\,(l) = H^+\,(aq) + OH^-\,(aq) \tag{13}$$

where

$$K_W = [H^+]\,[OH^-] \tag{14}$$

$$= 0.68 \times 10^{-14}\ mol^2/L^2 \text{ @ } 20°C \text{ (Larson \& Buswell, 1942)}$$

The equilibrium alkalinity and carbon dioxide concentrations can be related to each by substituting equations 2, 5, 6 and 14 into equation 12:

$$\frac{Alk}{50,000} = [CO_2] \cdot \left(\frac{K_0 K_1}{[H^+]} + \frac{K_0 K_1 K_2}{[H^+]^2}\right) + \frac{K_w}{[H^+]} + [H^+] \tag{15}$$

or approximately in the pH range from 6.5 to 9.5:

$$\frac{Alk}{50,000} = [CO_2] \cdot \left(\frac{K_0 K_1}{[H^+]} \right) \quad (16)$$

or

$$C_{CO_2} = Alk \cdot 10^{(6.3-pH)} \quad (17)$$

where C_{CO_2} is the concentration of carbon dioxide in mg/L. Since C_{CO_2} is about 0.5 mg/L for water in contact with the atmosphere, the saturation pH will be:

$$pHs = \log Alk + 6.6 \quad (18)$$

where pHs is the saturation pH. At any pH value lower than the saturation value, the water will be supersaturated with carbon dioxide.

Carbonate System Kinetics

The rate of interconversion of various carbonate forms affects the buildup of carbon dioxide in an aquaculture system. The rate of ionization of carbonic acid into bicarbonate and carbonate ions is nearly instantaneous but the rate of hydration of carbon dioxide into carbonic acid is relatively slow (Kern, 1960). Based on the hydration reaction:

$$CO_2 (aq) + H_2O (l) \Leftrightarrow H_2CO_3 (aq) \quad (19)$$

The rate equation for the hydration reaction is:

$$\frac{d[CO_2]}{dt} = -k_{CO_2} \cdot [CO_2] \quad (20)$$

where

k_{CO_2} = 0.03 sec^{-1} (Kern, 1960)

The rate of the dehydration reaction is:

$$\frac{d[H_2CO_3]}{dt} = -k_{H_2CO_3} \cdot [H_2CO_3] \quad (21)$$

where

$k_{H_2CO_3}$ = 20 sec^{-1} (Kern, 1960)

Accumulation occurs when the rate of production of carbon dioxide by the fish and microbial population exceeds the rate at which carbon dioxide is being lost to water replacement and to the atmosphere. Carbon dioxide will then build up the carbonic acid concentration. As

it does, the concentration of bicarbonate will increase and the concentration of carbonate will go down. With these changes in the relative amounts of carbonic acid and its ion products, the pH will drop to a lower value. If carbon dioxide is removed from solution, carbonic acid will slowly dehydrate to reestablish the equilibrium. As this happens, bicarbonate will disproportionately release carbonic acid and carbonate ions into solution.

Mass Transfer

Air stripping is a mass transfer process in which water is contacted with air to reduce its concentration of carbon dioxide (or other volatile liquids or gases). The rate of mass transfer $\left(J_{CO_2}\right)$, as defined by Fick's law, is proportional to the product of the total interfacial contact area (A) per unit system volume (V) and the concentration gradient $\left(X^{eq}_{CO_2} - X_{CO_2}\right)$(Treybal, 1980):

$$J_{CO_2} = K_L \frac{A}{V}\left(x^{eq}_{CO_2} - x_{CO_2}\right) \tag{22}$$

The concentration gradient is the driving force for mass transfer. In the expression for the concentration gradient, $X^{eq}_{CO_2}$ is the limiting molar concentration of carbon dioxide defined by Henry's Law and X_{CO_2} is the actual molar concentration of carbon dioxide in the water. The term $\frac{A}{V}$, represents the specific interfacial area, which is sometimes represented by the symbol a. The proportionality constant K_L is called the overall mass transfer coefficient. The overall mass transfer coefficient is the sum of the resistance to mass transfer across both liquid and gas interfaces, k_L and k_G, respectively:

$$\frac{1}{K_L} = \frac{1}{K^u_H \cdot k_G} + \frac{1}{k_L} \tag{23}$$

As stripping occurs along the axis of a stripping column, the concentration of CO_2 changes, making the driving force for mass transfer a function of depth. Equation (22) can be manipulated to relate the mass transfer per differential change in depth, d(Z), as shown by Cornwell (1990):

$$d(Z) = \frac{L_{mol} \cdot d\left(X_{CO_2}\right)}{K_L \cdot a \cdot \left(X_{CO_2} - X^{eq}_{CO_2}\right)} \tag{24}$$

After integration, the resulting expression can be used to calculate the column depth required to achieve a given effluent concentration from a given influent concentration:

$$Z = \frac{L_{mol} \cdot \left(X_{CO_2}^{inf} - X_{CO_2}^{eff}\right)}{K_L \cdot a \cdot DF_{LM}} \tag{25}$$

where, L_{mol} is the superficial molar liquid flow rate (mol sec^{-1} m^{-2}) and DF_{LM} is the log mean of the driving force at column exit and entrance.

$$DF_{LM} = \frac{DF_{exit} - DF_{ent}}{\ln\left(\frac{DF_{exit}}{DF_{ent}}\right)} \tag{26}$$

and

$$DF_{eff} = X_{eff} - X_{eff}^{eq} \tag{27}$$

$$DF_{inf} = X_{inf} - X_{inf}^{eq} \tag{28}$$

Onda et al. (1968) reported a method for calculating the values of k_L, k_G, and a (actually use the wetted area, a_w, instead of a) for use in the design of air strippers.

$$k_L \cdot \left(\frac{\rho_L}{\mu_L \cdot g}\right)^{1/3} = 0.0051 \cdot \left(\frac{L_m}{a_w \cdot \mu_L}\right)^{2/3} \cdot \left(\frac{\mu_L}{\rho_L \cdot D_L}\right)^{-1/2} \cdot \left(a_t \cdot d_p\right)^{0.4} \tag{29}$$

$$\frac{a_w}{a_t} = 1 - \exp\left\{-1.45 \cdot \left(\frac{\sigma_c}{\sigma_L}\right)^{0.75} \cdot \left(\frac{L_m}{a_t \cdot \mu_L}\right)^{0.1} \cdot \left(\frac{L_m^2 \cdot a_t}{\rho_L^2 \cdot g}\right)^{-0.05} \cdot \left(\frac{L_m^2}{\rho_L \cdot \sigma_L \cdot a_t}\right)^{0.2}\right\} \tag{30}$$

$$\left(\frac{k_G}{a_t \cdot D_G}\right) = 5.23 \cdot \left(\frac{G_m}{a_t \cdot \mu_G}\right)^{0.7} \cdot \left(\frac{\mu_G}{\rho_G \cdot D_G}\right)^{1/3} \cdot \left(a_t \cdot d_p\right)^{-2} \tag{31}$$

where: a_t = total specific surface area of the packing; a_w = wetted specific surface area of the packing; d_p = nominal packing diameter; σ_L = surface tension for the liquid (0.073 N/m @ 20°C); σ_c = critical surface tension for the particular packing material; L_m = liquid mass flux; G_m = gas mass flux; μ_L = liquid viscosity (0.0010 kg/m/s@ 20°C); ρ_L = liquid density (998 kg/m^3 @ 20°C); D_g = gas diffusivity (1.38×10^{-5} m^2/s,CO_2 @ 20°C); D_L = liquid diffusivity (19.6×10^{-10} m^2/s, CO_2 @ 25°C); and, g = gravitational acceleration constant (9.81 m/s^2) (data as tabulated in Cornwell, 1990). Consistent units must be used throughout (e.g., SI units).

The method of Onda et al. (1968) has been reviewed intensively (Kavanaugh & Trussell, 1980; Cornwell, 1990; Haarhoff and Cleasby, 1990; and Thom and Byers, 1993), particularly in the water treatment field, and has been shown to perform with an accuracy of ±30 percent with 90 percent confidence (Staudinger et al., 1990). Thom and Byers (1993) reported a review of 90 pilot and full-scale air strippers where the Onda et al. model was found to overestimate mass transfer 75 percent of the time with an average overestimate of 37 percent.

Measurement of K_L and a independently is difficult, therefore, the product of the terms (K_La) is generally determined. The measurement of K_La is dependent upon water quality factors and the type of stripping equipment used. Piedrahita and Grace (1989) and Sherwood and Holloway (1940) have measured K_La values for packed CO_2-stripping chambers.

AIR STRIPPING CONSIDERATIONS

Carbon dioxide can be stripped from water with any of the non-closed aeration systems that are commonly used in aquaculture, as described by Colt and Orwicz (1991) and others. Carbon dioxide has a Henry's law constant 200 to 300 times that of oxygen; consequently, bubbles formed from diffused aeration readily become saturated with CO_2, requiring enormous quantities of air to achieve substantial transfer rates when compared with the air-flow rates required for oxygen transfer alone. This explains why it is more effective to move water through air, as is done with surface aerators and air strippers, than it is to move the air through the water, as is done with subsurface aerators (Colt and Orwicz, 1991). Passing water through air provides a much larger ratio of air to water volume, needed for CO_2 exchange, than passing air through water. Also when water droplets are formed while passing through air, the shortened diffusion distance (a function of droplet diameter) enhances mass transfer out of the liquid phase.

The design of counter-current air-stripping columns requires selection of the following parameters:

- liquid loading rate;
- air to water volumetric loading ratio, this selection determines the air loading rate;
- packing depth; and
- packing material; size and type

These parameters are selected to balance removal efficiency and stripping costs. Equation (25), in combination with equations (26)-(31), were solved in an algorithm (Appendix A) programmed into Mathematica™ (Wolfram Research, Champaign, Illinois) which is illustrated in Table 1. With the algorithm, the depth of a column required to air-strip CO_2 can be calculated, for a given media, as a function of both removal efficiency and volumetric air to water loading ratio, G/L (Figure 2).

Essentially, a CO_2 stripper should be designed to meet the following criteria:

1. a hydraulic fall of 1 to 1.5 m (3 to 5 ft),
2. a hydraulic loading of 1.0 to 1.4 $m^3/min/m^2$ (25 to 35 gpm/ft^2),
3. a counter-current air:water ratio of 6 to 10 by volume.

Two common types of counter-current CO_2 strippers are illustrated in Figure 3. A high porosity packing or splash screens are needed to avoid flooding or gas hold-up. If high solids loadings are expected, a stripping tower with screens or trays is easier to maintain than a packed tower. The air stripper can be designed with an outlet just below the media support

Table 1. Algorithm for calculating column height for CO_2 stripping unit. The inputs selected in this illustration assume a temperature of 20°C, a process removal efficiency of 0.8, random plastic media, a volumetric gas to liquid ratio (G/L) of 5, and CO_2 concentration in the air influent equal to standard atmospheric levels.

1. Constant Inputs			2. Variable Inputs		
MW_{CO_2}	=	44.0 g/mol	$C_{CO_2}^{inf}$	=	30.0 mg/L
MW_{air}	=	29.0 g/mol	f_{rem}	=	$\frac{X_{inf}}{X_{eff}} = 0.8$
MW_{H_2O}	=	18.0 g/mol	L_{vol}	=	0.015 $m^3/s/m^2$
$[H_2O]$	=	55.6 mol/L	G/L	=	5
P_T	=	1 atm	a_t	=	105 m^2/m^3
K_H	=	1.43×10^3 atm	σ_c	=	33×10^{-3} N/m
K_H^u	=	1.07	d_p	=	0.0508 m
g	=	9.8 m/s^2	Y_{inf}	=	0.00035 mol/mol
ρ_G	=	1.2 kg/m3			
ρ_L	=	998 kg/m3			
μ_G	=	1.82×10^{-5} kg/m/s			
μ_L	=	0.0010 kg/m/s			
σ_L	=	0.073 N/m			
D_L	=	19.6×10^{-10} m^2/s			
D_G	=	1.38×10^{-5} m^2/s			

Table 1. (continued).

3. Calculations of mol fractions and required flow rates	4. Calculation of log mean driving force

$$X_{inf} = \frac{C_{CO_2}^{inf}}{1000 \cdot [CO_2] \cdot MW_{CO_2}}$$

$$X_{eff} = X_{inf} \cdot (1 - f_{rem})$$

$$X_{inf}^{eq} = \frac{P_T \cdot Y_{inf}}{K_H}$$

$$Y_{eff} = \frac{X_{inf} - X_{eff}}{G/L} + Y_{inf}$$

$$X_{eff}^{eq} = \frac{P_T \cdot Y_{eff}}{K_H}$$

$$L_{mass} = L_{vol} \cdot \rho_L$$

$$L_{mol} = \frac{L_{mass} \cdot 1000}{MW_{H_2O}}$$

$$G_{vol} = L_{vol} \cdot G/L$$

$$G_{mass} = G_{vol} \cdot \rho_G$$

$$G_{mol} = \frac{G_{mass} \cdot 1000}{MW_{air}}$$

$$DF_{eff} = X_{eff} - X_{eff}^{eq}$$

$$DF_{inf} = X_{inf} - X_{inf}^{eq}$$

$$DF_{LM} = \frac{DF_{eff} - DF_{inf}}{\ln(DF_{eff}/DF_{inf})}$$

Table 1. (continued).

5. Calculations of wetted area and mass transfer coefficients

$$a_w = a_t \cdot \left\{ 1 - \exp\left\{ -1.45 \cdot \left(\frac{\sigma_c}{\sigma_L} \right)^{0.75} \cdot \left(\frac{L_{mass}}{a_t \cdot \mu_L} \right)^{0.1} \cdot \left(\frac{L_{mass}^2 \cdot a_t}{\rho_L^2 \cdot g} \right)^{-0.05} \cdot \left(\frac{L_{mass}^2}{\rho_L \cdot \sigma_L \cdot a_t} \right)^{0.2} \right\} \right\}$$

$$k_L = 0.0051 \cdot \left(\frac{\rho_L}{\mu_L \cdot g} \right)^{-1/3} \cdot \left(\frac{L_{mass}}{a_w \cdot \mu_L} \right)^{2/3} \cdot \left(\frac{\mu_L}{\rho_L \cdot D_L} \right)^{-1/2} \cdot \left(a_t \cdot d_p \right)^{0.4}$$

$$k_G = 5.23 \cdot a_t \cdot D_G \cdot \left(\frac{G_{mass}}{a_t \cdot \mu_G} \right)^{0.7} \cdot \left(\frac{\mu_G}{\rho_G \cdot D_G} \right)^{1/3} \cdot \left(a_t \cdot d_p \right)^{-2}$$

$$K_L = \frac{1}{\frac{1}{K_H^u \cdot k_G} + \frac{1}{k_L}}$$

6. Calculations of column height

$$Z = L_{vol} \cdot \left(\frac{X_{inf} - X_{eff}}{K_L \cdot a_w \cdot DF_{LM}} \right)$$

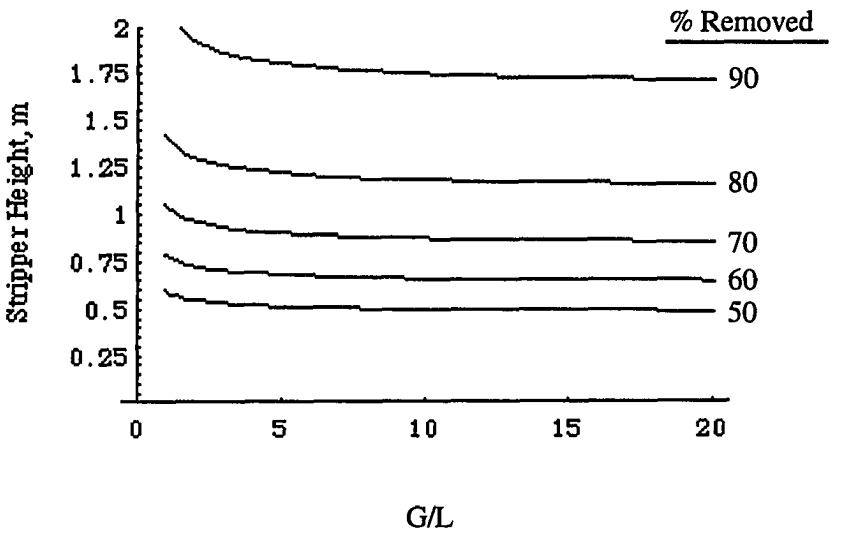
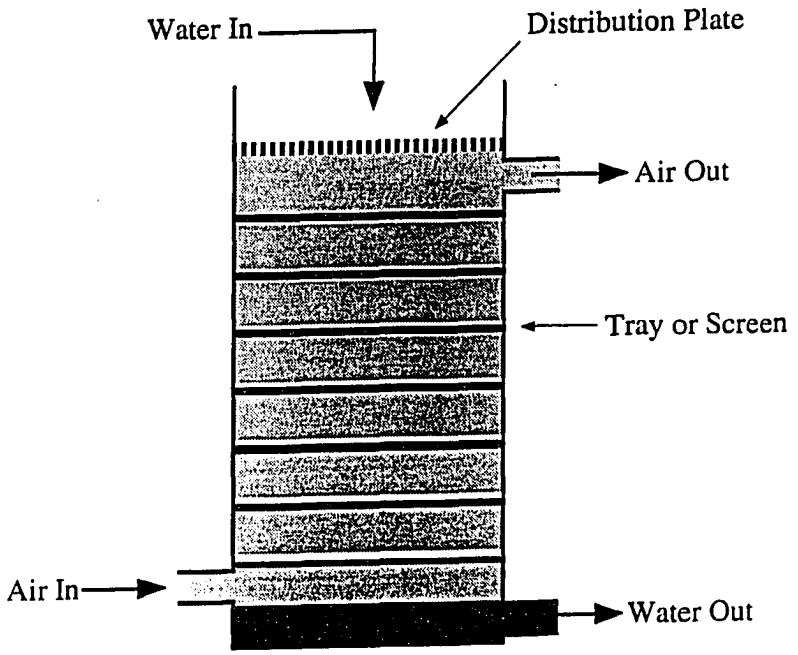
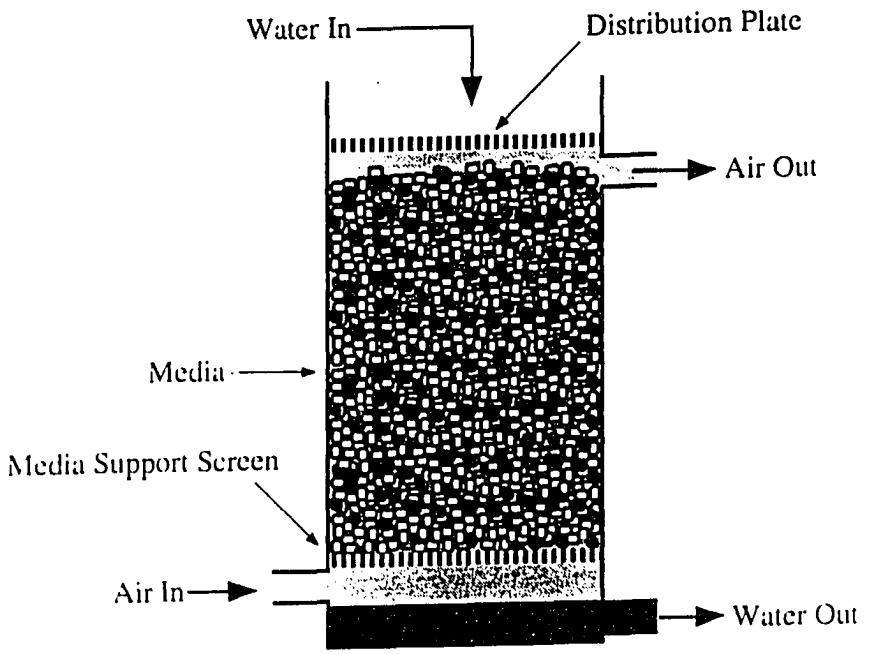


Figure 2. Depth of column required to air-strip CO_2 as a function of percentage removed and volumetric air to water loading ratio (G/L) for the stripping details shown in Table 3.



Tray Tower



Packed Tower

Figure 3. Two common types of air strippers.

matrix and just above the water surface so that foam can be vented with a portion of the air flow.

The concentration of carbon dioxide at various locations in a recirculating aquaculture system is illustrated in Figure 4. The water enters the rearing tank with a given level of carbon dioxide, C_0. If the rearing tank is a completely mixed system, the carbon dioxide level will increase abruptly to a constant level, C_1, which accounts for the difference between the amount of carbon dioxide being generated by the fish and the amount being lost to the atmosphere through the air-water interface. Additional carbon dioxide is generated by the microbes in the biofilter, which increases the carbon dioxide concentration sent on to the air stripper, C_2.

As the water travels through the air stripper, the CO_2 concentration decreases, approaching the value predicted by Henry's Law, $C^{eq}_{CO_2}$. A short time after leaving the stripper, the CO_2 concentration increases to a value that is more in balance with the alkalinity at the new pH. The alkalinity of the water hasn't changed, but the relative proportions of the bicarbonate ion and the carbonate ion has. Potentially, half of the carbon contained in the bicarbonate alkalinity can be released as carbon dioxide.

The kinetics of equilibrium plays an important role in whether or not carbon dioxide will accumulate in the rearing tanks. Carbon dioxide will accumulate if the rate at which it is lost to the atmosphere or converted into carbonic acid is less than the rate at which fish are producing the carbon dioxide. At high fish densities, the carbon dioxide produced by the fish does accumulate causing the carbon dioxide in the rearing tanks to be greater than the equilibrium value based on pH and alkalinity. Thus, the actual carbon dioxide levels in the rearing tanks should be measured with a carbon dioxide probe.

As was noted earlier, the driving force in the mass transfer of carbon dioxide from water into air is $\left(X_{CO_2} - X^{eq}_{CO_2}\right)$. The limiting concentration of carbon dioxide, $X^{eq}_{CO_2}$, depends on the amount of carbon dioxide in the air supplied to the stripping tower. Under typical conditions, the concentration of CO_2 leaving the stripper in the gas phase can easily be four times greater than inlet gas levels (Figure 5). The driving force for mass transfer is diminished when the limiting concentration of carbon dioxide is very high. Therefore, it is important in recirculating aquaculture systems enclosed in a building that air leaving the CO_2 stripper be vented from the building to avoid carbon dioxide accumulation in the air within the building. Because the molecular weight of CO_2 (44 g/mol) is greater than the average molecular weight of air (29 g/mol), CO_2 tends to seek the lowest level possible (AWWA,

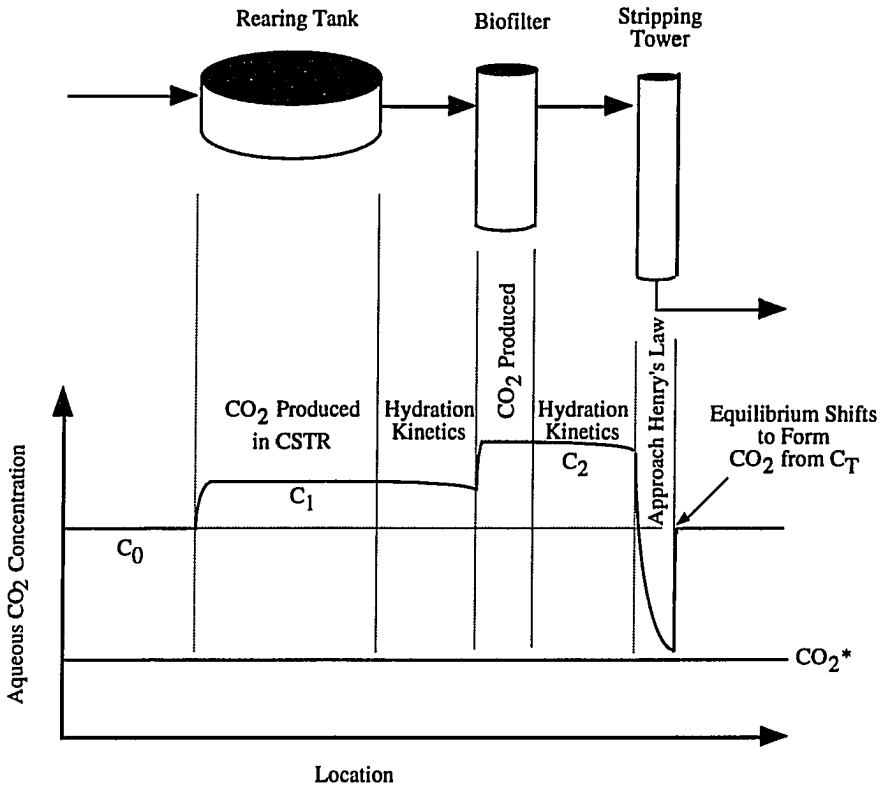


Figure 4. Illustration of the CO_2 kinetics across a culture tank and stripping tower.

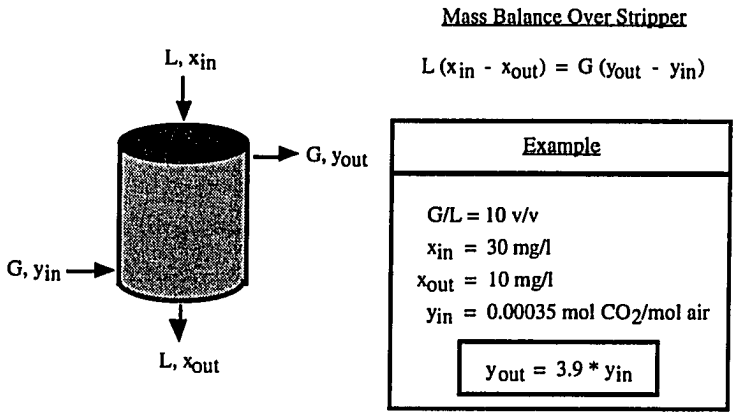


Figure 5. Mass balance over a CO_2 stripping tower indicates that the air passing through the tower can increase its concentration of CO_2 nearly four fold.

1990) and should be vented from the floor level. If venting the building in cold climates, an air-air heat exchanger is recommended to conserve energy.

