EVALUATION OF RECIRCULATING SYSTEMS FOR THE CULTURE OF CHANNEL CATFISH

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ABSTRACT

Channel catfish can be cultured at high densities in carefully managed recirculating raceway systems. Various flow rates, exchange rates, and tank to filter ratios were investigated in ten recirculating systems employing biological filters, settling chambers and foam strippers. Limestone, shells, styrofoam and teflon rings served as effective filter media, but coal slag restricted water flow and was not satisfactory. An equation was developed to evaluate the effects of system design on water quality. Water quality varies directly with fresh water exchange, flow rate per tank, and the filter size. Production was greater in systems with small tanks and large filters (5 lb/ft^3) than in systems with large tanks and small filters (1 lb/ft^3). Densities in excess of 7 lb/ft^3 per tank have been obtained, indicating recirculating systems may become an increasingly important method of fish culture.

INTRODUCTION

The development of nutritionally complete feeds has permitted the culture of channel catfish under increasingly intensive conditions. Recirculating raceways and tank culture systems have been the subject of several recent investigations (U. S. Dept. Interior, 1972; Liao and Mayo, 1972). In Georgia, outdoor raceways have produced about 20 times as many pounds per acre as that commonly obtained in open ponds (Brown, Chesness, and Chapman, 1971). Some of these raceways are using small oxidation ponds as a biological unit to recondition discharged waters for recirculation. In large outdoor raceways recycling conserves water and minimizes discharges. Discharges are heavily polluted with metabolic waste products of fish; the biochemical oxygen demand (BOD) of 100,000 one-pound fish is equivalent to that of 150,000 one-pound chickens (Murphy and Lipper, 1970). If the government requires discharge permits for fish framing operations and discharges must be limited, recycling water through culture systems may be more economical than flow-through raceways.

Indoor flow-through raceways using high turnover rates and heated water have been used to intensively culture catfish throughout the year (Knight, 1970; Andrews *et al.*, 1971; Stickney, Murai, and Gibbons, 1972). An indoor closed raceway permits an economical control of temperature and a greater control of other environmental factors than do open outdoor systems. Indoor recirculating raceways have been investigated for their production potential during the winter months (Allen, 1972) and throughout the year (Simco, 1972). We are presently studying the effects of varying flow rates, exchange rates, filter and tank sizes on recirculating systems.

This work was supported in part by an MSU Faculty Research Grant, OWRR Grant B-028-TENN, Ralston Purina Co. and by the Fish Farming Experimental Station, Bureau of Sport Fisheries and Wildlife, Stuttgart, Arkansas.

DESIGN AND OPERATION

Ten recirculating systems have been constructed at Memphis State University since August, 1970, and another system is presently being assembled. The systems have employed from one to seven tanks each, a biological filter, a primary settling chamber, a final clarifier, and a pump arranged in a basic flow scheme (Fig. 1). Slight deviations from this basic scheme produced individual systems with distinct capabilities (Table 1).

System S-1 was the first and least productive system. Each system built thereafter was designed to serve specific functions and, when it fulfilled its usefulness, was disassembled with the component parts being used in other systems. Seven of the systems are now in use and are all located indoors.

In any recirculating system the drains should be as large as possible. Slime producing bacteria proliferate in the nutrient rich waters of intensive culture systems and with the normal detritus present can block drain lines. Tank drains smaller than 2" proved ineffective in our systems. Collection lines feeding into the filter must be at least twice this large. Globe valves were unsatisfactory; however, gate valves open fully, are easily cleaned when clogged, and cost only slightly more than the globe valves.

In our system S-2, water was originally pumped at the rate of 10 gpm/tank, but after two years the flow was restricted to 2 gpm/tank and the distribution lines had to be replaced. In S-7 the original flow rate was 70 gpm but declined to 45 gpm in 6 months. The distribution lines were cleaned and subsequently the flow increased to 60 gpm.

Our only water source is chlorinated city water and large or rapid additions of fresh water cannot be tolerated. Fish metabolism tends to lower the pH of recirculating systems and some buffering agent is necessary. Mollusc shells and, to a lesser extent, crushed limestone serves as a satisfactory buffering material. The buffering agent should be placed so that it remains in continual contact with moving water. If the shells are allowed to become coated over the detritus, their buffering action is reduced. Shells placed so that water trickles over them tend to remain clean and provide proper buffering, yet still serve as a site of attachment for filter microflora.

