Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Aquacultural Engineering 33 (2005) 258–270
aquacultural engineering
www.elsevier.com/locate/aqua-online

Effluent and production impacts of flow-through aquaculture operations in West Virginia

Roger C. Viadero Jr.[a,*], James H. Cunningham[a], Kenneth J. Semmens[b,1], Aislinn E. Tierney[a]

[a] West Virginia University, Department of Civil and Environmental Engineering, Post Office Box 6103, Morgantown, WV 26506-6103, USA
[b] West Virginia University, Post Office Box 6108, Morgantown, WV 26506-6108, USA

Received 21 February 2005; accepted 23 February 2005

Abstract

In light of recent changes to federal regulatory requirements placed on the aquaculture industry, aquaculture operators must act proactively to maximize their production to meet demands, compete with new operations, and maintain compliance with effluent standards. As a result, water quality characterization was conducted at six anonymous facilities using flow-through design, rearing mostly rainbow trout (*Oncorhynchus mykiss*) that were selected based on various water sources, operation, size, and effluent treatment.

Average concentrations and mass loadings of regulated parameters were within regulatory limits and increased in direct proportion to the mass of fish reared. However, when comparing effluent pollutant concentrations and loads with West Virginia National Pollutant Discharge Elimination System (NPDES) permit limitations, the potential for increased production existed at each facility. Based on the current West Virginia NPDES limit of 30 mg/L for total suspended solids (TSS), each facility could increase production from 147 to 819%. However, with a more stringent TSS limitation of 5 mg/L net used in states in the western US, two facilities would have to reduce production from 37 to 44%, while the other sites could increase production from 19 to 170%. Consequently, the opportunity to increase production under any set of regulatory constraints was a function of

* Corresponding author. Tel.: +1 304 293 3031x2611; fax: +1 304 293 7109.
E-mail address: RCViadero@mail.wvu.edu (R.C. Viadero Jr.).
[1] Tel.: +1 304 293 6131.

0144-8609/$ – see front matter
doi:10.1016/j.aquaeng.2005.02.004

annual fish production, legal requirements, and the implementation of effective effluent treatment processes.

Keywords: Effluent; Water quality; Trout; Production; Regulation

1. Introduction

In order to reduce pollutant loadings nationwide, the US Environmental Protection Agency (US EPA), has developed new effluent management standards for private and public aquaculture operations, which meet specific criteria (US EPA, 2004). Further, stream antidegradation legislation and total maximum daily loads (TMDLs) are considered emerging issues of concern to aquaculture operators. The development of data on existing effluents and treatment processes is a proactive step toward maintaining the future sustainability of the industry.

Aquaculture is a growing industry for the production of fish for both recreation and food markets. An abundance of water resources, topography, and close proximity to eastern markets give West Virginia a unique opportunity for future growth. The objectives of this study were to provide industry, State, and Federal stakeholders with baseline effluent water quality data specific to West Virginia flow-through facilities, to help concerned parties make informed decisions regarding new regulations and to examine the potential to increase production, based on effluent pollutant load and permit limitations. To attain these objectives, a water quality characterization was conducted at six anonymous facilities using flow-through design, rearing mostly rainbow trout (*Oncorhynchus mykiss*) that were selected based on various water sources, operation, size, and effluent treatment.

2. Background

In June 2004, a final rule was issued by the US EPA to establish effluent limitations and new source performance standards for aquaculture operations. Under the new rule, facilities that meet the following criteria for direct discharges of wastewater will be regulated: (1) flow-through systems with fish production $\geq$100,000 lbs/year (45,359 kg/year), (2) recirculating systems that discharge wastewater at least 30 days a year, and (3) net pen or submerged cage systems used to produce $\geq$100,000 lbs of fish per year. According to the US EPA, compliance with this regulation will only affect 242 facilities.

Wastewaters from flow-through aquaculture operations are discharged directly into receiving water bodies and are regulated under the Federal Clean Water Act (CWA) of 1977. As in many states, West Virginia is delegated by the US EPA to regulate these discharges through the West Virginia Department of Environmental Protection (WV DEP). In West Virginia, facilities that raise cool/coldwater aquatic animals and discharge effluent more than 30 days per year or produce above 9072 kg (20,000 lbs) per year are classified as concentrated aquatic animal production facilities (CAAPFs) and are required to obtain a National Pollutant Discharge Elimination System (NPDES) permit (Ewart et al., 1995).