WATER EXCHANGE CONSIDERATIONS

Carbon dioxide and ammonia are generated by the fish in the rearing tank of an aquaculture system. The carbon dioxide and ammonia concentrations can be maintained at an acceptable level by wasting water from the rearing tank and replacing it with makeup water with a lower carbon dioxide content. In a recirculating aquaculture system, water treatment processes are used to conserve water. Processes such as biofilters can transform ammonia into nitrate but they generate additional carbon dioxide. Air strippers can lower the concentration of carbon dioxide to a level that is about the same as that of the makeup water. An air stripper must be selected that can lower the carbon dioxide concentration to the selected level for a selected rate of flow.

Liao and Mayo (1972) developed a generalized mass-balance to help predict the metabolic byproduct concentration in a rearing unit at any degree of water treatment for reuse (Figure 6).

The efficiency of stripping, the amount of CO_2 produced by the fish and biological treatment microbes, and the amount of water recirculating all combine to control the concentration of CO_2 in the culture tanks of a water reuse system (Figure 6). Solving the mass balance over the system under steady-state conditions allows for prediction of the concentration of CO_2 in the rearing tank (Liao and Mayo, 1972):

$$C_{CO_2} = P_{CO_2} \cdot \frac{V_{tank}}{Q} \cdot \frac{1}{1 - R + (R \cdot f_{rem})} \cdot 10^6 \left[\frac{mg}{kg}\right] \tag{32}$$

where,

R = fraction of water reused, unitless
V_{tank} = volume of rearing tank, L
Q = water flow rate through culture unit, L/day
P_{CO_2} = CO_2 generation rate, kg CO_2 produced per L rearing space per day
C_{CO_2} = concentration of CO_2 at outlet of rearing unit, mg/L
f_{rem} = fraction of CO_2 removed across stripper, unitless

The rate that CO_2 is produced within the system is proportional to the product of the culture biomass and the feeding rate:

$$P_{CO_2} = a_{CO_2} \cdot \rho_{fish} \cdot r_{feed} \tag{33}$$

where,

ρ_{fish} = density of fish in the rearing tank, kg fish per L rearing space

r_{feed} = feeding rate, kg feed per kg fish per day

a_{CO_2} = CO_2 produced as a proportion of feed fed, kg CO_2 per kg feed

Some of the carbon dioxide generated in the rearing tank will be lost across the air-water interface to the air over the rearing tanks (r_{loss}). The rate at which it will be lost will depend, in part, on the concentration of carbon dioxide concentration in the rearing tank. If r_{loss} is much smaller compared to P_{CO_2}, then the overall CO_2 generation rate can be represented by equation (33).

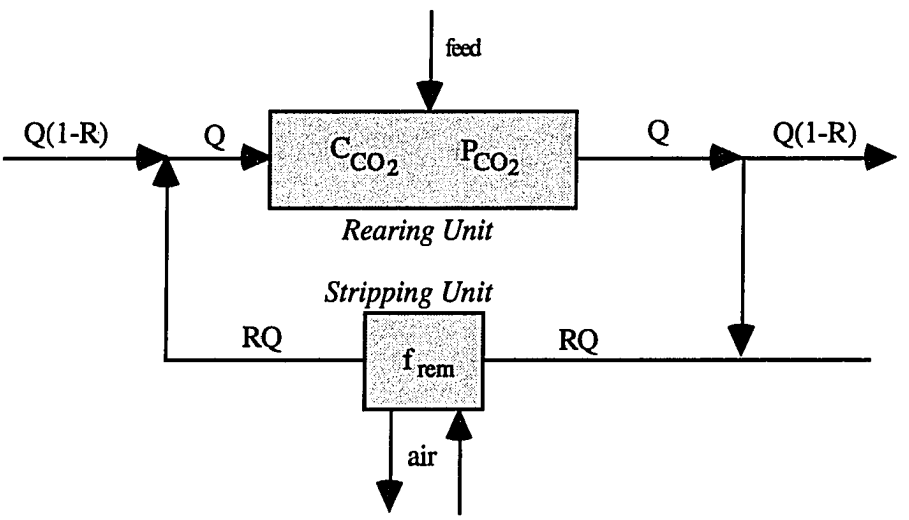


Figure 6. Illustration of generalized model governing metabolite level within a water reuse system (as shown in Liao and Mayo [1972]).

CHEMICAL TREATMENT

Alkalinity plays an important role in aquaculture. An alkalinity of at least 50 mg/L as $CaCO_3$ should be maintained during nitrification to prevent pH instability in the system (Gujer and Boller, 1984). Fish in low alkalinity waters have a lower buffering capacity in their blood than fish in more alkaline waters (Randall, 1991). Differences in the buffering capacity of the blood might explain why a given carbon dioxide concentration has a larger effect on fish physiology in low alkalinity waters than it does in more alkaline waters.

Chemical treatment can be used to maintain a pH that will minimize the potentially toxic effects of ammonia and carbon dioxide in recirculating aquaculture systems. The treatment process consists of adding a supplemental source of alkalinity such as lime, caustic soda, soda ash, or sodium bicarbonate to the water. Lime, caustic soda and soda ash react with carbon dioxide producing bicarbonate alkalinity. Adding sodium bicarbonate is simply a source of bicarbonate alkalinity.

Lime is generally purchased as calcium oxide, CaO, which is also known as burned lime, quick lime, or unslaked lime. When calcium oxide is added to water it hydrates forming calcium hydroxide, $Ca(OH)_2$, which is also known as slaked lime. Although calcium hydroxide is very soluble in water, the dosages that are normally used produce a slurry that is called "milk of lime" because of its chalky appearance. When calcium hydroxide dissolves in water, it produces hydroxide ions that react with carbon dioxide forming bicarbonate ions:

$$OH^- (aq) + CO_2 (aq) \Leftrightarrow HCO_3^- (aq) \qquad (34)$$

Caustic soda, NaOH, is more expensive than lime. It is very soluble in water. When caustic soda dissolves in water, it dissociates and releases hydroxide ions into solution that react with carbon dioxide forming bicarbonate ions. Soda ash, Na_2CO_3, is also a more expensive source of alkalinity than lime. It, too, is very soluble in water. When soda ash dissolves in water, it dissociates releasing carbonate ions into solution that react with carbon dioxide forming bicarbonate ions:

$$CO_3^= (aq) + CO_2 (aq) \Leftrightarrow 2HCO_3^- (aq) \qquad (35)$$

Sodium bicarbonate, $NaHCO_3$, is a popular chemical additive for maintaining

alkalinity in a recirculating aquaculture system (Bisogni and Timmons, 1991). It is very soluble and dissociates in water releasing bicarbonate ions. Bicarbonate ions do not react with carbon dioxide but they can shift the equilibrium of the carbonic acid system. When bicarbonate is added to water, the carbonic acid concentration is increased almost instantaneously and that eventually increases the concentration of carbon dioxide.

The percentage of dissolved inorganic carbon existing as CO_2 and the percentage of total ammonia existing as NH_3 are a function of pH (Figure 7). Comparing the range of pH values where ammonia and CO_2 coexist indicates that the smallest fractions of both CO_2 and ammonia coexist in a pH range from 7.5 to 8.2, depending upon temperature. Recirculating systems can operate at a given pH to minimize the toxic effects of either or both CO_2 or NH_3, depending upon which is more limiting. Changing the system pH only 1 unit lowers the corresponding equilibrium CO_2 concentration 10 fold (Figure 8).

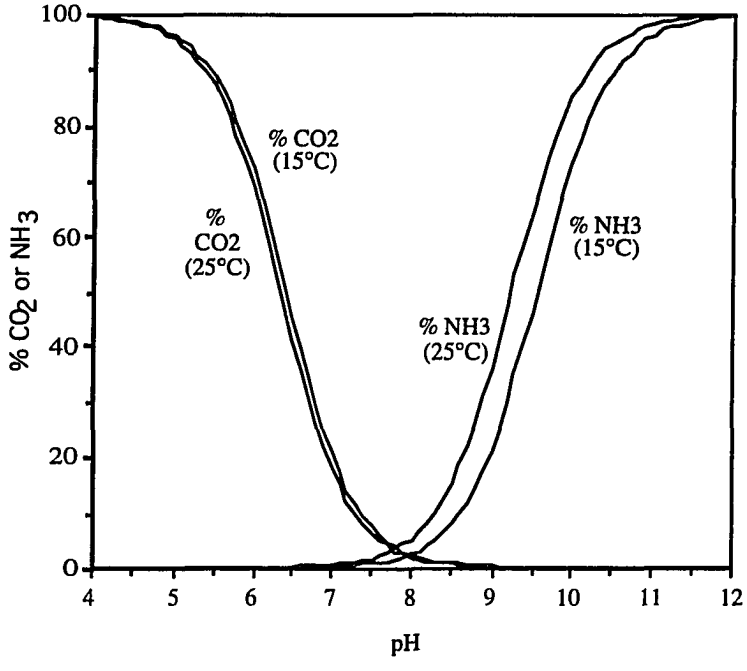


Figure 7. Percentage of carbon dioxide and ammonia as a function of pH.

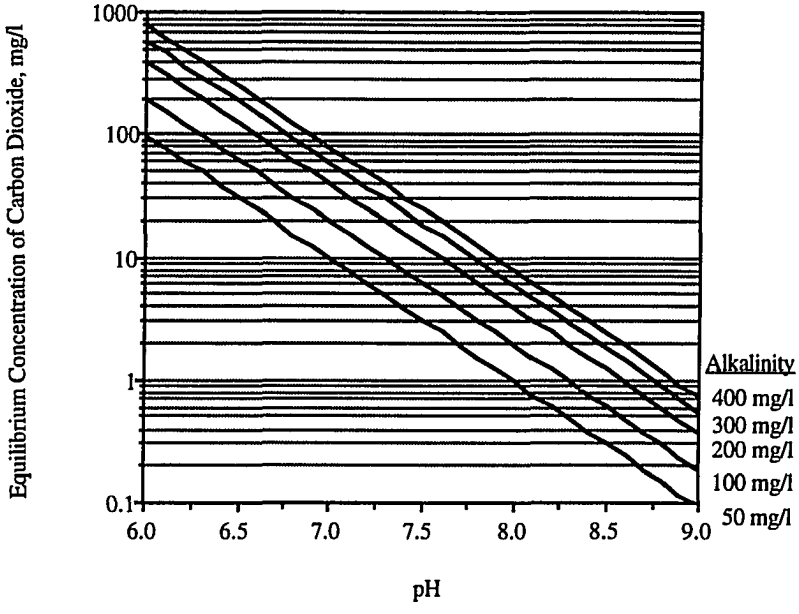


Figure 8. Fluctuation of CO_2 levels in equilibrium with the carbonic acid system as a function of pH and alkalinity.

SUMMARY--UNDERSTANDING AND TREATING CO_2 PROBLEMS

Study of the literature and communication with producers indicated that little was known and less published on the understanding and control of CO_2 problems within recirculated systems. The results of a study on the equilibrium of carbon dioxide in solution and it's removal by air stripping and chemical addition indicated:

- The efficiency of CO_2 removal, the amount of CO_2 produced by the fish and the biological treatment process, and the rate of water recirculated all combine to control the concentration of CO_2 within the culture tank;
- High density fish culture systems utilizing pure oxygen addition typically require some method of CO_2 removal, because these systems typically lack much air to water contact;
- It is more effective to strip CO_2 by cascading water through air, than by blowing air through water;
- Carbon dioxide stripped from the water should be vented from enclosed buildings;
- Chemical treatment using lime, caustic soda, soda ash or sodium bicarbonate can be used to maintain a pH that will minimize the potentially toxic effects of CO_2 and NH_3;
- A pH between 7.5 to 8.2 will minimize the relative proportions of CO_2 and NH_3.

The design criteria for CO_2 removal in counter-current air stripping columns are given. In addition, a computer algorithm was developed for calculating the depth of a stripping column required for a given media, removal efficiency and volumetric air to water ratio.

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PAPER II. USE OF LOW-HEAD, STATIC-MEDIA FILTERS FOR CLARIFICATION AND NITRIFICATION IN A RECIRCULATING FISH CULTURE SYSTEM

INTRODUCTION

The removal of ammonia (a metabolic by-product of protein metabolism) in the nitrification step of a biofiltration process and avoidance of nitrite accumulation, produced if incomplete nitrification occurs, are the most important functions of the water reconditioning stages in closed-system aquaculture (Liao and Mayo, 1974) as it is most critical to the continued health and growth of the fish. In once-through or single-pass aquaculture systems, ammonia is flushed away with fresh water. In reuse systems, however, ammonia must be removed from the system to prevent its accumulation in the recycled water. The primary method for treating ammonia is via biological nitrification. The process of nitrification in closed-system aquaculture has received considerable attention; however, nitrification cannot be considered separate from clarification because the performance of nitrifying filters is affected by the water's organic content, both dissolved and suspended. It has not been obvious that adequate clarification or removal of suspended solids must be achieved prior to the nitrification process to ensure sustainable ammonia removal.

The objectives of this research were to evaluate nitrification, clarification and the relationship between clarification and nitrification in a closed system for rearing walleye to food size. Water treatment processes amenable for use in converting abandoned water and waste water treatment plants into commercial sites for fish culture were selected. Because of their prevalance in abandoned waste water treatment plants, up-flow, static-media, rock or plastic media filters were evaluated. Static media filters were used as both biofiltration and clarification unit processes. Both single-stage and two-stage style biofiltration units were studied in separate pilot recirculating aquaculture systems. The system using a single-stage biofilter was provided with a settling basin to clarify the water prior to biofiltration. The two-stage biofilter system incorporated a carbonaceous treatment unit (roughing filter) followed by a nitrification unit with supplemental aeration between the two stages. Within the roughing filter system (RFS) removal of ammonia, suspended solids and oxygen demand were evaluated across the biofilter and across the roughing filters at different roughing filter hydraulic loading rates. Within the sedimenation basin system (SBS), ammonia removal and oxygen demand across the biofilter were evaluated at different biofilter hydraulic loading rates. Nitrification and oxygen consumption rates were used to compare single-stage and two-stage biofiltration systems. Biofilter and roughing filter maintainance is discussed.

Biological Filtration

The role of biofiltration in recycle aquaculture, a term coined for labeling attached growth biological treatment processes, is not really true filtration (i.e., the passage of water containing suspended solids through a porous media for the purpose of solids/liquid separation), but a process in which heterotrophic and autotrophic microbes attached to a support medium biologically oxidize (by metabolism) a portion of the ammonia nitrogen and the biodegradable organics (the oxygen required for this oxidation is called the biochemical oxygen demand, or BOD) in a waste stream. Retention of the microbe population is obtained by their attachment to the wetted or submerged surfaces of the biofilter medium, providing the long solids retention time required for good biological oxidation. Ammonia is oxidized by autotrophic bacteria (called nitrifying bacteria) and biologically degradable organic compounds are oxidized by heterotrophic microbes. Typically the autotrophic and heterotrophic microbes coexist on the the media surface in the biofilter.

The media used in attached growth systems must have a relatively high specific surface area (i.e., surface per unit volume) and an appreciable voids ratio. The specific surface area is important as it controls the amount of bacterial growth that can be supported in a unit volume. The voids ratio is critical for adequate hydraulic performance of the systems, i.e., the treatment of the flow with the generation of minimal head losses. In addition, the media must be inert, non-compressible, and non-biologically degradable on a relative time scale. Media is classified according to its packing characteristics, i.e., random packing versus structured packing. Random packing media can be crushed rock or river gravel, or some form of plastic or ceramic material shaped as spheres, rings, or saddles. Structured media can be crossed stacks of redwood slats, or more commonly plastic blocks composed of corrugated plates or tubes.

Competition for space and oxygen in biofilters

The oxidation of organic compounds and ammonia in static-bed biofilters does not take place simultaneously, as it can in a suspended growth treatment process (such as activated sludge), but successively (Kruner and Rosenthal, 1987; and Schlegel, 1988). If sufficient BOD is present, organic compounds will be oxidized preferentially before ammonia is utilized as heterotrophic microbes outcompete autotrophic bacteria for space on the biofilter media (Wanner and Gujer, 1984; Harremoes, 1982; and Schlegel, 1988). After sufficient organic oxidation occurs, the heterotrophs do not have the organic substrate requirement necessary to dominate the surface space on the media and autotrophic bacteria can compete, providing nitrification (Kruner and Rosenthal, 1987). However, Schlegel (1988) states that poor

nitrification is not a result of carbon oxidizing bacteria outcompeting the nitrifying bacteria in the biofilter, but competition from heterotrophic protozoa.

The nitrification in biofilters is reduced by an additional factor, oxygen deficiency, caused by the carbonaceous oxygen demand exerted by the heterotrophic organisms located up-filter of the autotrophic nitrifiers (Liao and Mayo, 1974; Bovendeur et al., 1990; Wanner and Gujer, 1984; Harremoes, 1982).

Because oxidation of the organics and ammonia are accomplished in two distinct steps, the processes for the removal of biodegradable organics and for ammonia must be designed separately. In addition, oxygen limitations to ammonia oxidation, imposed by the carbonaceous oxygen demand, necessitates a design need to increase the available oxygen prior to nitrification. Therefore, to ensure proper nitrification, single-stage biofilters should be designed and operated with a mechanism to provide adequate available oxygen to remove both the carbonaceous and ammonia loads. Supplemental oxygenation can be used to provide adequate available oxygen to single-stage biofilters by either recycling while reaerating or supersaturating the feed stream with oxygen. With two-stage biofilters, supplemental oxygenation can be used prior to the second-stage biofilter to help ensure nitrification.

Nitrification

Bacteria convert ammonia into nitrate in a two-step process called nitrification. Two different groups of nitrifying bacteria, both believed to be obligate autotrophs (consume CO_2 as their primary carbon source) and obligate aerobes (require O_2) are needed for complete nitrification (Sharma and Ahlert, 1977). Although there are several species of nitrifying bacteria, Cutter and Crump (1933) found that *Nitrosomonas* showed considerably higher ammonia conversion rates than the others. It is generally assumed that *Nitrosomonas* converts ammonia into nitrite, NO_2^-, and that *Nitrobacter* converts the nitrite into nitrate, NO_3^-. The stoichiometry for these energy conversion reactions, ignoring cell synthesis, are (EPA, 1975):

$$NH_4^+ + 1.5\ O_2 + 2\ HCO_3^- \rightarrow NO_2^- + H_2O + H_2CO_3 \quad (1)$$

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^- \quad (2)$$

Taking nitrifier synthesis together with nitrification, the overall relationship between ammonium, bicarbonate, and oxygen consumed and cell mass, nitrate, water, and carbonic acid produced is (EPA, 1975):

$$NH_4^+ + 1.86\ O_2 + 1.98\ HCO_3^- \rightarrow 0.0206\ C_5H_7NO_2 + 0.980\ NO_3^- + 1.041\ H_2O + 1.88\ H_2CO_3 \quad (3)$$

As given by the stoichiometry, nitrification and nitrifier synthesis requires consumption of about 4 mg of oxygen and between 6.0 and 7.4 mg of alkalinity (as $CaCO_3$) for every mg of

ammonia as nitrogen converted to nitrate (EPA, 1975). Because ammonia and nitrite are both toxic to fish at low levels, monitoring the levels of ammonia and nitrite in the culture system tanks provides a measure of the performance of the biofilter and provides a warning of conditions that may inhibit fish growth or cause a fish kill. High levels of nitrite will occur if there is an imbalance between the bacterial populations of *Nitrosomonas* and *Nitrobacter*. Most commonly, high levels of nitrite occurs within the first month of biofilter start-up (Manthe and Malone, 1987) because the *Nitrobacter* grow slower than the *Nitrosomonas*.

Oxygen has been demonstrated to be both the metabolism-limiting and flux-limiting reactant for bulk liquid ammonia nitrogen concentrations greater than 4 mg/L in attached growth systems (Gullicks and Cleasby, 1986). At a pH of 7.5 and a temperature of 25 °C, commonly encountered in closed-system aquaculture, 1.77 percent of the total ammonia nitrogen exists in the NH_3 form (Piper et al., 1982). A total ammonia nitrogen concentration of 4.0 mg/L results in an unionized ammonia concentration of 0.071mg/L, which is growth limiting for most cold- or cool-water fishes. Therefore, nitrification in closed-system aquaculture for cold or cool water fishes must occur at ammonia concentrations below 4 mg/L. Under these conditions, the bulk ammonia concentration controls the nitrification rate until depletion of oxygen to less than 2.0 mg/L (Gullicks and Cleasby, 1986). Inhibition of nitrification occurs at dissolved oxygen concentrations less than 2.0 mg/L (Schoberl and Engel, 1964). Conversely, unusually high oxygen concentrations have not been found to inhibit nitrification (Haug and McCarty, 1972). Haug and McCarty (1972) found that to keep the oxygen from being rate limiting, the dissolved oxygen levels need to be maintained in a stoichiometric ratio to the actual total ammonia nitrogen concentration in the biofilter. They also found that oxygen concentrations above the stoichiometric requirement resulted in no increase in the rate of ammonia oxidation, but concentrations less than the stoichiometic amount reduce the rates of oxidation.

Alkalinity can be rate limiting at bulk liquid concentrations less than 50 mg/L (Gujer and Boller, 1984) and below pH values of 7 (Figure 1).

Temperature affects the maximum nitrification rate (Metcalf and Eddy, 1991):

$$r_{max,TAN}(T) \cong r_{max,TAN}(@T = 15°C) \cdot e^{\{0.098 \cdot (T-15)\}} \qquad (4)$$

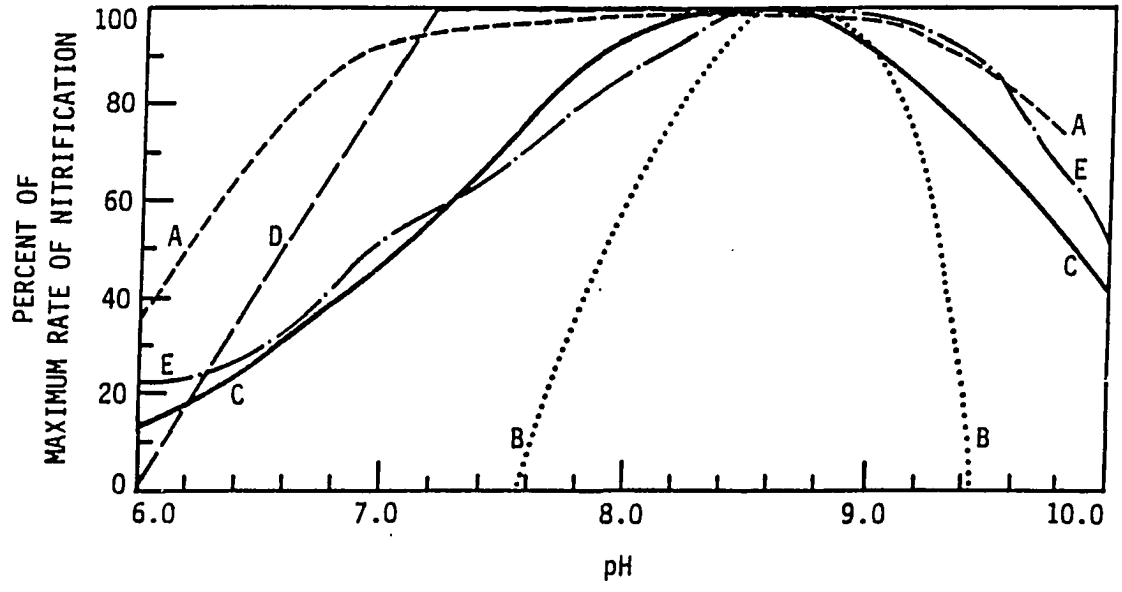
where,

$r_{max,TAN}$ = maximum ammonia removal rate, g TAN removed per m^2 of biofilm per day

T = temperature, °C

The process of nitrification depends on the performance of living organisms, it is sensitive to time, substrate concentrations (dissolved oxygen, dissolved and particulate organic

carbon, and total ammonia nitrogen), temperature, pH, and perhaps to chemicals used for chemotherapy of the fish. To avoid toxic effects of chemotherapeutics, recycle systems must be designed to permit by-passing the biofilter when chemically treating the fish. In addition, sharp fluctuations in the temperature, pH, or dissolved oxygen can inactivate bacteria or reduce the rate of ammonia removal. Both the design engineer and the fish culturist must be aware of the factors affecting the well-being of the biofilter.



KEY SYMBOL	ENVIROMENT	REFERENCE
A	NITROSOMONAS - pure culture	ENGLE AND ALEXANDER (1958)
B	NITROSOMONAS - pure culture	MEYERHOF (1917)
C	ACTIVATED SLUDGE AT 20 C	SAWYER ET AL. (1973)
D	ACTIVATED SLUDGE	DOWNING AND KNOWLES (1966)
E	ATTACHED GROWTH REACTOR AT 22 C	HUANG AND HOPSON (1974 a,b)

Figure 1. Effect of pH on nitrification rate (after Sawyer et al., 1973 as presented by Gullicks, 1987).

Heterotrophic oxidation of organics

Two different forms of organics, soluble and particulate, are oxidized in the biofilter. Dissolved organic compounds are removed biologically by diffusion of the soluble components into the microbial film, followed by enzymatic oxidation resulting in the production of additional microbial biomass, ammonia, carbon dioxide, and short chain carbon compounds such as organic acids (Kruner and Rosenthal, 1987). Upon entering the biofilter, suspended solids are adsorbed on the biofilm surface and the organics must be hydrolyzed before they can be assimilated into the biofilm (Sarner and Marklund, 1984).

The organic matter is used by heterotrophic microorganisms as a source of carbon for cellular synthesis and as a source of energy. The generalized reaction governing the microbial aerobic metabolism of organic matter is

$$\text{Organic material} + O_2 + \text{nutrients} \rightarrow CO_2 + H_2O + \text{new cells} + \text{nutrients} + \text{energy} \quad (5)$$

The cell mass (empirical formulation $C_5H_7NO_2$) can undergo further degradation according to:

$$C_5H_7NO_2 + 5\ O_2 \rightarrow 5\ CO_2 + 2\ H_2O + NH_3 \quad (6)$$

No exact striochiometry can be given for the oxidation of organics because the molecular formulation of organic material varies from waste to waste. The net results of microbial respiration in the biofilter are a decrease in ammonia, biodegradable organics, alkalinity, and pH, and an increase in oxidation products of organics, as well as, nitrite, nitrate and free (dissolved) CO_2.