Jetting of water into tanks has been more effective than either spraying or splashing for increasing oxygen levels. Openings reduced to produce a jetting action quickly become clogged in recirculating systems. Tank distribution lines become clogged not only by the bacterial slime, but also by snails, plants, and any other debris pulled into the pump. The pump intake must be protected, and any protective screening must be cleaned daily. If the pump is placed before the filter and gravity flow is used to return water to the tanks, a distribution flume will be satisfactory. The use of "V" - notches to distribute water from the flume will reduce the problem of clogged intake lines. If any mechanical failure occurs in a heavily stocked system, the reaction time before the problem is corrected is critical. In heavily stocked tanks an interruption in water flow of 30 to 45 minutes may kill all of the fish; more fish have been lost to mechanical failure than to disease in our systems. Pumps need to be protected by float switches that shut off the pump in case the pump out chamber goes dry. Makeup water added through a float valve on the incoming water line will continually replace water lost by leakage, splash-out, or evaporation. If possible, a 100% backup for pumps, electrical power, aereators, and water supplies should be provided. Electrical power failures terminated some of our earlier studies, but now all of our systems are protected with self-starting emergency generators.

Regardless of how well a system is designed and its degree of built-in protection, it can be no more successful than its management will allow. Fish under intensive culture are subjected to very unnatural conditions. Poor management techniques that might normally pass unnoticed in outdoor ponds, or that could be quickly corrected in flow-through systems, become disasters in recirculating systems. The filter must always be protected to maintain water quality. Any disease or parasite treatment used must be handled to minimize delterious effects upon the filter. In a recirculating system any pathogen found in one tank quickly spreads to all other tanks. Although fish may be treated immediately after diagnosis, intolerable losses may still result under intensive conditions. Disease free fish are a must. If new fish are to be introduced into the system, they should be treated before stocking. Once new fish are placed into the system we have found the first two weeks to be the most critical. If during this time the fish can adapt to the new environment, their chances for continued survival are good. To survive, the fish must adapt to the crowding and handling stresses, and to the possible changes in water conditions reflected by D. O., pH, NH_3, turbidity, temperature, hardness, etc. Conditions that would be satisfactory for lightly stocked extensive cultures may be lethal for heavily stocked intensive cultures. Toxicants and disease organisms are not diluted but are intensified in closed recirculating systems. The innocous occurrences, such as over feeding, that might be acceptable in a pond cannot be tolerated in closed systems. Uneaten food may over tax filter capabilities. Proper management is the key to success in a closed system.

Indoor systems do not reflect the diel fluctuations observed in outdoor systems (Figs. 2 and 3). In one of our recirculating systems exposed to sunlight an intensive bloom of *Scenedesmus dimorphos* developed and fish mortalities resulted due to mechanical obstruction of the gills. At a concentration of 0.05 g/l, oven dried weight, gills were blocked; but below 0.03 g/l, no mortalities occurred (Parker, 1972).

In any system waste components are in two phases, solid and dissolved. Before dissolved waste products can be effectively handled the solids must be removed. Solids can be removed by chemical floculation, centrifugation, pressure filtration, or settling. Metering chemicals for floculation requires not only the expense of chemicals and control devices, but also the removal of those chemicals to prevent toxicity to the fish. Centrifugation and pressure filtration both have high energy requirements and pressure filters on intensive culture systems must be continually backwashed. The simplest and least expensive method of solid removal is settling. Settling chambers can be compactly designed to effectively remove solids (Culp and Conley, 1970).

A settling chamber with large internal surface areas separated by weirs allows for the progressive removal of solids from the water (Fig. 4). Such a settling chamber should be cleaned by drawing solids from the bottom allowing the internal surfaces to remain coated. The internal surfaces provide a site for bacterial attachment, and the settling chamber thus serves also as a biological filter. The solids removed are excellent organic fertilizers (Parizek *et al.*, 1967).

Dissolved waste products, specifically ammonia, are the most toxic and potentially limiting metabolites in a recirculating system. Biofilters can detoxify ammonia through the nitrogen cycle first to nitrites and then to nitrates. The nitrification process is more efficient at high oxygen levels but occurs to some extent under low oxygen levels (Spotte, 1970). As oxygen levels decrease and anaerobic bacteria replace the aerobic bacteria, ammonification and deamination begin to occur more rapidly than nitrification. This results in a "sour" filter and toxic anaerobic metabolites increase in the system.

Insufficient removal of solids prior to biofiltration accelerates the loading of the filter and lowers oxygen levels in the filter bed. Thus as solids increase in the filter bed, conditions change from aerobic to anaerobic and toxic metabolites begin to increase. Ideally, biological filters would be self-cleaning and slough off old cells and particulate matter before anaerobic conditions develop. The loading and cleaning capacity of a filter is largely determined by the type of media used in the bed. Historically, sand and gravel have been most commonly used in filter beds. Smaller particles have a larger surface area per volume than do large particles; finer sand and gravel would furnish more surface area for bacterial attachment. However, as the particle size decreases, the void spaces between particles decrease, and the filter bed tends to load up faster. Water channelizes through a loaded filter and oxygen levels decrease in those areas without an adequate flow of water, and anaerobic bacteria begin to predominate. Al alternative to the sand-gravel media is a plastic media. Several types of plastic media are now on the market for use in sewage treatment plants (Pazar, 1971). Granite weighs approximately 90 lb/ft^3 whereas the plastic media weighs only about 5 lb/ft^3. The surface area of the plastic media (27 ft^2/ft^3) is about equal to granite (30 ft^2/ft^3), but the void space is about twice as great (plastic, 95% void; granite, 45% void). In addition to weight reduction the plastic material tends to move slightly with water flow and is somewhat self-cleaning. Plastic media resists channelization in updraft and submerged filters. Even in trickle filters small sized gravel will load until water cannot flow through it, but plastic media of similar size will remain functional. In trickle filters a styrofoam packing material has been very effective. It provides large surface areas for bacterial attachment, is extremely light weight, and has large void spaces to facilitate high oxygen tensions in the filter bed. Due to its bouyance it is not suitable for updraft or submerged filters.