Table 1
NPDES permit requirements for cool/coldwater aquaculture facilities in West Virginia

Parameter	Mass load (kg/day)		Concentration (mg/L)	
	Average monthly	Maximum daily	Average monthly	Maximum daily
BOD_5	196 (432 lbs/day)	392 (865 lbs/day)	30	60
TSS	196 (432 lbs/day)	392 (865 lbs/day)	30	60
TAN	N/A	62 (136 lbs/day)	N/A	10.44[a]
SS	N/A	N/A	N/A	0.2
DO	N/A	N/A	Minimum 6.0	Minimum 6.0
pH	N/A	N/A	6–9	6–9
Flow	N/A	N/A	N/A	Monitor

[a] Based on NH_3 water quality standard of 20 μg/L, 18.9 °C, and pH of 6.55.

Current West Virginia NPDES permit requirements for aquaculture facilities are presented in Table 1. The impact of the future promulgation of total maximum daily loading (TMDL) requirements are not taken into account in Table 1.

Three primary types of waste are generated from aquaculture operations: (1) organics measured as 5-day biochemical oxygen demand (BOD_5), (2) nutrients (e.g., total ammonia nitrogen (TAN), unionized and ionized ammonia (NH_3 and NH_4^+), nitrate (NO_3^-), and total phosphorus (TP)), and (3) solids measured as total suspended solids (TSS). Typical average increases from influent to effluent during routine operation for BOD_5 ranged from 0 to 15.6 mg/L, from 0.01 to 1.52 mg/L for TAN, from 0 to 1.68 mg/L for nitrate, from 0 to 0.591 mg/L for TP, and from 0 to 100 mg/L for TSS (Hinshaw and Fornshell, 2002; Liao, 1970; Train et al., 1977; UMA Engineering, 1979; Solbé, 1982; Bergheim et al., 1984; Kendra, 1991; Cripps, 1995).

The addition of feed is the main source of the direct and indirect production of pollutants in aquaculture process waters. For instance, it is known that salmonids retain only about 30% feed nitrogen (N) and phosphorus (P), if all the feed is consumed (Ramseyer and Garling, 1997). The presence and subsequent dissociation of uneaten feed and metabolic byproducts (fish fecal matter) result in both dissolved and suspended waste products which exert an oxygen demand on receiving waters and increase nutrient (nitrogen and phosphorus) loading. Consequently, facilities in which more fish are reared must apply more feed, and have higher pollutant concentrations, than facilities with fewer fish.

Current approaches to waste management in flow-through aquaculture systems include the use of sedimentation to produce clarified effluent and to concentrate biosolids (Hinshaw and Fornshell, 2002). Other approaches such as the reduction of dissolved pollutant loading through diet optimization have also been studied (Gatlin and Hardy, 2002; Cho, 1997).

3. Materials and methodologies

3.1. Study sites

Six West Virginia aquaculture facilities participated in this study. All were flow-through facilities, which reared predominantly rainbow trout (*O. mykiss*); however, limited numbers of brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*) were also raised at all but two facilities (E and F). Each site was characterized based on water source, facility size, effluent treatment, and operator-feeding practices, as summarized in Table 2.

In general, each operation consisted of a serial array of raceways and utilized gravity or mechanical aeration to maintain necessary dissolved oxygen concentrations. However, the configurations at Facilities E and F were slightly different. A process flow diagram of Facility E is presented in Fig. 1, to clearly show several unique features at the site. At Facility E, circular tanks were used as fish rearing units and there were two effluent outfalls at the site. Further, Facilities E and F were the only two sites at which mine water was used as process water for fish culture. Both facilities used the same source water which was conditioned by first removing CO_2(g) using packed aeration columns, followed by the injection of O_2(g) into process waters to increase the dissolved oxygen concentration.

Due to sensitivity related to effluent characteristics, the identity of specific participants was withheld, as per agreement with the operators.

3.2. Sampling and analysis

Influent and effluent water quality was monitored at each site to ascertain net effects on water quality. Each facility was visited approximately every 6 weeks for 1 year followed by quarterly sampling for an additional year. During each site visit, the following measurements were made: flow rate, water temperature, pH, dissolved oxygen (DO), specific conductance, and turbidity. Additionally, grab samples were collected and analyzed in the laboratory for the following constituents: 5-day biochemical oxygen