The rate of biodegradation of organic matter is affected by the organic make-up of the carbonaceous oxygen demand (cBOD), the presence of solids, and also by temperature. Particulate organic matter will reduce the removal of soluble organics (Rusten, 1984; and Sarner and Marklund, 1984). Rusten (1984) recommends that biological filters used for oxidizing organics be designed based upon total organic load, because it gives a much better correlation between removal rates and loading rates than a design based upon soluble organic matter. The oxidation of organic matter by heterotrophic microbes can limit the amount of ammonia oxidized by nitrifying bacteria due to competition for space and oxygen. During high rate filtration, high cBOD loads select for heterotrophic microbes to the extent that nitrification may not occur (Kruner and Rosenthal, 1987).

Clarification

Suspended solids in aquaculture systems are a major source of carbonaceous oxygen demand, and if not reduced before biofiltration, will inhibit both nitrification (McHarness and

McCarty, 1973; and Kruner and Rosenthal, 1987) and the heterotrophic oxidation of organics (Sarner and Marklund, 1984; and Kruner and Rosenthal, 1987). Suspended solids are typically removed by coagulation/ sedimentation, filtration or sieving. Settleable solids are removed similarly or by sedimentation.

The clarification unit process must be reliable and fairly constant in effectiveness to shield the nitrifying biofilter from heavy loads of dissolved or suspended organics. Large variations in organic loading can occur: (1) diurnally between light and dark photo periods or in the hours just after feeding, (2) periodically following tank cleaning or fish harvesting, (3) intermittently during periods when flow through the tank is changed or when interruptions or changes in the feed or feeding regimes produces excesses of uneaten feed, and (4) gradually as fish growth produces greater mass densities.

As just discussed, organics promote the growth of heterotrophic organisms that inhibit the nitrification process. In addition, high solids (organics) loadings can also foul or plug nitrifying biofilters, and can result in: (1) reduced available surface area, (2) shortened hydraulic retention times, (3) encouraged growth of heterotrophic microbes, (4) and odor problems. The later can produce off-flavor problems in the cultured fish.

Sedimentation basins have been the most common method used for clarification prior to the nitrification process because of simple operation and minimum head loss. Sedimentation occurs when particles having a mass density higher than the surrounding water are acted on by gravity to remove them from the water column. However, sedimentation basins often fail to meet the organic reduction necessary to shield the biofilter under the adverse conditions often encountered. Such problems can cause the nitrifying biofilter to shut down "overnight" and result in catastrophic fish mortality from ammonia or nitrite toxicity.

In closed-system aquaculture, roughing filters have the potential to be a better clarification process prior to nitrification than sedimentation. Roughing filters are a type of clarifier used for reducing both the organic load and the quantity of filterable solids reaching biofilters. Roughing filters are also biological filters, where microbial activity reduces ammonia and dissolved organics in the waste water. Unlike sedimentation basins, roughing filters can remove dissolved and nonsettleable particulate organics as well as settleable organics. And because roughing filters combine sieving, sedimentation, and absorption processes, they should be more effective at shielding nitrifying biofilters from organics even with large variations in organic loading. Sieving occurs when water containing particles is passed through a pore space; particles larger than the pore space are retained above the pore

space in down flow filters. Absorption occurs when particles in the water impact a surface and become attached.

Solids Flushing and Filter Maintenance

The problems resulting from accumulation of organic solids in the void spaces within static-media biological filters has limited their effectiveness in recycle aquaculture. Accumulation of organic solids typically results from high organics loading on the filter, coupled with improper solids flushing from the filter. However, solids accumulation in static filter beds is based on both physical and biological mechanisms. Physically, suspended or settlable solids are entrapped within the filter voids due to settling, sieving, and interception. Biologically, cell mass is produced by the microbial metabolism of substrates (primarily organics and ammonia) passing through the filter, both on the surface of the media and in the voids between the media. Cell mass resulting from nitrifying bacteria is desired. Cell mass resulting from heterotrophic organisms, though required to some extent, increases plugging problems in static media filters used for biological treatment. As well, heterotrophic microorganisms inhibit the nitrification process by out-competing nitrifying organisms for space and oxygen. If inhibition of nitrification becomes overwelming, ammonia accumulation in the system will threaten the fish. Organic loading, resulting from both entrapped suspended solids and dissolved organics in solution, serve as a food source for the heterotrophic microoganisms. If the retention time of the filter sludge (organic solids and heterotrophic micro-organisms) is of sufficient duration, thick growths of heterotrophic organisms in the filter result and add to the plugging problem due to the mechanism of physical accumulation. If oxygen becomes limiting, anaerobic organisms such as *Beggiotoa* can grow and produce much thicker biological films, plugging the filter.

The characteristics of the media in a static media filter ultimately influences the removal of suspended, settleable, and dissolved organics as well as the head loss generated and the success of flushing the fllter. Media with sufficient voids for use in roughing filters can be random media such as uniform crushed rock over 5 cm (2 in) diameter, or plastic media over 2.5 cm (1 in) diameter, and structured media such as plates or tubes. However, operation and maintenance of the roughing filter will vary with each media type and size.

EXPERIMENTAL PROCEDURES

Two separate recycle system biofilters were tested, one containing roughing filters, and the other containing a settling basin. Both systems had the clarifier, e.g., roughing filters or settling basin, in series prior to the nitrifying biofilter (Figure 2). The operational variables for the two recycle systems (fish loading, feeding rates, biofilter hydraulic loading rate, etc.) were the same except for the method of clarification and the flow rate through the clarifier. Each system used a 155 cm (5 ft) diameter, 75 cm (2.5 ft) deep, fiberglass rearing tank, operated at a capacity of about 1000 liters (265 gallons). Each system also used a 3.35 m (11 ft) tall, 61 cm (24 in) diameter aeration column where the recycle water was passed counter-current to diffused air. Diurnal variations in waste production were minimized by lighting continuously and feeding the walleye at 30 min intervals.

Roughing Filter System

The three experimental roughing filters were operated in parallel just down stream from the rearing tank and prior to the nitrification filters (Figure 3). This arrangement ensured that each roughing filter received water of identical waste composition. Effluent water from the center drain of the rearing tank was pumped to the roughing filters, where it was split three ways for up-flow through the filters. Typically, only a portion of the flow through the roughing filters passed through the biofilters. The remaining flow, which bypassed the biofilters, overflowed to the rearing tank after reaeration. The effluent from the roughing filter was split because, in all treatments but one, the experimental hydraulic loading rates through the roughing filters required more flow than was required for the biofilter. The flow through the nitrifying biofilters was held constant during the roughing filter study. The water following the roughing filters was reaerated when passed counter-current to diffused air in a 3.05 m (10 ft) deep, 0.61 m (2.0 ft) diameter column. The biofilter effluent was partially reaerated before reentering the rearing tank by injecting air into the outlet pipe four feet before it entered the tank.

Roughing filter

Three 35.6 cm (14 in) I. D. by 1.60 m (5.25 ft) deep steel columns (Figure 4) were used as the roughing filter vessels. Each vessel was used to test a different filter media. The specific surface area, m^2/m^3 (ft^2/ft^3), differed between the three media (Table 1), and thus the total specific surface area also varied between the filters. Each filter vessel had identical inlet and outlet positions, flow distribution, and media depth. The inlet was centered in the bottom

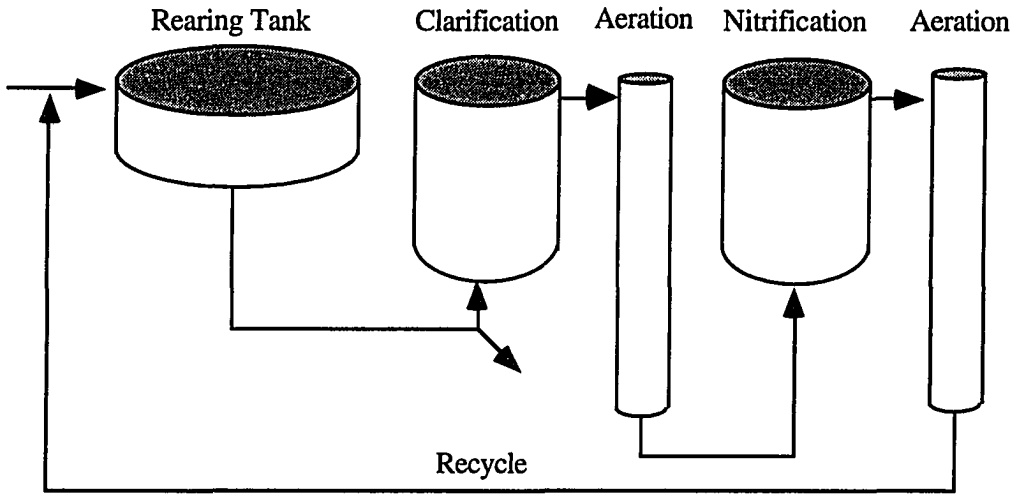


Figure 2. The clarifier (roughing filter or settling basin) is placed so that it is in series and prior to the nitrifying biofilter.

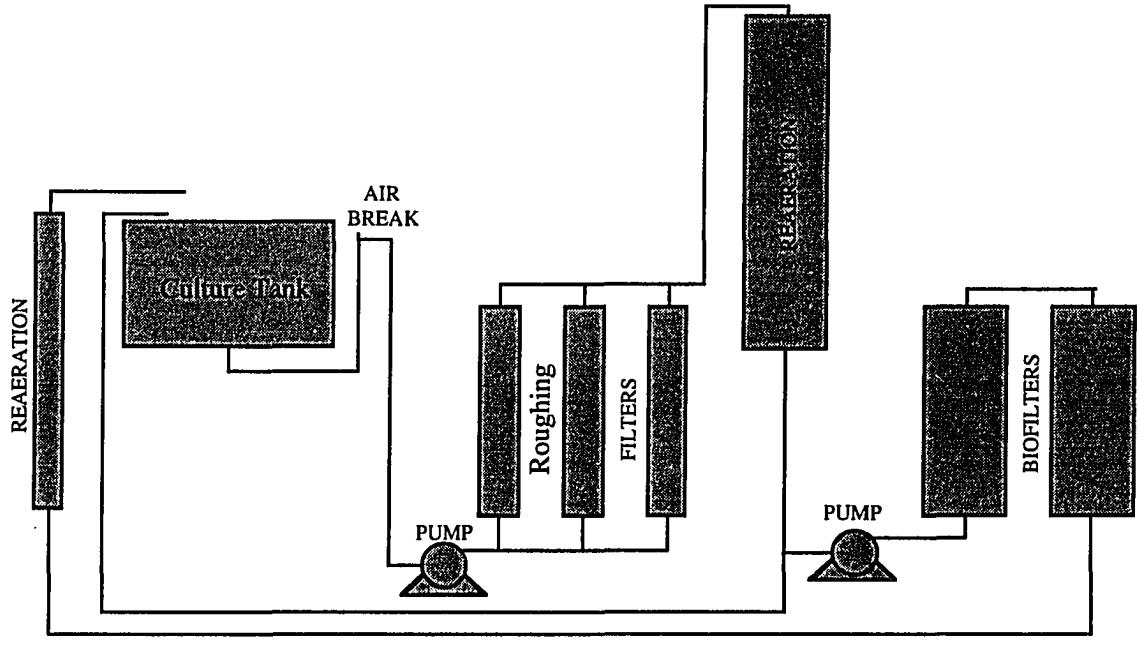


Figure 3. Roughing filter recycle system.

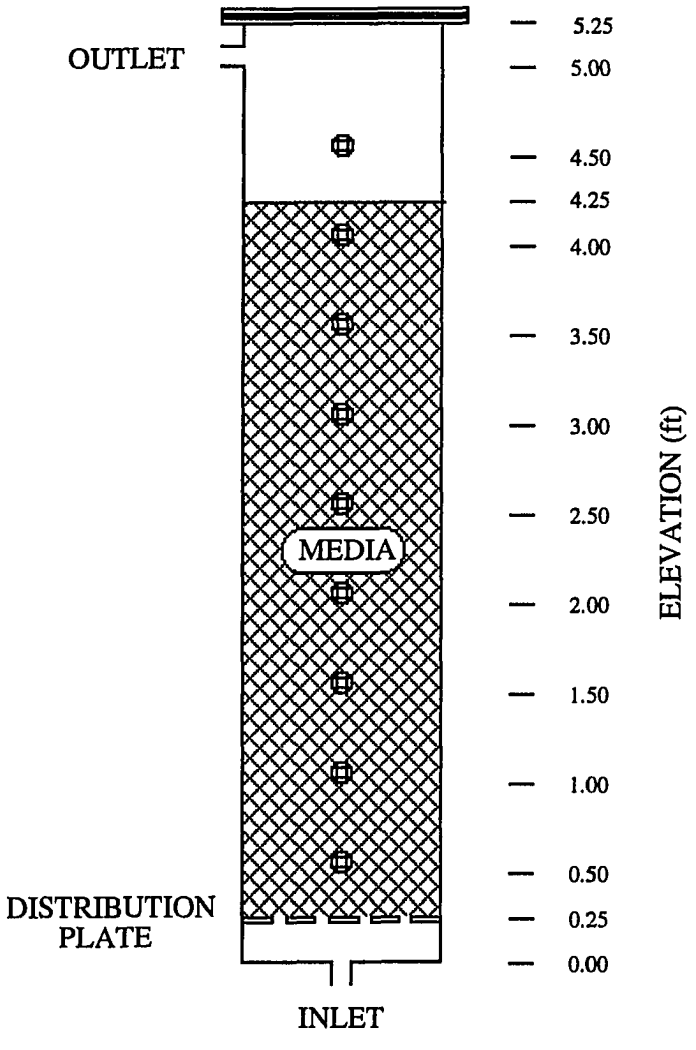


Figure 4. Roughing filter plan showing inlet, outlet, distribution plate, and media.

Table 1. Roughing filter media characteristics.

Media	Void Space (%)	Specific Surface Area m^2/m^3 (ft^2/ft^3)	Specific Gravity
Crushed quartzite, 5 cm (2 in)	40-50	75.4 (23)	2.5
Crushed quartzite, 2.5 cm (1 in)	40-50	148 (45)	2.5
Random 5 cm (2 in) NORPAK	94	102 (31)	0.97
Tubular NORPAK, 1.2 m (4 ft) long x 5 cm (2 in) dia.	93	108 (33)	0.97

of each column, the outlet on the side of the column 1.52 m (5 ft) above the intlet. A distribution plate was located 7.6 cm (3 in) above the inlet. The space below the distribution plate contained no media and provided for uniform flow distribution while in normal operation or when draining. Above the distribution plate rested 1.22 m (4 ft) of media. In the column with the random pack plastic media, a 2.5 cm by 2.5 cm (1 in x 1 in) media retaining screen was used above the media to keep the (specific gravity of 0.97) media from expanding. There were 20.3 cm (8 in) of column free of media between the top of the media and the outlet.

Three media types (Table 1) were tested in the roughing filters: a uniform 5 cm (2 in) crushed quartzite rock, a 5 cm (2 in) random pack polyetheylene media (NSW series 2 in Bio-Pak90), and a structured pack media that consisted of 5 cm (2 in) diameter, 1.2 m (4 ft) long, continuous, axially oriented tubes (NSW series 2 in NORPAK). The random pack consisted of approximately 5 cm (2 in) long by 5 cm (2 in) diameter tubes of the same configuration as the structured tubular media, differing only in the tubular length and packing efficiency. The biofilter was packed with 1.9 to 3.2 cm (0.75 to 1.25 in) crushed quartzite rock. The random pack plastic media, structured tubular pack plastic media, 5 cm crushed rock and 2.5 cm crushed rock media had surface areas of 102, 108, 75 and 148 m^2/m^3 (31, 33, 23 and 45 ft^2/ft^3), respectively.

The hydraulic loading rate through the roughing filters was an experimental variable. Five hydraulic loading rates were evaluated: 70, 120, 180, 250 and 350 $m^3d^{-1}m^{-2}$. Because the bed volume was fixed, the hydraulic retention time through the filter varied with the hydraulic loading rate.

Nitrifying biofilter

Existing 61.0 cm (24 in) I.D. by 1.60 m (5.25 ft) high steel columns were used as the nitrification biofilters. These biological filters had been in operation for approximately one year in an earlier aquaculture experiment (Peterson, 1992). The columns were packed to a depth of

145 cm (4.75 ft) with 2.5 cm (1 in) effective diameter crushed quartzite rock (specific surface area ≈ 148 m^2/m^3 or 45 ft^2/ft^3). The biofilter columns had the same general configuration as the roughing filter columns, except that the biofilter columns were 61 cm (24 in) diameter. Each filter vessel had identical inlet and outlet positions, flow distribution, and media depth. The inlet was centered in the bottom of each column, the outlet on the side of the column 1.52 m (5 ft) above the intlet. A distribution plate was located 7.6 cm (3 in) above the inlet. The space below the distribution plate contained no media and provided for uniform flow distirbution while in normal operation or when draining. Above the distribution plate rested 1.22 m (4 ft) of media. In the column with the random pack plastic media, a 2.5 cm by 2.5 cm (1 in x 1 in) media retaining screen was used above the media to keep it (specific gravity of 0.97) from expanding. There were 20.3 cm (8 in) of column free of media between the top of the media and the outlet.

The nitrifying biofilter was operated at a constant loading rate during the roughing filter study. Evaluation of the roughing filters at different hydraulic loading rates constrained the flow to the nitrifying biofilters to a hydraulic loading rate of approximately 120 $m^3/d/m^2$ (m^2 is the empty bed cross sectional area for flow in the filter). Liao and Mayo (1974), however, recommend that submerged rock filters used for nitrification in recirculating aquaculture systems be designed with hydraulic loadings between 88 and 147 $m^3d^{-1}m^{-2}$ (1.5 and 2.5 gpm/ft^2) and a filter bed depth of 1.22 m (4 ft) or more.

Settling Basin System

A second closed-system was used to investigate the performance of a biofilter for nitrification when a settling basin was used for clarification (versus a roughing filter). In this recycle system (Figure 5), the effluent from the rearing tank was passed upflow through a sedimentation basin prior to nitrification, as an alternative to passing through roughing filters as described above. During the nitrification studies the overflow rate through the settling basin was maintained at approximately 120 m/d and the hydraulic loading rate through the biofilter was maintained at 60, 80, 120, 170 and 210 $m^3d^{-1}m^{-2}$ (empty bed, cross-sectional area) during the different treatments.

The design of the sedimentation basin was based upon the criteria reported by Liao and Mayo (1974) for solids reduction before nitrification filters; e.g., overflow rate of around 120 m/d, retention time of 0.25 to 0.50 hour, and water depth of at least 1 m. An existing fiberglass dish bottom 760-liter tank (model no. C4693, Raven Inc.), 1.59 m deep by 0.814 m internal diameter, was used for the sedimentation basin (Figure 6). The basin was operated

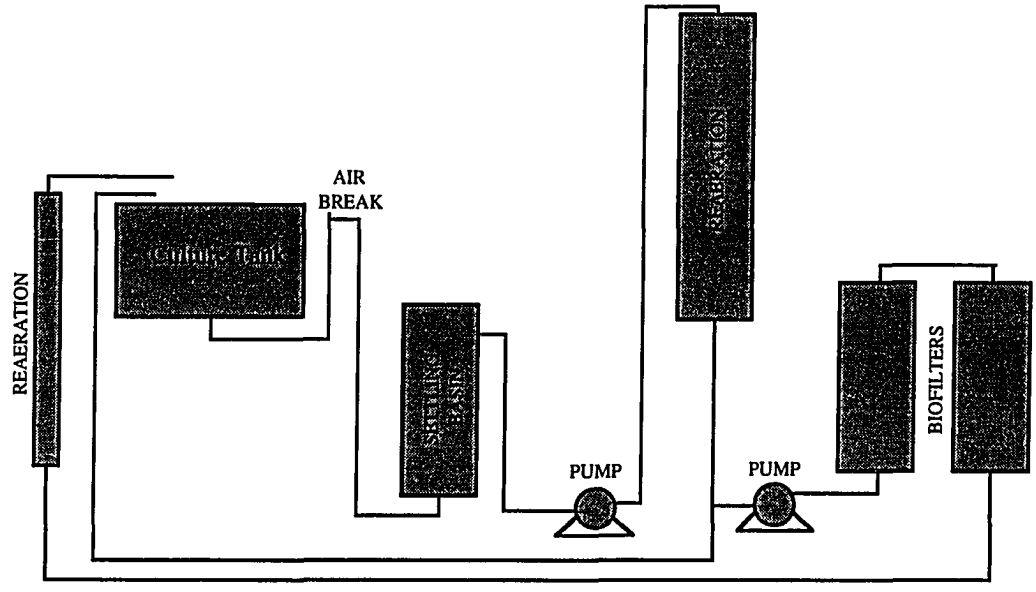


Figure 5. Sedimentation basin recycle system.

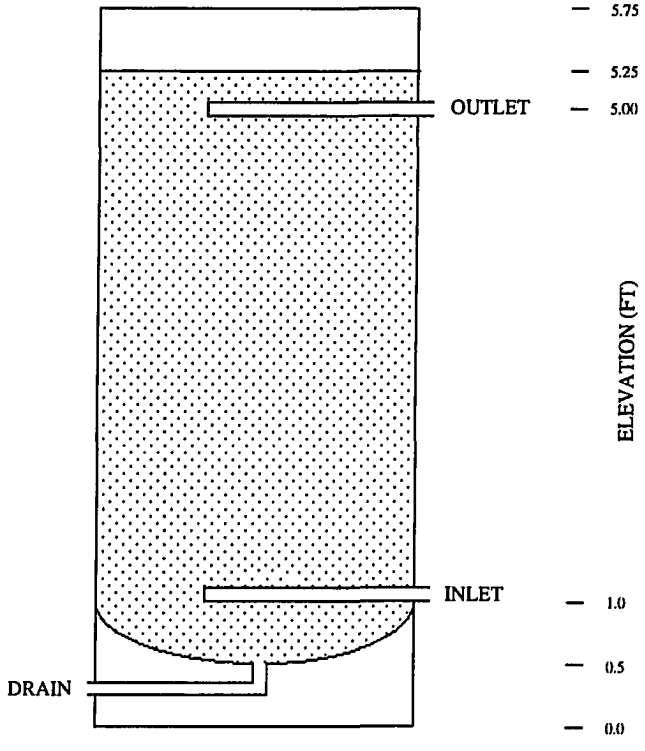


Figure 6. Settling basin showing inlet, outlet, and drain locations.

upflow using a depth of 1.22 m, an overflow rate of 120 m/d and a hydraulic retention time of 0.8 hr.

Water Characterization

Analysis of water quality was based on *Standard Methods for the Examination of Water and Waste water* (APHA, 1989). Total organics were quantified by the 5-day carbonaceous biochemical oxygen demand test (Standard Methods number 507). Dissolved oxygen was measured by the azide modification method (Standard Methods number 421 B). Ammonia was measured using the ion selective electrode method (Standard Methods number 417 E). Solids were measured as total (Standard Methods number 209 A), suspended (Standard Methods number 209 C), and dissolved (difference between total and suspended solids) and were further categorized according to fixed or volatile (Standard Methods number 209 D).

Measuring solids removal was complicated because of difficulty in obtaining representative samples from the influent and effluent. The majority of solids entered the filter as large particles unequally distributed in the flow. Therefore, solids removal could not be accurately quantified by the difference in influent and effluent concentrations. However, by flushing the filters daily and collecting a sample of the well mixed solids-laden wash water, the amount of solids removed in a filter was quantified.

Two to three weeks were required to obtain results at a given treatment of hydraulic and pollutant loading rate. Because of the biological nature of the system, approximately seven to 14 days were allowed for the roughing filters and biofilters within each system to reach steady-state between changes in loading rate. Once steady-state was reached each system was monitored for an additional five to ten days to determine steady-state removal efficiencies.

RESULTS

Ammonia removal rates (g TAN removed per m^2 surface per day) were determined for the roughing filters and the biofilters in the roughing filter system at low (24 kg/m^3 [1.5 lb/ft^3], Table 2) and high (48 kg/m^3 [3.0 lb/ft^3], Table 3) fish culture tank densities and at several roughing filter hydraulic loading rates. Oxygen consumption rates (g dissolved oxygen removed per m^2 of media surface per day) were similarly determined across the roughing filters and biofilters within the roughing filter system (Tables 4 and 5). A hydraulic loading treatment was replicated at completion of the low fish loading experiment to determine repeatability (Tables 6 and 7). Solids removal within the roughing filters was also measured in the roughing filter system (Table 8). Solids from the roughing filter backwash were collected and analyzed to detemine total, suspended and dissolved solids and the percentage of the total solids and the suspended solids which were volatile or fixed (Table 9). Change in carbonaceous oxygen demand (cBOD), a measure of biodegradable organics, was also determined for each roughing filter (Table 10).

Ammonia removal rates were determined in the biofilters in the sedimentation basin system at the low and high fish loading rates (Tables 11 and 12) and at several biofilter hydraulic loading rates. Oxygen consumption rates was similarly determined in the roughing filter system (Tables 13 and 14).