Of the three types of filters, submerged, updraft, and trickle, the updraft and trickle seem more adaptable to intensive culture systems. The submerged, in which the water flow is horizontal through the filter bed, loads up more quickly and is more difficult to backwash than the other two types. The trickle and updraft filters tend to be self-cleaning and require only infrequent backwashing. Frequent backwashing of any biological filter removes the bioflora and reduces its effectiveness until the bioflora is reestablished. The filter in our system S-2 was initially backwashed weekly and ammonia levels increased to approximately 7 ppm. When the filter was allowed to age without backwashing, ammonia levels declined and normally remained below 1 ppm. Although trout normally tolerate only about 3 ppm of ammonia (Liao and Mayo, 1972), channel catfish survived 22 ppm ammonia during a power failure and generally fed well up to levels of 5 ppm.

Partially submerged rotating discs have been investigated as a means of sustaining an aerobic microflora in filters that might normally be low in oxygen (Borchardt, 1971). The rotating discs were designed for sewage treatment and were effective in handling sudden loads which might normally over tax filters of other designs. We are presently investigating rotating discs and baskets for their adaptability to intensive recirculating culture systems. The rotating filter media which is only intermittently submerged should remain aerobic and be self-cleaning.

After any biological filter a final settling chamber or clarifier is essential. Clarifiers with circular water flows have been designed to spin out the particulate matter, and then to reduce the water velocity to settle out more solids.

Vigorous agitation causes foaming if there is a high content of organic matter in the water. Removal of this foam results in a reduction of BOD. A continuous feed foaming apparatus can be any device that will produce and remove foam. Foam collecting collars placed around agitators allow the foam to rise out of the water and dry to a solid. A counter-current flow of air and water through a vertical pipe has effectively produced and removed foam. A foam stripper can also be constructed of an aspirator with a foam collecting platform wherever water is being released under pressure. In our system S-2 we placed two foam strippers on the inlet of T-1 (tank 1) and one stripper in T-2, but water was jetted directly into T-3. Jetting produced better oxygenation than the foam strippers; however, oxygen was higher at the effluent end of the tanks with strippers than in those without. The lower oxygen consumption in tanks with foam strippers was attributed to BOD removal.

In any system, the flow rate into each tank controls the exchange of that tank. In flow-through systems it appears that the optimum exchange rate may be about 1.5 hours per exchange (Allen, 1972). In trout culture, ammonia levels have been directly related to water inflow and not to the changeover rate within the raceway (Speece, 1973). In our recirculating systems faster exchange rates have been more productive. In system S-3, ammonia levels increased not only with stocking density but also inversely with exchange rate. Exchange rates of 6 or 7 minutes per tank maintained water quality similar to the filter effluent, but lower exchange rates allowed waste metabolites to accumulate in the tanks.

The maintenance of satisfactory water quality in a recirculating system is affected not only by management but by system design. In a flow-through system, water quality is directly proportional to the volume of inflow. In a recirculating system other factors drastically affect water quality. The ratio of the tanks to filter volume (R_a), the time (T) it takes all water to pass once through the filter, the exchange rate (E) or percent of fresh water added per day, the retention time of the water in the tanks (R_t), and the retention time of water in the filter (R_f) are all intricately related to water quality. Obviously the larger the filter, or the lower the tank/filter ratio, the better water quality should be. Also, faster turnover of the recycled water and shorter retention time in the tanks results in improved water quality. As the retention time in the filter increases, and as the percent of fresh water added per day increases, the water quality increases. These realtionships are expressed by the equation,

$$Q = \frac{R_f \times E}{R_t \times T \times R_a} \qquad \text{(Equation 1)}$$

where Q is water quality, R_f is retention time in the filter in minutes, E is the exchange or percent of fresh water added to the system per day, R_t is the retention time in the tank in minutes, T is the turnover time or the time in minutes for all the water to pass through the filter once, and R_a is the tank to filter ratio. Water quality, Q, is a numerical evaluation of the relationships of these factors that influence water quality through system design. Water quality, Q, increases proportionally with the fresh water exchange (E) and flow rate, but varies inversely with retention time per tank and tank to filter ratio.