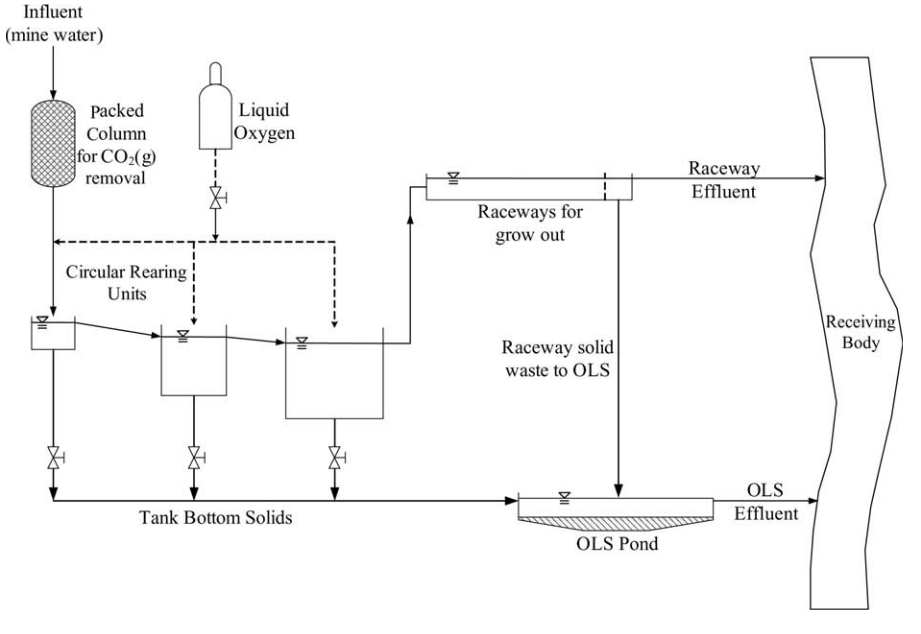

Fig. 1. Process flow diagram of Facility E.

Table 2
Characteristics of the six study facilities

Characteristic	Facility					
	A	B	C	D	E	F
Water source	Spring	Spring	Spring	Spring	Mine[b]	Mine[b]
Annual feed mass kg (lbs)	>18144 (>40000)	<9072 (<20000)	<9072 (<20000)	<9072 (<20000)	>18144 (>40000)	9072–18144 (20000–40000)
Annual fish production kg (lbs)	90718 (200000)	13608 (30000)	13608 (30000)	<9000 (<19842)	57000 (125664)	36000 (79366)
Fish lbs/(gal min) (kg/(m^3 d))	153 (378)	39.3 (97.1)	93.8 (232)	39.4 (97.3)	68.9 (170)	67.7 (167)
Effluent treatment	Sediment basin	Sediment basin	Sediment basin	None	Off-line sediment pond	Off-line sediment pond
Feeding practice	Hand (measured)	Hand (measured)	Automated (pull string)	Automated (pull string)	Hand (measured)	Hand (measured)
Aeration method	Water aspiration	Intermittent use of liquid oxygen	Gravity	Gravity	Liquid oxygen	Liquid oxygen
Feed type[a]	38/11	40/23	40/23	42/16	38/11	38/11

[a] Crude protein to fat ratio.
[b] Same water source used at Facilities E and F.

Table 3
Approved analytic methods used in the study (US EPA, 1999; APHA, 1998)

Analytic parameter	Method (US EPA/APHA)
pH	150.1/4500-H^+
Dissolved oxygen	360.1/4500-OG
Total suspended solids (TSS)	160.2/2540-D
Biochemical oxygen demand (BOD_5)	405.1/5210
Specific conductance	120.1/2510-B
Nitrite (NO^{2-})	353.2/4500
Nitrate (NO^{3-})	353.2/4500
Total ammonia nitrogen (TAN)	350.1/4500
Total phosphorus (TP)	200.7/3120-B

demand, total suspended solids, total ammonia nitrogen, nitrite (NO_2^-), nitrate, and total phosphorus. Samples were collected, preserved, and analyzed in accordance with approved analytic methods, as summarized in Table 3 (US EPA, 1999; APHA, 1998).

3.3. Quality assurance and quality control

A stringent quality assurance/quality control (QA/QC) protocol was established to ensure the generation of reliable and defensible data. Quality assurance procedures for field analysis and equipment followed the recommendations outlined in *US EPA: Handbook for Sampling and Sample Preservation of Water and Wastewater* (US EPA, 1982). The QA/QC protocol for grab samples included triplicate sampling and analyte-specific measures as outlined in *Standard Methods for the Examination of Water and Wastewater* (APHA, 1998). Analytic values below method detection limits were managed in accordance with US EPA protocols and suspected ''outliers'' were subjected to Dixon's Extreme Value Test for analysis prior to removal (US EPA, 1998).