Table 2. Ammonia removal across the roughing filter system at the low fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Ammonia Loading Rate, $g/m^2/d$	Influent TAN, mg/L	Effluent TAN, mg/L	TAN Removal Rate, $g/m^2/d$	TAN Removal Efficiency,[a] %
		Roughing Filter HLR ≅ 70 $m^3/m^2/d$, n = 6[b]				
Rock RF	70 (6)[c]	0.20 (0.05)	0.26 (0.07)	0.20 (0.04)	0.044 (0.035)	20.4 (13.6)
Random RF	73 (5)	0.15 (0.03)	0.26 (0.07)	0.16 (0.03)	0.058 (0.028)	36.9 (11.8)
Structured RF	65 (7)	0.13 (0.04)	0.26 (0.07)	0.16 (0.02)	0.048 (0.035)	35.2 (18.0)
Aeration Column	118 (5)		0.17 (0.03)	0.12 (0.02)		30.4 (7.5)
Biofilter	118 (3)	0.03 (0.01)	0.12 (0.02)	0.09 (0.02)	0.009 (0.002)	25.1 (8.6)
		Roughing Filter HLR ≅ 120 $m^3/m^2/d$, n = 14				
Rock RF	115 (14)	0.39 (0.11)	0.31 (0.08)	0.29 (0.09)	0.021 (0.051)	6.5 (15.9)
Random RF	115 (13)	0.29 (0.08)	0.31 (0.08)	0.26 (0.08)	0.049 (0.026)	17.9 (12.4)
Structured RF	113 (15)	0.26 (0.07)	0.31 (0.08)	0.27 (0.08)	0.033 (0.033)	7.4 (16.9)
Aeration Column	117 (14)		0.26 (0.12)	0.24 (0.07)		13.0 (14.8)
Biofilter	118 (2)	0.07 (0.02)	0.24 (0.06)	0.14 (0.05)	0.029 (0.012)	41.4 (10.4)
		Roughing Filter HLR ≅ 250 $m^3/m^2/d$, n = 9				
Rock RF	258 (10)	0.90 (0.32)	0.32 (0.12)	0.30 (0.12)	0.044 (0.077)	5.2 (8.6)
Random RF	260 (8)	0.67 (0.24)	0.32 (0.12)	0.31 (0.12)	0.014 (0.039)	2.0 (5.6)
Structured RF	244 (7)	0.60 (0.24)	0.32 (0.12)	0.30 (0.12)	0.037 (0.034)	5.7 (5.8)
Aeration Column	261 (9)		0.31 (0.12)	0.28 (0.12)		8.1 (7.7)
Biofilter	118 (7)	0.08 (0.03)	0.28 (0.12)	0.21 (0.07)	0.021 (0.018)	23.1 (11.7)
		Roughing Filter HLR ≅ 350 $m^3/m^2/d$, n = 5				
Rock RF	349 (10)	1.45 (0.20)	0.38 (0.05)	0.36 (0.07)	0.075 (0.142)	5.8 (11.0)
Random RF	350 (12)	1.07 (0.14)	0.38 (0.05)	0.36 (0.09)	0.042 (0.141)	4.7 (14.8)
Structured RF	357 (6)	1.03 (0.13)	0.38 (0.05)	0.36 (0.09)	0.141 (0.193)	14.2 (18.8)
Aeration Column	362 (10)		0.35 (0.08)	0.36 (0.12)		-1.6 (24.1)
Biofilter	118 (6)	0.11 (0.04)	0.37 (0.13)	0.26 (0.09)	0.033 (0.016)	29.5 (8.1)

[a] these values were calculated from the difference in individual influent and effluent TAN concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that ammonia was produced, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 3. Ammonia removal across the roughing filter system during the high fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Ammonia Loading Rate, $g/m^2/d$	Influent TAN, mg/L	Effluent TAN, mg/L	TAN Removal Rate,[a] $g/m^2/d$	TAN Removal Efficiency,[a]
		Roughing Filter HLR ≅ 70 $m^3/m^2/d$, n = 3[b]				
Rock RF	79 (1)[c]	0.43 (0.08)	0.49 (0.09)	0.54 (0.05)	-0.043 (0.042)	-11.4 (13.0)
Random RF	65 (1)	0.26 (0.05)	0.49 (0.09)	0.49 (0.09)	0.000 (0.000)	0.0 (0.0)
Structured RF	72 (1)	0.27 (0.04)	0.49 (0.09)	0.46 (0.10)	0.018 (0.017)	7.3 (7.2)
Aeration Column	118 (2)		0.50 (0.08)	0.37 (0.09)		25.5 (8.2)
Biofilter	105 (3)	0.10 (0.03)	0.37 (0.09)	0.33 (0.08)	0.011 (0.005)	10.9 (3.5)
		Roughing Filter HLR ≅ 120 $m^3/m^2/d$, n = 8				
Rock RF	122 (23)	0.58 (0.14)	0.44 (0.11)	0.46 (0.12)	-0.019 (0.075)	-4.9 (13.2)
Random RF	124 (28)	0.43 (0.11)	0.44 (0.11)	0.48 (0.18)	-0.036 (0.099)	-9.0 (19.8)
Structured RF	122 (18)	0.40 (0.09)	0.44 (0.11)	0.47 (0.19)	-0.023 (0.096)	-4.2 (21.1)
Aeration Column	126 (24)		0.47 (0.16)	0.41 (0.14)		13.0 (13.0)
Biofilter	118 (2)	0.12 (0.04)	0.41 (0.14)	0.26 (0.05)	0.043 (0.033)	30.6 (19.8)
		Roughing Filter HLR ≅ 180 $m^3/m^2/d$, n = 5				
Rock RF	175 (4)	1.03 (0.28)	0.54 (0.15)	0.60 (0.21)	-0.115 (0.131)	-10.3 (10.5)
Random RF	175 (11)	0.76 (0.21)	0.54 (0.15)	0.53 (0.14)	0.008 (0.047)	0.6 (6.9)
Structured RF	173 (11)	0.71 (0.18)	0.54 (0.15)	0.52 (0.17)	0.026 (0.036)	4.7 (6.4)
Aeration Column	179 (9)		0.55 (0.17)	0.52 (0.14)		3.6 (8.1)
Biofilter	118 (0)	0.15 (0.04)	0.52 (0.14)	0.34 (0.17)	0.052 (0.028)	35.0 (20.3)
		Roughing Filter HLR ≅ 250 $m^3/m^2/d$, n = 5				
Rock RF	256 (13)	1.50 (0.41)	0.53 (0.13)	0.58 (0.13)	-0.126 (0.101)	-9.1 (6.8)
Random RF	251 (14)	1.09 (0.31)	0.53 (0.13)	0.53 (0.08)	0.010 (0.117)	-1.7 (12.1)
Structured RF	252 (17)	1.03 (0.29)	0.53 (0.13)	0.47 (0.14)	0.127 (0.118)	12.7 (11.9)
Aeration Column	260 (15)		0.52 (0.11)	0.47 (0.13)		10.6 (7.7)
Biofilter	115 (7)	0.14 (0.29)	0.47 (0.13)	0.42 (0.14)	0.015 (0.024)	10.6 (13.5)
		Roughing Filter HLR ≅ 350 $m^3/m^2/d$, n = 4				
Rock RF	341 (7)	1.57 (0.76)	0.42 (0.21)	0.44 (0.19)	-0.078 (0.317)	-9.4 (22.6)
Random RF	338 (12)	1.16 (0.57)	0.42 (0.21)	0.43 (0.15)	-0.033 (0.321)	-11.2 (37.6)
Structured RF	337 (14)	1.09 (0.54)	0.42 (0.21)	0.38 (0.20)	0.111 (0.189)	10.5 (12.1)
Aeration Column	348 (11)		0.42 (0.18)	0.35 (0.18)		18.0 (16.8)
Biofilter	107 (7)	0.09 (0.04)	0.35 (0.18)	0.31 (0.16)	0.008 (0.005)	8.8 (4.3)

[a] these values were calculated from the difference in individual influent and effluent TAN concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that ammonia was produced, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 4. Oxygen consumption across the roughing filter system during the low fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Oxygen Loading Rate, $g/m^2/d$	Influent Dissolved Oxygen, mg/L	Effluent Dissolved Oxygen, mg/L	Oxygen Consumption Rate, $g/m^2/d$	Oxygen Consumption Efficiency,[a] %
			Roughing Filter HLR ≡ 70 $m^3/m^2/d$, n = 6[b]			
Rock RF	68 (7)[c]	3.4 (0.4)	4.6 (0.2)	2.6 (0.3)	1.4 (0.1)	42 (6)
Random RF	72 (5)	2.7 (0.2)	4.6 (0.2)	2.7 (0.4)	1.1 (0.1)	41 (7)
Structured RF	62 (4)	2.2 (0.2)	4.6 (0.2)	2.6 (0.4)	0.9 (0.2)	42 (7)
Aeration Column	118 (0)		2.7 (0.4)	6.1 (0.2)		-134 (24)
Biofilter	118 (0)	1.8 (0.1)	6.1 (0.2)	1.9 (0.2)	1.3 (0.0)	70 (2)
			Roughing Filter HLR ≡ 120 $m^3/m^2/d$, n = 14			
Rock RF	119 (6)	6.3 (0.4)	4.9 (0.2)	2.9 (0.3)	2.6 (0.3)	41 (6)
Random RF	120 (4)	4.7 (0.2)	4.9 (0.2)	2.8 (0.4)	2.0 (0.3)	43 (7)
Structured RF	120 (4)	4.5 (0.2)	4.9 (0.2)	2.9 (0.4)	1.8 (0.3)	40 (7)
Aeration Column	123 (5)		2.8 (0.3)	6.5 (0.3)		-138 (33)
Biofilter	102 (2)	1.9 (0.1)	6.5 (0.3)	2.6 (0.4)	1.2 (0.1)	59 (6)
			Roughing Filter HLR ≡ 250 $m^3/m^2/d$, n = 9			
Rock RF	260 (9)	15.1 (0.9)	5.3 (0.3)	4.5 (0.2)	2.2 (0.3)	14 (2)
Random RF	261 (6)	11.2 (0.5)	5.3 (0.3)	4.6 (0.2)	1.4 (0.2)	13 (2)
Structured RF	242 (7)	9.8 (0.6)	5.3 (0.3)	4.6 (0.2)	1.2 (0.3)	12 (2)
Aeration Column	261 (8)		4.6 (0.2)	6.3 (0.2)		-37 (5)
Biofilter	118 (0)	1.9 (0.1)	6.3 (0.2)	2.6 (0.4)	1.1 (0.1)	59 (6)
			Roughing Filter HLR ≡ 350 $m^3/m^2/d$, n = 5			
Rock RF	355 (13)	23.6 (1.1)	6.1 (0.3)	5.2 (0.4)	3.2 (0.9)	14 (4)
Random RF	353 (10)	17.3 (0.6)	6.1 (0.3)	5.2 (0.5)	2.5 (1.1)	14 (6)
Structured RF	354 (13)	16.4 (1.1)	6.1 (0.3)	5.3 (0.4)	2.2 (0.8)	13 (4)
Aeration Column	364 (12)		5.2 (0.4)	9.3 (0.4)		-78 (15)
Biofilter	118 (0)	2.7 (0.1)	9.3 (0.4)	5.6 (0.3)	1.1 (0.1)	40 (3)

[a] these values were calculated from the difference in individual influent and effluent concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that oxygen was generated, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 5. Oxygen consumption across the roughing filter system during the high fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Oxygen Loading Rate, $g/m^2/d$	Influent Dissolved Oxygen, mg/L	Effluent Dissolved Oxygen, mg/L	Oxygen Consumption Rate, $g/m^2/d$	Oxygen Consumption Efficiency,[a] %
			Roughing Filter HLR ≡ 70 $m^3/m^2/d$, n = 3			
Rock RF	80 (2)[c]	3.7 (0.3)	4.2 (0.5)	0.5 (0.5)	3.3 (0.4)	88 (11)
Random RF	65 (1)	2.2 (0.2)	4.2 (0.5)	0.5 (0.5)	2.0 (0.2)	89 (10)
Structured RF	73 (3)	2.4 (0.3)	4.2 (0.5)	1.1 (0.4)	1.8 (0.3)	75 (8)
Aeration Column	118 (0)		0.7 (0.4)	5.3 (0.4)		-899(515)
Biofilter	105 (2)	1.4 (0.1)	5.3 (0.4)	0.7 (0.4)	1.2 (0.1)	88 (7)
			Roughing Filter HLR ≡ 120 $m^3/m^2/d$, n = 8[b]			
Rock RF	121 (20)	5.6 (1.2)	4.3 (0.6)	1.6 (0.7)	3.5 (0.5)	63 (13)
Random RF	123 (23)	4.2 (1.0)	4.3 (0.6)	1.3 (0.7)	2.9 (0.3)	70 (15)
Structured RF	121 (15)	3.9 (0.7)	4.3 (0.6)	2.1 (0.8)	1.9 (0.3)	51 (13)
Aeration Column	125 (20)		1.7 (0.7)	5.7 (0.7)		-296(157)
Biofilter	118 (1)	1.7 (0.2)	5.7 (0.7)	0.9 (0.6)	1.4 (0.2)	85 (10)
			Roughing Filter HLR ≡ 180 $m^3/m^2/d$, n = 5			
Rock RF	173 (9)	9.8 (1.1)	5.2 (0.4)	2.1 (0.4)	5.9 (0.8)	60 (6)
Random RF	178 (12)	7.5 (1.0)	5.2 (0.4)	2.6 (0.5)	3.8 (1.0)	50 (10)
Structured RF	170 (16)	6.8 (1.1)	5.2 (0.4)	3.2 (0.4)	2.7 (1.1)	38 (11)
Aeration Column	178 (13)		2.6 (0.3)	6.4 (0.6)		-148 (25)
Biofilter	118 (0)	1.9 (0.2)	6.4 (0.6)	0.9 (0.2)	1.6 (0.2)	86 (3)
			Roughing Filter HLR ≡ 250 $m^3/m^2/d$, n = 5			
Rock RF	267 (10)	13.3 (1.7)	4.5 (0.6)	2.6 (0.8)	5.7 (1.2)	44 (11)
Random RF	263 (9)	9.7 (1.4)	4.5 (0.6)	3.3 (0.7)	2.7 (0.7)	28 (7)
Structured RF	264 (13)	9.2 (1.0)	4.5 (0.6)	3.5 (0.8)	2.0 (0.6)	23 (9)
Aeration Column	272 (11)		3.1 (0.7)	5.8 (1.1)		-88 (26)
Biofilter	115 (7)	1.7 (0.4)	5.8 (1.2)	1.4 (1.1)	1.3 (0.2)	78 (11)
			Roughing Filter HLR ≡ 350 $m^3/m^2/d$, n = 4			
Rock RF	340 (6)	19.9 (3.8)	5.4 (1.1)	4.1 (1.0)	3.3 (0.7)	24 (4)
Random RF	340 (10)	14.7 (2.7)	5.4 (1.1)	4.5 (1.1)	2.0 (0.5)	17 (4)
Structured RF	337 (11)	13.8 (2.6)	5.4 (1.1)	4.7 (1.3)	1.8 (0.6)	14 (6)
Aeration Column	348 (9)		4.4 (1.1)	6.8 (1.1)		-61 (44)
Biofilter	106 (6)	1.8 (0.3)	6.8 (1.1)	3.2 (1.4)	1.0 (0.2)	55 (16)

[a] these values were calculated from the difference in individual influent and effluent concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that oxygen was generated, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 6. Replication of ammonia data for a single hydraulic loading treatment (low fish loading).

Unit Process	Average HLR, $m^3/m^2/d$	Influent TAN, mg/L	Effluent TAN, mg/L	TAN Removal Rate,[a] $g/m^2/d$	TAN Removal Efficiency,[a] %
First Replicate: Roughing Filter HLR ≅ 120 $m^3/m^2/d$, n = 6[b]					
Rock RF	114 (21)[c]	0.37 (0.11)	0.36 (0.14)	0.019(0.063)	6.7 (19.2)
Random RF	113 (17)	0.37 (0.11)	0.31 (0.11)	0.057(0.020)	19.5 (13.6)
Structured RF	108 (23)	0.37 (0.11)	0.32 (0.12)	0.043(0.018)	17.1 (12.8)
Aeration Column	115 (21)	0.33 (0.12)	0.29 (0.08)		7.2 (19.0)
Biofilter	118 (1)	0.29 (0.08)	0.17 (0.05)	0.035(0.017)	39.9 (11.6)
Second Replicate: Roughing Filter HLR ≅ 120 $m^3/m^2/d$, n = 8					
Rock RF	116 (6)	0.25 (0.05)	0.23 (0.05)	0.022(0.039)	6.3 (12.5)
Random RF	118 (8)	0.25 (0.05)	0.21 (0.05)	0.041(0.031)	16.3 (11.2)
Structured RF	117 (6)	0.25 (0.05)	0.22 (0.04)	0.022(0.048)	7.6 (21.0)
Aeration Column	120 (7)	0.18 (0.05)	0.18 (0.05)		18.7 (10.6)
Biofilter	119 (3)	0.18 (0.05)	0.11 (0.04)	0.023(0.007)	43.0 (9.1)

[a] these values were calculated from the difference in individual influent and effluent TAN concentrations; individual removal efficiencies were then averaged to give the result reported; also, (-) values indicate that ammonia was produced, not removed;

[b] n is the number of data points used in obtaining the average;

[c] values contained within ( ) are standard deviations.

Table 7. Replication of oxygen data for a single hydraulic loading treatment (low fish loading).

Unit Process	Hydraulic Loading Rate $m^3/m^2/d$	Influent Dissolved Oxygen, mg/L	Effluent Dissolved Oxygen, mg/L	Oxygen Consumption Rate,[a] $g/m^2/d$	Oxygen Consumption Efficiency,[a] %
First Replicate: Roughing Filter HLR ≡ 120 $m^3/m^2/d$, n = 6[b]					
Rock RF	123 (6)[c]	4.8 (0.3)	2.5 (0.4)	3.1 (0.3)	49 (6)
Random RF	119 (2)	4.8 (0.3)	2.5 (0.5)	2.2 (0.3)	47 (8)
Structured RF	119 (2)	4.8 (0.3)	2.5 (0.5)	2.2 (0.3)	49 (8)
Aeration Column	123 (4)	2.5 (0.5)	6.8 (0.3)		-181 (46)
Biofilter	119 (2)	6.8 (0.3)	2.3 (0.4)	1.3 (0.1)	66 (6)
Second Replicate: Roughing Filter HLR ≡ 120 $m^3/m^2/d$, n = 8					
Rock RF	116 (7)	4.9 (0.1)	3.3 (0.3)	2.1 (0.4)	33 (7)
Random RF	122 (6)	4.9 (0.1)	3.0 (0.3)	1.9 (0.3)	38 (7)
Structured RF	121 (5)	4.9 (0.1)	3.3 (0.2)	1.5 (0.3)	32 (6)
Aeration Column	123 (6)	3.2 (0.2)	6.2 (0.3)		-94 (21)
Biofilter	120 (3)	6.2 (0.3)	2.9 (0.4)	1.0 (0.2)	53 (7)

[a] these values were calculated from the difference in individual influent and effluent concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that oxygen was generated, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 8. Solids removal during the daily roughing filter backflush.

	Rock Roughing Filter, mg/L				Random Roughing Filter, mg/L				Structured Roughing Filter, mg/L			
	TS	VS	SS	VSS	TS	VS	SS	VSS	TS	VS	SS	VSS
Low Fish Loading												
HLR = 70 m/d	1190	652	491	442	1126	593	355	324	915	392	212	192
HLR = 120 m/d	1300	790	471	435	1211	702	578	495	1186	667	338	335
HLR = 250 m/d	1038	527	367	335	1136	613	510	457	1022	512	339	309
HLR = 350 m/d	641	236	111	101	881	457	341	311	828	416	323	288
Average	1042	551	360	328	1088	591	446	396	988	497	303	281
Total Solids Removed During Daily Flushing of Roughing filters, kg/d	0.116				0.186				0.169			
Total Solids Removed from Roughing Filters During Daily Flushing Divided by 1/3 of the Total Dry Mass of Fish Feed Fed on Daily Basis, %	25.9[a]				41.6[a]				37.8[a]			
High Fish Loading												
HLR = 120 m/d	1883	1313	1960	1835	893	599	563	531	740	451	347	345
HLR = 180 m/d	1385	846	644	627	1457	900	372	355	1217	668	248	239
HLR = 250 m/d	2194	1657	1557	1506	1732	1204	1307	1252	1418	925	867	851
HLR = 350 m/d	1478	974	848	795	1340	846	810	742	1034	555	524	494
Average	1735	1198	1252	1191	1356	887	763	720	1102	650	497	482
Total Solids Removed During Daily Flushing of Roughing filters, kg/d	0.192				0.232				0.188			
Total Solids Removed from Roughing Filters During Daily Flushing Divided by 1/3 of the Total Dry Mass of Fish Feed Fed on Daily Basis, %	21.6[b]				26.0[b]				21.1[b]			

Table 9. Volatile, fixed and suspended solids composition of daily roughing filter backflush.

Roughing Filter Backflush	% Total Solids			% Volatile Suspended Solids
	Volatile	Fixed	Suspended	
Rock	60.0	40.0	50.1	93.4
Random	58.6	41.4	45.9	90.9
Structured	53.6	46.5	35.0	94.8
Overall Average	57.4	42.6	43.7	93.0

Table 10. Change in carbonaceous oxygen demand (cBOD) across each roughing filter.

Hydraulic Loading Rate, m/d	Roughing Filter Influent cBOD, mg/L	Roughing Filter Effluent cBOD, mg/L	cBOD Loading Rate, $g/m^2/d$			cBOD Removal Rate,[a] $g/m^2/d$		
			Crushed Rock Media	Random Plastic Media	Structured Plastic Media	Crushed Rock Media	Random Plastic Media	Structured Plastic Media
Low Fish Loading								
70	10.5	11.4	8.0	6.0	5.6	-0.7	-0.5	-0.5
120	10.7	11.9	14.1	10.4	9.8	-1.6	-1.2	-1.1
250	7.8	8.4	21.4	15.8	14.9	-1.6	-1.2	-1.1
350	6.0	8.4	23.0	17.0	16.1	-9.2	-6.8	-6.4
Average	8.8	10.0	16.6	12.3	11.6	-3.3	-2.4	-2.3
High Fish Loading								
70	36.9	38.2	28.3	20.9	19.8	-1.0	-0.7	-0.7
120	21.0	18.7	27.6	20.4	19.3	3.0	2.2	2.1
180	17.2	16.1	33.9	25.1	23.7	2.2	1.6	1.5
250	28.0	28.0	76.7	56.7	53.6	0.0	0.0	0.0
350	31.8	34.7	121.9	90.2	85.2	-11.1	-8.2	-7.8
Average	27.0	27.1	57.7	42.7	40.3	-1.4	-1.0	-1.0

[a] negative (-) values indicate that cBOD was produced, not removed;

Table 11. Ammonia removal across the settling tank system during the low fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Ammonia Loading Rate, $g/m^2/d$	Influent TAN, mg/L	Effluent TAN, mg/L	TAN Removal Rate,[a] $g/m^2/d$	TAN Removal Efficiency,[a] %
			Biofilter HLR ≅ 60 $m^3/m^2/d$, n = 4[b]			
Settling Basin	118 (1)[c]		0.32 (0.17)	0.30 (0.20)		4.6 (12)
Aeration Column	210 (3)		0.30 (0.13)	0.27 (0.18)		12 (13)
Biofilter	64 (2)	0.04 (0.02)	0.27 (0.14)	0.23 (0.16)	0.0054(0.011)	7.9 (22)
			Biofilter HLR ≅ 80 $m^3/m^2/d$, n = 5			
Settling Basin	118 (2)		0.25 (0.06)	0.22 (0.14)		14 (6)
Aeration Column	210 (3)		0.22 (0.06)	0.20 (0.13)		10 (36)
Biofilter	79 (2)	0.04 (0.02)	0.20 (0.09)	0.14 (0.14)	0.011 (0.011)	28 (19)
			Biofilter HLR ≅ 120 $m^3/m^2/d$, n = 5			
Settling Basin	118 (2)		0.35 (0.13)	0.33 (0.17)		4.5 (7)
Aeration Column	210 (4)		0.33 (0.12)	0.31 (0.14)		7.4 (5)
Biofilter	122 (1)	0.10 (0.04)	0.31 (0.13)	0.19 (0.17)	0.038 (0.025)	37 (8)
			Biofilter HLR ≅ 170 $m^3/m^2/d$, n = 8			
Settling Basin	119 (2)		0.36 (0.38)	0.40 (0.19)		-6.8 (17)
Aeration Column	211 (4)		0.40 (0.45)	0.40 (0.14)		1.9 (14)
Biofilter	170 (2)	0.17 (0.2)	0.40 (0.47)	0.28 (0.05)	0.050 (0.025)	40 (22)
			Biofilter HLR ≅ 210 $m^3/m^2/d$, n = 3			
Settling Basin	123 (2)		0.35 (0.09)	0.39 (0.10)		-16 (33)
Aeration Column	220 (4)		0.39 (0.13)	0.34 (0.09)		12 (14)
Biofilter	204 (3)	0.17 (0.05)	0.34 (0.09)	0.21 (0.08)	0.062 (0.026)	39 (11)

[a] these values were calculated from the difference in individual influent and effluent concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that ammonia was produced, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 12. Ammonia removal across the settling tank system during the high fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Ammonia Loading Rate, $g/m^2/d$	Influent TAN, mg/L	Effluent TAN, mg/L	TAN Removal Rate, $g/m^2/d$	TAN Removal Efficiency,[a] %
			Biofilter HLR ≅ 60 $m^3/m^2/d$, n = 5[b]			
Settling Basin	122 (0)[c]		2.0 (0.5)	2.1 (0.6)		-5.4 (7)
Aeration Column	217 (0)		2.1 (0.6)	2.0 (0.5)		5.1 (8)
Biofilter	58 (0)	0.29 (0.07)	2.0 (0.5)	2.0 (0.6)	0.0077(0.015)	3.6 (6)
			Biofilter HLR ≅ 120$m^3/m^2/d$, n = 14			
Settling Basin	117 (1)		0.56 (0.20)	0.60 (0.26)		-6.0 (23)
Aeration Column	208 (2)		0.60 (0.26)	0.48 (0.23)		20 (6)
Biofilter	120 (2)	0.15 (0.07)	0.48 (0.23)	0.27 (0.12)	0.063 (0.041)	42 (8)
			Biofilter HLR ≅ 170 $m^3/m^2/d$, n = 6			
Settling Basin	114 (3)		0.53 (0.20)	0.60 (0.22)		-14 (18)
Aeration Column	203 (5)		0.60 (0.22)	0.50 (0.20)		16 (9)
Biofilter	167 (5)	0.21 (0.09)	0.50 (0.20)	0.32 (0.17)	0.076 (0.031)	39 (15)
			Biofilter HLR v 210 $m^3/m^2/d$, n = 9			
Settling Basin	125 (3)		0.50 (0.06)	0.55 (0.12)		-11 (20)
Aeration Column	222 (5)		0.55 (0.12)	0.43 (0.08)		21 (11)
Biofilter	211 (7)	0.23 (0.04)	0.43 (0.08)	0.27 (0.06)	0.084 (0.031)	37 (10)

[a] these values were calculated from the difference in individual influent and effluent concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that ammonia was produced, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 13. Oxygen consumption across the settling tank system during the low fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Oxygen Loading Rate, $g/m^2/d$	Influent Dissolved Oxygen, mg/L	Effluent Dissolved Oxygen, mg/L	Oxygen Consumption Rate,[a] $g/m^2/d$	Oxygen Consumption Efficiency,[a] %
			Biofilter HLR ≅ 60 $m^3/m^2/d$, n = 3[b]			
Settling Basin	118 (1)[c]		6.8 (0.4)	6.2 (0.5)		9.7 (6)
Aeration Column	210 (3)		6.2 (0.5)	7.0 (0.5)		-15 (44)
Biofilter	64 (2)	1.1 (0.1)	7.0 (0.5)	1.2 (1.4)	0.93 (0.24)	83 (16)
			Biofilter HLR ≅ 80 $m^3/m^2/d$, n = 8			
Settling Basin	118 (2)		7.1 (0.2)	6.5 (0.2)		8.0 (9)
Aeration Column	210 (3)		6.5 (0.2)	7.6 (0.2)		-16 (26)
Biofilter	79 (2)	1.5 (0.0)	7.6 (0.2)	4.7 (0.3)	0.57 (0.01)	38 (11)
			Biofilter HLR ≅ 120 $m^3/m^2/d$, n = 5			
Settling Basin	118 (2)		6.3 (0.6)	5.7 (0.6)		10 (11)
Aeration Column	210 (4)		5.7 (0.6)	6.7 (0.5)		-20 (25)
Biofilter	122 (1)	2.0 (0.2)	6.7 (0.5)	4.3 (0.6)	0.73 (0.14)	36 (3)
			Biofilter HLR ≅ 170 $m^3/m^2/d$, n = 5			
Settling Basin	119 (2)		6.0 (0.4)	5.2 (0.6)		8.9(13)
Aeration Column	211 (4)		5.5 (0.5)	6.4 (0.9)		-24(157)
Biofilter	170 (2)	2.9 (0.3)	6.8 (0.8)	4.5 (0.9)	1.0 (0.1)	35 (10)
			Biofilter HLR ≅ 210 $m^3/m^2/d$, n = 4			
Settling Basin	123 (2)		5.8 (0.5)	5.2 (0.6)		11 (8)
Aeration Column	220 (4)		5.2 (0.6)	6.3 (0.7)		-22(515)
Biofilter	204 (3)	3.2 (0.3)	6.3 (0.7)	3.7 (0.6)	1.3 (0.2)	42 (7)

[a] these values were calculated from the difference in individual influent and effluent concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that oxygen was generated, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

Table 14. Oxygen consumption across the settling tank system during the high fish density trial.