Using this equation we can analyze any given recirculating system and determine if it would be more practical to increase fresh water exchange, water flow into the tank, or the size of the filter to improve water quality. The equation

$$W = F \times L \times I \qquad \text{(Equation 2)}$$

where W is the total weight in the system of the carrying capacity, F is the loading factor for the system, L is the average fish length in inches, and I is the gpm of the fresh water inflow, was developed for the trout industry (Piper, 1970). This equation is used to predict carrying capacities in flow-through raceways for fish of any given length. Since the carrying capacity cannot be directly related only to gpm in a recirculating system, this equation must be modified for use in recirculating systems. Substituting Q for I the equation becomes

$$W = F \times L \times Q \qquad \text{(Equation 3)}$$

and from equation 1 we develop

$$W = \frac{F \times L \times R_f \times E}{R_t \times T \times R_a} \qquad \text{(Equation 4)}$$

These equations only indirectly evaluate the filter efficiency of a recirculating system, but they do so on empirical terms. When any factor (ammonia, D. O., pH, BOD, CO_2, etc.) becomes limiting, the carrying capacity will have been reached under those conditions and the loading factor can be determined. To evaluate the effectiveness of different methods of water purification, types of filter media, or perhaps the effect of foam strippers in any one system, respective carrying capacities can be established and the resulting loading factors compared. This equation has its limits, as any system has a finite carrying capacity; however, this equation can be used to evaluate the design of recirculating systems.

For example, to predict water quality in a recirculating system consisting of a 3000-gallon tank, a 1000-gallon filter, a pump rated at 60 gpm, and a 10% exchange rate, equation 1 is used.

$$Q = \frac{R_f \times E}{R_t \times T \times R_a}$$

Substituting into the equation: (Equation 1)

$$Q = \frac{1000/60 \times 0.10}{3000/60 \times 4000/60 \times 3}$$

$Q = 1.67 \times 10^{-4}$.

The Q of the same system when the pumping rate is doubled to 120 gpm becomes:

$$Q = \frac{1000/120 \times 0.10}{3000/120 \times 4000/120 \times 3}$$

$Q = 3.33 \times 10^{-4}$.

Doubling the fresh water exchange rate would result in:

$$Q = \frac{1000/60 \times 0.20}{3000/60 \times 4000/60 \times 3}$$

$Q = 3.33 \times 10^{-4}$.

Doubling the filter size would also increase Q:

$$Q = \frac{2000/60 \times 0.10}{3000/60 \times 5000/60 \times 1.5}$$

$Q = 5.35 \times 10^{-4}$.

Instead of raising fish in the 3000-gallon tank and using a 1000-gallon filter, reverse the situation to a 1000-gallon tank, a 3000-gallon filter, a 60 gpm pump, and a 10% exchange:

$$Q = \frac{3000/60 \times 0.10}{1000/60 \times 4000/60 \times 0.33}$$

$Q = 1.34 \times 10^{-2}$.

This theoretical system having a Q of 1.34×10^{-2} is similar to our system S-7 ($Q = 1.89 \times 10^{-2}$), with a 0.047% exchange in which we have produced 5.3 lbs/ft^3 for the entire system. Thus, a 4000-gallon (476 ft^3) system might produce approximately 2400 pounds of fish. The original example (tank/filter, 3:1) with a Q of 1.67×10^{-4} compares to our system S-2 ($Q = 1.48 \times 10^{-4}$) where the maximum production was 1.35 lbs/ft^3 in the system. With a similar production the theoretical system with the 3000-gallon tank could produce only 644 pounds of fish. The carrying capacity and water quality of recirculating systems increase as the filter size, flow rate, or exchange rate increase (Fig. 5).

The potential carrying capacity of a recirculating system is dependent upon the design of the system. The most valid method for comparing loads in recirculating systems may be the total pounds of fish per cubic foot of the system. This accounts for the volume of water in the filter as well as in the tank. Our systems have produced from 1.1 (S-1) to 7.2 (S-7) lbs/ft^3 in the tank; however, the same loads are 0.34 (S-1) and 5.3 (S-7) lbs/ft^3 of water on the system basis. In terms of flow rate they are, respectively, 7.3 and 9.0 lbs/gal. per minutes. Thus on a lbs/gal. per minutes basis the two systems may seem almost comparable when in reality they are very dissimilar in terms of their carrying capacities.