4. Results and discussion

4.1. General water quality trends

Average concentration and mass loads in the influent and effluent, along with the net change in regulated parameters (DO, TSS, TAN, and BOD_5) through each system are presented in Table 4. Further, average water flow rates and ranges are presented in Table 5. In general, concentrations of measured pollutants at each facility were within acceptable ranges and were generally comparable to data summarized by Hinshaw and Fornshell (2002). Further, the generation of pollutants typically correlated with fish production, where higher pollutant concentrations and mass loads were observed at operations, which produced a greater mass of fish. Further, overall trends in mass loading based requirements were generally similar to those presented for concentration-based limits.

pH values were within the regulatory range of 6–9 and remained unchanged through all but two facilities. At Facilities E and F, a statistically significant increase in average pH was

Table 4
Average concentrations and mass loadings of regulated parameters

Facility	DO (mg/L)			TSS (mg/L(kg/day))			TAN (mg/L(kg/day))			BOD_5 (mg/L(kg/day))		
	Influent	Effluent	ΔC	Influent	Effluent	ΔC (ΔM)	Influent	Effluent	ΔC (ΔM)	Influent	Effluent	ΔC (ΔM)
A	9.16	7.25	−1.91	2.5 (17)	11.5 (85.5)	9.0 (68.4)	0.07 (0.47)	0.31 (2.35)	0.24 (1.88)	1.4 (10.2)	4.7 (34.5)	3.3 (24.3)
B	9.33	10.23	0.90	1.8 (5.9)	3.6 (14.1)	1.9 (8.2)	0.07 (0.23)	0.10 (0.36)	0.03 (0.13)	1.4 (6.0)	1.4 (6.0)	0.00 (0.00)
C	9.43	10.4	0.97	2.7 (4.6)	6.9 (12.3)	4.2 (7.7)	0.09 (0.16)	0.21 (0.37)	0.12 (0.21)	1.4 (2.5)	1.7 (3.0)	0.3 (0.5)
D	9.33	8.07	−1.26	3.0 (8.8)	10.9 (36.1)	7.90 (27.3)	0.05 (0.17)	0.23 (0.52)	0.18 (0.35)	1.4 (3.9)	2.4 (6.3)	1.0 (2.4)
E	6.14	7.66	1.52	2.4[a]	7.9[a]	5.5[a]	0.24[a]	0.31[a]	0.07[a]	1.4[a]	4.4[a]	2.9[a]
E OLS	6.14	9.22	3.08	2.4[a]	5.7[a]	3.3[a]	0.24[a]	0.30[a]	0.06[a]	1.4[a]	1.7[a]	0.3[a]
F	9.93	8.25	−1.68	2.4 (13.7)	6.4 (37.4)	4.0 (23.7)	0.03 (0.23)	0.36 (2.15)	0.33 (1.92)	1.4 (9.13)	2.8 (18.6)	1.3 (9.47)
Typical[b]						0–100			0.01–1.52			0–15.6

[a] Effluent from Facility E was split between two outlets (see Fig. 1). Flow split was variable during the study; thus, no mass-based loads calculated.
[b] Hinshaw and Fornshell (2002), UMA Engineering (1979), Boaventura et al. (1997).

Table 5
Average water flow rates and ranges measured at study facilities

Facility	Location of measurement	Method of measurement	Average water flow rate (m^3/d) (range)
A	Influent pipe	Timed volumetric measurement	7142
B	Effluent structure	Rectangular streamlined weir	4166 (1139–8399)
C	End of raceways	Rectangular streamlined weir	1745 (1055–2616)
D	Earthen raceways	Product of water velocity and cross-sectional area	2741(932–5178)
E	Influent pipes	Timed volumetric measurement	2276 (343–3063)
F	Discharge ditch	Product of water velocity and cross-sectional area	6387 (3036–11571)

observed as water flowed through the system. The increase in pH was attributed to the removal of CO_2(g) from mine water via packed aeration columns, followed by additional off-gasing as water flowed through the raceway system.

At all facilities, the average DO concentrations were above the regulatory requirement of 6 mg/L; however a net decrease between average influent and effluent DO concentrations was observed at Facilities A, D, and F. Based on paired *t*-test analyses (conducted at 95% confidence; Hayter, 1994), the change in DO concentration from influent to effluent was not significant at Facilities B or C ($P > 0.05$) over the study period. This observation was attributed to low fish density, adequate reaeration, and sufficient solids removal at the sites. Effluent DO concentrations at Facilities A, D, and F were significantly lower ($P < 0.05$) than influent DO during the study period. Reductions in DO concentration through Facilities A and D were attributed to the higher density of fish and the degradation of biosolids in the sedimentation basin at Facility A and the earthen raceways of Facility D. In contrast, a significant increase in the DO concentration was observed at Facility E, where liquid oxygen was injected directly into process waters.

BOD_5 values were also below the regulated average monthly limit of 30 mg/L, with a high of 12 mg/L occurring at Facility A, the largest producer in the study. A statistically significant increase in BOD_5 concentration was observed between the influent and the effluent at Facilities A and E, with increases of 3.3 and 2.9 mg/L, respectively. However, BOD_5 concentrations never came close to exceeding the regulatory limit of 30 mg/L, at any of the study sites.