Unit Process	Hydraulic Loading Rate, $m^3/m^2/d$	Oxygen Loading Rate, $g/m^2/d$	Influent Dissolved Oxygen, mg/L	Effluent Dissolved Oxygen, mg/L	Oxygen Consumption Rate, $g/m^2/d$	Oxygen Consumption Efficiency,[a] %
Biofilter HLR ≡ 60 $m^3/m^2/d$, n = 6[b]						
Settling Basin	122 (0)[c]		5.8 (0.3)	4.4 (0.3)		23 (8)
Aeration Column	217 (0)		4.4 (0.3)	5.9 (0.3)		-33(16)
Biofilter	58 (0)	0.8 (0.1)	5.9 (0.3)	0.37(0.40)	0.79 (0.1)	94 (7)
Biofilter HLR ≡ 120$m^3/m^2/d$, n = 14						
Settling Basin	117 (1)		5.3 (0.8)	4.5 (1.2)		15(17)
Aeration Column	208 (2)		4.5 (1.2)	5.7 (1.0)		-29(18)
Biofilter	120 (2)	1.7 (0.3)	5.7 (1.0)	1.2 (1.1)	1.3 (0.2)	80(15)
Biofilter HLR ≡ 170 $m^3/m^2/d$, n = 9						
Settling Basin	114 (3)		5.4 (0.3)	4.3 (0.5)		20 (6)
Aeration Column	203 (5)		4.3 (0.5)	5.8 (0.4)		-34(10)
Biofilter	167 (5)	2.4 (0.2)	5.8 (0.4)	1.5 (0.2)	1.8 (0.1)	73 (3)
Biofilter HLR ≡ 210 $m^3/m^2/d$, n = 5						
Settling Basin	125 (3)		5.1 (0.5)	4.3 (1.0)		17(21)
Aeration Column	222 (5)		4.3 (1.0)	5.8 (0.9)		-42(29)
Biofilter	211 (7)	3.1 (0.5)	5.8 (0.9)	2.3 (0.8)	1.9 (0.2)	62 (9)

[a] these values were calculated from the difference in individual influent and effluent concentrations; individual removal efficiencies were then averaged and reported; also, (-) values indicate that oxygen was generated, not removed; [b]n is the number of data points used in obtaining the average; [c]values contained within ( ) are standard deviations.

DISCUSSION

Ammonia, cBOD, Oxygen and Solids Removal in Roughing Filters

Ammonia and oxygen removal rates (Figures 7 and 8) and removal efficiencies (ammonia:Figures 9; oxygen:Figure 10) were measured in the roughing filters at a low and a high fish loading rate. Results indicate that the high fish loading generally increased oxygen utilization (Figures 8 and 10) and decreased nitrification (Figures 9 and 11) over the lower fish loading. Overall, structured media demonstrated the greatest ammonia removal and the least oxygen demand (Figures 7 to 10). Rock media had the greatest oxygen removal rate (Figure 8).

There were no real trends indicating an improvement in TAN or oxygen removal rates, or TAN removal efficiency, at increased hydraulic loading rates (Figures 7, 8 and 9). Oxygen removal efficiency, however, showed a definite trend to decrease at increased hydraulic loading rates (Figure 10).

Approximately 4 mg/L of dissolved oxygen are required to biologically oxidize 1 mg/L ammonia (as nitrogen) to nitrate (EPA, 1975). Comparison of data on ammonia removal rates (Tables 2 & 3) to data on oxygen removal rates (Tables 4 & 5), indicates that less than 25% and 13% of the oxygen demand within the roughing filters and biofilter within the RFS, respectively, were due to nitrification (Table 15). The remaining 75 (plus) percentage of the oxygen demand was likely due to oxidation of dissolved and particulate organics by heterotrophic organisms within the filter, and to endogenous respiration within the biofilm.

Carbonaceous BOD removal rates across each roughing filter were inconsistent (some removal and some production) and low relative to the cBOD loading rate (Table 10). Sloughed cell mass was probably responsible for much of the inconsistancy with the cBOD removal data.

The random packed plastic media tended to remove more solids (based on the amount of solids flushed daily) than the other media evaluated (Table 8). There was no real trend in solids removal at the different hydraulic loading rates (Table 8). Solids removal (Table 8) averaged out to 29 percent of the feed fed (dry mass basis) overall (35 and 23 percent in the low and high fish loading studies, respectively).

Results indicate that the tubular-structured media performed better than the random packed or rock media. Fewer solids were removed by the structured-tubular media than by the random packed media. This could indicate that better solids back-flushing from the structured-tubular media probably also occured (this would make sense based upon the long and continuous void spaces within the structured-tubular media). Better solids flushing properties

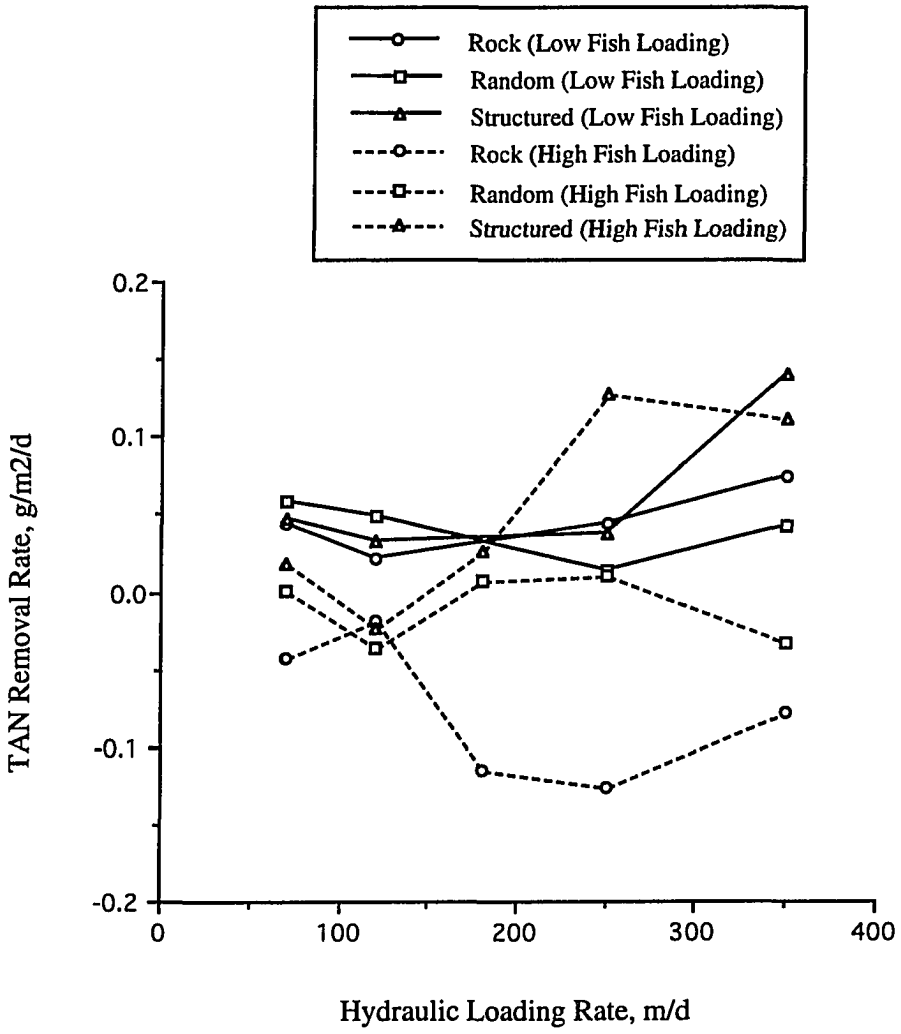


Figure 7. Ammonia removal rate in the roughing filters at two different fish loadings and as a function of hydraulic loading rate.

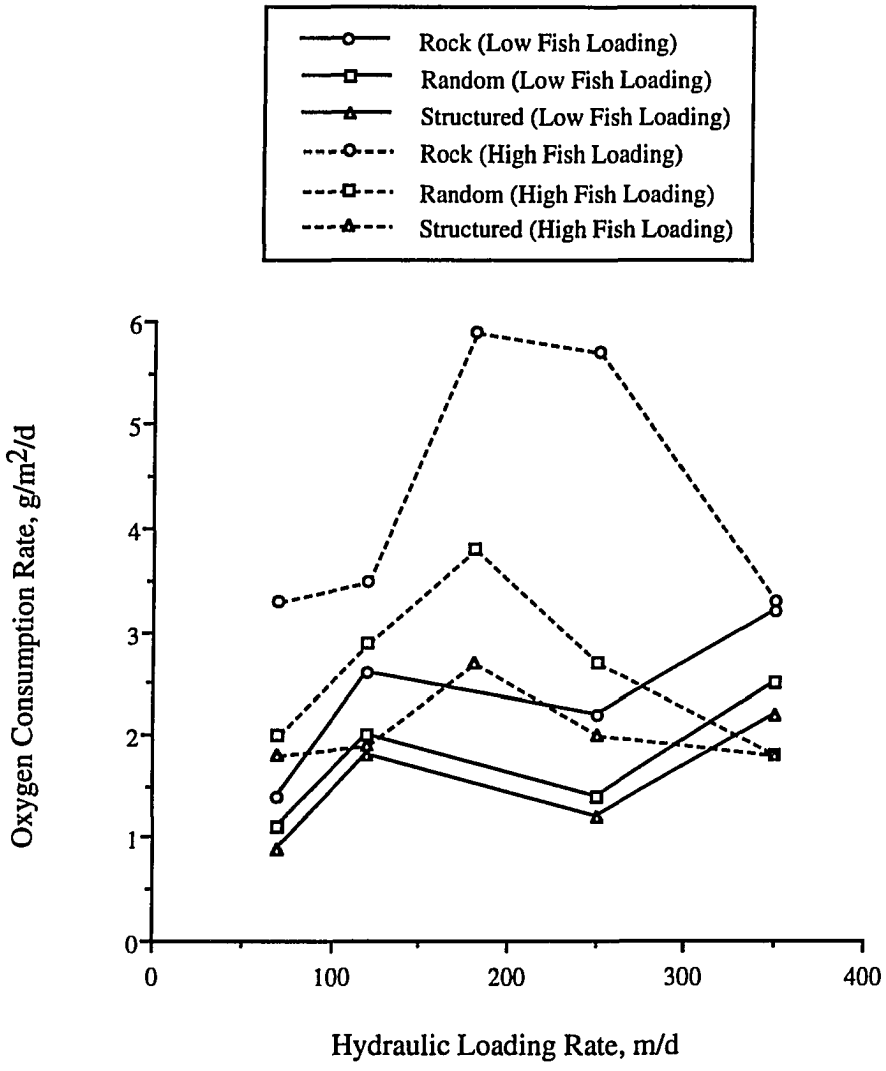


Figure 8. Oxygen removal rate in the roughing filters at two different fish loadings as a function of hydraulic loading rate.

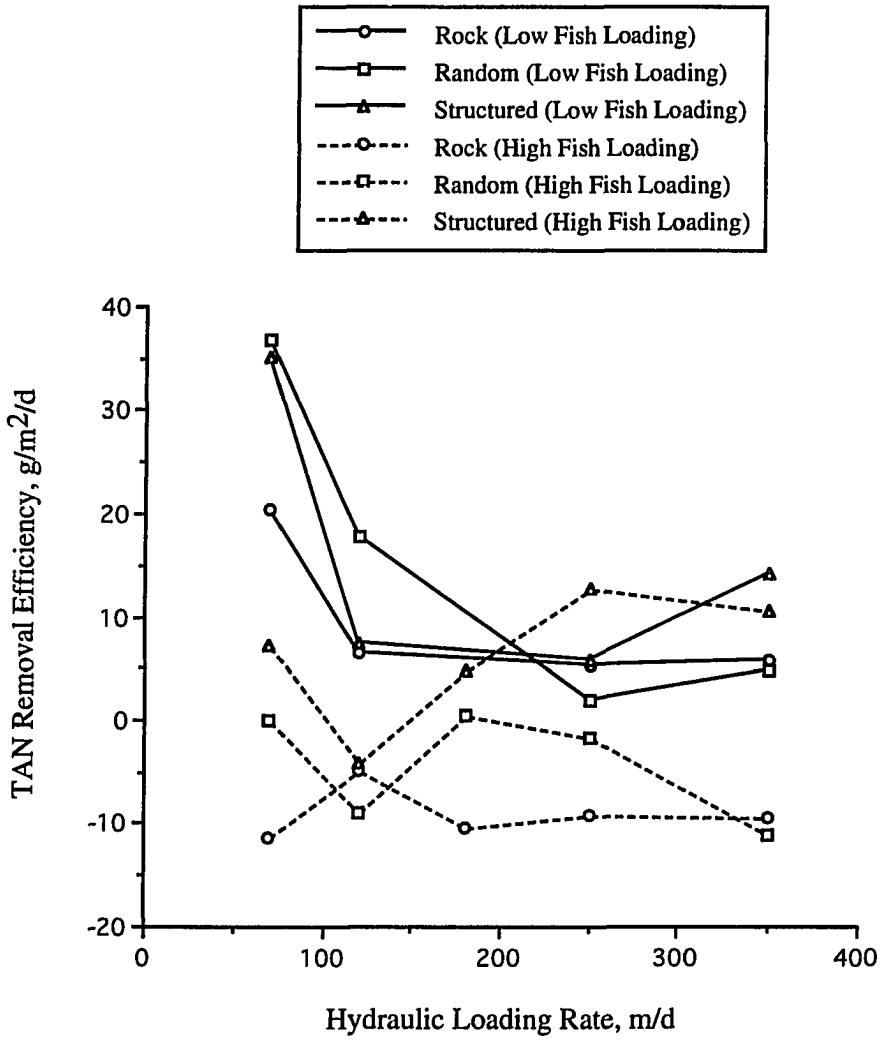


Figure 9. Ammonia removal efficiency in the roughing filters at two different fish loadings as a function of hydraulic loading rate.

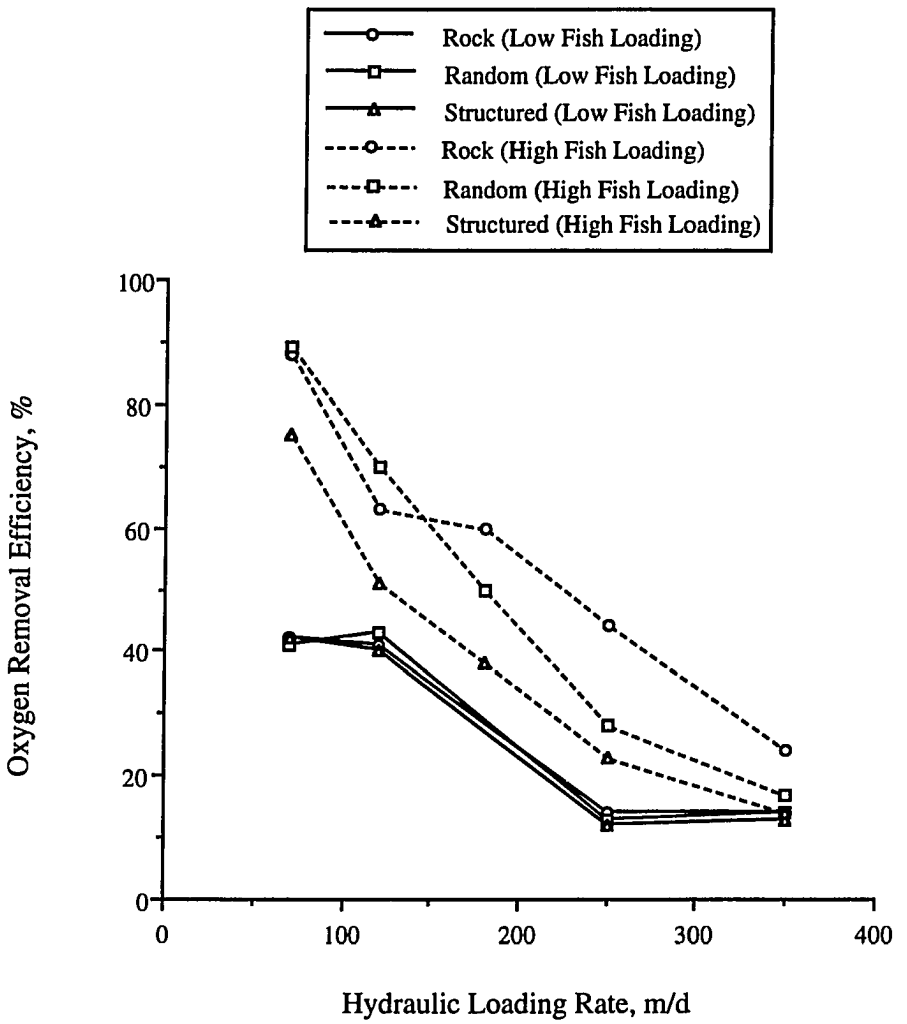


Figure 10. Oxygen removal efficiency in the roughing filters at two different fish loadings as a function of hydraulic loading rate.

Table 15. Percent of the overall oxygen demand within the roughing filters due to nitrification of ammonia.

Hydraulic Loading Rate thru Roughing Filters, m/d	Percent Oxygen Demand Due to Nitrification, $\left(\frac{\text{Nitrification Oxygen Demand}}{\text{Total Oxygen Demand}}\right)\cdot 100$			
	Rock Media	Random Plastic Media	Structured Plastic Media	RFS Biofilter
Low Fish Loading				
70	12.6	21.1	21.3	2.8
120	3.2	9.8	7.3	9.7
250	8.0	4.0	12.3	7.6
350	9.4	6.7	25.6	12.0
High Fish Loading				
70	0.0	0.0	4.0	3.7
120	0.0	0.0	0.0	12.3
180	0.0	0.8	3.9	13.0
250	0.0	1.5	25.4	4.6
350	0.0	0.0	24.7	3.2

exhibited by the tubular-structured media could explain the lower oxygen consumption rates and the as good or better nitrification. Also, the availability of the structured tubular surfaces may be a factor in explaining it's performance.

Effects of Clarification on Ammonia and Oxygen Removal in Biofilters

Oxygen consumption rates in the biofilters following the clarifiers also tended to increase from the low fish loading to the high fish loading (Figures 11 and 12). The oxygen and ammonia removal rates in the RFS biofilters appeared to be constant with roughing filter hydraulic loading rate, but may be greatest at approximately 200 m/d (Figures 12 and 13). The oxygen and ammonia removal rates in the biofilters within the settling basin system increased significantly with increasing hydraulic loading rate (Figures 11 and 14). The TAN removal rates ranged from 0.01 to 0.05 $g/m^2/d$ in the RFS biofilter and from 0.01 to 0.08 $g/m^2/d$ in the SBS biofilter, indicating that clarification with a sedimentation basin or a roughing filter had no noticeable effect on nitrification in the biofilter downstream.

The rate at which ammonia is removed by nitrification is related to the ammonia loading rate; this relation can be described with modified Monod kinetics (Monod, 1942):

$$r_{TAN} = r_{max,TAN} \cdot \frac{TAN}{TAN + k_{1/2,TAN}} \qquad (7)$$

where,

TAN = total ammonia nitrogen loading rate, g TAN per m^2 of biofilm per day

r_{TAN} = TAN removal rate, g TAN per m^2 of biofilm per day

$r_{max,TAN}$ = maximum TAN removal rate, g TAN per m^2 of biofilm per day

$k_{1/2,TAN}$ = TAN loading where $r_{TAN} = 1/2 \cdot r_{max}$, g TAN per m^2 of biofilm per day

The data on TAN removal rate for each roughing filter and biofilter were manipulated and plotted (Figure 15) for graphical determination of the Monod type constants used in Equation 7 (Table 16). The maximum TAN removal rate coefficients indicate that either biofilters (RFS and SBS) could remove ammonia more rapidly than could the roughing filters on a per m^2 basis.

Recirculation Rate

When designing recirculating systems it is important to consider the rate that water is passed through the culture tank and through the unit treatment processes because this has a

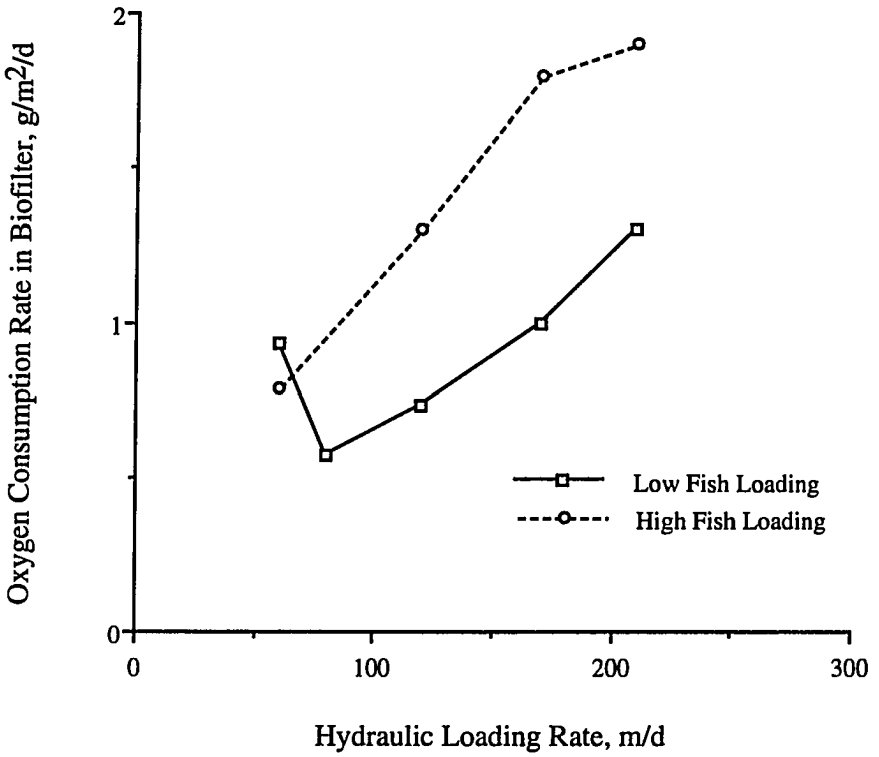


Figure 11. Oxygen consumption rate in the SBS biofilters, at two different fish loadings, as a function of the biofilter hydraulic loading rate.

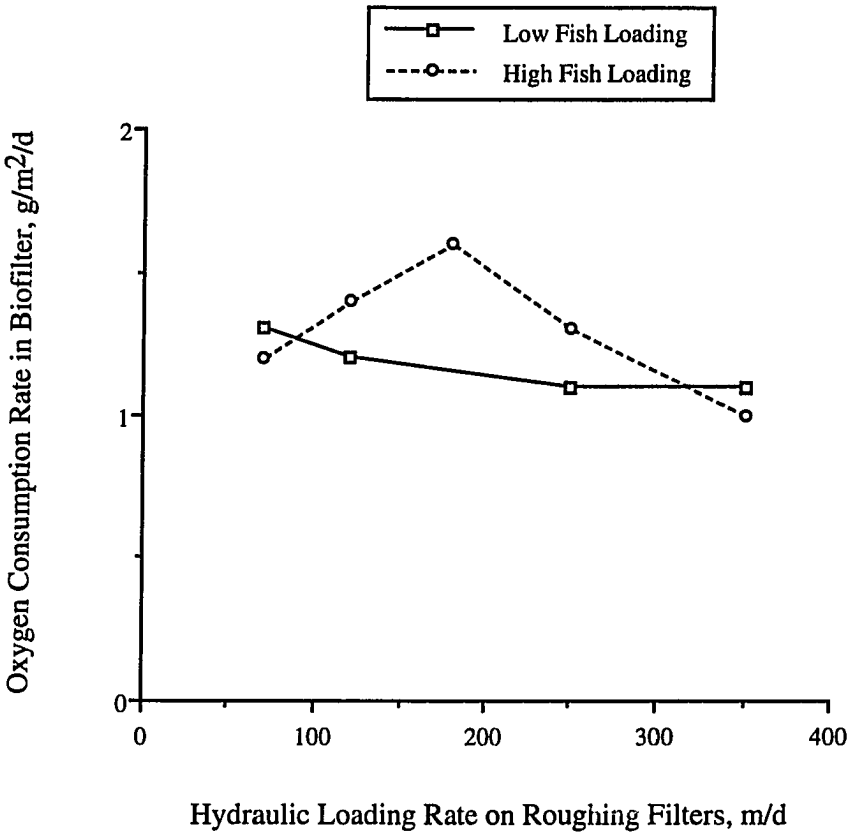


Figure 12. Oxygen consumption rate in the RFS biofilters, at two different fish loadings, as a function of the roughing filter hydraulic loading rate.