The upper limits for fish production in closed systems have not been established, but commercially feasible production levels are being approached. To compare our small systems with a large commercial size unit, we calculated Q for a typical controlled environment system designed for rearing salmon (Burrows and Combs, 1968). This system featured 20-75′ x 16′ rearing ponds with 8-75′ x 20′ filters, a flow rate of 12,000 gpm and a water exchange of 2% of the pumping rate (330% exchange/day). Assuming a pond depth of 4 ft the Q for this system is 8.0. Our Q values are at least approaching the range of this production size unit. If a comparable amount of fresh water were added to our system S-7 (3.3 exchanges/day rather than the rate of one exchange/21 days), it would have a Q value of 2. By increasing filter size, flow rate, and exchange rate, recirculating systems with higher Q values can be designed; but as designs become more elaborate, costs increase. The design which will be most economical is dependent upon such factors as the local water supply, heating requirements, and market demand.

SUMMARY

Ten recirculating systems have been built at Memphis State University to evaluate their feasibility for the culture of channel catfish. Indoor systems are relatively stable and do not exhibit the diel fluctuations of D. O., pH, CO_2, etc., found in outdoor ponds. Intensively stocked systems have high nutrient levels that result in dense algal blooms in outdoor systems. Sedimentation seems to be the most economical and reliable method for removal of solids. Solid removal lowers BOD, potential ammonia, and nutrient levels. The solids removed are excellent fertilizers.

Self-cleaning settling chambers and final clarifiers remove particulate matter and extend the life of biofilters. Biofilters will quickly detoxify ammonia to less innocous nitrates. Light weight filter material with large void spaces was appropriate for intensive culture systems. Partially submerged rotating discs which are self-cleaning and aerobic may be an effective filter which will tolerate sudden loads of waste. If dissolved organic substances accumulate, the addition of foam strippers can reduce the BOD load in the system.

Water quality is limited by system design; the design determines the maximum water quality obtainable when proper management practices are followed. Water quality in a flow-through system is controlled primarily by the rate of inflow. In a recirculating system water quality is controlled by the fresh water inflow or exchange rate, the flow rate per tank, and the filter size. An increase in any of these variables will result in an increase in water quality. A formula relating water quality with these variables has been prepared. The design of any recirculating system is dependent upon the economics of constructing and maintaining that system as related to the local water supply, heating costs, and market demand.

Our recirculating systems have produced in excess of 7 lbs/ft^3 per tank and over 5 lbs/ft^3 for the entire system. As the market increases, supply decreases, and land and water become more limited, the production of fish in recirculating systems may become an increasingly important method of fish production.

Table 1. Characteristics of Memphis State University recirculating raceway systems.

System number	Filter retention time (R_f)	Tank retention time (R_t)	Turnover time (T)	Tank: filter ratio (R_a)	Maximum water quality (Q)
S1	17.8	168.0	180	8.5:1	4.09×10^{-6}
S2	11.2	33.6	45	3.0:1	1.48×10^{-4}
	22.4	72.0	90		6.88×10^{-5}
S3	25.0	7.0	88	1.9:1	1.28×10^{-3}
	33.3	80.0	117		1.12×10^{-4}
S4	11.2	28.0	39	2.5:1	2.46×10^{-4}
S5	8.4	21.0	29	2.5:1	3.32×10^{-4}
S6	13.0	33.6	47	2.6:1	1.89×10^{-4}
S7	13.6	6.0	9	0.4:1	3.31×10^{-2}
	21.1	9.3	14		2.39×10^{-2}
S8	6.4	2.7	25	3.0:1	1.90×10^{-2}
		27.3			1.90×10^{-3}
S9	34.4	33.6	54	1.0:1	1.13×10^{-3}
S10	11.2	22.4	33	2.0:1	4.48×10^{-4}
S11	12.8	21.0	34	1.7:1	6.40×10^{-4}

Table 1. (Cont.)

System number	Tanks (gal)	Tanks (no.)	Filter (gal)	Total water (gal)	Flow rate (gpm) tank	Flow rate (gpm) filter	lbs/gal/min	lbs/ft³/tank	lbs/ft³/system
S1	336	7	250	2550	2	14	7.3	1.1	0.34
S2	336	3	336	1344	10	30	14.5	2.2	1.35
					5	15			
S3	400	6	1000	3500	5	40	17.3	6.7	1.12
	55	2							
S4	420	2	336	1176	15	30	*	*	*
S5	420	2	336	1176	20	40	*	*	*
S6	336	3	390	1398	10	30	*	*	*
S7	420	1	950	640	70	70	9.0	7.2	5.3
S8	110-		510	2050	10-		**	**	**
	265	8			40	80			
S9	336	6	2059	3238	10-		**	**	**
					30	60			
S10	336	2	336	1008	15	30	*	*	*
S11	420	2	510	1350	20	40	*	*	*

*Used for experiments other than growth studies
**Production studies not yet completed.