All TSS measurements were below the average monthly regulatory limit of 30 mg/L. A high TSS measurement of 25 mg/L was taken at Facility D, which did not have any effluent treatment. However, the peak TSS concentration was still below the regulated maximum daily concentration of 60 mg/L. The average increase in TSS concentrations between the influent and effluent increased significantly at all facilities, where the average change in TSS concentrations ranged from 1.9 to 9.0 mg/L. However, the changes were consistent with literature values ranging from 0 to 100 mg/L, as reported by Hinshaw and Fornshell (2002), UMA Engineering (1979), and Boaventura et al. (1997). The lowest change in TSS concentration was observed at Facility B, which had low fish production and used a sediment pond for effluent treatment. In contrast, the greatest change in TSS was seen at Facility D, which also had low production, though no effluent treatment was used.

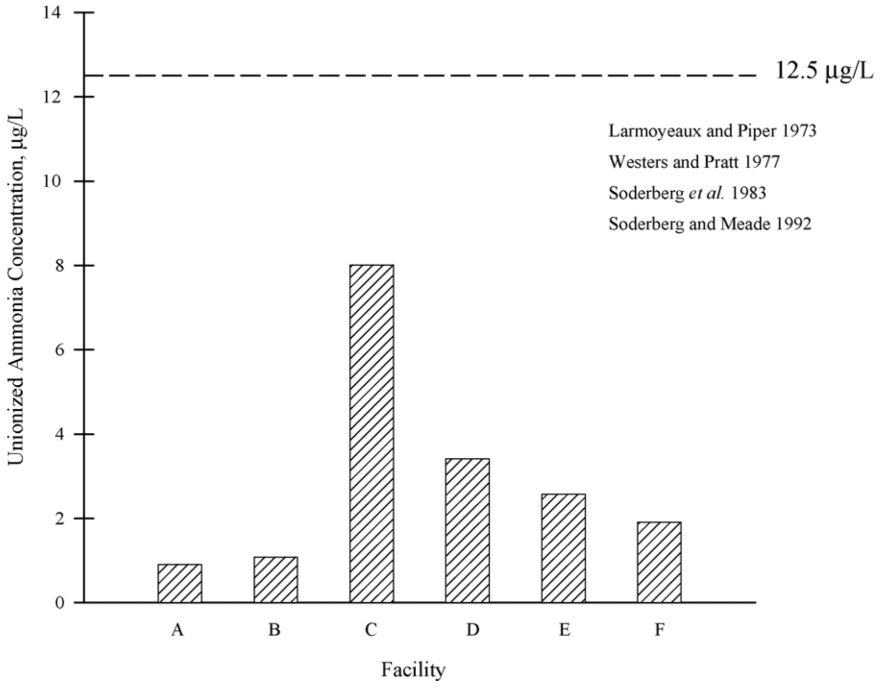

Fig. 2. Effluent unionized ammonia (NH_3–N) concentrations at participating facilities.

All measured TAN values were well below the regulatory limit of 10.4 mg/L, with a high value of 1.0 mg/L occurring at Facility D, the producer with no effluent treatment. In addition to TAN, unionized ammonia (NH_3–N) was produced at each facility. However, NH_3–N concentrations were on the order of $\sim 10^{-4}$ mg/L, as presented in Fig. 2. One accepted NH_3–N threshold for adverse effects on trout is 0.0125 mg/L NH_3–N (Larmoyeaux and Piper, 1973; Westers and Pratt, 1977; Soderberg et al., 1983; Soderberg and Meade, 1992). However, the threshold for NH_3–N effect on growth is disputed and NH_3–N concentrations as high as 0.04 mg/L NH_3–N (Meade, 1985), 0.05–0.2 mg/L (Colt and Armstrong, 1981), and 0.07 mg/L (Thurston et al., 1984) have been reported. Under any of the standards presented above, NH_3–N production at each facility was well below limits for adverse effects to either fish in the culture system or in receiving waters.