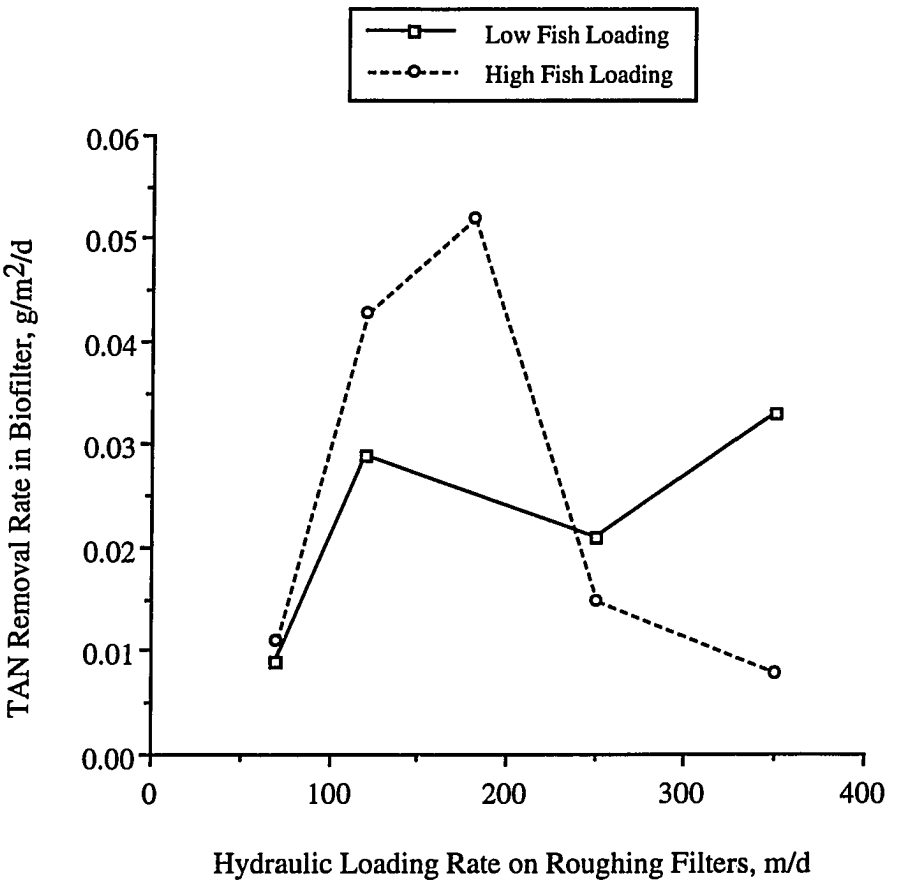


Figure 13. Ammonia removal rate in the RFS biofilters, at two different fish loadings, as a function of the roughing filter hydraulic loading rate.

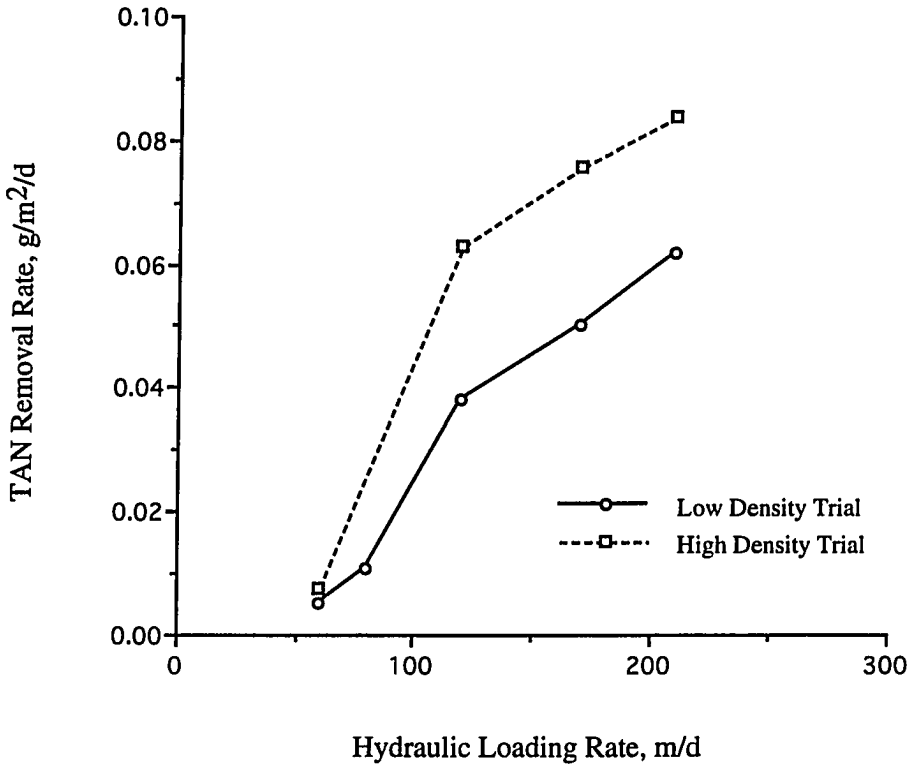
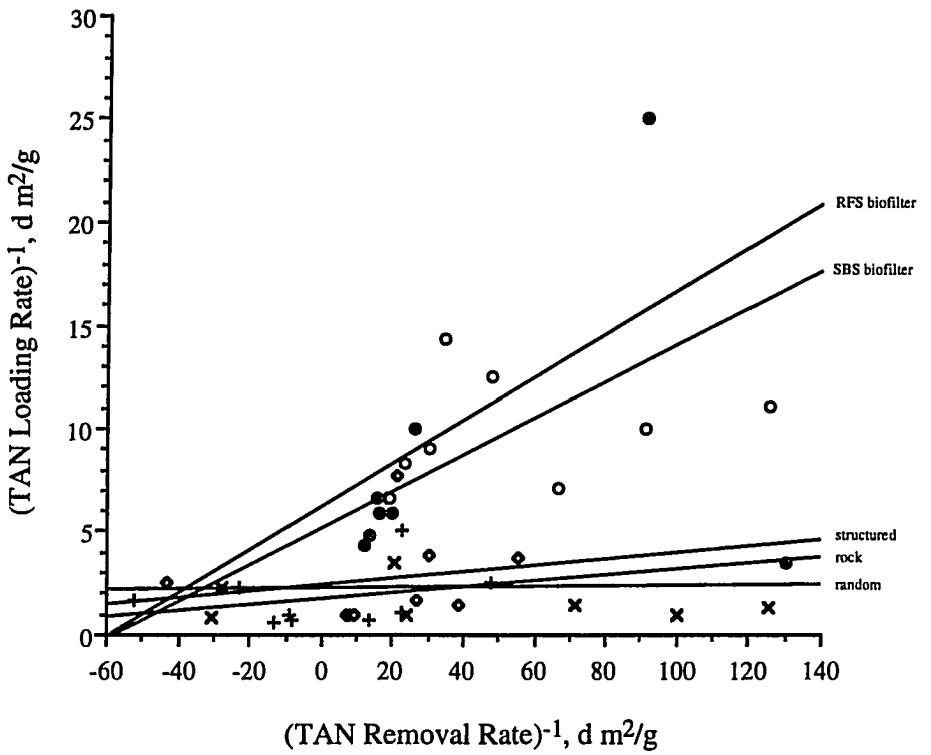


Figure 14. Ammonia removal rate in the SBS biofilters, at two different fish loadings, as a function of the biofilter hydraulic loading rate.



+	Rock RF	y = 1.742 + 0.01433x	R^2 = 0.090
×	Random RF	y = 2.223 + 0.001390x	R^2 = 0.054
◇	Structured RF	y = 2.371 + 0.01534x	R^2 = 0.037
○	RFS Biofilter	y = 6.131 + 0.1044x	R^2 = 0.254
●	SBS Biofilter	y = 5.069 + 0.08908x	R^2 = 0.432

Figure 15. Plot of the inverse of the TAN removal rate versus the inverse of the TAN loading rate to graphically determine Monod-type constants.

Table 16. Monod-type coefficients for nitrification within the roughing filters and biofilters.

Unit Process	$r_{max,TAN}$ ($g/m^2/d$)	$k_{1/2,TAN}$ ($g/m^2/d$)
Roughing Filter		
Rock	0.0069	0.41
Random	0.00063	0.45
Structured	0.0065	0.42
RFS Biofilter	0.017	0.16
SBS Biofilter	0.018	0.20

large influence on the concentration of ammonia within the culture tank and, as just illustrated above, on the efficiency of ammonia removal in the biofilters. Circular fish-culture tanks can be approximated as ideal mixed-flow reactors. The concentration of ammonia in the effluent of single-pass fish culture tanks (Figure 16, part i) is then:

$$C_{TAN} = C_{TAN,0} + \frac{V_{tank}}{Q} \cdot P_{TAN} \cdot 10^6 \left[\frac{mg}{kg}\right] \tag{8}$$

where,

$C_{TAN,0}$ = concentration of TAN flowing into culture unit, mg/L
C_{TAN} = concentration of TAN within (and in effluent) culture unit, mg/L
V_{tank} = volume of water contained within culture unit, L
Q = water flow rate through culture unit, L/day
P_{TAN} = TAN generation rate, kg ammonia produced per L rearing space per day

The rate that TAN is produced within the system is proportional to the product of the culture biomass and the feeding rate:

$$P_{TAN} = a_{TAN} \cdot \rho_{fish} \cdot r_{feed} \tag{9}$$

where,

ρ_{fish} = density of fish in the culture tank, kg fish per L rearing space
r_{feed} = feeding rate, kg feed per kg fish per day
a_{TAN} = TAN produced as a proportion of feed fed, mg TAN per kg feed

This research on water-reuse systems evaluated nitrification within a system containing a settling basin (SBS) and also within a system containing roughing filters (RFS). Within the SBS (Figure 16, part ii), the concentration of ammonia in the culture tank was controlled by the degree of nitrification in the biofilter, the amount of ammonia produced by the fish, and the amount of water recirculating. Liao and Mayo (1972) derived an equation for predicting the concentration of ammonia within the culture tank of SBS type recirculating systems:

$$C_{TAN} = P_{TAN} \cdot \frac{V_{tank}}{Q} \cdot \left(\frac{1}{1 - R + (R \cdot f_{rem})}\right) \cdot 10^6 \left[\frac{mg}{kg}\right] \tag{10}$$

where,

R = fraction of water reused, unitless
f_{rem} = fraction of TAN removed across biofilter, unitless

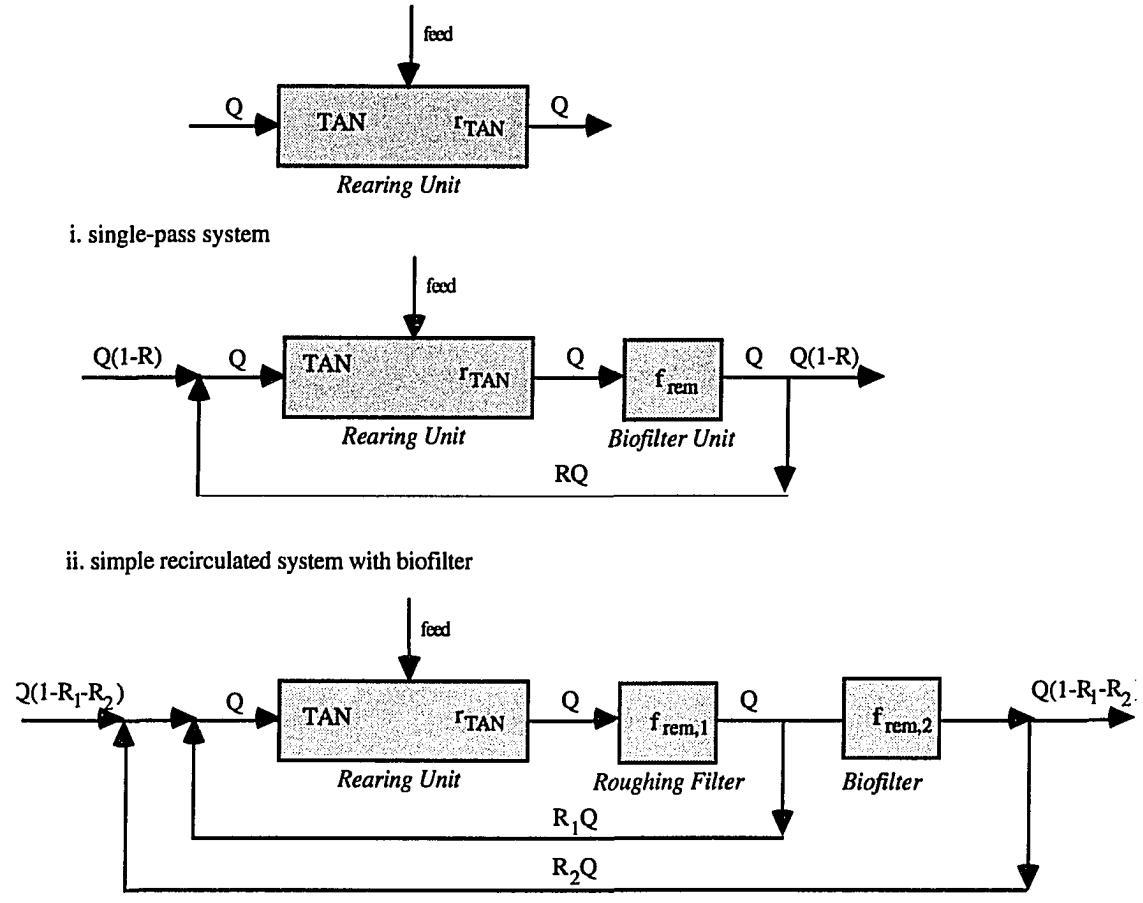


Figure 16. Illustration of generalized model governing metabolite level within (i) a single-pass system, (ii) a simple recirculating system, and (iii) a recirculating system with a roughing filter prior to the biofilter.

In the case of the RFS (Figure 16, part iii) a similar relation can be derived for predicting the concentration of ammonia in the culture tanks as a function of the efficiency of nitrification in both the biofilter and the roughing filter, the amount of ammonia produced by the fish, and the amount of water recirculating through each unit:

$$C_{TAN} = P_{TAN} \cdot \frac{V_{tank}}{Q} \cdot \left(\frac{1}{1 - R_1 + \left(R_1 \cdot f_{rem,1}\right)} \right) \cdot \left(\frac{1}{1 - R_2 + \left(R_2 \cdot f_{rem,2}\right)} \right) \cdot 10^6 \left[\frac{mg}{kg} \right] \quad (11)$$

where,

R_1 = fraction of water reused passing the roughing filter, unitless

R_2 = fraction of water reused passing the biofilter, unitless

$f_{rem,1}$ = fraction of TAN removed across roughing filter, unitless

$f_{rem,2}$ = fraction of TAN removed across biofilter, unitless

Filter Headloss

The Ergun equation (12) can be used to predict clean filter head loss;

$$\frac{\Delta P}{L} \cong \frac{150 \cdot \mu_L \cdot S_p^2}{36} \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot v_0 + \frac{1.75 \cdot \rho_L \cdot S_p}{6} \cdot \frac{(1-\varepsilon)}{\varepsilon^3} \cdot v_0^2 \quad (12)$$

where: $\Delta P/L$ is the pressure drop per unit length of bed, S_p is the particle specific surface area, ε is the void fraction, μ_L is the viscosity, ρ_L is the liquid density, and v_0 is the superficial velocity. The particle specific surface area is related to the bed specific surface area according to $S_b = S_p \cdot (1 - \varepsilon)$.

During typical operation of static media filters utilizing large media, the hydraulic loading rate is expected to be less than 587 $m^3 d^{-1} m^{-2}$ (10 gpm/ft^2). At this hydraulic loading, the clean filter headloss across each of the three filter media and distribution plates were below limits of detection (less than 1 mm of H_2O). Calculation of headloss with the Ergun equation (12) supports the findings of negligible resistance to flow across clean filters. However, after two years of operation, this hydraulic loading resulted in a headloss across the "biologically overgrown" media and distribution plate of less than 4, 2 and 2 mm of H_2O, respectively, for rock, random plastic, and structured plastic media.

Solids Flushing

Fouled pore spaces within biofilters or roughing filters can result in elevated head loss and reduction in nitrification which can produce catastrophic consequences to the culture of fish. Therefore, providing adequate flushing of solids from the filter is critical to the design of the filter. In this research, solids were flushed from the media voids daily by reversed flow flushing and bimonthly by air scour coupled with reversed flow flushing (Table 17). Good solids flushing requires a properly designed underdrain, a drainable filter, a high velocity of a reversed flow of water, and a means for air scouring. Properly designed underdrains provide a support for the media and forces the water, during regular operation or during flushing, to flow uniformly through the bed.

The process that the static media filter is to be used for (e.g., clarification, nitrification or denitrification) sets the frequency that the filter should be flushed of solids. The frequency of solids flushing affects the oxygen uptake in the filter, the nitrification and denitrification occuring in the filter, and the headloss across the filter. Frequent flushing reduces the concentration of stored sludge and washes out the microorganisms suspended and growing within the stored sludge. The microorganisms (Figure 17) exert a high oxygen demand which inhibits aerobic metabolism, such as nitrification, in the filter. The microoganisms also solubilize the organics stored in the sludge, reducing the amount of solids that can be removed from the system, and further increase the heterotrophic oxygen demand of the attached growth.

If the static media are to be used for clarification only, then a high solids loading in the roughing filters requires frequent (daily) flushing. Frequent flushing washes out the suspended microorganisms, reducing organics solubilization, and thereby, reduces the heterotrophic oxygen demand. Preventing solubilization of organics reduces the potential for heterotrophic growth, helping the nitrifying organisms compete for space and oxygen on the media surface within the downstream biofilter.

If the static media is to be used for nitrification, but has a high solids loading such as in a roughing filter, then frequent (daily) flushing is required. As well as reducing solids solublization, as just discussed, frequent flushing reduces the oxygen demand from the sludge and, depending upon the oxygen loading rate on the filter, leaves adequate oxygen for nitrification to occur on the filter media.

If the static media is to be used for nitrification, but has a low solids loading such as in a nitrifying biofilter following a clarifier, then less frequent (weekly) flushing is advantageous. Observations indicated that less frequent flushing, under conditions of low solids loading, allowed accumulation of microorganisms within the void spaces of the media. The build up of

Table 17. Solids flushing techniques used for maintaining roughing filters.

Simple down-flow flushing (practice daily).
1. Close the filter influent valve.
2. Rapidly open the filters effluent valve. Drain the filter in pulses to optimize the difference in water head and to provide more pressure/velocity shocks to free the trapped solids. Two or more short pulses are more effective than a single drain-down.
3. Start normal filter operation by opening the filter influent valve.
Air scour followed by downflow solids flushing (practice bimonthly).
1. Close the filter influent valve.
2. Slowly open the valves controlling the filters air scour until the water in the roughing filter rolls vigorously, approximately 1.3 cfm per square foot of filter area (Leitritz and Lewis, 1976).
3. Maintain the air scour for 1 to 2 hours (Leitritz and Lewis, 1976).
4. Turn the air off.
5. Rapidly open the filter's effluent valve. Drain the filter in pulses to optimize the difference in water head and to provide more pressure/velocity shocks to free the trapped solids. Two or more short pulses are more effective than a single drain-down.
6. Start normal filter operation by opening the filter influent valve.

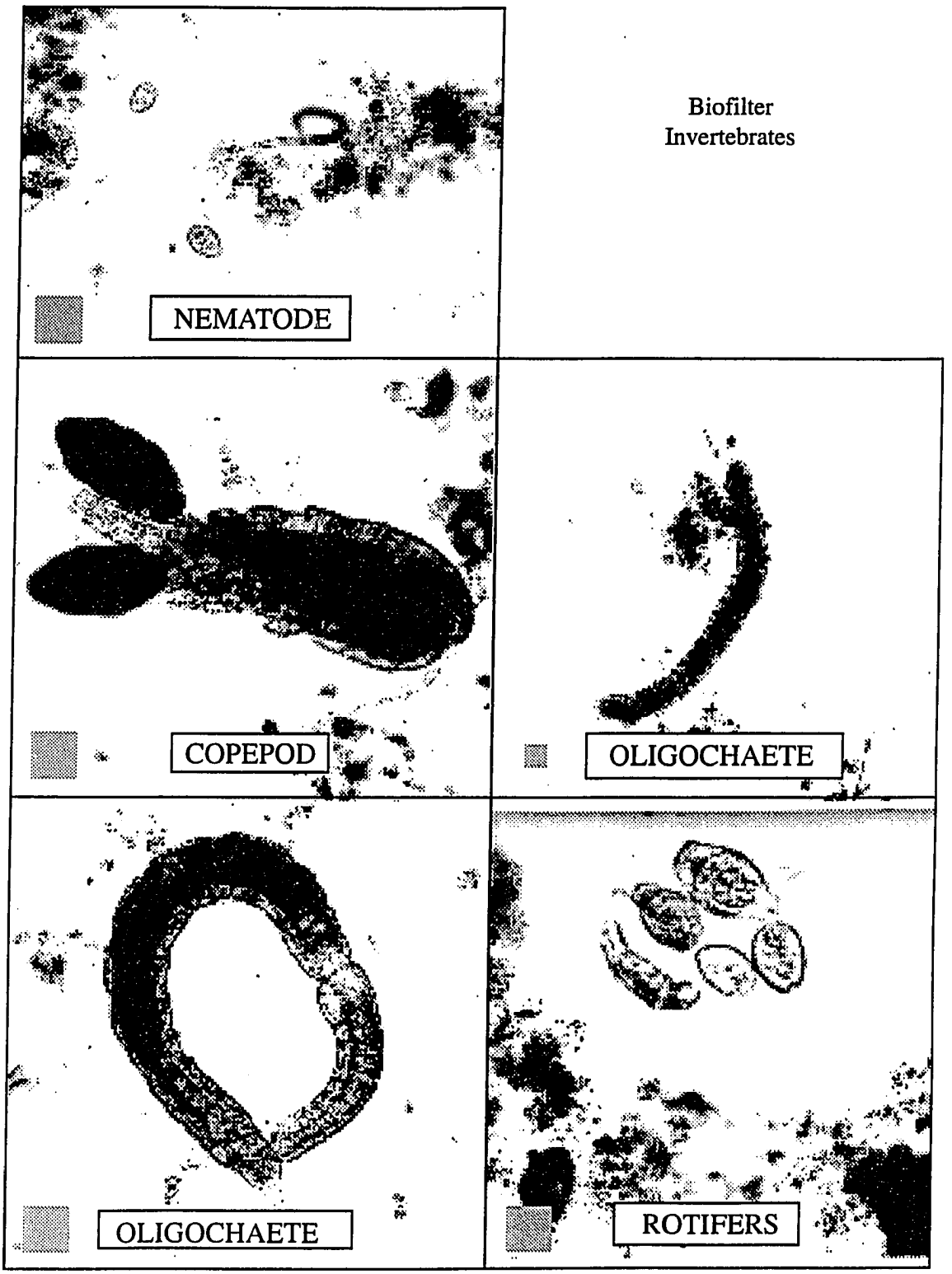
these biologically active solids increases nitrification to a point, as nitrifying organisms also reside in the suspension within the voids. However, it was observed that too much accumulation of solids within the voids reduced the nitrification rate probably due to conditions favoring growth of heterotrophs which could prey upon and out-compete nitrifying bacteria for space and oxygen.

Denitrification within the static-media filters was observed when the oxygen demand at the head of the filter was great (due to stored solids), or if the oxygen loading rate was low enough for anoxic conditions to exist in the filter.

Sludge organisms

Many large microorganisms were observed in the sludge flushed from the static media filters (Figure 17). Oligochaetes and rotifers were particularly easy to observe, being visible to

Figure 17. Types of organisms found in the sludge flushed from the static media filters. The occurrence and relative concentration of organisms observed in the sludge was observed to vary with solids loading and sludge storage time in the filter. However, no quantitative data on the occurrence and concentration of organisms were recorded.


Biofilter
Invertebrates
NEMATODE
COPEPOD
OLIGOCHAETE
OLIGOCHAETE
ROTIFERS

the naked eye. Many ciliates were observed under the oil emersion lense of a light microscope. However, no quantitative data on the occurence and concentration of organisms were recorded.

Media Selection

The tubular media (NSW, 4 ft long 2 inch NORPAK) was selected because the continuous vertical void spaces it posesses provides it with the potential for plug free operation. These continuous vertical void spaces run from filter top to bottom, minimizing constrictions to the axial flow of water through the column that tend to foul other types of media. Similarly, the continuous tubular void spaces enhance the cleaning of the media by providing a non-tortuous and unblocked passage for solids to be flushed through. However, the continuous vertical void spaces may slightly reduce solids removal in the media that is due to entrapment. For filtration to occur, interception or entrapment of suspended particles along the tube fins or side walls must occur. The polyethylene random pack medium was selected because of its high void ratio. In addition, it was of interest because it is the exact same media as the tube media, except that it has been chopped into units of approximately 2 inch length. With the random pack, there were no continuous flow paths as in the tubular media. The much more abundant constrictions in the flow path should have provided more opportunity for filtration but less ease of flushing solids.

The 1 and 2 inch rock media, though low on void space, were selected because of their low cost, availability, and frequency of use in waste water treatment and aquaculture biofilters.