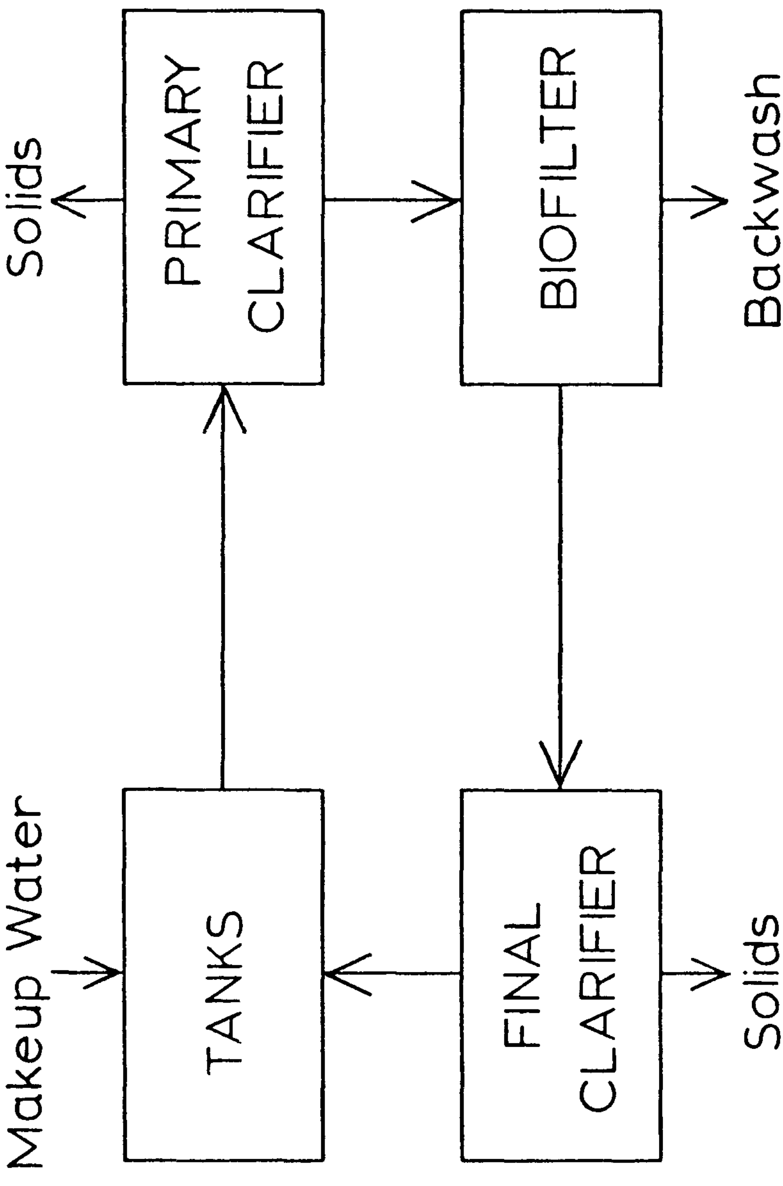

Figure 1. Basic flow scheme for MSU recirculating systems.