4.2. Potential for production increases

Presented in Fig. 3 are the average discharge concentrations of regulated parameters (TSS, TAN, and BOD_5) for each facility as well as West Virginia State NPDES discharge limitations. Since the effluent concentrations of regulated pollutants were well below regulatory requirements, it was believed that each of the facilities had the ability to further increase the density of fish being raised. Consequently, an analysis of additional production potential was made. To simplify the analysis and maintain focus on effluent production, the assessment was based entirely on effluent pollutant load and corresponding discharge

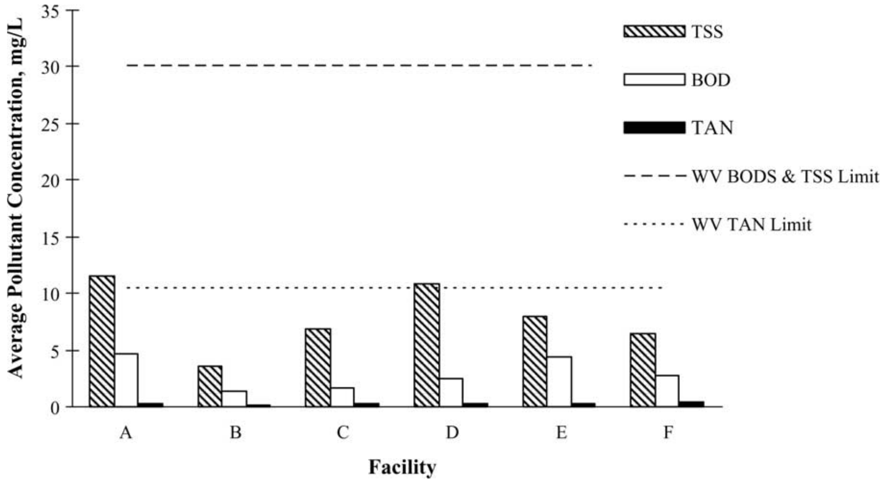

Fig. 3. Average discharge concentrations of regulated parameters (TSS, TAN, and BOD_5) for each facility as well as West Virginia State NPDES discharge limitations.

limits. Factors such as the metabolic requirements of fish and the carrying capacity of each facility were not addressed. TSS was judged to be the pollutant most likely to limit production and was used as a limiting factor in subsequent analyses.

Using the freeboard in TSS concentration, the average effluent TSS concentration and flow for each facility, the mass load freeboard (MLF) was calculated and related to an equivalent amount of feed. The amount of feed was then used to determine the corresponding mass of fish that could be produced, using relationships presented in Eqs. (1) through (3) (IDEQ, 1998).

$$M_p = \frac{C_{fb}Q}{10^3 \text{g/kg}} \tag{1}$$

$$M_{feed} = \frac{M_p}{F_{pp}} \tag{2}$$

$$M_{fish} = \frac{M_{feed}}{1.2} \tag{3}$$

where M_p is pollutant mass (kg/day), C_{fb} freeboard concentration (g/m^3), Q flowrate (m^3/day), M_{feed} feed mass (kg/day), F_{pp} pollutant production factor = 0.300, and M_{fish} is fish mass (kg/day). Species-dependent factors used in these calculations were based on a dry feed with 10% moisture, digestibility of 80%, and a feed conversion of 1.2 (IDEQ, 1998; Castledine, 1986). It should be noted that research-based factors which influence pollutant production and characteristics can be variable; thus, the specifications used in subsequent analyses were selected from the literature as a uniform means for comparison and could be altered based on site-specific data.

Presented in Table 6 are the percent changes in production, which could be realized at each facility based on the current West Virginia TSS limitation and those required in Idaho

Table 6
Potential production impacts of two effluent TSS limitations

Facility	West Virginia 30 mg/L limitation	Idaho and Washington 5 mg/L net limitation	Potential change in production, kg/year (lbs/year)	Potential % change in production
A	133,555 (294,438)	147	−47,120 (−103,882)	−44
B	111,510 (245,838)	819	5,913 (13,036)	170
C	40,922 (90,218)	301	−3,308 (−7,293)	19
D	53,136 (117,145)	390	−16,341 (−36,026)	−37
E	225,593 (497,347)	392	−29,603 (−65,263)	51
F	152,632 (336,496)	421	−9260 (−20,415)	23

and Washington (Colt and Tomasso, 2001; IDEQ, 1998). The opportunity to increase productivity scaled inversely to the existing mass of fish produced at the facilities, due to relative differences in pollutant MLF. For example, based on the West Virginia TSS limitation of 30 mg/L, the lowest potential increase in productivity of 147% was predicted for Facility A, at which the highest mass of fish was raised (Fig. 4). In contrast, a