The specific surface area of filter media typically plays an important role in media selection, whether designed for nitrification or the oxidation of organics. However, in the case of roughing filters, the media acts to enhance clarification by providing surface area for flocculation to occur as well as providing surface area to support microbial growth. Unless there is a means for expanding the fllter bed, because of the build up of solids in static media filters, the specific surface area of the media is not as important as the size and location of void spaces in the filter medium.

SUMMARY--STATIC-MEDIA FILTERS

This project was oriented towards using unit processes amenable for converting abandoned water and waste water treatment plants into commercial sites for culturing food fish within recirculating systems. The abandoned facilities typically contain large, deep, circular and/or rectangular tanks which had been used as clarifiers or, in the case of waste water treatment plants, were packed with crushed rock and used as trickling filters. Some of these empty tanks could function well for culturing food-fish on a large-scale. It was thought that other empty tanks could be converted into settling basins for clarifying the recirculating water and that the old trickling filters could be used as submerged biofilters or possibly roughing filters. Review of the literature indicated that although better unit processes might be available, the unit processes available at abandoned water and waste water treatment facilities might function well for use within recirculating-aquaculture production systems and are low cost. This section described the research conducted on the performance of static-media filters used for nitrification and clarification and on the performance of either settling basins or static-media roughing filters at maintaining nitrification efficiency within the biofilter downstream.

A three-unit aquaculture pilot plant was equipped for growing walleye from fingerling to food-size fish. The growth of the walleye was observed in two closed-systems and in a single-pass system for a period of two years. Normal operating conditions within the closed-systems only required addition of water for replacing water lost to solids flushing and evaporation, approximately 5-10% of the system volume per day.

Several water treatment processes were incorporated into the pilot plant. In pilot-plant operation, the treatments required to make recycled water acceptable for fish growth were:

- control of suspended solids levels to reduce the oxygen demand in the nitrification process units,
- control of ammonia below concentrations toxic to the cultured fish (0.02 mg/L NH_3),
- control of dissolved gases to maintain moderate levels of dissolved oxygen (> 4 mg/L) and low levels of dissolved CO_2 (< 20 mg/L) in the rearing tanks,
- control of pH (> 7) and alkalinity (50 mg/L) to maintain conditions for nitrification and fish health.

Two clarification processes were used for removing organic solids from the recirculated water: sedimentation basins and roughing filters. The design of the pilot plant permitted the use of a range of hydraulic and solid loading rates to evaluate these clarification processes.

Nitrification was evaluated using submerged, static-media, biological filters over a range of hydraulic and ammonia loading rates. Acceptable levels of oxygen and carbon dioxide were maintained by bubbling compressed air through diffusers in the culture tank and in separate aeration columns.

The results of the study on nitrification and clarification within submerged, static-media filters indicated:

- The nitrification rate was greater on media within biofilters treating a clarified flow than within roughing filters acting as their own clarifiers;
- The type of clarifier (sedimentation basin versus roughing filter) did not noticeably affect the rate of nitrification within the biofilter downstream;
- The oxygen and ammonia consumption rates within the biofilters tended to increase with increased hydraulic loading rate through the media;
- The structured plastic media with continuous, straight and vertical void spaces provided higher nitrification rates and lower oxygen demand rates than random packed rock or plastic media;
- The oxygen demand due to nitrification within the roughing filters and biofilter within the RFS were less than 25% and 13% of the total filter oxygen demand, respectively;
- The structured plastic media with continuous, straight and vertical void spaces removed less solids than did the random plastic pack, but showed better solids back-flushing than the random rock or plastic media;
- The rate that captured suspended solids were removed from the clarification process impacted nitrification within the biofilters and overall water quality, with increasing removal rate improving nitrification and water quality;

In ultra-intensive systems, the rate that water is recycled is generally set by the maximum oxygen requirements of the culture tank (Colt and Orwicz, 1991). Therefore, the systems clarifier and biofilter usually treat the full flow of reused water. I recommend selecting a two-stage biofiltration process (roughing filter followed by biofilter), over a single-stage biofilter preceeded by a settling basin, for treating the full recirculated flow. In the two-stage process, the roughing filter will both clarify and reduce the oxygen demand of the flow and possibly provide some nitrification. When designing the roughing filter, select structured plastic media (tubular NORPAK) and size the clarifier based on a media depth of 1.2 m (4 ft) and a hydraulic loading rate of 180 to 250 m^3/d per m^2. Design a reaeration stage between the roughing filter and biofilter. When designing the biofilter, select and size the reactor based on

a media depth of 1.2 m (4 ft) and a hydraulic loading rate of 120 to 180 m^3/d per m^2. Select a highly-porous-plastic media and calculate the total surface area available within the biofilter. If oxygen is not limiting, the amount of nitrifying capacity of the biofilter is dependent upon the specific surface area of the media. Calculate the amount of ammonia produced by the fish per day and use that to calculate the biofilter's surface specific ammonia loading rate. This rate should be less than 0.05 g TAN applied per m^2 per day. Check the oxygen demand across the biofilter assuming that the overall oxygen demand is 9 times the oxygen demand due to nitrification alone. If necessary, adjust the design by selecting a different packing media or by changing the hydraulic loading rate through the biofilter.

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PAPER III. CULTURE OF WALLEYE FROM FINGERLING TO FOOD-SIZE IN A RECIRCULATING SYSTEM

ABSTRACT

High retail prices and limited supplies have provided the economic incentive for developing culture techniques for the commercial production of food size walleye. Closed system aquaculture appears to be the method of choice for culturing walleye to food size because it provides opportunity to maintain culture temperature for maximizing growth. Pond-reared walleye fingerlings (84 d post hatch, 87 mm, 5.0 g) were trained to formulated feed and reared within the recirculating systems until 18 months of age. The results showed that the average walleye can be grown intensively from fingerling to food size (0.65 kg or 1.4 lb) in approximately 2 years from hatch. The fastest growing 20% of the population would reach market size within 16 months. The growth rates were greater than rates reported by others. The walleye were hardy, withstanding temperatures up to 28 °C several times and total ammonia nitrogen values up 10 mg/L (pH of 7.0, unionized ammonia of 0.06 mg/L) for several days.

INTRODUCTION

The walleye (Figure 1) is one of the most popular freshwater game fish in North America and Canada. In the 1991 national survey of fishing, the walleye/sauger species group ranked seventh among all species and species groups in freshwater exclusive of the Great Lakes, with 37.3 million angler days (USDI and USDC, 1993). In the Great Lakes, the walleye/sauger species group ranked first in angler-days (USDI and USDC, 1993). More than a billion walleye are stocked by the United States and Canada for the purpose of maintaining populations of walleye for recreational fishing (Conover, 1986). Walleye are also prized as a food fish, but, except for a few tribal fisheries, the only commercial source of food-size walleye to the general public is imported from Canada principally as a frozen fillet. Given the favorable name recognition for walleye by the public, and a limited commercial supply, a premium price is obtained for walleye at the retail level, typically selling for $5.60 to 7.00 per pound for skin-on fillets. The high market value for walleye provides the economic incentive for developing walleye culture techniques for the commercial production of food-size (636 to 681 g) walleye. Extensive (pond) culture of walleye to food-size in the northern latitudes, such as used for catfish, is not promising due to the short growing seasons. The optimum temperature for growth of fingerling walleye ranges from 22°C Smith and Koenst, 1975) to 26°C, depending on light intensity (Hokanson and Koenst, 1986). Hokansen and Koenst (1986) 26°C as optimal at 5 lux. Cai and Summerfelt (1992) estimated that the optimal temperature for walleye metabolism was 25.3°C at 45 lux light intensity.

Because of the cost for heating water to temperatures around 25°C, only recycle aquaculture systems are practical. These systems also have advantages in abatement of culture facility effluents, therefore, recirculated aquaculture systems appear to be the method of choice for rearing walleye to food size.

In order to design a closed system walleye culture facility properly, empirical information is needed on fish growth, oxygen requirements, and production of ammonia, BOD, and suspended and settleable solids. Calculation of carrying capacity, oxygen demand, or biofilter surface area requirememts, commonly use metabolic functions per unit of feed fed (oxygen or ammonia-feed ratio). Forsberg and Summerfelt (1992a) reported the ammonia-feed ratio (kg NH_3-N per kg feed) was 14.3 and 14.4 for 4.1 to 45.5 g walleye fed 41 and 61% protein diets, respectively. Forsberg and Summerfelt (1992b) reported the ammonia-feed ratio was 21 at 20°C and 27 at 25°C for fish with average group weights ranging from 3.3 to 5.6 g. The weight specific rate of metabolism of walleye is a function of the power of 0.86 of the

body weight at 20°C and 0.78 at 25°C for oxygen consumption, and the power of 0.85 at 20°C and 0.63 at 25°C for ammonia excretion (Cai and Summerfelt, 1991). The effects of weight and feeding frequency on metabolism of juvenile walleye were described by Yager and Summerfelt, (1993a). That experiment was conducted with the same single-pass system used in the present study. Yager and Summerfelt (1993b) reported that there were significant differences among mean metabolic rates and variation in metabolic rates for both oxygen consumption and ammonia excretion for 1, 2, 3 and 15 feedings per day. The mean oxygen consumption rate for 1 feeding per day was greater than any other feeding schedule. The ammonia excretion rate increased progressively during the day when fish were fed 3 or 15 times daily.

Walleye have not been previously reared to food-size (636 to 681 g live weight) commercially in either pond or tank culture systems. Experimental data for intensive culture of walleye greater than 100-125 mm is extremely limited (Nickum, 1978 &1986). Siegwarth and Summerfelt (1993) described the growth of walleye reared from 146 mm (24-25 g) to 783 days post hatch in 120 L tanks (52 x 55 by 42 cm deep) when the walleye averaged 351 mm and 425 g. The growth rates were slower than that of wild populations, which suggests that small tank size, feeding rates (1.6 to 2.0% body weight per day), and suboptimum temperature (about 21°C) may have reduced the growth rates.

There are some data reported on growth of fingerling walleye in intensive culture systems (Roth, 1990; Skurla and McDonald, 1988; Kuipers, 1990; Yager, 1991) but empirical data is limited to fingerling fish. The purpose of this paper is to define the growth of walleye to food size at temperature of ~24 °C in intensive, reuse culture systems.

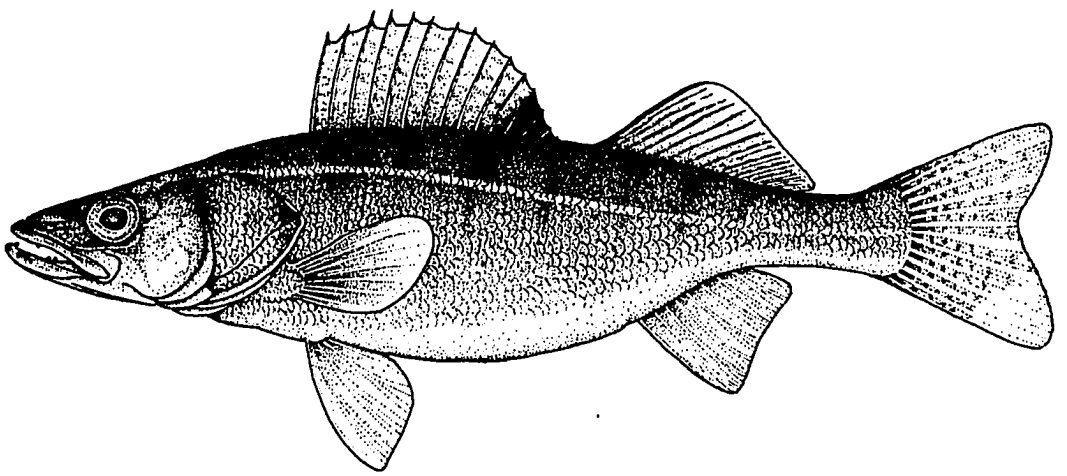

Figure 1. The walleye, *Stizostedion vitreum* (Illustration by Robert Wittmer, Des Moines, IA).

MATERIALS AND METHODS

Culture System

Walleye were reared in a system being used to research nitrification and clarification in closed-cycle aquaculture. Each system contained a 155 cm (5 ft) diameter, 75 cm (2.5 ft) deep, fiberglass rearing tank, operated at a capacity of about 1,000 liters (265 gallons). The layout of the recycle system is discussed in a separate paper, Paper II. Fresh water, approximately 5% of the total system volume, was added daily for solids flushing and replacement of water lost due to evaporation.

Walleye Source

The fish were hatched in the Iowa Department of Natural Resources Spirit Lake Hatchery, Spirit Lake, Iowa, from eggs and sperm obtained from fish captured from Spirit Lake and East and West Okoboji Lakes about April 24, 1990. Walleye are about 7.1 mm at hatching and weigh 5 mg (Siegwarth and Summerfelt, 1993). The fry were stocked in Welch Lake at approximately 3 days post hatch. The fingerling walleye (~54 days posthatch) were obtained from Welch Lake, a fingerling production site of the Iowa Department of Natural Resources, Spirit Lake Hatchery, on July 17, 1990. The fingerling averaged 5.0 g weight and 48.0 mm long when they were stocked in the tanks.

Feeding

The initial daily feeding rate, during the period where the fingerlings were trained to pelleted feed, was 16% of body weight. A high feeding rate was used to encourage feeding and to limit cannibalism. The fingerlings were started on a no. 4 crumble of BioTrainer® (Bioproducts, Warrenton, Oregon). This is a semi-moist (22% moisture) feed, with a high level of krill, that must remain frozen before use. It was fed every 10 minutes, 24 hours per day with constant lighting (10 lux). In the first week of feeding, the feed was coated with oxytetracycline in gelatin and fed at a rate of 3 g active per 45.5 kg of fish per day (Piper et al., 1982). When the walleye were nearing 11 g, the feed size was increased to a 2.5 mm (3/32 inch) BioDiet® pellet (a non-frozen, semi-moist fish feed; Bioproducts, Warrenton, Oregon) and the feed rate cut to 8% per day by weight. At an average weight of about 15 g, the feed size was increased to 3 mm BioDry 1000 pellets (Bioproducts, Warrenton, Oregon) and the feeding rate was gradually reduced to 3% per day by weight. The fish were reared on 3% per day by weight BioDry 1000 (BioProducts, Warrenton, Oregon) to an average of 250 g. The

pellet size was increased with fish size: 4 mm pellet for 40 g fish; 6 mm pellet for 80 g fish; and 8 mm pellet for 160 g fish. The fish were fed a 9.5 mm pellet of U.S.F.W.S. walleye grower ration (Nelson & Sons, Inc., Murray, Utah) in April 1991 when the walleye were averaging about 250 g. The walleye were fed 1.8% per day by weight on grower ration to the end of the study.

Walleye Density

Initial fingerling stocking density was 1.25 fish/L. The walleye grew into a density of 48 kg/m^3 without restocking; thereafter, walleye were moved into and out of a holding tank to maintain fish densities of 24 and 48 kg/m^3 in the experimental culture tanks as required for experiments on the unit treatment processes within the recycle system. A density of 72 kg/m^3 was attempted for a short period, however, this density was discontinued because the dissolved oxygen could not be maintained above 4 mg/L with only diffused air for aeration.

Water Quality

Analysis of water quality was based on *Standard Methods for the Examination of Water and Wastewater* (APHA 1989).

Alkalinity

Alkalinity was typically 60 mg/L as $CaCO_3$ and ranged from 40 to 120 mg/L.

Ammonia

Ammonia was measured using the ion-selective electrode method (APHA, 1989). The total ammonia nitrogen (TAN, NH_3-N) varied substantially during the period due to variations in recycle conditions being tested concurrently. Total ammonia was typically between 0.5 and 1.0 mg/L as N. However, during a few periods TAN reached values up to 10 mg/L as N (unionized ammonia of 0.06, pH of 7.0, temperture of 25°C). Some of these periods lasted several days and corresponded to periods when culture temperatures reached 28°C. No increase in mortality was observed during the periods of high ammonia levels.

Dissolved oxygen

Dissolved oxygen was measured by the azide modification method (APHA, 1989). Dissolved oxygen within the culture tank was typically around 5 mg/L or 6.5 mg/L, depending upon the fish density being tested in the recycle trials.

Light

The room was illuminated by a single bulb (30 W) reflected upward against the ceiling. Light intensity was approximately 10 lux at the water surface within the culture tanks.

pH

The pH ranged between 6.5 and 8 and was typically between 6.8 and 7.2.

Temperature

The average culture temperature was 24°C. Upon introduction of the pond reared fingerlings to the intensive culture system, and while the fingerlings were being pellet trained, the temperature was held at 20°C to reduce columnaris disease. The maximum temperature observed was 28°C during the summer. Handling the fish at the elevated temperatures resulted in columnaris outbreaks and mortalities.

Turbidity

Unfiltered turbidity, as measured with a turbidimeter (Hach Company, Ames, Iowa), ranged between 15 to 30 NTUs; however, during periods of biofilter sloughing, turbidities reached 120 NTUs.

RESULTS

Walleye Growth Rate in an Intensive Recycle System

Walleye grew from an initial average length of 87 mm and 5.0 g to an average of 345 mm and 345 g in 286 days. Tanks were restocked twice, when the fish were 370 and 445 days old, to reduce densities of 24 or 48 kg/m^3 to carry out experiments on treatment processes within the systems. When the tanks were restocked, the fish that were added were smaller, which is why the mean length and weight is less after restocking (Figures 2 and 3). Growth rate is expressed in terms of length or weight (Figures 2 and 3). In addition, growth of the fastest growing 20 % is also shown (Figures 2 & 3).

Length to Weight Relationship

The relationship between fish length and weight is curvilinear. A log-log (base 10) transformation of length-weight data provides a straight line fit (Figure 4). The equation for this relationship from 3000 length-weight measurements is (Table 1):

$$\log_{10}(W) = 2.929 \log_{10}(L) - 4.91 \quad (1)$$

where W is the weight of the fish in grams and L is the length of the fish in mm.

Condition Factor (k) to Size Relationship

The condition factor, k (Fulton type), is the ratio of fish weight to length cubed times 10^5 (a scaling constant used to achieve integer status). The condition factor of the walleye over the entire culture period was independent of weight but inversely proportional to length (Figure 5).

Relative Weight to Size Relationship

The relative weight of a fish is the ratio of the oberved weight to the length-specific standard weight times 100. The length-specific standard weight (W_S) of walleye has been defined to be (Murphy et al., 1990):

$$\log_{10}(W_s) = 3.180 \log_{10}(L) - 5.453 \quad (2)$$

The relative weight of the walleye over the entire culture period is shown to be inversely related to both length and weight (Figure 6).

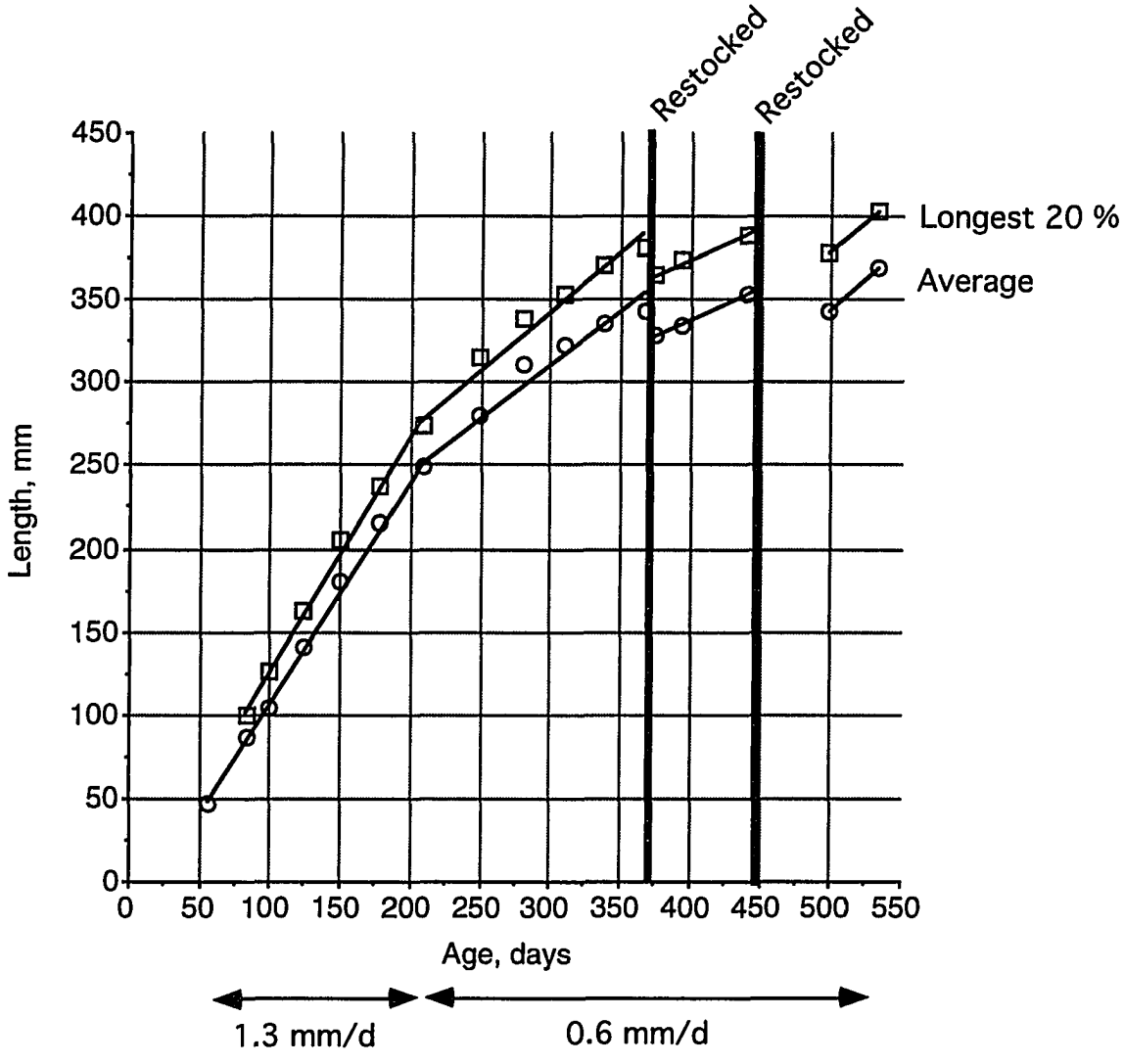

Figure 2. Growth in length of walleye in the experimental recycle system at an average temperature of 24 °C. Data points for average lengths are for a sample of at least 50 fish on each date.

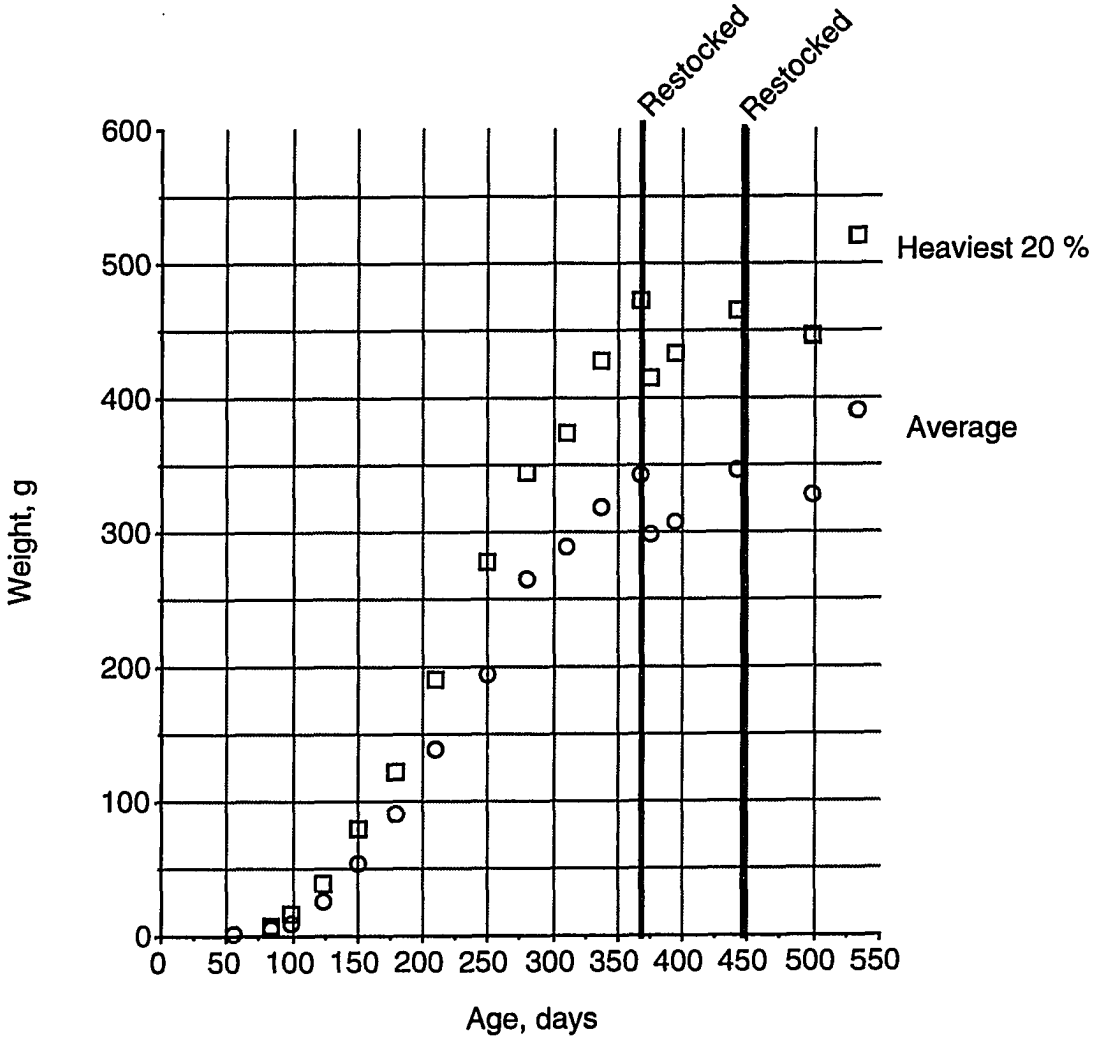

Figure 3. Growth in weight of walleye in the experimental recycle system at an average temperature of 24 °C. Data points for average weights are for a sample of at least 50 fish on each date.