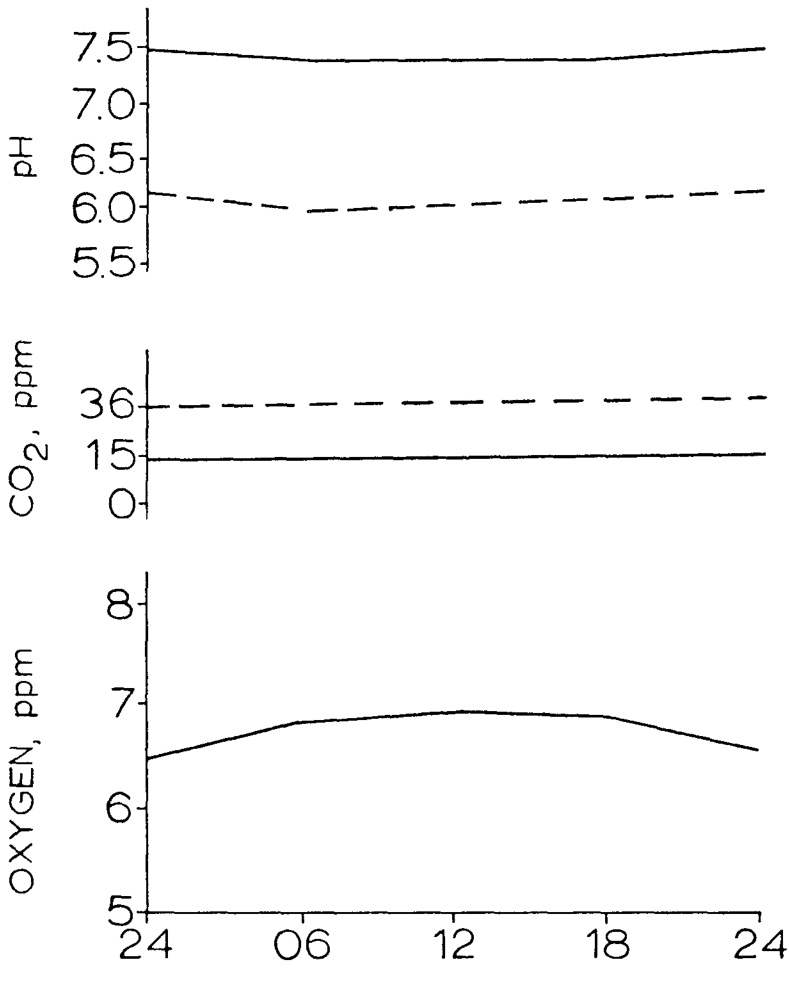

Figure 2. Diel water characteristics of an indoor recirculating raceway system before (dashed lines) and after (solid lines) buffering with shells and limestone.

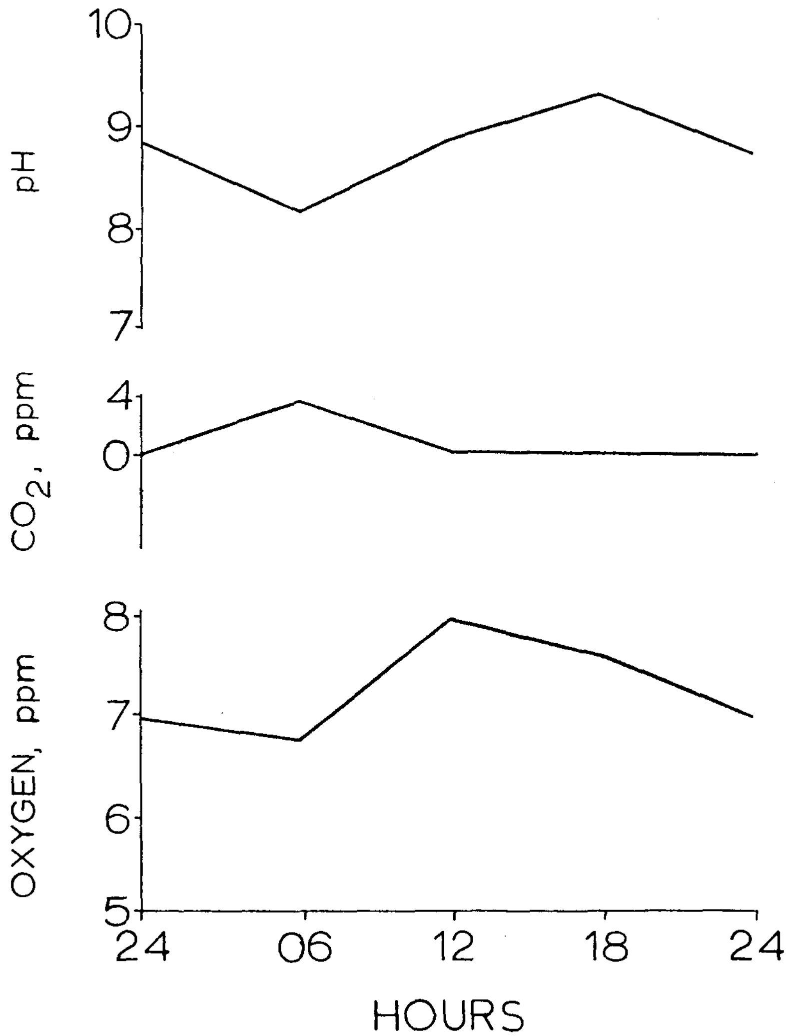

Figure 3. Diel water characteristics of an outdoor recirculating raceway system.