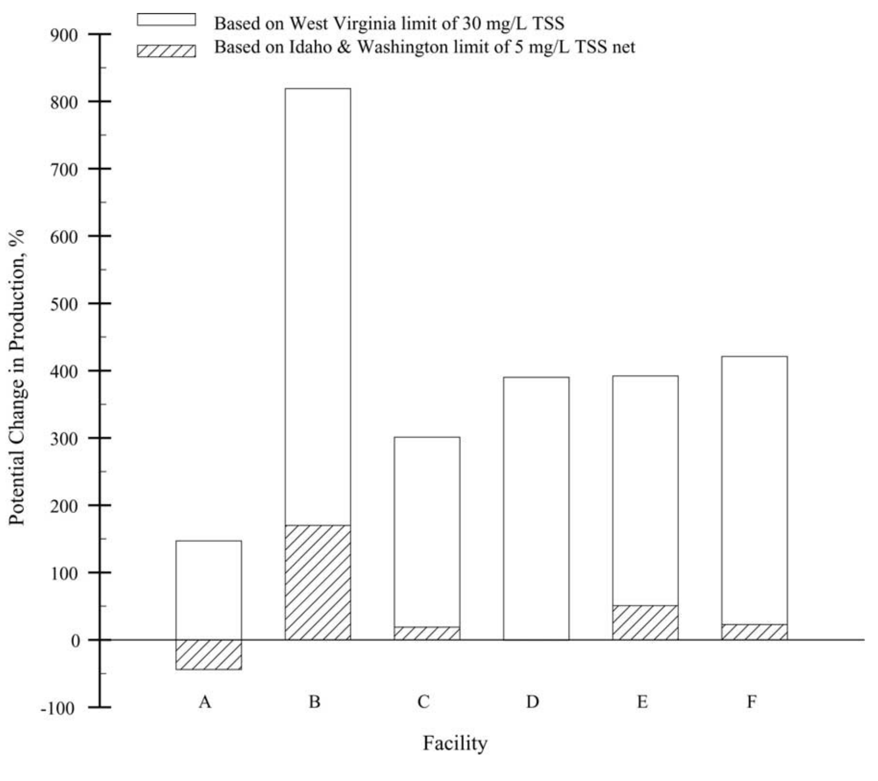

Fig. 4. Current and projected fish production based on West Virginia average monthly TSS limit of 30 mg/L and the Idaho and Washington limits of 5 mg/L net.

productivity increase of 819% was projected for Facility B due to the relatively low mass of fish currently being produced, and the correspondingly greater pollutant MLF. Although the lowest annual mass of fish raised was at Facility D, the potential for future productivity was predicted to be lower than at Facility B, due to the lack of effluent treatment processes at Facility D. Consequently, if even a modest investment in effluent treatment were made at site D, the potential for additional production would increase.

When the lower effluent TSS concentration of 5 mg/L net, required for permitted aquaculture facilities in Idaho and Washington, was used in the analysis, production at sites A and D, would have to be reduced from 37 to 440%. An increase in production was predicted for the other facilities. As a result, the opportunity to increase productivity was a function of existing mass of fish reared at each facility, regulatory requirements, and the presence or lack of effluent treatment processes.

5. Conclusion

The future relevance of more stringent environmental regulations is likely to be non-uniform across the industry in West Virginia and the nation at large, due to the range in annual mass of fish raised at aquaculture facilities. For example, only two of the six operations in this study are likely to be affected (A and E). All of the West Virginia trout rearing operations examined in this study have the potential to increase fish production, based on freeboard between effluent pollutant concentrations/loads and regulatory requirements. It was found that the use of even modest treatment processes such as sedimentation can produce sufficient freeboard in pollutant mass loading to allow for future increases in production, while maintaining regulatory compliance. Consequently, the analyses presented in this study may be used in future economic assessments of the relative costs and benefits of enhancement to effluent treatment works, with emphasis on production potential. Similarly, this approach serves as an equal means for operators to compare production increases with future loading-based regulations such as TMDLs.

References

American Public Health Association (APHA), 1998. Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, Washington, DC.

Bergheim, A., Hustveit, H., Kettelsen, A., Selmer-Olsen, A.R., 1984. Estimated pollution loadings from Norwegian fish farms, II: investigations 1980–1981. Aquaculture 36, 157–168.

Boaventura, R., Pedro, A.M., Coimbra, J., Lencastre, E., 1997. Trout farm effluents: characterization and impacts on the receiving streams. Environ. Pollut. 95, 379–387.

Castledine, A., 1986. Aquaculture in Ontario. Ontario Ministry of Natural Resources, Ontario Ministry of Agriculture and Food, Ontario Ministry of the Environment Publications, Queen's Printer, Ontario.

Cho, C., 1997. Reduction of waste output from salmonid aquaculture through feeds and feeding. Prog. Fish-Culturist 59, 155–160.

Colt, J., Armstrong, D., 1981. Nitrogen toxicity to crustaceans, fish and molluscs. In: Allen, L., Kinney, E. (Eds.), Proceedings of the Bio-Engineering Symposium for Fish Culture, American Fisheries Society, Traverse City, MI.