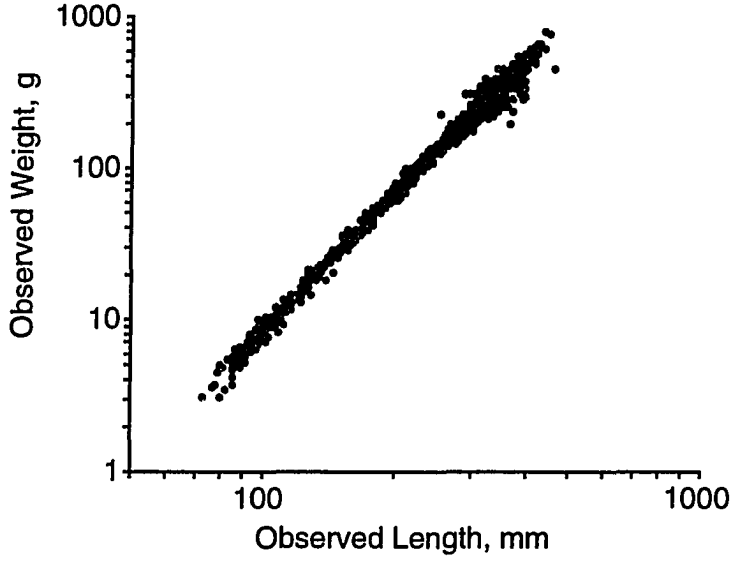

Figure 4. Relationship between length and weight of walleye (2963 data points) grown in closed systems: $\log_{10}(W) = 2.929 \cdot \log_{10}(L) - 4.91$

Table 1. Body shape relationships for tank-reared walleye.

Length, mm	Weight (g)	Condition Factor (g/mm^3)	Relative Weight (%)
100	8.87	0.90	107
110	11.73	0.89	106
120	15.13	0.89	105
130	19.13	0.89	104
140	23.77	0.88	103
150	29.09	0.88	102
160	35.15	0.88	101
170	41.97	0.87	100
180	49.62	0.87	99
190	58.14	0.87	97
200	67.56	0.86	96
210	77.94	0.86	95
220	89.32	0.86	94
230	101.74	0.85	93
240	115.25	0.85	92
250	129.89	0.85	91
260	145.70	0.84	90
270	162.73	0.84	89
280	181.02	0.84	88
290	200.62	0.83	87
300	221.56	0.83	86
310	243.89	0.83	85
320	267.66	0.82	83
330	292.91	0.82	82
340	319.67	0.82	81
350	348.00	0.81	80
360	377.93	0.81	79
370	409.51	0.81	78
380	442.78	0.80	77
390	477.78	0.80	76
400	514.56	0.80	75
410	553.15	0.79	74
420	593.60	0.79	73

[a]weight calculated from length (mm) vs. weight (g) regression of 2963 length-weight measurements: $\log_{10}(W) = 2.929 \cdot \log_{10}(L) - 4.91$

[b]relative weight at a given length as calculated from the regression: $W_r = -0.108 \cdot L + 118.0$.

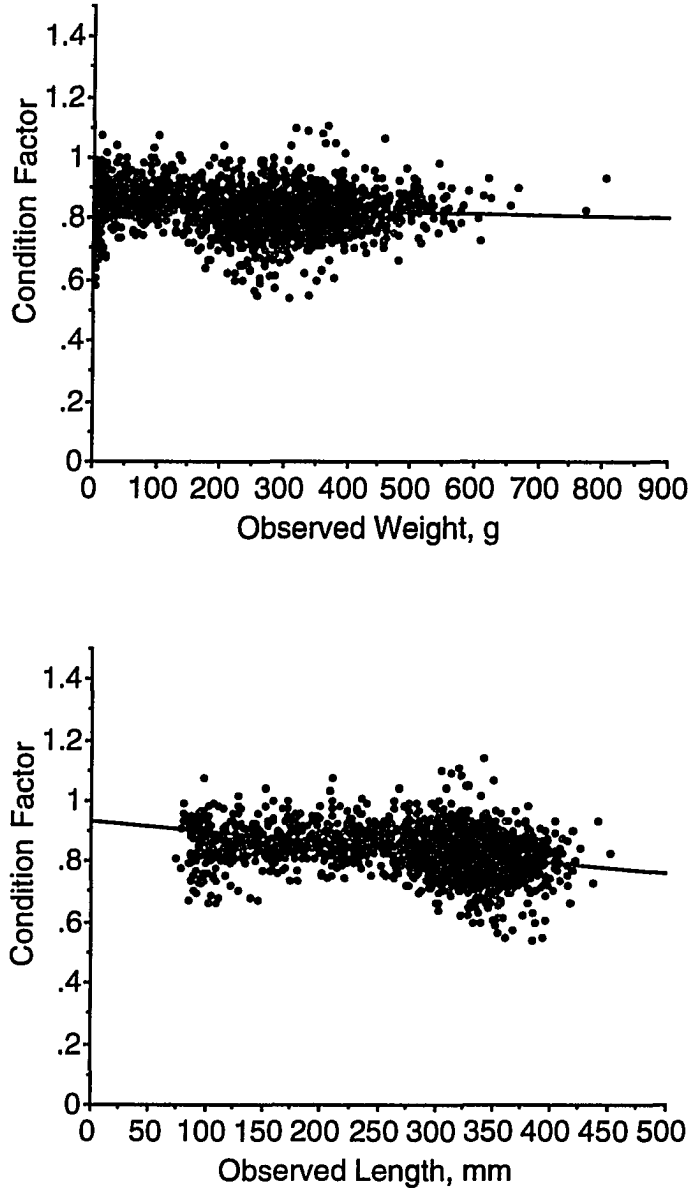

Figure 5. Relationship between condition factor (k) and fish length (lower) and weight (upper) (2963 data points; average k = 0.83; $k = -3.373 \times 10^{-4} \cdot L + 0.932$; $k = -4.387 \times 10^{-5} \cdot W + 0.843$).

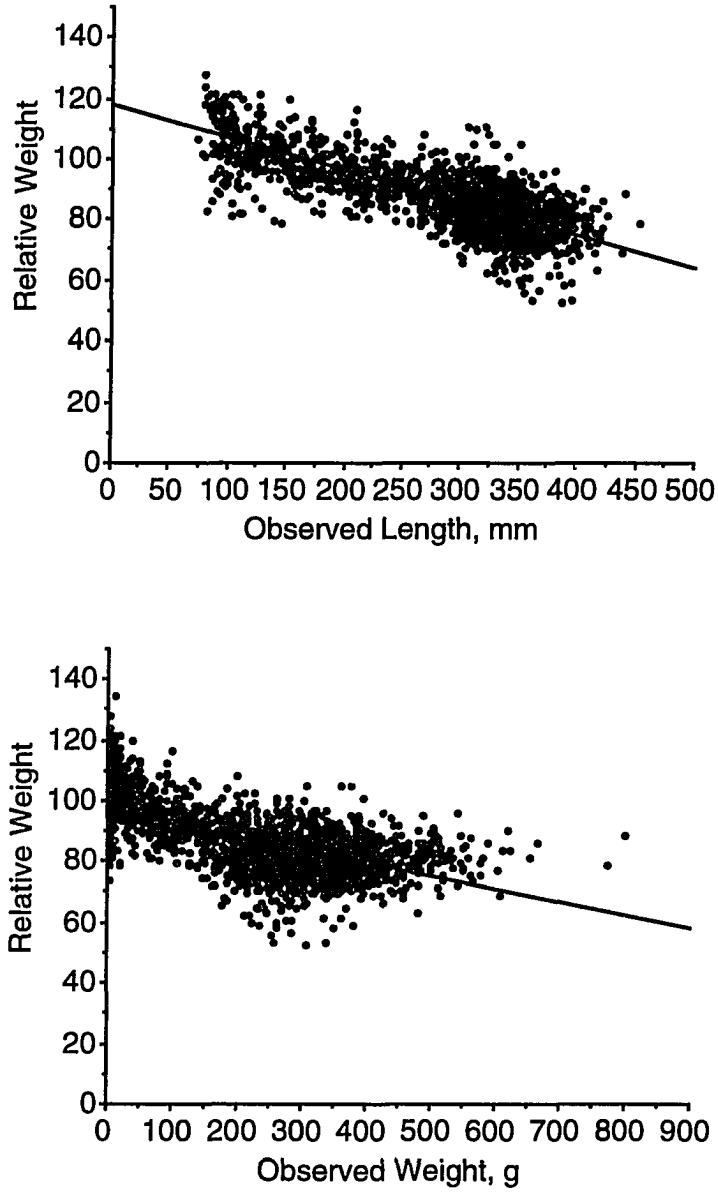

Figure 6. Relationship between relative weight and fish size. (2963 data points; average W_r = 86.0; W_r = -0.108·L +118.0; W_r = -0.043·W + 96.8)

DISCUSSION

High retail prices and limited supplies has provided the economic incentive for developing culture techniques for the commercial production of food size walleye. Closed system aquaculture appears to be the method of choice for culturing walleye to food size because it provides opportunity to rear fish at high fish densities and at a temperature for maximizing growth. The purpose of this section were to define the growth of walleye to food size at a temperature (~24°C). A temperature of 26°C has been defined as the optimum temperature for growing juvenile walleye (Hokanson and Koenst, 1986).

The results showed that walleye can be grown in intensive culture systems to food size (0.65 kg or 1.4 lb) in approximately 2 years from hatch. The fastest growing 20 % would reach market size within 16 months. The growth rates (mm/d) were much better than reported by others (Table 2). The increase in growth rate found may be due to several factors: temperature, tank size, turbidity, or some other water characteristic. Kuipers (1990) used smaller tanks than the present experiment, 200 vs. 1100 L. Kuipers (1990) and Yager (1991) both used single-pass systems and thus had water with characteristics significantly different than found in the recycle system. As well, the holding systems were single-pass during the Kuipers (1990) and Yager (1991) experiments. In this work, growth was slower and general health, particularly tail fin erosion, was poorer for walleye cultured within the single-pass system compared to walleye reared in the recycle environments. The author believes that the much greater turbidity in the recycle system minimized the stress on the walleye. Conversely, the walleye seemed more stressed in the single pass system, based on observation of the walleye in the clear water found in the single pass system. The single pass system did use treated tap water. However, the tap water was degassed, passed through activated carbon filters and chemically treated with sodium sulfite to remove toxic chlorine or chloramines. The chlorine and chloramine concentrations were below levels detectable by Hach techniques (i.e., less than 0.01 mg/L total chlorine). Walleye are a wild species and have not been domesticated for food fish culture. The oldest line of a captive walleye is only to its third generation (Nagel, personal communication). On the other hand trout have been cultured intensively for over 100 years, resulting in several "domesticated" strains and detailed knowledge of trout metabolism and growth. Trout have the growth and conversion benefits of domestication. Domestication of walleye should lead to improved growth rates and feed conversion, therefore, resulting in less time and production cost to reach market-size.

Table 2. Growth rates of walleye reported in the literature.

Author	Temperature (°C)	Size Studied (start - finish, mm)	Growth Rate (mm/d)
Malison et al. (1990)	21	117-170	0.62
Barrows et al. (1988)	21	124-168	0.63
Seigwarth and Summerfelt (1990)	17	146-156	0.12
	21	147-178	0.45
Seigwarth and Summerfelt (1992)	25	176-215	0.55
Seigwarth and Summerfelt (1993)	21	285-324	0.31
Stettner et al. (1992)	20	154-195	0.58
Yager (1991)	23	313-344	0.26
		258-329	0.54
Kuipers (1990)		10-220	0.79
Present Study	24	50-250	1.3
	24	250-370	0.6

Walleye appeared fairly hearty for a coolwater fish. During parts of the summer, the water temperature reached 27-28 °C for several weeks. Also, periods occurred when the total ammonia reached 10 mg/L as N. Little mortality was seen in the fish during these intervals of elevated temperature or ammonia. However, when the fish were handled during the occurrence of elevated temperature or ammonia, then a number of mortalities showing signs of columnaris disease resulted.

SUMMARY--WALLEYE PRODUCTION WITHIN RECIRCULATING SYSTEMS

High retail prices and limited supplies have provided an economic incentive for developing culture techniques for the commercial production of food size walleye. Closed system aquaculture appears to be the method of choice for culturing walleye to food size because it provides opportunity to maintain culture at high fish densities and at a temperature for maximizing growth. The purpose of this paper was to define the growth of walleye to food size at a fairly constant temperature (~24 °C) in recirculated systems. The results of the study on walleye growth indicated:

- Walleye were grown from fingerling (5-8 cm) to food-fish size in approximately 2 years from hatch within recirculating systems at an averaged temperature of 24°C;
- Walleye apperaed fairly hearty for a cool water fish, withstanding temperatures up to 28°C and total ammonia nitrogen values up to 10 mg/L (pH≈7.0) for several days at a time;
- Walleye were cultured at densities of 24, 48 and 72 kg/m^3, however, when cultured at 72 kg/m^3, dissolved oxygen levels could not be maintained consistently above 4.0 mg/L within the recirculating systems used.

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GENERAL SUMMARY AND DISCUSSION

Aquaculture production within recirculating systems is being driven by the need for conservation of water resources, control of the culture environment, alternative site locations, reduction in production cost through intensification and economies of scale, and an increased emphasis to reduce, manage and control effluents. Recirculating technology allows aquaculture to be market and demand driven rather than limited by natural resource factors. Technological advances now make it possible to culture a wide variety of species in almost any location. The present challenge, however, is to develop, integrate, and refine recirculating aquaculture production technology so that it is economically feasible for commercial production of food products.

Review of Aquaculture

Recirculating systems must contain unit processes which function for fish rearing, clarification, ammonia and BOD reduction, aeration/oxygenation, CO_2 and pH control, and sometimes disinfection. Most successful, large-scale, commercial aquaculture producers using recirculating technologies have gone to deep (2 to 5 m) round culture tanks, microsieve filters for clarification, fiuidized-bed biological reactors for ammonia and BOD control, pure oxygen injection systems for oxygenation, and air-stripping columns and/or chemical treatment for CO_2 control. Many researchers and producers agree that the clarification process is the most critical for making recirculating systems successful, because solids control influences the efficiency of all other unit processes within these systems. Clarification has also generally turned out to be the most capital and operational costly unit process, particularly with the introduction of fluidized-bed biofilters which have been demonstrating relatively low capital and operational costs.

Understanding and Treating CO_2 Problems

Study of the literature and communication with producers indicated that little was known and less published on the understanding and control of CO_2 problems within recirculated systems. PaperI was devoted to the issues of CO_2. The results of a study on the equilibrium of carbon dioxide in solution and it's removal by air stripping and chemical addition indicated:

- The efficiency of CO_2 removal, the amount of CO_2 produced by the fish and the biological treatment process, and the rate of water recirculated all combine to control the concentration of CO_2 within the culture tank;
- High density fish culture systems utilizing pure oxygen addition typically require some method of CO_2 removal, because these systems typically lack much air to water contact;
- It is more effective to strip CO_2 by cascading water through air, than by blowing air through water;
- Carbon dioxide stripped from the water should be vented from enclosed buildings;
- Chemical treatment using lime, caustic soda, soda ash or sodium bicarbonate can be used to maintain a pH that will minimize the potentially toxic effects of CO_2 and NH_3;
- A pH between 7.5 to 8.2 will minimize the relative proportions of CO_2 and NH_3.

The design criteria for CO_2 removal in counter-current air stripping columns are given. In addition, a computer algorithm was developed for calculating the depth of a stripping column required for a given media, removal efficiency and volumetric air to water ratio.

Static-Media Filters for Nitrification and Clarification

This project was oriented towards using unit processes amenable for converting abandoned water and waste water treatment plants into commercial sites for culturing food fish within recirculating systems. The abandoned facilities typically contain large, deep, circular and/or rectangular tanks which had been used as clarifiers or, in the case of waste water treatment plants, were packed with crushed rock and used as trickling filters. Some of these empty tanks could function well for culturing food-fish on a large-scale. It was thought that other empty tanks could be converted into settling basins for clarifying the recirculating water and that the old trickling filters could be used as submerged biofilters or possibly roughing filters. Review of the literature indicated that, although better unit processes might be available, the unit processes available at abandoned water and waste water treatment facilities might function well for use within recirculating-aquaculture production systems and are low cost. Paper II describes research conducted on the performance of static-media filters for nitrification and clarification and on the performance of either settling basins or static-media roughing filters for maintaining nitrification efficiency within the biofilter downstream.

A three-unit aquaculture pilot plant was equipped for growing walleye from fingerling to food-size fish. The growth of the walleye was observed in two closed-systems and in a

single-pass system for a period of two years. Normal operating conditions within the closed-systems only required addition of water for replacing water lost to solids flushing and evaporation, approximately 5-10% of the system volume per day.

Several water treatment processes were incorporated into the pilot plant. In pilot-plant operation, the treatments required to make recycled water acceptable for fish growth were:

- control of suspended solids levels to reduce the oxygen demand in the nitrification process units,
- control of ammonia below concentrations toxic to the cultured fish (0.02 mg/L NH_3),
- control of dissolved gases to maintain moderate levels of dissolved oxygen (> 4 mg/L) and low levels of dissolved CO_2 (< 20 mg/L) in the rearing tanks,
- control of pH (> 7) and alkalinity (50 mg/L) to maintain conditions for nitrification and fish health.

Two clarification processes were used for removing organic solids from the recirculated water: sedimentation basins and roughing filters. The design of the pilot plant permitted the use of a range of hydraulic and solid loading rates to evaluate these clarification processes. Nitrification was evaluated using submerged, static-media, biological filters over a range of hydraulic and ammonia loading rates. Acceptable levels of oxygen and carbon dioxide were maintained by bubbling compressed air through diffusers in the culture tank and in separate aeration columns.

The results of the study on nitrification and clarification within submerged, static-media filters indicated:

- The nitrification rate was greater on media within biofilters treating a clarified flow than within roughing filters acting as their own clarifiers;
- The type of clarifier (sedimentation basin versus roughing filter) did not noticeably affect the rate of nitrification within the biofilter downstream;
- The oxygen and ammonia consumption rates within the biofilters tended to increase with increased hydraulic loading rate through the media;
- The structured plastic media with continuous, straight and vertical void spaces provided higher nitrification rates and lower oxygen demand rates than random packed rock or plastic media;
- The structured plastic media with continuous, straight and vertical void spaces removed less solids than did the random plastic pack, but showed better solids back-flushing than the random rock or plastic media;

- The rate that captured suspended solids were removed from the clarification process impacted nitrification within the biofilters and overall water quality, with increasing solids removal rate improving nitrification and water quality;

Walleye Production Within Recirculating Systems

High retail prices and limited supplies has provided an economic incentive for developing culture techniques for the commercial production of food size walleye. Closed system aquaculture appears to be the method of choice for culturing walleye to food size because it provides opportunity to maintain culture at high fish densities and at a temperature for maximizing growth. The purpose of Paper III was to define the growth of walleye to food size at a fairly constant temperature (~24 °C) in recirculated systems. The results of the study on walleye growth indicated:

- Walleye were grown from fingerling (5-8 cm) to food-fish size in approximately 2 years from hatch within recirculating systems at an averaged temperature of 24°C;
- Walleye apperaed fairly hearty for a cool water fish, withstanding temperatures up to 28°C and total ammonia nitrogen values up to 10 mg/L (pH≈7.0) for several days at a time;
- Walleye were cultured at densities of 24, 48 and 72 kg/m^3, however when cultured at 72 kg/m^3, dissolved oxygen levels could not be maintained consistently above 4.0 mg/L within the recirculating systems used.

Implications of Findings and Future Research Needs

These findings indicate that abandoned water and waste water treatment facilities could be converted for use as recirculated aquaculture systems. The most reliable and successful design would use the large circular tanks for rearing fish and for water retention reservoirs. I recommend the use of fluidized-sand beds as the biofiltration unit process because of their reliability and cost effectiveness (Summerfelt and Cleasby, 1993). Microsieve filters are recommended for clarification because they continuously remove a large fraction of the solids from the recirculated systems (Summerfelt et al., 1994; Libey, 1993). Oxygenation with either U-tubes or enclosed splash columns is recommended to allow the system to maximize production by increasing carrying capacity (Colt and Watten, 1988; Speece et al., 1988; Westers 1989). Carbon dioxide stripping with splash columns is also recommended. The splash columns need not be enclosed or ventilated if the recirculated system is not enclosed within a building. The splash columns, however, must be enclosed and vented outdoors if the recirculated system is to be within a building.

Future research is needed to:

- evaluate the economics of producing walleye, or other species, within abandoned water or waste water facilities;
- estimate, over the course of a year, the probable water temperature within a recirculated system constructed from an abandoned water or waste water treatment facility, (assuming a given design, heat input, tank covering, etc.);
- quantify the market potential of walleye within this region;
- determine the maximum density (kg per m^3 of rearing space) of walleye which can be sustained when metabolites such as oxygen, ammonia or carbon dioxide are not limiting;
- develope a more efficient and less costly walleye grower diet;
- compare the costs of constructing new culture tanks to the costs of removing rock substrate from abandoned trickling filters.

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APPENDIX

Stripper Design Algorithm

Constant Inputs

Molar Concentration of Water, mol/L

```
co=55.6
```

Molecular Weight of CO_2,g/mol

```
mwcd=44.0
```

Molecular Weight of water, g/mol

```
mwwater=18.0
```

Molecular Weight of air, g/mol

```
mwair=29.0
```

Total Gas Pressure, atm

```
pt=1
```

Mol Fraction of CO_2 in Influent of Vapor Phase, mol/mol

```
yinf=0.00035
```

Henry's Law Constant (20 C), total pressure x vapor phase mol fraction / liquid phase mol fraction, atm

```
kh=1.43*10^3
```

Unitless Henry's Law Constant (20 C), total pressure x vapor phase mol fraction / liquid phase mol fraction, atm

```
khu=1.07
```

Density of Water (20 C), kg/m^3

```
denw=998.
```

Density of Air (20 C), kg/m^3

```
dena=1.2
```

Viscosity of Water (20 C), kg/m/s

```
viscw=0.0010
```

Viscosity of air (20 C), kg/m/s

```
visca=1.82*10^{-5}
```

Surface Tension of Water (20 C), N/m

```
stl=0.073
```

Surface Tension of Packing, N/m

```
stp=33.*10^{-3}
```

Gravitational Acceleration Constant, m/s^2

```
gc=9.81
```

Diffusity of CO_2 in Vapor Phase (20 C), m^2/s

```
difg=1.38*10^{-5}
```

Diffusity of CO_2 in Liquid Phase (25 C), m^2/s

```
difl=19.6*10^{-10}
```

Variable Inputs

Influent Concentration of CO_2 in Liquid Phase, mg/L

```
cinf=30
```

Fraction of CO_2 Removed from Liquid Phase, unitless

```
remx=.
```

Liquid Loading Rate, m^3/s per m^2 cross-section (1 m^3/s per m^2 = 1471 gpm per ft^2 =)

```
lvol=0.015
```

Volumetric Ratio of Gas to Liquid Flowrates, vol per time over vol per time

```
goverl=.
```

Type of Packing--Glitsch Ballast Rings

Specific Surface Area of Packing, m^2/m^3

```
at=105
```

Nominal Size of Packing, m

```
dp=0.0508
```

Calculations

Determining Mol Fractions and Molar Flow Rates

Mol Fraction of CO_2 in Influent of Liquid Phase, mol/mol

```
xinf=cinf/(co*1000.*mwcd)
```

Mol Fraction of CO_2 in Effluent of Liquid Phase, mol/mol

```
xeff=xinf*(1-remx)
```

Theoretical Mol Fraction of CO_2 in Influent of Liquid Phase that would result from Equilibrium with the influent Vapor Phase Concentration, mol/mol

```
xinfeq=pt*yinf/kh
```

Mol Fraction of CO_2 in Effluent of Vapor Phase (from mass-balance), mol/mol

```
yeff=((xinf-xeff)/goverl)+yinf
```

Theoretical Mol Fraction of CO_2 in Effluent of Liquid Phase that would result from Equilibrium with the Effluent Vapor Phase Concentration, mol/s

```
xeffeq=pt*yeff/kh
```

Liquid Mass Loading Rate, kg/s per m^2 cross-section

```
lmas=lvol*denw
```

Liquid Molar Loading Rate, mol/s per m^2 cross-section

```
lmol=lmas*1000./mwwater
```

Gas Volumetric Loading Rate, m^3/s per m^2 cross-section (1 m^3/s per m^2 = 1471 gpm per ft^2 =)

```
gvol=goverl*lvol
```

Gas Mass Loading Rate, kg/s per m^2 cross-section

```
gmas=gvol*dena
```

Gas Molar Loading Rate, mol/s per m^2 cross-section

```
gmol=gmas*1000./mwair
```

Log Mean Driving Force for Transfer of CO_2 across the column, DF_{lm}

Driving force for transfer of CO_2 at the effluent, mol/mol

```
dfeff=xeff-xeffeq
```

Driving force for transfer of CO_2 at the influent, mol/mol

```
dfinf=xinf-xinfeq
```

Log mean of the exit and entrance driving forces for transfer of CO_2 across the column, mol/mol

```
dflm={dfeff-dfinf}/{Log[{dfeff/dfinf}]}
```

Overall Mass Transfer Coefficients, $K_L a$

Interfacial area through which transfer occurs, aw

```
aw=at*{1.0-Exp[-1.45*{stp/stl}^0.75*{lmas/{at*viscw}}^0.1
*{lmas^2*at/{denw^2*gc}}^-0.05*{lmas^2/{denw*stl*at}}^0.2]}
```

Resistance to transfer across the liquid phase interphase, k_L

```
kl=0.0051*{denw/{viscw*gc}}^-0.3333*{lmas/{aw*viscw}}^0.66667*
{viscw/{denw*difl}}^-0.5*{at*dp}^0.4
```

Resistance to transfer across the gas phase enterphase, k_g

```
kg=5.23*at*difg*{gmas/{at*visca}}^0.7*{visca/{dena*difg}}^0.3333*
{at*dp}^-2.0

kkl=1/{1/{khu*kg}+1/kl}
```

Resistance to transfer across the gas phase enterphase, k_g

Column Height

```
height=lvol*{xinf-xeff}/{kkl*aw*dflm}

Plot[height, {goverl, 1, 30}]
```