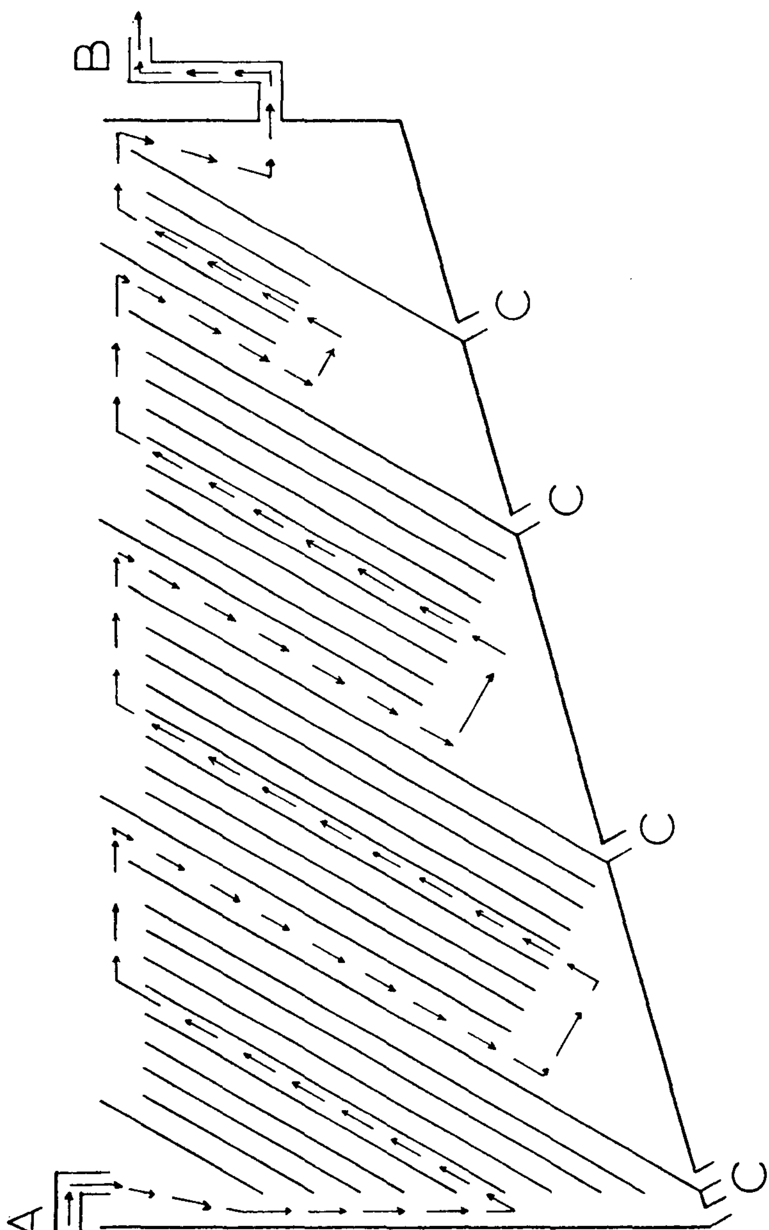

Figure 4. Settling chamber with multiple tube-clarifiers (A—influent; B—effluent; C—sludge drains).

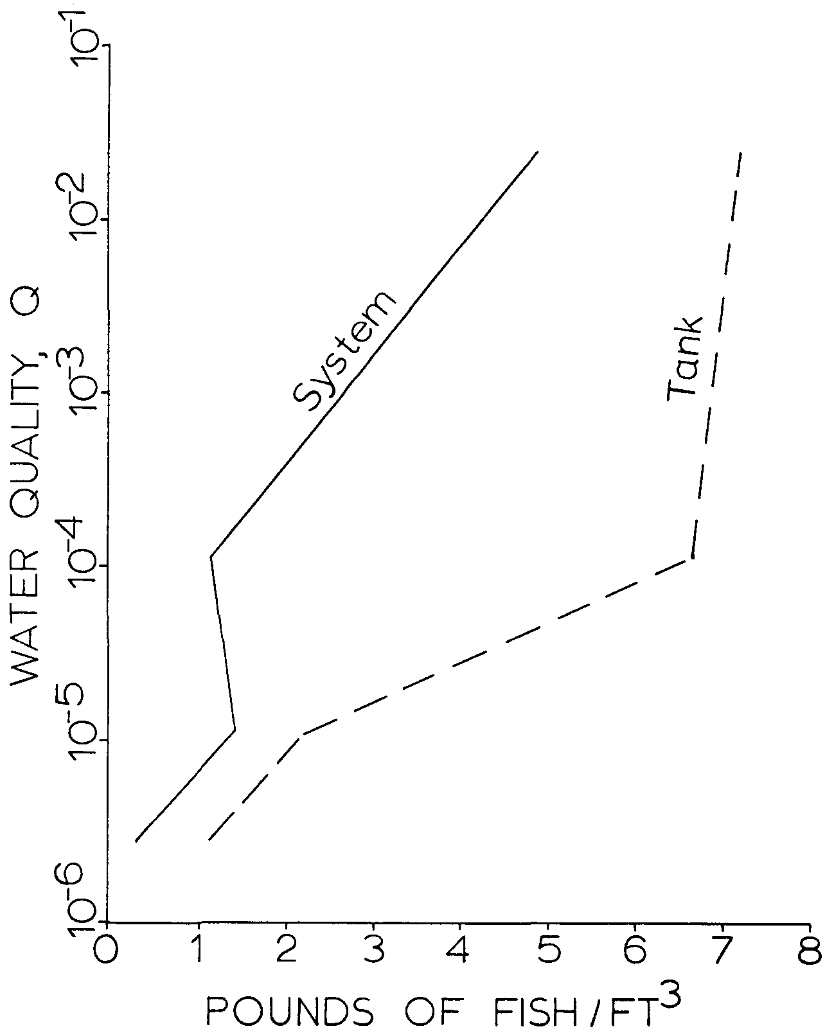

Figure 5. Standing crops of fish obtained in recirculating systems having various water quality, "Q," values.

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