Colt, J., Tomasso, J., 2001. Hatchery water supply and treatment. In: Wedemeyer, G. (Ed.), Fish Hatchery Management.second ed. American Fisheries Society, Bethesda, MD, pp. 91–186.
Cripps, S., 1995. Serial particle size fractionation and characterization of an aquacultural effluent. Aquaculture 133, 323–339.
Ewart, J., Hankins, J., Bullock, D., 1995. State Policies for Aquaculture Effluents and Solid Wastes in the Northeast Region. Northeastern Regional Aquaculture Center Bulletin No. 300.
Gatlin, D., Hardy, R., 2002. Manipulations of diets and feeding to reduce losses of nutrients in intensive aquaculture. In: Tomasso, J. (Ed.), Aquaculture and the Environment in the United States. U.S. Aquaculture Society, Baton Rouge, Louisiana.
Hayter, A., 1994. Probability and Statistics for Engineers and Scientists. PWS Publishing Co., Boston, MA.
Hinshaw, J., Fornshell, G., 2002. Effluents from raceways. In: Tomasso, J. (Ed.), Aquaculture and the Environment in the United States. U.S. Aquaculture Society, Baton Rouge, Louisiana.
Idaho Division of Environmental Quality (IDEQ), 1998. Idaho Waste Management Guidelines for Aquaculture Operations. Idaho Department of Health and Welfare, Division of Environmental Quality, Twin Falls, Idaho.
Kendra, W., 1991. Quality of salmonid hatchery effluents during a summer low-flow season. Trans. Am. Fish. Soc. 120, 43–51.
Larmoyeaux, J., Piper, R., 1973. Effects of water reuse on rainbow trout to sub-lethal concentrations of ammonia. Water Res. 35, 2–8.
Liao, P., 1970. Pollution potential of salmonid fish hatcheries. Water Sewage Works 117, 291–297.
Meade, J., 1985. Allowable ammonia for fish culture. Prog. Fish-Culturist 47, 135–145.
Ramseyer, L., Garling, D., 1997. Fish Nutrition and Aquaculture Waste Management. Illinois–Indiana Sea Grant Program, Publication CES-305.
Soderberg, R., Flynn, J., Schmittou, H., 1983. Effects of ammonia on growth and survival of rainbow trout in intensive static-water culture. Trans. Am. Fish. Soc. 112, 448–451.
Soderberg, R., Meade, J., 1992. Effects of sodium and calcium on acute toxicity of un-ionized ammonia to atlantic salmon and lake trout. J. Appl. Aquacult. 1, 83–92.
Solbé, J., 1982. Fish-farm effluents: a United Kingdom Survey. In: Alabaster, J., (Ed.), Report of the European Island Fisheries Advisory Commission (EIFAC) Workshop on Fish-Farm Effluents, Silkeborg, Denmark, 26–28 May 1981. EIFAC Technical Paper No. 41, Rome, Italy.
Thurston, R., Russo, R., Luedtke, R., Smith, C., Meyn, E., Chakoumakos, C., Wang, K., Brown, C., 1984. Chronic toxicity of ammonia to rainbow trout. Trans. Am. Fish. Soc. 133, 56–73.
Train, R., Briedenback, A., Beck, E., Schaffer, R., Anderson, D., 1977. Development Document for Recommended Effluent Limitations Guidelines and Standards of Performance for the Fish Hatcheries and Farms Point Source Category. Effluent Guidelines Division, Office of Water and Hazardous Materials, U.S. Environmental Protection Agency, Washington, DC, USA.
UMA Engineering, 1979. Salmon Rearing Facilities Waste Water Study—Waste Characterization. Prepared for the Department of Fisheries and Oceans, Vancouver, British Columbia, Canada.
US EPA, 1982. Handbook for Sampling and Sample Preservation of Water and Wastewater, EPA 600/4-82-029. U.S. Environmental Protection Agency, Washington, DC.
US EPA, 1998. Guidance for Data Quality Assessment, Practical Methods for Data Analysis, EPA 600-R-96-084, Office of Research and Development. U.S. Environmental Protection Agency, Washington, DC.
US EPA, 1999. Methods and Guidance for Analysis of Water, EPA 821-C-99-001. U.S. Environmental Protection Agency, Washington, DC.
US EPA, 2004. Effluent Limitations Guidelines and New Source Performance Standards for the Concentrated Aquatic Animal Production Point Source Category, Final Rule, 40 CFR Part 451, Federal Register, 23 August 2004.
Westers, H., Pratt, K., 1977. Rational design of hatcheries for intensive salmonid culture based on metabolic characteristics. Prog. Fish-Culturist 39, 157–165.